HIWeather

A research activity on High Impact Weather
within the World Weather Research Programme

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EXECUTIVE SUMMARY

Despite substantial advances in both forecasting capability and emergency preparedness, recent years have seen a large number of natural disasters that have cost many lives, displaced large numbers of people, and caused widespread damage to property and infrastructure. Many of these disasters result from severe weather interacting with society. At the same time, less severe weather events place a continuing strain on society through more frequent impacts of smaller magnitude. This is especially evident in less developed countries with more fragile economies and infrastructure. In addition, weather forecasts are becoming increasingly important for economic applications (e.g. forecasting energy supply and demand) and for protecting the environment. In all these areas users of weather information expect more sophisticated guidance than was the case ten years ago.

The THORPEX programme delivered major advances in the science of weather forecasting thus providing the knowledge basis for improving early warnings for many High Impact Weather events for one day to two weeks ahead. At the same time, new capabilities in short range forecasting arising from the use of new observations and convective-scale Numerical Prediction Models and Ensemble Prediction Systems have made it possible to provide warnings of weather-related hazards, directly, up to one or two days ahead. Together with advances in coupling prediction models and better understanding by social scientists of the challenges to achieving effective use of forecasts and warnings, these advances offer the basis for a dramatic increase in the resilience of communities and countries to the threat of hazardous weather and its impacts. The time is ripe to capitalise on these advances. The High Impact Weather project (HIWeather) is a ten year activity within the World Weather Research Programme 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"

The scope of the project is defined by the needs of users for better forecast and warning information to enhance the resilience of communities and countries in responding to a carefully selected set of hazards. While not comprehensive, they cover a wide range of impacts so that advances in building resilience to them may be expected to have more general relevance. The selection has been guided by their importance as a cause of disasters, by relevance to developing countries, by vulnerability of those living in megacities, and to span the complete range of climate regimes.

Urban flood: including flooding from the sea, rivers and directly from rainfall that exceeds drainage capacity, and including rain-induced landslides; with particular emphasis on flood impacts in the growing megacities of the developing world, especially those situated in the tropics and subtropics. Flooding is the most common cause of disasters in the world today. Since most of the world's major cities lie either on the coast or on a major river, the problem is set to increase as cities grow, sea level rises, and the hydrological cycle becomes more intense in a warming atmosphere. Management of floods varies according to their scale and source. For large river floods with large forecast lead times, river controls can be used to either make space for the water or to retain it upstream of vulnerable populations. For coastal floods with large lead times, evacuation may be most appropriate. For flash floods and surface water flooding, local protection and movement of people requires more precise forecasts at much shorter lead times.

Wildfire: emphasising requirements associated with fire fighting and fire management as well as prediction of fire risk. Increasing use of wilderness areas for recreation and the spread of human settlement into forested areas are both increasing the risk from this hazard. Fire is associated with drought and high temperatures, so there will be opportunities for linking with the Sub-seasonal-To-Seasonal project in extended range prediction of these conditions. However, management of live fires also requires a detailed knowledge of both the vegetation state and wind, which can only be predicted for very short periods ahead.

Localised Extreme Wind: including localised wind maxima within tropical and extra-tropical cyclones (e.g. sting jets), downslope windstorms, and tornadoes. Great advances have been made in the prediction of both tropical and extra-tropical cyclones over the past decade, but wind damage and disruption mostly occur in small areas, e.g. within embedded mesoscale and convective scale weather systems. Decisions on appropriate protective action depend on knowing the location, timing and intensity of these localised wind maxima.

Disruptive winter weather: including snow, ice, fog & avalanche, and focussing on transport, energy and communications impacts. While not usually the cause of disasters, this collection of hazards, with related meteorological causes and overlapping impacts, is a major source of social and economic disruption in mid- and high-latitude regions. There will be opportunities to work with the Polar Prediction Project on this hazard.

Urban Heat Waves and Air Pollution: while extreme heat and poor air quality may occur separately, both are associated with long-lived weather patterns, both give rise to similar health responses, and major heat-related disasters tend to involve both ingredients. There will be opportunities to work with the Sub-seasonal-To-Seasonal project on the extended range predictability of blocking events, but the main focus will be on the spatial and temporal variability of the hazard and the influence of the urban fabric through emissions and heat fluxes from the built environment.

The research required to deliver enhanced resilience to these hazards will be carried out in five themes that cover areas traditionally separated into the physical and social sciences. Achieving the outcomes of the HIWeather project depends on these two scientific communities working together. Research objectives have been identified within each theme that, together, will enable specific advances in the management of impacts from the five hazards. Many of the initial activities in the themes will be focused on gathering and sharing evidence of current best practice, to bring the communities together, for use as a springboard for new work and to support capacity building through knowledge exchange activities.

Predictability and Processes. Research will be focused on the meteorological processes that influence the predictability of High Impact Weather: control of convective-scale predictability by large scale processes in tropical & extra-tropical latitudes; differences in predictability of hazardous weather relative to “normal” weather; association with forecasts that are very sensitive to initial state; mechanisms that produce quasi-stationary hazardous weather systems; role of diabatic heating; role of boundary layer and land surface; pre-conditioning of the land surface for hazards. These research challenges will be addressed through the use of datasets from recent and planned field experiments, especially the planned North Atlantic waveguide experiment, NAWDEX/DOWNSTREAM, Lake Victoria experiment, LVB-HyNEWS, and La Plata basin experiment, ALERT.AR/RELAMPAGO, through co-ordinated case studies and model inter-comparisons, and in review papers and targeted workshops.

Multi-scale Forecasting of Weather-Related Hazards. Research covers the observations, nowcasting, data assimilation, modeling and post-processing required to forecast weather-related hazards using coupled numerical weather, land surface, ocean and chemistry models, including modeling of floods, landslides, bushfires, air pollution etc. Research will focus on advances in the whole prediction chain needed to forecast the hazards, on prediction at convective-scale (<3km), on coupled modeling and on the use of ensembles to quantify probability and uncertainty. Specific activities will be carried out reviewing the use of existing and new observation sources; comparing new approaches to multi-scale coupled modeling and data assimilation systems, drawing on parallel activities in the Sub-seasonal-To-Seasonal project; developing ensemble perturbations for small scales and hazards; and meeting the product specifications identified by the Communications theme. The research will make use of a catalogue of hazardous weather case studies developed with the Predictability & Processes theme, together with datasets from recent and planned field experiments, re-analyses and re-forecasts, and will demonstrate and evaluate new techniques in Forecast Demonstration Projects.

Human impacts, Vulnerability & Risk. Research will be led by social scientists, with a focus on the interface between the physical hazard and the human impact. It will cover modeling of the role of the built environment in hazards, and of the exposure and vulnerability of individuals, businesses and communities. Workshops are planned to draw the physical and social science communities together through agreed definitions of key words and concepts, which will be documented in a white paper. Research will initially focus on building a community of interested scientists across NHMSs, academia and the private sector to review recent experience and current capabilities, to document the requirement and state-of-the-art in meeting it, and to identify and prioritise gaps in hazard prediction inputs, impact models and evaluation capability. This will inform subsequent activities in impact monitoring and in the construction, evaluation and deployment of impact models. Identifying and sharing best practice will be a recurrent activity for this theme, while Demonstration Projects will provide opportunities for evaluating new capability.

Communication. Research will focus on the choices of information content, language, format and media channels used, spatial and temporal precision, timeliness and context that together determine whether forecasts & warnings will be received, trusted, understood and acted on. A catalogue of post-event reviews will be developed, together with regular surveys and workshops involving weather services, private sector meteorologists and key user groups. This will be used to assess high impact weather communication methods and their transferability, leading to a published review paper. This initial work will inform subsequent activities in developing communication methodologies and monitoring responses. Identifying and sharing best practice will be a recurrent activity for this theme. New capability will be evaluated in Forecast

Demonstration Projects and success stories shared. Workshops and special sessions at conferences will be convened and a journal special issue is planned to attract social scientists to contribute in this field.

User-oriented Evaluation. Research will focus on the profile of accuracy and value through the forecasting, warning & communication chain with an emphasis on the information required by decision makers to build their trust in the information they receive. An inter-comparison project will assess whether recent advances in meteorological verification can usefully be extended to more variables, including the hazards themselves for which allowing for observation quality will be important. A white paper will be published and new techniques will be evaluated in Forecast Demonstration Projects. Together with the Communication theme, a catalogue of post-event reviews of the effectiveness of forecasts & warnings will be compiled. Targeted workshops and conference sessions will be held to involve users and social scientists in exploring metrics of the value of forecasts & warnings in user decision making. Evaluation requires observations so this theme will work with the Human Impacts, Vulnerability and Risk theme to investigate how to use new sources of data in verification. Research on economic benefit of forecasts & warnings, will also be carried out through workshops involving economists and private sector meteorologists, leading to the publication of a white paper.

Eight cross-cutting activities have been identified across the themes to draw them together: applications in the forecasting process, design of observing strategies, uncertainty, field campaigns and demonstrations, knowledge transfer, use of verification, impact forecasting and data management/archiving. Some of these serve to ensure that key common areas of expertise are applied throughout the project, while others will enable the pooling of skills and resources so as to take forward and demonstrate the results of multiple research themes.

Many of the research and cross-cutting activities will converge on field campaigns, Research Development Projects and Forecast Demonstration Projects (RDP/FDPs), which will be focussed on particular hazard forecasting problems in specific climates so as to establish an evidence base of best practice that may be applied globally. Such activities include the planned North Atlantic Waveguide and Downstream development EXperiment (NAWDEX/DOWNSTREAM), which will link activities across a variety of spatial and temporal scales, drawing on both the academic and operational communities; the Lake Victoria Experiment (LVB-HyNEWS), whose aims include developing hazard warnings for those working on the Lake; and the ALERT.AR/RELAMPAGO project to investigate severe thunderstorms in the La Plata basin of South America. Further RDP/FDPs will be promoted, probably in conjunction with field experiments aimed at broader objectives, in the areas of urban flooding, winter weather (including the CHAMP project in North America), fire weather (possibly with a planned experiment in Australia) and extreme local winds (including the PECAN project in the USA). It is also planned to use available forecasting testbeds, including the Hazardous Weather Testbed in the USA, to evaluate advances in use of observations, modelling and product generation.

The proposed research will revolutionize the knowledge available to be used in support of weather-related hazard management, both through development of new capabilities and through sharing of existing good practice, providing better accuracy and more relevance, from systems designed with proactive risk reduction and effective emergency-response as their aim. At the same time, the research benefits will cascade to “normal” weather, enabling National Meteorological and Hydrological Services to make more effective contributions to their national economies, especially in less developed countries. These outcomes will contribute significantly to delivering the aims of the follow-on to the Hyogo Framework for Action, which will be agreed at Sendai in 2015.

The research will build on advances made in THORPEX and dovetail closely with the other two projects arising from THORPEX: the Polar Prediction Project and the Subseasonal-To-Seasonal project. The WWRP and THORPEX working groups, particularly PDP, DAOS, TIGGE, WGNR, MWFR, JWGFVR and SERA, have played key roles in defining the project and, along with WGNE, their successors will be important contributors to the research. Links with the Climate Impacts community in WCRP will be developed to enable research results gained in HIWeather to be applied to assist communities and countries in their adaptation to a changing climate. The cooperation between the academic and operational communities developed in THORPEX will be maintained and strengthened. The programme will work closely with other international and national programmes in disaster reduction and hazard forecasting, and will establish links with major business-led programmes that address weather sensitivities. A primary goal will be to build capacity in less developed countries, particularly through RDP/FDPs, engaging widely with the academic and emergency response communities in the host countries.

The project will be governed by a Steering Group consisting of two co-chairs representing the physical and social sciences, together with chairs of task teams for each of the research themes. These task teams will consist of the PIs of activities being carried out in the theme and experts on specific topics as appropriate. The Steering Group will report to WMO through the WWRP and will be advised by a Strategic Advisory Group consisting of senior representatives of key user communities, including Disaster Reduction, Weather Services, Economic Development and Health as well as the relevant WMO Commissions, CBS, CHy and CIMO.

The project will be working in an area that has traditionally been very fragmented, both in discipline and geography. Success will depend on attracting people to meet and work together in workshops, conference sessions and summer schools. To achieve this, the project will require administrative support in the form of an International Coordination Office and financial support from a trust fund amounting to at least SFR200,000 per year to cover travel to management meetings, costs of workshops, publications and travel to scientific meetings for participants from developing countries.

Table of Contents

1 Introduction

1.1 Mission Statement

The overall objective of the High Impact Weather (HIWeather) project is 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"

1.2 Key Project Components

A concerted international effort to enhance our ability to mitigate the consequences of high impact weather for social, environmental and economic concerns and activities is of critical importance to the world at this time because of the observed increases in exposure and vulnerability to high impact weather as a result of population growth, urbanisation, and climate change.

HIWeather is a research activity within the World Weather Research Programme (WWRP), defined by the needs of users for applications that use weather-related information. The advances made in this project will enable emergency responders, business users and the public to take actions that will both reduce their vulnerability to adverse weather impacts that affect their safety, health, property, businesses and infrastructure and to take advantage of positive impacts that will enhance their prosperity and well-being.

The structure of the project has five aspects (Fig. 1). It is motivated and guided by the **applications** in the external world (outer ring), where the needs are articulated and the benefits realised. The interaction and communication with the stakeholders takes place within the **engagement** activities (inner ring), that provide the interface between the science and its application. Within the **research themes** (columns) the needs of society are addressed by advancing the science. A set of **cross cutting activities** (ellipses) integrates the research. Here we explain the scope of each component.

Applications (outer ring)**:** weather related aspects of global society that the mission statement seeks to deliver outcomes to.

1. Social. A key role of governments is to provide their citizens with security. In the case of threats from natural hazards, this extends to protection of life, of shelter, of the provision of sufficient food, energy and water and of the means of earning a livelihood. It also includes maintenance of law and order. Protective actions may be taken at local, regional or national level, depending on the scale of the impact and the capability of local agencies. Effective protection requires planning, preparation and prioritisation, all of which depend on accurate knowledge of the hazard and its potential impact on citizens and communities.
2. Economic. Countries, businesses and individuals are affected financially by high impact weather. Many businesses, such as airlines, energy utilities and insurance are highly weather sensitive and use sophisticated management techniques to minimise their

exposure to loss which depend on accurate knowledge of the weather and how it will affect them and their clients.

3. Environmental. The well being of individuals and communities depends on the health of the ecosystems in which they live and from which they draw natural services of air, freshwater, sea, soil, vegetation, insects, recreation etc. Protection of these natural services is managed by a variety of agencies which need to balance their beneficial use against degradation. They depend on accurate knowledge of how both the hazard and the mitigations deployed by others will affect the ecosystems that they manage.

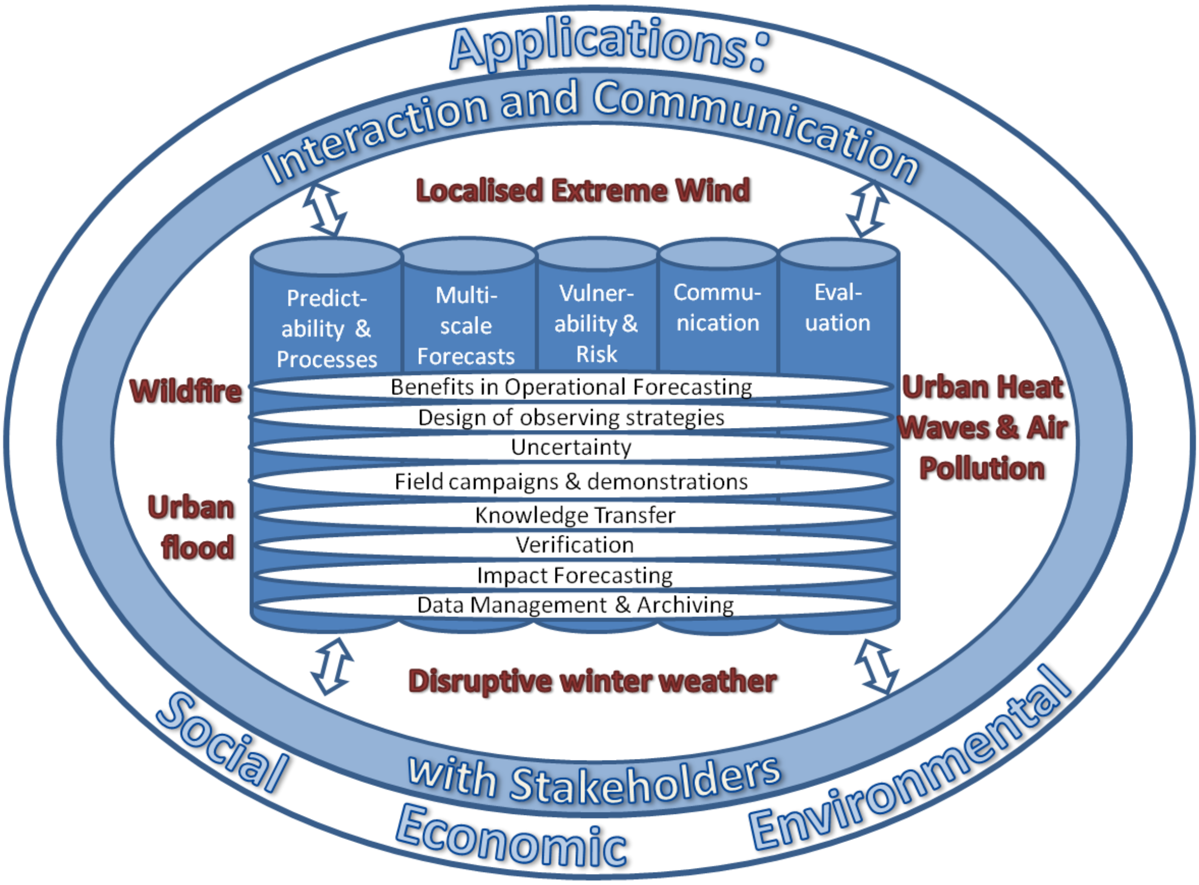

Fig.1 Conceptual diagram of the project (see text for explanation)

- **Research Themes** (pillars). These are areas of core research in which academia, research institutions and operational forecasting centres will work together to address the gaps in capability needed to deliver the mission statement. Much was achieved in THe Observing system Research and Predictability EXperiment **(**THORPEX) to develop these links and this work will be continued, particularly to more effectively include the social sciences. A key role of the Research & Development Projects (RDPs) and Forecasting Demonstration Projects (FDPs) will be to establish these links in less developed countries.

1. Predictability and processes: Improve our knowledge and understanding of the factors that determine the predictability of high impact weather through observation and analysis of processes in the physical environment and through diagnosis of model errors.

2. Multi-scale forecasts: Enhance the capability to forecast weather impacts through improved multi-scale analysis and prediction of the relevant variables in coupled modelling systems.
3. Human Impacts, Vulnerability and Risk: Produce more relevant forecasts and warnings through assessment of the impact of the predicted hazard on individuals, communities and businesses, their vulnerability and hence the risk.
4. Communication: Achieve more effective forecast-based decisions through better communication of forecasts & warnings of hazards & their impacts.
5. User-Oriented Evaluation: Identify deficits in and grow trust in forecasts, justify their implementation and use, and guide further research and development through evaluation of forecasts & warnings of hazards, their impacts and the effectiveness of their communication.

Cross-cutting activities and issues (ellipses)**:** will be addressed by multi-disciplinary teams drawn from multiple research themes.

1. Benefits in operational forecasting: The challenges and requirements of the operational forecasting process will be elicited to help define the priorities of the individual research themes. The resulting research and knowledge will be used to inform and recommend changes to the operational forecasting process. The constraints and needs of implementation will be an underlying concern of several of the themes, particularly the communication theme.
2. Design of observing strategies: while conventional observing systems are well supported through WMO Commission for Basic Systems (CBS) activities, there is a need for research into the opportunities and limitations of observing strategies for the future global observing system. The research should consider the potentially conflicting demands of deploying local technologically advanced observing systems relative to maintaining more traditional observational capability globally. A new priority for this activity will be to look at the needs and opportunities for updating the social and economic data, such as traffic flows and chronic illness distributions, required by impact models and for real-time observations of impacts and responses, potentially including the use of crowd-sourcing, social networks, and ubiquitous sensors.
3. Uncertainty: is an underpinning characteristic of all the physical and socio-economic systems represented in the research themes. Forecasts are expected to be probabilistic requiring improved knowledge of processes that lead to uncertainty and improved methods of quantifying and evaluating uncertainty; key issues in communication revolve around expressing and perceiving uncertainty.
4. Field campaigns and demonstrations: will provide observations and model outputs to support new understanding, to verify modelling advances, to understand user needs, and to test the value of new products and communication methods. Datasets from previous campaigns will be exploited further and new programmes (including RDPs and FDPs) initiated. This activity should enhance academic and operational collaboration.
5. Knowledge Transfer: while stakeholder engagement is treated separately as indicated by the arrows in the concept diagram, knowledge transfer between disciplines, between advanced to less advanced centres and between academic experts and operational centres is a key cross-cutting activity.
6. Verification: while the research theme on evaluation is focussed on new research that supports process understanding, model development, communication, use and value of

forecasts, the application of verification principles has a role in all research activities that will be co-ordinated by the Evaluation theme. It also has a key role in identifying and measuring the benefits achieved by the High Impact Weather project itself.

7. Impact Forecasting: the emphasis across all of the research themes is on predicting impact-related parameters that, alongside the weather forecast variables, will support effective decision making. This requires input from the vulnerability and risk theme into the other themes.
8. Data Management and archiving: both model and observation data needs to be made readily available to support HIWeather research activities. To complement the routine THORPEX Interactive Grand Global Ensemble (TIGGE) and TIGGE-Limited Area Model (LAM) datasets, demonstration projects will be encouraged to set up high-resolution convective-scale ensemble forecast datasets consistent with TIGGE-LAM standards. This activity should enhance collaboration between researchers and operational Numerical Weather Prediction (NWP) centres.

External engagement (inner ring)**:** it is essential that the project is user-driven and outcomes oriented. The science must work together to deliver new capabilities that will benefit users of forecast and warning information.

- Links with other initiatives: Key international programmes, especially in disaster risk reduction, are already in place. It is important not to overlap with them, but to ensure that weather-related aspects are adequately dealt with. This will be particularly key with respect to business-led initiatives such as the development of next generation air traffic management and large scale energy management systems.
- Interaction and communication between researchers and stakeholders: relevant stakeholders range from global and national scale funding agencies to individuals. A range of activities will be needed from individual engagement at the local level during FDPs, through regional scale workshops for emergency response and business groups, to major conferences and briefing sessions for international bodies.
- Education and outreach: aspects of human impacts of weather and of the communication, interpretation and use components of forecast delivery are not widely understood in the meteorological community. This project provides an opportunity to facilitate wider understanding, especially amongst young scientists who will be the scientific and policy leaders of tomorrow.

The project will dovetail closely with other activities of WWRP. High impact weather plays an important role in the other two post-THORPEX projects: the Polar Prediction Project (PPP) and the Sub-Seasonal to Seasonal (S2S) project so that links with these projects will be developed. The project will draw heavily on the expertise of the WWRP working groups.

The project will last for ten years, with a substantive mid-term review in the fifth year allowing for any necessary adjustment to the programme to meet objectives in years six to ten.

1.3 Key Project Goals

The overall mission of the project will be achieved through the following key actions:

- Improve knowledge and understanding of the processes that generate weather-related hazards so as to assess their predictability
- Develop multi-scale coupled forecasting systems of the weather-related hazards, including new observation sources, advances in data assimilation and modelling and ensemble prediction, and definition of new products.
- 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.
- 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.
- 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.

In pursuing these goals, the following overarching principles will be examined:

- Forecasts and warnings increase resilience when they improve decisions made by users.
- The response 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.
- An effective forecasting and warning service depends on trust. An important component of building trust is evaluation and open communication of relevant verification metrics from every link in the chain.
- Advances in capability are accepted when operational services and operational staff participate in experiments that demonstrate benefit.

1.4 Development of the HIWeather Implementation Plan

WWRP THORPEX has been a ten-year research programme with a focus on accelerating improvements in the forecasting of high-impact weather 1 to 14 days ahead. It will finish at the end of 2014. Before the THORPEX International Core Steering Committee (ICSC) meeting in October 2012, a consultation exercise was carried out to gather views on possible THORPEX follow-on programmes. Strong support was given to the proposal of establishing "a new 10 year programme … jointly, where appropriate, with the WCRP with a focus on improving the predictability of high impact weather from hours to a season (seamless prediction) and within the framework of a changing climate".

For the post-THORPEX era an important question was "what must be built upon, what is missing, what will make a difference, is worth investing in and should be promoted within the WWRP?" The WMO Executive Committee (EC) meeting (EC-64, June/July 2012), gave approval for the launch of two new WWRP projects that developed out of THORPEX: the S2S and PPP projects. These two projects, with their own trust funds, are seen as part of the THORPEX follow-on programme. The S2S project, in particular, is a key to defining the link to the World Climate Research Programme (WCRP). A common theme of many of the responses to the ICSC consultation was that there was a need for continued research focused on high-impact weather on the time and space scales addressed in THORPEX but with the important extension to shorter time and space scales. Important new aspects of this proposal were a stronger motivation from applications and engagement with stakeholders, improving small scale, short range forecasts for a variety of weather-related applications, bridging the gap between the short time scales and the sub-seasonal time scales, research into evaluating and communicating forecast information, and gaining the societal benefits of enhanced forecasting capabilities.

Thus a task team was established to develop a proposal for a High Impact Weather research activity within WWRP. Following the appointment of Sarah Jones as chair and Brian Golding as consultant, and a Town Hall meeting at the American Meteorological Society Annual Meeting in January 2013, an initial workshop was held at the Karlsruhe Institute of Technology in March 2013 to define the scope and objectives of a High Impact Weather post-THORPEX Project. Subsequently a task team was appointed to guide production of the proposal. This team held three teleconferences in the early part of June 2013, following which members prepared the first outline version of a Project proposal that was submitted to a joint meeting of the THORPEX ICSC and the WWRP Scientific Steering Committee (SSC) in July 2013. This meeting identified some key areas needing improvement but endorsed the direction of the proposal and requested that it be modified for presentation to the Commission for Atmospheric Sciences (CAS) meeting in November 2013. Teleconferences of the task team were held in September to agree a more focussed set of objectives for the proposal, and these were followed up by additional inputs for the second draft for CAS. At its meeting in Antalya in November 2013, CAS endorsed the project on the basis of an updated executive summary and a more detailed presentation, but requested more work on the definition of the work plan. This was reinforced by a THORPEX EC meeting in Exeter in December 2013. A further revision of the Implementation Plan was prepared as input to a workshop of the task team held in June 2014 at the National Oceanic and Atmospheric Administration (NOAA) headquarters in Silver Spring, USA, to define the work plan. This workshop completed the definition of the challenges that would be addressed by each research theme and make good progress towards defining the activities to be undertaken. These outputs were used in a presentation to a side meeting of the WMO EC in Geneva in June 2014. At its main meeting, EC adopted the proposal for HIWeather and recommended that a trust fund be set up to support its work. The project was discussed in depth and received wide support at the first World Weather Open Science Conference in Montreal in August 2014 and in the associated meetings of the WWRP working groups.

2 Requirements and Benefits

Statistics of natural disasters show that weather-related socio-economic impacts have increased substantially over recent decades. In the light of increasing population, climate change and urbanisation it is expected that this will continue. In this section we present evidence for this, outline advances in science that provide opportunities for improving resilience; and identify the benefits that can be achieved by this project.

2.1 Vulnerability of Society to High Impact Weather

Despite substantial advances in both forecasting capability and emergency preparedness, recent years have been marked by a large number of natural disasters that have cost many lives, displaced large numbers of people, and caused widespread damage to property and infrastructure, as shown in figure 2.

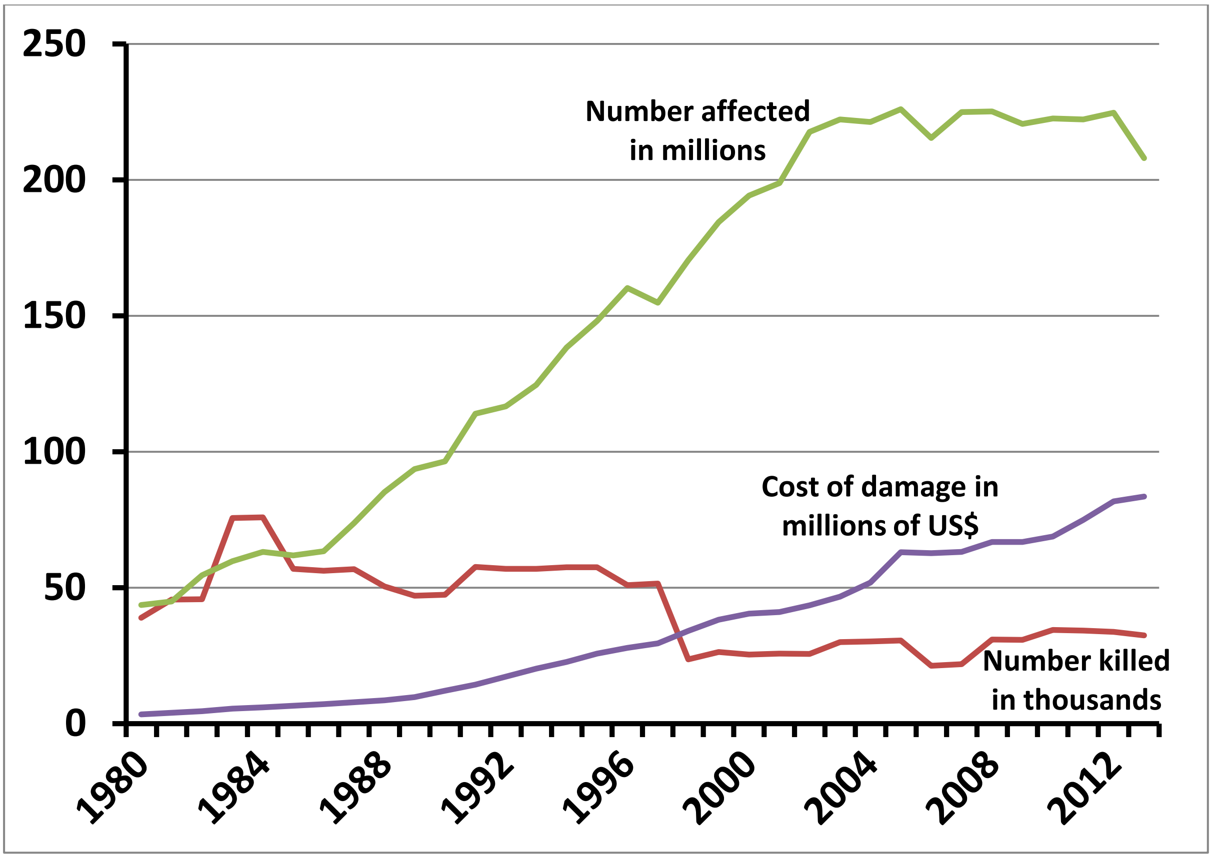

Fig. 2 15-year running means of weather-related disaster impacts recorded in EM-DAT: The OFDA/CRED International Disaster Database, www.em-dat.net, of the Université Catholique de Louvain, Brussels, Belgium. In interpreting this graph, note that reporting practise and efficiency vary through time and between countries.

Disasters occur when the ability of a population to protect itself from the impact of the weather is overcome. As countries become more developed, the level of protection becomes greater so that natural disasters become restricted to rarer, more extreme events. Protection may take the form of building codes and planning regulations that give permanent protection from some types of impact or of warnings and procedures that reduce exposure to the impact or of support that reduces the time to recover once the initial impact has occurred.

High impact weather includes not only disasters, but also those weather events whose impacts can be absorbed by society, but at significant cost. For instance, developed countries affected by winter weather, e.g. ice and snow that could kill many people in road accidents and stop business from operating, mitigate these impacts by the use of clearance equipment and by spreading of chemicals that inhibit freezing. The impact remains high, but has been largely transferred from a cost in lives and loss of business to a shared financial cost paid in taxes. Improved forecasts of high impact weather can lead to significant benefits for economic applications, e.g. improved local forecasts of cloud cover and boundary layer wind can prevent electricity grid overload.

The most destructive disasters of recent years are summarised below from information in the EM-DAT database:

Floods
The database splits flooding from rainfall through rivers and flooding from windstorms through storm surges. Taken together, flooding is by far the most frequent cause of disasters that kill more than 1000 people. Some of the most serious have been from the devastating Myanmar Tropical Cyclone (TC) of May 2008 (over 135,000 killed), the Haiti floods of May 2004 (over 2,500 killed), the New Orleans floods caused by Hurricane Katrina in 2005 (over US$100 billion), and the Thailand floods of August 2011 (over US$40 billion). Flash floods are the frequent cause of smaller losses and fatalities. Some of the largest losses of life come from landslides precipitated by flooding.

Wildfires
Wildfires are mostly too localised to cause large loss of life from a single event. An exception was the Black Saturday bushfires in Australia in February 2009, which killed 173 and injured 414. However, the cost of damage to property has been substantial in recent years, most notably from the 2005 fires in the USA, which cost over US$2 billion.

Extreme Wind
The principal extreme wind impacts recorded by EM-DAT are the European windstorms, including storms Lothar and Martin in 1999 (US$15bn), Erwin/Gudrun in 2005 (US$6bn), Kyrill in 2007 (US$9bn) and Klaus in 2009 (US$5bn). Extreme winds in TCs are also a major cause of damage and death. Individual tornadoes are generally more localized, but the Joplin, USA, tornado of May 2011 was exceptional, with 158 people killed and 1000 injured.

Severe Winter Weather
Severe wintry weather frequently claims lives in affected countries. However, in terms of disasters, the 2008 Afghanistan blizzard stands out with more than 1,000 deaths from a single event.

Heatwaves
Many epidemiological studies have demonstrated that high temperatures are positively correlated with increased mortality and morbidity relative to normal conditions. Exceptional heat waves with large death tolls in recent years have included the European heat wave of

2003 which saw more than 10,000 deaths and the 2010 heat wave in Russia when more than 50,000 died.

2.2 Opportunities to increase resilience

Improved weather observations, forecasts and warnings, their improved communication and the use of that information can enhance resilience by helping people prepare for predicted high-impact weather in ways that reduce negative impacts, that enable advantage to be taken of positive impacts, and that enhance the post-event recovery process.

Recent advances in global weather prediction, especially those developed during THORPEX, have dramatically improved the capability to provide early warnings of large scale severe weather events. Progress has been made through better understanding of the physical processes, improved use of observations in NWP, and the development and application of ensemble prediction systems. Gains have particularly been achieved in the lead times for predicting tropical cyclone landfall, large scale flooding, and extreme temperature events. With its focus on lead times of one day to two weeks, THORPEX did not address the problem of high precision forecasting required for localised impacts, such as flash floods, wildfires, winter weather and severe convective weather.

However, research in limited area high resolution modelling and the availability of larger computers has advanced NWP capabilities to the point where useful forecasts can be made for a few hours ahead of the location, timing and intensity of some of these events, permitting the use of a “warn-on-forecast” approach to responding to these hazards in place of the traditional “warn-on-observe” approach. Further advances in the science of prediction for the first day will enable further migration to “warn-on-forecast” with consequent benefits to achievable warning lead times, as well as greater spatial and temporal detail in forecasts and warnings of hazardous phenomena.

During THORPEX, advances were made in engaging social scientists in the specification of requirements for improved forecasts and forecast products. This has now created an environment where further integration with the social sciences is possible and desirable. At the same time, it has become increasingly clear in recent years that the full benefits of hazard forecasting capabilities are not being realised due to challenges in their communication, interpretation and use, and that current technological advances offer enormous opportunities for innovation in these areas.

As an example, despite excellent forecasts of its landfall, there was substantial avoidable damage and loss of life from Hurricane Sandy in October 2012. A review by the National Oceanographic and Atmospheric Administration of the US Department of Commerce identified twenty-three recommendations for changes to management practices for severe weather in the US National Weather Service. These can be summarised in three broad areas for improvement, all of which are based on the implementation of available science and technology, and all of which are relevant to this project:

- Observing and forecasting of weather impacts: in this case, especially storm surge and resultant coastal flood inundation

- Communication of forecasts and warnings: including nomenclature, product design, use of web sites, use of social media, interfaces with private sector

- Training: especially in weather impacts and in the needs and responses of those receiving the forecasts and warnings

A further aspect of building resilience is the use of climatological estimates of extreme weather to inform policy decisions, e.g. on building and drainage standards. The project will seek to achieve benefits in this area primarily through collaboration with key WCRP programmes, especially the Understanding and Predicting Weather and Climate Extremes Grand Challenge.

2.3 Foci of the project

In order to maximise the gains that will be achieved through the project, it is proposed to focus on the science needed to address five hazards, their impacts and the actions taken in response to them:

Urban flood, including flooding from the sea, rivers and directly from rainfall, with particular emphasis on flood impacts, including landslides, in the growing megacities of the developing world, especially those situated in the tropics and subtropics.

Wildfire, emphasising requirements associated with evacuation, property protection, fire fighting and fire management rather than the longer range problem of predicting elevated fire risk.

Localised Extreme Wind, including localised maxima within tropical and extra-tropical cyclones (e.g. sting jets), tornadoes, downbursts and downslope windstorms.

Disruptive winter weather, including snow, ice, fog & avalanche, and focussing on transport, energy and communications impacts.

Urban Heat Waves and Air Pollution, with particular emphasis on health impacts in the growing megacities of the developing world.

While this selection inevitably excludes some significant weather impacts, it is sufficiently broad to capture the key areas in which meteorological and related sciences will contribute to increased resilience in the next decade. Urban flooding, heat and air pollution are of particular concern for the megacities of the developing world, especially those in tropical and sub-tropical climates. The wind hazard takes past success in improving the forecast locations and tracks of tropical cyclones, extratropical cyclones and convective storms, to the next level, focussing on the wind structure and intensity within them. While the occurrence of wildfires is tied to long period weather regimes outside the scope of this project, the ability to manage fire and the incidence of fatalities are both closely related to small scale wind structure during a fire. Finally disruptive winter weather hazards are of greatest concern in middle and high latitudes where major economic and social impacts are particularly associated with mesoscale and cloud-scale processes that control the type and intensity of precipitation in freezing and near-freezing temperatures.

Each of the following sections, on the five selected hazard areas, addresses the impacts of the hazard, represented diagrammatically as an impact cascade, the key stakeholders who have to deal with its impacts, the options they have for reducing those impacts and the information they need to do so, the prospects for providing that information if the proposed research goes ahead and the benefits that could follow from that, with some examples of recent occurrences, and a response timeline showing lead times of decisions and actions by the main stakeholders. The latter are colour-coded as follows:

Key
Ready: Monitoring & Planning
Set: Preparation
Go: Warning & Action
Technical: On-site activities

Fig. 3 Key to timeline diagrams of actions by key stakeholders

2.3.1 Urban Flood

What are the direct impacts? – casualties from drowning / collapse of buildings / burial in landslides; distress to people who have lost relatives / are injured / made homeless; displaced people, disruption to services (education, health etc), business interruption, surface water flooding; sewer overflows; landslides/mudslides; river overtopping; ocean overtopping; breach of levees / flood defences; transport links cut; water/energy infrastructure put out of action; closure of underground malls etc; disease from polluted floodwater; deposition of debris / sediment; morbidity from toxic material in sediment.

Who are the interested parties? – national government; city authorities; emergency managers; fire & rescue; voluntary response sector; transport, water & energy companies; businesses; public; insurance companies.

What can they do to reduce the impact? – have staff on standby; open rescue centres ahead of flood; operate upstream river controls; install temporary flood defences (e.g. sandbags); clear storm drains/channels of trash; move goods / vehicles / vulnerable people to less exposed locations, pre-position recovery assets, advance/defer deliveries.

What information do they need? – probability / timing / locations of exceedance of critical depth thresholds at key decision lead times; timing of defence overtopping / breach; velocity of flood flow; duration of flood; probability / timing/ speed of landslide; track record (how often does it happen when forecast? Is it likely to be bigger or smaller than forecast…).

What could we provide from the HIWeather project? Improvements in coupled precipitation / river flow forecasting; in coupled precipitation / sewer flow forecasting; in river inundation forecasting and in coupled precipitation / landslide forecasting; coupled storm surge and ocean wave forecasts for vulnerable coastlines; provision of probabilistic information at a variety of lead times and spatial scales; guidance on how to communicate forecasts and warnings;

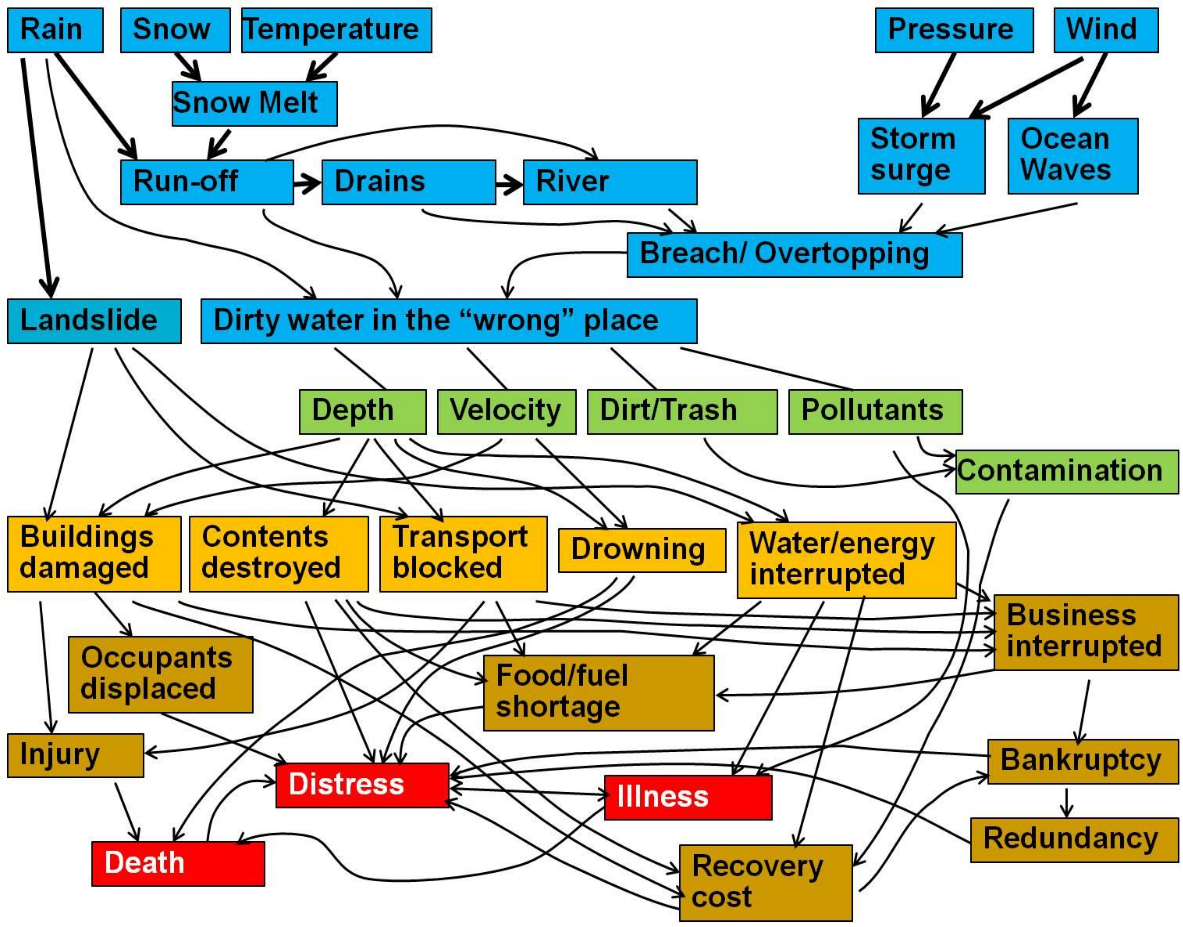

Fig. 4 Simplified impact cascade for flooding & flood-induced landslides. Blue/green shows the cascade of physical processes. Beige/brown are 1st & 2nd order socio-economic impacts. Red shows human impacts. Note multiple drivers of business interruption and human distress.

What would be the benefits? Reduce scale of flood (through better use of flow controls and temporary defences); reduce damage to moveable property; reduce duration of water / energy infrastructure outages; reduce casualties – especially at high exposure locations such as hospitals, community halls, etc; reduce economic loss to businesses; better social support to homeless; better response by insurers; faster recovery.

Scenarios to consider include: Ouagadougou 2009, Flash flooding Toronto 2013; Central European floods 2013, Katrina 2005 & Sandy 2012 (Contrasting scenarios of Tropical Cyclone Landfall in US), La Plata 2012, Bangkok 2011, Queensland 2010, Boscastle 2004, St Asaph 2012 (early warning of flash flood enabled rest centres to be prepared), Colorado front range flood 2013 (emergency messages broadcast prior to event), Zhouqu mudslide 2010, Oran mudslide 2009.

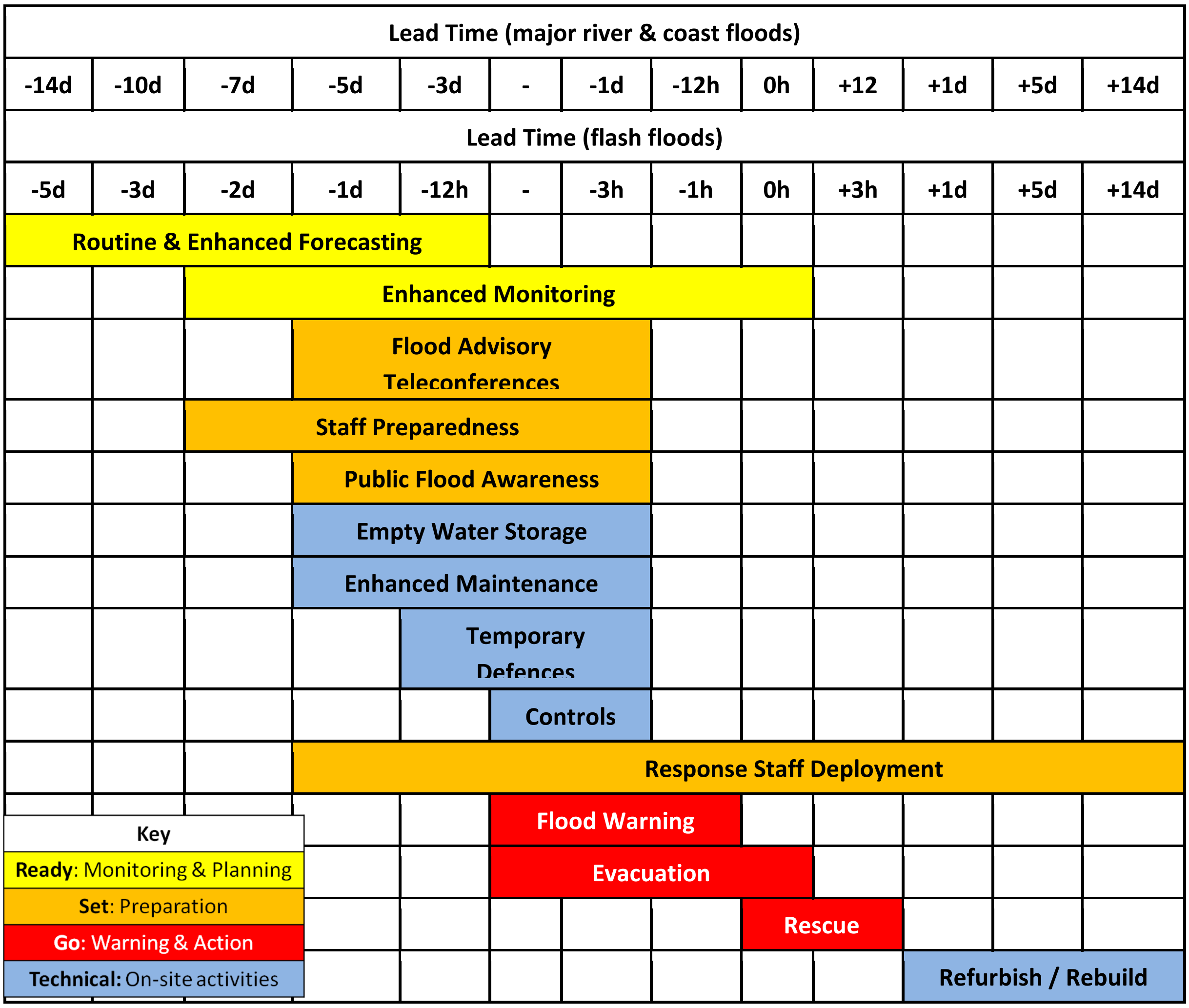

Fig. 5 Selected timelines of mitigation actions taken by responders to floods

2.3.2 Wildfire

Direct impacts – casualties from burns / smoke inhalation / stress; population made homeless (temporarily or over longer time period); loss of natural & crop vegetation resources; soil erosion or landslide in subsequent rain; mobilization of toxic material in soil → loss of water quality; property damage / destruction; stock loss; distress to people injured / made homeless → Depressive illness / Post Traumatic Stress Disorder etc; loss of water / energy / telecom due to destroyed infrastructure; transport links cut; smoke impacts (respiratory illness due to poor air quality, impact on crops, e.g. grape taint, transport disruption); loss of business due to damage / transport disruption; disruption of public services due to damage / transport disruption; increased load on insurance helplines due to property damage; economic costs of clear-up; increased demand on ambulance / emergency rooms.

Who are the interested parties? – city / rural authorities; emergency managers; fire & rescue; health sector; transport, water, energy & telecom companies; businesses; public; insurance companies.

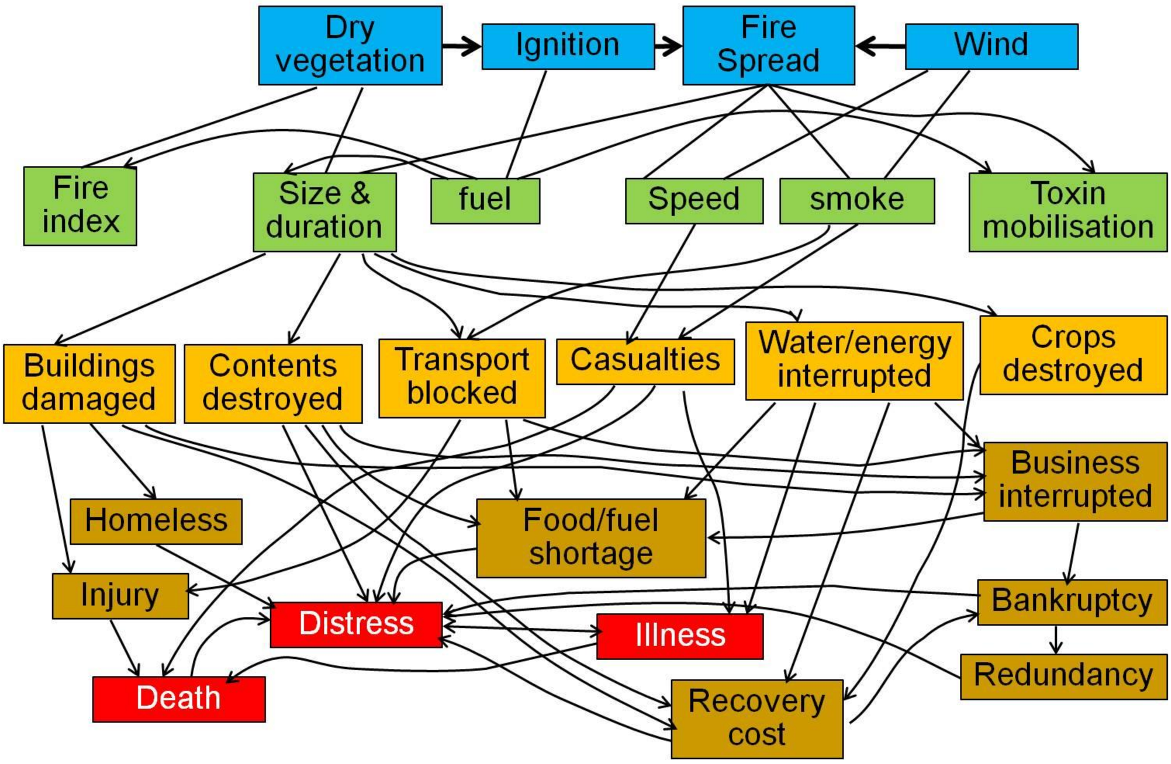

Fig. 6 Simplified impact cascade for wildfires. Blue/green shows cascade of physical processes and relevant parameters. Beige/brown are 1st & 2nd order socio-economic impacts. Red shows human impacts.

What can they do to reduce the impact? – have staff / equipment on standby; open shelters / rescue centres ahead of fire / evacuation; close access to vulnerable land areas, e.g. national parks; reduce burning-off; extinguish with water/fire retardant; contain with firebreaks; prepare people for evacuation, clear shrubs/ trees/ grass near structures; protect properties by spraying with water; evacuate vulnerable people / equipment / goods / vehicles to less exposed locations; community education; invoke personal bushfire plans.

What information do they need? – early warnings of potential scale (area, duration) and impact; probability of threshold exceedance (fire danger) at key decision points; probability of ignition (arson, lightning, carelessness); fire initiation, movement / spread velocity – timing of changes, fire intensity / temperature; fuel state; smoke density, plume spread direction & speed, composition, height & thickness; track record (how often does it happen when forecast? Is it likely to be bigger or smaller than forecast…).

What could we provide from the HIWeather project? Forecasts of extreme conditions of temperature / humidity / wind; improved observation & prediction of soil & vegetation moisture content in fire risk forecasts; provision of probabilistic information at a variety of lead times and spatial scales; improved prediction of wind gust fronts that accelerate / change direction of fire movement; best practice in fire propagation prediction; techniques for representing the impact of the fire on the wind field in fire propagation models; best practice in smoke dispersion from wildfires; improved estimation of smoke emission; best practice in fire risk index prediction; more effective communication of the meaning of high fire risk; prediction /communication of the health impacts of smoke inhalation.

What would be the benefits? Reduce scale of bushfire impacts; reduce down time of transport / water / energy infrastructure; reduce fatalities – especially at highly vulnerable locations such as hospitals, community halls, etc; reduce economic loss to businesses – by enabling them to temporarily relocate ahead of fire; more effective firefighting; reduce size of fire by enabling quicker reinforcement of firefighting resources; reduce distress to those affected by enabling quicker & more effective social support.

Scenarios to consider include: Southeast Australia, Black Saturday, 7 Feb 2009 (early warnings enabled evacuation, but many people still died); Russia, 2010, California Rim Fire, Aug 2013; Greece, 2007, Indonesia, 2012, UK, 2011, Waldo Canyon fire near Colorado Springs, 2012.

Lead Time												
-5d	-4d	-3d	-2d	-36h	-24h	-18h	-12h	-6h	-3h	0h	+1d	+5d
Routine & Enhanced Forecasting												
			Enhanced Monitoring									
Mobilise staffing & resources												
	Heightened fire danger warnings											
	Deploy fire fighting equipment											
			Extinguish/Contain existing fires									
			Fire bans & evacuation advice									
						Plan evacuation						
								Back Burning				
									Warning			
									Evacuate			
									Deploy			
										Damping down		
											Refurbish/Rebuild	

Key
Ready: Monitoring & Planning
Set: Preparation
Go: Warning & Action
Technical: On-site activities

Fig. 7 Selected timelines of mitigation actions taken by responders to wildfires

2.3.3 Localised Extreme Wind

What are the direct impacts? – casualties from impact with flying / falling debris; property damage; people made homeless, transport links cut by fallen trees / property; water / energy / telecom infrastructure damaged / destroyed; disruption of airport approach / departure schedules; road / rail delays due to reduced speeds; transport disruption due to accidents.

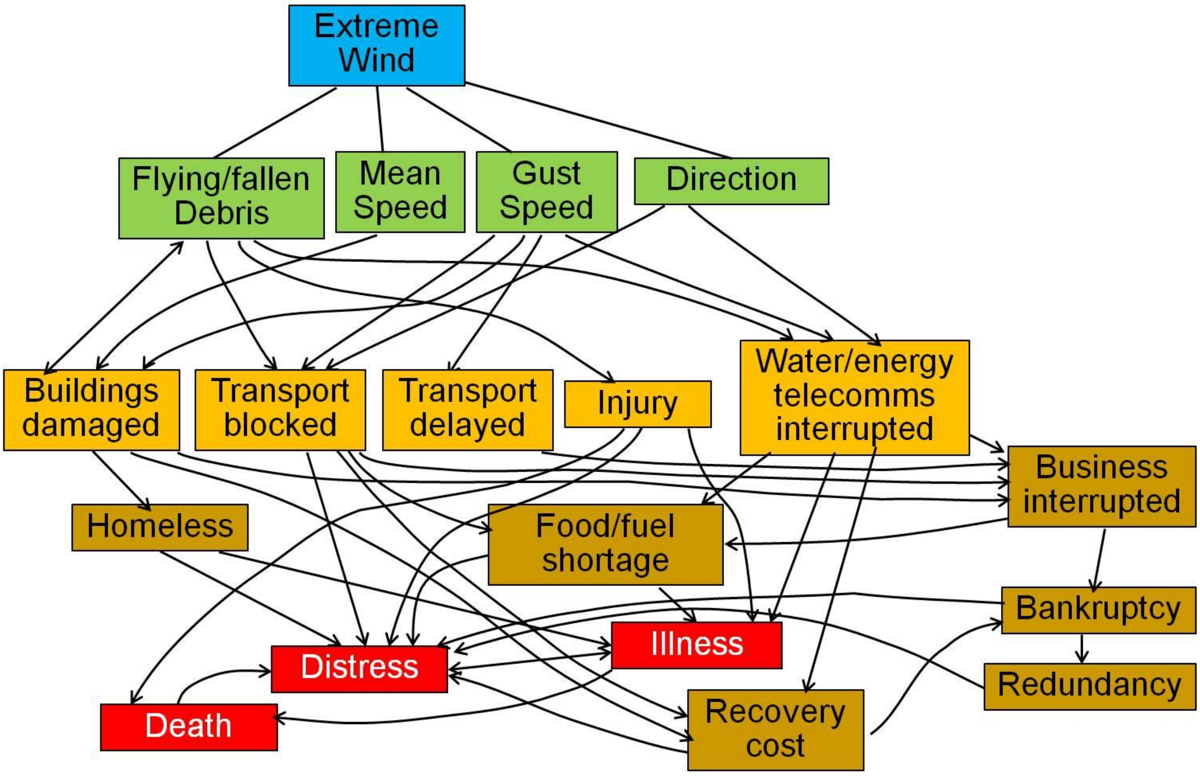

Fig. 8 Simplified impact cascade for extreme wind. Blue/green shows cascade of physical processes and relevant parameters. Beige/brown are 1st & 2nd order socio-economic impacts. Red shows human impacts.

Who are the interested parties? – national government; local authorities; emergency managers; fire & rescue; ambulance / emergency room; transport operators / managers; water, energy & telecom companies; businesses; public; public event organisers; marine, surface & air transport authorities.

What can they do to reduce the impact? – people take shelter / avoid travel; reschedule transport, maintenance / rescue staff on standby; move vulnerable people to safe refuges; general evacuation; cancel / relocate public event, pre-position transport assets for faster recovery, prepare for power outages.

What information do they need? – peak wind gust speed & direction; area and altitude affected; duration; timing relative to peak travel / working hours; likelihood of vehicles being blown over; likelihood of building damage; likelihood of trees being blow down; record of historical forecast accuracy vs scale/intensity.

What could we provide from the HIWeather project? Improved prediction of local variation of mean wind intensity, especially associated with squalls, tornados, downbursts; improved relationships of wind gust to mean wind, taking into account orographic and urban environment influences; shared best practice in the relationship between wind speed and impact on trees / vehicles / buildings; improved methods for communication of risks from high winds; shared best practice on verification of local wind maxima & impact.

What would be the benefits? Reduce recovery time of infrastructure; Reduce casualties – especially on roads and at high exposure locations such as hospitals, schools, etc; reduce economic loss to businesses.

Scenarios to consider include: Europe - Kyrill (2007) & Lothar (1999); North America - Perfect Storm Oct 1991, Hurricane Andrew 1992, Superstorm March 1993, Oklahoma tornados 2011, Tornado Super Outbreak Apr 2012, Moore tornado 2013, Hurricane Sandy 2012; South America - Buenos Aires Tornado Outbreak Apr 2012, Asia - Super Typhoon Haiyan 2013.

Lead Time (tropical & extra-tropical cyclones)												
-14d	-10d	-7d	-5d	-3d	-2d	-1d	-12h	0h	+12h	+1d	+5d	+14d
Lead Time (convective & local storms)												
-5d	-3d	-2d	-1d	-12h	-6h	-3h	-1h	0h	+3h	+1d	+5d	+14d
Routine & Enhanced Forecasting												
		Enhanced Monitoring										
			Staff Preparedness									
			Public Awareness									
			Enhanced Maintenance									
			Response Staff Deployment									
					Warning							
					Evacuation							
					Prepare Hospitals							
							Take Shelter					
								Rescue				
										Refurbish/Rebuild		

Key
Ready: Monitoring & Planning
Set: Preparation
Go: Warning & Action
Technical: On-site activities

Fig. 9 Selected timelines of mitigation actions taken by responders to extreme winds

2.3.4 Disruptive Winter Weather

What are the direct impacts? – road casualties and disruption by loss of adhesion or low visibility or collapse of trees / structures leading to blockage by accidents; disruption of railways by loss of adhesion; disruption of air transport due to ice/snow by need for de-icing and by loss of adhesion on taxiways and runways, disruption of aviation by landing / taxiway restrictions due to low visibility; danger to ships through icing; casualties / property damage / transport disruption due to burial by avalanche; energy transmission / telecommunications links by collapse of cables / structures / trees, casualties due to pedestrian loss of adhesion on footways & accidents while clearing snow; increased load on ambulances / emergency departments due to accidents; increased load on insurance helplines due to accidents; loss of business due to inability of people to travel; distress caused by lack of energy / food / fuel

/ communication; morbidity due to inability to obtain medication etc; environmental impacts of ice treatment chemicals.

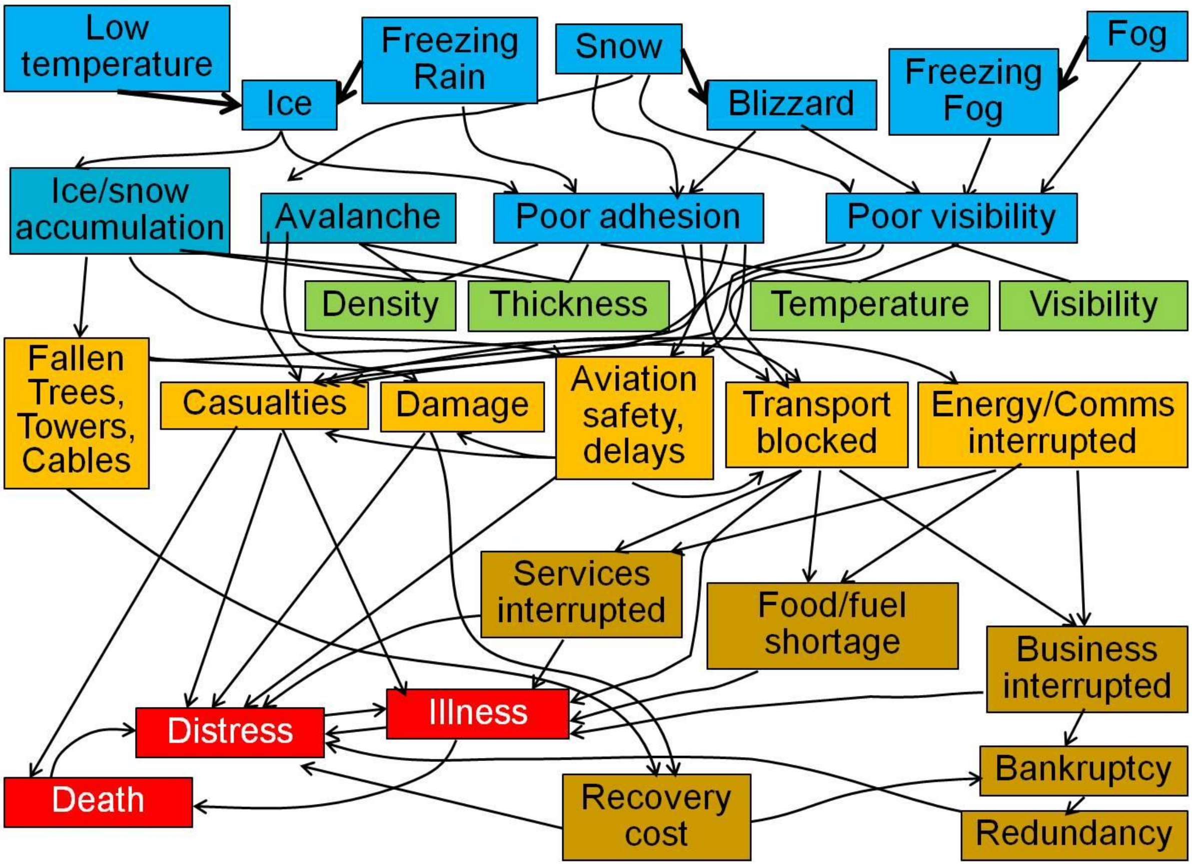

Fig. 10 Simplified impact cascade for winter weather. Blue/green show cascade of physical processes and relevant parameters. Beige/brown are 1st & 2nd order socio-economic impacts. Red shows human impacts.

Who are the interested parties? – city authorities; emergency managers; fire & rescue; ambulance / hospitals; transport, energy & telecom companies; ski resorts; businesses; transport authorities; highway managers (intelligent signage etc); logistics companies; route planning services; public.

What can they do to reduce the impact? – early triggering of small avalanches; chemical treatment roads / rails; set reduced speed limits, people avoid travel, close roads &/or open rescue centres ahead of main route blockage; reschedule flights; have maintenance / rescue staff on standby; pre-stock-up with food / fuel; reroute / reschedule deliveries, pre-close public services / businesses to reduce travel; pre-deliver or delay business stock; reinforce insurance help-lines.

What information do they need? – snow depth / density / stability; road adhesion, ice growth rate / thickness, probability of masts, cables, trees collapsing, snow depth, extreme low visibility, timing relative to peak travel times, actual conditions at individual road resolution; forecast probability of major disruption of main transport route, airport, electricity or telephone; information on alternative transport routes; record of historical forecast accuracy in similar situations.

What could we provide from the HIWeather project? Improved prediction of snow / rain transition, surface snow intensity, surface temperature over road / rail surfaces in stable boundary layers; accumulation of ice on surfaces / structures / trees; formation of ice on untreated and treated roads; formation, maintenance & dispersion of thick fog (<200m); influence of aerosol content on visibility; state-of-the-art modeling of snowpack structure; shared best practice in defining avalanche risk.

What would be the benefits? Reduce casualties from road accidents; reduce economic impact of transport accidents; reduce casualties at ski resorts; reduce distress to those caught in road blockages; reduce economic loss to businesses by optimally rearranging operations; reduce recovery time for energy / telecom outages & airport / road / rail closures.

Scenarios to consider include: Closure of UK M11 motorway January 2003, heavy snowfall in Austria January 2012, Canadian Ice Storm 1998, post-Sandy New York snow 2012; Heathrow Airport closure December 2010, UK closure of schools January 2013, which reduced travel, resulting in reduced transport disruption from a major snowfall; major US east coast winter storms - planes moved to safe locations ~3 days ahead, changes to air schedules pre- planned, trains stopped at safe places, shops pre-stocked goods; South China consecutive snow / freezing rain Jan 2008, trees / cables broken, transport disrupted.

Lead Time												
-5d	-3d	-2d	-1d	-12h	-6h	-3h	-1h	0h	+3	+1	+5	+14
Routine & Enhanced Forecasting												
		Enhanced Monitoring										
			Staff Preparedness									
			Public Awareness									
	Deploy clearance equipment											
			Deploy Response Staff									
			Prepare Hospitals									
			Warnings & Advice									
				Close public facilities								
						Close Roads						
								Rescue				
								Recover Infrastructure				

Key
- **Ready**: Monitoring & Planning
- **Set**: Preparation
- **Go:** Warning & Action
- **Technical:** On-site activities

Fig. 11 Selected timelines of mitigation actions taken by responders to winter weather

2.3.5 Urban Heat Waves and Air Pollution

What are the direct impacts? – increased morbidity / mortality amongst vulnerable people – old, poor, infirm, sick; drowning of people trying to keep cool; increased use of air conditioning; increased energy and water demand possibly leading to rationing; distress to people unable to keep cool; increased public disorder; increased incidence of infectious disease / food poisoning; respiratory / cardio-vascular disease; heat stress / heat stroke; disruption to road / rail due to melting of surface / buckling of rails; closure of businesses / public buildings / public services due to health & safety thresholds; closure of energy / water / business infrastructure due to excessive temperature of cooling water; increased demand on funeral / burial services.

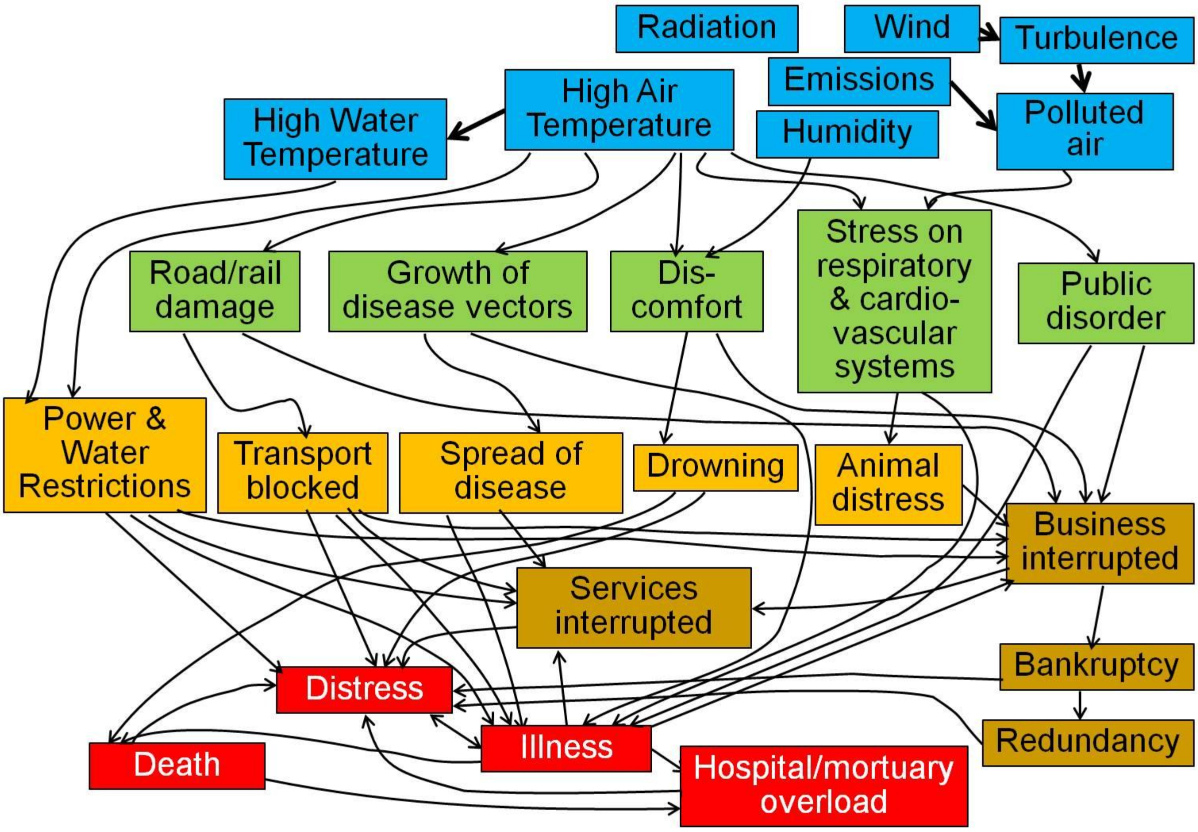

Fig. 12 Simplified impact cascade for heat/air pollution. Blue/green shows cascade of physical processes and relevant parameters. Beige/brown are 1st & 2nd order socio-economic impacts. Red shows human impacts.

Who are the interested parties? – national government; city authorities; emergency managers; fire & rescue; health sector; transport, water & energy companies; businesses; public; sports / outdoor activity organizers; mortuary operators.

What can they do to reduce the impact? – advice to individuals, open designated cool spaces where people without air-conditioning can cool down; reduce emissions; advance / delay business activity; pre-close businesses / public services; prepare for raised water / energy demand; maintenance staff on standby; prepare ambulances / emergency rooms for increased demand; reschedule sports / outdoor activities; increase fluids intake; evacuate vulnerable people to cooler locations.

What information do they need? – air temperature, humidity and radiation, expressed as a comfort index relative to pre-determined thresholds; minimum temperature; duration above maximum / minimum temperature thresholds; area affected; surface temperatures of road, rail, buildings etc; river water temperature; air quality / pollution index; pollutant concentrations; changes in energy / water demand; estimates of emergency room demand;

physiological stress as a function of clothing / environment / activity; track record of forecasts.

What could we provide from the HIWeather project? Better representation of urban fabric in prediction models; better forecasts of comfort indices; more skilful forecasts of health impacts; coupled river temperature forecasts; sharing of best practice in water & energy demand forecasts; sharing of best practice on thresholds for curtailing sports / outdoor activities; improved communication of risks and responses in heat waves; more accurate forecasts of air quality and of impact of reducing emissions; improved modelling of emissions in city scale air quality models.

What would be the benefits? Improve air quality (through controls on emissions); Reduce casualties – especially at high exposure locations such as hospitals, care homes, etc and in sport / outdoor activity; reduce economic loss to businesses.

Scenarios to consider include: Summer 2003 in Western Europe, Summer 2010 in Russia, Autumn 2013 in Eastern and Northeastern China.

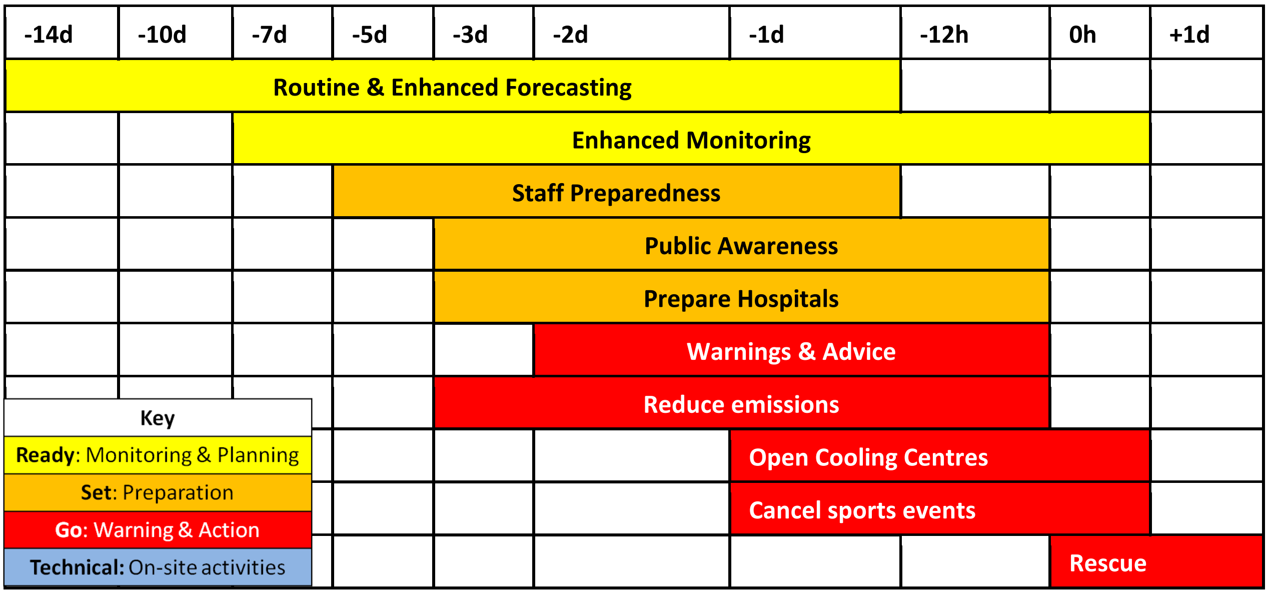

Fig. 13 Selected timelines of mitigation actions taken by responders to heat waves and air pollution

2.4 Achievable benefits

Recent advances in meteorological understanding and modelling have made it possible to predict on the space and time scales which are needed for forecasting the impacts that cause greatest damage and loss of life. Further research over the next few years offers the potential for dramatic improvements in the ability of convective-scale models to predict severe weather in the first few hours, as well as continuing improvements to the lead times of useful forecasts of tropical and extratropical cyclones and other larger scale disturbances that create the environment for high impact weather. A ten year project will enable the achievement in parallel of:

- Research into achieving more effective communication, interpretation and uses from existing forecasting capabilities
- Improvement of model and forecast capabilities
- Advancement of the fundamental process knowledge which is needed to underpin future improvements.

Targeted FDPs will enable the adoption of improved forecasting capabilities for warning of specific types of high impact weather in specific countries. The benefits of such demonstrations will be large provided the local weather service and its customers are involved and the experiment is seen as an opportunity to solve their problem with available science. Comprehensive evaluation will be crucial for obtaining acceptance of new approaches for subsequent operational implementation. Additional benefit will come from these demonstration experiments by establishing best practice that can be shared with other countries, that can be used to deal with other hazards, or that can be applied in assessing trends due to climate change for use in policy decisions. In order to maximise these diverse benefits, such FDPs must be carried out in collaboration with a broad range of stakeholders.

Advances in understanding of the best ways to communicate forecasts so as to reduce the impact of a given hazard will be highly dependent on the type of threat and the culture of the particular groups at risk. While products and communication methods will need to be designed with these dependencies in mind, the generic principles of how to go about this can be defined and established as best practice on the basis of RDPs / FDPs. Subsequent application of such best practice will deliver benefits much wider than the particular hazards and cultures studied, provided the research is formulated appropriately.

Benefits to business applications within sectors such as energy, transport, water, insurance and agriculture, are highly dependent on the management structures in use. In some of these, research is active to generate improved information systems, often in order to enable competitive advantage to be gained. The HIWeather project will not generally become involved in such projects which often depend on access to confidential information, but will engage with these stakeholders at appropriate levels in order to share experience and best practice in impact prediction and communication. However, in the context of specific demonstration projects, the opportunity to engage with local businesses will be sought in order to enable benefits to be assessed and best practice to be established, as was done in the Sydney 2000 Olympics FDP.

As illustrated in figure 14, resilience to natural hazards is as much a function of the factors that cause and maintain vulnerability as of the weather and our ability to predict its impacts. Nevertheless, gains in resilience arising from improved warning systems have the potential to support economic development, which itself can lead to increased resilience.

A key outcome of the project will be a body of evidence that can be used by WMO and by NMHSs to justify the introduction of improved forecasting and warning services. In particular, it will result in evidence-based examples of best practice in forecasting and warning of weather-related hazards, which can be adopted by developing countries. That evidence will include information on weather forecast accuracy, precision and reliability; on the hazards and their impacts that can realistically be forecast and the accuracy with which that can be achieved; on the products that best convey the information, the delivery channels needed to reach particular groups of people, and the delivery strategies that deliver the highest benefits in terms of resilience. Widespread dissemination and use of such a body of evidence will achieved through engagement with institutional stakeholders including those within the WMO, e.g. Severe Weather Forecast Demonstration Projects (SWFDP); within the wider United Nations, e.g. UN International Strategy for Disaster Reduction (UNISDR), UN Educational, Scientific and Cultural Organisation (UNESCO); and within regional and world institutions, e.g. European Commission, Association of Southeast Asian Nations (ASEAN), African Union, World Bank.

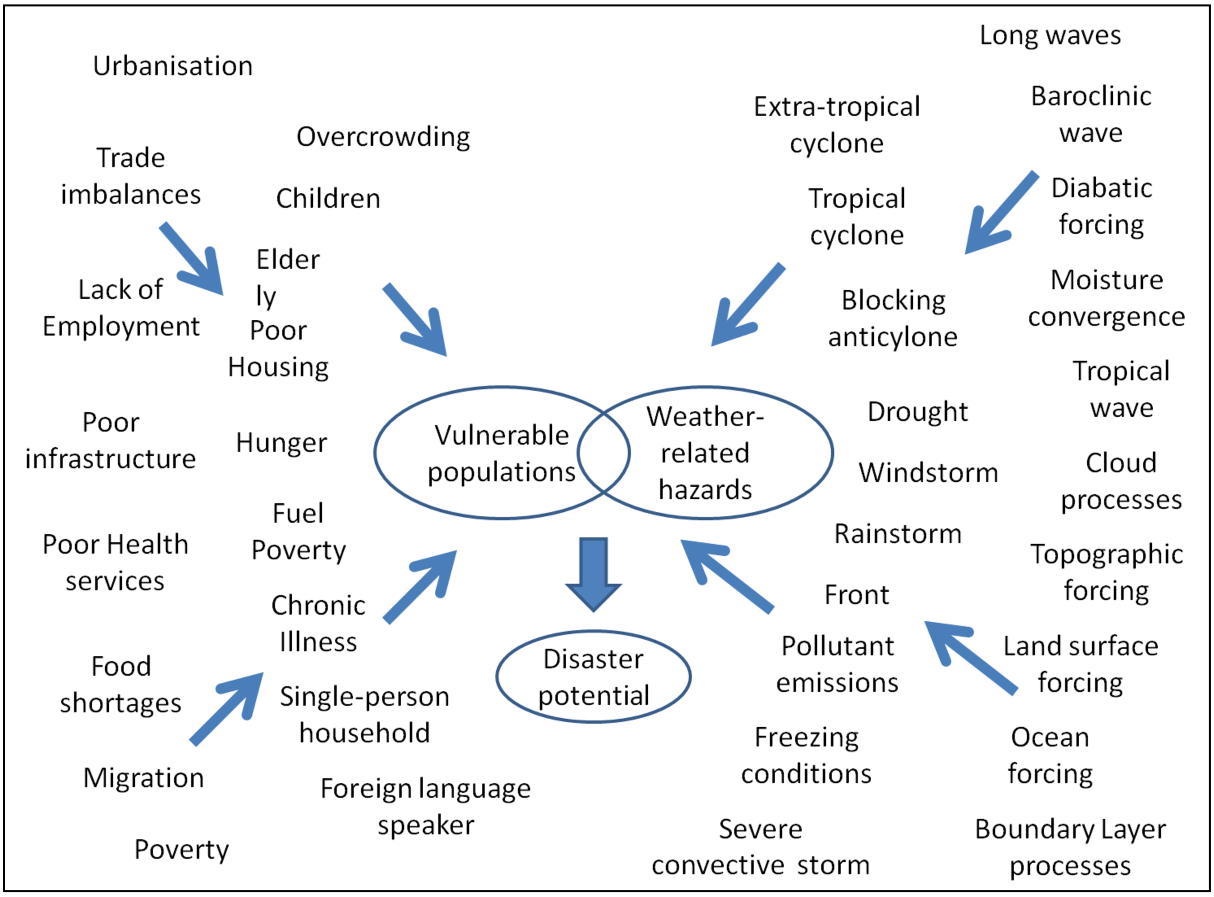

Fig. 14 Illustration of some change processes in society and indicators of vulnerability on the left; atmospheric processes and high impact weather systems on the right that may come together to bring vulnerable populations into contact with weather-related hazards leading to human impacts and potentially to disaster. Increased resilience requires attention to both hazard and vulnerability.

3 Research Themes

In section 2, we have defined a set of hazards and explored the information required by stakeholders when taking decisions to mitigate their impacts. This should provide a clear basis for warning services. However, surveys and anecdotal evidence show that forecasts and warnings are often misinterpreted or not used effectively by some users. Research with emergency responders, members of the public, and others has identified many reasons for ineffective use of some forecasts and warnings, but they may be summarised under the following headings:

- **The information was not received when, where & by whom it was required**: due to sub-optimal communication media, format, or lead time, inadequate preparedness, lack of integration with management software or procedures, or degraded mobile or other communication services.

- **The information was not understood by the recipient or was inappropriately interpreted**: due to format, content, or language that was not a good fit to the recipient's capabilities, interests or needs.

- **The information was not that required by the recipient**: who needed operational thresholds, impact information, vulnerability information, non-meteorological information, more detail or precision, information relevant to their situation.

- **The information was not believed by the recipient**: due to insufficient trust or track record, inadequate convergence in successive forecasts, insufficient supporting evidence, lack of confidence indication, inadequate training.

- **The information was not sufficiently accurate**: due to model error, poor model initialisation, poor uncertainty modelling, poor coupling of hazard and impact models, inadequate spatial or temporal resolution, inadequate observations, lack of verification.

More generally, forecasts and warnings are only one source of information in people's decisions, and they are often received, interpreted and used differently than providers intended. Addressing these challenges in the forecasting and warning process is the key to increasing resilience and underpins the scientific challenges of the project, which have been grouped into five research pillars:

- Increasing knowledge and understanding of the predictability & processes of weather systems that generate hazards, so as to enable the production of more accurate forecasts and warnings of the meteorological source.

- Improving Multi-scale forecasting of hazards using coupled numerical weather, ocean, land surface, ice & air quality modelling, nowcasting, data assimilation & post-processing systems so as to produce more accurate and relevant information about the likelihood of occurrence of hazards at the time and space scales required.

- Developing capability to forecast the human impacts, exposure, vulnerability & risk of hazards to people, buildings, businesses, infrastructure and the environment using a variety of tools so as to produce user-relevant risk and response information for decision making.

- Improving the capability to Communicate hazard forecasts & warnings through appropriate media and using a range of formats so as to reach a variety of stakeholders in at-risk communities and to be usable and used by risk managers and the public in decisions that help increase resilience.

- Evaluating hazardous weather, impact & risk forecasts, alerts & warnings and the resulting responses with user-relevant metrics so as to identify weaknesses, prioritise improvements, build up trust and justify investment in operational services through the establishment of track records.

3.1 Predictability and Processes

This theme is concerned with increasing our knowledge and understanding of the processes that lead to the selected hazards and hence their potential predictability. It deals both with the slowly evolving large scale processes that create the environment for high impact weather and with the fast, small scale, processes associated with the hazard itself. Better understanding is needed of the processes governing convective-scale development and their dependence on the initial state. Synoptic scale precursors need to be correctly represented to achieve useful downscaled forecasts and to enable early preparation and issue of warnings.

Hazards in tropical, subtropical and extra-tropical regions will, in general, be associated with different types of weather systems. However, some science questions are independent of these differences. Interaction between the free atmosphere and the urban canopy is of crucial relevance to high impact weather in the future as an increasing proportion of the world's population lives in megacities. Processes that enhance or diminish a hazard are also important – e.g. radiation effects of the built environment, concentration and dilution of pollutants, frost and fog hollows.

Research is required on processes that determine onset of and changes in flow regimes. Better knowledge is required of the relationship of forecast error growth to weather regimes on all scales, for use in data assimilation, ensemble predictions and in forecast post-processing and interpretation. Further questions pertain to the representation of synoptic situations associated with different high impact weather events in medium-range forecasts. Are errors in intensity and structure of precipitation fields due to low resolution or to an inadequate representation of the processes involved?

Process understanding comes from consistently relating cause and effect and depends critically on the availability of data – both observations and model output. This theme will draw heavily on the "field experiments and demonstration projects" cross-cutting activity for these datasets. The TIGGE archive and YOTC dataset remain as powerful resources for these investigations.

In mid-latitudes, generation of high impact weather events is typically associated with precursors at upper levels. The prominent tropopause-level jetstream is characterized by an intense meridional potential vorticity (PV) gradient on isentropic surfaces, which acts as a waveguide for synoptic scale Rossby waves. Nonlinear amplification of these waves can result in wave breaking events leading to filamentary PV streamers and cut-offs, and to anomalous meridional moisture fluxes. These structures may ultimately result in urban flooding, disruptive winter weather or localized strong winds. Alternatively, they may lead to the blocking events that may result in heat waves, wildfires and air pollution episodes. It has been shown that wave evolution can be strongly modified by moist diabatic processes. Successful prediction of mid-latitude weather hazards thus presupposes a correct representation of (i) the structure of the waveguide (i.e., the jet location and intensity), (ii) waveguide disturbances (typically in the form of PV anomalies approaching the jet), and (iii) the modulation of the disturbances by intense convective or large-scale cloud systems. Davies and Didone (2013) reported significant PV errors in global medium-range forecasts, probably due to inaccurate representation of moist processes. Research is needed into the interaction of Rossby wave dynamics with moist diabatic processes and specifically the intensity, evolution and interactions of upper-level jetstreams (Martius et al. 2011).

In regions with high topography, mesoscale orographic effects (e.g., flow blocking, channeling, lifting, downslope wind storms) can lead to particular localised hazards, e.g. foehn storms, bora, potential for flash floods or landslides. The advent of very high-resolution numerical models and/or coupling of precipitation and river/sewer flow or landslide models offer forecasts of unprecedented detail, but predictability of the hazards needs to be investigated. Bifurcations between different flow regimes remain a critical issue that can lead to substantial miss-forecasts of orographic precipitation and intense wind events.

Convection-permitting NWP models have shown remarkable realism in their simulation of severe convective storm events. However, research is needed to establish the sensitivity of forecast accuracy to details of the microphysics and turbulence parametrisations in these models, and to characterize this for use in data assimilation and ensemble prediction schemes. Furthermore, a better process understanding is needed to improve nowcasting systems which close the gap between observations and NWP in the timescale of minutes.

Interactions between the boundary layer and surface conditions need to be studied to establish the complexity of coupling that is relevant to nowcasting and very short range forecasting. Particular areas of complexity requiring improved understanding include atmospheric responses to the complex topographic gradients of mountainous areas; the influence of the urban fabric and the role of coastal ocean circulations, including tides, in modulating land-sea contrasts. Local surface coupling may also be important where intense precipitation changes the surface properties, saturating the ground, temporarily covering large areas with water and feeding contaminated fresh water into the coastal ocean.

In the Tropics, a diverse range of synoptic scale disturbances, e.g. Kelvin waves, Easterly waves, Equatorial Rossby waves, Monsoon disturbances and Tropical Cyclones, create the dynamical environment in which high impact weather events occur. Within these systems a variety of convective systems develop that may produce high impact weather. Understanding the inception and interaction of synoptic scale tropical disturbances remains weak. Observational studies typically capture only part of the spectrum of interaction, while modelling studies depend on the ability of the models to react realistically to parametrized convection fluxes.

Many of these areas of research deal with atmospheric processes that are also of importance to scientists modelling and predicting climate change. A characteristic of work is this theme will therefore be collaboration with WCRP initiatives and programmes, including the Global Energy & Water Exchanges project (GEWEX), the Climate and Ocean: Variability, Predictability and Change project (CLIVAR) and several of the WCRP Grand Challenges.

3.1.1 Key Challenges

a) Convective-scale high impact weather systems often develop in response to conditions created by planetary and synoptic scale circulations, both in tropical and extra-tropical latitudes. We need to understand aspects of those large scale circulations that create conditions leading to hazardous weather, e.g. large scale moisture transport, and hence define their relevance to predictability on timescales of up to 15 days.
b) Anecdotal evidence suggests that weather is less predictable than usual during some high impact weather events. We need to understand whether this is the case in general, and if so, to quantify the predictability that is achievable for high impact weather. In particular, we need to understand whether and how often this is reflected in the existence of bifurcations in the forecast trajectory (e.g. changes of track of Tropical Storms, splitting or not of severe convective storms).
c) The impact of most high impact weather is heightened if the weather system is stationary or quasi-stationary. We need to understand what mechanisms produce quasi-stationary hazardous weather systems and how predictable they are.
d) The dynamical structure of most high impact weather systems is influenced by diabatic heating. We need to understand the role of diabatic heating in creating the conditions for high impact weather, whether its effects can be quantified from observations and the level of complexity with which moist diabatic processes must be represented in order to represent the interaction with Rossby wave dynamics accurately.
e) Most weather-related hazards are experienced at or near the surface and are influenced by surface and boundary layer processes, many of which are parametrized even in the finest resolution NWP models. We need to understand the role of those processes, e.g. in triggering convection, so as to enable development of parametrizations that better represent their influence, especially for urban areas and mountainous terrain.
f) Some hazards depend on pre-conditioning (e.g. saturated ground for flooding, dry vegetation for fire, dry ground for excess heat, cold ground for snow & freezing rain). We need to understand how best to represent this pre-conditioning in prediction systems.
g) For flooding from storm surges, we need to better understand the relationship between storm structure, bathymetry and surge response
h) For flooding from convection, we need to explore the use of stochastic parametrizations to represent convection uncertainty.
i) For flooding from rainfall, we need to better understand the relationship between what can be observed (e.g. by radar and satellite) and the aspects of the atmospheric state that determine its short range evolution.
j) For wildfires, we need to understand the aspects of the wind field that are critical to determining the behavior of the fire, and the way in which the fire feeds back onto the wind field at those scales.
k) For extreme winds, we need to understand the sensitivity of surface wind predictions to model vertical resolution and boundary layer parametrization.

l) For winter weather, we need to understand the sensitivity of predictions of precipitation phase to different aspects of the model, including the microphysics parametrization, and the role of surface and boundary layer preconditioning.
m) For heat and air pollution, we need to better understand the role of the urban canopy in creating dangerous conditions, and the sensitivity of forecasts to the accuracy of the boundary layer inversion and the representation of aerosol and chemistry, so as to enable the design of efficient coupled models.

3.1.2 Selected Activities

a) Prepare a review paper on the occurrence and predictability of damaging winds associated with different types of weather system, including the influence of the boundary layer and land surface and implications for their representation in models.
b) Create a catalogue of high impact weather events (focusing on Urban Floods, Extreme Local Winds and Disruptive Winter Weather) for which datasets are available. Set up a wiki facility to enable case information to be added.
c) Select 1 or 2 cases of each type for use in inter-comparisons. Identify the critical parameters and thresholds for these cases and design protocols that will enable inter-comparison of high impact weather prediction capability. Recruit prediction systems, collect and archive results and publish the results.
d) Lead the cross-cutting activities to design and execute field campaigns and RDPs focused on multi-scale predictability, the primary candidates being: in mid-latitudes, the THORPEX North Atlantic Waveguide & Downstream Development Experiment (NAWDEX/DOWNSTREAM); in the African Tropics, the Lake Victoria Basin - Hydroclimate to Nowcasting Early Warning System (LVB-HyNEWS) and in sub-tropical South America, the Research & Development project for improving the prediction of high impact weather systems over the La Plata Basin (ALERT.AR)/ Remote sensing of Electrification, Lightning & Mesoscale / microscale Processes with Adaptive Ground-based Observations (RELAMPAGO). Link with other field campaigns that address key challenges.
e) Together with the Multi-Scale Forecasting theme, initiate a series of workshops focused on advancing knowledge and understanding of the sources of convective and turbulent scale errors and the growth of these errors during timescales from one to twelve hours.
f) Together with the Multi-Scale Forecasting theme, quantify uncertainty in microphysics processes, parameters and fields, and assess the implications for the interaction with dynamical fields.
g) Hold targeted workshops on wildfires, with the aim of understanding the processes that are important in creating hazardous conditions, including large scale control, stationarity, diabatic heating and pre-conditioning.
h) Hold a workshop with mathematicians to explore aspects of highly non-linear behavior, particularly bifurcations, of relevance to high impact weather, and to identify mathematical tools for describing and predicting such behavior. Apply the results to the design of convective-scale probabilistic forecasting systems.
i) Hold a summer school to set up a grand ensemble integration facility for reforecast convective-scale ensembles.
j) Lead a cross-cutting activity to develop the use of models by operational meteorologists to diagnose the origins of hazardous weather features, e.g. using back trajectory techniques. Evaluate the benefit in FDPs, testbeds etc. and publish the results.

k) Lead the cross-cutting activity, in collaboration with mathematics experts, to review and synthesise work on stochastic physics and model error in ensembles, and to promote new work, leading to publication of new recommendations for parametrization design for ensemble prediction systems.
l) Lead the cross-cutting activity to develop and apply model diagnostic tools to identify model processes that have caused major forecast errors (busts).

3.2 Multi-scale Forecasting of weather-related hazards

This theme covers forecasting by coupled physical modelling systems including atmospheric physics and chemistry, ocean and the land surface, and covers modelling of floods, landslides, bushfires, pollution, etc.. While particular interactions are specific to the hazards selected in HIWeather, the principles of coupled modelling have been well established in the Earth System Modelling community that underpins current research on seasonal and climate prediction. The planned research will draw heavily on aspects of that work under several WCRP programmes and grand challenges, especially GEWEX. This theme will also work closely with the S2S project, and with the CAS Working Group on Numerical Experimentation (WGNE) and the Global Atmosphere Watch (GAW) Working Group on Urban Research, Meteorology & Environment (GURME) on modelling issues.

i. Observations & Nowcasting

For effective and successful forecasting and warning of high impact weather events on timescales of minutes to one hour, high-resolution observations in time and space are needed. Despite major advances in NWP, computing time and model spin-up result in a gap between analysis time and the availability of useful forecasts. Future improvements in convective-scale NWP and data assimilation on the timescale of this project will shorten but not eliminate this gap. Thus observation-based nowcasting systems will remain essential for warnings at very short timescales, dovetailing with very high resolution NWP at longer timescales. To provide the best possible basis for nowcasting and NWP, new approaches to obtaining very high resolutions of observations are required, using both ground- and satellite-based remote sensing, deployment of dense networks of low cost sensors, and crowd sourcing. Research in the Predictability & Processes theme on processes leading to initiation and evolution of high impact weather events will provide the basis for more advanced nowcasting techniques.

ii. Data Assimilation (DA)

A major focus on initializing convective-scale models is needed to achieve the required accuracy of forecasts of high impact weather in the first day. Data assimilation for these models is in its infancy and needs to be developed so that small scales are initialized consistently with the large scales, without distorting the latter, and so that the boundary layer, in particular, is initialized consistently with the land and ocean surface, and with the atmospheric aerosol content.

Initialisation at the convective scale requires the exploitation of new observation sources, highlighted above, which have very different error characteristics from conventional observations including much higher probability of gross error, correlated error, and large biases. For remotely sensed data, the observations may be averaged over areas larger than a model grid cell. Research into the appropriate complexity of cloud assimilation will be necessary as models develop increasingly sophisticated representations of microphysics that relate in complex model-dependent ways to the observed quantities.

Characterization of the time and space variability of the observation and forecast background errors for data assimilation are key to obtaining more accurate forecasts. In particular, development is needed in:

a) methods suited to the non-linear and non-Gaussian errors typical of convective scale model evolution
b) methods that handle position errors

iii. Model Development

Improved forecasts of High Impact Weather depend on model improvements both to extend predictive skill of synoptic scale environments associated with high impact weather and to provide more precise and accurate small scale detail. Prediction of weather impacts requires more sophisticated coupling of NWP with physical impact models (e.g. for storm surges and floods).

Particular challenges for model development are associated with:

- development of a new generation of scale independent or scale adaptive parametrizations, e.g. stable boundary layer, cloud-related turbulence, cloud microphysics;
- representation of process uncertainty through stochastic schemes;
- development of parametrizations of partially resolved processes spanning 0.5 to 5 grid cells – the "grey zone";
- optimization of ocean-atmosphere-aerosol–land surface coupling strategies for small scales and short-to-medium lead time forecasts;
- representation of weather impacts transmitted through land geophysical processes, biological processes and responses of buildings, vehicles, infrastructure, etc.

iv. Ensemble Forecasting

While ensemble forecasting on the synoptic scale has matured over the past two decades, there is a need for research to improve its performance in convective-scale models – both as a result of their much shorter grid-lengths and also their smaller domain size (typically national- or city-scale rather than continental-scale).

- Design of perturbations to represent initial uncertainties in the ensemble forecasts is closely linked to data assimilation (3.2.1). The size and structure of ensemble initial condition perturbations should be determined using objective ensemble data assimilation methods.

- Evolution of forecast uncertainties is governed by the representation of model errors using techniques such as stochastic physical parameterizations. These techniques need to be designed to represent uncertainties in model physics with particular focus on high-impact weather events, e.g. the impact of errors in cloud microphysics on forecasts of heavy rainfall, low visibility or temperature extremes.

- New perturbation strategies are needed to overcome under-spreading in surface weather parameters. Ensemble members currently usually share the same initial surface conditions which likely leads to significant underestimation of the uncertainties in forecasts of near-surface conditions. This may be dealt with by perturbing lower boundary specifications or by using coupled ensembles.

- Interaction with the sea surface is a special example of the influence of surface conditions. Coupled ensembles may be needed to represent the uncertain impact of diurnal variations in coastal waters on sea-breeze fronts etc.

- A key motivation of ensemble forecasts is to capture the risks of high-impact events in the tail of the statistical distribution. This has implications for ensemble size.

v. Post-processing, product generation and human interpretation

Turning raw model outputs into the information required to be communicated to users requires calibration and removal of biases in the physical variables and in their probability distributions, time and space aggregation or downscaling to match user requirements, and diagnosis of ancillary variables of interest to the user that are not part of the model.

Calibration of direct model output is important for high impact weather forecasts. While the value of using reforecast datasets to calibrate products such as the Extreme Forecast Index has been demonstrated for medium range forecasts, more research is needed to explore strategies appropriate for convective-scale models.

A key step in the use of ensemble prediction systems is to relate the ensemble sample frequency to the probability of the event occurring. This is dependent on the perturbation strategy, the size of ensemble, the spread/skill relationship of the system, and may also be dependent on weather regime. Experience with medium range ensemble prediction systems needs to be tested at the convective scale, with special emphasis on the performance in the wings of the distribution. There is also a need for work on ensemble post-processing methods that preserve the forecast covariance structure, e.g. for use in flood forecasting. For some applications, there is a need for scenarios with user-defined characteristics rather than probabilities. Methods for extracting these from the ensemble distribution need to be developed.

Compact presentations of raw NWP information are required for operational forecasters and there is a need to investigate factors that limit the utility of automatic warnings. Methodologies are also needed to combine ensemble NWP outputs with nowcasts to achieve seamless predictions of high impact weather events form minutes to hours.

3.2.1 Challenges

i. Observations & Nowcasting

- Current operational weather observing networks are unable to capture the detail of the weather that causes hazards, the hazards themselves, or the impacts of those hazards.

New developments in ground- and space-based remote sensing, in the widespread deployment of low cost sensors, and in crowd sourcing, need to be harnessed to provide the required information. The major challenges are in sourcing and quality controlling these observations.

- The next generation of coupled physical models that will be used for hazard prediction will need observations to initialise the processes that are necessary for skilful predictions. We need to identify observation sources that are able to deliver the required information.
- Apart from precipitation, for which FDPs have provided valuable inter-comparison opportunities, most nowcasting methods have been developed for specific locations or specific applications, with little analysis of the relative performance of different approaches across a range of applications. The development of rapid-update convective-scale DA/NWP systems offers an alternative, more physically-based approach to nowcasting a wide range of hazards. We need to establish the best approaches to nowcasting weather-related hazards, whether observation-driven, NWP-driven, or a hybrid of the two.

ii. Data Assimilation

- Traditional approaches to data assimilation at synoptic- and meso- scales rely on weak nonlinearity of the equations. This no longer holds for convective-scale motions. We need to develop data assimilation methods that can cope with this stronger non-linearity.
- Hazard forecasts must be updated more frequently than traditional synoptic and mesoscale forecasts, perhaps every hour or less. This places demands on the design and efficiency of data assimilation that are different from those placed on traditional 6-hourly cycles. Data assimilation systems that are able to meet these needs require development.
- Many observation types with comparable resolution to that of global models, e.g, most satellite data, become relatively coarsely spaced on the convective scale. New observation operators that account for this ‘error of representativeness’ are required.
- The assimilation process is strongly influenced by the specification of model error. Given that both synoptic-scale and convective-scale structures will need to be accounted for, new approaches to the specification of model error are required.
- Component models in coupled prediction systems are usually initialised independently. However, some coupled processes need to be initialised consistently. We need to develop methods of achieving this.

iii. Model Development

- Routine hazard forecasting requires the development of coupled prediction systems involving the atmosphere and its composition, land, ocean and ice. Current initiatives are based either on using Earth System Models designed for climate prediction, or on opportunistic coupling of components that happen to be available. We need to identify the aspects of coupling that enable accurate hazard prediction and to develop interface schemes that provide the best forecasts.
- Forecasting of convection-related hazards depends on accurate representation of convective initiation. We need to develop model parametrizations that produce reliable accuracy in this respect.

- Convective-scale models have been developed with widely different levels of detail in the microphysics parametrizations. We need a better understanding of the benefits of more detailed schemes, and to use them to improve simpler parametrizations.
- The land surface interacts with the atmosphere at both local and synoptic scales. Models often use parametrizations of gravity wave and frictional drag that are designed to provide the correct synoptic scale forcing. We need to understand how to accurately parametrize local interactions without degrading the synoptic scale response.

iv. Ensemble Forecasting

- Global ensemble prediction systems have achieved a useful level of consistency between predicted uncertainty and observed error for smoothly varying atmospheric variables. We need to achieve similar reliability and to produce well-calibrated probabilities for hazard-related variables.
- Consistent with solving the multi-scale and coupled model data assimilation challenges, we need to develop ensemble perturbation techniques that reproduce observed error growth rates in multi-scale coupled prediction systems.

v. Post-processing, product generation & human interpretation

- Extracting information from raw NWP output that users will find helpful and easy to understand remains a difficult problem except in some highly structured application areas. Together with the Communications theme, we need to develop more effective products.
- There are particular problems in communicating ensemble-based uncertainties, which will be compounded in convective-scale models where the uncertainties are coming from processes at very different scales. We need to develop better ways of using ensembles and more user-oriented means of communicating uncertainty.
- Some locally developed diagnostic outputs have potentially much greater value if their applicability could be extended globally. Examples include fire risk indices and ocean & river flood estimation methods. We need to develop the global parameter sets that will enable these products to be generated in a seamless way across the world.

3.2.2 Selected Activities

a) Hold a workshop on the requirements & opportunities for capturing and quality controlling high resolution (in time & 3D space) observations of weather, hazards and their impacts, including the use of new ground-based remote sensing techniques, high density deployment of cheap sensors, and crowd sourcing. Liaise with the WMO Integrated Global Observing System (WIGOS) on the inclusion of convective-, turbulent- and urban-scale observing systems in the next Observation Impact Workshop.
b) Hold a workshop to review current approaches to nowcasting and to make recommendations about future development directions using both simple physical representations of key processes and rapid update convective-scale DA/NWP systems.
c) Inter-compare nowcast techniques using data from recent and planned field campaigns.
d) Hold a workshop to review the current state of kilometre-scale data assimilation.
e) Carry out an inter-comparison of coupled data assimilation systems.
f) Hold a workshop & course on nonlinear coupled data assimilation**.**
g) Develop a climatology of model error at kilometre-scale in regional reanalyses, stratified according to hazard-related processes, e.g. precipitation, convection, boundary layer

h) Carry out an inter-comparison of advanced radar data assimilation systems, with a focus on object evaluation (e.g. storm initiation, timing & location) and prepare a review article.
i) Carry out an inter-comparison of adaptive observing strategies and prepare a review article.
j) Carry out a case-study inter-comparison to evaluate current capability for simultaneous synoptic and convective scale assimilation.
k) Review the contribution of improvements in boundary layer and land surface assimilation to hazard prediction.
l) Develop techniques to assess the sensitivity of hazard forecasts to observational inputs.
m) Together with the Predictability & Processes theme, hold an inter-comparison of convective-scale modelling systems, using case studies, RDP datasets and reanalyses, with specific relevance to the selected hazards. Specific foci to include coupled models, performance in multiple scale cases, boundary layer performance.
n) Review the validity of commonly used approaches to model parametrization at very high resolution and develop improved approaches.
o) Together with the Predictability and Processes theme, quantify uncertainty in microphysics processes, parameters and fields, and assess the implications for the interaction with dynamical fields.
p) Through a process of review, assessment and inter-comparison, develop a comprehensive suite of physically-based perturbations that accurately capture uncertainty in prediction of the selected hazards resulting from all scales and all components of coupled systems.
q) Carry out an inter-comparison of kilometre-scale ensemble prediction systems and their products and prepare a review article.
r) Together with the Evaluation theme, evaluate new approaches to ensemble verification, particularly with relevance to hazard predictions.
s) Together with the Evaluation theme, evaluate improved ensemble diagnostics in case studies and FDPs
t) Together with the Communication theme, identify gaps between the outputs of existing NWP systems and the requirements of forecasters and end users. Develop new user-oriented products and evaluate in FDPs
u) Explore the value of convective-scale reanalyses and ensemble reforecasts through comparison of model and observed climatologies of high impact weather and its precursors.
v) Lead the cross-cutting activity to demonstrate and evaluate the benefit of enhanced observations, including dense networks of sensors focused on monitoring particular hazards (e.g. temperature for the heat hazard), to the real-time production and communication of hazard warnings in FDPs. Document and publish results, including challenges in gathering, quality controlling and displaying the observations.
w) Lead the cross-cutting activity, in collaboration with NMHSs and space-based Earth Observation agencies, building on the Committee on Earth Observation Satellites (CEOS) database and other initiatives, to create a catalogue of observations required for monitoring, forecasting, communicating and verifying weather-related hazards and their impacts, of the required spatial and temporal sampling and accuracy, and of candidate new and existing data sources. Promote implementation and real-time international exchange of these observations.
x) Lead the cross-cutting activity to raise the level of expertise in high impact weather prediction by involving operational meteorologists in HIWeather research, particularly

through evaluation activities in FDPs, testbeds and proving grounds, WMO Training Centres etc.

y) Lead the cross-cutting activity to develop an international collaborative activity to collect social media, volunteer and other professional data for use in monitoring, nowcasting and data assimilation.
z) Contribute to a cross-cutting activity to review and synthesise work on stochastic physics and model error in ensembles, and to promote new work, leading to publication of new recommendations for parametrization design for ensemble prediction systems
aa) Contribute to a cross-cutting activity to review and publish the implications of uncertainty across the whole spectrum of the work of HIWeather and how these propagate to influence the ability to enhance resilience.

3.3 Human Impacts, Vulnerability & Risk

This theme lies at the heart of the project. As part of the production process, it deals with the challenges of translating probabilistic forecasts of physical hazards into impact-based risk assessments, taking account of hazard generation in human systems, the exposure of individuals and communities to the hazard, and the vulnerability of those affected. Conversely, as part of the specification of the need for warning services, it identifies the role that weather forecasts might play in enabling individuals and communities to minimise hazard impacts. Quantitative models that relate the occurrence, severity, duration or other important aspects of the physical hazard to consequences of significance for human systems need to be developed, evaluated, peer reviewed and shared.

Hazards result from the interaction of weather with other natural phenomena and human systems. Often the damage is caused by interactions between weather and the built environment created by humans – e.g. in windstorms it is often loose building materials, while in floods it may be engineering failures.

Physical hazards may affect a variety of social, health or economic systems through death and injury; physical and mental illness; damage to buildings or infrastructure; contamination of land; or disruption to business, government and welfare services. Many of these effects are highly non-linear with poorly understood thresholds beyond which impacts may be irreversible. In particular, the transition from the normal response of distress to the abnormal one of physical and mental illness and its consequent loss of economic productivity and cost of treatment and care, is poorly understood and needs to be better studied.

The impact of a hazard depends on the extent to which individuals, businesses, communities & infrastructure are exposed to it, i.e. how likely is the hazard to impact on the receptor? This depends on the relation of receptors to the hazard, e.g. what traffic is using a road during a severe wind storm, how many aircraft are flying a route that is affected by thunderstorms, or which utilities are affected by flooding. Access to current socio-economic data is a key requirement to enable exposure models to be developed, evaluated and shared between academic institutes.

The impact of a hazard also depends on the vulnerability of exposed individuals, businesses, communities and infrastructure, i.e. how sensitive is the receptor to the impact? This depends on how the receptor responds, what reserves they have to call on, and how well prepared they are. Vulnerability data and models depend on a detailed understanding of the cultures of groups of people within the population. Generic relations between the characteristics of such groups and their behaviours can provide first-order information, but they are usually not directly applicable in specific high impact weather event situations. However, detailed studies in representative locations, synthesised across contexts, can enable the development and documentation of best practice that can be applied by National Meteorological and Hydrological Services (NMHSs) and disaster reduction agencies. Differing responses to different types of hazard need to be identified, in particular between slow onset and sudden onset impacts.

Expertise in the science required for this theme is widely disbursed in academia and in the user domain, and bringing these diverse communities together will be a challenge. This challenge is common to the climate and seasonal forecasting endeavours, where the emphasis is on policy rather than management responses. Links with the Climate Impacts community in WCRP and beyond will be established to ensure that expertise gained here is made available to be used in these broader contexts.

3.3.1 Key challenges

a) There are currently few people dedicated to research on vulnerability and risk to high impact weather that are linked to the weather forecasting community. We need to build capacity to define, conduct, review and communicate vulnerability and risk research and applications.
b) Much of the current in-depth work on human impacts, exposure, vulnerability and risk from high impact weather is based on particular users and locations. We need to assess, develop and improve approaches to assess weather-related vulnerability and risk and the additional benefit of providing such information in addition to the hazard forecast. This will involve examining the full range of approaches from simple overlays of physical hazard and exposure variables (e.g., to determine population within weather warning areas) to sophisticated real-time dynamic modelling of impacts (e.g., streamflow, hourly energy demand). It should cover:
    - treatment of chronic, long-term impacts separated in time and/or space from the specific event (e.g., effects of time required to recover and rebuild from loss of dwelling can induce stress, mental illness; creates vulnerabilities to subsequent events)
    - methods to distinguish evolving high consequence events/thresholds for which special or more focused/relevant communications (pre-, during, post-event) must be provided to aid the needed risk management decision
    - techniques such as spatial and temporal analogues, e.g. analysis of scenarios that assess current vulnerabilities to past events (e.g., applying historical strong TC scenario to a modern city and estimating impacts)
c) While socio-economic data are collected in many countries, permitting estimation of impacts, there are few ground-truth data available. We need to explore the use of social media to construct or validate impact models.
d) Most datasets of population, socio-economic status, employment etc are static, based on infrequent censuses. However recent work has begun to explore combining such data to create time-dependent information. We need to further develop this capability to represent the dynamic nature of vulnerability**.**

e) We need to identify and characterize vulnerabilities across populations for the selected hazards, including vulnerable populations who have not or only rarely exposed, e.g., Somalia TC, Myanmar TC
f) We need to understand the reasons for counter-intuitive responses to risk warnings, and in particular to understand trade-offs in risks (e.g., fishermen going hungry vs. risking death when there is a high wave warning)

3.3.2 Selected Activities

a) In collaboration with other themes, build capacity to define, conduct, review and communicate vulnerability and risk research and applications
    - Foster/nurture sustained relationships with practitioners and researchers that have experience working with (or within) sectors and organizations that are sensitive to the selected hazards (e.g., health, transportation)
    - Hold a series of surveys and small workshops to solicit contributions to a larger white paper (i.e., chapters, case studies, decision problems); inventory of on-going vulnerability and risk research; and multinational research proposal(s). The meetings would focus on specific hazards/risks and sensitive sectors and target social and interdisciplinary researchers and practitioners involved in the production and delivery of weather services and management of risk.
    - Propose, organize and participate in special themed sessions at international meetings in the impact/vulnerability/risk community and social or interdisciplinary science meetings.
    - Publish the white paper as a special issue of an interdisciplinary journal with a shorter update/note to a meteorological-oriented journal, e.g. Bulletin of the American Meteorological Society (BAMS).
b) Develop an inventory of weather-related risk and impact models; establish a research database of impact, vulnerability, and risk information to track how things change with time through the project; develop an analytical framework to categorize and assess the state of risk & impact modelling and its benefits for each hazard and sector/outcome.
    - Through literature review and interviews with representatives from key operational forecasting and research centres, engaging private sector as a priority, including existing databases of vulnerability to extreme events, and adding potential near-term effects of climate change (changing hazards, exposure, vulnerability)
    - Identify go-to people in each hazard to assist researchers. Note some impact & vulnerability models and data are proprietary and there will be sensitivities.
    - Identify issues with impacts that are slow to appear or chronic.
    - Prepare and publish a white paper on the distinctions between those aspects of the selected hazards to which human impacts are highly sensitive and those that have little sensitivity, and the relevance of these results to current and potential prediction capabilities so as to highlight priority areas for hazard prediction research.
    - Contribute findings to the white paper in a) with emphasis on identifying knowledge gaps, data issues, novel methodological practice, appropriate case studies, treatment of diversity in people/culture/countries, comparison across hazards.
c) Lead the cross-cutting activity to describe an operational forecasting production structure that includes socio-economic impact models and products and to promote it through training events, conferences and publications.

d) In collaboration with the Communication and Evaluation themes, catalogue post-event case-study evaluations, identifying similarities and differences, sources of hazard information, usage of advice in decision making and good practice in evaluation
e) Contribute to the cross-cutting activity to develop an international collaborative activity to collect social media, volunteer and other professional data to construct and validate impact models.
f) Lead the cross-cutting activity to prepare a catalogue of the principal variables that characterise information requirements for stakeholder decision making, including the most significant thresholds, and the nature of the impact response.
g) Develop capability to model dynamic vulnerability (e.g. flows of traffic, weekend/holiday, demographics, marginal populations, Lake Victoria fisher exposure, etc.)
   - Hold workshops on approaches to modelling vulnerability, the benefits of dynamic vs static modelling, and the availability of data.
   - In collaboration with the climate change adaptation community.
   - Include environmental (e.g., soil dryness/wetness, tree leafout), social (e.g., mass events/gatherings), other secondary effects; integration of models/representations of dynamic vulnerability (compatibility issues, etc.)
   - Compare across hazards
   - Start with a narrow scope, then broaden

3.4 Communication

In order for weather forecasts and warnings to have value, the information created must be communicated to people at risk, received, understood, and used. Effective communication of high impact weather forecasts and warnings includes disseminating the information to the people that need and can use it, through appropriate channels, and conveying the information so that it is understood, interpreted, and used in ways that promote appropriate protective action. It includes both applied work to improve communication practice, and research to understand the reasons for underlying existing communication gaps (or unmet needs) and ways to improve them.

Expertise in several fields, including behavioural psychology, marketing and communication science will be brought together to contribute to this work, which has much in common with communication problems in other risk-related contexts, particularly health. While the aim of forecasts and warnings is to influence specific decisions and actions, this work will also be relevant to the issue of using science to influence policy which is a concern of climate scientists. Links will be developed with relevant parts of the climate community to ensure that relevant findings are shared.

3.4.1 Key Challenges

a) We currently lack fundamental understanding about which communication methods work better or worse in different high impact weather contexts, and their dependence on characteristics of the audience. It is important to diagnose communication successes and gaps when high impact weather events happen; to synthesize findings across cases and regions and to transfer findings nationally and internationally across hazards and user sectors, so as to improve communication in future events.

b) Social Media are rapidly becoming an important communication medium for a large section of the population. We need to understand how social media are and can be used in high impact weather forecast and warning communication, interpretation and use and to encourage and improve use of social media in weather communication.
c) Effective interpretation and use of forecasts and warnings has been associated with trust in the product and its source. To improve the use and value of forecasts, we need to understand the reasons for reduced trust and, where appropriate, enhance communication about forecast improvements, using success stories, especially in developing countries.
d) Many research projects and practical implementations of hazard communication are being undertaken around the world. We need to draw together this work to identify best practice so as to improve communication of forecasts and warnings, including uncertainty at all points along the information chain.
e) There are currently a small number of scientists with in-depth relevant expertise working in this area and connected to weather communication. We need to involve more people with expertise in communication, interpretation and use of forecast and warning information in decision making, and related social sciences, in the HIWeather program.

3.4.2 Selected Activities

a) In collaboration with other themes, build capacity in communicating high impact weather information through targeted workshops, conference sessions and reviews involving social science and other relevant researchers, operational staff, service providers and end users. Promulgate current capability in both the meteorological and impact community through publication of a white paper and/or special issues of journals.
b) Improve forecast and warning communication, including uncertainty information, by identifying and sharing good practice:

- Hold an international workshop with high impact weather and communication experts to review successes & gaps in communication across cases and regions, publish the results and design a reporting template for case studies.
- Follow up with case studies as new high impact weather events occur, drawing out lessons learned for forecasters and for decision makers.
- Conduct subsequent international workshops to develop and periodically update communication best practices
- Develop communication projects for researchers to work with NMHSs on how they interact with partners, including communication with vulnerable groups (channels, messages)
- Conduct periodic electronic surveys of NMHSs to compile and transfer internationally knowledge about communication with different audiences
- Conduct research projects to investigate communication and interpretation and use of forecast and warning information, including uncertainty, for different hazards and international locations.
- Initiate a series of annual or biennial training courses for operational meteorologists to raise the standard of communication, particularly of uncertainty, to both emergency managers and the public, possibly in association with the WMO Regional Training Centres. Use past cases as the basis for training exercises.

c) In collaboration with the Vulnerability & Risk and Evaluation themes, catalogue post-event case-study evaluations, identifying similarities and differences, sources of hazard information, usage of advice in decision making and good practice in evaluation
d) Lead the cross-cutting activity, together with impacts agencies (emergency management, health etc), to develop an international collaborative activity for the collection of social media, volunteer and other professional data to construct or validate impact models. Given the rapid evolution of internet and social media communication, this work will need to evolve as the project progresses.

- Develop standards for data collection, including use of hashtags (e.g. #snow)
- Develop methods of quality control and interpretation,
- Use proactive requests for people to contribute data
- Start narrow & simple, then compare across hazards, countries/cultures

e) Lead a cross-cutting activity to review the influence of trust, salience, beliefs and other factors on the communication, use and application of weather information in decision-making and the implications for effective forecasting & warning.
f) Lead a cross-cutting activity, in collaboration with operational meteorologists and CBS, to develop interpretation aids in high resolution deterministic & ensemble NWP and hazard predictions and improved mechanisms for communicating probabilistic information based on different user capabilities, constraints and information needs. Document the material for use in training, e.g. at WMO training centres, and as COMET (or similar) training modules.
g) Lead a cross-cutting activity to review and publish the implications of uncertainty in weather forecasts and warnings across the whole spectrum of the work of HIWeather and how these propagate through the forecast-to-users chain to influence the ability to enhance resilience.

3.5 User-Oriented Evaluation

Improvements in community resilience are ultimately achieved through improvements in all elements of an information chain that links accurate weather information, forecast provision in an appropriate form for a potential user, timely access to that information, understanding of the information, and ability to make use of it and respond appropriately to achieve socio-economic benefits. Measuring the effectiveness and improvements in all links of the value chain will be important in the HIWeather project.

Murphy (1993) defined three aspects of a “good” forecast: consistency (represents the forecaster’s best judgement), quality (accuracy and other measures of meteorological performance), and value (enables better decisions). Evaluation research in the HIWeather project will address new challenges in measuring quality and value, including the accuracy of weather and hazard predictions, the decision-making value of warnings, and the final benefit of forecast applications as measured in social, economic, and environmental terms. The closely related cross-cutting verification theme (Section 4.6) focuses on the practical aspects of applying available verification methodologies.

Evaluation of High Impact Weather forecast quality must answer several types of questions including:

- What is the nature (magnitude, bias, distribution) of the errors in the forecasts and how do the errors depend on the forecast itself?
- What improvements should be made to the forecasting system to improve its performance?
- To what degree are the forecasts more skilful than a naïve forecast like persistence, climatology or random chance?
- Which forecast performs better when more than one is considered?
- How do forecast errors propagate, confound, and conflate through the seamless hazard prediction process to the final intended user?

While the first two questions may be of primary interest to modellers and other researchers who are developing forecasting systems, the other questions must also be addressed in order to demonstrate impact to stakeholders and justify investment in forecasting research and development.

Standard verification approaches for medium range NWP have limited usefulness for very high resolution (mesoscale and convective scale) forecasts. Several new verification methods have been proposed for evaluating the spatial structures simulated by high resolution models and this remains an active area of research. While most of these spatial methods measure forecast quality, some of them (e.g., variograms) address the realism of the forecast, which may be of particular interest to modellers.

Spatial verification approaches are now starting to be applied to high resolution ensemble forecasts, but much remains to be done to understand what can be learned from these approaches, both in terms of quantifying ensemble performance, and in calibrating and post-processing ensembles to improve forecast quality and utility. The utility of spatial verification for evaluating hazard impact forecasts (e.g., flood inundation, fire spread, blizzard extent and intensity, pollution cloud) needs to be explored, especially since graphical advice and warnings are becoming more common.

Characterisation of timing errors is also very important, not only for model output but also for warnings where there are two additional free parameters, lead time and duration. Little work has been done to quantify timing errors, especially for graphical warnings, in spite of those products becoming increasingly common. Knowledge of the useful lead time for communicating the hazard and taking protective action is important for developing user confidence in the warnings.

High impact weather often involves extreme values of wind, precipitation, or severe weather which are rare and/or difficult to observe. Some new “extremal dependency” metrics have been proposed for quantifying the accuracy of categorical forecasts for rare events, which are better able to discriminate between the performance of competing forecasts at the far end of the distribution. The utility of these scores for evaluating forecasts of high impact weather and its impacts requires further investigation.

Evaluation methodologies appropriate for particular high impact weather hazards need further development. For example, in the case of tropical cyclones, track and intensity verification has been done for many years but additional evaluations are needed for storm structure, precipitation, storm surge, landfall time/position/intensity, consistency, uncertainty, and additional information to assist forecasters (e.g., steering flow) and emergency managers. The predicted occurrence and evolution of cyclones at long lead times (genesis, false alarms and missed events) also requires further research.

Methods for evaluating hazard impacts are even less mature. Users are interested in knowing the quality of downstream predictions for physically linked quantities like flood height, fire spread rate, visibility, road conditions, comfort indices, etc. (see Section 2.3). Metrics for evaluating these quantities need to be developed in close collaboration with key users, linked directly with their decision making needs.

Observations of impacts are not routine and the meteorological community does not necessarily have access to the sources of observational data needed for evaluation. It will be necessary to partner closely with the relevant agencies and media to share data. It may be possible for the high impact weather community to influence governments and other stakeholders to introduce routine hazard monitoring. Enticing new sources of information, for example from webcams, social media, crowd-based observing networks like WoW and sensor networks external to national meteorological services, should be explored for their utility in evaluating hazard impact forecasts. Observational errors affect the ability to quantify the performance of high impact weather forecasts, especially in extreme environments where observations may be less reliable (e.g., wind-related under-catch of precipitation in gauges, attenuation of radar reflectivity in extreme rainfall). Strategies for accounting for observational error in verification are urgently needed. More robust approaches such as quantile verification or evaluating forecasts in “observations space” should be encouraged. This is also true for evaluating impact predictions, especially when the reliability of the data is less well understood and quality control methodologies are still being developed.

Forecast value and benefit is related to accuracy, but goes further to measure the societal and economic advantage to users of using the forecasts and warnings in their decisions. These attributes are much harder to measure than the quality of the weather predictions, as users’ decisions are affected by the methods of communication used to convey the forecast (addressed in Section 3.5), their trust in the forecasts, their vulnerability and exposure to risk, and psychological and environmental factors influencing their interpretation and use of forecast and warning information. In addition, competing factors (e.g., economic considerations) may impact the users’ responses. A complication, when verifying value, is that observations are unable to report what the impact of a hazard would have been in the absence of the forecast. Some of the most straightforward forecasts to evaluate are those where, for safety reasons, the hazard is largely mitigated and forecasts are used to reduce the mitigation cost. Both aviation and winter road maintenance are close to this situation. Methods are needed to measure improvements in the protection of life and property in response to forecasts and warnings, where a “do nothing” baseline may not be available or desirable.

An important goal is measuring the economic benefit that can potentially be gained in various sectors (industry, government, public, etc.) through improvements in the quality, timeliness and communication of forecasts of high impact weather and associated hazards. This goal is of interest to stakeholders in terms of reducing their costs and losses, and NMHSs to justify investment in improved services and supporting infrastructure like supercomputing and observation networks. Partnerships with stakeholders will be needed to link improvements in prediction with (sometimes confidential) knowledge of hazard-related costs and losses to assess economic benefit.

A related question concerns the individual sensitivity to forecast error, i.e. what are tolerable and acceptable errors (as defined by traditional verification) and how does this vary among sectors? For example, the interplay between hits, misses and false alarms is such that in order to achieve a certain probability of detection one may need to make a decision to warn at a fairly low probability, which introduces a high over-forecasting bias. Depending on the costs and losses associated with false alarms and misses, different warning thresholds will be optimal for different users, The simple cost/loss model used in verification metrics like Relative Economic Value are frequently criticized as overly simplistic, and more work needs to be done to apply more appropriate economic models when linking forecast accuracy with value.

In the same way that evaluation underpins all of the research pillars in HIWeather, it is also a key unifying expertise across weather and climate. Close collaboration will be maintained with WCRP activity in this area through the Joint Working Group on Verification Research (JWGFVR).

3.5.1 Key Challenges

a) Recent work has demonstrated the value of using diagnostic and spatial verification methods to evaluate precipitation forecasts. We need to develop appropriate verification methods for new kinds of temporal and spatial high impact weather forecasts (e.g., high resolution ensembles, extremes, nowcasts, warnings, downstream hazards, etc.)
b) There are currently a very small number of scientists working in the area of user-focused evaluation. We need to pull in more people with expertise in the area of social, economic, and environmental sciences to assist with appropriate methods of evaluation, and from important impact sectors to help understand the decisions made in response to high impact weather and associated hazards.
c) Analysis of information content typically shows that information is apparently lost at each stage of the information chain (e.g., forecasts, communication, interpretation, use, value). We need to develop and apply methods to evaluate the impact and effectiveness of information at each stage, including measuring improvements in resilience.
d) Effective use of forecasts and warnings has been associated with trust in the product and its source. We need to build users' trust by providing information about how good the forecasts were in the past and the reasons for incorrect forecasts, and developing and applying user-focused verification approaches.
e) Evaluation of hazards, impacts and response are limited by access to data. We need to use social media and non-standard data for evaluation and to improve collection of this information to make it easier to use.
f) Governments require assessments of the value of forecasting and warning services to national economies. Very few comprehensive studies have been undertaken. We need to develop and apply approaches to quantify the socio-economic benefits of high impact weather forecasts, including identifying avoided losses.

3.5.2 Selected Activities

a) In collaboration with other themes, build capacity in assessing the value of hazard warnings and advice through targeted workshops, conference sessions and reviews involving risk reduction and social science researchers, operational staff, service providers and key user groups. Promulgate current capability in both the meteorological and impact community through publication of a white paper and/or special issues of journals. Identify go-to people in each hazard to assist researchers.
b) Through workshops and inter-comparisons, involving social scientists, operational meteorologists and users, and building on a review of current capability, identify appropriate methods and metrics for evaluating hazard forecasts and warnings that reproduce subjective judgement. Evaluate selected methods with users in FDPs.
c) Together with the multi-scale forecasting theme, develop and evaluate improved ensemble diagnostics and new approaches to ensemble verification, particularly with relevance to hazard predictions, evaluate in case studies and FDPs.
d) Develop and apply techniques for evaluating errors in warning timing/duration and demonstrate in FDPs.
e) Develop robust approaches for accounting for observation uncertainty in verification and demonstrate in case studies, RDPs and FDPs.
f) In collaboration with the Vulnerability & Risk and Communication themes, catalogue post-event case-study evaluations, identifying similarities and differences, sources of hazard information, usage of advice in decision making and good practice in evaluation.
g) Contribute to a cross-cutting activity to identify and promulgate good practice in enhancing user trust by assessing and communicating forecast successes and failures and their causes and improvements to forecast capability from a user perspective.
h) Contribute to a cross-cutting activity to develop an international collaborative activity to collect social media**,** volunteer and other professional data, through application and assessment of data quality metrics and use of the data in verification.
i) Through workshops and demonstrations, collaborate with experts in other fields, e.g. World Bank, International Association of Evaluators, International Council of Science (ICSU) Council on Evaluation, World Framework for Climate Services (WFCS), National Science Foundation (NSF) Hazards SEES), to raise interest in assessment of the value of weather services and, in particular, in stepwise evaluation of mitigation of hazard potential, leading to publication of a white paper.
j) Lead a cross-cutting activity to use reviews, workshops and participation in the design and execution of FDPs to develop an understanding of the propagation of error and value through the processing chain from meteorological observation and forecast to information use and user benefit.
k) Lead a cross-cutting activity, in collaboration with operational meteorologists and CBS, to develop verification tools that enable operational meteorologists to judge the value of new products and capabilities. Evaluate the benefit in FDPs, testbeds etc. and publish the results.

l) Lead a cross-cutting activity, in collaboration with operational meteorologists and CBS, to develop real-time verification facilities that support operational meteorologists in assessing the accuracy of the current forecast. Evaluate the benefit in FDPs, testbeds etc. and publish the results.

4 Cross-Cutting Issues and Activities

While research themes are oriented to solving specific problems related to the selected hazards, the cross cutting activities deal with issues that are common to all research themes or to activities that will be undertaken jointly by groups of research themes.

4.1 Benefits in Operational Forecasting

The current High Impact Weather forecasting process, whilst varying greatly across the globe, generally involves subjectively interpreting model forecasts of the weather and other data in order to decide whether issuing a warning is appropriate. Model forecasts may be obtained from a very wide range of sources, but typically include deterministic and ensemble forecasts at varying resolutions, supplemented by background observations and 'environmental' information (e.g. river levels). This may then be combined with knowledge of the 'impact response function', which can be simple and customer-specific (e.g. wind and wave thresholds for ferry operations) or much more complex, as with many public-service warnings. In a number of NMHSs systems are being developed to combine all of these sources of information to produce automated guidance to the forecaster. The forecaster then has a vital role in communicating forecasts and warnings (including the associated uncertainty) in a way that will support decision makers at all levels of their society.

The above process cuts across all the research themes of the HIWeather project. Interpretation of observations and model forecasts is based on understanding of the physical processes involved. As models provide better predictions, including of the impacts, the need for the forecaster to understand the relevant processes becomes wider and more demanding. Currently, human impacts are almost entirely estimated subjectively, but if targeted warnings are to be obtained at high resolution, automated methods will become essential, changing the nature of the warning process. Nevertheless, the forecaster will still need to understand the nature of the impact and society's vulnerability to it in order to frame warnings and other information appropriately. Advanced techniques of verification can offer information to forecasters for use in interpreting forecasts. However, new communication methods, required to improve the interpretation and use of forecasts and warnings, are likely to have the biggest impact on the forecasting process. The need to promulgate warning information on social media has already produced dramatic changes to the roles of forecasters, and further changes will certainly follow. In some high risk decision making situations, the need to take account of the hazards, the impacted communities / infrastructure and the available mitigation resources has led to the use of collaborative decision making techniques in which diverse experts jointly negotiate a decision. It is likely that use of such approaches will grow, leading to new challenges for NMHSs in managing these organisational, technological and communications interactions. Ultimately it will remain the forecaster's responsibility to ensure that the information provided is not just useful, but useable and used, requiring that it is delivered in the right form, to the right people, at the right time.

On the global stage there are clear disparities in forecasting and warning capability between developed and poorer nations. Through FDPs and sharing of best practice, this project will foster the dissemination and use of model forecasts and interpretation expertise to address the needs of less developed nations, where commonly the impacts are greatest and resilience least. It can also assist these countries to develop climatologies of weather variables related to impacts, so that frequency of occurrence is understood for use in planning, and to calibrate severe weather products and warnings. In the absence of adequate observational datasets, these may be estimated using reanalyses and hindcasts. Deriving such climatologies from convective-scale models will be a fruitful area of future work.

Work is also needed to more clearly define impact response functions for the application areas of the project – social, economic and environmental – to tie these in with the forecasts and model climate information, and to make such information readily available to forecasters with warning responsibility.

Within WMO, the project will work closely with CBS and the Public Weather Service (PWS) programme to facilitate implementation of the new capabilities developed during the project into operational forecasting (CBS is responsible for operational forecasting and PWS for issuing forecasts to the public). The WMO SWFDP has successfully demonstrated application of the 'Cascading Forecasting Process' in which products and new technical capabilities are moved from global to regional and then national centres to strengthen the capacity of NMHSs in developing and least developed countries. The SWFDP has already improved the lead-time and reliability of alerts of high-impact hydro-meteorological events leading to demonstrable protection of life. Close liaison with SWFDP will provide an effective knowledge transfer route for the new capabilities to be developed in HIWeather.

4.1.1 Key Challenges

a) Providing the evidence needed by the forecaster to enable effective communication of the hazard situation to key users

b) Providing adequate evidence of track record to enable the forecaster to attach confidence limits to communication

c) Supporting the forecaster in decision making through provision of supporting information to the forecast guidance: latest and recent observations and their match to forecast; agreement between multiple forecast sources; access to historical archives; access to summaries of relevant process studies / training materials; access to scenario assessment tools.

d) Supporting the development of systems to provide automated guidance to the forecaster including identifying research needs across all themes as well as working to quantify the potential and limitations of providing automated guidance for the specific hazards in HIWeather.

4.1.2 Selected Activities

a) Led by the Multi-Scale Forecasting theme, raise the level of expertise in high impact weather prediction by involving operational meteorologists in HIWeather research, particularly through evaluation activities in FDPs, testbeds and proving grounds, WMO Training Centres etc.

b) Led by the Predictability & Processes theme, develop the use of models by operational meteorologists to diagnose the origins of hazardous weather features, e.g. using back trajectory techniques. Evaluate the benefit in FDPs, testbeds etc. and publish the results.

c) Led by the Communication theme, in collaboration with operational meteorologists and CBS, develop interpretation aids in high resolution deterministic & ensemble NWP and hazard predictions. Document the material for use in training, e.g. WMO training centres, and as COMET (or similar) training modules.

d) Led by the Evaluation theme, in collaboration with operational meteorologists and CBS, develop verification facilities that enable operational meteorologists to judge the value of new products and capabilities. Evaluate the benefit in FDPs, testbeds etc. and publish the results.

e) Led by the Evaluation theme, in collaboration with operational meteorologists and CBS, develop real-time verification facilities that support operational meteorologists in assessing the accuracy of the current forecast. Evaluate the benefit in FDPs, testbeds etc. and publish the results.

4.2 Design of Future Observing Strategies

Current observing systems do not meet the time and space scale requirements of high impact weather prediction, nor do they observe most weather impacts nor people's responses to forecasts and warnings.

All of the research themes have implications for observations. Advancing our understanding requires the collection of highly resolved datasets and their use, with models, to identify the processes that cause high impact weather to develop. Models depend critically on observations for their initialisation. Assessment of human impacts depends on collection of exposure datasets and data on vulnerability. Verification requires data on the key impact variables, while advances in communication methods depend on collection and in-depth analysis of qualitative and quantitative data on people's responses to different methods.

The current observing networks have largely been developed to meet the requirements of synoptic scale forecasting on a global scale and severe storm nowcasting on a local scale. The global requirement has driven a migration from *in situ* measurement to satellite-based sounding instruments, while the local requirement has largely been met with increasingly sophisticated radar systems. These remote-sensing systems require supporting *in situ* data to ensure they remain calibrated. The change of emphasis for local forecasting from forecaster-based nowcasting systems to NWP models is creating a much enlarged requirement for atmospheric monitoring at fine resolution (~10km and less) which may lead to changes to priorities in existing networks, but is unlikely to be fully met by these current approaches to observing. Work is required to:

a) Design observing networks that are fit for purpose on multiple scales
b) Evaluate the future impact of new observations and observing strategies
c) Explore adaptive use of observations

Recent technological developments have raised the possibility of extremely high densities of sensors being deployed, while social networking and crowd sourcing have opened the possibility to obtaining high densities of impact data and potentially of communication, interpretation and uses of warnings, all in real time. However, these opportunities come with enormous challenges in the use of the data, especially in quality control.

4.2.1 Key challenges

a) Design strategies for optimal observation networks for multiple scales (km-scale, mesoscale and synoptic scale), suitable for use in both NWP DA and nowcasting, and deliverable using practicable mixes of observing systems.
b) Account for data assimilation schemes, correlated observation errors, combined sets of diverse observations when designing new observation strategies
c) Identify the satellite sensors (or combinations thereof) that are most relevant for specific hazards.
d) Identify the dependence of hazard prediction improvements on dense observations.
e) Identify observation requirements for monitoring the selected hazards and for assessing forecast accuracy.
f) Quality assurance and control, especially for impact data sources.
g) Data access policies and protocols for data management

4.2.2 Selected activities

a) Led by the Multi-Scale Forecasting theme, develop the use of adjoint-based data impact and/or data denial analysis techniques to km-scale data assimilation experiments so as to establish the value of different data sources in prediction of high impact weather, as measured by metrics developed in the Evaluation theme. Apply these techniques, together with Observing System Experiments (OSEs) and Observing System Simulation Experiments (OSSEs) to assess the costs and benefits of possible future observing system configurations.
b) Led by the Multi-Scale Forecasting theme, demonstrate and evaluate the benefit of enhanced observations, including dense networks of sensors focused on monitoring particular hazards (e.g. temperature for the heat hazard), to the real-time production and communication of hazard warnings in FDPs. Document and publish results, including challenges in gathering, quality controlling and displaying the observations.
c) Led by the Multi-Scale Forecasting theme, in collaboration with NMHSs and space-based Earth Observation agencies, build on the Committee on Earth Observation Satellites (CEOS) database and other initiatives, to create a catalogue of observations required for monitoring, forecasting, communicating and verifying weather-related hazards and their impacts, of the required spatial and temporal sampling and accuracy, and of candidate new and existing data sources. Promote implementation and real-time international exchange of these observations.
d) Led by the Multi-Scale Forecasting theme and with impacts agencies (emergency management, health etc), build international capability in observing weather-related human impacts and responses for use in monitoring, nowcasting, data assimilation, impact model construction and validation, with particular emphasis on data collection, quality control, and interpretation. The activity will include development of standards for obtaining data from social media, including the use of hashtags (e.g. #snow),

considerations of when and how to solicit data, and variations between hazards, countries and cultures.

4.3 Uncertainty

Most of the relevant impacts are not deterministically predictable on the time and space scales required by users, nor will they ever be due to the fundamental limits on atmospheric predictability. Thus, uncertainty is a common factor in understanding, modelling and communicating high impact weather information.

A fuller appreciation is required of the un-predictability of many severe weather details even at time scales of hours. The ‘deterministic limit’ can be defined as the point in lead time beyond which threshold-based deterministic forecasts are more likely to be wrong than right, i.e. where hits = misses + false alarms, or Critical Success Index (CSI) = 0.5. This is a very useful metric to convey the need to account better for uncertainty. For instance, the deterministic limit is typically only minutes, for convective storms, or hours for many other phenomena. Warnings are needed much further in advance, and so intrinsically have to contain a probabilistic element.

There is strong evidence in the literature of the potential financial benefits of optimal use of probabilistic forecasts / warnings in certain decision scenarios. However it has been difficult to achieve these benefits in practice due to the complexity of most information interpretation and use situations. It is important, therefore, to examine uncertainty communication from the user perspective, and to engage in direct co-education of users and providers. Increased promulgation of probabilistic warnings / forecasts is also needed via experimental or web-site ‘testbeds’ – and in due course, where appropriate, more promulgation of official warnings in probabilistic terms.

A best practice strategy is needed for progressing from deterministic forecasts to deterministic warnings informed by probabilistic forecasts to probabilistic warnings for appropriate weather and user scenarios. Wherever possible the uncertainty in the weather forecast should be propagated into the impact forecast and should be assessed and communicated to take account of the use to which it will be put by the recipient.

Evaluating more and less successful examples of the use of probabilistic information and the reasons for the successes and challenges, and making use of those lessons, will be important aspects of the mutual education process and the improvement of uncertainty communication.

4.3.1 Key Challenges

a) Unresolved processes in NWP models have traditionally been parametrized on the basis that net fluxes are deterministically defined by the grid-scale variables. Recent work in stochastic physics schemes and in model error representation for ensembles has challenged this. We need to gain a better understanding of these results and of their implications for model design.
b) Requirements for hazard advice are frequently presented in deterministic terms because specific decisions have to be made, often quickly. This naturally results in a tendency for the science behind hazard advice to be developed in deterministic terms. We need to

establish a culture of thinking from an uncertain framework, of working in probabilistic terms, and of taking risk-based decisions across the breadth of the work of HIWeather, where appropriate from a scientific and user perspective.

4.3.2 Selected Activities

a) Led by the Processes and Predictability theme, and in collaboration with mathematics experts, work on stochastic physics and on model error in ensembles will be reviewed and synthesised, and new work promoted, leading to publication of new recommendations for perturbation techniques and parametrization design for ensemble prediction systems.
b) Led by the Communication theme, review and publish the implications of uncertainty in weather forecasts and warnings across the spectrum of the work of HIWeather and how these propagate through the forecast-to-use chain to influence the ability to enhance resilience, with particular emphasis on the creation and communication of probabilistic forecasts and warnings. Promote examples of good practice through interactions with researchers, providers and other stakeholders and through project media opportunities, including a website blog and newsletter.

4.4 Field Campaigns and Demonstration Projects

No single big experimental period is appropriate to the nature of this project. On the other hand, entirely local initiatives are insufficient to advance a global capability. Understanding, modelling and forecasting require high resolution datasets for many types of high impact weather and for the pathways through which the impact is made manifest. Combined field / modelling experiments address this need, focussed on particular weather regimes, preferably on locations and periods when they occur with high likelihood. Research into communication of forecasts, perceptions of recipients, and the actions they take, cannot currently be modelled, so must be undertaken in the field. Given the different responses of different cultures, sampling strategies are critically important. Evaluation depends on enhanced datasets, particularly of the end impact.

These diverse needs can best be met through a planned series of internationally supported experiments incorporating enhanced observations for understanding and forecast development; routine prediction for evaluation and technology transfer; engagement & trialling (with both forecasters and users) for format, reach and relevance, evaluation and trust building. These specialist datasets should be complemented by comprehensive archives of high resolution model outputs over limited areas. It is anticipated that the TIGGE and TIGGE-LAM archives will provide the infrastructure for this.

WWRP has established a set of guidelines for running RDPs and FDPs, including principles of data availability in real time / delayed mode, principles for engaging user communities in the design and execution of FDPs, and principles for performance evaluation. These will form the basis for selection and planning of the cross-cutting experiments in HIWeather. The design of these experiments needs to involve users from the outset so as to ensure that the problem being addressed is aligned with the real problems of those who live and work in the area. Communication, interpretation and the use of information should also be considered from the start to ensure that the users and societal benefit are kept as primary foci.

HIWeather will also participate in testbeds where these address key research issues, and will seek to extend their scope to include prediction of impacts and communication.

Initially, HIWeather will focus on the design and implemention of three experiments: NAWDEX/DOWNSTREAM, LVB-HyNEWS, and ALERT.AR/RELAMPAGO that address key areas of cross-cutting research. Datasets from other recent and planned experiments will be valuable inputs to HIWeather research, and it is likely that HIWeather will wish to become engaged in the design and implementation of additional experiments in future, particularly relating to hazards for which few field experimental data are available.

4.4.1 NAWDEX / DOWNSTREAM

The THORPEX North Atlantic Waveguide and Downstream Development Experiment (NAWDEX/DOWNSTREAM) is an international initiative to perform coordinated in-situ measurements of disturbances and their evolution along the North Atlantic jet stream and the resulting (high-impact) weather over the USA and Europe. HIWeather links to NAWDEX/DOWNSTREAM will be led by the Predictability and Processes theme and will involve the Multi-Scale Forecasting theme, relating principally to the Urban Flooding and Extreme Local Wind hazards. It is expected that the downstream impact experiments will involve other themes in due course.

4.4.1.1 Selected Challenges

a) Understand the factors that trigger or modify wave-guide disturbances, e.g. Tropopause polar vortices (positive PV anomalies); Warm Conveyor Belt outflow (negative PV anomalies); Extra-tropical transition of tropical cyclones; Precursor wave packets
b) Understand the processes which impact on wave-guide disturbances and their downstream evolution including: Waveguide representation; Downstream evolution of PV anomalies; Modification from Greenland; *Local* modification of Rossby waves by positive and negative PV anomalies.
c) Identify and attribute systematic errors in model representations of waveguide perturbations resulting from diabatic processes and associate them with downstream weather forecast errors
d) Assess and improve the ability of ensemble prediction systems to represent uncertainty arising from errors in forcing of waveguide disturbances by diabatic processes
e) Understand the downstream impact of diabatically modified PV anomalies in wave breaking (sensitivity to upstream disturbances, fine scale aspects), their influence on synoptic features (e.g. Blocking ridges, Cut-off cyclones, Stationary troughs) and the consequent predictability of associated heavy rainfall and severe wind events.

4.4.2 LVB-HyNEWS

This large project is an amalgam of three proposals: A WWRP/WGNR proposal to study weather hazards to fishermen on Lake Victoria, A WCRP/GEWEX proposal to study water balance in the Lake Victoria basin, and an East Africa Commission proposal to study weather impacts on air traffic management. HIWeather is linked mainly with the first of these, specifically to the development of capabilities to monitor and predict hazards related to nocturnal convection that result in many fatalities to fishermen on Lake Victoria. The project will be carried out in association with the East Africa SWFDP. There are links to all

HIWeather research themes with particular relevance to Extreme Local Wind hazards, but the lead will be through the Multi-Scale Forecasting theme, and particularly through the WGNR and its successor. For the FDP components, the Communication and Evaluation themes will be key contributors.

4.4.2.1 Selected Challenges

a) Understand the initiation process of nocturnal thunderstorms over Lake Victoria, using remote and in situ observations with the purpose of developing reliable forecast and warning systems.
b) Understand factors governing the strength of thunderstorm downdrafts and outflows over Lake Victoria and resultant impact on wave height, using in situ and remote sensing observations so that accurate nowcasts of low-level wind speed and direction can be produced.
c) Develop and evaluate relationships between observed hazardous weather conditions near the lake surface, such as severe winds, and features observable remotely in infra-red satellite images or lightning maps, such as variations in cloud top temperature or lightning frequency.
d) Evaluate and enhance the ability of ocean wave prediction models, applied to Lake Victoria, to reproduce observed relationships between hazardous wave conditions detected by instrumented boats and the forcing wind fields obtained from Doppler radar and *in situ* wind observations.
e) Evaluate the capability of kilometre-scale NWP models to accurately model the interaction of synoptic scale atmospheric structure with the local topographic forcing, so as to predict the forcings that give rise to severe convective weather over the Lake.
f) Develop and evaluate data assimilation capabilities for kilometer-scale NWP run over the Lake.
g) Develop and evaluate relationships between outputs from NWP models run over the lake and the hazardous weather conditions that cause loss of life, especially wind speed and direction.
h) Relate the occurrence of fatal and non-fatal accidents on Lake Victoria to observed hazardous weather conditions associated with nocturnal convection over the Lake.
i) Develop thunderstorm nowcasting techniques for Lake Victoria that can be utilized by the weather services in Kenya, Uganda and Tanzania

4.4.2.2 Timescales

LVP adopted as a WWRP RDP	2012
HYVIC adopted as a WCRP/GEWEX project	2012
Heads of East Africa NMHSs support combined LVB-HyNEWS project	2014
Proposed experimental period	2016-9

4.4.3 ALERT.AR / RELAMPAGO

The La Plata region of South America is the location for some of the strongest convection in the world, particularly as measured by electrical activity and frequency of flood-generating precipitation. It is also home to a cluster of rapidly developing megacities, including Buenos Aires and Sao Paulo. ALERT.AR is planned to use observations from the RELAMPAGO field experiment to test convective scale NWP models and their coupling to hydrological prediction models, to develop process-based nowcasting techniques for implementation in the NMHSs of the region and to evaluate the impact and communication of forecasts and warnings to decision makers. The links to HIWeather are potentially across all research themes relating to the Urban Flood hazard. A kick-off meeting was held in 2013 and the RELAMPAGO field campaign is planned for late 2017.

4.4.3.1 ALERT.AR / RELAMPAGO science focus areas

- Convective lifecycle
- Microphysics & Aerosols
- Electrification
- Severe Weather: wind, hail, tornadoes, floods
- Hydrometeorology: land surface, flooding
- Nowcasting & forecasting
- Societal Impacts

4.4.3.2 Timescales

Kick-off meeting	2013
Proposal Submitted	2014
NCAR workshop	2014
Workshop	2015/6
EOP / IOP	2017-8

4.4.4 Other relevant experiments

4.4.4.1 South China Monsoon Rainfall Experiment (SCMREX)

From the onset of the South China Sea monsoon in middle or late May to the northward shift of the monsoon rain belt in middle or late June, the first rainy season in southern China causes flash floods, loss of life and economic damage. SCMREX aims to improve understanding and prediction of heavy rainfall during this period. The primary links with HIWeather are in the Predictability and Processes and Multi-Scale Forecasting themes for Urban Flooding. The SCMREX field campaign was in April – June 2013.

4.4.4.2 TOkyo Metropolitan Area Convection Study (TOMACS) for extreme weather resilient cities

TOMACS is a study of severe weather in the Tokyo area of Japan coupled with studies of socio-economic impacts and responses. A WWRP RDP has been set up to use data from the TOMACS IOPs to conduct an international testbed study for deep convection and its impacts. TOMACS is linked with the Dallas-Fort Worth Urban Test-bed through participation of Colorado State University. The main links with HIWeather will be through aspects of the Multi-Scale Forecasting and Evaluation themes applied to urban flooding. The results of the TOMACS social experiments will be important inputs to the HIWeather Vulnerability & Risk and Communication themes. The TOMACS field campaign was held in 2011-13. The research phase continues until 2016.

4.4.4.3 Plains Elevated Convection At Night (PECAN)

PECAN aims to advance the understanding and forecast skill of the processes that initiate and maintain nocturnal convection in the Great Plains. The principle links to HIWeather are in the convection aspects of Predictability and Processes, data assimilation and modelling in Multi-Scale Forecasting and in the Observing Strategies cross-cutting theme, as they relate to severe convective weather leading to Urban Flood and Extreme Local Wind hazards. The field campaign is planned for June-July 2015.

4.4.4.4 Coupled Hydrology-Atmospheric Modelling and Prediction in the Laurentian Great-Lakes-St Lawrence River of North America (CHAMP)

CHAMP is a joint Canada - US project that aims to develop an integrated modelling capability for the Great Lakes – St Lawrence basin of North America and to demonstrate its capability to contribute both to enhanced management of the water balance in the basin and to the provision of more accurate weather impact forecasts and warnings. The principle links with HIWeather will be in the coupled modelling aspects of the Multi-Scale Forecasting theme and in the prediction of Disruptive Winter Weather.

4.4.4.5 Hazardous Weather Testbed

This testbed is run by the Storm Prediction Center of the National Weather Service each spring at its Oklahoma site. Several models are used to create a variety of convective scale deterministic and ensemble predictions in parallel with operational products. Parallel interpretations are carried out so as to assess the value of new and advanced techniques.

4.4.4.6 HYMEX

A ten year programme of high impact weather studies and experiments around the Mediterranean.

4.4.4.7 A joint weather & hydrology experiment

Opportunities for a joint experiment with HEPEX involving coupled atmospheric-hydrological prediction of flash floods

4.4.4.8 A fire weather experiment

Candidates may include a European Union Horizon 2020 bid by Mediterranean countries, or post-2013 fire season activities in Australia or the fire component of the Finnish Meteorological Institute contribution to the EU RAIN (Risk Analysis of Infrastructure Networks in response to extreme weather) project

4.4.4.9 A winter weather experiment,

Possibly in collaboration with CHAMP (see above).

4.4.4.10 A heat wave and air quality impacts experiment

Possibly in partnership with the S2S project and preferably involving a tropical megacity – this would need to follow an epidemiological study design and would need to extend over several years unless it was in a country with sufficiently comprehensive existing baseline health statistics

4.4.4.11 Health impact experiments

Opportunities to develop multi-country weather and health field programmes addressing other hazards, notably flood and fire.

4.5 Knowledge Transfer

Wide gaps in knowledge exist at the present time between the scientific disciplines that must work together to forecast impacts, between research and operations, and between different countries. Separately from work with the external stakeholders, activities will be needed to bridge these gaps if full benefit is to be obtained from the project.

The RDP/FDPs will provide excellent opportunities for bringing together scientists from different disciplines and different countries to address a common problem. Every effort will need to be made to ensure that maximum benefit is obtained from these opportunities, especially for those working in the host country. In addition to planning meetings, it is necessary for this to include working links with local academic institutes and with local emergency response organisations.

Opportunities should also be created to enable sharing of the research results at a higher level through international conferences and/or workshops. These should involve scientists from a broad range of disciplines and countries and should not be split into parallel sessions that separate different research or user communities.

4.5.1 Key Challenges

a) The most vulnerable populations and many of the most hazardous events occur in countries that cannot deploy the most advanced hazard forecasting technologies now available. We need to transfer expertise gained in HIWeather to enable research institutes and NMHSs in all countries to effectively contribute to raising their own country's resilience.
b) Future progress in increasing resilience to weather-related hazards depends on attracting the best researchers to work together in the fields represented in HIWeather. We need to inspire young researchers to work in these fields and give them the inter-disciplinary outlook needed for effective benefits to be gained.
c) Different countries have reached different levels of capability in observing, modelling and forecasting. We need to use different methods of transferring capabilities according to the ability of the recipient NMHS to make use of them.
d) New HIWeather capabilities will be developed on the basis of limited datasets. We need to ensure that they are transferable to other locations and situations before their operational adoption.

e) Language and culture are important factors influencing perception of forecasts and warnings. We need to identify those aspects that must be accommodated to study communication / behaviour and translate knowledge between countries.

4.5.2 Selected Activities

a) FDPs will have a primary focus on knowledge transfer to the host NMHS and its local offices and to local academic institutes so as to build up local capability in research and applications. Secondments (in both directions) will be used to support this aim.
b) Summer schools will be held on topics identified in the research pillars to enable young researchers and practitioners, especially from developing countries, to gain knowledge in particular areas in which HIWeather has delivered gains in capability.
c) Reviews of topics identified in the research pillars, will be published as white papers and/or journal issues, enabling widespread access to the results.
d) Results of research and evaluation of its application will communicated through conferences and workshops, including training sessions attached to conferences, and used to create on-line training material for operational meteorologists and users, suitable for use by member countries, e.g. through the COMET programme.

4.6 Verification

Verification will be necessary to support all themes of the HIWeather project. The Evaluation theme (3.4) identified a number of issues and questions on *how* to evaluate weather and hazards forecasts and warnings, and societal, economic, and environmental benefits deriving from improved weather and hazard knowledge and communication. Practical applications of verification within each of the HIWeather project themes are discussed below.

The Predictability and Processes theme focuses on understanding the physical processes leading to high impact weather, and therefore requires an evaluation approach tailored to deep understanding. Observational datasets, especially from field campaigns, will be particularly important for describing processes, assimilation into numerical models, and verifying model simulations to establish the validity and credibility of models so that they can be confidently applied in studying the processes of interest. While traditional verification methods have limited usefulness in this context, many of the newer diagnostic approaches may provide useful information to aid understanding of errors in model processes. Errors in model processes can also be investigated through data assimilation, where the relative size of the analysis increments in different variables can provide clues as to which processes are being poorly represented. Advanced visualisation (3D animations, enhanced imagery, etc.) of observation datasets and modelled fields can greatly assist in process understanding and assessing whether the modelled atmospheric flows, evolution of clouds, etc. are well represented.

Verification of multi-scale prediction of weather-related hazards has much in common with routine verification performed at most national meteorological centres, which is used to monitor performance over time, guide development of numerical models, nowcasting systems or other objective guidance products, and assist human forecasters in improving their prediction accuracy and reliability. High impact weather verification should focus on surface variables such as precipitation, wind, temperature, lightning, etc., using both site-specific and spatial (gridded) approaches to meet the needs of a variety of users.

In recent years there have been guidelines established by WMO discussing best practice verification for deterministic and ensemble NWP, public weather forecasts, precipitation, cloud, and tropical cyclone forecasts, and it is recommended that these guidelines be the starting point for routine verification of high impact weather. Spatial verification and new scores for extremes (EDI, SEDS, etc.) and site-specific verification (e.g., SEEPS) are becoming routinely applied at national centres and should be used in this project. Particular attention should be paid to verifying the timing aspects of weather forecasts and warnings. Real-time verification, even just a picture or a map, would be particularly valuable for forecasters. The HIWeather project should encourage participants to apply best practice verification to experimental forecasts, and it can also collate existing high impact weather verification information from where it is being produced through WGNE, SRNWP, and other international activities.

The meteorological community has less experience in verifying the hazards caused by the weather (floods, landslides, bushfires, etc.). As noted above, observations of hazards are non-standard and difficult to obtain, making routine verification of hazard predictions very difficult. Further, the hazard predictions themselves are often made by agencies outside of the usual meteorological ones. Ensemble prediction, now common in meteorology, may still be quite novel within some hazard communities. The HIWeather project will need to partner with hazard scientists and practitioners who may already be key users of high impact weather information, to assemble forecast and observation datasets and work together to develop appropriate prediction and verification strategies. The meteorological community has a long history of forecast verification know-how which is attractive to those other communities. Some progress in hazard verification has been made, particularly in hydrology (e.g., NOAA's Ensemble Verification System for streamflow forecasts).

Quantifying the benefit of improvements in high impact weather and hazard prediction on socio-economic impacts is a primary goal of the HIWeather Project. Risk reduction can partly be achieved through more timely and accurate predictions leading to reduced exposure to high impact weather and associated hazards, and facilitating improved preparation and more rapid relief response to reduce negative impacts of high impact weather hazards. Of particular interest will be the added value of probabilistic information which supports more informed decision making on a variety of time scales. The quantitative verification carried out for multi-scale weather and hazard prediction must be propagated through to evaluation of the associated risk reduction. This will involve synthesis with a large variety of demographic, geographic, and other datasets, to enable the exposure and vulnerability components of the risk calculation to be estimated. As with the hazard verification, it will be necessary to partner with scientists and practitioners working in the risk assessment area, and with government agencies holding the relevant datasets (census bureaux, etc.), in order to estimate the risk reduction. Because this is such a vast endeavour, it will be more feasible for the HIWeather project to select some tractable case studies that can be analysed in sufficient depth to allow robust conclusions to be made.

Verifying the benefit of improved communication in achieving more effective response will need to be developed with social scientists in the context of the Communication research theme. Surveys are a common approach to collecting information on the effectiveness of different communication strategies and will be employed here, both to verify that the communication changes have been effective, and to evaluate their impact on the behaviour of the recipients.

4.6.1 Key Challenges

a) Understanding the propagation of error and useful information content from meteorological observation, through forecast, to user decisions and outcomes.
b) Connecting verification measures to process understanding and model improvement: both in terms of routine performance and occasions of gross error – forecast busts.
c) Connecting verification measures to the information requirements of users

4.6.2 Selected Activities

a) Led by the Evaluation theme, use reviews, workshops and participation in the design and execution of FDPs, to develop an understanding of the propagation of error and value through the processing chain from meteorological observation and forecast to response and user benefit.
b) Led by the Processes and Predictability theme, develop and apply model diagnostic tools to identify model processes that have caused major forecast errors (busts).
c) Involve users in all stages of the design and execution of FDPs to ensure acceptance of results.
d) Involve HIWeather researchers in Severe Weather Forecast Demonstration Project activities that help NMHSs support each other in providing warnings, including building relationships with national disaster agencies.

4.7 Impact Forecasting

The focus on impacts is central to the whole project, with particular input from the Human Impact, Vulnerability & Risk research theme. It will influence the processes studied, the development of models, and the type of communications used.

Impact forecasting requires knowledge of what information is most important to specific audiences for their decisions to reduce impacts and vulnerabilities and mitigate risks. This includes understanding the variables required (e.g., depth of flooding, power outages), the spatial and temporal resolutions (and averaging) required and usable (may differ by audience, even for one type of impact forecast), and the appropriate forms of uncertainty information (e.g., probabilities, scenarios, etc.)

Impacts may be forecast using tools of varying complexity. One of the simplest is to relate the human impact directly to the source of the hazard using an ‘impact response function’. The ability of such simple approaches to provide useful information, both at the awareness raising and warning timescales needs to be established for a varied range of impacts and applications.

Some impact response functions change smoothly with the source while others have discontinuous behaviour. Understanding the differences is important in guiding research in the multi-scale forecasts and processes themes. The dependence of the impact response on regional sensitivities and climate should be emphasised.

4.7.1 Key Challenges

a) Stakeholder operational decisions are focused on mitigating impacts that result from specific hazard conditions occurring. Work in all research themes must be focused on what causes or results from the occurrence of these hazard conditions.

4.7.2 Selected Activities

a) Led by the Vulnerability & Risk research theme, a catalogue will be prepared of the principal variables that characterise information requirements for stakeholder decision making, including the most significant thresholds, and the nature of the impact response.
b) Led by the Vulnerability & Risk theme, describe an operational forecasting production structure that includes socio-economic impact models and products and promote it through training events, conferences and publications

4.8 Data Management & Archiving

A key facilitator of research is the easy availability of field and model data for research purposes. Existing guidelines for the conduct of FDPs & RDPs will go some way to addressing this issue, requiring that as much observational data as possible are made available through the GTS in real time, and that remaining datasets are freely available to researchers within as short a time as possible.

There is no equivalent guideline on the availability of model data at present, but it is proposed that for each RDP/FDP, modelling centres should be encouraged to implement consistently configured km-scale ensemble prediction systems and to make the data available to the TIGGE-LAM archiving centre for as long a period as practicable covering the enhanced observational period. The TIGGE-LAM archiving centre is requested to archive and provide access to these datasets. If it is not possible for TIGGE-LAM to do this, archiving centres should be defined for each activity to take on this role, using an agreed archiving standard.

Standards for storage of social and health survey data should follow best practice in the field, taking account of any precedents in WMO. Appropriate confidentiality and ethical safeguards must be adhered to.

A major source of information for improving global NWP systems has come from historical reanalyses. HIWeather will promote the development and inter-comparison of regional limited-area reanalyses using km-scale data assimilation and modelling systems. The value of such reanalyses depends to a great degree on their accessibility for research. HIWeather will encourage centres that generate such reanalyses to make them freely and easily available for analysis and further processing, using the same archiving standard.

Case studies used in inter-comparisons require participants to have access to data that are not normally shared, such as common definitions of topography and land use, as well as to observations and model fields. Lead centres for such inter-comparisons will ensure that such datasets are easily accessible in standard formats.

4.8.1 Key Challenges

a) Archiving, research access and (where applicable) public access to high resolution forecasts, observations and products from HIWeather field campaigns, case studies, inter-comparisons, and surveys in standard formats.

4.8.2 Selected Activities

a) Led by the Multi-Scale Forecasting theme, agree data format, storage & access standards for the project, taking account of existing standards and WMO guidance.
b) Led by the Multi-Scale Forecasting theme, ensure that as much data as possible is shared in real time during field experiments.
c) Led by the Vulnerability and Risk theme, ensure that necessary ethical safeguards are built into all survey work undertaken.
d) Led by the Multi-Scale Forecasting theme, agree data archiving and access structures for each data-generating component of the project prior to start of data production.
e) Led by the Multi-Scale Forecasting theme, ensure that metadata and data summaries are published as appropriate.

5 External Engagement

The Engagement strategy will evolve through three phases:

Phase 1: Prior to submission of the proposal to ICSC/WWRP Joint Steering Committee, WMO Commission for Atmospheric Sciences and WMO Executive Committee, to draw on the knowledge of user requirements already present in the Task Team and through them from their host institutes and WWRP/THORPEX working groups.

Phase 2: During preparation of the Implementation Plan, links have been established as detailed below, with experts in a wide variety of stakeholder organisations. Many of these have reviewed or commented on draft versions of the Plan:

Hydrology: Contact has been established with the joint chairs of HEPEX and with the Flood Forecasting Centre for England and Wales and it is planned to establish a link with the WMO Commission for Hydrology and UNESCO's International Hydrology Programme.

Air Quality: A link has been established with the WMO/GAW Urban Research Meteorology & Environment (GURME) project.

Health: Health professionals from the UK and USA attended the June 2014 Silver Spring workshop. Contacts have been established with The European Centre for Environment and Human Health, Public Health England and the joint WMO-WHO office.

Emergency Response: Indirect links with the emergency response communities have been identified through the Weather Ready Nation initiative in the USA, through the Natural Hazards Partnership in the UK and through the Bureau of Meteorology in Australia. Indirect links with emergency responders have also been established through the WMO/CBS Severe Weather Forecast Demonstration Projects in South Africa, East Africa and the Pacific Islands.

Disaster Reduction: Links have been established with the Science Advisory Committee of the UNISDR and with the Integrated Research in Disaster Reduction (IRDR) programme.

Economic Value: Links have been established with the World Bank, Climate Services Partnership, and within the WMO (PWS, WWRP-SERA) who are involved in preparing a guide to aid NMHSs in assessing the socio-economic value of weather services.

Insurance: A link has been made with the Natural Catastrophes section of Munich Re.

Energy: It is planned to identify a link with the power generation community

Transport: A link has been established with the Single European Sky Air Traffic Management Research (SESAR) project.

User impacts and needs: The SERA group of WWRP is committed to contributing to HIWeather.

Phase 3: While the underpinning goals and outline of the project have been informed by the user inputs described above, more formal statements of requirement will be developed through user engagement activities which will guide individual research activities during the project. Strategic guidance on the direction of the project will be provided through a Strategic Advisory Group which will be formed from a selection of key stakeholders.

During the project, engagement activities will go through a series of cycles, generically illustrated in Figure 15. The research itself will naturally lead to a higher level of user engagement of the Communication, Vulnerability and Risk and Evaluation themes. The Multi-Scale Forecasting theme will be more focussed on engagement with NMHSs, while the Predictability and Processes theme will focus on engagement with modellers. These different levels of engagement will be brought together at Steering Group meetings and, particularly at the Strategic Advisory Group meetings, when the whole project will be subject to scrutiny from a stakeholder viewpoint. On a longer timescale, FDPs will provide focussed periods when research themes become more engaged with user needs. Each FDP will require a gradual aligning of theme activities towards particular user needs in advance, a high level of integration during the field component, and a continuing engagement afterwards as results are analysed and disseminated.

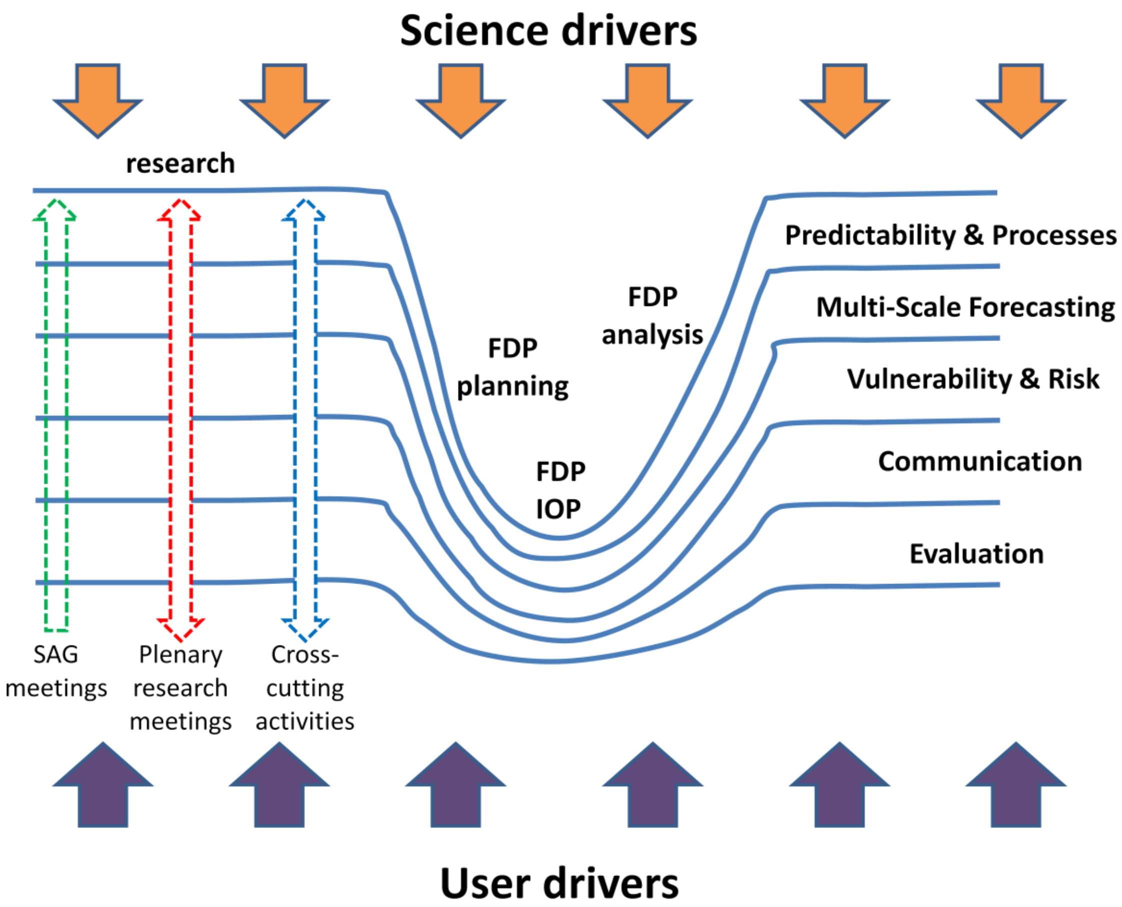

Fig. 15 Generic illustration of how engagement across the research themes and with users will evolve during HIWeather. Different aspects of the research will be involved in different FDPs, occurring at different times so, as a whole, the project will have several research/FDP cycles of different lengths overlapping at any one time.

5.1 Linking with Other Initiatives

It is anticipated that the main interface with the international disaster reduction agenda will be through the WMO DRR and thence through UNISDR and IRDR. The World Bank is a key funder of disaster reduction initiatives. Engagement with private sector initiatives such as Google Crisis Response will also be explored.

The programme will draw on other parts of WMO as key interfaces to stakeholders and as repositories of the required scientific knowledge, including:

CBS/GDPFS/SWFDP: The Severe Weather Forecasting Demonstration Projects are the primary customers for the outputs of HIWeather in developing and least developed countries. They work to build up the capabilities of NMHSs in these countries to provide forecasting and warning services that reduce the impact of severe weather. HIWeather will work with SWFDPs to evaluate and transfer knowledge of new nowcasting and forecasting techniques and new approaches to producing and communicating warnings.

GAW/GURME: The GAW Urban Research Meteorology & Environment Project is planning studies of urban impacts, particularly associated with air pollution. HIWeather will work with GURME on the Urban Heat Waves and Air Pollution hazard, and more generally on broadening the scope of urban weather impact studies.

CAS/WWRP&WCRP:WGNE/S2S/PPP: HIWeather will work closely with several of the programmes run under the WMO Commission for Atmospheric Science and WCRP. In particular, the advances in multi-scale modelling, involving model inter-comparisons, will be undertaken in collaboration with the Working Group on Numerical Experimentation (WGNE), which carries out an ongoing programme of such work, mainly focussed on improving the performance of global weather and climate models. HIWeather will collaborate with the Sub-Seasonal to Seasonal (S2S) post-THORPEX project in relation to the “Get Ready” phase of severe weather preparedness, especially for the longer timescale hazards, such as wildfires (related to droughts), large scale floods (related to wet and/or stormy seasons) and extreme heat and air pollution (related to anticyclones), and to the interface with users. HIWeather will also maintain contact with the PPP project to ensure that opportunities for joint work under the Disruptive Winter Weather hazard are taken up. There are several other opportunities for collaboration with aspects of the WCRP GEWEX programme and several WCRP Grand Challenges, especially with relation to extremes of precipitation and their role in the water cycle. Important challenges in hazard modelling are shared with the WCRP CLIVAR programme and with the Clouds, Circulation and Climate Sensitivity Grand Challenge. More specifically, linkages with the WCRP Grand Challenge on “Understanding and Predicting Weather and Climate Extremes” will be explored.

Expert & Working Groups of WWRP & THORPEX: DAOS, PDP, TIGGE, WGMWFR, WGNR, SERA, JWGFVR: HIWeather has been well supported by the WWRP and THORPEX working groups throughout the preparation of the proposal and Implementation Plan and it is expected that this will continue with their successors under the new WWRP structure. PDP has taken a lead in developing the plan for the Processes and Predictability theme; DAOS, WGNE, WGMWFR, and PDP have contributed substantially to the multi-scale modelling theme, JWGFVR has been the main source of input to the evaluation theme and SERA has contributed to the formulation and offered to take the lead of the Human Impact, Vulnerability & Risk and Communication themes. WGMWFR and WGNR have contributed to the cross-cutting activities related to field experiments and demonstration projects.

The programme will link up with key National and International Science Initiatives to enable it to deliver the advances required. These include:

UK: Natural Hazards Partnership (NHP), Foresight, Natural Environment Research Council (NERC) Flooding from Intense Rainfall programme, Living With Environmental Change (LWEC)

USA: Weather Ready Nation

France: Prevassemble (Ensemble methods for prediction and data assimilation)

Germany**:** Predictability ANd Dynamics Of Weather Systems in the Atlantic-European sector (PANDOWAE); Hans Ertel Centre for Weather Research; DFG Collaborative Research Centre TR32: "Patterns in Soil-Vegetation-Atmosphere Systems - Monitoring, Mo**d**elling an**d D**ata Assimilation"; BMBF Initiative "High Density Clouds and Precipitation for Climate Prediction"

Europe: High Impact Events and Climate Change theme of the European Climate Research Alliance

Mediterranean Countries: Hydrological Cycle in Mediterranean Experiment (HYMEX)

Hydrological Prediction: Hydrological Ensemble Prediction Experiment (HEPEX)

It will also take account of major industry initiatives, such as SESAR and the Next Generation Air Transportation System (NextGen) in Air Traffic Management and projects in the power and insurance industries, establishing mutually beneficial links with these initiatives where possible.

5.2 Linkages Between Academia, Research Institutions and Operational Centres

The success of the programme in achieving its outcomes will depend substantially on the successful linking of physical science disciplines required for the forecasting of natural hazards, with appropriate social science and related disciplines, including economics, psychology, sociology, anthropology, and public policy, and with interdisciplinary fields such as hazards / disaster studies, communication studies, and risk communication. Different fields bring different theories, concepts, and methods that will be needed to reach the programme goals. The link between academic and operational institutions retains a high priority. These links are fostered by operational forecast systems being made available as research and teaching tools, as well as exchanges of Ph.D. students and early career researchers between academic and operational institutions.

The programme must provide a pathway for seamless integration of demonstrably successful research products into operational forecasting and communications, including

a) Use of “Testbeds” that permit the objective evaluation of research products by forecasters
b) Transition and maintenance of successful products after evaluation and implementation
c) Communication of prioritised operational challenges to the research community
d) Provision of operational systems, including post-processing and product generation for use in research demonstrations

The key mechanism for achieving these linkages will be through the FDP/RDPs which should involve local and international contributions of all of the research themes with the local operational bodies including the NMHS.

5.3 Interaction and Communication with Stakeholders

The High Impact Weather programme will interact with several groups of stakeholders:

- National Governments and International bodies that will sponsor and fund implementation of the advances achieved in the project

- NMHSs who will deliver the improved services enabled by the programme

- Emergency Response, Business & Media organisations who are the bodies that will initiate and/or carry out the mitigation actions prompted by the new services

- Individuals who will ultimately take action, or not, as a result of receiving public warnings

Successful mitigation of an impact depends on the right information being provided to the right people at the right time; that it is understood, and that it is acted on.

The right information will be provided by NMHSs and their partners using the advances in forecasting capability developed within this project, provided that the users’ needs have been adequately defined. Some of these requirements were discussed by those involved with particular user-sectors at the Karlsruhe workshop and are reflected in this plan. It is a two-way process requiring scientists to identify and discuss potential capabilities with users as well as users to identify and discuss their needs. This process will be continuous through the project using key presentations at workshops and conferences to take the requirement forward. The most effective activities are expected to be in the context of FDP/RDPs which must involve local stakeholders from the start, so that the problems are defined in the local community context.

The format and delivery channels used for providing information are critical to its being understood by the recipient. Activities within each FDP/RDP will address these issues, evaluating the communication value of different information, delivered in different ways and through different channels. Early engagement with local media channels will be critical to success.

Increasing the ultimate beneficial use of the information is what will determine the value of the project. Research into how to achieve improvements in this area remains in its infancy. Evaluating improvements achieved in FDP/RDPs will be an important component of their planning and execution, and must involve survey work amongst affected individuals and/or community groups.

Implementation of the improvements requires that the benefit is measured and that both costs and benefits are clearly documented and communicated to those who have to prioritise investment. Engagement with these groups will require working through the WMO's inter-governmental links and involvement in policy making conferences and initiatives. The project will ensure that participants in these processes are aware of the potential and priority of this work through major global conferences, review papers and specialist briefings.

Oversight by stakeholders will be achieved through the Strategic Advisory Group, which will consist of senior representatives of key user communities, and will meet yearly to review the direction of the project.

5.4 Training and Outreach

To be successful the project must break down barriers between disciplines and especially between the physical and social sciences. The next generation of scientists needs to be trained to think and solve problems across these disciplines. This can be achieved by training activities with young scientists and especially those from developing countries. The RDP/FDPs described under the cross-cutting activity on Field Campaigns and Demonstration Projects will provide the most effective training opportunities. These will be focussed principally on the countries and regions within which they are carried out. The venues for FDP/RDP meetings and workshops will be chosen so as to enable the maximum participation of local scientists.

6 Governance and Management

The project sits within the World Weather Research Programme (WWRP) of WMO under the overall direction of the WWRP Scientific Steering Committee (WWRP-SSC).

6.1 Steering Group

The project Task Team will steer the project until a Steering Group is formed. It is proposed that this consist of two co-chairs, representing the physical and social sciences, and the chairs of five task teams, one for each research theme. The Steering Group will meet at least once a year. More frequent meetings are expected to be needed in the early years of the project. . The co-chairs of the HIWeather Steering Group will report to the Chair of the WWRP-SSC

6.2 Strategic Advisory Group

The primary stakeholder input to the project as a whole will be through a strategic advisory group consisting of representatives of key user communities including Disaster Reduction, Economics, Weather Services, Insurance and the relevant WMO commissions: Commission for Instruments & Methods of Observation (CIMO), CBS, Commission for Hydrology (CHy), WWRP, WCRP, WGNE, GURME.

6.3 Task Teams

Each research theme will be managed by a task team consisting of a chair and the Principal Investigator of each planned activity in the theme, together with experts on specific topics as appropriate.

6.4 International Coordination Office

An International Coordination Office (ICO) will coordinate day to day activities of the project and manage logistics of workshops and meetings. This will be based in Geneva. The staff requirements are at least one full-time scientist. These requirements will be supported through the trust fund or through Junior Professional Officers on secondment to WMO.

6.5 Web site

Information on the project and its progress will be shared through the HIWeather web site, including research theme pages for information exchange between participants (wiki or similar).

6.6 Monitoring and Review

Regular review will take place as part of regular Steering Group teleconferences and meetings, to track progress on the Implementation Plan. A role of the evaluation theme will be to develop metrics of success of the project and to report them to annual reviews.

7 Financial Plan

The work of HIWeather is in a field characterised by highly localised, hazard-specific and application-specific research activities. Much of the benefit of the project will come from drawing together those who carry out these activities and exposing them to new ideas and capabilities. Achieving this will require a high level of international coordination and facilitation, supported by the resources of an International Coordination Officer and a Trust Fund. The Trust Fund will be needed to support: travel to Annual Steering Group and Advisory Group Meetings, attendance of developing country scientists at workshops and summer schools, preparation of member surveys, publication of reviews and white papers. We estimate that SFR200k p.a. is needed in the Trust Fund or through contributions in kind to support these activities. The main research activities of HIWeather will be funded through grants from national and regional research funding bodies through their normal calls, through bids to international funding agencies, and through participation of NMHS research staff.

8 Implementation Schedule

ACTIVITY	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
Management										
Steering Group	■	■	■	■	■	■	■	■	■	■
Advisory Group	■	■	■	■	■	■	■	■	■	■
Progress Reviews					■					■
Predictability & Processes										
Review wind hazard	■									
Catalogue hazards & impacts	■	■								
Case study intercomparison		■	■	■						
Lead RDPs & links to other field campaigns	■	■	■	■	■					
Workshops on error growth										
Uncertainty in microphysics & dynamical interaction (XC)			■	■	■					
Fire workshop	■									
Non-linearity workshop		■								
Convective scale ensemble reforecast database			■	■	■					
Develop model-based diagnosis tools (XC)										
Review of model uncertainty (XC)	■	■	■							
Diagnose forecast busts (XC)										
Multi-Scale Forecasting										
Workshops on hi-res obs: Requirements and Opportunities	■	■	■							
Workshop on nowcasting systems: Review and Development	■	■								
Workshop on km-scale DA: Review	■	■								
Develop physically-based nowcasting systems		■	■	■						
Inter-compare coupled data assimilation systems					■	■	■	■	■	
Workshop and Course on non-linear, coupled DA					■					
Develop model error climatologies at km-scale		■	■	■						
Inter-compare radar DA: Review article		■	■	■						
Inter-compare adaptive observing strategies: Review article		■	■	■						
Case study intercomparison of multi-scale DA			■	■	■					
Assess influence of boundary layer & land surface DA			■	■	■					
Assess sensitivity of hazard forecasts to observations			■	■	■					
Case study model inter-comparisons (with PP)		■	■	■						
Review parametrization performance at km-scale			■	■	■					
Uncertainty in microphysics & dynamical interaction (XC)			■	■	■					
Develop km-scale ensemble perturbation methods		■	■	■						
Inter-compare km-scale ensemble systems: Review Article					■					
Develop ensemble verification metrics	■	■	■	■	■					
Develop ensemble hazard diagnostics	■	■	■	■	■					
Develop user-oriented products	■	■	■	■	■					
Explore value of reanalyses & reforecasts		■	■	■						
Catalogue obs requirements (XC)		■	■							
Evaluate enhanced observing in FDPs/testbeds (XC)		■	■							
Involve operational meteorologists in FDPs etc (XC)	■	■	■							
Social Media (XC)	■	■	■							

Review of model uncertainty (XC)	■	■	■							
End to end treatment of uncertainty (XC)				■	■					
Human Impacts, Vulnerability & Risk										
Build research capacity	■	■	■							
Produce an inventory of existing methods (XC)	■	■	■							
Catalogue case studies of successes & failures (XC)	■	■								
Develop impacts-based forecasting structure (XC)										
Social Media (XC)				■	■					
Impact thresholds catalogue (XC)	■	■	■							
Develop capability for dynamic vulnerability										
Communication										
Build research capacity	■	■	■			■				
Review & share good practice	■	■	■	■			■			■
Catalogue case studies of successes & failures (XC)	■	■								
Social Media (XC)	■	■	■							
Build trust (XC)		■	■	■						
Develop guidance on using km-scale models (XC)	■	■								
End to end treatment of uncertainty (XC)				■	■					
User-Oriented Evaluation										
Build research capacity	■	■	■							
Review and share good practice	■	■	■		■		■			
Improved ensemble diagnostics and verification	■	■								
Techniques for errors in warning timing/duration	■	■								
Accounting for observation uncertainty	■	■	■	■	■					
Catalogue case studies of successes & failures (XC)	■	■								
Build trust (XC)		■	■	■						
Social Media (XC)	■	■	■							
Build collaboration with experts in other fields		■	■	■						
End to end treatment of uncertainty (XC)				■	■					
Verification tools for new capabilities (XC)			■	■	■					
Real-time verification (XC)		■	■	■						
Benefits in Operational Forecasting										
Involve operational meteorologists in FDPs etc (MSF)	■	■	■							
Develop model-based diagnosis tools (PP)										
Develop guidance on using km-scale models (C)	■	■								
Verification tools for new capabilities (E)			■	■	■					
Real-time verification (E)		■	■	■						
Design of Future Observing Strategies										
Use model techniques to assess future strategies										
Evaluate enhanced observing in FDPs/testbeds (MSF)		■	■							
Catalogue obs requirements (MSF)		■	■							
Social Media (MSF)			■	■	■					
Uncertainty										

Review of model uncertainty (MSF)	■	■	■							
End to end treatment of uncertainty (E)				■	■					
Field Campaign & Demonstration Projects										
Preparation for NAWDEX (PP)	■									
NAWDEX (PP)		■								
Data Analysis for NAWDEX (PP)			■	■	■					
Preparation for LVB-HyNEWS (MSF)	■	■								
LVB-HyNEWS (MSF)			■							
Data Analysis for LVB-HyNEWS (MSF)				■	■	■				
Preparation for ALERT.AR (MSF)	■	■	■							
RELAMPAGO EOP/IOP (MSF)			■							
Data Analysis for ALERT.AR (MSF)				■	■					
Knowledge Transfer										
Local involvement in FDPs	■	■	■							
Summer Schools			■	■	■	■	■	■	■	■
Reviews, White Papers & Journal Papers			■	■	■	■	■	■	■	■
Training		■	■	■	■	■	■	■	■	■
Verification										
Propagation of error (E)										
Diagnose forecast busts (PP)										
Build trust (C)		■	■	■						
Impact Forecasting										
Impact thresholds catalogue (VR)	■	■	■							
Develop impacts-based forecasting structure (VR)										
Data Management & Archiving										
Agree standards (MSF)	■									
Maximise real time reporting (MSF)	■	■								
Ensure ethical safeguards (MSF)	■	■	■	■	■	■	■	■	■	
Agree archive plan (MSF)	■	■								
Publish metadata (MSF)			■	■	■					

(XC) indicates that this is a cross-cutting activity that the research theme will be involved in.

(PP), (MSF), (VR), (E), (C) indicates a cross cutting activity led by the research theme with the indicated initial letters.

Abbreviations

ALERT.AR	Research & Development project for improving the prediction of high impact weather systems over the La Plata Basin
AQ	Air Quality
BAMS	Bulletin of the American Meteorological Society
C	Communication research theme of HIWeather
CAS	WMO Commission for Atmospheric Sciences
CBS	WMO Commission for Basic Systems
CEOS	Committee on Earth Observation Satellites
CHAMP	Coupled Hydrology-Atmospheric Modelling and Prediction
CHy	WMO Commission for Hydrology
CIMO	WMO Commission for Instruments & Methods of Observation
CLIVAR	WCRP Climate and Ocean: Variability, Predictability and Change project
COMET	US UCAR programme in Environmental Science Education & Training
CRED	Centre for Research on the Epidemiology of Disasters
CSI	Critical Success Index
DA	Data Assimilation
DAOS	WWRP WG on Data Assimilation and Observing Systems
DOWNSTREAM	Dynamics & Observations of the Waveguide: North-South Transport & Rossby wave Excitation over Atlantic Mid-latitudes (US contribution to NAWDEX)
DRR	WMO Disaster Risk Reduction programme
E	Evaluation research theme of HIWeather
EC	WMO Executive Committee
EDI	Extremal Dependency Index
EM-DAT	OFDA-CRED International Disaster Database
EO	Earth Observation
EOP	Extended Observing Period
EU	European Union

FDP WWRP Forecasting Demonstration Project

FfIR NERC Flooding from Intense Rainfall programme

GAW WMO Global Atmospheric Watch

GEWEX WCRP Global Energy & Water Exchanges project

GURME GAW WG on Urban Research, Meteorology & Environment

Hazards SEES: NSF SEES programme of Interdisciplinary Research in Hazards and Disasters

HEPEX Hydrological Ensemble Prediction Experiment

HIWeather WWRP High Impact Weather project

HyMeX Hydrological Cycle in Mediterranean Experiment

ICO International Coordination Office

ICSC THORPEX International Core Steering Committee

ICSU International Council of Science

IHP UNESCO International Hydrology Programme

IOP Intensive Observing Period

IRDR ICSU/ISSC/UNISDR programme for Integrated Research on Disaster Reduction

ISSC International Social Science Council

JSC WWRP/THORPEX Joint Steering Committee

JWGFVR WWRP/WCRP Joint Working Group on Verification Research

LVB-HyNEWS Lake Victoria Basin - Hydroclimate to Nowcasting Early Warning System

LWEC UK Living With Environmental Change

MSF Multi-Scale Forecasting research theme of HIWeather

MWFR WWRP WG on Mesoscale Weather Forecasting Research

NCAR US National Centre for Atmospheric Research

NERC UK Natural Environment Research Council

NextGen Next Generation Air Transportation System

NMHS National Meteorological and Hydrological Service

NHP UK Natural Hazards Partnership

NMWFR WWRP WG on Nowcasting & Mesoscale Weather Forecasting Research

NOAA US National Oceanic and Atmospheric Administration

NSF US National Science Foundation

NWP Numerical Weather Prediction

OFDA USAID Office of Foreign Disaster Assistance

OSE Observing System Experiment

OSSE Observing System Simulation Experiment

PANDOWAE Predictability ANd Dynamics Of Weather Systems in the Atlantic-European sector, a research group of the German Research Foundation

PDEF WWRP WG on Predictability, Dynamics & Ensemble Forecasting

PECAN Plains Elevated Convection At Night

PP Predictability & Processes research theme of HIWeather

PPP WWRP Polar Prediction Project

PTSD Post-Traumatic Stress Disorder

PV Potential Vorticity

PWS CBS Public Weather Service programme

RAIN Risk Analysis of Infrastructure Networks

RDP WWRP Research & Development Project

RELAMPAGO Remote sensing of Electrification, Lightning & Mesoscale / microscale Processes with Adaptive Ground-based Observations

SCMREX South China Monsoon Rainfall Experiment

SEDS Stable Extreme Dependency Score

SEEPS Stable Equitable Error in Probability Space

SEES US NSF portfolio in Science, Engineering & Education for Sustainability

SERA WWRP WG on Social & Economic Research Applications

SESAR Single European Sky Air Traffic Management Research

SWFDP CBS Severe Weather Forecast Demonstration Project

S2S WWRP/WCRP Sub-seasonal-To-Seasonal Project

TC	**Tropical Cyclone**
THORPEX	**THe Observing system Research and Predictability EXperiment**
TIGGE	**THORPEX Interactive Grand Global Ensemble**
TIGGE-LAM	**TIGGE Limited Area Models ensemble**
NAWDEX	**North Atlantic Waveguide & Downstream development Experiment**
TOMACS	**TOkyo Metropolitan Area Convection Study**
UCAR	**US University Corporation for Atmospheric Research**
UN	**United Nations**
UNESCO	**UN Educational, Scientific and Cultural Organisation**
UNISDR	**UN International Strategy for Disaster Reduction**
USAID	**US Agency for International Development**
VR	**Human Impacts, Vulnerability & Risk research theme of HIWeather**
WCRP	**WMO World Climate Research Programme**
WFCS	**World Framework for Climate Services**
WG	**Working Group**
WGMWFR	**WWRP WG on Mesoscale Weather Forecasting Research**
WGNE	**CAS Working Group on Numerical Experimentation**
WGNR	**WWRP WG on Nowcasting Research**
WHO	**UN World Health Organisation**
WIGOS	**WMO Integrated Global Observing System**
WMO	**UN World Meteorological Organisation**
WWRP	**WMO World Weather Research Programme**
YOPP	**PPP Year Of Polar Prediction**

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