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# High Impact WeatherProject

A draft proposal
for a research activity within the World Weather Research Programme
prepared for consideration at the THORPEX ICSC / WWRP JSC

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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 are caused by severe weather. 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 weather forecasting for one day to two weeks ahead, enabling early warnings to be provided for many High Impact Weather events. Further gains in the lead time of early warnings are achievable with continued research. At the same time, new capabilities in the observing system combined with advances in predicting the uncertainty in weather forecasts and in very short range forecasting at high resolution have made it possible to forecast many weather impacts directly and social scientists have begun to understand some of the challenges to achieving effective responses to warnings. The time is ripe to capitalise on these advances. We propose a five-to-ten year programme 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 work is defined by the needs of users for applications that will enhance their resilience in three areas of impact: economic, social and environmental.

The research required to achieve the goals of the programme is divided into five pillars: predictability and understanding; multi-scale modeling; human impacts, vulnerability and risk; evaluation and communication. These themes cover areas traditionally separated into the physical and social sciences. Achieving the outcomes of the High Impact Weather project depends on these two scientific communities workingtogethermuch more effectively.

There are common issues and activities across these themesthat are required to draw them together. Seven cross-cutting activities have been identified for the programme: applications in the forecasting process, design of observing strategies, uncertainty, field campaigns and demonstrations, knowledge transfer, verification, and impact forecasting.

The research programme will build on advances made in THORPEX and dovetail closely with the two current projects arising out of THORPEX: the Polar Prediction Project and the Seasonal-to-Subseasonal project. The WWRP and THORPEX working groups / expert teams will play an integral role in the defining and carrying out the research programme. The cooperation between the academic and operational communities developed in THORPEX will be maintained and strengthened. A key activity for this programme that was developed within THORPEX but will be implemented beyond THORPEX is the planned North Atlantic

Waveguide and Downstream Development Experiment (T-NAWDEX), as this has the potential to link activities across a variety of spatial and temporal scales as well as drawing in both the academic and operational communities.

Many of the activities will come together in a series of Research Development Projects and Forecast Demonstration Projects, which will be focussed on particular weather impact problems in particular places so as to establish an evidence base of best practice that may be applied globally. In addressing these weather impact problems, multiple research themes will be involved to advance understanding and modelling, but also to establish improved ways of communicating the forecasts and warnings and of evaluating their effectiveness.

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 the RDP/FDPs engaging widely with the academic and emergency response communities in the host countries.

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# 1 Introduction

## 1.1 Mission Statement

**The overall objective of the High Impact Weather 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 applications 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.

We propose a research activity within the World Weather Research Programme, defined by the needs of users for applications that use weather-related information. The advances made in this programme willenable 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 proposed programme has five aspects (Fig. 1).The project is motivated and guided by the **applications** in the external world (outer ring), where the needs are articulated and the benefits obtained. 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: including distress, morbidity and mortality as a result of weather impacts on individuals, on the infrastructure on which society depends, and on the businesses that provide them with goods and employment.
2. Economic: including damage to property and infrastructure, and impacts on businesses, both positive and negative, including loss of the ability to trade.
3. Environmental: including loss of biodiversity and habitat, toxic releases both due to the weather-related hazard and during mitigation and recovery activities,

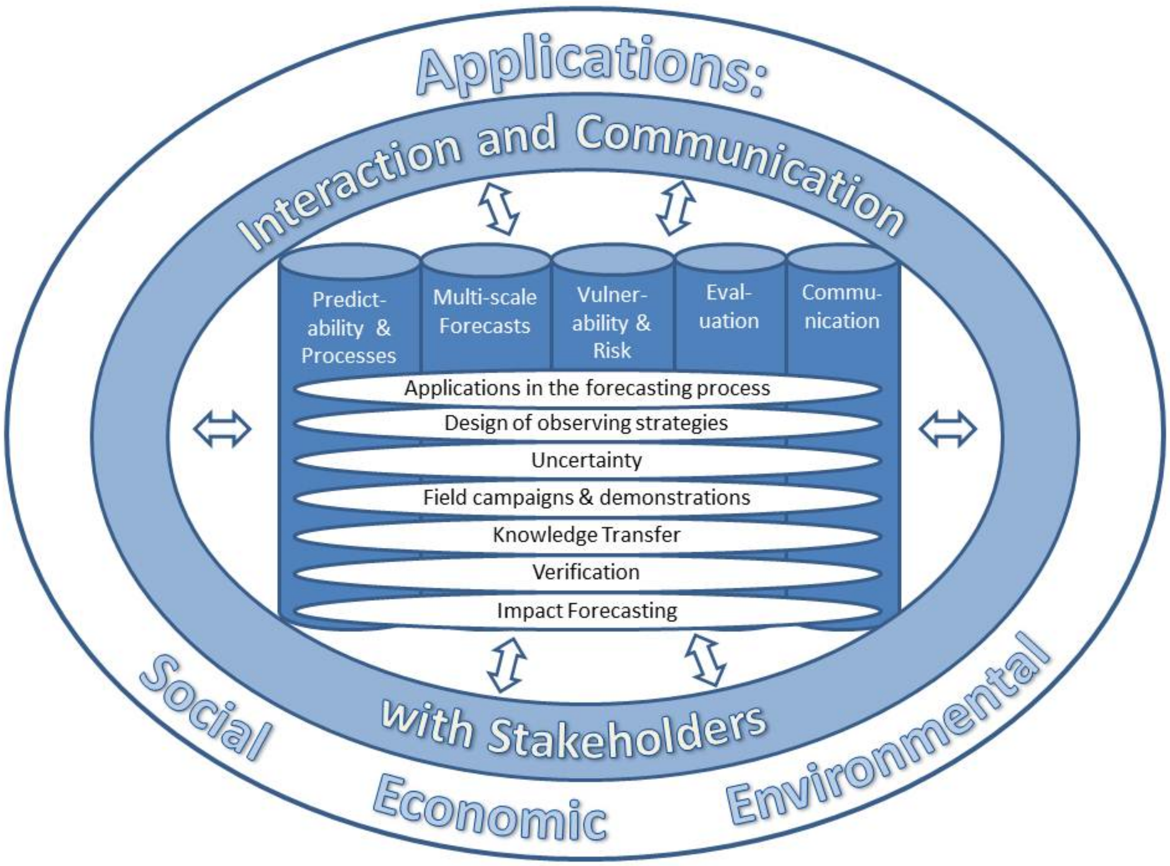


Fig.1 Conceptual diagram of the project (see text for explanation)

**Research Themes**(columns): areas of core research to address gaps in capability needed to deliver the mission statement.

1. Predictability and processes: Improve our understanding ofthefactors 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 prediction of the relevant variables in coupled modelling systems.
3. 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. Evaluation: Identify deficits in and grow trust in forecasts and justify their implementation and use through evaluation of forecasts & warnings of hazards & their impacts.
5. Communication: Achieve more effective responses to forecasts through better communication of forecasts & warnings of hazards & their impacts.

**Cross-cutting activities and issues** (ellipses)**:** will be addressed in several research themes and activities that require several research themes to work together.

1. Applications in the forecasting process: The challenges of the operational forecasting process will help define the priorities of the research themes. These will then develop capability that needs to inform and change the operational forecasting process in order to be implemented. 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 CBS activities, but 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 sophisticated 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 observations of impacts and responses, possibly making use of crowd-sourcing, social networks, and ubiquitous sensors.
3. Uncertainty: is an underpinning discipline for all themes. Forecasts are expected to be probabilistic and key issues in communication revolve around expressing uncertainty.
4. Field campaigns and demonstrations: will provide observations and model outputs to support new understanding, to verify modelling advances, to gather user needs, and to test the value of new products and communication methods. Datasets from previous campaigns will be exploited further and new programmes 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 to operational centres is a key cross-cutting activity.
6. Verification*(working title)*: while the research theme on evaluation is focussed on research that supports communication and response to forecasts, verification also has a role in process understanding and model development requiring input from the evaluation theme into the others. 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 on impacts will permeate all of the research themes, requiring input by the vulnerability and risk theme into the others

**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 external users.

- 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 keywith respect to business-led initiatives such as the development of next generation air traffic management and large scale energy management systems.
- Promoting Links between academia, research institutions and operational forecasting centres. Much was achieved in this respect by THORPEX, but this project needs to maintain and develop these links but extend the scope further, particularly to include

social science academics. A key role of the RDP/FDPs will be to ensure these links are developed in less developed countries.

- 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 demonstration projects (FDPs), through regional scale workshops for emergency response and business groups, to major conferences and briefing sessions for international bodies.
- Foster education and outreach: aspects of human impacts of weather and of the communication and response 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 activities within the programme will dovetail closely with the activities of WWRP. High impact weather plays an important role in the other two post-THORPEX projects: the Polar Prediction Project and the Sub-Seasonal to Seasonal project so that links with these projects will be developed. The project will draw heavily on the expertise of the WWRP working groups.

It is proposed that the programme last for five years, initially, with an option for extension by another five years.

## 1.3 History of the Proposal

WWRP THORPEX is a ten-year research programme with a focus on accelerating improvements in the forecasting of high-impact weather 1 to 14 days ahead. The THORPEX programme is due to 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”.WMO EC meeting (EC-64, June/July 2012), gave approval for the launch of two new WWRP projects that developed out of THORPEX: the sub-seasonal to seasonal (S2S) and polar prediction (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 WCRP.

For the post-THORPEX era an important question must be “what must be built upon, what is missing, what will make a difference, is worth investing in and should be promoted within the WWRP?” 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 weatheron 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 are 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 andcommunicating forecast information, and gaining the societal benefits of enhanced forecasting capabilities.

Following 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 KIT, Karlsruhe 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 the production of this proposal. This team held three teleconferences in the early part of June 2013, following which, members submitted material which has been collated into this first outline version of a Project proposal.

## 1.4 Next steps

This is a first draft of the High Impact Weather Project proposal. The purpose of this document is to promote discussion with the ICSC / JSC and obtain guidance from the joint meeting, so as to expand and improve the proposal. **With this draft we do not yet cover all aspectsat the same level of detail, but rather provide an overview of the content and structure of the project.**

Following discussion of this draft of the proposal at the joint THORPEX ICSC and WWRP JSC meeting the task team members will contribute in more detail to the proposal content and entrain expertise from their national and international contacts as appropriate. This will lead to a refined and more detailed proposal for submission to CAS.

## 2 Requirements and Benefits

Statistics of natural disasters show that weather-related 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, the last ten years has 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.

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 can reduce the time to recover the 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 – 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 grid overload.

The most destructive disasters of recent years are summarised below from EM-DAT: The OFDA/CRED International Disaster Database, www.em-dat.net of the Université Catholique de Louvain, Brussels, Belgium.

**Floods**

Nine major floods have each killed over 1000 people in the last ten years, the most fatalities (more than 2500) being from the Haiti floods of May 2004, while the costliest (over $40 billion) were the Thailand floods of August 2011. Most of these have been floods from major river systems that have covered huge areas. However, serious loss of life and damage also occur in response to more frequentand localised flash floods in small river systems. Some of the largest losses of life have come from landslides precipitated by flooding.

**Tropical Cyclones**

There have been nine tropical cyclones in the past ten years that have each killed over 1000 people, the most fatalities (over 135,000) being from the devastating Myanmar cyclone of May 2008, while the costliest (over $100 billion) was Hurricane Katrina which struck the US city of New Orleans in 2005. The most devastating impacts have been due to storm surges driven by the strong winds, but major impacts from river flooding are also characteristic of these storms.

**Heatwaves**

Periods of very hot weather claim many lives in most years. However, exceptional heat waves with large death tolls in recent years have included the European heat wave of 2003 which saw more than 10000 deaths, and the 2010 heat wave in Russia when more than 50000 died.

**Cold Waves and Severe Winter Weather**

Severe wintry weather claims large numbers of lives every year in affected countries. However, in terms of disasters, the 2008 Afghanistan blizzard stands out with more than 1000 deaths from a single event.

**Wildfires**

Like flash floods, wildfires are too localised to cause large loss of life from a single event. 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 $2 billion.

**Severe Convective Weather**

Like flash floods and wildfires, severe convective weather is too localised to cause large loss of life from single events. However, aggregated across many storms, the annual death toll and damage from tornadoes, severe hail, downbursts and lightning can be substantial. More than 300 lives were lost in a single tornado outbreak in the USA in April 2011.

## 2.2 Opportunities to increase resilience

Improved weather 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 of HIW events, 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 severe weather events. Progress has been made through better understanding of the physical processes, improved usage 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 the 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 forecasting 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.

During THORPEX, considerable 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. 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 weaknesses in their communication and understanding, and that current technological advances offer enormous opportunitiesfor 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 has 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 flooding
- 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

## 2.3 Achievable benefits

Recent advances in meteorological understanding and modelling have made it possible to predict on space and time scales that are needed to forecast 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 five year project will enable the achievement in parallel of:

Research into achieving more effective responses from existing forecasting capabilities

Improvement of model and forecast capabilities

Advancement of the underpinning knowledge which will result in future improvements.

Targeted demonstration projects 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.

Advances in understanding of the best ways to communicate hazard forecasts so as to reduce their impact will be highly dependent on the type of hazard 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 research and demonstration projects. 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 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 HIW 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 businesseswill 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.

A key outcome of the project will be a body of evidence that can be used by WMO and by National Weather Services to justify the introduction of improved forecasting and warning services. That evidence needs to 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 must be achieved through engagement with institutional stakeholders including those within the WMO (e.g. SWFDP) within the wider UN (e.g. ISDR) and within the world community (e.g. the World Bank, the EU etc).

# 3 Research Themes

The research themes will focus on key gaps and research questions that both need answering and which the science is ready to address. Impacts that are within scope include those from windstorms, floods (ocean, river and pluvial), , air pollution, bushfires, heat and cold waves, ice / snowstorms, along with application-specific impacts from non-extreme conditions such as low winds, cloud cover, and sub-zero temperatures.

## 3.1 Predictability and Processes

This theme is concerned with understanding the processes that lead to HIW and hence its potential predictability. It is concerned both with the slow processes that create the environment for high impact weather and with the fast processes that are generally associated with the impact itself. At short lead times, better understanding is needed of the processes governing convective-scale development and their dependence on the initial state, while at long lead times, the synoptic scale precursors need to be correctly represented in order to achieve useful downscaled forecasts.

The two sub-sections below deal with tropical and extra-tropical research areas respectively. However, there are some science questions that are independent of the different atmospheric structures in these areas. In particular, the 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 dissipate a hazard are also worthy of research – e.g. radiation effects of the built environment, concentration and dilution of pollutants, frost and fog-prone areas.

Research is also required on the processes that determine onset of and changes in flow regimes and on the ability of models to represent these changes. Better knowledge is required ofthe 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 due 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.

### 3.1.1 Extratropical Environment

The generation of HIW in midlatitudes is typically associated with precursors at upper levels. The prominent tropopause-level jetstream is characterized by an intense meridional 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 the formation of filamentary PV streamers and cutoffs, which in turn can induce anomalous meridional moisture fluxes and trigger HIW events at the end of the oceanic storm tracks. The propagation and amplification of the waveguide disturbances can be strongly modified by moist diabatic processes (e.g., via the outflow of warm conveyor belts (Grams et al. 2011) or deep convective systems into upper-level ridges). For the prediction of upper-level induced midlatitude HIW this sequence of processes implies that crucial ingredients for a successful forecast are the 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) of the modulation of the disturbances by intense convective or large-scale cloud systems. No robust validation exists of the representation of jet intensity in global analysis and forecast data. Concerning the instigation, development and breaking of Rossby waves at the tropopause, Davies and Didone (2013) reported significant PV errors in global medium-range forecasts, likely also because of inaccurate representation of moist processes. Research oriented towards improving medium-range predictions of HIW should therefore further investigate 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 HIW events, often with a very local character (e.g., foehn storms, bora). Here the advent of very high-resolution numerical models offers the possibility to represent details of the topography in unprecedented detail. It will be important to investigate in detail the predictability of HIW events related to orographic flows in this new generation of NWP models. Potentially, the bifurcation between the flow over and flow around regimes, which is highly sensitive to the temperature and humidity structure of the impinging flow, remains a critical issue that can lead to substantial misforecasts 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 parametrizations in these models, and to characterize this for use in data assimilation and ensemble prediction schemes.

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. This may be especially significant in the coastal zone where the fine details of the coastline can produce large gradients in surface temperature both in the atmosphere and in the ocean. The extent to which the response is modulated by the tidal changes in the ocean may be significant in some regions. 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.

#### 3.1.2 Tropical Environment

The occurrence of High Impact Weather in the tropics is much less directly tied to a particular type of synoptic scale weather system than it is in the extratropics. However, in the same way as in middle latitudes, synoptic scale disturbances of various kinds create the dynamical ingredients that enable high impact weather to occur. These disturbances are very diverse, including Kelvin waves, Easterly waves, Equatorial Rossby waves, Monsoon disturbances, Tropical Cyclones and others. Within these systems a variety of convective systems develop that form the spawning ground for many high impact weather events.

Understanding of the inception and interaction of synoptic scale tropical disturbances remains weak despite much recent work. 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. Progress is being made in both areas, but much work remains to be done.

The processes that give rise to severe convective systems at particular locations and times within the synoptic environment and which determine the evolution of those systems, remain largely unknown in the Tropics. Significant examples include:

- Topographically driven nocturnal convection on Lake Victoria in East Africa is modulated by the passage of Easterly Waves, but the nature of the modulation is unclear, and in particular, the determinants of the location of the severe weather are not known.
- The processes that lead to the creation of a Tropical Cyclone are still unclear, despite increasing capability of NWP models to simulate cyclone formation.
- The processes that produce active and break periods in Monsoon Circulations

Another key area of research into tropical weather systems is to understand the processes that link the tropics and extra-tropics, including the forcing of mid-latitude response to tropical convection systems in the monsoon, in cloud clusters and in the MJO; and the extra-tropical transition of tropical cyclones,their interaction with jet stream dynamics and the formation of extreme extratropical storms.

## 3.2 Multi-scale prediction of weather-related hazards

This theme covers forecasting by coupled physical modelling systems including atmospheric physics and chemistry, ocean and the land surface, including modelling of floods, landslides, bushfires, pollution, etc.. The sub-themes address the different aspects of such coupled modelling systems.

### 3.2.1 Observations &Data Assimilation

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 its aerosol content.

Currently used observations are inadequate to specify the initial state in sufficient detail. Research is needed to identify opportunities for obtaining denser data and to access and develop these capabilities, e,g, radar reflectivity, dense GPS TCWV networks, mobile phone link attenuation for rainfall intensity, solar cell data, VIIRS DNB radiances, crowd-sourced observations (e.g. WOW), rapid scan geostationary satellite winds, observations that contribute to improved depiction of low clouds at night.

Many of these sources 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 quantities observed by satellite, radar, lidar and visual observers.

Characterization of the time and space variability of the observation and forecast background errors for data assimilation are key to obtaining more accurate forecasts.

- Errors evolve non-linearly and error distributions become highly non-Gaussian on the convective scale; novel methods to treat non-Gaussianity and non-linearity are required
- Current DA methods do not handle position errors well
  - Highly local structures in the *a priori* estimate of forecast error
  - more R&D in topics such as ‘field alignment’ will be necessary
- Need better and more objective models for model (tendency) errors in ensemble data assimilation and ensemble prediction (including errors in boundary conditions)
- Further progress in variational / ensemble hybridization techniques is necessary

This sub-theme will also contribute to other themes, especially “predictability & processes” and “evaluation”, through the cross-cutting activity on the design of future observing strategies.

#### 3.2.2 Model Development

Improved forecasts of High Impact Weather depend on model improvements both to extend the predictability of extreme conditions in medium range forecasts, and to provide more precise and accurate detail in short and very short range forecasts. Specific areas of research will be prioritised according to their potential for delivering more precise, accurate and reliable forecasts of high impact weather at lead times from minutes to two weeks.

Forecast information on the impact of the weather needs to be improved through more sophisticated coupling of physical impact models (e.g. for storm surges, floods, etc) with NWP models. Where the impact drives processes that feed back into the atmosphere, the benefits of using the same coupled models for feedbacks as for impacts should be investigated.

- Representation of processes that are important at small scales, e.g. stable boundary layer, cloud-related turbulence, cloud microphysics including aerosol interactions and electrification.
- The representation of uncertainty in parametrized processes needs further study to determine the benefits of including stochastic schemes in models of different resolution and forecast length.
- Research is needed into better methods for dealing with partially/poorly resolved processes that span 0.5 to 5 grid cells – the “grey zone”.

- Ocean-atmosphere-aerosol–land surface coupling strategies need to be optimised for small scales and short-to-medium lead time forecasts.
- Representation of weather impacts that are transmitted through land geophysical processes, biological processes, responses of buildings, vehicles, infrastructure, etc

### 3.2.3 Ensemble Forecasting

For the time and space scale requirements of the project, forecasts need to be probabilistic. While ensemble forecasting techniques are fairly mature for larger-scale global or regional models, there is a particular need for more research to address these issues for 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). The smaller domain size also means that nesting techniques and the treatment of boundary conditions need particular attention.

- 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.

- The evolution of the 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 the 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.

- Errors and uncertainties in surface conditions will also affect the forecast evolution. Typically, an ensemble of forecast runs will share the same initial surface conditions (or will represent surface uncertainties in only a very limited way). This is likely to be a significant factor in underestimating the uncertainties in forecasts of near-surface conditions. Further research is needed to how best to represent the impact of these uncertainties in ensemble forecasts.

- Interaction with the sea surface is a special example of the influence of surface conditions. While coupled models are well established for (global) seasonal forecasts, atmosphere-ocean interactions may also be significant for short-range, convective scale forecasts – for example the effect of diurnal variations in coastal waters will impact the weather via sea-breeze fronts etc. In an ensemble forecasting context, the ultimate aim would be to run an ensemble of coupled atmosphere-ocean models to fully capture the forecast uncertainties.

- A key motivation of ensemble forecasts is to enable the risks of high-impact events in the tail of the statistical distribution. This has implications on the design of the ensemble: even if the ensemble is optimally designed to represent uncertainties, a larger ensemble is needed to properly estimate the risk of low-probability high-impact events. Research is needed to find the optimal balance between the benefits of higher resolution compared to a larger ensemble size.

- For medium range ensembles, there is a need to develop perturbation strategies that provide adequate forecast spread for those parameters associated with surface weather impacts, which currently tend to be underspread. This will likely require closer links between initial perturbations and data assimilation and better representation of model errors. As medium range forecasts are increasingly produced with coupled atmosphere-ocean-sea ice models, perturbation strategies will need to develop accordingly.

#### 3.2.4 Post-processing, product generation and human interpretation

This sub-theme acts to turn the raw model outputs of physical variables into the information required to drive assessments of human impacts and to be communicated to users. It includes calibration and removal of biases in the physical variables and in their probability distributions, time and space aggregation or downscaling to match 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 HIW. While the value of using reforecast datasets to calibrate products such as the Extreme Forecast Index has been well demonstrated for medium range forecasts, more research is needed to determine the best way to do this, and to explore calibration strategies appropriate for convection-permitting models.

A key step in the use of ensemble prediction systems is to relate the sample frequency obtained from the ensemble 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 the 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 that preserves the covariance structure of the forecasts, as required for flood forecasting, and blending ensemble outputs with nowcasts. 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.

Key weaknesses in current NWP capability that continue to require post-processing are:

- Tropical cyclones - track forecasts significantly improved; intensity forecasts still require calibration.
- Extreme rainfall events – medium range models have insufficient resolution to capture the true intensities. Statistical and dynamical downscaling offer solutions with different strengths and weaknesses. This is a potential area for collaboration with HEPEX.

An important aspect in this sub-theme is to develop compact ways of reducing and combining the wealth of information available to the operational forecaster as well as investigating the factors that limit the utility of automatic warnings.

## 3.3 Human Impacts, Vulnerability & Risk

This theme takes probabilistic forecasts of physical hazards generated by coupled modelling systems and turns them into assessments of the risk of human impacts, dependent on the exposure and vulnerability of the individuals, businesses and communities affected.

- Hazards result from the action of weather or other natural phenomena on humans and human systems. Often the damage is caused by the built environment created by humans – eg in windstorms it is often loose building materials. Quantitative models that connect the natural hazard to the real hazard need to be developed, evaluated, peer reviewed and shared.

- Exposure of individuals, businesses, communities & infrastructure to hazards – how likely is the hazard to impact on the receptor. This component is concerned with the relation of receptors to the hazard – eg what traffic will use a road during a severe wind storm, how many aircraft will be flying a route that is affected by thunderstorms, which utilities will be affected by flooding. Exchange of socio-economic data will enable exposure models to be developed, evaluated and shared between academic institutes.
- Vulnerability of individuals, businesses, communities and infrastructure to hazards – how sensitive is the receptor to the impact – depends on how the receptor responds, on what reserves they have to call on, on how well prepared they are. Vulnerability data and models depend critically on detailed understanding of the cultures of groups of people within the population. Generic relations between the characteristics of such groups and their behaviours do not currently exist and are unlikely to be of wide applicability. However, detailed studies in representative locations should enable the development and documentation of best practice that can be applied by national weather services and disaster reduction agencies. Differing responses to different types of hazard need to be identified, in particular between slow onset and sudden onset impacts.
- A key impact of high impact weather, and especially of natural disasters, is on health and well-being. The transition from the normal response of distress to the abnormal one of mental illness and its consequent loss of economic productivity and cost of treatment and care, is poorly studied. The generic applicability of results in this area is likely to be intermediate between that of the impact on the built environment and the culturally-dependent impact on individuals. However, there is little evidence at present to enable results obtained in one population to be generalised to others.

## 3.4 Evaluation

Murphy (1993) defined three aspects of a "good" forecast: consistency (represents the forecaster's best judgement), quality (accuracy), and value (enables better decisions). Evaluation research in the HIW project should address challenges in measuring quality and value, especially the final benefit of forecast applications as measured in social, economic, and environmental terms. The cross-cutting verification theme (4.6) focuses on the practical aspects of quantifying forecast accuracy and value including observations, experimental design, and recommended methodologies.

### 3.4.1 Forecast Accuracy

Evaluation of HIW forecast accuracy must answer several types of questions:

- 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 accuracy?
- To what degree are the forecasts more skilful than a naïve forecast like persistence, climatology or random chance?
- Which is the more accurate forecast when more than one is considered?

While the first two questions may be of primary interest to modellers and other researchers who are developing forecasting systems, the third and fourth 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 (Gilleland et al. 2009), and this remains an active area of research. While most of these spatial methods measure the forecast accuracy, 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 forecastaccuracy and utility (see for example Gallus 2010).

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.

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 (e.g., Ferro and Stephenson 2011), which are better able to discriminate between performance of competing forecasts at the far end of the distribution. The utility of these scores for evaluating HIW requires further investigation.

In the case of tropical cyclones, track and intensity verification have been done for many years but additional evaluation is needed for storm structure, precipitation, storm surge, landfall time/position/intensity, consistency, uncertainty, and additional information to assist forecasters (e.g., steering flow). The predicted occurrence and evolution of cyclones at long lead times (genesis, false alarms and missed events) also requires further research.

Observational errors affect the ability to quantify the accuracy of high impact weather forecasts, especially in extreme environments where observations may be less reliable (e.g., wind-related undercatch of precipitation in gauges, attention 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 verifying forecasts in "observations space" should be encouraged.

#### 3.4.2 Forecast Value and Benefit

Forecast value and benefit is related to accuracy, but goes further to measure the societal and economic advantage to users of basing their decisions on the forecasts. This is much harder to measure than the accuracy of the predicted weather, as users' decisions are affected by the method of communication used to convey the forecast (addressed in 3.5), their trust in the accuracy of the forecasts, vulnerability and exposure to risk, and psychological and environmental factors influencing their response.

The HIW project will endeavour to measure forecast value and benefit through addressing a number of questions. The first set of questions concerns the conversion of weather forecasts and warnings into hazard forecasts and warnings that may be more directly relevant to users, and how to observe and verify hazard impacts.

- How can forecasts of high impact weather best be translated into forecasts of hazards (e.g., aviation and road safety, flood risk, damage to infrastructure, etc.) to encourage more effective response?
- How do forecast errors propagate, confound, and conflate through the seamless hazard prediction process to the final intended user?
- Can verification techniques developed in the meteorological field be applied and adapted to evaluate forecast quality through a longer chain of predictions?
- Observations of impacts are not routine – how should we address this? Limit evaluation to periodic surveys? Introduce routine monitoring? Use existing “professional” sources such as the media or emergency services? Create crowd-based observing networks like WoW? Scrape data from the social media, e.g. twitter & facebook? What are the issues with each?

The second group of questions concerns the evaluation of benefits potentially gained through the use of high impact weather forecasts to reduce impact. Note that for human impacts effective communication of the forecasts should reduce or even remove the impact. In fact the most straightforward forecasts to evaluate may be those where mitigation is total but costly and forecasts are used to reduce the cost while maintaining zero impact. Both aviation and winter road maintenance are close to this situation.

- What improvements can be made in the protection of life and property through more timely and accurate forecasts of high impact weather and associated hazards? How can this gain be quantified in light of mitigation of impacts in response to forecasts, given that the “do nothing” option often leads to undesirable outcomes?
- What economic benefit can potentially be gained in various sectors (industry, government, public, etc.) through improvements in the accuracy and communication of forecasts of high impact weather and associated hazards?
- Which environmental decisions and outcomes have the greatest potential to benefit from improvements in high impact weather forecasts, and how could this best be realized?
- What is the individual sensitivity to forecast error, and what are tolerable and acceptable errors as defined by traditional verification and by various sectors?The interplay between hits, misses and false alarms is such that in order to achieve a certain POD or threat score one would need to make a decision to warn at a fairly low probability, which introduces a high over-forecasting bias.

## 3.5 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 HIW 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.
- Includes both applied work to improve communication practice, and research to understand the reasons underlying existing communication gaps (or unmet needs) and ways to improve them.
- Important to communicate effectively with multiple audiences (different user sectors, and different audiences within “the public”). Doing so requires understanding different audiences’ capabilities, needs, perspectives, and decision processes.
- Important to define audiences and goals for communicating with those audiences, in order to design effective communication strategies and measure success.
- Theories, knowledge, and methods from fields such as communication of health risks and hazards can help guide HIW communication research and practice. There is “science of communication” that can be used as a starting point, although specific ideas will still need to be tested in specific HIW communication settings.
- Most effective ways to communicate HIW forecasts and warnings will vary by country and region, due to differences in culture, existing dissemination and communication practices, experiences with HIW, etc.
- HIW communication is rapidly changing with technological development, and communication strategies will need to understand and account for evolutions such internet and mobile phone communication and social media. However, will also need to make sure to communicate with the most vulnerable populations, including people who face challenges receiving, interpreting, or acting upon HIW forecasts and warnings.

# 4 Cross-Cutting Issues and Activities

## 4.1 Applications in the Forecasting Process

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 warning issue is appropriate. Model forecasts may be 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.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 this proposal. Interpretation of observations and model forecasts is based on understandingof the 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 response to 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. 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 between developed and poorer nations. This project can help foster the spread 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 the 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. One such example is the so-called ECMWF 'M-Climate', which is complemented by severe weather products derived from this – the 'extreme forecast index' and the 'shift of tails'. Climatologies derived from convective-scale models will be a fruitful area of future work.

Work is also needed to more clearly define impact response functions for all 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.

The project must work closely with CBS and PWS to facilitate implementationof the new capabilities developed during the project into operational forecasting. (CBS is responsible for operational forecasts and PWS for issuing forecasts to public). The WMO Severe Weather Forecast Demonstration Project has successfully demonstrated the 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 for 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.

## 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 the responses that people make to 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 on survey data on vulnerability. Verification requires data on the key impact variables, while advances in communication methods depend on surveys of 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 forecasting locally. 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-basednowcasting systems to NWP models is creating a much enlarged requirement for atmospheric monitoring at fine resolution (~10km and less) which is unlikely to be met by current approaches. However, some adjustment of the priorities in existing networks may result from these requirements. Work is required to:

- Explore adaptive use of new observations
- Observing network needs to be fit for purpose on multiple scales, from local nowcasting (0 to 6 hours) through to continuing to advance the global predictive capability
- Consider well-constructed Observing System Simulation Experiments (OSSEs) to evaluate the future impact of new observations and observing strategies in the context of all existing observation types. Development of a global OSSE capability (covering multiple scales) would facilitate progress in this area.

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 responses to warnings, all in real time. However, these opportunities come with enormous challenges in the use of the data, especially in quality control.

## 4.3 Uncertainty

Most of the relevant impacts are not deterministically predictable on the time and space scales required by users, so uncertainty is a common factor in understanding, modelling and communicating High Impact Weather.

A fuller appreciation is required of the un-predictability of many severe weather details even at time scales of hours. The ‘deterministic limit’ is the point in lead time beyond which threshold-based deterministic forecasts are more likely to be wrong than right, ie where hits = misses + false alarms, or 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 some other phenomena. Warnings are needed much further in advance, and so intrinsically have to have a probabilistic element.

There is strong evidence in the literature of the financial benefits of appropriate use of probabilistic forecasts/warnings. However putting this into practice has been painfully slow– needing direct education of users, and indirect via increased promulgation of probabilistic warnings/forecasts in experimental or web-site ‘testbeds’– and in due course more and 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. 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 that it will be put to by the recipient.

Evaluating successful examples of the use of probabilistic information, such as depiction of the Hurricane “cone of uncertainty”, and making use of the lessons from these and other uses, will be important aspects of the education process.

## 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 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 response 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 coupled RDP/FDPs incorporating enhanced observations for understanding and forecast development; routine prediction for evaluation and technology transfer; user engagement & trialling (both forecasters and professional 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.

The design of these experiments needs to involve end users from the outset so as to ensure that the problem being addressed is aligned with the real problem of those who live and work in the area. Elements of communication and response should also be considered from the start to ensure that the end user benefit is kept as the focus.

A key role of the High Impact Weather programme will be to coordinate archiving, access to and exploitation of datasets of value to the research. These will include the detailed observations and model outputs from the field experiments and FDP/RDPs and from previous and related experiments such as T-PARC, YOTC, COPS and YOPP. It will also include access to data from “testbeds” and reanalyses and from exchange of operational forecasts, including the TIGGE and TIGGE-LAM archives.

The following planned experiments are relevant to the aims of the programme and are candidates to form part of it:

- T-NAWDEX: Plans for the aircraft-based THORPEX North Atlantic Waveguide and Downstream Development Experiment (T_NAWDEX) emerged from discussions in the Predictability and Dynamical Processes Working Group of THORPEX. The key objective of this international initiative, currently supported by scientists from Canada, France, Germany, Switzerland, the UK and the U.S., is to perform coordinated in-situ measurements of disturbances and their evolution along the North Atlantic jetstream, as well as the resulting (high-impact) weather over Europe. The plan is to operate with two high-altitude and long-range Gulfstream-V aircraft (HIAPER and HALO, respectively) from both sides of the North Atlantic and to follow the lifecycle of a Rossby wavetrain from its triggering phase (potentially from an extratropical transition of a tropical storm, a warm conveyor belt associated with an ordinary western North Atlantic cyclones, or a coherent stratospheric PV-vortex approaching the jet), through the amplification to the wave breaking stage. The combination of temperature profilers, scanning wind lidars, and Doppler radar instruments should allow, for the first time, to obtain a detailed in-situ picture of the PV structure of the midlatitude jetstream, and of potential causes for inaccuracies of predicting its disturbances.Experiments are being planned in the USA and UK to link with T_NAWDEX, including DOWNSTREAM & OUTFLOW over the USA and a convective-scale weather project to study impacts over the UK.
- Lake Victoria RDP/FDP: understanding the nature of HIW produced by nocturnal convection that causes fatalities on the Lake, its relationship with remotely observable signatures and with model predictions, developing nowcasting techniques and guidance products for local NWSs, communicating and developing trust in forecasts, technology transfer to regional academia & NWSs. Current aim is for a field phase in late 2016. This

project will link with the WCRP HYVIC project on the water cycle in this area, and with the East African SWFDP.

- SCMREX FDP: a proposed study of high impact weather associated with the monsoon in the South China Sea.
- TOMACS FDP: a very highly instrumented study of severe weather in the Tokyo area of Japan coupled with studies of socio-economic impacts and responses.
- PECAN: Plains Elevated Convection At Night (USA)
- HYMEX: a ten year programme of high impact weather studies and experiments around the Mediterranean.
- La Plata RDP/FDP: focussed on the violent convective storms that affect the La Plata Basin in South America and on their impacts, especially on the cities of that region.
- Great Lakes – Saint Lawrence RDP
- Opportunities for a joint experiment synergy with the US Severe Weather Testbed on severe convective weather impacts
- Opportunities for a joint experiment with HEPEX on hydrological impacts

## 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.

## 4.6 Verification

Verification will be necessary to support all themes of the HIW 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 aspects of verification within each of the HIW 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 HIW project should encourage participants to apply best practice verification to experimental forecasts, and it can also collate existing HIW 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 discussed previously, 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 HIW 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 HIW 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 more rapid response to provide relief for victims of HIW 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 bureaus, etc.), in order to estimate the risk reduction. Because this is such a vast endeavour, it will be more feasible for the HIW 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.

## 4.7 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 involves understanding specific societal vulnerabilities and risk related to High Impact Weather, and 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 form 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 othershave 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.

## 5 External Engagement

The Engagement strategy is to work in three phases:

Phase 1: Prior to submission of the outline proposal to ICSC/WWRP JSC, 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 full proposal, to engage with national and international bodies that already engage with users in relevant ways.

Phase 3: During the project to meet with end users at a variety of levels so as to define user needs for each of the science themes.

### 5.1 Linking with Other Initiatives

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

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
GAW/GURME/SDS-WAS
CAS/WWRP/WCRP/WGNE/S2S/PPP
Expert & Working Groups of WWRP & THORPEX: DAOS, PDP, WGNR, SERA, …

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, Foresight, NERC FFIR programme
USA: Weather Ready Nation
France: Prevassemble
Germany: PANDOWAE, Hans Ertel Centre for Weather Research
Mediterranean Countries: HYMEX
Hydrological Prediction: HEPEX
Polar Prediction: PPP
Sub-seasonal to Seasonal Prediction: S2S

It will also take account of major industry initiatives, such as SESAR and 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 andOperational 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 for addressing specific problems, including economics, psychology, sociology, anthropology, and public policy, as well as 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

- "Testbeds" that permit the objective evaluation of research products by forecasters
- Transition and maintain successful products after evaluation
- Communication of prioritised operational challenges to the research community
- 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:

- o National Governments and International bodies that will sponsor and fund implementation of the advances achieved in the project
- o National Meteorological and Hydrological Services (NMHSs) who will deliver the improved services enabled by the programme
- o Emergency Response, Business & Media organisations are the bodies that will initiate and/or carry out the mitigation actions prompted by the new services
- o Individuals 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 using the advances in forecasting capability developed within this project provided that the 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 proposal. It is a two-way process requiring scientists to advertise potential capabilities as well as users to identify 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.

## 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 Joint Scientific Committee (WWRP-JSC).

## 6.1 Project Steering Group

The projectTask Teamwill steer the project until it is formally initiated when it will be replaced by a project Steering Group

## 6.2 International Coordination Office

An International Coordination Office (ICO) will coordinate day to day activities of the project and manage logistics of workshops and meetings.

## 6.3 Monitoring and Review

Regular review will take place as part of annual Steering Group meetings, to track progress on theImplementation 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

There are four types of activities for which funding will be needed for the project, and potential funding sources:

(1) Travel for Annual Steering Group Meetings – from WMO

(2) Staffing and Operation of International Coordination Office – from WMO/host institute

(3) Workshops/seminars – from research funders/WMO for knowledge transfer

(4) Science campaigns and research funding - from research funding agenciesand participating institutions