High Impact Weather Project
(HIWeather)

A proposal
for a research activity 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 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 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 responses to 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. 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 the resilience of communities and countries in responding to five hazard areas:

> **Urban flood**, including flooding from the sea, rivers and directly from rainfall, with particular emphasis on flood impacts in the growing megacities of the developing world, especially those situated in the Tropics.
>
> **Wildfire**, emphasising requirements associated with 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 / air quality**, with particular emphasis on health impacts in the growing megacities of the developing world.

The research required to deliver enhanced resilience to these hazards is divided into five themes: predictability and understanding; multi-scale prediction of weather-related hazards; human impacts, vulnerability and risk; user-oriented evaluation; 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 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.

Seven cross-cutting issues/activities have been identified across the themes that are required to draw them together: applications in the forecasting process, design of observing strategies, uncertainty, field campaigns and demonstrations, knowledge transfer, use of verification, and impact forecasting. 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 come together in a series of field campaigns, Research Development Projects and Forecast Demonstration Projects (RDP/FDPs), which will be focussed on particular weather impact and forecasting problems in particular climatological settings 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, and to establish improved ways of communicating forecasts and warnings and of evaluating their effectiveness. One such activity, for which planning started within 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. Another is the Lake Victoria Experiment, whose aims include understanding the links between what is observed remotely and the hazards to those working on the Lake, development of improved NWP models, applications of NWP and nowcasting methods to predict the hazard, and improved methods of communicating with the fishermen at risk. Several other field campaigns, RDP/FDPs are proposed for inclusion in the Project, associated with understanding, predicting and responding to the five hazards, and covering a wide variety of geographical areas. Some of these are already being developed as distinct proposals, but will gain greatly from the international focus and participation that the HIWeather Project will bring to them. They include the North American PECAN (nocturnal convection) and Great Lakes – St Lawrence projects; the Asian TOMACS and SCMREX projects and the South American La Plata Basin project.

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 Subseasonal-to-Seasonal project. The WWRP and THORPEX working groups / expert teams will play an integral role in the defining and carrying out the research programme. 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 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 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 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 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 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,

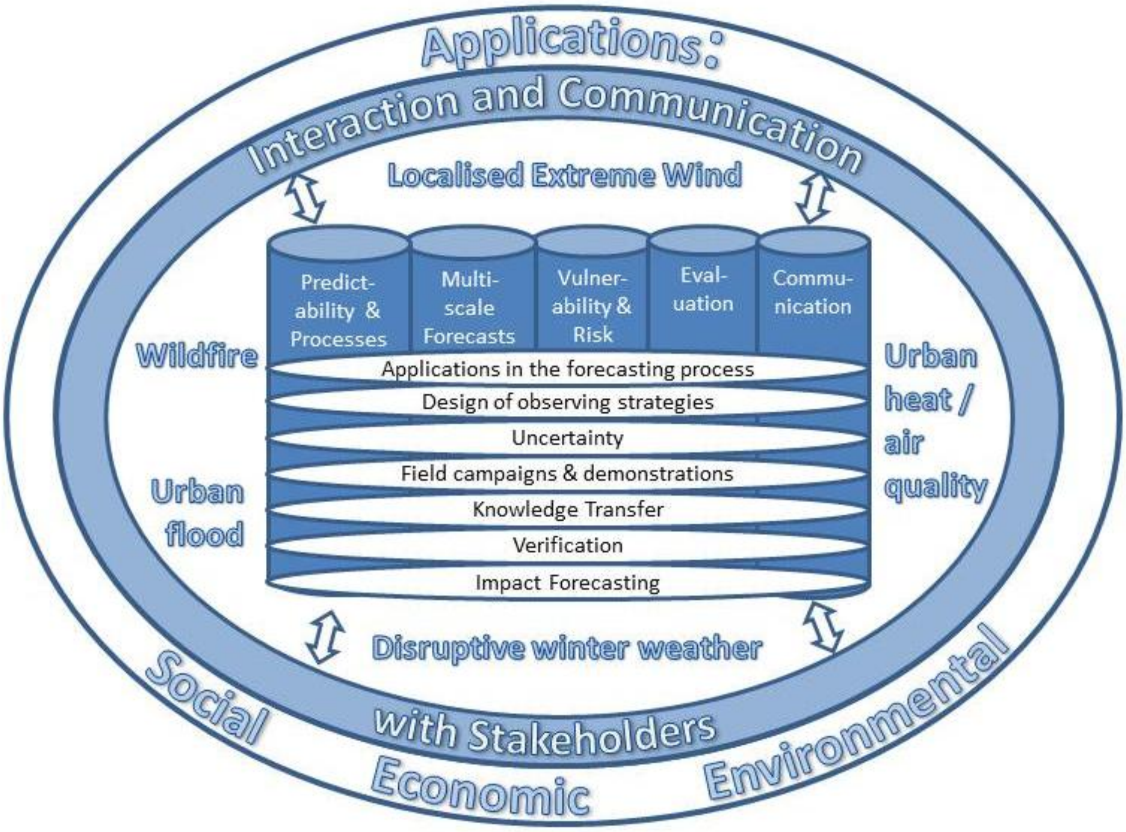


Fig.1 Conceptual diagram of the project (see text for explanation)

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 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 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, 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 requiring improved knowledge of processes that lead to uncertainty and improved methods of quantifying and evaluating uncertainty; 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 and 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 key with 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 Key Project Goals

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

- Improve predictions of mid-latitude storms and floods through better understanding and modelling of the role of diabatic potential vorticity generation in perturbing the waveguide.
- Improve predictions of tropical rainstorms through better understanding and modelling of the interactions between mesoscale and cloud-scale processes, and of the relationship of these processes to the hazard.
- NWP nowcasting – initialising the km-scale weather features so as to accurately predict their evolution on the 1-6hr timescale – probably using ensemble DA approaches
- Optimising km-scale NWP predictions of rainstorms in different climates – particularly the representations of cloud mixing & microphysics
- Develop a methodology for evaluating the reduction in impact of weather hazards due to forecasts and warnings

1.4 Project Objectives

- Develop & demonstrate successful data assimilation systems that simultaneously initialise convective-scale and synoptic scale weather systems.
- Clarify roles of turbulent mixing and cloud microphysics in determining convective cloud development and use to improve km-scale model performance
- Develop and implement improved NWP model representations of the influence of turbulence, surface processes and radiation on boundary layer weather systems in km-scale models.

- Demonstrate enhanced forecasting systems for hazardous weather associated with tropical and mid-latitude convection in several regional experiments and document for implementation in NWSs with a wide range of underlying capabilities.
- Develop and promulgate protocols for observation of weather-related hazards and their impacts, and metrics for verification of forecasts and warnings of these quantities.
- Evaluate high-density low-cost sensors and social network-based observation collection systems; develop & promulgate recommendations for their integration with existing data sources.
- Compare and evaluate coupled atmosphere-land-ocean-air chemistry modelling systems of varying complexity for prediction of weather-related hazards, and make recommendations for their use, including:
    - atmosphere-fire behaviour models
    - atmosphere-air quality models for urban applications.
    - atmosphere-flood models for urban applications.
    - atmosphere-land surface models for transport winter maintenance applications
- Develop & evaluate predictive relationships between weather hazards and health outcomes.
- Develop tiered best practice for calculation of exposure to hazards, including the use of advanced techniques to use time-varying exposure in real-time.
- Develop and demonstrate best practice for carrying out social experiments in hazard warning & response.
- Promote best practice in routine application of baseline and post-event social surveys to monitor growth in resilience from the use of hazard forecasts & warnings.
- Develop and promulgate a portable toolbox of human-impact models, including standards for interfacing with NWP.
- Clarify sensitivity to diabatic processes of the structure & development of mid-latitude waveguide disturbances, especially in those aspects that produce high impact weather, and demonstrate resulting improved NWP forecast accuracy.

1.5 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 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 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 and communicating 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 prepared the first outline version of a Project proposal that was submitted to a joint meeting of the THORPEX ICSC and the WWRP JSC 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 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. CAS endorsed the project on the basis of an updated executive summary, together with a more detailed presentation.

1.6 Next steps

This draft includes responses to issues raised at CAS meeting in Antalya in November 2013 and at the THORPEX EC meeting in Exeter in December 2013. A workshop of the task team is planned for June 2014 in the USA. This will provide input for a final version iof the proposal to be submitted for approval at the WMO Executive Council in May 2014.

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 frequent and 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 High Impact Weather 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, 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 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 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 Focus of the project

In order to maximise the gains that will be achieved through the proposed 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.

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

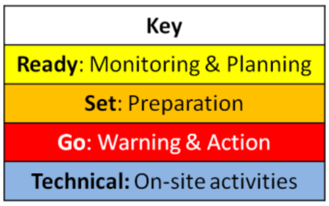
Localised Extreme Wind, including localised maxima within tropical and extra-tropical cyclones (e.g. sting jets), tornadoes, downbursts and downslope windstorms.

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

Urban heat / air quality, with particular emphasis on health impacts in the growing megacities of the developing world.

While this selection inevitably excludes some 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. The two urban hazards are of particular concern for the megacities of the developing world, especially those in 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. The final hazard is focussed on middle and high latitudes where major economic and social impacts result from the occurrence of hazards arising from low temperatures and stable boundary layers associated with long winter nights.

Each of the following sections on the five selected hazard areas addresses the impacts of the hazard, 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, some examples of recent occurrences of this hazard, and a response timeline. The latter is colour-coded as follows:



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

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.

What information do they need? – probability / timing / locations of threshold exceedance (depth & velocity) at key decision lead times; timing of defence overtopping / breach; 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 if High Impact Weather project goes ahead? Improved prediction of 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;

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; provide 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 (2 contrasting scenarios for flooding associated with TC Landfall in US), La Plata example, Bangkok 2011, Queensland 2010, St Asaph 2012, when early warning of a flash flood that overtopped defences enabled rest centres to be prepared ahead of evacuation, Colorado front range flood 2013 when radio and TV emergency messages broadcast prior to event, Zhouqu town mudslide 2010 with serious casualties.

Timeline:

<table>
<tr><th colspan="13">Lead Time (major river & coast floods)</th></tr>
<tr><th>-14d</th><th>-10d</th><th>-7d</th><th>-5d</th><th>-3d</th><th>-2d</th><th>-1d</th><th>-12h</th><th>0h</th><th>+12h</th><th>+1d</th><th>+5d</th><th>+14d</th></tr>
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<tr><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td colspan="3">Refurbish / Rebuild</td></tr>
</table>

2.3.2 Wildfires

What are the direct impacts? – casualties from burns / smoke inhalation / stress; population made homeless (temporarily or over longer time period); burned natural & crop vegetation erosion in subsequent rain → mobilization of toxic material in soil; property damage / destruction; stock loss; distress to people injured / made homeless → PTSD etc, loss of water / energy / telecom due to destroyed infrastructure; transport links cut; smoke impacts (respiratory illness due to poor air quality, 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 / A&E.

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

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 individual bushfire plans.

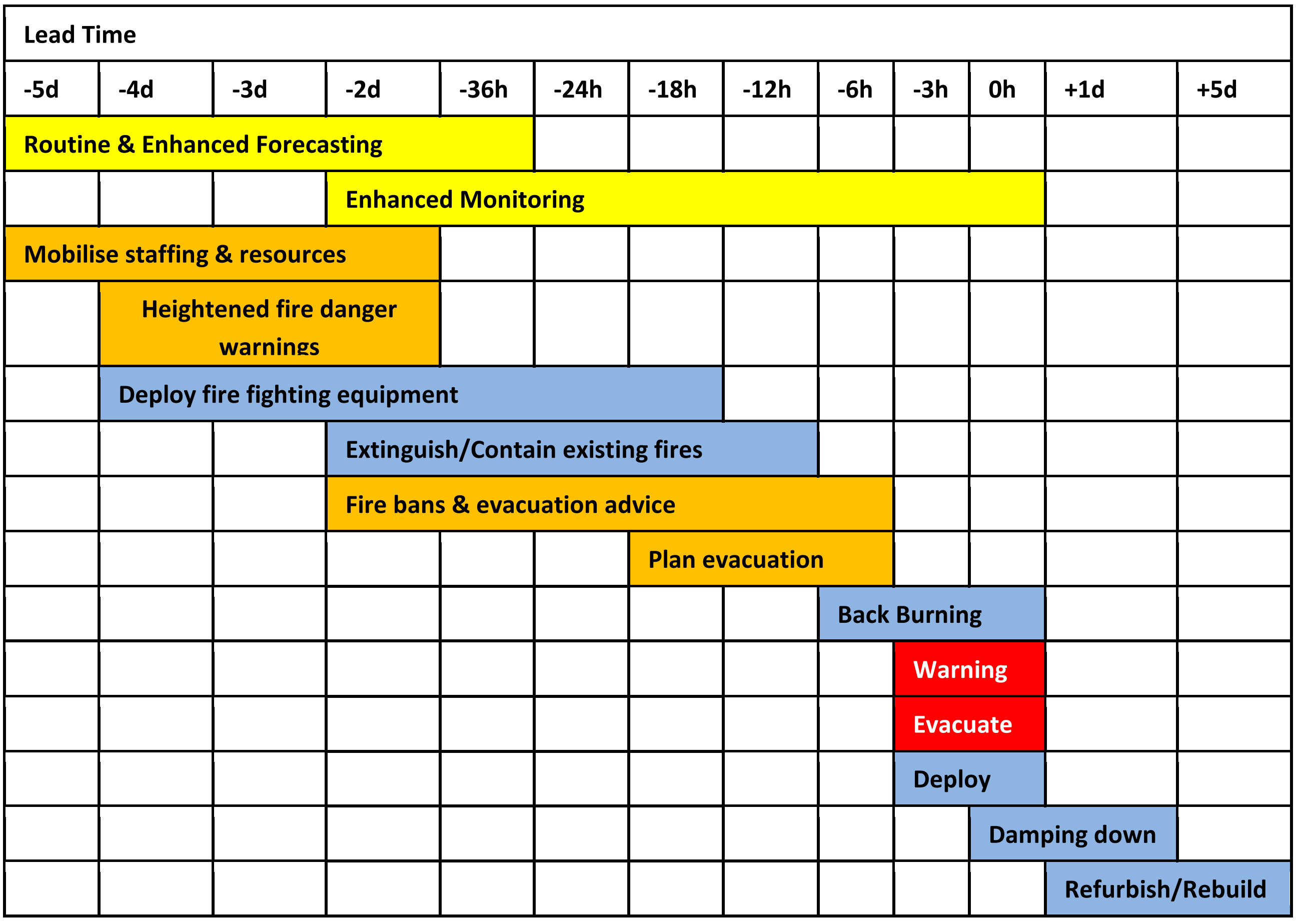
What information do they need? – early warnings of potential scale (area, duration) and impact; probability of threshold exceedance (fire danger) at key decision points; probability of ignition (arson, lightning, carelessness); fire initiation, movement / spread velocity – timing of changes, fire intensity/temperature; 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 if High Impact Weather project goes ahead? 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; identify / share best practice in fire propagation prediction; develop techniques for representing the impact of the fire on the wind field in fire propagation models; identify/share best practice in smoke dispersion from wildfires; improve estimation of smoke emission; Identify/share best practice in fire risk index prediction; communicate the meaning of high fire risk more effectively; predict & communicate 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: Feb 2009 bushfires in SE Australia, Russian wildfires in 2010, Rim Fire in California in Aug 2013; 2007 Greek forest fires, Indonesian fires of 2012, UK fires of 2011, Black Saturday (7 Feb 2009) in SE Australia, when early warning of extreme fire weather conditions enabled households to evacuate (in spite of this, many people died), Waldo Canyon fire near Colorado Springs 2012.

Timeline:



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	

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.

Who are the interested parties? – national government; local authorities; emergency managers; fire & rescue; ambulance / A&E; 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 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; track record vs scale/intensity.

What could we provide if High Impact Weather project goes ahead? Improved prediction of local variation of mean wind intensity, especially associated with squalls, tornados, downbursts; improved relationships of wind gust to mean wind; 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: Oklahoma tornados 2011, Moore tornado 2013, Post TS Sandy, Winter storms such as Kyrill (2007), Lothar (1999), March 1993 Superstorm, June 29 2012 Derecho, Oct 1991 Perfect Storm; May 31 2013 El Reno Tornado; Apr 25-28 2012 Tornado Super Outbreak; 1992 Hurricane Andrew; Sep 2012 TS Lee; 2013 mSuper Typhoon Haiyan

Timeline:

<table>
<tr><td colspan="13">Lead Time (tropical & extra-tropical cyclones)</td></tr>
<tr><td>-14d</td><td>-10d</td><td>-7d</td><td>-5d</td><td>-3d</td><td>-2d</td><td>-1d</td><td>-12h</td><td>0h</td><td>+12h</td><td>+1d</td><td>+5d</td><td>+14d</td></tr>
<tr><td colspan="13">Lead Time (convective & local storms)</td></tr>
<tr><td>-5d</td><td>-3d</td><td>-2d</td><td>-1d</td><td>-</td><td>-6h</td><td>-3h</td><td>-1h</td><td>0h</td><td>+3h</td><td>+1d</td><td>+5d</td><td>+14d</td></tr>
<tr><td colspan="6">Routine & Enhanced Forecasting</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td colspan="5">Enhanced Monitoring</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td></td><td colspan="4">Staff Preparedness</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td></td><td colspan="4">Public Awareness</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td></td><td colspan="4">Enhanced Maintenance</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td></td><td colspan="10">Response Staff Deployment</td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td colspan="3">Warning</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td colspan="4">Evacuation</td><td></td><td></td><td></td><td></td></tr>
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<tr><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td colspan="2">Rescue</td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td colspan="3">Refurbish/Rebuild</td></tr>
</table>

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 rail by loss of adhesion; disruption of air transport due to ice/snow by need for de-icing then by loss of adhesion on taxiways then by loss of adhesion on 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 / A&E 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.

Who are the interested parties? – city authorities; emergency managers; fire & rescue; ambulance / A&E; transport, energy & telecom companies; ski resorts; businesses; transport authorities; public.

What can they do to reduce the impact? – early triggering of small avalanches; treat road/rail; 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; track record (how often does it happen when forecast? Is it likely to be bigger or smaller than forecast…)

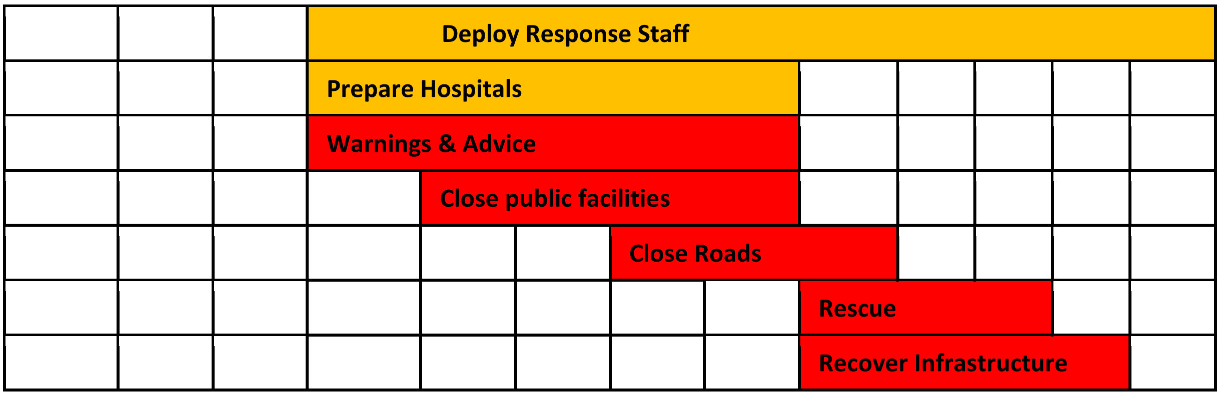
What could we provide from High Impact Weather project? Improved prediction of snow/rain transition, surface snow intensity, surface temperature over road etc surfaces in stable boundary layers; accumulation of ice on surfaces/structures/trees; formation of ice on untreated and treated roads; formation, 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 of 1998, post-Sandy New York snow 2012; Heathrow Airport closure December 2010, closure of schools in January 2013 in parts of England & Wales, 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 part of China, consecutive snow and freezing rain events in Jan 2008, trees and cables broken, transportations severely disrupted over large area.

Timeline:

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

2.3.5 Urban Heat / Air Quality

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.

Who are the interested parties? – national government; city authorities; emergency managers; fire & rescue; ambulance / A&E; 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-con 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 ambulance / A&E for increased demand; reschedule sports / outdoor activities; increase fluids intake; evacuate vulnerable people to cooler locations.

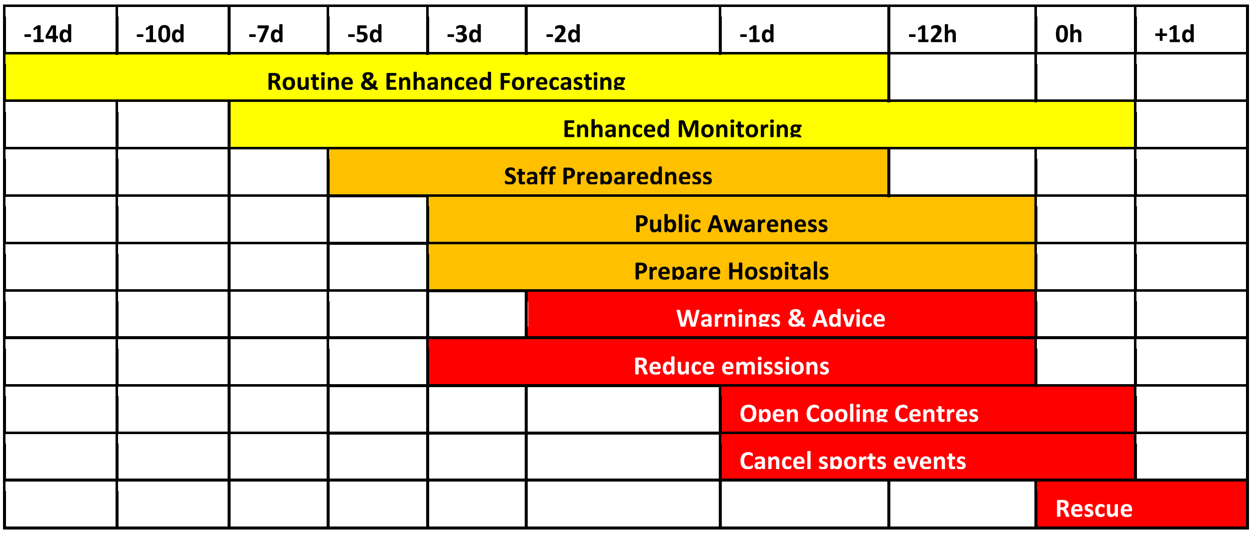
What information do they need? – air temperature, humidity and radiation, expressed as a comfort index relative to pre-determined thresholds; minimum temperature; duration above max/min thresholds; area affected; surface temperatures of road, rail, buildings etc; river water temperature; air quality/pollution index; pollutant concentrations; changes in energy / water demand; estimates of A&E demand; physiological stress as a function of clothing / environment / activity; track record of forecasts.

What could we provide if High Impact Weather project goes ahead? 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 AQ and of impact of reducing emissions; improved modelling of emissions in city scale AQ 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

Timeline:



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<tr><th>-14d</th><th>-10d</th><th>-7d</th><th>-5d</th><th>-3d</th><th>-2d</th><th>-1d</th><th>-12h</th><th>0h</th><th>+1d</th></tr>
<tr><td colspan="7">Routine & Enhanced Forecasting</td><td></td><td></td><td></td></tr>
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<tr><td></td><td></td><td></td><td></td><td colspan="4">Prepare Hospitals</td><td></td><td></td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td colspan="3">Warnings & Advice</td><td></td><td></td></tr>
<tr><td></td><td></td><td></td><td></td><td colspan="4">Reduce emissions</td><td></td><td></td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td><td colspan="3">Open Cooling Centres</td><td></td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td><td colspan="3">Cancel sports events</td><td></td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td colspan="2">Rescue</td></tr>
</table>

2.4 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 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.

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 challenges related to the hazards specified in section 2.3 and the research activities that are needed to address these hazards and the related impacts and applications.

3.1 Predictability and Processes

This theme is concerned with understanding the processes that lead to the defined hazards and hence their potential predictability. It deals both with the slow and rather large scale processes that create the environment for the appropriate high impact weather events and with the fast and rather small scale processes that are generally associated with the hazard itself. At short lead times, better understanding is needed of the processes governing convective-scale development and their dependence on the initial state. At long lead times, the synoptic scale precursors need to be correctly represented in order to achieve useful downscaled forecasts and to be able to act well before the event by issuing warnings and start preparations.

Most of the key hazards may affect tropical, subtropical and extra-tropical regions respectively, and thus can be associated with different types of weather events. 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 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 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.

The generation of weather events that may lead to one of the defined hazards in the 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, on the one hand, 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. These structures constitute one of the prerequisites for the formation of weather systems, like extratropical cyclones or mesoscale convective systems that eventually may entail the hazard of urban flooding, disruptive winter weather or localized strong wind. Wave breaking or the strong nonlinear amplification of midlatitude ridges, on the other hand, can lead to significant blocking events that may precondition the hazards of urban air quality and wild fires. 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).

Based on this sequence of processes, a successful forecast of upper-level induced midlatitude weather events that may be accompanied by the occurrence of a hazard, 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. 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 such weather events 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 hazards, often with a very local character (e.g., foehn storms, bora, potential for flash floods or land slides). Here the advent of very high-resolution numerical models and/or the coupling of precipitation and river/sewer flow or landslide forecasting offer the possibility to represent details of the topography in unprecedented detail. It will be important to investigate in detail the predictability of the several hazards 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 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. 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.

The occurrence of weather events causing the selected hazards 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 such weather events 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.

3.1.1 Key Challenges

- Improve model representations of the mid-latitude wave guide, its disturbances and their modulation by moist diabatic processes as a prerequisite for improved forecasting of downstream wind and precipitation hazards. Identify the characteristics and processes that determine the predictability of the downstream evolution and to which the development of hazardous weather is sensitive.

- Improve forecasts of the location and timing of intense convective rainfall and other extreme events. This will help to assess the probability of the hazard, e.g. urban flooding arising from blockage of drainage systems and from surface water inundation.

- Develop an understanding of the processes involved in the initiation and evolution of weather systems related to the hazards and the processes that are important for their predictability, e.g.

    - Determine the nature of the modulation of nocturnal convection over Lake Victoria by the passage of Easterly Waves, the local topographic and cloud processes that determine the location and severity of the hazardous convection.
    - Clarify the processes that lead to the creation of a tropical cyclone and that determine its structure and severity. Identify those processes on which predictability is dependent.
    - Identify the processes that lead to active and break periods in Monsoon Circulations and that determine the severity of convection in the active periods.
    - sensitivity of intense precipitation (& local extreme winds) in extratropical cyclones to upstream diabatic PV generation
    - sensitivity of tropical convection to larger scale atmospheric & topographic forcing
    - develop a relationship between tropical convective cloud structure, observed by satellite & lightning detection & predicted by NWP, and dangerous surface winds

    - understand the sensitivity of precipitation type & intensity to microphysics in shallow cloud systems, especially near 0^oC
    - Understand the sensitivity of visibility to microphysical parameterisations

- Improve understanding of processes that link the tropics and extra-tropics, including the forcing of mid-latitude responses 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.

- Improve understanding of key processes during atmosphere and land / sea surface interaction, e.g. development of convection and its interaction with the environment.
    - sensitivity of convective precipitation to local land / ocean characteristics, especially urban areas, soil moisture & SST

- Improve understanding of the sensitivity of the selected weather hazards to the characteristics of the land surface, especially the urban land surface. Determine the effect of this sensitivity on current and potential predictability of the hazards.
    - processes involved in temperature variability in the urban landscape
    - km-scale representation of pollutant concentrations in the urban landscape
    - sensitivity of fire-front propagation to feedback between fire & atmosphere
- Develop a theoretical foundation for adjustment processes in km-scale models

3.1.2 Selected Activities

- Use model simulation and historical studies to identify the role of diabatic PV Use model simulation and historical studies to identify the role of diabatic PV generation in the evolution of disturbances on the North Atlantic waveguide and the relationship between diabatic PV generation in the formation phase and the occurrence of hazardous weather in the mature and dissipating phases of mid-latitude cyclones. Use the results to design the T-NAWDEX and associated field experiments, then use the resulting data to test and improve models and to design observing networks that enable improved prediction.
- Use model simulation and historical studies to identify the role of travelling synoptic-scale disturbances in the initiation and intensity modulation of tropical rain systems in East Africa, South America, SouthEast Asia and other vulnerable parts of the tropics and sub-tropics. Use the results to design the LVP/HYVIC and LPB-ReD field experiments, then use the resulting data, together with that from SCMREX, TOMACS and other experiments to test hypotheses regarding the predictability of surface hazards, to test and improve NWP model performance and to design observing networks needed to hazard prediction.
- Use results of km-scale model simulations and inter-comparisons of tropical convection and extra-tropical convection to develop improved model parametrizations of convective-cloud processes, including cloud mixing and microphysics, for km-scale models, in collaboration with WGNE.

- Use data from the LVP / HYVIC field campaigns to evaluate the skill of nowcast and NWP predictions of nocturnal convective development and associated hazardous surface conditions on Lake Victoria
- Hold a series of intercomparisons of model results to generate hypotheses about the nature of convective-scale model precipitation biases and priorities for improved observations, modelling and/or data assimilation. With DAOS & WGNE 2015-22
- stimulate progress in 2-way coupled fire-atmosphere models to produce testable hypotheses of fire behaviour; evaluate coupled fire-atmosphere models on small scale controlled burns in a range of climate / vegetation regimes; design and execute a field experiment to test 2-way coupled models & evaluate simpler 1-way coupled fire behaviour models; use results to parametrize fire interactions on convective scale NWP models.

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 & Nowcasting

For an effective and successful forecasting and warning of high impact weather events on the timescale 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 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 warning operations at very short time scales. These systems must be improved by incorporating more detailed process descriptions and more observations. To provide the best possible basis for nowcasting, advanced observational systems are needed which measure various aspects of the macro- and microphysical state of the atmosphere, clouds and precipitation. Additionally, research in the processes leading to convective initialisation and research in the evolution of high impact weather events on various scales is needed. Both the disregard of lifecycle effects and the inability to introduce new convective cells in the projected field that did not exist at the time of the nowcast are seen as major deficiencies of current nowcasting strategies. A better understanding of the underlying processes will support the development of advanced nowcasting systems that will considerably improve operational weather warning e.g. for emergency managers or hydrological services.

3.2.2 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 the atmospheric 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. Weather-On-the-Web: wow.metoffice.gov.uk), 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.

3.2.3 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.

Particular challenges for model development are associated with:

- the development of a new generation of scale independent / scale adaptive parameterizations to better represent 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 to determine the benefits of including stochastic schemes in models of different resolution and forecast length;
- the development of better methods for dealing with partially/poorly resolved processes that span 0.5 to 5 grid cells – the “grey zone”;
- the optimization of ocean-atmosphere-aerosol–land surface coupling strategies for small scales and short-to-medium lead time forecasts;
- the representation of weather impacts that are transmitted through land geophysical processes, biological processes, responses of buildings, vehicles, infrastructure, etc.

3.2.4 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.

3.2.5 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 High Impact Weather forecasts. 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. Additionally, methodologies have to be developed that best combine NWP (ensemble) outputs with nowcasting to achieve seamless predictions of high impact weather events form minutes to hours.

3.2.6 Key Challenges

a) Observations & Nowcasting:

- Improve observational, remote sensing and nowcasting systems as well as seamless-scale cross prediction systems to combine forecasts from nowcasting systems and from numerical weather prediction systems
- Assess how the forecasting and warning processes can be improved
- Improve the detection of high impact weather regimes using observational and remote sensing data
- Develop appropriate physically-based nowcasting algorithms to identify, detect, classify and forecast areas of occurring high impact weather with accuracy in the timescale of minutes to the first hour.
- Develop strategies for capturing observations of the HIWeather hazards and their impacts

b) Data Assimilation & Ensembles

- Overcome issues resulting from non-linearity and thus non-Gaussianity of small-scale processes and from correlations or observation errors
- Demonstrate a DA scheme that successfully initialises deep convective cells while maintaining synoptic scale balances including ability to reliably adjust to match observed convective storm location
- Assimilate various observations continuously in time and improve matching between coarse observations and finer model grid
- Quantify the importance of small-scale errors versus large-scale errors
- Develop and improve quality control for severe weather systems
- DA related to hazards requires better representation of boundary layer
- For wildfires: nonlinearity and irreversibility - traditional DA approaches may lead to physically unrealistic state
- Develop coupled DA & ensemble perturbation schemes for coupled ocean-atmosphere-land surface – chemistry models
- Improved observation and data assimilation of soil and vegetation moisture
- Evaluate the potential contribution of DA to “parameter estimation” as well as to “state estimation” for poorly constrained processes such as microphysics in km-scale models.

c) Model development:

- Overcome deficiencies in representation of soil moisture and moisture field in boundary layer and lower troposphere to improve nowcasting and prediction of surface parameters, e.g. during convective initiation.
- More accurate forecasts for cloud field and precipitation
- Improvement of microphysical processes in model initial conditions
- Capture larger scale synoptic and topographic effects while resolving increased surface roughness and urban heat island effects
- Develop ocean modelling techniques to permit extension of regional scale storm surge and wave predictions into the surf zone

d) Post Processing and Human Interpretation:

- Better usage of probability information
- A fire risk index suitable for incorporation into a global NWP model, i.e. that is valid globally and that uses land surface information from the model.
- Globally applicable ocean and river flood estimation techniques

3.2.7 Selected Activities

a) Observations & Nowcasting:
  - Observation & nowcasting of winter weather, including ice, snow and fog, particularly where processes are occurring below the beam height of conventional radars
  - Demonstration and evaluation of new methods in a winter weather IOP
  - Development of improved radar processing algorithms to correct for attenuation in heavy precipitation
  - Demonstration and evaluation of new methods of radar correction in tropical precipitation during the LPB-ReD project.
  - Development of high resolution rainfall observing methods and their integration for urban areas in support of real time drainage control, including use of attenuation information from fixed microwave links and low cost public sources of data together with conventional and high frequency radar.
  - Hold a workshop on integration methods for rainfall observations, possibly in association with an inter-comparison experiment
  - Demonstrate high resolution rainfall observations in urban areas during field campaigns associated with the tropical rainfall in the LPB-ReD project in South America and with mid-latitude rainfall in the downstream components of the T-NAWDEX project over N. America and Europe and in the PECAN project over central North America.
  - Using data from LVP, LPB-ReD, SCMREX, TOMACS and PECAN and previous campaigns, intercompare and extend the validity of nowcasting techniques that identify the probability of severe weather (intense rain, lightning and/or wind – including tornadoes) associated with individual convective storm cells
  - Development & demonstration of techniques for observing & mapping of temperature in urban areas, including the quality control and use of low cost sensors and the gathering, quality control and use of data from public sources, including vehicles and mobile phones
  - Ditto for winter weather, especially snow and its impacts.

b) Data Assimilation & Ensembles
  - Use extended km-scale evaluation, particularly from regional reanalyses, to establish the climatology of model error in key aspects of hazardous weather prediction, including convective cell behaviour and boundary layer evolution.
  - Hold an intercomparison experiment(s) on advanced capabilities in assimilation of radar data in the context of one or more of the RDP datasets
  - Hold an intercomparison focussing on the improved assimilation of high frequency satellite, radar and in situ observations to predict cell evolution on the 10-50km scale over forecast lead times of one to three hours (i.e. the next two or three generations of storm cells), using object-focussed evaluation methods that focus on the hazard potential of the cells. Cases to include storm initiation as well as developing and decaying storm areas.

- Develop improved methods of initialising boundary layer atmospheric structure and land surface conditions in both clear and cloudy conditions through quality control & assimilation of novel observations & through improved use of existing observations, focussed on prediction of shallow weather systems, especially near the freezing level
- Develop appropriate evaluation methods and metrics for winter weather from shallow weather systems
- Hold a winter weather data assimilation inter-comparison & evaluation experiment, possibly in collaboration with PPP/YOPP or with a transport-oriented programme such as SESAR, focussed on the initialisation and accurate forecasting up to one day ahead of fog, cloud, snow and icing in shallow boundary-layer weather systems close to the freezing level, in a well-instrumented urban or semi-urban area, in conjunction with an IOP or field campaign.
- Hold a data assimilation workshop to evaluate capabilities of new research in multi-scale data assimilation using selected comparison cases with clearly defined large scale and small scale evolution characteristics. The relative benefits of larger or smaller domains may also be part of this exercise.
- Evaluate the sensitivity of hazardous weather prediction to forcing from the land and sea surface and the benefits of two-way interaction in coupled models, particularly with regard to boundary layer processes that lead to convective initiation and to shallow winter weather systems.
- Trial improved approaches to Boundary Layer cloud and fog Data Assimilation in a winter weather RDP
- Carry out a study of the sensitivity of end-produce hazard forecasts to observational inputs, to guide where research effort should be focussed.

c) Model development:

- Improved quantification of correlated uncertainty in microphysics processes, parameters and fields
- Improve modelling of boundary layer
- Improved models and representation of model error. Accurate specifications of model error are required for DA. Treatment of model error covariance on DA remains an open question.
- Fundamental research on characterising microphysics in models; in parallel quantifying microphysical uncertainty
- Explore the validity of parametrizations in current mesoscale models under very high resolutions and improve them

d) Post Processing and Human Interpretation:

- Intercomparison of NWP model based fire risk indices at global scale and in a wildfire RDP

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

3.3.1 Key Challenges

- In section 2.3, a very wide range of direct and indirect human impacts were listed. For each hazard warning application, a subset of these impacts will be of concern. However, for research inter-comparison purposes, modelling toolboxes are needed that provide consistent sets of outputs. HIWeather will establish priority sets of impacts for different hazards, and promote the exchange of computer codes for individual impacts, and their interfaces to weather & environment models.
- While acute impacts of hazards can often be readily identified and tackled, the indirect effect on the mental health of a population may have a much longer term economic and social impact. Evaluation of such impacts depends on before-and-after social surveys. HIWeather will promote the establishment of routine health & well-being surveys, using best practice in survey design, to serve as benchmarks for multiple post-event surveys so as to measure initial impact and recovery. It will also emphasise the importance of the continuation of existing routine surveys, including those set up for general epidemiological purposes, and of using them to support hazard impact research through additional post-event surveys.
- Current approaches to quantitative exposure assessment usually take fixed definitions of the distribution of receptors. While this may be a reasonable assumption for buildings, it is much less good for infrastructure, and clearly

inadequate for people. HIWeather will promote research into representations of the variability of exposures arising from movement of people and changes in demands on infrastructure etc..

- Vulnerable segments of the population need to be treated distinctly in hazard warning systems. There are commonalities between different countries that can be used to set best practice in assessing such special needs. These segments may have different patterns of movement throughout the day and week, which need to be identified. Again, there is value in comparing and contrasting research from different countries and cultures to establish best practice in defining the characteristics of these vulnerable populations.

3.3.2 Selected Activities

- A series of workshops will be held to bring together impact modellers and to inter-compare approaches to impact modelling, with the aim of creating shared modelling and calibration toolboxes with common interfaces and outputs. The toolboxes will have sections for hazard-specific impacts as well as for generic impacts.
- A workshop will be held to bring together those working on research into the health impacts of hazards to agree on the best approach to developing work in this field. In particular the role of routine long-term population level surveys will be assessed as a baseline for post-event surveys. The need to establish baseline surveys in a greater variety of countries, especially in less developed countries, will be a key consideration.
- Examples of the use of dynamic exposure data and or the sensitivity of impact predictions will be exchanged between HIWeather participants to promote development of suitable datasets and their use in more countries.
- Results of previous research into vulnerable populations will be compared to seek to identify an internationally consistent best practice, which will be promulgated in a report

3.4 User-Oriented 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 HIWeather 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 High Impact Weather 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 forecast accuracy 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 High Impact Weather forecasts 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 HIWeather 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.

3.4.3. Key Challenges

- Require a spectrum of metrics to evaluate model performance, ranging from traditional 500 hPa geopotential height to storm-centred meteorological variables to hazards such as type and duration of precipitation and ultimately to impacts such as roads blocked, buildings flooded and excess hospitalizations caused.
- Development of proper verification methods for high resolution model products, and for severe weather elements.
- Collecting sufficient sample sizes for rare/extreme events to support robust evaluation of forecasts and warnings.
- Extend use of spatial verification methods to precipitation type, cloud & fog; to probabilistic predictions, and to time as well as space displacements.
- Lack of observational data at all scales; insufficient and incoherent depth-damage information; lack of guidance on reporting damage and loss during floods making comparisons across different testbeds difficult..
- Lack of sufficiently high density and quality observational data at relevant scales
- Lack of guidance and consistency on reporting damage and loss (e.g., during floods) makes evaluation difficult, especially across different testbeds.
- Understanding how to best make use of new and non-routine data sources, especially from social media.
- Communicating forecast quality to users outside the meteorological community in a way that is meaningful to them.
- Communicating quality of probabilistic forecasts to external users.
- Converting meteorological information into hazard impact information, especially information that can be quantitatively evaluated.
- How to assess reduction in harmful impact of High Impact Weather due to improved weather forecasts and warnings when people mitigate against the impact.
- Obtaining economic information from industry on costs and losses associated with weather hazards and decisions to act (or not) based on forecasts.
- Establish methodology for attribution of benefits to the phases of the production chain: weather forecast, hazard forecast, impact forecast, communication - so that improvement can be focussed on the most effective phases.
- Develop & implement best practice in allowing for observation uncertainty in evaluation

3.4.4. Selected Activities

- Conduct a new verification methods intercomparison project (MesoVICT) to assess the applicability of existing and new verification methods to deterministic and ensemble forecasts of High Impact Weather in complex terrain from high resolution models.
- Explore the application of quantitative satellite-derived metrics developed for scoring the forecast structure of tropical cyclones to other types of weather systems.
- Develop new verification strategies based on more intelligent use of observations and analyses and accounting for observation uncertainty.

- Engage with external users to develop metrics that are meaningful to them, and encourage them to share their impact data with the weather community.
- In partnership with users, conduct experiments to explore the propagation of High Impact Weather forecast error to hazard impact prediction error and the impact this has on user decision making.
- Work with Google, social media providers to source hazard impact data (what, where, when)
- Develop, evaluate and promote verification metrics for cloud and fog (or visibility)
- Continue to establish the value and applicability of spatial verification methods for precipitation through comparative verification of RDP and FDP forecasts – especially in relation to subjective interpretation – and extend to precipitation type, cloud & fog

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 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 underlying existing communication gaps (or unmet needs) and ways to improve them.

3.5.1 Key Challenges

- Understand different audiences' capabilities, needs, perspectives, and decision processes so as to communicate effectively with multiple audiences (different user sectors, and different audiences within "the public").
- Define audiences and goals for communicating with those audiences, in order to design effective communication strategies and measure success.
- Use theories, knowledge, and methods from fields such as communication of health risks and hazards to help guide High Impact Weather 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 High Impact Weather communication settings.
- The most effective ways to communicate High Impact Weather forecasts and warnings will vary by country and region, due to differences in culture, existing dissemination and communication practices, experiences with High Impact Weather, etc.
- High Impact Weather 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 High Impact Weather forecasts and warnings.
- Define a manual of best practice for communication of complex and uncertain forecast information to different decision makers (e.g. emergency management officials, transportation managers, members of the public) at required lead times in the run-up to each of the selected hazards.

- Effective implementation of Flood Management and response plans under uncertainties using probabilities effectively. Deconstructing institutional barriers.

3.5.2 Selected Activities

- Review urban flood warning & response systems and develop a best-practice specification for what should be communicated, to whom, when, and by what means. Determine the cultural dependency of this.
- Evaluate the benefits of audience-specific messaging of warnings.
- Identify the key parameters that should accompany warnings of flood, fire, wind, heat, air quality & winter weather and investigate whether they vary between cultures.
- Develop best practice for provision of hazard information to decision makers in the emergency response community. Evaluate whether there are cultural dependencies.
- Establish & promulgate best practice for the process of agreeing hazard warning services for emergency responders, public and business users.
- Trial the value of new social media capabilities for promulgation of warnings, including the ability to track the response.
- Compare understanding and responses to warnings in different countries & cultures, identify dependence on their human environment and draw conclusions on the transferability of such research and its results

4 Cross-Cutting Issues and Activities

???While research themes are oriented to solving specific problems related to the target hazards, cross cutting activities are to do with the application of existing science/technical expertise across the whole project???

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 understanding of 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 implementation of 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.

4.1.1 Key Challenges

- Providing the evidence needed by the forecaster to enable convincing communication of the hazard situation to end users
- Providing adequate evidence of track record to enable the forecaster to attach confidence limits to communication
- Supporting the forecaster in decision making through provision of support facilities 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.

4.1.2 Selected Activities

- Providing the evidence needed by the forecaster to enable convincing communication of the hazardous situation to end users
- Providing adequate evidence of track record to enable the forecaster to attach confidence limits to communication

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 nowcasting 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-based nowcasting 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.

4.2.1 Key challenges

- Design strategies for optimal observation networks for multiple scales (km-scale and synoptic scale), suitable for use in both NWP DA and nowcasting, and deliverable using practicable mixes of observing systems.
- Account for data assimilation schemes, correlated observation errors, combined sets of diverse observations when designing a new observation strategy
- Need to identify the satellite sensors (or combinations of) that are most relevant for specific hazards
- Create a dense network of street level temperature sensors. Find out the requirements concerning observations in relation to the envisaged improvement of urban heat & air quality forecasting: - Can this be done through OSEs or adjoint-based/ensemble based sensitivity studies in geographical areas where sufficient observations are available? – Are OSSEs the only other alternative?
- Highly heterogeneous rainfall and drainage needs to be captured with in situ point sensors; achieve radar coverage, events are rare and may not take place during observational campaign. Also, data needs to be collected and shared

4.2.2 Selected activities

- Develop and promulgate data impact metrics that reflect hazardous weather in km-scale models.
- Apply adjoint-based data impact (FSO) and/or data denial analysis techniques to km-scale data assimilation experiments in each of the field campaigns so as to establish

the value of different data sources, including new remote sensing techniques and new high density networks of low cost sensors.

- Develop and promulgate sampling guidelines for observation requirements for verification of hazards and their impacts.
- Observing system experiments (OSEs) and Adjoint-based impact studies (e.g. forecast sensitivity to observations or FSO) with real observations. Observing system simulation experiments (OSSEs) with systematic configurations of current and future observation platforms
- Identify observation sources that could be used to reinforce hazard communication messages.
- Demonstrate and evaluate the use of enhanced hazard warnings incorporating observation reinforcement in one or more FDPs
- Promote the international exchange of new observation sources, especially those needed for assimilation in and evaluation of NWP
- Identify which new observations are practical to be collected; e.g. dual-polarisation data from weather radars, aircraft based humidity observations and which types of observations are most necessary for data assimilation, nowcasting and verification and evaluation.
- Develop strategies for observing network design – including refinement of spatial & temporal resolution and accuracy requirements - suitable for multi-scale weather prediction and candidate observing technologies that may deliver
- Identify which existing observations may be used more fully. E.g. Doppler-wind data from weather radars (maybe in few regions on the globe this is mature, elsewhere probably not) better usage of ground-based GNSS/GPS data: slant delays tomography instead of TCWV?
- Exploitation of air traffic control radar data such as Mode-S, ADS.B. etc. (potential of providing temporarily and spatially highly resolved obs)
- OSE /adjoint based impacts /OSSE Regarding ‘combined sets of diverse obs’: Aim for further studies which tell about the proper partitioning of humidity, temperature and wind obs. Other variables? Note: combined in-situ profile obs of RH, T and wind are rare (radiosondes) at the moment, and we get lot of more vertical profiles of T and wind only (aircrafts) Do we need more vertically highly resolved (ideally in-situ) humidity obs?
- Combination of OSSE (complex to set up) and subjective cost-benefit analyses of future observation types.
- Compare with high resolution IR imagery

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.

4.3.1 Key Challenges

- Requirements for hazard advice are naturally presented in deterministic terms because specific decisions have to be made. This naturally results in a tendency for the science behind hazard advice to be developed in deterministic terms. Establishing a culture of thinking from an uncertain framework, of working in probabilistic terms, and of taking risk-based decisions requires an educational programme across the breadth of the work of High Impact Weather.

4.3.2 Selected Activities

- A workshop will be organised and a review published on the implications of uncertainty across the whole spectrum of the work of HIWeather and how these propagate to influence the ability to enhance resilience.
- Examples of good "uncertainty thinking" at all stages of the hazard warning process will be promulgated to those engaged in HIWeather 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 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.

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 planned for the HIWeather programme.

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. This list is currently focussed on the windstorm and rainstorm hazards. We are seeking to engage with countries planning to carry out relevant work in the other hazard areas to formulate RDP/FDPs in those areas.

4.4.1 T-NAWDEX / DOWNSTREAM / OUTFLOW / …

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 jet stream, 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 wave train from its triggering phase (potentially from an extra-tropical 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 mid-latitude jet stream, 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.

4.4.1.1 Selected Challenges

- Factors triggering or modifying wave-guide disturbances
    - Tropopause polar vortices (positive PV anomalies)
    - Warm Conveyor Belt outflow (negative PV anomalies)
    - Extra-tropical Transition of tropical cyclones
    - Precursor wave packets
- Processes impacting wave-guide disturbances
- Evolution of Rossby waves along the waveguide
    - Waveguide representation
    - Downstream evolution of PV anomalies
    - Modification from Greenland
    - *Local* modification of Rossby waves by pos. and neg. PV anomalies
- Downstream impact of diabatically modified PV anomalies
    - Wave breaking
        - Sensitivity to upstream disturbances
        - Fine scale aspects
    - Wave breaking influence on synoptic features
        - Blocking ridges
        - Cutoff cyclones (anticyclonic wave breaking) → Heavy rain/convection
        - Stationary troughs → Heavy rain
- Predictability issues?

4.4.1.2 Selected Activities

The objectives of T-NAWDEX and the associated field campaigns will be addressed through consideration of the following six hypotheses:

- **There are systematic errors in model representation of waveguide perturbations**.
- These systematic errors are attributable to diabatic processes manifested as errors in PV distribution that correspond to errors in the jet stream, which in turn lead to errors in forecasts of high-impact weather downstream.
- The contribution to error from disturbances is relative to their diabatic character (and scale).
- Predictability as measured by ensemble prediction systems is sensitive to diabatic processes.
- Predictability is dependent on the basic state of the waveguide.
- Tropical source error differs from polar source error.

4.4.2 Joint WWRP Lake Victoria Project (LVP) / WCRP Hydroclimate Lake Victoria (HyVIC) / EAC Navigation Early Warning Systems (NEWS) project: LVB-HyNEWS

Lake Victoria proposed RDP/FDP: understanding the nature of High Impact Weather produced by nocturnal convection that causes fatalities to fishermen on the Lake, its relationship with remotely observable signatures in satellite and lightning data and the capability of model predictions (theme 1), developing nowcasting techniques and guidance products for local NWSs (themes 2 & 3), communicating and developing trust in forecasts (themes 4 & 5), technology transfer to regional academia & NWSs (themes 2,3 & 4). Planning started in late 2011 and the 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. The current plan for a RDP focussed on gaining understanding and testing hypotheses that will support improved forecasting methods. A FDP will be needed to follow this to evaluate the effectiveness and benefit of the new methods in the local operational context. This should be carried out under the umbrella of the East African SWFDP.

4.4.2.1 Selected Challenges

The scientific goals of the LVP are:

- Develop a thorough understanding of the initiation process of nocturnal thunderstorms over Lake Victoria, using remote and in situ observations with the purpose of developing reliable convective outlooks, nowcasts and warning systems.
- Develop knowledge of factors governing the strength of thunderstorm downdrafts and outflows over Lake Victoria and resultant impact on wave height, using Doppler radar, radiosonde, and other remote sensing observations so that accurate nowcasts of low-level wind speed and direction can be produced.
- 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.
- 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.
- Collect observations to evaluate the capability of kilometer-scale Numerical Weather Prediction 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.
- Collect and, where possible, deliver in real time observations needed to develop and evaluate data assimilation capabilities for kilometer-scale Numerical Prediction Models run over the Lake.
- Collect and, where possible, deliver in real time observations to develop and evaluate relationships between outputs from Numerical Weather Prediction models run over the lake and the hazardous weather conditions that cause loss of life, especially wind speed and direction.
- Collect reports of the occurrence of fatal and non-fatal accidents on Lake Victoria so as to relate them to observed hazardous weather conditions associated with nocturnal convection over the Lake.
- Based on the knowledge gained from the field program develop thunderstorm nowcasting techniques for Lake Victoria that can be utilized by the weather services in Kenya, Uganda and Tanzania

4.4.2.2 Selected Activities

The objectives of the LVP will be addressed through the investigation of 16 hypotheses, as follows:

i. Initiation of thunderstorms affecting Lake Victoria Basin

Hypothesis 1. The daytime thunderstorms surrounding Lake Victoria are initiated by lake breezes and/or anabatic flow along the slopes of the mountains.

Similar to sea breezes that result when solar heating of the land draws in the cooler air over the ocean, lakes and even wide rivers (Simpson 1994; Asefi e al. 2012) produce similar breezes. These breezes are very effective in initiating convective storms. Satellite cloud imagery, precipitation and lightning data suggests that storm initiation by this mechanism is very prevalent for Lake Victoria as well. Lake Victoria is at an altitude of about 1000 m and the surrounding terrain reaches altitudes of 3000-4000 m to the east and northeast of the lake. Based on satellite data, afternoon heating along the slopes of these mountains also appears to be a very effective mechanism in initiating storms. Thus it is very likely that there is further initiation as outflows from the mountain storms and sea breeze storms interact.

Hypothesis 2. Nocturnal thunderstorms are initiated along the northeast coast by land breezes that are enhanced by downslope flow from the mountains to the east and outflows from local afternoon and evening thunderstorms. Variability in location is related to the strength, depth and density of individual downslope flows from individual mountain valleys.

The location of the initiation of the nighttime thunderstorms that occur over LVB is highly variable. The long period climatology frequency data shown in Fig. 3 suggests that many of the storms initiate along the northeast coast and move to the southwest over the lake. It is not currently understood why the northeast coast would be favored over other locations. Possibly this is a result of interacting land breezes from both the north and east coastal regions. Relatively cool land breezes passing over the warm lake are likely to initiate storms very similar to the reverse process when cool lake breezes move over the warm land during the day. These flows may also be intensified by easterly flow produced by downslope flow of varying intensities from the individual mountain valleys to the east and possibly environmental large scale flow from the east or north, under distinct mesoscale and synoptic scale weather regimes. Gust fronts remaining from evening thunderstorms over the land may be interacting with the land breezes as well.

Hypothesis 3. Nocturnal thunderstorms initiate over the lake as a result of a) land breezes moving over the relatively warm lake, b) wind convergence zones created by horizontal thermal boundaries or gradients in the lake or c) large scale wind confluence over the lake.

In contrast to what is commonly observed with a lake breeze initiating storms in a ring over the land, land breezes do not appear to initiate storms in a ring over the lake, parallel to the shoreline. And given the very large size of LAKE VICTORIA and lack of observation, preferred patterns and orientations of storm initiation over the lake are not well known. Semazzi et al. (2012) has indicated that warm currents are present in the lake. The MSG Spinning Enhanced Visible and Infrared Imager (SEVIRI) Sea Surface Temperature (SST) data can be used in identifying the existence of these warm currents. These currents might establish convergent wind patterns that initiate storms over the unstable air over the lakes; similar situations for storm initiation have been reported by Li and Carbone (2012) over the open ocean. Other initiation mechanisms are suggested by large scale flow patterns documented by (Ba and Nicholson, 1998; Laing et al. 2011) that suggest occasionally large scale easterly and westerly flows would collide over Lake Victoria.

Hypothesis 4. The timing and/or location of "lake-initiated" nocturnal thunderstorms occurs when or where the near-surface air becomes 2-3˚C cooler than the lake surface temperature.

Hydrological investigations of the lake by Flohn and Fraedric (1966) indicated that rainfall over the lake was dramatically enhanced by a nocturnal lake-breeze circulation that produces convergence over the center of the lake. Although the increased convergence was deemed sufficient for enhancement of convection and rainfall, further enhancement was believed to be achieved through the thermal instability of the boundary layer over the lake arising from the cooling of the air over the warmer water. No direct measurements were available in the hydrologically-based lake studies of Flohn and Fraedric (1966) and others; all estimates were indirectly calculated based on land stations or dynamic models. Using NSF LAOF in conjunction with water measurements and instrumented buoys from HYVIC and satellite-derived SST measurements, the potential now exists to get direct measurements of lake surface temperature.

ii. Storm Intensification and severity

Hypothesis 5. Regardless of where the nocturnal storms initiate they reach their most intense stage with regards to updraft and downdraft strength over the lake as a result of the influx of relatively warm moist air into the updrafts.

Little is known about when the nocturnal storms reach maturity and produce their strongest downdrafts and outflows. We theorize this would be over the lake when the relatively warm and moist air is being ingested into the storms.

Hypothesis 6. Nocturnal thunderstorms that produce the most intense downdrafts and outflows hazardous to the boating community are associated with preferred regions of the lake where strongest surface convergence and thermal gradients in the water routinely occur.

Semazzi et al. (2012) has indicated that warm currents are present in the lake. Warm water currents are favored locations for intense thunderstorm activity, as has been observed with the warm pool in the Pacific Ocean during the TOGA-COARE experiment, the Gulf Stream (Minobe et al. 2008) current along the eastern U.S. seaboard, and with the intensification of hurricanes as they pass over warmer water currents in the Gulf of Mexico. Lake temperature measurements are planned under the complimentary GEWEX HYVIC field program for Lake Victoria (Semazzi et al. 2012), and with collection of MSG SST data; thus, there is some likelihood that the location of prevailing warm currents might be identified.

Hypothesis 7. The intensity of the thunderstorm downdrafts and subsequent surface winds are influenced by evaporational cooling as the precipitation falls through drier mid- and lower-level environmental air. Precipitation loading within these tropical storms may also play a major role in downdraft strength. The relative humidity profile is defined by the daily mesoscale or synoptic scale influences, thus the potential for strong outflows can likely be predicted with NWP assuming there are sufficient observations.

The mechanisms for downdraft production are well known from the microburst studies conducted in the 1980's by Srivastava (1987) and McCarthy et al. (1982), among others. Mechanisms include precipitation loading, evaporative cooling of the air from precipitation falling into dry air and transport of high momentum mid-level winds into the downdraft and down to the surface. What is unknown is the relative frequency of occurrence of any one of these mechanisms in producing strong downdrafts and outflows in the storms over Lake Victoria. Furthermore, while it is likely that only a small subset of storms actually produce strong diverging winds over the lake, the percentage is unknown.

iii. Observations for initialization and verification of Numerical Weather Prediction models

The WMO Severe Weather Forecast Demonstration (SWFDP), European Organization for the Exploitation of Meteorological Satellites (EUMETSAT) and the UK Met Office are conducting a pilot forecasting experiment of convective storms for LAKE VICTORIA using satellite images from the Meteosat SEVIRI instrument and Numerical Weather Prediction outputs from a 1.5km convection-permitting configuration of the Unified Model. However, evaluation of these experimental forecasts is currently impossible due to the absence of verification observations of precipitation intensity and lake level winds. This proposed field program would provide the necessary verification information. Also experiments can be conducted with the enhanced observations from the field program to test how additional observations may improve these non-radar-based forecasting and nowcasting systems.

Hypothesis 8. Current kilometer-scale Numerical Weather Prediction forecasts for Lake Victoria are unlikely to reliably predict the timing and location of hazardous nocturnal convection.

Current convective-scale Numerical Weather Prediction forecasts for Lake Victoria are produced by dynamically downscaling global model forecasts using a detailed specification of the local topographic forcing. It is unlikely that this provides sufficient information to enable the NWP forecasts to distinguish reliably between hazardous and non-hazardous nocturnal convection, or to reliably predict the location of the most severe convection.

Hypothesis 9. Assimilation of additional observations into kilometer-scale Numerical Prediction Models will substantially improve the ability of the model outputs to distinguish reliably between hazardous and non-hazardous nocturnal convection over Lake Victoria.

Experiments with using subsets of the detailed observations from the field experiment will enable conclusions to be drawn about the ability of future NWP models to provide useful forecasts in a range of scenarios of future observation availability.

Hypothesis 10. Enhancements to the domain and resolution (both vertical and horizontal) will likely enable improved predictions of hazardous surface weather conditions over Lake Victoria.

Observations from the field campaign will enable case studies to be performed with a variety of Numerical Weather Prediction models at non-operational resolutions so as to determine the optimal configurations for future operational systems.

iv. Dynamics of thunderstorm outflows and wave height

The three most important factors controlling wave height are wind speed, wind duration, and fetch. The short-lived and spatially confined nature of the thunderstorm downdraft outflows creates a highly complex field of wind forcing for the growth and interaction of packets of Lake wave energy. The interaction of these packets is further complicated by the highly variable directions of the downdrafts. The current generation of ocean wave models represents the main aspects of the underlying physics, but is likely to need further development to adequately simulate the wave conditions observed on Lake Victoria.

Hypothesis 11. Interactions between strongly duration and fetch limited packets of lake-surface waves associated with individual thunderstorm downdrafts, can create highly dangerous cross seas that are not well represented by existing ocean wave models.

Observations from Doppler radar, High Frequency (HF) radar [if available] for measuring waves and currents, and in situ instruments on the lake will be used to characterize the duration and spatial variability of the downdraft outflows, to evaluate models of the generation of high energy wave packets on the Lake, and to investigate the nature of the interactions between wave packets generated by different downdrafts. Comparisons with idealized duration and fetch limited wave growth experiments in wave tanks will give insight into the processes at work on the Lake. Improvements to existing models will be developed to provide more realistic forecasts.

v. Development of thunderstorm nowcasting/warning capabilities and societal implications

Hypothesis 12. There is a close relationship between observable features of the wind and/or wave conditions over the Lake and the occurrence of serious accidents, whether fatal or not, to Lake users.

The ultimate purpose of the Field Campaign is to achieve increased resilience of the local community to severe weather on the Lake through increased understanding and through the demonstration of an experimental warning capability. The value of the work is dependent on establishing a relationship between predictable features of the physical environment and the impact on local users of the Lake. The combination of detailed records of the impacts with the meteorological and lake observations from the field campaign will enable the extent of this link to be established, justifying the subsequent application of the project results.

Hypothesis 13. There are signatures in the infra-red satellite images and/or the lightning frequency maps that are associated with the occurrence of current and/or future severe winds near the Lake surface.

A variety of indices can be calculated from the multiple IR channels available from SEVIRI on the Meteosat satellite. Of particular interest are those that have historically been associated with severe convection such as overshooting tops and rapid growth. Clusters of very high lightning frequency, particularly cloud-to-cloud lightning, has also been shown to have predictive capability for severe convection. The observations will be used to establish the degree to which these associations provide a basis for a reliable warning service for the Lake.

Hypothesis 14. Kilometer-scale NWP forecast outputs contain signals that are associated with the occurrence of severe wind events near the Lake surface.

While it is unlikely that direct model output of Lake surface winds is sufficiently accurate to be used directly to formulate warnings, there is a good chance that there are model diagnostics that relate to the mechanisms that research will identify as being key drivers of the severe winds and that can therefore be used to provide a probabilistic indication of the likelihood of severe conditions occurring somewhere in an area and period of time. The observations will enable identification of the most reliable model predictors for severe winds over the Lake.

Hypothesis 15. Data collected from this field program on storm initiation and severity will provide the necessary information for development of a nowcasting system that provides advance notice of hazardous conditions over Lake Victoria.

The overarching goal of this entire project is the development of a nowcasting system to warn Lake users of severe storms that will be hazardous to boats. The intent is that this nowcasting system would be utilized by the Kenya, Uganda and Tanzania weather services. Nowcasting the initiation of storms is needed in order to provide increased warning time for the boating community. Several mechanisms may contribute to initiation of thunderstorms in the LVB and observations are required to determine the factors controlling storm initiation. Previous experience indicates that NWP forecasts of convective storm initiation do not provide sufficient temporal and spatial accuracy and reliability for the boating community to take precautions and avoidance actions. Heuristic nowcasting techniques, which do have some skill in nowcasting storm initiation (Wilson et al., 2004) require scientific understanding of the initiation processes in each location-specific region (Lake Victoria, in this case); thus high resolution observations, detection of boundary layer convergence lines and development of heuristic rules are required for nowcasting storm initiation (Mueller et al. 2003).

Of the many nocturnal storms occurring over Lake Victoria, only a few produce sufficiently intense winds to capsize boats. Similar to the research done on microburst-producing storms, it is important to understand which storms over water have the potential to produce damaging surface winds. Thus for warnings, it will be necessary to nowcast storm severity attributes such as rain intensity, lightning frequency and most importantly, wind velocity at lake level. Lightning frequency within storms and satellite-based estimates of precipitation rate only provide an estimate of current storm intensity not a nowcast of storm intensification or severity in the future. At best they could provide estimate of future lightning intensity or rainfall rate based on the past intensity trends. However, nowcasts based on the trending of intensity have shown little skill (Tsonis and Austin, 1981). Heuristic techniques have shown some skill in nowcasting storm intensity (Wilson et al., 2010) however not in nowcasting specifically for storm outflow strength. Thus a very important part of this field program is understanding factors related to convective storm downdraft strength and resulting surface winds for the predictability of the potentially small number of severe events. There has been considerable work in this area based on previous microburst studies (e.g. Kamburova and Ludlum, 1966, Fujita 1981, Wakimoto 1985, Srivastava 1987, Roberts and Wilson, 1989) that we would make use of in conducting this field program and subsequent data analysis. Implicit in the development of nowcasting techniques for Lake Victoria is the inclusion of reliable and accurate NWP 0-6 hr forecasts of rainfall, winds, and stability. Instrumental for warning the boating community of hazardous weather is accurate prediction of water height based on detected and forecast thunderstorm winds.

Hypothesis 16. A nowcasting system that is able to provide warnings, of sufficient precision and accuracy for Lake users to change their behaviors, can be formulated from a combination of NWP, remotely sensed observations and in situ observations.

On the basis of the understanding derived from research associated with the field campaign, it is expected that a set of forecasting processes can be determined that would enable severe wind conditions from nocturnal thunderstorms to be predicted, given the complete datasets available during the field campaign. Further work will establish (a) that the predictions are sufficiently precise, accurate, reliable and for far enough ahead to convince Lake users to change their behavior when warnings are issued and (b) that the predictions can be made with a subset of the available observations and tools that are, or can be made, available operationally to the countries in this region. The observations from the Field Campaign will provide the basis for determining which information is essential to the provision of adequate nowcasts, and hence which enhancements to the local observational capabilities must be made.

4.4.2.3 Timescales

LVP adopted as a WWRP RDP	2012
HYVIC adopted as a WCRP/GEWEX project	2012
Special session at WWRP/WGNR conference in Rio	2012
Field campaign proposal submitted to NSF	2013
Heads of NMHSs of East Africa meeting	2014
Proposed EOP	2015-8
Proposed IOP	Sep-Oct 2016
Main research activities	2016-9

4.4.3 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 to the Yangtz-Huai River Valleys in middle or late June, the first rainy season in southern China reaches its peak in terms of occurrence frequency and intensity of heavy rainfall, which usually leads to flash floods and waterlogging disasters, causing tremendous losses to lives and properties and can bring huge damages to the economy of the society. In order to better understand the heavy rainfall during the first rainy season in southern China and to improve the capability of numerical weather prediction (NWP) for heavy rainfalls, the “Southern China Monsoon Rainfall Experiment” (SCMREX) is planned.

4.4.3.1 Selected Challenges

To improve the forecast skill of the heavy rains, it is desirable to explore the reasons for convection initiation and formation of convective clouds, as well as the processes and conditions for the development, intensification and upscale organization of the convective clouds. The relevant scientific questions are broadly as follows:

(1) In terms of convection initiation, what determines its timing and location? What are the roles of the LLJ, low-level shear line, and vortices? What role does the cold air play? What are the roles of the underlying surface (i.e., mountains, coasts)? What is the role played by the convection initiation in forming clouds and precipitation?

(2) In the respect of upscale growth and organization of convective clouds, why can the convective clouds grow? How are they organized to form MCSs, and through what dynamical and physical processes? What are the roles of the internal circulations of the

convective clouds and the environmental factors, respectively? What roles do the warm rain and ice-phase cloud microphysical processes play? How does their relative importance vary with the clouds' evolution?

(3) Regarding the internal structure of convective clouds and their relations to surface rainfall, what are the horizontal and vertical distributions of microphysical properties (hydrometeor phase, type, and size distribution) within the interior of the convective clouds and MCSs? How do these properties evolve during the life cycles of the clouds / MCSs? How are the microphysical properties of the clouds related to the thermodynamic fields and dynamical circulations of the clouds themselves and of their environmental atmosphere? How are the properties of the clouds and atmosphere aloft related to rainfall at the surface?

4.4.3.2 Selected Challenges

The specific objectives of this project are as follows:

1) Microscale features and processes of convective clouds
By combining the to-be-collected observational datasets, mesoscale reanalysis, and high-resolution modeling: To investigate the microscale structures of the convective clouds at southern China, i.e., properties of hydrometeors and flows in the interior of the clouds, and how they evolve; To understand the processes that govern evolution of the microscale properties of the convective clouds, focusing on the roles of the mesoscale thermodynamic and dynamic conditions of their environmental atmosphere and the interactions between the ambient atmosphere and the clouds.

2) Properties and processes in the PBL
By combining the to-be-collected observational datasets, mesoscale reanalysis, and high-resolution modeling: To analyze the 3D dynamic and thermodynamic structures of PBL; To reveal interactions between PBL and convection; To investigate topographical effects on PBL and thus convective systems.

3) NWP Model physical schemes for cloud-resolving modeling of the southern China heavy rainfall
To evaluate the state-of-the-art physical schemes in models, the cloud microphysical and PBL schemes in particular, through comparing between the observations and simulations; To refine the schemes and even develop new schemes for better modeling of heavy rainfall in southern China at the explicit-deep convection scale (i.e., cloud-resolving scale).

4) Data assimilation techniques for short-term forecast of the southern China heavy rainfall
To improve the technology of error estimate and assimilation of various observational data; To identify the dominant observational elements for developing comprehensive analysis and quick integration systems; To develop 3D cloud analysis technology to integrate multiple types of observations from satellites, soundings, radars and other ground-based observations; To develop and improve the technique and methods for short-term forecast of heavy rainfall events in southern China.

5) NWP model evaluation for QPF in southern China
A number of NWP models will be run in real time during the field campaign. The advanced data assimilation technique and real-time radar data assimilation will be performed for model comparisons and the regional ensemble NWP will also be conducted for the region during the campaign. Detailed in-depth evaluation will be performed during and after the field campaign using the to-be-obtained observational data sets. Based on the evaluation results, more studies will be conducted to improve at least parts of the models in terms of QPF in southern China.

4.4.3.3 Timescales

The field campaign for SCMREX was planned for April to June 2013.

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

TOMACS proposed RDP: a very highly instrumented study of severe weather in the Tokyo area of Japan coupled with studies of socio-economic impacts and responses. Builds on a domestic project, 2010-2015. We have decided to utilize some areas of TOMACS (e.g., studies on extreme weather with dense meteorological observations, and the development of nowcasting/prediction systems) in order to conduct an international testbed study for deep convection by proposing a RDP project relating to the WWRP working groups of Mesoscale Weather Forecasting Research (WG-MWFR) and Nowcasting Research (WGNR). While taking the IOP periods of the TOMACS field observations and our successive budgetary situation into consideration, we set the RDP period to three years, from July 2013 to June 2016.

4.4.4.1 Selected challenges

Currently, one of the most challenging areas in mesoscale meteorology is the prediction of High Impact Weather caused by mesoscale convective systems via high resolution data assimilation. Understanding the mechanisms of Localised High Impact Weather and the urban effect on their evolution are also important scientific areas. Observational data, nowcasting, and numerical modeling, including data assimilation to reduce the gap between nowcasting and the initial condition of numerical models, are key factors for the prediction of Localised High Impact Weather. As a part of TOMACS, quantitative precipitation nowcasting (QPN) with X-band polarimetric radars are conducted by the Japanese National Research Institute for Earth Science and Disaster Prevention (NIED). The Short Term Ensemble Prediction System (STEPS) owned by the Australian Bureau of Meteorology is also implemented as an advance nowcasting system. As for data assimilation techniques, cloud resolving variational methods (3D-VAR and 4DVAR) and the Local Ensemble Kalman Filter (LETKF) will be applied by the Meteorological Research Institute (MRI), NIED, and the international participants.

TOMACS also aims to implement social experiments on extreme weather resilient cities in collaboration with the related governmental institutions, local governments, private companies, and residents. The social experiments will be carried out in four study fields: (1) rescue services, (2) risk management, (3) infrastructure, and (4) education. The main purpose of the social experiments is to evaluate how the advanced weather information will provide effective warnings, and promote proper evacuations and rescue activities. Before implementing a social experiment, surveys were conducted for each experimental field on what information is appropriate and on the effective means of transmitting such information. For rescue services, real-time and nowcast rainfall data derived from a dense radar network are provided to the rescue staff to evaluate how such information can make rescue activity more efficient. For risk management, forecast information is given to the staff of local governments. Warnings based on this information are informed to citizens experimentally. In the infrastructure experiment, warnings of Localised High Impact Weather are provided to a construction site by a siren and email. For educational purposes, high school students are also incorporated into this project. We use observation and forecast data to raise awareness of Localised High Impact Weather to the students.

TOMACS will exchange information with the Dallas-Fort Worth (DFW) Urban Test-bed through participation of Colorado State University (CSU) in TOMACS. The Dallas Fort Worth Water Research Network (DFW-WARN) is a research and innovation network linking academic researchers, local stakeholders, and industry to address water issues as they relate to urban sustainability, in particular, flood hazard warning and mitigation as well as management and design of urban water infrastructure. The DFW-WARN will leverage the remote sensing assets of the CASA Dallas-Fort Worth (DFW) Urban Test bed, a network of eight X-band, dual-polarimetric radars to be deployed across the DFW region linked to existing in-situ observational networks of rain gauges and stream gauges, and existing radars. The network will provide comprehensive, low-altitude mapping of real-time rainfall rates across the metroplex with unprecedented spatiotemporal resolution and increased accuracy (Wang et al. 2010) compared to the state of the art. By linking these new observations with the appropriate cyber infrastructure, existing multi-sensor databases and hydrologic-hydraulic modeling frameworks, we will enable the development of new scientific knowledge. The goal of DFW-WARN is to create new knowledge that translates to user-relevant information for better policy, and organizational and individual decision-making. This effort necessitates a multidisciplinary approach comprised of natural, environmental, computational, social, policy, and cultural perspectives (NSTC 2007).

DFW-WARN will draw together researchers across disciplines and sectors, with outreach to the cities of Tokyo and Mumbai for cross-cultural comparisons of human behavior and exchanges of other scientific and technical research. Primary academic partners include the University of Texas at Arlington (UTA, lead), University of Massachusetts at Amherst (UMass), Colorado State University (CSU), the University of Colorado at Colorado Springs (UCCS), the University of North Texas (UNT), and the University of Wisconsin (UW). Regional stakeholder partners include the North Central Texas Council of Governments (NCTCOG), the emergency management community in DFW, Vision North Texas, the hydrologic ensemble prediction (HEP) Testbed for the Upper Trinity River and the West Gulf River Forecast Center.

4.4.4.2 Timescales

TOMACS field campaign IOP	2011-3
TOMACS extended observation period	2013-4
Forecasting experiments	2013-5
Social impact experiments	2013-5
RDP international workshop	2013
RDP international workshop	2014
RDP international workshop	2015

4.4.5 Research & Development project for improving the prediction of heavy precipitating systems over the La Plata Basin (LPB-ReD) and Remote sensing of Electrification, Lightning & Mesoscale / microscale Processes with Adaptive Ground-based Observations (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. It is also home to a cluster of rapidly developing urban centres. The mechanisms controlling variability of the convection are not understood, so there is a lack of capability to predict severe events affecting urban populations.

The RELAMPAGO field experiment is currently planned for 2016, involving scientists from Argentina, Brazil and the USA. It builds on the CHUVA campaign centred over Santa Maria in Brazil, in late 2012.

LPB-ReD is planned to use the observations from RELAMPAGO to test convective scale NWP models and their coupling to hydrological prediction models, and to develop process-based nowcasting techniques for implementation in the NMSs of the region.

A kick-off meeting for the project is planned for late 2013 to begin to formulate the objectives and activities of the project.

4.4.5.1 Selected activities

Development of a regional ensemble prediction system for the La Plata area, based on that currently developed for the CHUVA area.

4.4.5.2 Timescales

Kick-off meeting of interested parties:	2013
RELAMPAGO field campaign	2016

4.4.6 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. Specifically, the four interconnected PECAN foci are:

Initiation and early evolution of elevated convection: This component seeks to advance knowledge of the processes and conditions leading to pristine nocturnal convective initiation (CI) and the initial upscale growth into MCSs. This goal will require the observing of mesoscale processes such as diabatically forced deep-tropospheric gravity waves, PV anomalies, and frontogenetic circulations that drive mass convergence and alter the vertical profile of stability and/or shear. Unique to PECAN is the focus on finer-scale processes, such as bores, solitary waves, and parent solenoidal circulations that are known to dominate convergence and CI in the daytime convective BL. Key questions include: How do these disturbances lift layers to a depth sufficient to overcome convective inhibition (CIN) and to surpass the level of free convection (LFC), both at night when the SBL is well-established, and during the evening when the lower boundary stabilizes? How do these disturbances affect turbulent exchanges across the SBL? How does this stabilization produce an environment that facilitates upscale growth of cellular convection and the evolution of the kinematic and microphysical properties of embryonic MCSs?

MCS internal structure and microphysics: This focus addresses the kinematic and dynamical structure and the microphysics of nocturnal MCSs, including impact of storm- and mesoscale downdrafts, rear-to-front flow, SBL erosion, cold pool spreading, bore formation, and the change from gust front based to elevated convection. Both persistently-elevated convection and transitions from surface-based to elevated and vice-versa will be examined. Key questions include: what are the hydrometeor size distributions and proportions of rimed and unrimed ice particle habits, and how well are particle types captured by the WSR-88D particle ID algorithm in MCSs? How can microphysical processes in developing/mature convective and stratiform regions of MCSs drive downdraft circulations that can depress or erode the SBL and produce waves on the SBL and bore-initiating outflow boundaries? What is the relation of the thermal and dynamic characteristics of MCS cold pools to the physics of evaporation and sublimation of particles in dry air in low- and middle levels of the MCSs? How does the vertical profile of latent cooling influence the vertical structure of wave/bore generation?

Bores and wave-like features: This component seeks new knowledge of how the mesoscale environment modulates the initiation, propagation, and demise of bores and other trapped wave disturbances that originate from convective cold pools and seeks to determine the inherent role of these systems in nocturnal MCSs. PECAN aims to detect and understand bores propagating away from their parent cold pool and those that remain an integral part of MCSs. The key question is to what extent bores and/or solitons play a role in the initiation and maintenance of elevated MCSs in the presence of a SBL through lifting isentropic layers to their LFC.

Storm- and MCS-scale NWP: This focus area will use the PECAN observations to improve prediction of nocturnal CI, MCSs, and, more generally, the diurnal cycle of warm season precipitation in the Great Plains. The work will range from MCS-scale cloud-resolving LES models, to convection-allowing NWP models, to coarser-resolution NWP models with convective parameterizations, and to global climate models. To accomplish this goal, the project will require evaluation of operational and research models at high resolution operating in real-time as well as the use of idealized simulations to isolate important dynamical and physical processes. Data assimilation experiments will be conducted to determine the observational strategies required for improving predictions and providing a robust technical basis for recent efforts to develop strategies to improve the national observing network and to build a new-generation national profiler network replacing the 404 MHz wind profilers, such as outlined in the 2009 NRC study "Observing Weather and Climate from the Ground Up: A Nationwide Network of Networks".

The three observational foci require a network of scanning Doppler radars to describe clear-air features, precipitation, and the flow field within, and a network of profiling or volume-scanning remote sensors sufficiently sensitive to monitor wind profiles and detect isentropic/humidity disturbances within and above the SBL, both in clear air and in cloud/precipitation. This network should have an elastic density to sufficiently map out the heterogeneity of the SBL and overlying high-momentum isentropic layers and the capability to zoom in and capture transient and/or propagating disturbances.

4.4.6.1 Selected Challenges

PECAN will have many specific hypotheses through its many proposals to NSF and elsewhere. The four overarching hypotheses (corresponding to the four foci) PECAN will be testing are as follows:

I. Nocturnal convection is more likely to be initiated and sustained when it occurs in a region of mesoscale convergence above the SBL.

II. The microphysical and dynamical processes in developing and mature stratiform regions of nocturnal MCSs are critical to their maintenance and upscale growth through determining the structure and intensity of cold pools, bores and solitary waves that interact with the SBL.

III. Bores and associated wave/solitary disturbances generated by convection play a significant role in elevated, nocturnal MCSs through lifting parcels above the SBL to levels at or near their level of free convection.

IV. A mesoscale network of surface, boundary-layer and upper-level measurements will enable advanced data assimilation systems to significantly improve the prediction of convection initiation. Advances in QPF associated with nocturnal convection will require either greatly improved convective parameterizations, or, more likely, horizontal and vertical resolutions sufficient to capture both SBL disturbances and convection.

4.4.6.2 Timescales

The PECAN field campaign is scheduled for June-July 2015

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

For more than a century, Canada and the US have been monitoring and managing physical characteristics of the Great Lakes. More recently, taking advantage of technological development in atmospheric and hydrological modelling and leveraging increased high performance capacity in computing, Canada and the US have been working in establishing multi-scale atmospheric-hydrological coupled modelling systems.

The hydro-meteorology of the basin is characterised by severe winters, in which the land-sea temperature contrast produces strong convection leading to severe winter weather conditions around the lake borders; a major flood and flow hazard during the spring melt season and severe summer convection. The basin is a key international water transport artery, for which flows must be carefully controlled. It contains many large cities and industrial areas that are vulnerable to weather disruption. It is also a major location for leisure activities with their associated weather risks.

The programme aims to develop an integrated modelling capability 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 programme has the capacity to contribute to most of the hazards focussed on by HIWeather, but with a particular emphasis on Disruptive Winter Weather. The work will cover all of the science themes of HIWeather, but will contribute particular to the Multi-Scale modelling theme in the area of coupled modelling.

4.4.7.1 Selected Challenges

- demonstrate the capacity for improvement to weather and hydrological forecasts of a coupled atmospheric-lake-ice-waves-hydrological numerical prediction system
- demonstrate that such environmental prediction systems have direct applications to the forecast and management of water levels and discharges in the Great-Lakes –St Lawrence system and ecosystem management
- develop and evaluate specialized forecasting products and information packages to allow the community of users to take advantage of new knowledge to assist decision-making on time-scales ranging from real-time nowcasting (for weather and hydrological forecasting) to monthly and annual (for the surface water system).

4.4.7.2 Timescale

tbd

4.4.8 Other opportunities currently being planned or sought

- HYMEX: a ten year programme of high impact weather studies and experiments around the Mediterranean.
- Opportunities for a joint experiment with HEPEX involving coupled atmospheric-hydrological prediction of flash floods
- Opportunities for 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
- Opportunities for a winter weather experiment, possibly in collaboration with the YOPP in the PPP project and/or with the snowstorm and freezing rain components of the Finnish Meteorological Institute contribution to the EU RAIN (Risk Analysis of Infrastructure Networks in response to extreme weather) project.
- Opportunities for 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

- 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

- Very different conditions in meteo-modernization and in variant degrees of scientific knowledge within WMO member countries. Development of comprehensive and advanced training documents on new techniques of High Impact Weather forecasting.
- Dynamic behaviour of urban flooding is very specific and depends on the test sites. How can be made sure that what is valid for one case study applies to another? Flash floods are rare, urban flooding even more so,

4.5.2 Selected Activities

- FDP programmes on high impact weather and training courses towards different trainees.

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 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 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 more rapid response to provide relief for victims of HIWeather 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 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

- Developments of proper verification methods for high resolution model products, and for severe weather elements.
- New verification strategies based on more intelligent use of observations or verifying (re) analyses?
- Comparing in-situ with satellite imagery
- Verification of events across different testbeds may depend on underlying data sets, interpretation, etc.

4.6.2 Selected Activities

- Assess the validities of exist verification methods for High Impact Weather in high resolution conditions and make improvements
- Use novel data assimilation methods to provide accurate spatio-temporal analyses of meteorological fields and hazards (rain/snow amount, flooding, heat duration, wind distribution). Couple these new analyses with novel verification metrics. In particular, neighbourhood verification techniques are important with predictability on the small scales being only a few hours at best. Quantitative satellite-derived metrics for scoring the structure of tropical cyclones are being devised; could extend these metrics to other types of weather systems.
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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 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

- Impact forecasting requires very detailed knowledge on spatio-temporal distribution of vulnerability and exposure and understanding of the physical processes as well as response pathways. EG, impact next to a kindergarden and hospital will be different, flooding of basements of houses is not the same as flooding tube stations; Impact linked to duration of exposure

4.7.2 Selected Activities

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.

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.

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, LWEC
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 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 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:

- National Governments and International bodies that will sponsor and fund implementation of the advances achieved in the project
- National Meteorological and Hydrological Services (NMHSs) who will deliver the improved services enabled by the programme
- Emergency Response, Business & Media organisations are the bodies that will initiate and/or carry out the mitigation actions prompted by the new services
- 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 project Task Team will 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 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

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 agencies and participating institutions