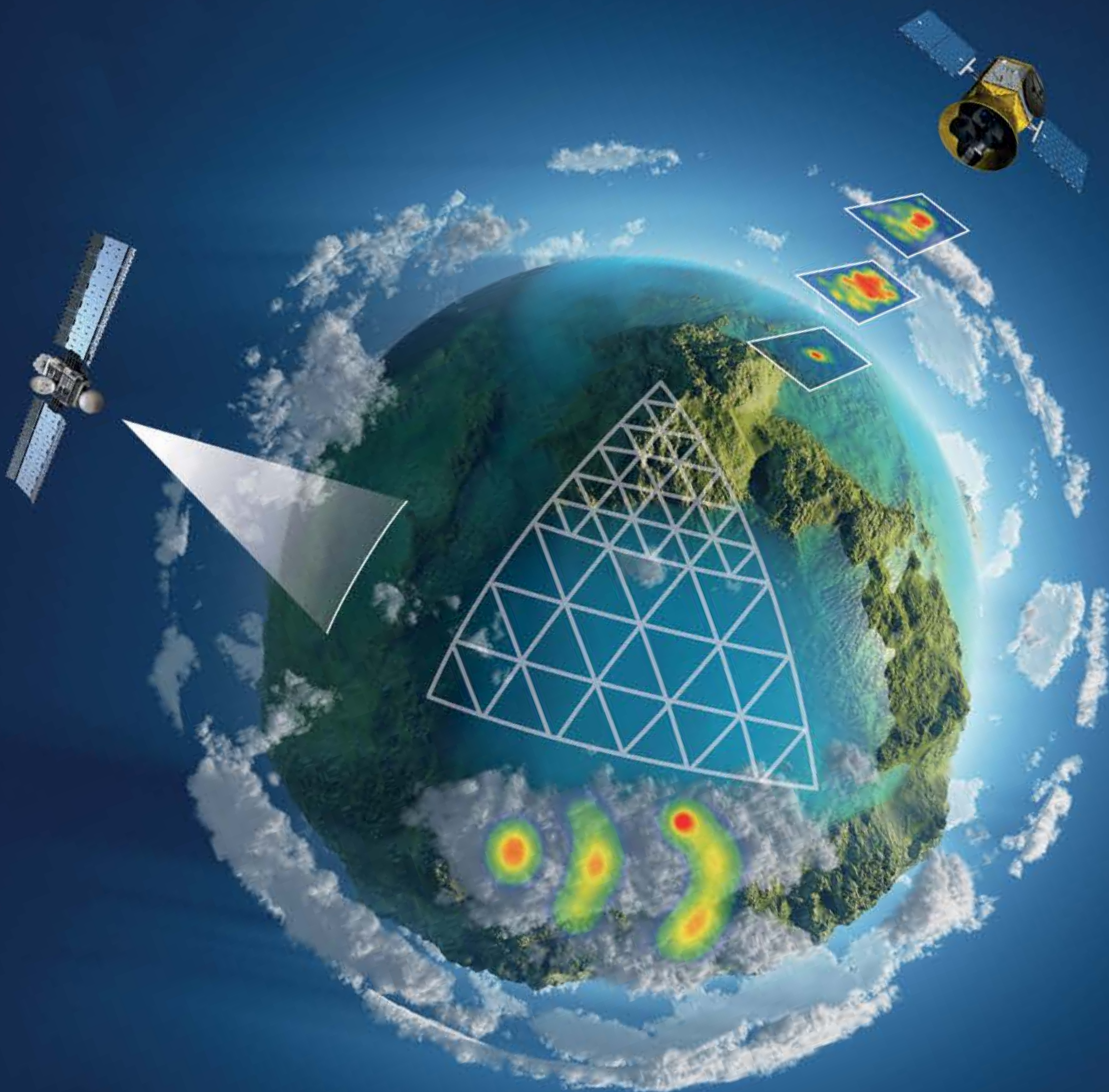
WWRP 2016 - 4

Catalysing Innovation in Weather Science:

WWRP Implementation Plan 2016-2023



WEATHER CLIMATE WATER

WORLD METEOROLOGICAL ORGANIZATION

WWRP WORLD WEATHER RESEARCH PROGRAMME

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This publication has been issued without formal editing.

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Welcome

Significant progress has been made over the past decades in advancing our capabilities in weather predictions. Today's 6 day weather outlook is as accurate as a 4 day forecast was 20 years ago. This gives society much more advance warning of weather hazards than before, allowing people to prepare and, thereby, limit the loss of lives and property.

New sources of atmospheric observations, faster supercomputers and advances in weather science together have revolutionized weather forecasting in the latter part of the 20th and the beginning of the 21st century. One significant contributor to this success was "The Observing system Research and Prediction Experiment (THORPEX)", a 10 year programme promoted under the WMO's World Weather Research Programme (WWRP).

The World Weather Open Science Conference 2014 (Montréal, Canada), brought together the entire weather science and user communities for the first time to review the state-of-the-art and map out the scientific frontiers for the next decade and more. As weather science advances, critical questions are arising such as about the possible sources of predictability on weekly, monthly and longer time-scales; seamless prediction; the development and application of new observing systems; the effective utilization of massively-parallel supercomputers; the communication, interpretation, and application of weather-related information; and the quantification of the societal impacts. The science is primed for a step forward informed by the realization that there can be predictive power on all space and time-scales arising from currently poorly-understood sources of potential predictability.

Based on the outcomes of this ground-breaking conference, the Scientific Steering Committee and the Working Groups of the WWRP have developed an Implementation Plan. This guidance on the programme's activities for the period 2016-2023 is developed around four major challenges that have been identified by WMO's Commission for Atmospheric Sciences. The four challenges, High-Impact Weather, Water, Urbanization and New Technologies and planned activities are well aligned with the needs, challenges and results outlined in the WMO Strategy 2016-2019. Therefore, it will be an important contribution to WMO fulfilling its mission to support Members in their work and meeting their commitments.

It is therefore a pleasure for me to introduce the WWRP Implementation Plan 2016-2023, which provides the foundation for continuing the advancement in weather sciences for the benefit of society. I wish to thank all WWRP contributing experts from the WMO Commission for Atmospheric Sciences, as well as reviewers and the broader scientific community, for their key contributions.

(P. Taalas)
Secretary-General

Foreword

Improving countries' capacity to face weather hazards in the context of global change and providing better services to all citizens worldwide are at the heart of the WMO strategy. Science and innovation are prerequisite for achieving these goals. Through the World Weather Research Programme (WWRP), WMO will push forwards the frontiers of weather science, exploring new predictive capabilities, connecting weather and climate communities, and improving all elements of the weather information value chain.

Over the last decades a number of major international research initiatives accelerated progress in weather science. For example, THe Observing system Research and Predictability EXperiment (THORPEX) contributed to a significant increase in weather forecast skill over the past 10 years. The World Weather Open Science Conference (Montreal, 2014) provided a unique occasion for the weather community to synthesize recent advancements and plan future innovative science. Despite all the advances, major loss event statistics constantly remind us of the gaps between scientific knowledge and its beneficial application to both routine and complex weather-related problems. Determining and reducing these gaps requires a strong interdisciplinary collaboration across different scientific communities.

The WMO's ability to promote innovation will be critical to future development of weather services and, in a broader sense, to accessibility of adequate services to all citizens. We are entering a new era in technological innovation and in the use and integration of different sources of information in a seamless way for improving society's resilience. An enhanced understanding of processes and their inherent predictability should go together with a better comprehension of how weather and climate information influences decision making processes, and with better strategies for communicating this information.

For 2016-2023 WWRP activities will focus on four major challenges, as identified by WMO´s Commission for Atmospheric Sciences: High-Impact Weather, Water, Urbanization, and Evolving Technologies. This WWRP Implementation Plan identifies the key scientific and implementation challenges and the actions required to address them. It emphasizes the need for international and interdisciplinary coordination, and the resulting benefits to WMO members. It provides the basis for the WWRP Scientific Steering Committee and external experts to evaluate the progress made.

Achieving these goals depends critically on partnerships between the global public, private and academic sectors of the weather enterprise. WWRP will link to those affected by weather and related multi-hazards and those charged with the responsibility of managing risks and consequences. Collaborations with key partners, such as Global Atmosphere Watch, the World Climate Research Programme, the WMO Commission for Basic Systems, and the hydrological operational and research communities are essential to address jointly areas of common interest, exploit synergies between the activities and avoid duplication. Furthermore, WWRP will involve and support early career scientists, as its long term success relies on their initiative and enthusiasm to push forward the frontiers of weather science.

This implementation plan provides a framework for the operational and academic research communities in different disciplines and countries to work together to advance weather science for the benefit of society. It is a valuable resource not only for experts related to WWRP but for anyone dealing with environmental prediction matters.

The implementation plan has been developed by the WWRP Scientific Steering Committee together with all the WWRP core projects, working groups, expert teams and the WMO secretariat. We would like to express our gratitude to all those who wrote, provided support and comments, and assisted in editing, proofreading and design. Our special thanks go to Neil Gordon, who combined these many and varied contributions into a coherent and focused plan.

We are very much looking forward to working with the international community to achieve the aims of WWRP.

(Sarah C Jones)
Chair WWRP Scientific Steering Committee

(Paolo M Ruti)
Chief World Weather Research Division

Executive Summary

Weather-related disasters pose a major threat to society, the environment and the economy. As the vulnerability to weather related hazards increases due to climate change, growing population, urbanization and other factors it is imperative to coordinate weather research targeted towards improving forecasts and warnings at international level. The impacts resulting from the underpinning hydro-meteorological events such as heat waves, droughts, floods, landslides, wind storms, landfalling tropical cyclones or severe convective storms are regional or local in nature. Many of these disasters, however, exhibit global connections and interdependencies, not only from a meteorological perspective, but also from an economic perspective. Considerable progress has been made during the past decades in advancing our knowledge and understanding of high impact weather events, as well as in the development of weather prediction and early warning systems that also take into account societal and economic impacts. These advances resulted in lives being saved, damage avoided and economic impacts averted. The WMO World Weather Research Programme (WWRP) has contributed significantly to this achievement – through THe Observing system Research and Prediction EXperiment (THORPEX) and other activities. However, much more needs doing to focus and accelerate future research advances and to achieve the full potential of products and services.

At a time when the impacts of weather and climate are still growing dramatically, it is important to develop strategies to strengthen the achievements in science and technology of the past, keeping in mind emerging and developing challenges.

WWRP promotes international and interdisciplinary research for more accurate and reliable forecasts from minutes to seasons, expanding the frontiers of weather science to enhance society's resilience to high-impact weather and the value of weather information for users. WWRP aims at Seamless Prediction by increasing convergence between weather, climate and environmental approaches. WWRP strengthens academic – operational partnerships and interdisciplinary collaborations, and enhances the role of Early Career Scientists.

As the science is advancing, critical questions must be addressed in order to advance seamless prediction from minutes to seasons. What limits our capability to predict the relevant features of high-impact weather events? What are the potential sources of predictability on monthly and longer time-scales? How can we optimize local and global observing capabilities, quantifying the benefit of existing data sources and exploring the potential of new data sources? How can we utilize massively-parallel supercomputers effectively? Given the novel demands emerging from a diversification of user needs, how do we improve the prediction of impacts and the communication of forecasts and warnings, including their uncertainty? Different regions of the world are faced with different weather-related challenges, have different technological capabilities with regard to observations, nowcasting and numerical weather prediction, and different socio-economic and cultural factors to consider. Meeting these challenges requires strong interdisciplinary collaborations between earth system scientists, social scientists and stakeholders.

With its new implementation plan, WWRP is setting the stage for connecting past achievements in weather science to new societal challenges, seamlessly linking weather research to environmental and climate enterprises. The research strategy towards the seamless prediction of the Earth system from minutes to months for the period from 2016 to 2023 has been developed along four of six emerging challenges that have been identified by WMO's Commission for Atmospheric Sciences (CAS) for the decade to come: High-Impact Weather, Water, Urbanization and Evolving Technologies.

High-impact weather

High-impact weather events have a growing societal and financial impact in a changing climate, on a growing population and the infrastructure it depends upon. Despite significant progress and advances in scientific understanding, monitoring and prediction achieved in recent years, major loss event statistics constantly remind us of the gaps between scientific knowledge and its beneficial application to both routine and complex weather-related problems faced by society. Identifying and effectively addressing these gaps requires close interdisciplinary collaboration between the research community, the stakeholders and the users of weather information. Seamless prediction of high-impact weather events at a wide range of scales (from nowcasting to seasonal prediction) must be improved, with a particular focus on local scales. Appropriate and targeted communication of forecasts and warnings, including the information on consequences of high-impact events, together with user-oriented verification is crucial for capitalizing on the achievements made in prediction of high-impact weather events.

WWRP will:

- Increase knowledge of the physical and social factors limiting the capability to predict, communicate and mitigate the impacts of high-impact weather events; identify how these limitations can be overcome; demonstrate the resulting improvements for specific high-impact weather events at lead times from minutes to seasons, from global to local, for different users in different parts of the world;

- Identify, characterise and quantify analysis and forecast uncertainty using advanced probabilistic methods, and develop corresponding data channels and communication mechanisms which support decision-making under uncertainty;

- Work with different science communities to develop modelling systems that fully integrate the most relevant components of the Earth system; link to and utilise socio-economic models and data to assess impacts;

- Develop end-to-end approaches from meteorology to impacts, in application areas of public health, commerce, industry, transport, water, energy, defence, agriculture, etc., taking into account the varying user needs in different parts of the world;

- Develop methods to verify forecasts and warnings of high-impact weather and its impacts and demonstrate their benefit, with a focus on probabilistic and impact-based methods, including collecting and processing suitable observations (particularly non-conventional weather observations by non-conventional means); assess the impact of near misses and false alarms; and evaluate the end-to-end forecast chain with emphasis on what is of value to the user;

- Connect knowledge and abilities to simulate high-impact weather events at high spatial and temporal resolution with larger scale climate change expertise to more confidently attribute linkages to longer term climate variability and change.

Water

Humanity depends on the availability of fresh water, not only for supporting life, but also for many human activities such as power generation, agriculture and industry. The water cycle is the crucial link between the various Earth system components that govern weather and climate processes. Reliable guidance on water related aspects, on both the weather and climate time scales, requires information from numerical models of the Earth System. However, the appropriate representation of the water cycle and its various processes still pose a challenge to these models. This results from the complexity of processes as well as from spatial and temporal resolution of the models. Enhancing predictive capabilities thus requires improvements in the representation of all phases of water in numerical models, and an enhanced coupling of atmospheric, oceanographic, hydrological and cryosphere models, alongside with a proper representation of atmospheric chemistry. Collaboration with experts and programmes from these fields, in particular on aspects of hydrology and atmospheric chemistry, is important to reach this goal.

WWRP will:

- Improve understanding, observation, assimilation and modelling of the components of the integrated water cycle in its three phases, and its global, regional and local interactions;

- Assess and exploit new in situ and remotely sensed hydro-meteorological observations;

- Improve understanding, observation and modelling of aerosol, cloud and water vapour aspects of precipitation processes, with a view to improved estimation and predictions of precipitation;

- Characterise and communicate how Quantitative Precipitation Estimate (QPE) and Quantitative Precipitation Forecast (QPF) uncertainty translates to hydrological uncertainty (and vice versa).

Urbanization

The population of urban areas will grow significantly in the next few decades, especially in Asia and Africa. Subsequent population stresses and changes in land usage may increase vulnerability even more. Urban environments are particularly sensitive to weather, air quality, climatic conditions and their variability. These aspects impact activities within cities, such as transportation, energy demand, construction, school access, tourism, both directly and indirectly. At the same time, cities are focal points for innovation, driving economic and societal progress locally, regionally and globally. Efforts undertaken in this respect will range from improved modelling, over aspects of communication to the development of best practise guidelines for establishing weather, climate and water related environmental services for cities to support urban planning and safe functioning of cities.

WWRP will:

- Improve understanding and knowledge of the relationship between the urban physical and built environment, the social, behavioural and economic needs of its population, and the requirements for integrated weather-related environmental services;

- Improve observations and understanding of the unique urban physical processes, including dynamical, chemical and hydrologic;

- Develop, validate and demonstrate urban prediction capabilities, toward building urban environment integrated information systems to support decision-making for different applications in different parts of the world.

Evolving technology

Development of computing technologies promotes the capability to run high-resolution and more complex ensemble based numerical weather prediction systems operationally. The projected exascale computing requires the development of systems capable of harnessing the future computing capacity. Data from non-conventional and probably inhomogeneous observations (e.g. smartphones) might play a more and more important role in developing and providing services. Sophisticated data assimilation techniques have to be developed to account for such novel data and achieve the best possible gain for forecast improvement with increasingly complex models. The increasing amount of data, due to high-resolution satellite data and ensemble forecasts poses a challenge for data archiving as well as for the prediction chain, where it has to be assured that new and improved forecasts are available and accessible to a wide range of users in a timely manner.

WWRP will:

- Conduct methodological research (numerical methods, coupling strategies, assimilation methods, observational and model data information exploitation, including post-processing) to ensure that scientific enhancements can be implemented in future forecasting systems, and that systems can provide timely services;

- Enhance access to services (observations, model output, data collection and pre-processing and global models) that require exceptional HPC and data handling, as an enabler for WWRP research;

- Share specialist methods and tools enabling complex modelling systems to be run by a wider community, including beyond WWRP;

- Prepare for exploitation of information from new, advanced observing systems, as well as commodity-technology-based data;

- Inform the design of the future global observing system.

Forward thinking

The WWRP aims for 2016-2023 will be achieved through research activities in the three core projects on High Impact Weather, Polar Prediction, and Sub-seasonal to Seasonal prediction as well as through the scientific guidance, technical advice and coordinating activities of the WWRP Working Groups and Expert Teams. These cover the following key research areas: predictability, dynamics and ensemble forecasting; data assimilation and observing systems; verification; socio-economic research applications; nowcasting and mesoscale research; tropical meteorology research; sand and dust storms; the scientific rationale for weather modification. Activities on numerical experimentation necessary for the WWRP implementation are coordinated jointly through CAS and the World Climate Research Programme. Dedicated research development and forecast demonstration projects allow a focus on the transition to operations, addressing, in particular, specific regional needs. WWRP is steered and progress is evaluated by the WWRP Scientific Steering Committee (SSC) under the auspices of CAS. The activities are coordinated and supported by the World Weather Research Division of the WMO Research Department. The programme will undergo external reviews by independent internationally recognized experts at appropriate intervals. The overall vision of WWRP and the challenges it will address are outlined in this document. An accompanying document further specifies the research activities for a 2-year period and will be updated and reviewed on a regular basis.

The aims of WWRP can be achieved only in partnership with other activities both within the WMO and with external organisations. Collaboration with Global Atmosphere Watch and the World Climate Research Programme is essential to achieve a seamless vision for weather, climate and atmospheric composition. A close cooperation with the WMO Commission for Basic Systems will facilitate both the research priorities and transition of research to operations. In particular, the WWRP implementation plan is the instrument to coordinate much of the underpinning research for the future seamless Global Data Processing and Forecasting System. Furthermore, addressing the challenges associated with High Impact Weather and Water requires the development of links with the Commission for Hydrology and with hydrological research activities outside the WMO.

WWRP will align operational and academic research agendas, create a forum with funding institutions and policy makers to improve the relevance of science in the society and create a network involving developed and developing countries. Through its projects, dedicated workshops and training opportunities, and its strong connection with other programmes and partners, WWRP provides a suitable framework and will play a key role in stimulating research activities and collaborations across a broad range of disciplines. Early career scientists will play a fundamental role in WWRP, in particular through partnership with the Young Earth Systems Scientists initiative.

A clear benefit to WMO members and all citizens emerges through the WWRP activities on facilitating the exchange of scientific and technical knowledge, to make the latest research advances more accessible and usable, especially for developing countries. Dedicated projects foster research advancements in the understanding and prediction of high-impact weather events from minutes to months. Projects that demonstrate the utilization of new achievements in an operational framework are another key aspect that makes the WWRP relevant to all countries. In summary, activities of the WWRP, in partnership with other international organizations, play a vital role in helping all nations strengthen their research capacity and services to better achieve their development aspirations.

The World Weather Research Programme

Mission

The WMO World Weather Research Programme (WWRP) promotes international and interdisciplinary research for more accurate and reliable forecasts from minutes to seasons, expanding the frontiers of weather science to enhance society's resilience to high-impact weather and the value of weather information for users. WWRP aims at Seamless Prediction by increasing convergence between weather, climate and environmental approaches. WWRP strengthens academic – operational partnerships and interdisciplinary collaborations, and enhances the role of Early Career Scientists.

About

As The Observing system Research and Predictability Experiment (THORPEX) concluded in 2014, the first World Weather Open Science Conference (WWOSC-2014) was held in Montreal, Canada. This major conference highlighted that global change and increasing societal and economic demands on weather-related information for numerous applications pose new challenges. This encouraged WWRP to renew its implementation plan, which will guide the WWRP activities from 2016-2023.

This scientific WWRP Implementation Plan (WWRP IP) outlines the overall vision of WWRP and the suggested activities to address the challenges. An accompanying document (WWRP IP – 2-year detailed plan) provides more detail on specific plans and measures of progress of a 2 year period and will be updated and reviewed on regular basis.

Short historical background on WWRP

The World Weather Research Programme was established in 1998 to address the growing societal impacts of high-impact weather events through advances in prediction research identified and developed by scientific working groups and projects focused in specific high priority areas. As an international programme of WMO, WWRP both helps initiate international and national research projects related to weather prediction and allows them to function more effectively. WWRP activities are overseen by WMO's Technical Commission for Atmospheric Sciences.

Since its foundation WWRP has initiated, endorsed, and facilitated numerous international research activities whose scientific challenges have required a critical mass of effort. WWRP's first Research and Development Project, the Mesoscale Alpine Programme (1999) had aimed to improve forecasts for atmospheric and hydrological processes over mountainous regions. The Sydney 2000 Forecast Demonstration Project (FDP), which supported the Sydney 2000 Olympics, aimed to demonstrate the capability of modern forecast systems at that time, and to quantify benefits in providing a real-time nowcast service, especially within an urban environment. The Olympic Games provide important examples of regularly-scheduled, internationally significant events during which there is a very high potential for impacts of severe weather to affect many people. Since the Sydney Olympics FDP several Olympic FDPs have followed, each reflecting state-of-art advances in weather science and services at local to regional scales. Moreover, tropical meteorology research activities have played a pivotal role in developing several regionally focused projects since the beginning of WWRP. The quadrennial International Workshop on Tropical Cyclones (IWTC) provides an important platform for coordination and exchange among researchers and forecasters.

In 2003, WMO established an international atmospheric research and development programme, **Th**e **O**bserving system **R**esearch and **P**redictability **Ex**periment – THORPEX (Parsons et al. 2016). As a major 10-year programme, THORPEX built upon the highly successful 15-year Global Atmospheric Research Programme (GARP) initiated in 1967. While GARP focused on clarifying critical but poorly understood aspects of atmospheric dynamics, which eventually led to significant improvements in the accuracy of weather forecasts, the primary goal of THORPEX was "Accelerating improvements in the accuracy of 1-day to 2-week high-impact weather forecasts for the benefit of society, the economy and the environment". THORPEX provided the essential framework for strong international collaborations in research into dynamics, predictability, and data assimilation, in major field experiments, in the exploitation of observation technologies and the development and use of ensemble prediction techniques. THORPEX fostered increased cooperation between the academic research community and National Meteorological and Hydrological Services (NMHS). Major achievements of THORPEX include addressing the potential of targeted observations through field campaigns, improved understanding of dynamical processes, developing and evaluating new data assimilation techniques and increasing the value of large multi-model ensemble prediction systems through the THORPEX Interactive Grand Global Ensemble (TIGGE) database. Progress has also been made in facilitating the development and application of new and improved verification methods to assess and enable improvement of the quality of weather forecasts, and in the provision of nowcasting information and mesoscale predictions.

The first World Weather Open Science Conference (WWOSC-2014) was held in Montreal, Canada to mark the achievements of THORPEX and define the future research agenda for seamless prediction of the earth system (Seamless Prediction from Minutes to Months, WMO-1156, 2015). This major international conference, the first of its kind for the weather research and operations community provided a critical basis for evaluating the current state of weather science and provided a vital stimulus for setting future research directions. This was accomplished by bringing together the broad weather research community with social scientists and end users from a range of perspectives to examine the rapidly changing scientific and socio-economic drivers of weather science. Experts reviewed the frontiers of knowledge, discussed the state-of-the-art and the future evolution of weather science, and emerging environmental services and their corresponding research needs.

The Commission for Atmospheric Sciences (CAS)

The mission of CAS is to support research in atmospheric science in order to reduce and mitigate disasters related to natural hazards, protect the environment and enhance understanding and response to environmental change. For fulfilling its mission, CAS promotes, coordinates and facilitates research in atmospheric and related sciences to advance understanding and prediction of atmospheric processes. It facilitates the effective transfer of knowledge and technology from research to operations. CAS is also in charge of coordinating the activities of the Commission with relevant WMO bodies and promote cooperation between WMO members, international scientific organizations, environmental institutions and other scientific groups.

During the 16th Session (2013) of the WMO Commission for Atmospheric Sciences, a set of six emerging societal and technical challenges and opportunities were identified for the decade to come. Four of these challenges – High-Impact Weather, Water, Urbanization and Evolving Technologies - clearly fall within the scope of WWRP. Facing these emerging challenges, WWRP now enters an era that will require developing new and stronger collaborations with key partners, WMO programmes and international initiatives. Sharing expertise and partnering to meet common objectives will be essential to address emerging societal challenges, and will benefit all who are involved. Past WWRP advances will be built on and extended through the working groups, expert teams and the three new core WWRP projects: the Sub-seasonal to Seasonal Project (S2S), the Polar Prediction Project (PPP) and the High-Impact Weather Project (HIWeather). Each of the projects will help to promote weather research towards achieving increased societal benefits from advances in weather science.

This new implementation plan summarizes key elements of the WWRP strategy to address the four major societal and technological challenges identified. The plan provides both a broader and longer term vision for the future of weather-related research and collaborations with key partners, as well as some concrete milestones on specific activities and actions to be updated regularly over a moving 2-year horizon.

What WWRP does

Weather prediction has achieved immense progress during the last few decades, driven by research, the availability of an increasingly sophisticated technological infrastructure that incorporates ongoing advances in telecommunications, computational and observational systems, and by the growing expectations of users of weather information. Due to scientific and technological advances, forecast t skill from 3-10 days ahead has been increasing by about one day per decade: Today's 6-day forecast is as accurate as the 5-day forecast ten years ago (Figure 1). THORPEX significantly contributed towards achieving these forecast advances. So today, high-quality probabilistic 5-7 day forecasts can be issued regularly. Such forecast improvements have led to lives being saved and avoidable damage and economic impacts averted. But much more needs to be done to achieve the full benefits that can be realized from products and services provided by the Weather Enterprise.

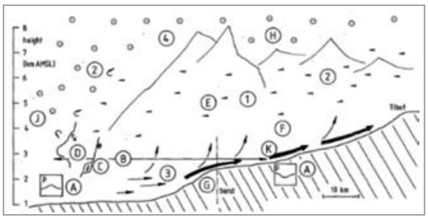
In some cases, predictive skill now extends beyond 10 days. This lead time provides an emerging capability to give advance early warning that can help to anticipate and potentially reduce consequences of high-impact weather events. At shorter lead times, more detailed forecasts of the structure and timing of weather-related hazards are becoming increasingly skilful. The concomitant development of ensemble methods now provides improved statements on the probability of occurrence for specific events, a key variable for numerous decision-making systems. Partly because of these advances, user needs have greatly diversified, and now routinely encompass broader environmental prediction products, such as air quality and hydrological predictions.

This progress has been made possible by research advances and technical developments contributed by operational centres, academic partners, providers of surface- and space-based observations and the computing industry. Through international initiatives led by WWRP, such as THORPEX and Research & Development and Forecast Demonstration Projects (see Figure 2), the WWRP in partnership with other international organizations plays a vital role in helping all nations strengthen their research capacity and services to

The Weather Enterprise

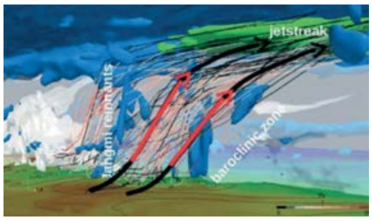
The weather enterprise is a well-established and successful partnership comprising global public, private and academic sectors, with common goals. There are new opportunities emerging to develop this partnership further that will enable the whole enterprise to grow and produce more accurate and reliable weather forecasts. The urgency to do this comes from the need to be even more effective in saving lives and protecting infrastructure because of vulnerability to weather hazards in a changing climate.

Groundbraking research achievements



GARP Publication Series No. 27

1967-1982: Global Atmospheric Research Programme (GARP). Groundbreaking achievements in process understanding, development and usage of observations and advancements in numerical modelling capabilities.



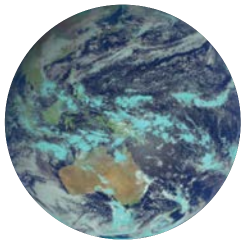
Grams et al., QJRMS

2005-2014: The Observing System Research and Predictability Experiment (THORPEX). Outstanding contributions to prediction of high-impact weather and tropical-extratropical-polar interactions, and to optimized use of observation, ensemble methods and society's use of weather information.

Improved observations

NASA

1960: First image from low-Earth orbital weather satellite TIROS 1. Launch of Meteosat 1 (ESA) and HIMAWARI 1 (JMA) in 1977



JMA, CIRA/NOAA-NESDIS

2015: Launch of latest HIMAWARI 8 (JMA), equipped with very high resolution instruments. Full disk: every 10 min, up to 500m spatial resolution

Increasing computer power

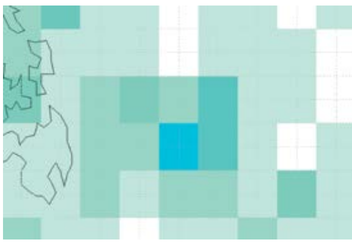
UCAR

1977: CRAY-1 supercomputer operational at NCAR and ECMWF. Computing power: 10% of smartphone

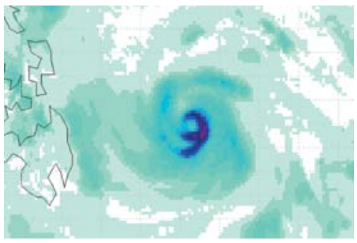
ECMWF

2016: Powerful supercomputers with computing power of ten-thousands of smatphones

Improved forecasts



1981: Global models run at ~200 km resolution. Example: Total precipitation of Typhoon Haiyan (2013) in DWD ICON shown at 200 km resolution



2016: Global models run at ~12 km resolution. Example: Total precipitation of Typhoon Haiyan (2013) in DWD ICON, shown at 12 km resolution

Figure 1: Significant advancements have been made in weather prediction, based on groundbreaking research, advanced process understanding, improved observation capacities, model development and increasing computing facilities

better achieve their development aspirations. WWRP serves as platform for the actions of many players (international organizations, national meteorological services, universities, research centers, donors, civil society) with **unique goals that**:

- Integrate operational and academic research agendas
- Create a forum with funding institutions and policy makers to improve the relevance of science in the society
- Create a collaborative network that includes both developed and developing countries
- Increase involvement of early career scientists from various disciplines

Ongoing contributions from the World Weather Research Programme, through its working groups and in particular through its major international research and development projects are crucial in fostering the necessary collaborations that accelerate progress by:

- Serving as an international focal point for weather research. WWRP initiates, leads, supports or participates in major international field campaigns and weather research projects that are well suited for international collaboration.
- Leading End-to-End Research and Development Projects (RDPs). The RDPs greatly improve understanding of atmospheric processes and their predictions, focusing especially on high-impact weather.
- Promoting dedicated Forecast Demonstration Projects (FDPs). FDPs encourage the utilization of relevant advances in weather prediction research in an operational setting to facilitate the transfer

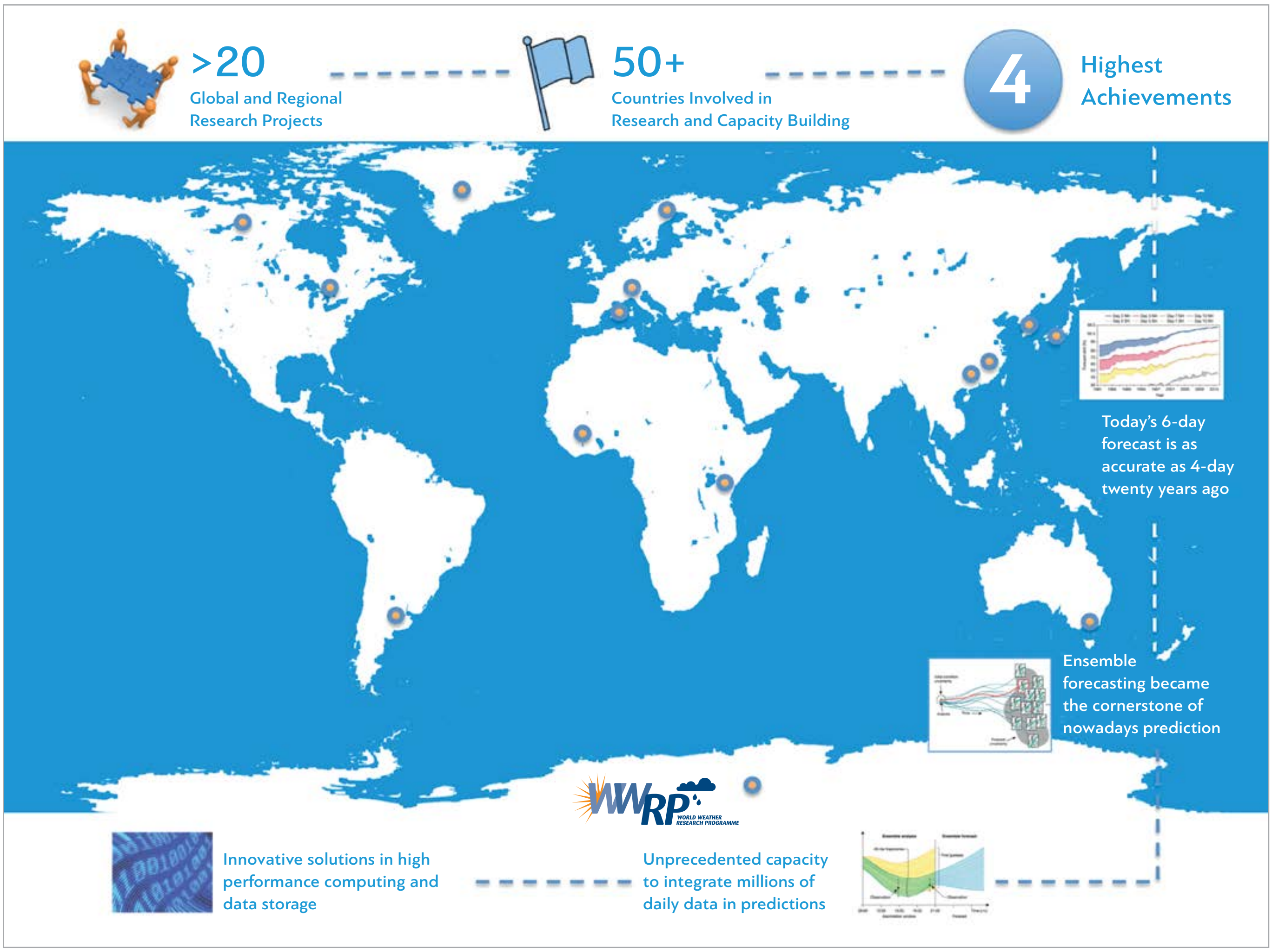


Figure 2: Progress in Weather Science - Projects and major achievements over the last two decades

WWRP definition of seamless prediction

Seamless prediction in the WWRP context considers all compartments of the Earth system as well as disciplines of the weather enterprise value chain (monitoring and observation, models, forecasting, dissemination and communication, perception and interpretation, decision- making, end-user products) to deliver tailor made weather information from minutes to months and from global to local.

of research results into operational practise to the benefit of WMO Programmes and Members.

- Initiating and coordinating data archive centres, such as the THORPEX Interactive Grand Global Ensemble (TIGGE). Making data from operational forecast centres easily accessible supports increased use by the public and research community, increases the value of these data for research purposes and strengthens collaboration between the operational and academic communities.

- Promoting international collaboration and exchange of scientific and technical knowledge. This is achieved through conferences, workshops, publications and training and helps to make the latest research advances more accessible and usable, especially for developing countries.

- Advancing the science of the social and economic application of weather related information and services and review and assist in the development and promotion of societal and economic related demonstration projects.

Through its actions, WWRP demonstrates that improvements in weather science and operational predictions can be accelerated through ongoing international cooperation. This in turn allows weather science to provide unique new opportunities to drive sustainable development in countries that are especially vulnerable to weather-related impacts. At a time when weather and climate impacts continue to grow dramatically, it is vital to develop strategies to continue to strengthen the science and technology to build upon advances in weather predictions and services that have been achieved over the past four decades. These strategies must address critical questions that arise on identifying and realizing potential untapped sources of predictability on weekly, monthly and longer time-scales; building seamless capabilities from minutes to months in advance; assess and exploit new observations; and optimal using local and global observations and emerging new capabilities provided by massively-parallel supercomputers. Other critical challenges involve developing improved methods to better communicate forecasts, warnings and related uncertainties predicting weather-related impacts and addressing demands for novel types of weather information that are emerging from the increasing diversity of user needs. Meeting these challenges will increasingly require strong interdisciplinary interactions and collaborations among physical scientists, social scientists and stakeholders.

To further capitalize on past achievements, three core projects have been developed by the WWRP Working Groups and their associated community expertise. These projects will help address the challenges outlined above and are the key components of WWRP research activities for the next decade. The first, the Sub-seasonal to Seasonal Project (S2S)[1] has been developed and run in collaboration with the World Climate Research (WCRP) Programme. The S2S project aims to improve understanding and forecast skill on sub-seasonal to seasonal timescales, and to promote increased use of S2S information into operational centres and the broader applications community. The mission of the Polar Prediction Project (PPP)[2] is to promote cooperative international research to explore the requirements for and evaluate the benefits of enhanced prediction information and services for various stakeholders in Polar Regions. The High-Impact Weather Project (HIWeather)[3] fosters cooperative international research to achieve a dramatic increase in resilience to high-impact weather, worldwide, through improving forecasts for timescales

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1 http://s2sprediction.net

2 http://www.polarprediction.net

3 https://www.wmo.int/pages/prog/arep/wwrp/new/high_impact_weather_project.html

of minutes to two weeks and enhancing their communication and utility in social, economic and environmental applications. All three projects will benefit from the international exchange and cooperation in an interdisciplinary context that has been developed within WWRP building from THROPEX. These projects also provide excellent new opportunity to further promote collaborative research and knowledge exchange across geographical and disciplinary boundaries under the framework of the WWRP.

Building for the future most effectively will also require increasing the involvement of early career scientists from diverse disciplines. These efforts will support the development of a new generation of Earth system scientists, allowing the community to benefit from their innovative ideas and expertise. WWRP is committed to building the role of young scientists more strongly into its programme and strategy. In collaboration with WCRP and the Global Atmosphere Watch (GAW) Programme, the WWRP supports an initiative of young Earth system scientists (YESS). This resulted in a new vision and approach to increasing the role of early career scientist in shaping scientific directions (YESS, 2016). For the decade to come, YESS has identified four major emerging scientific frontiers that will increasingly influence future environmental science and services:

- User frontier: balancing user-driving demands and fundamental research
- Communication frontier: disseminating knowledge
- Scale frontier: seamless environmental prediction
- Human frontier: need for interdisciplinary Earth system science in the Anthropocene.

Why WWRP is important for society

The world we are living in is changing. An ever-growing population, in particular in densely populated urban regions give rise to population stresses and land usage change. At the same time, urban environments and the infrastructure they are relying on become more and more complex and interdependent, increasing their sensitivity and vulnerability to weather-related impacts. Strong economic development and associated demand on production and transportation are another factor that is highly sensitive to weather and its impacts. New opportunities also arise from the availability of a wealth of information from various sources. The size and complexity of such 'big data' makes data processing with traditional tools and applications nearly impossible. The volume of data will continue to increase in an unprecedented way making the need to capture, store and mine this information increasingly important. At the same time, interconnecting and analysing big data may help reveal undiscovered aspects and new information layers.

To meet these emerging challenges, the weather prediction system of the future must provide accurate, seamless and timely information regarding the location, timing, and structure of weather-related hazards across space and time scales from local to global and minutes to months in advance. Such information will help reduce the impacts of weather-related hazards only if it is translated into products that are useful for end users and communicated in a manner that can be integrated directly into decision-making processes. Regions around the world differ greatly in weather-related challenges, technology for observations and predictions, and socio-economic and cultural factors. These differences must be considered and addressed.

Developing such seamless high-impact weather prediction capabilities requires to understand and quantify weather-related impacts, to estimate and communicate forecast uncertainty, to address diverse stakeholder requirements, to provide actionable information, and to effectively incorporate weather data and information into decision-making processes. This calls for effective collaborations among diverse experts within an interdisciplinary framework that brings together physical and social scientists. Addressing societal impacts will also require working closely with forecast end users to better understand and quantify weather-related impacts, as well as to develop strategies for more effectively communicating information to enable end users to manage specific risks. New technological approaches need to be explored in order to exploit all source of information involving experts from different backgrounds and ways of thinking.

The activities of the WWRP projects, Working Groups and Expert Teams are key contributions to the development of seamless high-impact weather prediction systems. Advances in model development, exploitation and best usage of observations and identification of untapped sources of predictability in the sub-seasonal to seasonal range will help to provide the best seamless forecast information possible. Collaboration and exchange with various stakeholders and users of forecast information will help to assess the impacts of weather events and the information needed for different user groups to mitigate these impacts. Cooperation with social scientists and communication experts will allow improving dissemination of forecast and warning information, in a language and format that meets the recipient's requirements. Through dedicated workshops and training opportunities, and strong connections with other programmes and partners, the WWRP provides the organizational framework necessary for stimulating international research activities and collaborations across widely varying experts and disciplines.

Setting the stage for the developing weather enterprise the WWRP will play an essential international role by connecting past achievements to future advances in weather science to address new societal challenges, with the ultimate objective of seamlessly linking weather, environmental and climate enterprises.

WWRP programme overview

With its new implementation plan, WWRP will ensure the realization of a research strategy towards the seamless prediction of the Earth system from minutes to months. This research strategy is developed to tackle four scientific and societal challenges identified by the Commission of Atmospheric Sciences (CAS, Box 1) (Figure 3): Urbanization, High-Impact Weather, Water and Evolving Technologies.

Each of these challenges comes with specific key research needs that are addressed by all component parts of the WWRP through concrete activities in 18 Action Areas. In order to respond to the challenges in the WWRP Action Areas, expertise is needed in the following key research areas: Dynamics and predictability of weather systems, aspects of monsoons and tropical cyclones, methods of data assimilation and observing systems, numerical experimentation, nowcasting and mesoscale prediction, ensemble methods, verification on a broad scale of forecasts and applications, socio-economic application of weather-related research and the scientific rationale on weather modification. Scientific guidance in these fields, technical advice and an evaluation of progress is provided by the eight WWRP Working Groups and Expert Teams, outlined in Figure 4, under the auspices of the WWRP Scientific Steering Committee.

The Working Group on Numerical Experimentation (WGNE), jointly established by the WCRP Joint Scientific Committee (JSC) and WMO's CAS has the responsibility of fostering the development of atmospheric circulation models for use in weather, climate, water and environmental prediction on all time scales and diagnosing and resolving shortcomings.

Nowcasting and Mesoscale Research Working Group (NMR) aims to advance the knowledge of nowcasting and mesoscale processes and predictability; to promote, and aid the implementation of nowcasting systems within National Meteorological Hydrological Services (NMHSs) and among their end-users, including the potential use of numerical modelling and assimilation of very high-resolution data.

The Societal and Economic Research Applications Working Group (SERA) aims to advance the science of the social and economic application of weather-related information and services and review and assist in the development and promotion of societal and economic related demonstration projects.

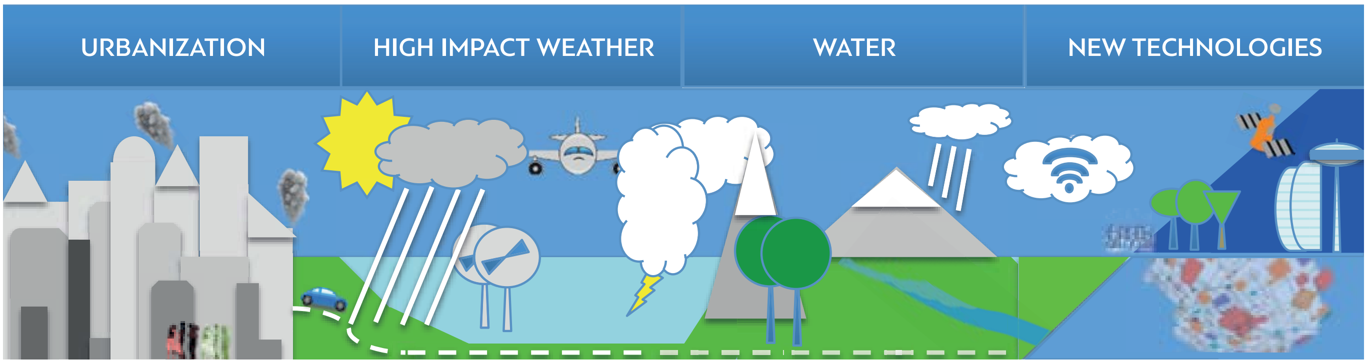

Figure 3: The four challenges identified by CAS that WWRP will address

The Joint Working Group on Forecast Verification Research (JWGFVR) plans and facilitates the development and application of improved diagnostic verification methods to assess and enable improvement of the quality of weather forecasts, including forecasts from numerical weather and climate models. To collaborate on forecast verification with the WGNE Working Group and WCRP.

The Working Group for Predictability, Dynamics and Ensemble Forecasting (PDEF) aims to advance the science of dynamical meteorology and predictability research, and their application to ensemble forecasting promoting the development of ensemble applications and the transition into operations.

The Working Group on Data Assimilation and Observing Systems (DAOS) aims to provide guidance to the WWRP to optimise the use of the current WMO Global Observing System (GOS). The DAOS Working Group will facilitate the development of data assimilation and observing system methodologies from the convective scale to planetary scales and for forecasts with time ranges of hours to weeks.

The Working Group on Tropical Meteorology Research (TMR) aims to identify and support the research initiatives of NMHSs on tropical cyclones and monsoons, especially in tropical countries generally including collaboration with groups in universities or research institutes, which are likely to lead to societal and economic benefits.

The Expert Team on Weather Modification (ETWM) aims to promote scientific practices in weather modification research through organizing the quadrennial scientific conferences on weather modification.

Members of these working groups are recruited from both meteorological services and academia and are renowned experts in their scientific field. WWRP's research activities to meet the scientific challenges are mainly developed, promoted and executed along the line of its three core projects - the Sub-seasonal to Seasonal Project, Polar Prediction Project and the High-Impact Weather Project.

The WWRP Scientific Steering Committee (SSC) provides the overall scientific guidance for the programme, identifies priorities, makes recommendations for and

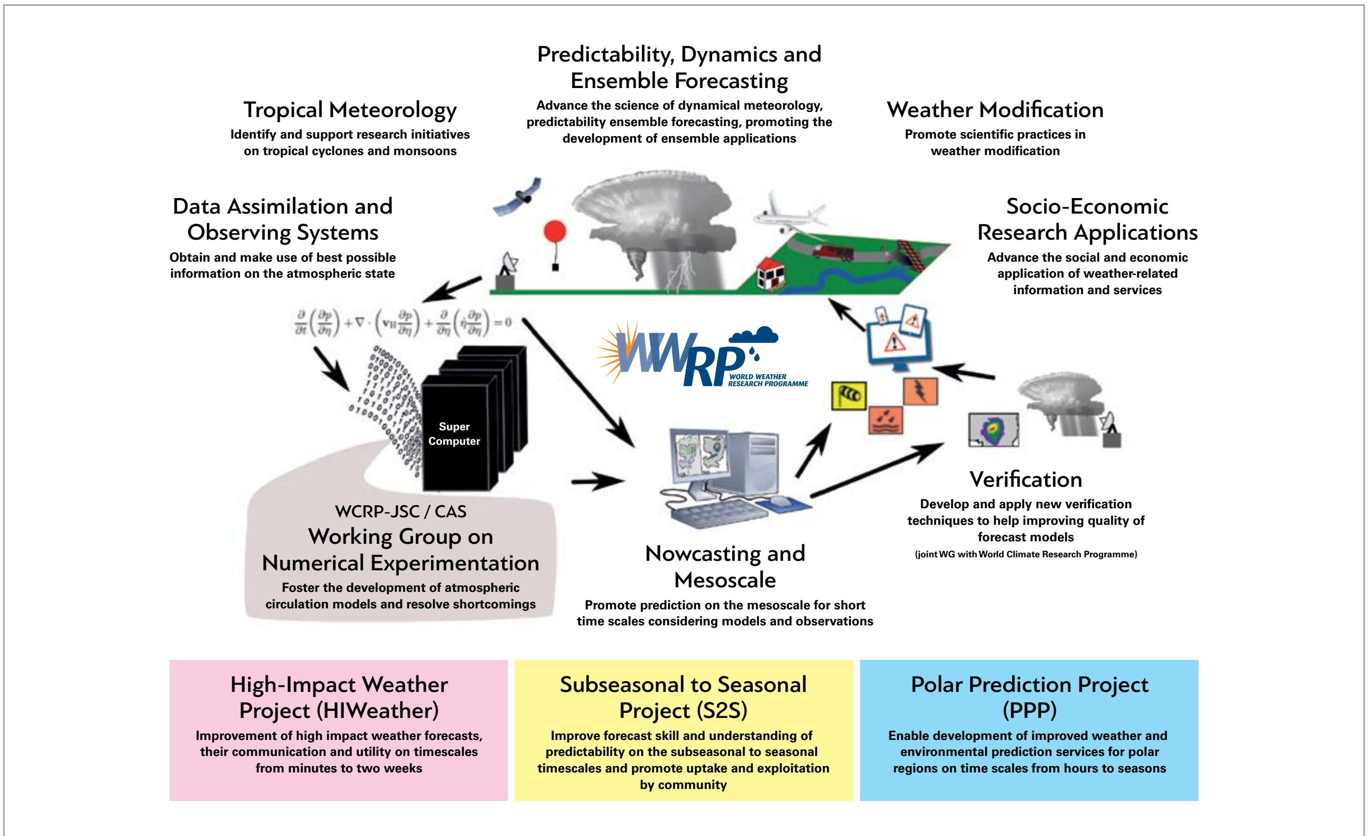

Figure 4: Aspects of the weather prediction chain that are covered by the eight WWRP Working Groups, Expert Teams and three core projects

evaluates the core projects, and the working group and expert team activities. The WMO Secretariat is in charge of facilitating and coordinating the various activities of the WWRP SSC, the Working Groups, Expert Teams and Projects. It is promoting international opportunities and partnerships, favouring WWRP development and ensuring that all countries are involved in science and technology in a concrete way. The activities of the three WWRP core projects are further supported by International Coordination Offices.

The progress and achievements of the WWRP activities related to the IP will be monitored through various processes based on a peer-reviewed approach which focusses on excellence, relevance and impact. This can be done by means of the annual WWRP SSC meetings and/or annual review by governing body meetings of WCRP/GAW/WWRP. Adding to this annual review, a second option could be a four yearly review by an independent panel of experts to oversee the achievements, gaps and challenges of the planned activities.

Anticipating and Responding to Societal Needs for Weather Information

Weather-related disasters pose a major threat to society, the environment and the economy. As the vulnerability to weather related hazards increases due to climate change, growing population, urbanization and other factors it is imperative to coordinate weather research targeted towards improving forecasts and warnings at international level. The impacts resulting from the underpinning hydro-meteorological events such as heat waves, droughts, floods, landslides, wind storms, land-falling tropical cyclones or severe convective storms are regional or local in nature. Many of these disasters, however, exhibit global connections and interdependencies, not only from a meteorological perspective, but also from an economic perspective. Noteworthy progress has been made during the past decades in the understanding of extreme events, the development of weather prediction and early warning systems that also take into account societal and economical aspects. To be useful for society today and in the future, these achievements have to undergo continuous advancements, thereby considering emerging societal and technical challenges. The new WWRP Implementation Plan 2016-2023 is built around the four societal challenges: High-Impact Weather, Water, Urbanization and Evolving Technologies .

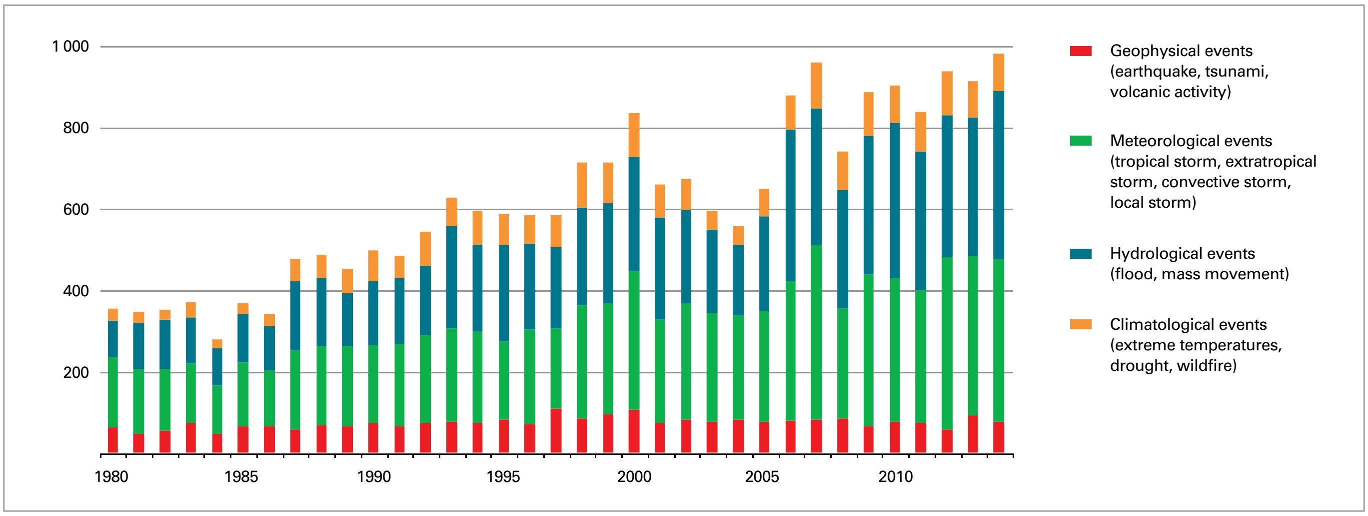

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Figure 5: Major loss event statistics for 1980-2014

Trends in impacts of hazards around the world

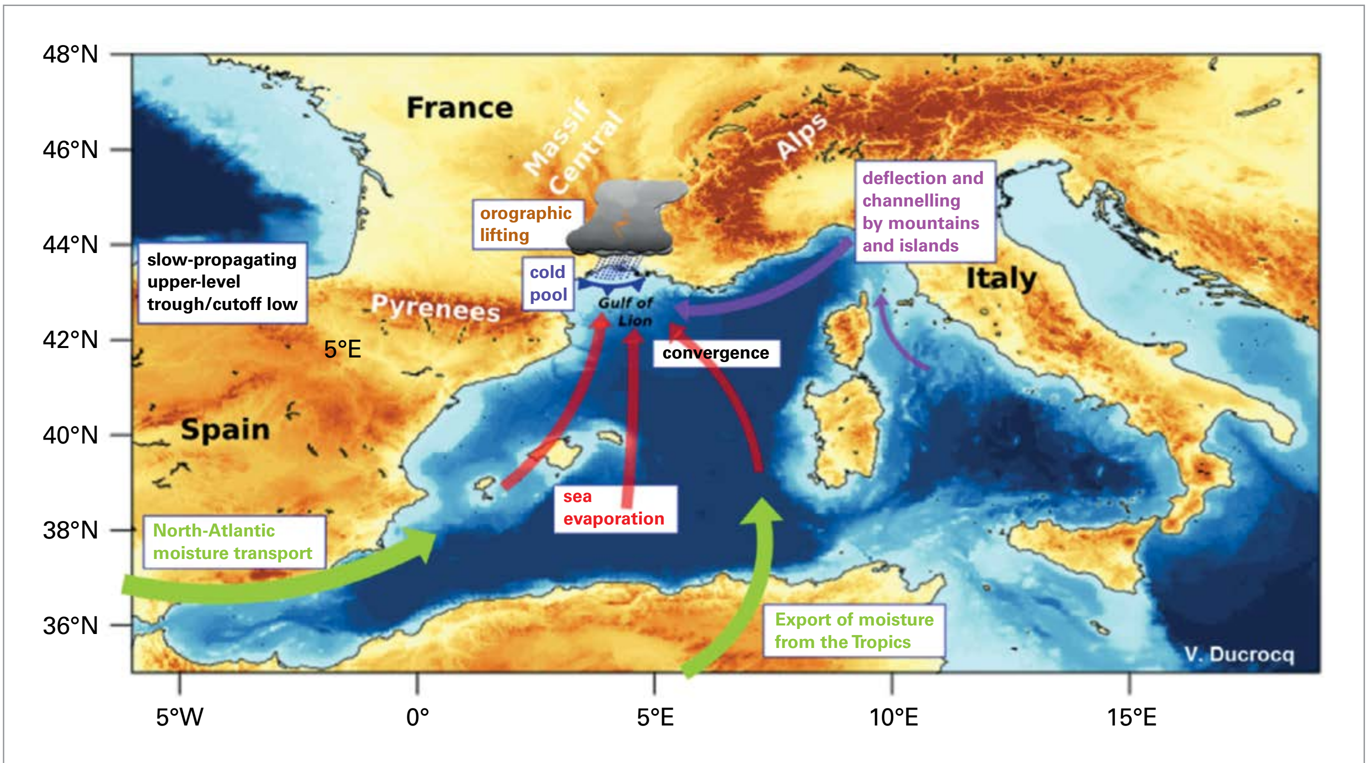
High-impact weather events have a growing societal and financial impact in a changing climate, on a growing population and the infrastructure it depends upon. Significant progress and advances in scientific understanding, monitoring, prediction, computing, telecommunications, and specialized services have been achieved in recent years. However, major loss event statistics (Figure 7) constantly remind us of the gaps between scientific knowledge and its beneficial application to both routine and complex weather-related problems faced by society. Identifying and effectively addressing these gaps requires the weather communities from governmental services, academia and the private sector, together with social and interdisciplinary scientists, to work in close collaboration between those affected by weather and related hazards and those charged with the responsibility of managing risks and consequences.

Seamless prediction of high-impact weather events at a wide range of scales (from nowcasting to seasonal prediction) has to be improved, with a particular focus on local scales where decisions need to be made. Thereby, high-resolution coupled modelling approaches will help to address the consequences of high-impact weather on a local scale and provide information required for decision-making. Appropriate and targeted communication of forecasts and warnings, together with user-oriented verification is crucial for capitalizing the achievements being made in prediction of high-impact weather events.

Water stresses

The water cycle is the crucial link between the various Earth system components that govern weather and climate processes. Humanity depends on the availability of fresh water, not only for supporting life of creatures and nature, but also for many of human activities. Water is a crucial resource for power generation, agriculture and industry. Abundance or scarcity are hence often at the core of weather- and climate related disasters, such as floods and storm surges on the one, and droughts and water shortage on the other hand. Global change due to population growth, availability of resources and climate change may further strengthen these issues.

A variety of processes make the water cycle a very complex regime. Energy exchange due to phase changes of water directly feeds into weather systems and has an impact on climate. Humidity, the presence of water



"Seamless Predictions from minutes to months", WMO, 2015

Figure 6: Complexity of the water cycle

in liquid and solid form, along with the availability of aerosols and the process of droplet nucleation in clouds link the water cycle also closely to aspects of atmospheric chemistry.

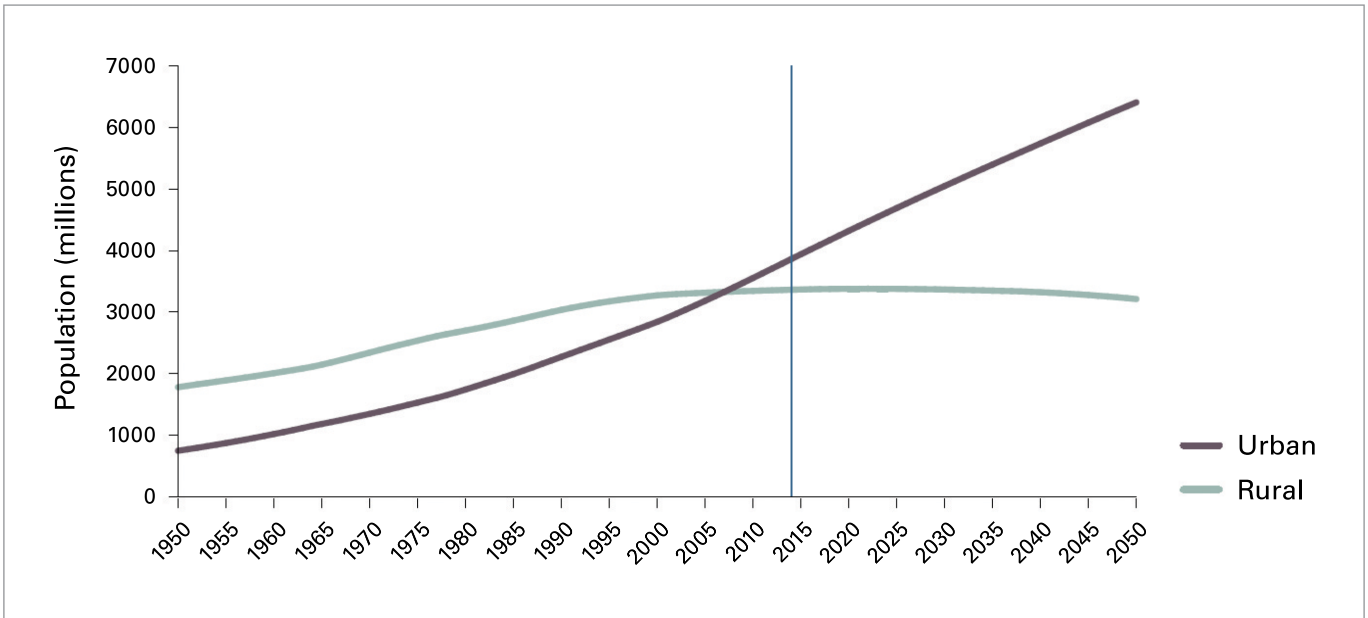
Despite its importance, the appropriate representation of the water cycle and its various processes still pose a challenge to numerical models of the atmosphere. This results from the complexity of processes, which partly has to be addressed through assumptions, as well as from spatial and temporal resolution of the models. To provide reliable guidance on water related aspects, on both the weather and climate time scales, information from numerical models is essential. This requires improvements in the representation of moist processes in numerical models, and an enhanced coupling of atmospheric, oceanographic, hydrological and cryosphere models, alongside with a proper representation of atmospheric chemistry. Collaboration with experts and programmes from these fields, in particular on aspects of hydrology and atmospheric chemistry is important to reach this goal.

Urbanization

From now until 2050 most population growth is expected to occur in cities and towns, especially in Asia and Africa, giving rise to population stresses and land usage change which may increase vulnerability. Urban environments are particularly sensitive to weather, air quality, climatic conditions and their variability. These aspects have profound direct and indirect impacts on activities within cities, like transportation, energy demand, construction, school access, tourism etc. If the city is of regional, national or even global importance, the impacts may reach far beyond the city limits. Impacts also relate directly to human health and well-being, both acute (e.g. epidemics) and chronic (e.g. respiratory). Increasing urbanization will further rise vulnerabilities to such weather and climate related hazards.

At the same time, cities are focal points for innovation driving economic and societal progress, locally, regionally and globally. Thus cities provide huge potential for mitigation and adaptation to changing atmospheric conditions, and sites where some of the greatest benefits will accrue from enhanced prediction through smarter models, data and climate services.

While urban areas range from extensive conurbations to megacities to large cities to smaller urban areas, these settings have important features in common: dense populations, impervious built surfaces, significant emissions of pollutants, heat and waste, etc. However, atmospheric conditions and forcing factors vary significantly, within as well as between cities. Considerable difference is also found for the needs in service, advice and warning of various stakeholders, like emergency managers, disaster relief organizations, transportation or industries, and the technology and ways of communication they are using. These factors



"World Urbanization Prospects: The 2014 Revision, Highlights", United Nations, Department of Economic and Social Affairs, Population Division (2014)

Figure 7: Development of rural and urban population from 1950 to 2050

must be recognized in the development of weather, climate, water and related environmental services in cities. Efforts undertaken in this respect will range from improved modelling, over aspects of communication to the development of best practise guidelines for establishing weather, climate and water related environmental services for cities to support urban planning and safe functioning of cities.

Rapidly evolving technology

A prerequisite for delivering reliable predictions on a broad variety of time scales is the progress towards a seamless and coupled modelling approach that allows for predictions from minutes to seasons (and even beyond), not only for weather but also for its impacts. Development of computing technologies promotes the capability to run global high-resolution models for operational purposes. The projected exa-scale computing also poses a major challenge to current dynamical cores and requires the development of systems capable of harnessing the future computing capacity.

Data from non-conventional and probably inhomogeneous observations (e.g. smartphones) might play a more and more important role in developing and providing services. Sophisticated data assimilation techniques have to be developed to account for this novelty of data and achieve the best possible gain for forecast improvement with increasingly high-resolution models. The increasing amount of data, due to high-resolution satellite data and ensemble forecasts poses a challenge for data archiving as well as for the prediction chain, where it has to be assured that new and improved forecasts are available and accessible as soon as possible. Rapid advances might also be possible for post-processing of model results, e.g. through machine learning.

Another challenge, but also opportunity is the continuous increase in mobility and development of associated technologies. Proper ways of distributing and communicating forecasts and warnings in a timely manner have to be explored. At the same time ways have to be found, e.g. through appropriate verification and accessibility of such results, to develop confidence in forecasts on the users side, to establish trust in sources of information.

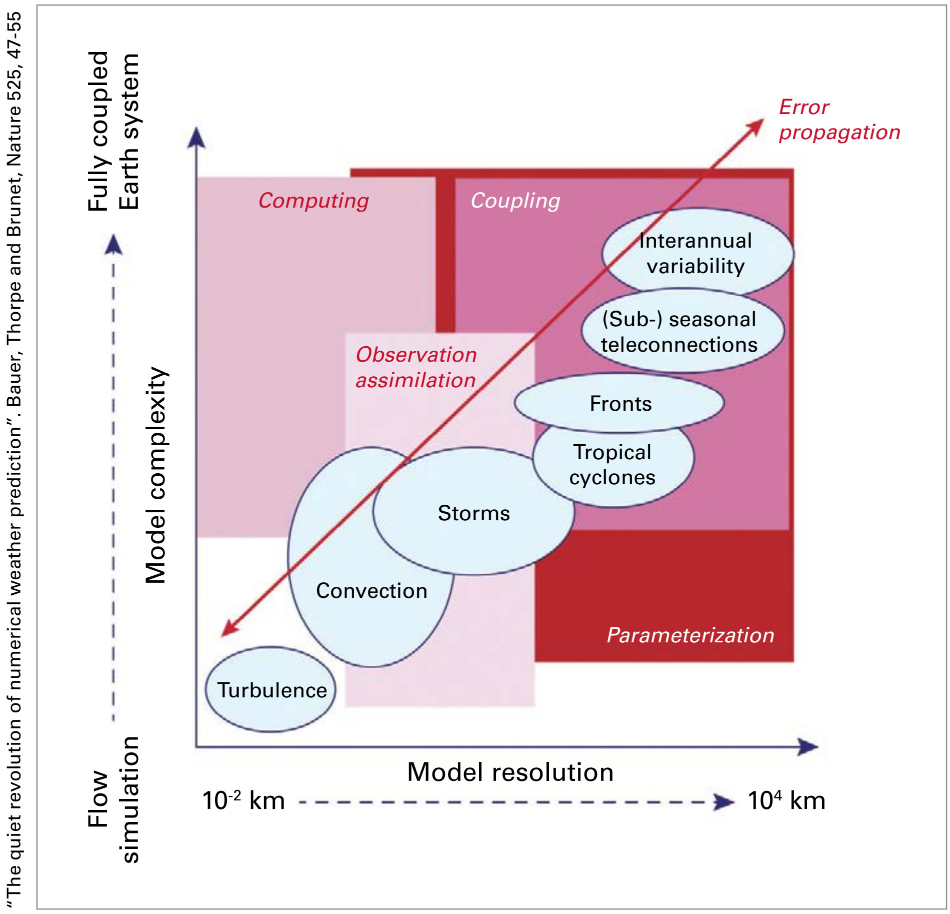


Figure 8: Key challenge areas for NWP in the future

Links to WMO strategic plan and expected results

The WMO Strategic Plan 2016 – 2019 sets the directions and priorities to guide the activities of WMO and its Members to help sustain and advance hydro-meteorological infrastructure, and improve our knowledge of the Earth system through science and technology. It reflects the decisions and route the World Meteorological Congress as supreme body of WMO has agreed upon at its 17th session held in 2015.

The WMO Strategic Plan is developed along three broad global societal needs and emphasizes several key priorities that will help to advance the realization of eight expected results. These results which cover all aspects that WMO is engaged in, will eventually benefit and improve the capacity of all WMO members for benefit of society, economy and environment (Figure 8).

The deliverables of the WWRP and its core projects, based on the activities proposed in the IP, are in line with the key priorities outlined in the WMO Strategic Plan 2016-2019 and are anticipated to help achieving the following expected results

- **Improved Service Quality and Service Delivery:** Engagement of users and decision-makers, research on better strategies for communicating information, forecasts and warnings, and the development of end-to-end approaches from meteorology to impacts that consider vulnerability and risk are important components of WWRP. These will help WMO members to enhance their capabilities to deliver and improve access to high-quality predictions, information, warnings and services in response to user needs and support their decision-making.

- **Reduced Disaster Risk:** WWRP activities will help to reduce risk and potential impact of hazards caused by hydro- and meteorological phenomena through improved forecast capabilities from minutes to months for high- impact weather events, for the components of the water cycle and on the urban scale. Addressing limitations, considering user needs and vulnerability, and increasing the understanding of relevant processes are key components of WWRP that will help to achieve this goal.

- **Improved Data Processing, Modelling and Forecasts:** Research on usage and development of new data

WMO Strategic Plan 2016 - 2019

Global Societal Needs	Key Priorities	Expected Results
Improved protection of life and property	Disaster Risk Reduction	Improved Service Quality and Service Delivery
End poverty, ensure sustainable resilient livelihoods, food security, sustainable access to water and energy, healthy lives, gender equality and economic growth, and combat climate change	Global Framework for Climate Services	Reduced Disaster Risk
Sustainable use of natural resources and improved environmental quality	WMO Integrated Global Observing System	Improved Data-Processing, Modelling and Forecasting
	Aviation Meteorological Services	Improved Observations and Data Exchange
	Polar and High-Mountain Regions	Advance Targeted Research
	Capacity Development	Strengthened Capacity Development
	Governance	Strengthended Partnerships
		Improved Efficiency and Effectiveness

Figure 9: Schematic overview of WMO Strategic Plan 2016-2019 (WMO-No. 1161)

assimilation and modelling capabilities, together with improved understanding of underlying physical processes and their representation in the modelling framework will help the capabilities of WMO Members to produce better information, predictions and warnings to support reduction of disaster risks, climate impact and adaptation strategies.

- **Improved Observations and Data Exchange**: The exploration of new observation techniques and systems, together with work on improving existing facilities, in operational applications and during field experiments or forecast demonstration projects will enhance WMO Members´ capabilities to access, develop, implement and operate new observing systems based on WMO standards.

- **Advance Targeted Research**: International research projects and field experiments conducted in the framework of the WWRP provide the opportunity for WMO Members to contribute to and draw benefits from the global research capacity.

- **Strengthened Capacity Development**: By means of Forecast Demonstration Projects, Research and Development Projects, dedicated workshops and other training opportunities, WWRP provides a means for members to enhance the capabilities of their staff and facilities which will help them to fulfil their mandate.

Links to other programmes/initiatives

The WWRP exists to develop, share and apply knowledge that contributes to societal well-being. This aim is reached by helping to manage weather-related risks to save lives and property, but also by enabling individuals, businesses, and institutions to manage weather conditions and maybe even take advantage of opportunities afforded by them.

Fundamental aspects of this knowledge include an improved understanding of atmospheric processes that give rise to weather phenomena and an enhanced ability to predict weather events and their consequences with sufficient spatio-temporal precision, accuracy and advanced warning to support decisions. Most of the challenges that have to be tackled along this line are not only faced by WWRP but by a variety of other international bodies and organizations (Figure 10). Hence, the necessity of collaborative efforts and work on these challenges is obvious and will be further promoted by WWRP and its activities in the upcoming years.

In particular, some of these activities engage the International Council of Science (ICSU), through its co-sponsorship of the Global Climate Observing System and WCRP and its academic constituency. Strong links exist to the International Association for Meteorology and Atmospheric Science (IAMAS) and the International Association for Hydrological Science (IAHS). For instance, the new ICSU programme Integrated Research on Disaster Reduction (IRDR) and WWRP co-host a joint SERA working group of weather forecast products and services. Beside engagements in working groups, further links to the academic community are provided through the YESS community, a growing international and interdisciplinary network of Early Career Earth System Scientists that is jointly supported from WMO's research arms WWRP, WCRP and GAW.

For improving the understanding of extreme events and their representation in models, and for building a seamless transition from weather to climate predictions, a close collaboration with WCRP, its experts and its Grand Challenges on "Understanding and Predicting Weather and Climate Extremes", "Clouds, Circulation and Climate Sensitivity", and "Regional Sea Level Change and Coastal Impacts" is crucial. Existing synergies when it comes to adaptation to weather and climate extremes, as well as the exploration of new data sources also calls for close collaborations of these communities. In addition, an active physics community is thriving through WCRP's Global Energy and Water Exchanges project (GEWEX), which runs numerous projects typically bringing together observations and large-eddies to global model hierarchies for process understanding and parameterization development, eventually serving both weather and climate communities.

Exchange with experts from WMO's Commission for Hydrology (CHy), UN Educational Science and Cultural Organisation (UNESCO) Hydrology panels or the UN International Groundwater Resources Assessment Center (IGRAC) will also be of importance for WWRP's activities on improving modelling and prediction of the water cycle. Joint efforts could focus on the development of innovative observing techniques in data-sparse regions or the assessment of soil saturation and ground water and assimilation of such data. Progressing research on coupled models, with a focus on urban scales and prediction of impacts, will eventually serve both the weather and hydrological communities and hence is another topic that calls for closer collaboration.

The Working Group for Numerical Experimentation (WGNE) is very active in bringing together modelling centres, sharing progress and running projects to tackle problems of common interest. It also provides a vehicle to link expertise in weather and climate science that is becoming increasingly valuable to both communities. For example, as NWP models move towards coupled oceans, there is clearly much to be learned from experiences with coupled seasonal and climate models.

Urban prediction and air quality are in the focus of the GAW Urban Research Meteorology and Environment (GURME) Project. Joint collaborations and exchange on urban aspects will be strengthened further in the future, extensions into public health, transport and energy sectors are reasonable. The WMO Sand and Dust Storm Warning Advisory and Assessment System (SDS-WAS) is another proof for successful collaborations between WWRP and GAW. GAW's expertise on atmospheric chemistry, aerosols, aerosol-cloud interaction and atmospheric deposition, as well as its strong observational component, makes them an ideal partner for further collaborations. These collaborations may cover the action areas on precipitation processes, observations network and data usage and activities in emerging countries, as well as coupled modelling aspects proposed in this WWRP IP.

Work on improving observations, developing new observing strategies and future global observing systems, but also on aspects of model development and data assimilation calls for establishing joint endeavours of WWRP and WMO's Commission for Basic Systems (CBS). In the quest to promote research focused on improving the accuracy, lead time and utilization of weather prediction and end-user engagement, it is critical to ensure that the developed research applications become part of operational processes. To bridge the gap between research and operations, close collaborations between the CAS and CBS communities was suggested by WMO Congress in 2015. This decision triggered the process for the gradual establishment of a future enhanced integrated and seamless Global Data-Processing and Forecasting Systems (GDPFS). The main purpose of the GDPFS is to prepare meteorological analyses and forecast products and make these available to Members in the most cost-effective way to support research and

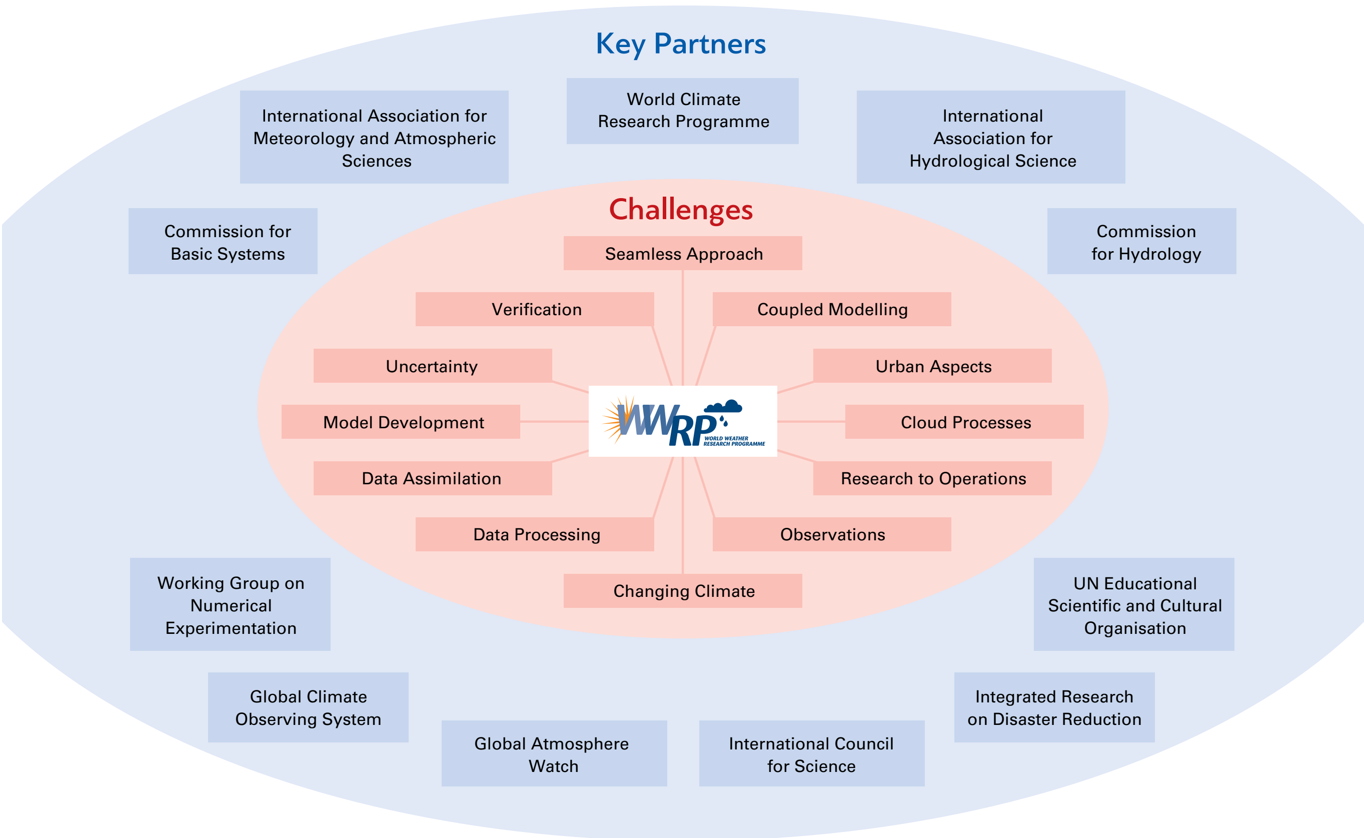


Figure 10: Challenges faced by WWRP and other international bodies and organizations

operational needs. A contribution to the WIGOS 2040 vision, based on WWRP research achievements will support future development of the best possible Earth System Observing capabilities.

The CBS Severe Weather Forecasting Demonstration Project (SWFDP) is successful in strengthening capacity in NMHSs in developing and least developed countries including Small Island Developing States (SIDSs) to deliver improved forecasts and warnings of severe weather to save lives, livelihoods and property. The SWFDP is primarily built on the Global Data Processing and Forecasting System (GDPFS) programme, in collaboration with Public Weather Services (PWS) programme, and the Agricultural Meteorology (AgM) programme of WMO. Strong links between WWRP and SWFDP also already exist and should be enhanced in the future to ensure that research also reach the Members from developing countries.

The WMO Regional Programme (RP) supports the six WMO Regional Associations, which coordinates regional activities by identifying the needs of Members, establishing requirements for regional networks, planning and monitoring progress; organizing regional subsidiary structures and promoting regional partnerships. The cross-cutting RP provides two-way communication between Members and the Secretariat, facilitating expert assistance particularly for developing and Least Developed Countries (LDCs), SIDSs and Island Territories. Through this programme, WWRP can build partnerships with relevant regional and sub-regional organizations, inter-governmental and economic groupings. Success in following this proposed future roadmap of weather and environmental prediction challenges will depend on the collaboration, strength, commitment and excellence of the above-mentioned organizations, working groups and research programmes. The past track record provides a solid base for confidence.

Addressing the Societal Challenges: Plan for 2016-2023

The WWRP IP is developed along four major societal and technical challenges that have been identified by WMO research community. For each of these challenges, a set of Action Areas has been defined. Within each of these Action Areas, selected activities by WWRP Working Groups and Core Projects will help to reach the overall WWRP programmatic goals. To be able to accommodate progress made during the programme or consider external developments, the WWRP IP consists of two documents:

1. **"Catalysing Innovation in Weather Science: WWRP Implementation Plan 2016-2023":** Outlines the broad structure and vision of WWRP for 2016-2013, introduces the four societal and technical challenges, the Action Areas and objectives that are set to meet the challenges.

2. **"WWRP 2-year detailed plan":** Details concrete activities within the Action Areas, together with the needed collaboration. This is an online living document, which will be updated regularly and hence allows to take into account and adjust to advances and developments reached by the research community. It will also include many of the projects and working groups that are also involved in education and training activities. These facilitate progress on research, assist with the transition from research to operations, and provide capacity development for many WMO Members - particularly the less developed. Details of these activities are also given in the separate document.

The following sections discuss in more detail each of the four themes. For each theme there are a number of Action Areas, and for each of those a number of objectives and concrete activities, which have been proposed by and involve one or more of WWRP's projects and working groups.

Figure 11: Structure of the WWRP IP 2016-2023

High-impact Weather: Toward impact-based forecasts in a variable and changing climate

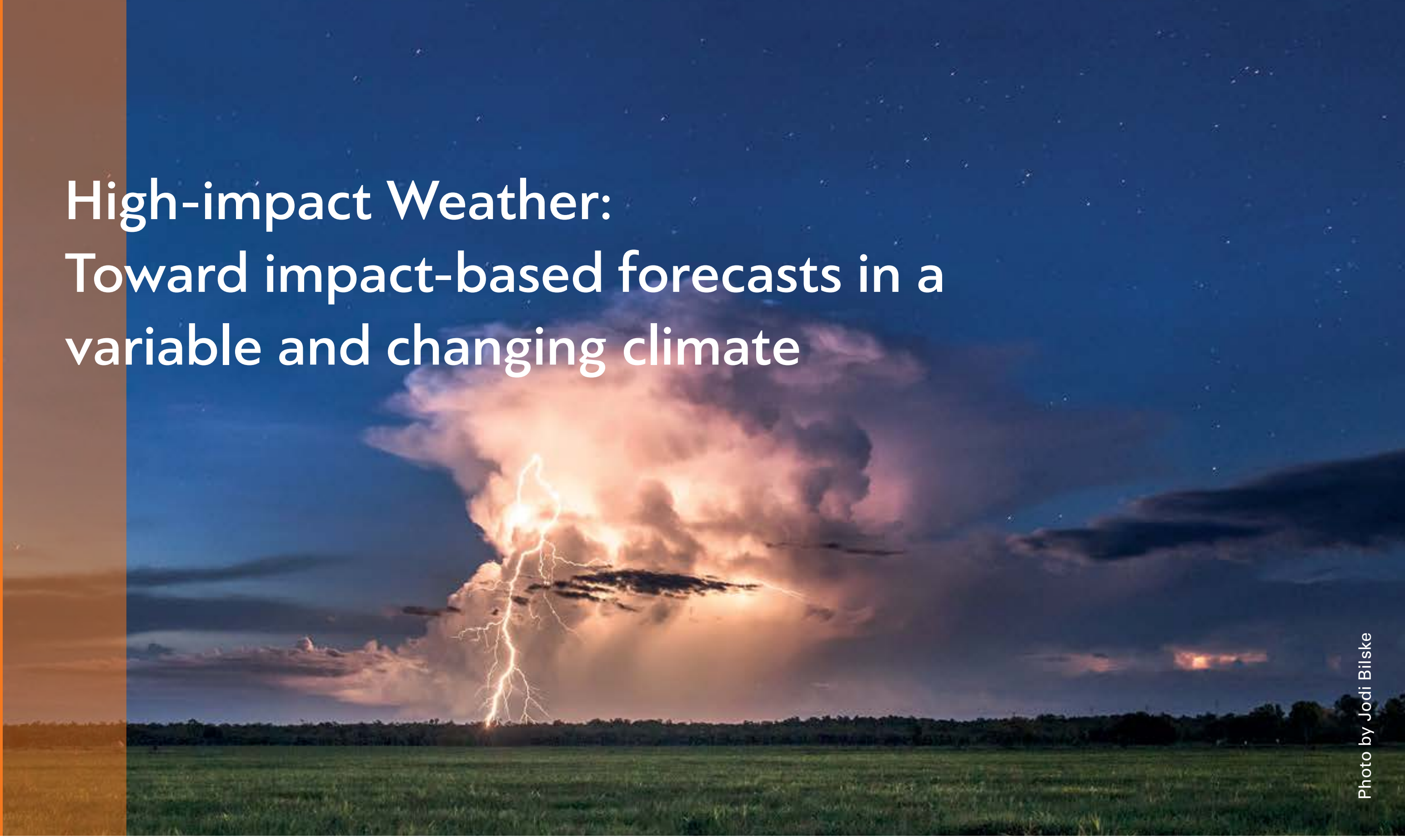


Photo by Jodi Bilske

Despite noteworthy progress in the development of weather prediction and early warning systems during the past decades, high-impact weather remains a serious risk to sustainable development in the 21st Century. High-impact weather is defined as weather that affects quality of life, is economically disruptive, or is life threatening. Depending on the nature of the impact, it can occur on any timescale and lead time, from minutes to seasons.

High-impact weather events increasingly affect Earth's population and the infrastructure it has a growing dependence on, especially given climate variability and change. Accelerated and focussed research is required to improve further the prediction of these events at a wide range of scales, especially at local scales where decisions are made. There is a need, too, to better understand the extent to which high-impact weather events can be attributed to the changing climate.

Work on this Theme directly supports the following strategic priority decided by the 17th World Meteorological Congress in 2015: "*Improve the accuracy and effectiveness of impact-based forecasts and multi-hazard early warnings of high-impact meteorological, hydrological and related environmental hazards from the tropics to the poles.*" It also directly supports delivery of the Sendai Framework for Disaster Risk Reduction global target to "... *increase the availability and access to multi-hazard early warning systems and disaster risk information ...*".

Key scientific challenges

High-impact weather crosses many time and space scales and interacting systems, requiring a seamless approach. Predictability and risk are affected by global and local nonlinear interactions across many different components of the Earth system, leading to diverse impacts on society and the environment. High spatial heterogeneity places significant demands on models, with particularly daunting challenges in modelling topographically complex regions and organized convective systems. Processes responsible for extreme weather are also often poorly understood and modelled. In addition, advances are needed to optimally use new remotely sensed and non-traditional observations to initialise models and verify forecasts and warnings of high-impact weather.

More understanding is needed of the socio-economic implications and decision processes related to high-impact weather. Besides technical challenges in generating probabilistic information, including development of ensemble prediction systems, advances in communication will provide the basis for public and decision-makers to act more effectively on weather-related risks. Integrated approaches will be required to develop coupled models that ultimately extend from physical impacts to effects on social and economic systems.

Research should improve simulations of high-impact events while not degrading simulations of ordinary events. To this end, tests of new high-impact weather prediction and response systems must include a selection of non-high-impact events – including those for which current forecasting systems had predicted high-impact weather with a non-negligible probability.

Key implementation challenges

A key implementation challenge is to identify and prioritise the research needed to respond to diverse stakeholder needs affected by high-impact weather. This will require ongoing dialogue with selected stakeholder groups. Toward this end, it will be vital to bring the impact, weather and climate communities more closely together to learn how to “talk the same language”. Weather and climate scales do naturally come together in the Sub-seasonal to Seasonal Project, and in WWRP’s Polar Prediction Project working with WCRP’s Polar Climate Predictability Initiative.

Developing seamless approaches to predicting extreme events and their impacts also will require strengthened collaborations with weather, climate, and impacts communities, as most extremes are manifested in regional to local weather events, some of which may be made more (or less) likely by climate conditions. There is a need to promote coordination and collaboration among partners in areas of cross-cutting interest, such as in understanding hazard-generating processes, quantifying vulnerability and risk, and in analyses/reanalyses of Earth system components (and their coupling) for research, applications, and services.

In relation to Attribution (AA 6 below) WWRP expertise will be critical in working together with WCRP to identify causes of high-impact events. While attribution requires understanding of climate drivers on larger space scales and longer time scales, observed high-impact events commonly occur on weather space and time scales in which much smaller weather scale processes are vital contributing factors. Critical adaptation decisions affecting countries and regions depend on knowledge of weather events that occur on spatial and temporal scales that are either poorly or not represented in current climate models, but are within the scope of WWRP weather research and modelling. An important question for extreme event attribution is whether current climate models and reanalyses that are now being used are applicable to these small-scale events. The weather community can play a vital role in helping to address this question.

Other challenges include:

- Making sure efforts are not being duplicated (as an aspect of working with other programmes and partners).
- Encouraging the climate community to better connect to national observational data capable of resolving impacts, rather than just relying on global datasets.
- Ensuring availability, consistency and access to observations of impacts (including information on hazard impacts, and vulnerabilities).
- Facilitating the transition from research to operations.
- Enabling a revolution in quantitative risk prediction by industrial and public sector users by working with them to feed appropriate processed data based on ensemble forecasts in near real-time, and providing advice on utilisation.

- More strongly engaging social science practitioners.
- Identifying appropriate communication language and format, medium and frequency for different stakeholders.

Key needs for international coordination

The complexity of research and of prediction systems demands multi-disciplinary expertise, with the "best and brightest" contributing internationally to the necessary research and development. International activities -including WWRP Forecast Demonstration Projects, Research and Development Projects, and the major Projects on High-Impact Weather, Polar Prediction, and Sub-seasonal to Seasonal Forecasting - can put together such teams and accelerate the achievement of what is needed. Coordination and collaboration can be enhanced through WWRP sponsorship of international and interdisciplinary real (and virtual) meetings and conferences.

As one example, weather and climate variability and changes in Polar Regions are a global problem. What happens in Polar Regions affects those that live outside as well as within Polar Regions, due to significant linkages with lower latitudes. Because of the complexity of science and logistical challenges affecting Polar Regions, expertise extends across many countries. International collaboration will be essential to achieving optimal progress.

Where limited national expertise is available, such as for Societal and Economic Research and Applications, international collaboration is needed to assemble enough expertise to make progress. International teams also broaden the opportunities for cross-disciplinary applications.

International collaboration allows a cross-fertilisation of ideas from diverse approaches in different countries, and from diverse modelling systems, tools and techniques. Success in one place can inspire others, and be the source of more generally applicable "best practice". Inter alia, the cross-fertilization, and capacity building, comes from internationally organized workshops and seminars, as well as publications.

Collaboration can be used to assemble new regional and global datasets - for instance, weather radar data, and information on impacts.

And, of course, WWRP will need to coordinate with other international programmes and bodies, including WCRP, IRDR, GAW including GURME, interdisciplinary science communities, relevant WMO Technical Commissions, and Regional Associations.

Resulting benefits for WMO Members

Overall, National Meteorological and Hydrological Services (NMHSs) will be more visible through improved services and involvement with partners and multidisciplinary communities, increasing their ability to attract support, especially in developing countries.

Significantly more WMO Members will be able to use and develop integrated prediction systems, giving NMHSs an improved ability to warn communities of high-impact weather, using better formulated actionable impact statements, warnings and alerts to mitigate loss of life, damage to property, and disruption of commerce. Services will cover many time scales and extend to environmental impacts, being based on integrated and seamless global prediction systems connecting weather and climate, including the WWRP contribution to developing a Global Integrated Polar Prediction System. NMHSs will also be more involved in multidisciplinary or holistic approaches to addressing coupled modelling challenges, giving them more visibility in their countries.

Research and development into coupled modelling will help bring about improvements in forecasts of high-impact variables or fields that are strongly coupled - for example, sea ice forecasts which depend on coupled ice, atmosphere, ocean and land hydrological processes such as river inflow.

NMHSs will be better able to augment deterministic forecasts with ensemble/probabilistic forecasts that provide greater value to users for decision-making, including improved early warnings, based on research and development into the role of uncertainty.

Partnerships with emergency management agencies and others involved in hazard impacts will be strengthened, enhancing the relevance of weather information and more effectively communicating uses for decision and policy making related to risk management. Populations will be safer and have enhanced quality of life through improved warnings of impacts. Economic benefits will be realized from better decision-making based on new impact-based services.

Research and development on verification, particularly of impacts, will support NMHSs moving into impact prediction. Quantifying benefits of weather forecasts and downstream impact predictions will highlight and increase the relevance of NMHSs with government and other stakeholders, and provide clearer and simpler demonstration of the end benefits of forecasts to users. Better understanding the value contribution of components of the end-to-end forecast chain will allow more efficient and targeted use of limited resources. The successful collection of unconventional data will improve situational awareness (current state/analysis and short-term nowcasting) and facilitate improved analyses for short-term dynamical forecasts.

WMO Members will be better able to address commonly asked questions on causes of high-impact events, and to what extent they may be influenced by climate change and variability, and thereby achieve a more confident basis for informing planning and policy decisions for risk management and adaptation. They will have the tools to understand the weather and water impacts of climate change and variability on their respective regions. They will better anticipate the changing distribution (frequency, geographic impact) of high-impact weather events, allowing them to build more sustainable infrastructure.

Action Areas

The Action Areas for this Theme *Address Limitations*, cope with *Uncertainty*, use *Fully Coupled* models, develop *Applications*, apply *Verification*, and assist with *Attribution* of events to climate variability and change.

AA 1: Address limitations

Increase knowledge of the physical and social factors limiting the capability to predict, communicate and mitigate the impacts of high-impact weather events; identify how these limitations can be overcome; demonstrate the resulting improvements for specific high-impact weather events at lead times from minutes to seasons, from global to local, for different users in different parts of the world

Use diagnostic and verification information to identify capabilities and limitations in predictions of high-impact weather at lead times from minutes to seasons.

Through targeted research on specific meteorological processes associated with high-impact weather (e.g. convection, surface interactions, etc.) improve understanding of those processes, and where possible develop the observational, algorithmic and numerical capacity to better predict them.

Through targeted research increase abilities to observe, understand, and predict variability and changes of the coupled air-ocean-ice-land system, and specifically to advance polar region forecasts and services for high-impact variables such as sea ice from hourly to seasonal time scales.

Work with users to more precisely define the weather variables and thresholds that are most associated with the impacts that concern them; develop improved understanding of relevant atmospheric processes and of the relation with modelled variables.

Achieve better understanding of where, when, how and why weather has high-impact, including

how environmental and socio-economic conditions antecedent to high-impact weather events contribute to their high impact, and why some users fail to act appropriately.

Incorporate better understanding of vulnerability and risk in forecasts of high-impact weather.

Increasingly work with social scientists, hydrologists, wave and storm surge forecasters, fire behaviour analysts, and other users of high-impact weather information as science partners to develop more effective hazard forecasts and warnings and improve community response.

Transfer new science on effective communication, including appropriate strategies for different cultures, into operational weather forecasting.

Support operational demonstrations of end-to-end high-impact weather and impact prediction, improved decision support, and evaluation.

Define and develop ethically acceptable methods for capturing and interpreting social media data on human responses to high-impact weather and associated warnings so as to evaluate warnings systems and to support emergency management decisions.

AA 2: Uncertainty

Identify, characterise and quantify analysis and forecast uncertainty using advanced probabilistic methods, and develop corresponding data channels and communication mechanisms which support decision-making under uncertainty

Improve quantitative descriptions of the uncertainty of the initial state, its evolution forward in time, and its propagation into impact forecasts and risk prediction.

Co-design communication mechanisms of uncertainty with users (e.g. emergency management).

Improve the resolution and reliability of ensemble-based meteorological predictions, including through post-processing, and connect the weather hazard probability to the consequent impacts on space and time scales for which decisions are made.

Develop improved diagnostics and verification tools from high-resolution ensembles that assist operational forecasters in predicting and warning of high-impact weather; enabling "warn on forecast" to be more widely used.

AA 3: Fully Coupled

Work with different science communities to develop modelling systems that fully integrate the most relevant components of the Earth system; link to and utilise socio-economic models and data to assess impacts

Improve, develop and assess fully coupled data assimilation systems, including all Earth system components.

Investigate the coupling of numerical environmental prediction models with impact models and observations (e.g. fire spread, river level).

Demonstrate coupled analysis/reanalysis capabilities

Work with social scientists in development of assimilation systems for socio-economic models that will ultimately lead to the coupling/linking of these models with physical models.

Improve the representation of fluxes of heat, moisture, momentum and constituents through the land – sea – ice -atmosphere interfaces, at all time & space scales, so as to reduce or remove the need for corrections at coupled model component interfaces.

Make significant advances with respect to coupling meteorological and hydrological models in particular, to enhance hydrological prediction (will be covered in Water Theme below).

AA 4: Applications

Develop end-to-end approaches from meteorology to impacts, in application areas of public health, commerce, industry, transport, water, energy, defence, agriculture, etc., taking into account the varying user needs in different parts of the world

Improve understanding of the requirements (timeliness, type of data most helpful, etc.) of health, commerce, transport, etc., areas with respect to environmental data and predictions, and of how that information is ultimately used operationally by these application areas.

Facilitate collaborations between meteorological application developers and end users in development of end-to-end applications, with strong user involvement throughout the planning, testing, implementation and continuous improvement stages, ensuring that the most relevant information is produced to support their decision-making under uncertainty.

Gain experience in working with different sectors on specific applications, to contribute to an improved knowledge base within the meteorological community on how to effectively develop end-to-end applications in partnership with users.

Define some well-developed end-to-end examples/ case-studies for service delivery.

Ensure that weather impact research projects include SERA science as an essential component.

Develop cross-domain coupled modelling systems, in partnership with scientists and users from other disciplines, that integrate weather and other data to meet user needs, and evaluate their effectiveness according to user-relevant metrics.

AA 5: Verification

Develop methods to verify forecasts and warnings of high-impact weather and its impacts and demonstrate their benefit, with a focus on probabilistic and impact-based methods, including collecting and processing suitable observations (particularly non-conventional weather observations by non-conventional means); assess the impact of near misses and false alarms; and evaluate the end-to-end forecast chain with emphasis on what is of value to the user

Develop new methods for verifying impact-based forecasts and apply these to hazard impact forecasts and warnings, demonstrating their benefit and supporting their further improvement.

Enable impact data to be shared more easily and widely using mutually agreed standard data formats.

Develop capabilities to use information sourced from citizen observations and other unconventional data for verification and forecast quality improvement.

Ensure that social scientists and social science methodologies (e.g. surveys, analysis of social media data, etc.) are increasingly included in end-to-end evaluation of projects and applications through to end-users, with appropriate planning and resourcing, critical awareness of applicability of methods to specific cases, and that weather scientists improve their skills in these areas.

Complete and validate impact-based forecasting demonstration projects, including examples of both readily quantified and less easily quantified impacts.

Work with the Commission for Basic Systems (CBS) to ensure that user-relevant verification standards are implemented operationally to compare deterministic and Ensemble Prediction System (EPS) accuracy at all time and space scales.

Work with CBS to enhance the international sharing of datasets, both conventional and unconventional.

AA 6: Attribution

Connect knowledge and abilities to simulate high-impact weather events at high spatial and temporal resolution with larger scale climate change expertise to more confidently attribute linkages to longer term climate variability and change

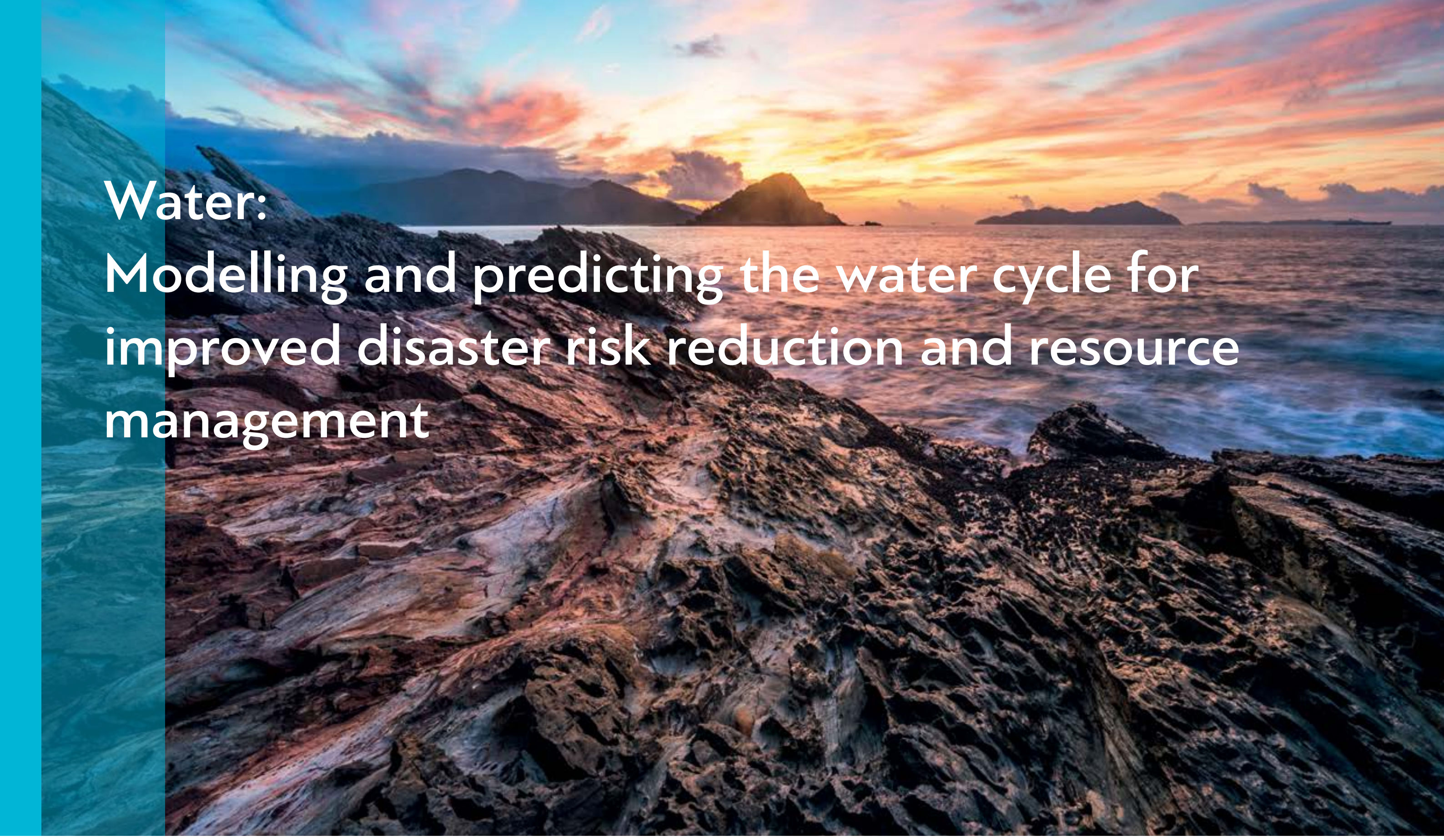
Strengthen coordination of weather and climate scientific communities in areas of complementary expertise through deeper engagement on this critical problem linking weather and climate.

Ensure that weather scientists and practitioners have a better understanding of the climate variability/climate change context of high-impact weather, that the climate community have a better understanding of how climate extremes are manifested as high-impact weather events, and that social scientists are involved in accessing related societal impacts.

Develop a more complete understanding of the multiple factors contributing to high-impact events, and identify how attribution uncertainties related to model limitations may be reduced through improved resolution, process representation or other actions.

Promote and facilitate the use of km-scale process understanding and impact modelling expertise in studies of the impacts of climate variability and change.

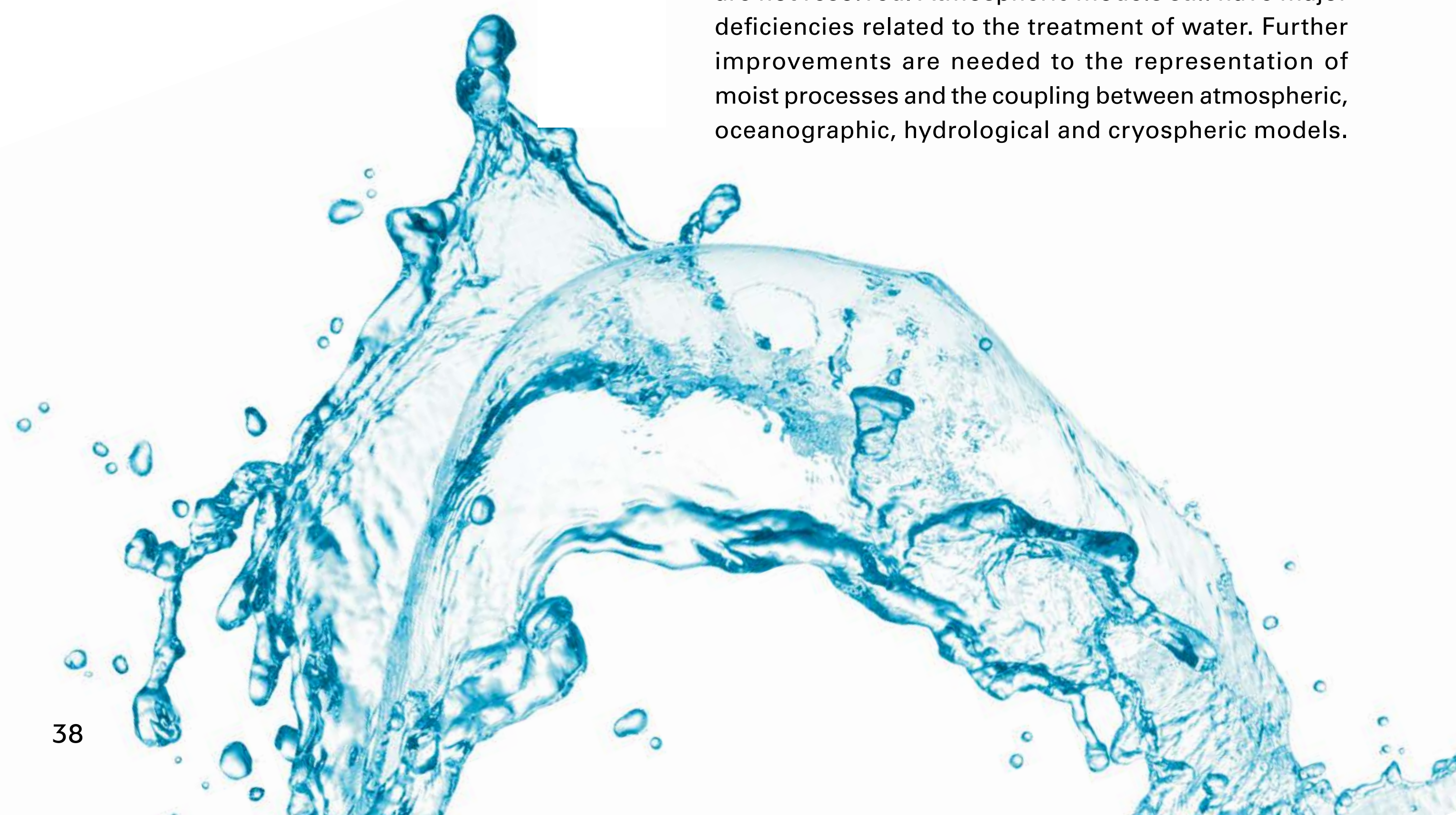
Facilitate the use of state of the art Numerical Environmental (atmosphere-ocean-sea-ice-hydrology) Prediction (NEP) convective scale models in regional climate modelling.



Water: Modelling and predicting the water cycle for improved disaster risk reduction and resource management

The water cycle provides a crucial link between the various Earth system components that govern weather and climate processes. Besides water supporting life, its relative abundance or scarcity is often at the core of weather-and climate-related disasters, such as floods and droughts. Humanity is dependent on fresh water from precipitation for many of its activities, including agriculture and energy generation. Both developed and developing parts of the world are exposed to water stress, and such stresses are likely to increase substantially in the future due to a range of factors affecting both water supply and demand.

Water cycle processes and associated energy exchanges are complex. The phase changes of water involve substantial exchanges of energy that feed into weather systems and impact climate. Furthermore, the numerical frameworks that represent water cycle process in atmospheric models are complex and most processes are not resolved. Atmospheric models still have major deficiencies related to the treatment of water. Further improvements are needed to the representation of moist processes and the coupling between atmospheric, oceanographic, hydrological and cryospheric models.



Key Scientific Challenges

Taking a seamless approach to water involves working across many time and space scales, and many interacting systems, including the cryosphere. Better understanding and modelling of moist processes is needed, including precipitation-generating processes. It is not enough to get the precipitation right; this must be through the correct processes, including the impact on microphysical processes of aerosols, chemistry, electric charge, and the morphology of ice. Understanding the processes better will also enable more informed decisions on the value of weather modification.

Availability of hydrological data, including ground water, and their use in coupled modelling approaches is a necessity to be able to provide forecasts and warnings on extreme events related to water, e.g. river flooding or flash floods, in particular in the urban context.

More understanding is needed of the socio-economic benefits, and decision processes, in relation to the integrated water cycle. Besides technical challenges in probabilistic information and ensemble approaches for the water cycle and impacts, there are many challenges in probabilistic communication of risks and opportunities.

Key implementation challenges

There are challenges to the national and international availability of water-related data, including weather radar data, river and ground-water data, and how they are calibrated, coded, and exchanged. Use of third party observations of rainfall and soil temperature and moisture could enhance moisture analyses and predictions. Data not available in real-time could be used in non-real time for research projects to demonstrate potential benefits.

Working across disciplines always has its challenges including differing language, space and time scales, and user requirements. Others include the development, application and optimal use of advanced remote sensing technologies (e.g. new satellite data), model and data assimilation methodology development, and methods to post-process output from weather and seasonal climate models for input to hydrological models.

Key needs for international coordination

As with weather, water doesn't respect political boundaries, so exchange of data and collaborative international research is needed. Increasingly, this should involve international sharing and exploitation of water related data. International collaboration extends to working together for some locations of the globe (e.g. mountains, Polar Regions) where hydro-meteorological processes are less well understood and represented, and where observations are often lacking. Moist process understanding and characterization are very complex and requires concerted efforts across communities.

National and international collaboration across the weather and hydrology domains can benefit from the experience of countries where this is already well developed. Some research is highly specialised (e.g. the role of aerosols) and expertise can be shared internationally. Satellite systems are inherently international; advances in retrievals or direct assimilation of satellite data can be shared.

WWRP will need to coordinate with, amongst others, WIGOS and CGMS (for satellite aspects); the climate community including WCRP, especially to minimise duplicated efforts; GEWEX; GCW; GAW (and through them to the International Global Atmospheric Chemistry project or IGAC); UNESCO hydrology panels; IGRAC; interdisciplinary science communities; relevant WMO Technical Commissions, including CHy, and CBS for better use of observations and new data sources; and Regional Associations.

Resulting benefits for WMO Members

NMHSs will be able to provide improved services for assessing and predicting precipitation, floods, and droughts on a variety of space and time scales, while strengthening the hydrological components of National Meteorological and Hydro-Meteorological Services. NMHSs and partners in the hydrological domain can enable better decisions when quantitative precipitation uncertainty information is available, and better information will be available to support agriculture and food production.

Improved water resource planning will be enabled in a world that is likely to face increased stress on water resources. There will be greater insight into more effective weather modification.

Action Areas

The Action Areas for this Theme cover the full *Integrated Water Cycle*, assess and exploit *New Observations*, improve knowledge and prediction of *Precipitation Processes*, and consider links to *Hydrological Uncertainty.*

AA 7: Integrated Water Cycle

Improve understanding, observation, assimilation and modelling of the components of the integrated water cycle in its three phases, and its global, regional and local interactions

Improve data assimilation for moist processes and coupled systems (including the land surface and vegetation).

Improve international exchange (together with CBS) and assimilation of weather radar data from all sites globally.

Improve use of remote sensing observations (soil moisture, discharge, vegetation) in land data assimilation systems.

Improve coupled modelling of atmosphere/land/ocean/water; in particular, vertical and lateral exchange processes need to be better understood and modelled.

Improve land surface models in coupled modelling systems to incorporate more hydrological processes; better represent snow; and use higher resolution land use information, including temporal variability.

Together with GAW, better understand and model atmospheric moist processes in all three phases, including cloud-aerosol-radiation interactions, air-sea exchanges, and surface-vegetation-atmosphere feedbacks.

Improve numerical forecasts of catchment conditions through collaboration of meteorological and hydrological scientists.

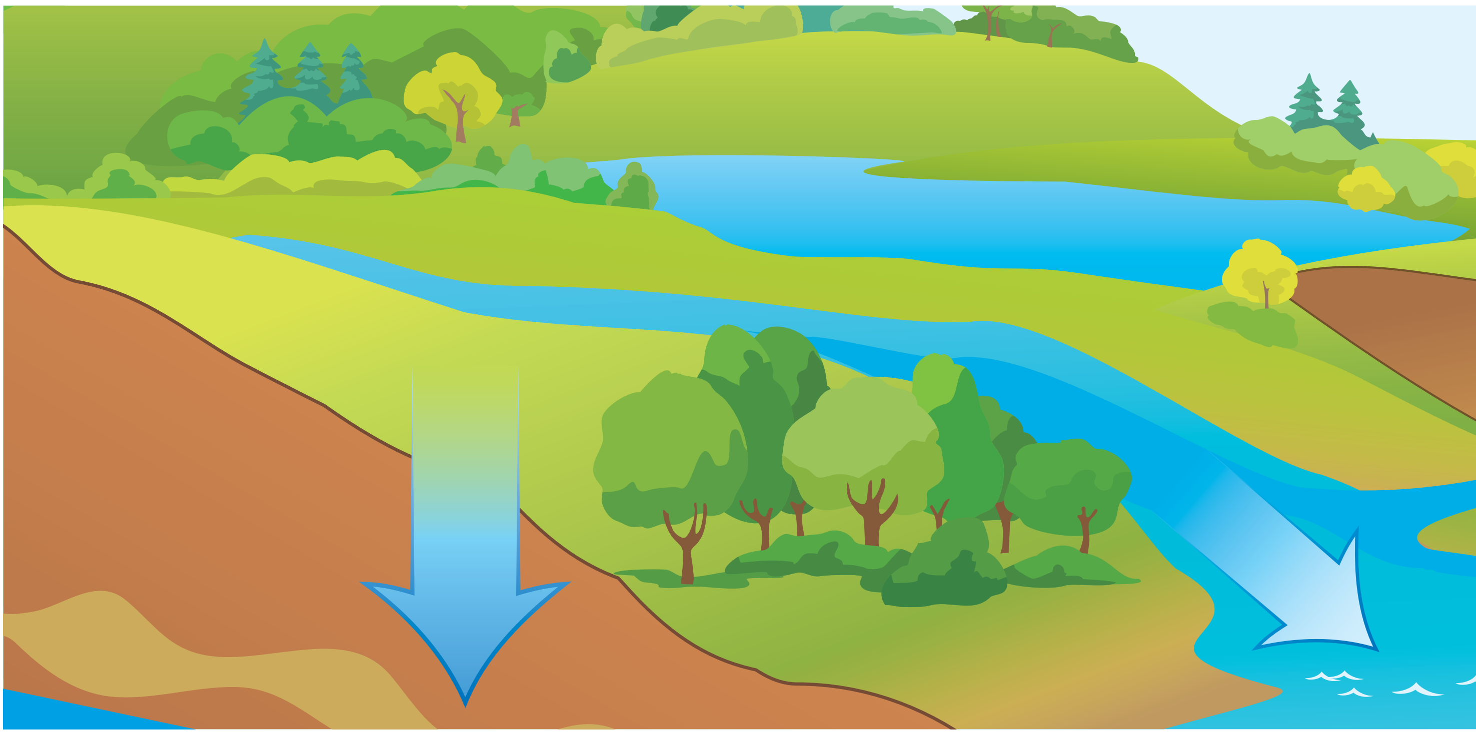
Increasingly use ensemble and probabilistic approaches to provide seamless precipitation and hydrological predictions across time and space scales.

AA 8: New Observations

Assess and exploit new in situ and remotely sensed hydro-meteorological observations

Evaluate the potential of new instruments or opportunities for observation of the water cycle variables (e.g. cloud radar, water vapour lidar, Global Navigation Satellite System data for water vapour/soil moisture/snow, 3rd party networks, ground water).

Increasingly share and process radar and other ground-based remote sensing as regional networks; combine



with in situ and satellite data to improve coverage, accuracy and utility.

Characterise errors in remotely sensed hydro-meteorological observations over most areas of the globe (some regions may yet be too hard, e.g. Polar Regions) and use to inform data assimilation, verification, and user applications.

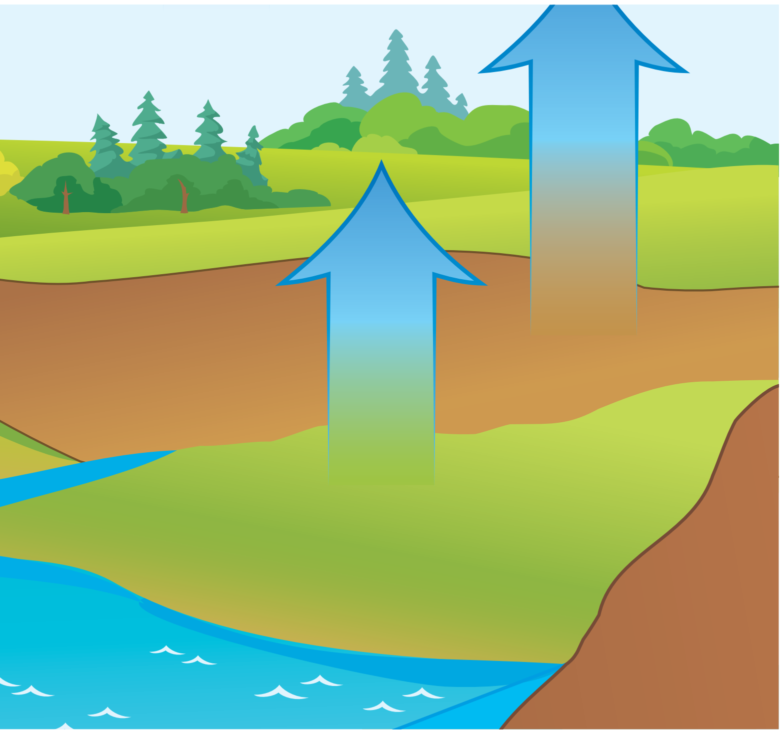
Routinely assimilate observations sensitive to all components of moist processes into numerical models; including through improvements in data assimilation algorithms and moist processes modelling.

Make appropriate use of remotely sensed precipitation observations for evaluation of model precipitation forecasts.

AA 9: Precipitation Processes

Improve understanding, observation and modelling of aerosol, cloud and water vapour aspects of precipitation processes, with a view to improved estimation and predictions of precipitation

In collaboration with GAW improve the understanding of aerosol activation in the atmosphere and how this affects radiative forcing of weather and climate; develop better understanding and modelling capabilities for cloud processes, particularly the distribution and importance of different ice crystal habits and the roles of aerosol and electric charge.



Make improvements to model physics and related data assimilation to better utilise observations of aerosols, cloud, and water vapour in initialising models and predicting convective initiation, rainfall enhancement/suppression, and other precipitation processes.

Develop new/better convective parameterizations for non-convection-permitting models (which remain relevant).

AA 10: Hydrological Uncertainty

Characterise and communicate how Quantitative Precipitation Estimate (QPE) and Quantitative Precipitation Forecast (QPF) uncertainty translates to hydrological uncertainty (and vice versa)

Develop improved estimates of QPE and QPF and their associated uncertainty.

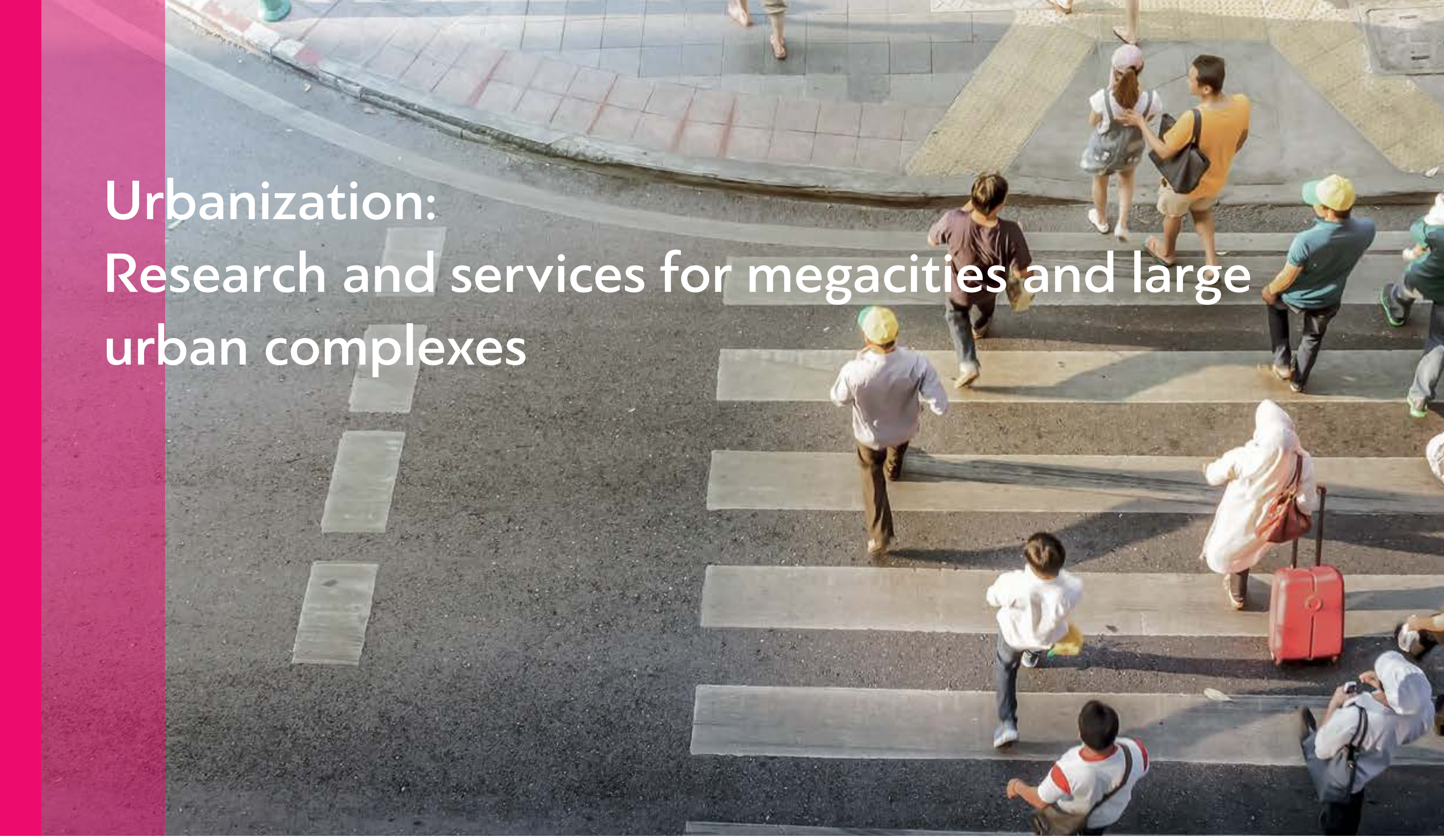
Use ensemble QPE/QPF to drive ensemble hydrological predictions.

Develop and apply effective methods (including post-processing) for downscaling precipitation from atmospheric models to derive more realistic space-time rainfall distributions that are better suited for hydrological prediction.

Use results from sensitivity experiments to different types of QPE/QPF uncertainty (bias, random error, spatial structure, etc.) to develop modelling and post-processing methodologies that improve hydrological prediction on a variety of space and time scales for different applications.

Gain a better understanding and develop new modelling approaches for overland flow from intense precipitation and from river/ocean inundation, including uncertainties due to limited knowledge and resolution of the surface; mobilisation of sediment and vegetation.

Improve streamflow models, especially in respect to their representation of vegetation and sediment and how this should vary between low flow and high flow conditions.



Urbanization: Research and services for megacities and large urban complexes

More than half the world's population lives in urban areas; both the proportion and the absolute numbers will increase throughout this century. High-density populations are especially sensitive to high-impact weather events and degradation of air quality, exacerbated by climate variability and change. These sensitivities arise through the enhancement of extreme events (e.g. flooding, drought, heat waves, storm surges, and air pollution episodes), health impacts (e.g. epidemics, and chronic diseases), and economic disruption (e.g. transportation, tourism, construction, infrastructure and school access).

It is essential to establish capabilities in urban areas for the provision of necessary environmental information for safe functioning of cities. This in turn can profit surrounding areas and set an example for other urban areas or cities within, or outside of, the country. This also calls for a seamless approach to understand and model the urban environment and the physical processes that govern it. Cross-cutting coordination and collaboration is required, as in many cases several wide ranging agencies have responsibilities for providing services that are impacted by weather and climate, as well as other potential hazards.

The overall objective is to help ensure sustainable urbanization in the developing world, through weather and climate resilience. This Theme directly responds to Resolution 68 of the 17th World Meteorological Congress ("Establishing a WMO Cross-Cutting Urban Focus") in which Technical Commissions are requested to "... *define relevant urban activities* ... [and to] .... *request their working bodies to integrate the urban dimension in their activities in a coherent manner*."

Key scientific challenges

Many of the scientific challenges of the Themes of High-impact Weather and Water are also valid for this Theme. In addition, there are unique aspects to urban areas, including the need for building and street resolution information; coping with inhomogeneities; data assimilation of measurements which are not representative of larger scales; use of high-density crowd-sourced data; unique atmospheric chemistry and interactions; and the need for an improved understanding and representation of urban boundary layers for air quality.

Beside the immediate urban environment, there are also remote impacts, such as downstream poor air quality and impact on the water cycle. For instance, precipitation changes might occur, due to availability of condensation nuclei, as might modifications in cloudiness impact temperatures.

Urban areas have unique social science challenges, with an opportunity to develop a model including social behaviours. Aspects to explore include service requirements, crowd behaviour, messaging, and trusted sources of information.

Key implementation challenges

The urban environment is complex and rapidly changing - including its landscape, energy use, reliance on infrastructure, population distribution, permeability of the surface, and social behaviours.

A highly interdisciplinary approach is needed; there are many agencies involved who don't normally consider meteorology, including those focusing on social and other services. Access to different sources and types of data is needed, often from non-NMHS sources. An integrated urban services approach will be needed.

The right balance will need to be sought between very high-resolution local modelling (very demanding on computer resources), and making use of post-processed information from larger scale models combined with local observations; verification aspects are themselves a challenge.

Forecasts are needed on many timescales to support urban decision-making - from very short-range detailed forecasts, out to seasonal scenarios for planning.

Key Needs for International Coordination

Because each urban environment is unique, international collaboration to share information and research, as well as approaches to services, will help shape best practice to the benefit of all. Urban modelling and decision support systems can benefit from international diversity in approaches and data collection methodologies, and then be tested and evaluated in multiple locations.

WWRP will need to coordinate with, amongst others: the Global Atmospheric Watch (GAW) programme, which includes the GAW Urban Research Meteorology and Environment project (GURME) and has strong links to the United Nations Environment Programme (UNEP); other WMO programmes for cross-cutting aspects (as in Resolution 68 (Cg-17)); CBS about observations; WCRP; the World Health Organization (WHO) for health issues; and UNEP (UNEP-Live is a database of relevant information).

Resulting Benefits for WMO Members

NMHSs and their partners will have access to improved tools for environmental monitoring and prediction, which benefit the community and enhance the impact of weather observations and forecasts. With a majority of the global population living in cities (54% currently, and expected to rise to 66% by 2050), improved weather and air chemistry forecasts in this environment could potential improve the quality of life for many. Improved understanding of the urban environment will help urban planners in developing their future infrastructure in a more sustainable manner.

Action Areas

The Action Areas for this Theme are to *Understand Needs*, improve *Observations and Processes*, and work towards *Urban Prediction* to support decision-making.

AA 11: Understand Needs

Improve understanding and knowledge of the relationship between the urban physical and built environment, the social, behavioural and economic needs of its population, and the requirements for integrated weather-related environmental services

Improve understanding of how the built environment of an urban area, coupled with the varying exposure and vulnerability of its inhabitants, determine the appropriate "messaging"

Develop spatial hazard/vulnerability/impact layers, through partnerships between meteorological agencies and urban/civil authorities, that can be viewed by forecasters and emergency managers, and used in applications to predict the impact of weather and environmental conditions on urban areas

Work with other disciplines to develop multi-layer information systems (air quality, meteorology, hazard, vulnerability, energy consumption, etc.) that support urban planning and decision-making

AA 12: Observations & Processes

Improve observations and understanding of the unique urban physical processes, including dynamical, chemical and hydrologic

Increasingly use third party networks, data from air quality monitoring sites, and crowd-sourced and other unconventional data to help fill the gaps in the measurement networks in urban areas; understanding the error characteristics of these data will be critical to using them effectively

Better characterize and model the unique dynamical, physical, chemical, and hydrological processes occurring

in urban environments and how they aggregate from street/building to district and city scale

Use observing system simulation experiments (OSSEs) and modelling studies to help define the requirements for urban observation networks (including observation position and choice of variables as well as density) and their potential benefits on model prediction accuracy

Identify and model key sources of chemical concentrations (industry, transportation, energy) and assimilate the distribution of these chemical constituents — not just from the source

AA 13: Urban Prediction

Develop, validate and demonstrate urban prediction capabilities, toward building urban environment integrated information systems to support decision-making for different applications in different parts of the world

Develop and validate high-resolution atmospheric models suitable for being run in complex urban environments and capable of producing reliable forecasts of basic meteorological variables and relevant human-health-related physical, chemical and biological properties.

Develop and validate post-processing approaches which downscale coarser resolution model data to street scale and blend it with high-resolution observations and nowcasts, leading to predictions of weather and air quality in urban areas.

Improve numerical analysis and predictions of air quality (including particles), through integrated global, regional, and local modelling.

Develop coupled high-resolution atmospheric and hydrological models, incorporating surface and sub-surface drainage, for prediction of flash flooding in urban areas.

Jointly develop new urban applications in partnership with external stakeholders, and demonstrate through FDPs and other activities, building on the successes of INCA-CE, MHEWS, TOMACS and other experiments; and adapt for application to other cities.

Evolving Technologies: Their impact on science and their use

New technologies in weather and related environmental monitoring observations, computing and social media will play an increasing role in developing and providing services. WWRP can help ensure that WMO Members are well positioned to exploit these.

Key scientific challenges

There are many science and technology challenges to be addressed to exploit advances in computing and communications power, including data management; numerical methods, data assimilation algorithms and grid formulations; optimal processing of large ensembles, very high-resolution models, and reforecasts; language, visualization of uncertain information and risk, product design and media choice; and the right balance of how to use the computing power (finer scales, more ensemble members, better physics, coupling, regional versus global models) and communications bandwidth (flexibility, speed, visual impact, content, etc).

Challenges in observing include extracting useful information from unconventional observations; exploiting next generation remote sensing; gathering data on human impacts and responses; and the ongoing effort to assess the relative contributions of different observing system components.

Another challenge is to ensure that the vast amount of (old and new) data sources have to be of well-defined quality to be used in data assimilation as well as for the purpose of validation and bias corrections to other products. Quality control is an essential part of the development of new observation data sources. For verification purposes, model-independent quality control methods are needed. Carefully quality controlled data are crucial for constructing reanalyses, which have been used extensively in weather and climate research, services and applications.

Key implementation challenges

It will be essential, but still a challenge, to make advances available as widely as possible, to avoid the growing gap between developed and developing countries. This requires having enough people with the right skills - including in computer science - and has implications for the training of the future workforce.

There are always implementation decisions to be made about computer code, including trade-offs between efficiency and speed versus understandability and maintainability.

Besides improved forecasts and warnings, better models and post-processing open up opportunities for much improved, highly customised commercial services. Individual WMO Members will make their own policy decisions on how much effort to devote to this, and on their involvement/partnership with the private sector in relation to service delivery.

While WMO is committed to free and unrestricted international exchange of data and products[4], data sharing policies will have to be taken into account. It cannot be assumed that all meteorological data are available everywhere, without cost implications or specific data sharing policies.

International coordination

Given the large resources required for their development, convergence on a smaller number of very good numerical modelling systems is likely to continue. International collaboration on methodological research enables other nations and centres to contribute to these advanced efforts, as well as benefitting from the results, and from very large datasets and high performance computing services hosted at major centres. Intercomparison of methods from diverse approaches also leads to insights and selection/refinement of optimal methodologies. Furthermore, sharing tools and experiences among different operational centres with different computing capacities, strategies, and operational requirements, helps all of them.

Novel observations will be inherently international, including those from commodity technology (e.g. mobile phones and home weather stations), which may have global collection, and processing centres. These are rapidly evolving areas, necessitating international collaboration if the meteorological community is to be prepared to exploit these new sources, and for informing the design of the future global observing system.

The rapid rate of change in communications media makes collaboration essential if weather service providers, whether public or private, are to make optimal use of the capabilities that are available to their users, while continuing to serve populations who only have access to older means of obtaining information. Such flexibility is especially important in the event of disaster, when available systems may be degraded.

WWRP will need to coordinate with, amongst others, CBS and CIMO (WMO's Commission for Instruments and Methods of Observation) about unconventional observations; stakeholders who may benefit from technical advances; and Regional Associations.

Resulting benefits for WMO Members

WMO Members will benefit from better numerical models that can take advantage of cheaper/more efficient computing, and lead to a speedier implementation of improved services based on improved technology. More accurate model-based guidance will be available to support forecasting and increased automation. Research will help define the best strategy for very high-resolution NWP at the regional/national level.

Access to community models will aid in the training of the next generation of staff at national meteorological and hydrological forecast offices. Besides benefitting from use of such models, WMO Members can also contribute to their development, thereby improving their own capacity. Better access to services from major centres will enable more scientists, especially in developing countries, to participate in the research.

Members will be able to use new observations to augment conventional observations to improve weather analysis, nowcasting and numerical prediction, to "ground-truth" forecasts and model guidance, and to verify forecasts available to them. Ultimately, a more effective global observing system will provide better analyses and predictions at lower cost.

4 See WMO Resolution 40, 12th Congress, 1995.

Action Areas

The Action Areas for this Theme invest in *Advanced Methods*, enhance access to global *Support Facilities*, develop and share *Tools*, prepare for *New Observations*, and inform the design of the *Future GOS*.

AA 14: Advanced Methods

Conduct methodological research (numerical methods, coupling strategies, assimilation methods, observational and model data information exploitation, including post-processing) to ensure that scientific enhancements can be implemented in future forecasting systems, and that systems can provide timely services

Focus new development on models and coupling strategies that take advantage of advanced computer architectures including GPUs.

Improve exploitation of multi-sensor, high-resolution observations.

Improve and implement efficient strategies for strongly and weakly coupled data assimilation to enhance the accuracy of predictions on long and short time scales.

Gain a better understanding of ensemble strategies – multi-model, stochastic/mixed physics, initial conditions, number of members needed.

Design efficient strategies for regional ensemble forecasting systems to be used by smaller NMHSs.

Develop and share strategies for optimising the use of compute cycles to balance the competing computing requirements of ensemble size, resolution, complexity, and post-processing for different applications.

Develop observation-based nowcasting techniques to enable frequent, rapid forecast updates of very short duration high-impact weather conditions to be produced.

Develop rapid-update convection-permitting NWP assimilating a variety of conventional and unconventional observations, to underpin improved very-short-range forecasts and warnings for high-impact weather, extending the "warn on forecast" capability.

Develop and apply improved post-processing methodologies to add value to numerical predictions by improving their accuracy and generating user-oriented products.

Develop and apply methods for the optimal combination of forecasts from different sources, leading to an optimized probability forecast.

Build improved tools for visualization and communication of forecast and impact information.

AA 15: Support Facilities

Enhance access to services (observations, model output, data collection and pre-processing and global models) that require exceptional HPC and data handling, as an enabler for WWRP research

Continue to support TIGGE, S2S, and similar data collection efforts, to enable and accelerate research worldwide; in light of increasing data volumes, develop policies and methods for distributed data archival/ retrieval

Develop and share (open source) tools and lessons-learned for handling and pre-processing such datasets and developing applications

Prepare and make available to the international community model datasets in formats suitable for post-processing and verification to enable smaller NMHSs to carry out these activities with their own national observation datasets (e.g. as support to SWFDPs).

Promote standardisation and increased sharing of observations and forecast datasets especially from special observing periods and case studies.

AA 16: Tools

Share specialist methods and tools enabling complex modelling systems to be run by a wider community, including beyond WWRP

Facilitate the creation of easily deployable, linked community forecast and impact models for research and operations with the necessary training (e.g. community workshops) to run these models.

Establish national and international "virtual laboratories" hosted by a modelling centre or a consortium of modelling partners, offering the capability to run models and visualise output.

Involve smaller centres in these "virtual laboratories" as a way to support capacity building and at the same time accelerate the development of complex modelling systems.

AA 17: New Observations

Prepare for exploitation of information from new, advanced observing systems, as well as commodity-technology-based data

Develop a much better understanding of the information content of new types of observations (e.g. sensors on mobile phones, transport-based sensors, new satellite sensors, etc.).

Identify observing instruments and methods that can provide information on the state of the atmosphere at scales required for assimilation by km-scale NWP models.

Assimilate new observations into models and multi-sensor analyses, and quantify the benefit of these new observations for situation awareness, model initialisation and forecast verification.

Develop the means to extract information on weather, its impacts and people's responses to warnings from social media and other open communications sources, while complying with ethical safeguards.

AA 18: Future GOS

Inform the design of the future global observing system

Improve understanding and quantification of the impact of existing and new observation data streams on the accuracy of numerical prediction, especially at the km-scale where there is currently a poorer idea of how best to assimilate observations.

Better understand the potential global and regional benefit of additional observing systems deployed to remote regions (oceans, Polar Regions).

Design a prototype more comprehensive global observing system that takes greater advantage of unconventional data sources (3rd party professional networks, crowd-sourced, mobile phones, social media, etc.).

Design a prototype adaptable observing system that (in a statistical sense) minimizes analysis and forecast uncertainty.

With CBS, develop and agree standards for data formats and quality control methodologies for new kinds of observations.

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