OUTLINE OF THE WWRP SCIENTIFIC PLAN (2016-2023)

Weather prediction has achieved immense progress during the last few decades, driven by research, by the development of an increasingly sophisticated infrastructure such as telecommunications, computational and observational systems, and by the expectations of users of weather information. Predictive skill now extends in some cases beyond 10 days, with an increasing capability to give many days early warning of severe weather events. At shorter lead-times more detailed forecasts of the structure and timing of weather-related hazards can be provided. The concomitant development of ensemble methods now routinely provides essential information on the probability of specific events, a key input in numerous decision making systems. Partly because of these advances, the needs of the users have simultaneously diversified, and now routinely encompass “environmental” prediction products, such as air quality or hydrological predictions.

This progress has been possible because of the research and technical developments carried out in operational centres, academic institutes, by surface and spaced-base observational data providers and in the computing industry. Over the last decades a number of major international research programs have been critical in fostering the necessary collaboration. In particular, the World Weather Research Programme (WWRP) and THORPEX have been major initiatives to accelerate this progress. As the science is advancing critical questions are arising such as about the possible sources of predictability on weekly, monthly and longer time-scales; seamless prediction from minutes to months; optimal use of local and global observing capabilities and the effective utilization of massively-parallel supercomputers. 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.

Consequently the time was right for the first major World Weather Open Science Conference (WWOSC) to examine the rapidly changing scientific and socio-economic drivers of weather science. The Open Science Conferences was designed to draw the whole research community together to review the frontiers of knowledge and to act as an international stimulus for the science and its future. Hence this Conference considered the state-of-the-art and the future evolution of weather science and also the related environmental services and how these need to be supported by research. These discussions were informed by research presentations and input by both providers and users of weather and environmental prediction services. The merits of key components of modern operational systems were discussed in depth, as well as the major scientific challenges still facing the community. The event also provided an important platform for early career scientists to obtain an overview of the state-of-the-art of weather science, to enter into discussions with established scientists, and to build their own network of early career scientists. The conference was co-sponsorsed by major scientific and operational bodies such as Environment Canada, National Council Research Canada, World Meteorological Organization (WMO) and the International Council for Science (ICSU). Finally, the World Weather Open Science Conference, attended by more than 1,000 meteorologists, forecasters, social scientists and application developers from 57 countries, has laid the foundations to face future challenges. The highly successful conference, held in Montreal from 16 to 21 August, 2014, achieved its grand goal to chart the future course of scientific research and its potential for generating new and improved weather services.

The overarching theme of the conference was “Seamless Prediction of the Earth System: from minutes to months”. The conference highlighted recent advances in weather science and in the science and practice of weather prediction. The Conference considered also areas where a predictive capability is emerging, including for a range of aspects of the natural environment, to provide predictions of importance in a range of different socio-economic sectors.

In this context the Earth system, and environmental prediction, encompasses the atmosphere and its chemical composition, the oceans, sea-ice and other cryosphere components, the land-surface, including surface hydrology, wetlands, and lakes. It also includes the short time-scale phenomena that result from the interaction between one or more components, such as severe storms, floods, heat waves, smog episodes, ocean waves and storm surge. On longer (e.g. beyond seasonal climatic) time scales, the terrestrial and ocean ecosystems, including the carbon and nitrogen cycles, and slowly varying cryosphere components such as the large continental ice sheets and permafrost are also part of the Earth system, but these time scales were not the subject of this Conference.

Conference speakers, panels and the audience investigated the opportunities for achieving major breakthroughs in weather science at the same pace as in the last 20 to 30 years if not more rapidly.

The scientific programme was organized around five science themes:

- The Data Assimilation and Observations research theme covers understanding and improving our current and future observational capability and ensuring it is used optimally for forecasting high-impact weather through advances in data assimilation. This research contributes to the international efforts to optimize the use of the current WMO Integrated Global Observing System (WIGOS), to design regional observing networks, and to develop well-founded strategies for the evolution of observations to support Environmental and Weather Prediction primarily for time scales of minutes to one season.

- The Predictability and Dynamical/Physical/Chemical Processes theme covers the knowledge of the dynamical, physical, and chemical processes needed to advance our understanding of the sources of predictability for seamless prediction of the earth system. It includes evaluation and improvement of parameterizations and explicit representations of dynamical, physical and chemical processes in numerical weather prediction (NWP) systems. It provides the link between field programmes, especially those associated with WWRP and THORPEX, and dynamics and predictability of high-impact weather events. It considers fundamental research into the design and utilization of ensemble prediction systems.This theme connects research in the academic dynamical/physical/chemical meteorology communities and the operational numerical weather prediction centres.

- The Interactions between Sub-systems theme covers research into the fundamental processes that determine these interactions, the technical developments needed to couple models of the interacting sub systems, and the evaluation of the resulting coupled system. It focuses on the coupling (one or two-way) of two sub-systems for prediction from a few hours to one season and for regional and global modeling forecasting applications. Interactions consider the following sub-systems: atmosphere, land-surface, ocean, sea-ice, chemistry and eco-systems.

- The Numerical Prediction of the Earth system: putting it all together research theme covers the development, the verification and the application of coupled NWP systems. The advances discuss in this theme build on the science of the previous three themes and result in state-of-the-art environmental forecasting systems for the atmosphere, ocean, cryosphere, land-surface, hydrology, and air-quality. The predictive skill of these NWP systems is such that they need now to be coupled to other physical sub-systems; i) to be able to continue improving their predictive skill; and, ii) to respond to an increase demand of new environmental applications.

- The Weather-related Hazards and Impacts theme, jointly convened with the User, Application and Social Science programme, covers research that combines advances made in observing systems, coupled NWP systems and new technology to provide decision-level information related to both hazards and impacts. With respect to hazards it includes techniques to merge information from observations and NWP towards seamless prediction at short time and space scales, applications such as meteorological workstations, and advances in the forecasting process including semi-automation of warnings to support operational meteorologists In addition, research into vulnerability and exposure for both single hazards and multi-hazards is included. With respect to impacts it focuses on the interactions between weather-related hazards, events or conditions, and important biophysical systems that are known to produce substantive societal consequences. Here emphasis is placed on research that quantifies impacts along with our ability to predict them using both deterministic and probabilistic methods, and lends itself to inclusion in decision support systems. Weather events on timescales, from minutes through to a season, and many types of hazard (acute and chronic) including muliti-hazard scenarios are considered. Example applications include models developed to estimate hydrologic or water quality conditions and attendant impacts (inundation, drought, and pollution), storm surge and structural wind damage, agricultural production, forest fire occurrence, energy demand, aviation hazards, and health-related outcomes from air pollution or excessive heat.

In addition to these five themes the three THORPEX legacy projects were discussed and presented in specific sessions:

- the WWRP Polar Prediction Project (PPP) that aims to promote cooperative international research that will enable the development of improved weather and environmental prediction for polar regions on the time-scale of hours to days;

- the Subseasonal to Seasonal Prediction Initiative, which is a joint WWRP-WCRP project to improve forecast skill and enhance knowledge of processes on the subseasonal to seasonal timescale with a focus on the risk of extreme weather, including tropical cyclones, droughts, floods, heat waves and the waxing and waning of monsoon precipitation;

- the High Impact Weather (HIWeather) project to promote cooperative international research to achieve a dramatic increase in resilience to high impact weather, worldwide, through improving forecasts for timescales of minutes to two weeks and enhancing their communication and utility in social, economic and environmental applications for a set of weather-related hazards: urban flood, wildfire, localized extreme wind, disruptive winter weather, urban heat waves and air pollution.

The aim of the user, applications and social sciences program was to provide an open forum where the experiences and perspectives of a variety of information providers and users could be combined with the latest applications and methodological advances in social science to:

- Demonstrate and document recent progress, highlighting and sharing lessons from both successful and ‘less successful’ projects and applications;

- Identify and deliberate areas of practice, social science research methods, and training and education requiring new or continued attention;

- Expand and connect the interdisciplinary weather and society community; and

- Develop conference positions and recommendations regarding the state and advancement of knowledge and practice.

Three focal areas were targeted for examination during the conference:

- Individual, collective, and institutional behaviour in response to the communication, interpretation, and application of weather-related information in decision-making;

- Understanding, measuring, and predicting the societal impacts of weather and the costs, benefits, and other impacts of weather-related information; and

- Better practices and guidance for designing, implementing, evaluating and sustaining decision support systems and tools.

1.1 CHALLENGES AND PRIORITIES FOR WEATHER SCIENCE

1.1.1 Observations and Data Assimilation

A well-designed observing system is prerequisite for seamless prediction of the earth system. Observations are essential for nowcasting, for initializing NWP models, as well as for evaluating both the individual components (e.g. parameterisations) and the end products of a seamless prediction system. The last fifty years have seen great progress in the availability of innovative observations of many geophysical variables on various different spatiotemporal scales; especially the environmental satellite network. Weather radar, lightning detector, ceilometers and other evolving instruments, including opportunistic observations like Global Navigation Satellite System, are expected to play an increasingly important role in future. The continuous exploitation of these observations with new observing platforms is now the priority. A major future challenge is to provide high-resolution observations networks for convective-scale NWP, whilst maintaining global observational coverage, including burden sharing at international level. Opportunities for the future observing system include synergetic use of different ground-based remote sensing systems, exploitation of new satellite platforms and sensors, full utilisation of in-situ observations and integrating new sources of data such as from crowd sourcing. Forthcoming environmental prediction systems will necessitate also a greater span of parameters (e.g. river flow, atmospheric pollutant concentration and aerosol).

Data assimilation is the foundation stone of numerical weather prediction bridging models and observations. Data assimilation methods combine increasing number and variety of observations with prior probabilistic information on flow-dependent model error. Pushing the limit of spatial resolution toward convective scale and forecast leadtime to sub-seasonal scale will unfold a new landscape of predictability, model uncertainties and ensemble prediction issues.

Data assimilation systems must account for the NWP model and observation error characteristics in the evolving global observation network. Only about 20% of most satellite data are actually assimilated because of difficulties in using the data over land, cloud and sea-ice, and the need to thin the data to diminish horizontal error correlations between measurements. A key challenge is to increase the amount of satellite used in these areas. As an example in cloud area the highly nonlinear and multi-variable characteristic of precipitation forbid active microwave rain radars to be assimilated in operational systems. To prioritize the research agenda on the utilization of observations, different and complimentary methodologies to address forecast sensitivity to observations have been developed like variational based and the more costly observing system experiments, real and simulated. Observation impact information is being used also for cost-benefit studies to guide the design of the future global observing system.

Variational data assimilation algorithms like 4D-Var can accommodate large numbers of observations. Nevertheless such algorithms require significant NWP model dependent infrastructure and representation of model errors requiring linear modelling of complex physical and dynamical processes. They also do not fully account for the model and flow-dependent prediction error characteristics. In contrast with 4D-Var, an ensemble data assimilation scheme typically requires fewer infrastructures and is less dependent on model. The ensemble permits fully flow-dependent error representation. Especially for increasing ensemble sizes, they scaled very well on massively parallel HPC. The advantages of both approaches have been implemented successfully in hybrid data assimilation schemes in numerous NWP centres. As horizontal resolution is increasing, data assimilation methods will need to tackle more assimilation of observations with non-Gaussian error distributions, like cloud and precipitation. This will be important challenges for both the variational and ensemble schemes. In the latter more physically based stochastic perturbation approaches perturbing the physics tendencies will be needed.

Major international field campaigns provide opportunities to both test scientific hypotheses and to test and develop new observing systems and observing strategies. Data assimilation methods can be used in the experimental design for field campaigns; the additional observations obtained can contribute to testing and developing data assimilation systems. Field campaigns designed to advance the science of weather forecasting require are increasingly dependent on strong international cooperation and the participation of academic and operational research scientists.

1.1.2 Processes and Predictability

Advances in our knowledge of the fundamental processes that determine weather-related hazards allows us to identify the factors that limit their predictability, evaluate weaknesses in forecast systems, and identify potential for significant improvements. Significant progress has been made in understanding the fundamental role of diabatic processes in the development and structure of weather systems and in tropical - extratropical interactions but open questions remain. In particular, the impact on predictability of organised convection on synoptic-to-planetary scale motions through the triggering and modification of Rossby wave trains should be identified. Further challenges are linked to identifying and predicting the fine-scale structure in weather systems, such as the distribution severe surface winds.

A key research goal in NWP is to quantify and reduce uncertainties in the representation of processes in numerical models relevant to the improvement of predictive skill. It includes evaluation and improvement of parameterizations and explicit representations of dynamical, physical and atmospheric composition processes in NWP systems through numerical experiments and field programmes studies. The representation of sub-grid physical processes with increasing spatial resolution will need to be revisited, especially for convection parameterization schemes where their underlying physical-statistical premises break down in the so-called “grey-zone” (horizontal resolution of 4 to 10 kilometers).

The modelling of diabatic and dynamical processes for convective clouds for the prediction of midlatitude and tropical weather systems is an outstanding challenge, including cloud micro-physics processes crucial for accurate quantitative precipitation prediction and types. The representation of tropical convection remains particularly difficult with most global models struggling with convective organization and the diurnal cycle. The accuracy of NWP forecasts is hugely sensitive to errors in the representation of convection that can have significant influence on the nonlinear dynamics associated with intensification of tropical cyclones. Making significant progress may require challenging some of the traditional paradigms for parameterization with future convection schemes across multiple columns that have memory and an inherent representation of uncertainty. They will also have to be scale-aware and able to cope with the problem of convection becoming partially resolved like in the grey-zone.

Eventually the advent of global convection-permitting numerical weather prediction models that have resolutions of the order of 1 km and increasingly represent explicitly nonlinear and turbulent processes will avoid the convection grey-zone issue. This will be a significant step forward to improve prediction of mesoscale weather systems and their interaction with synoptic scale circulation. These NWP systems of the future will be significantly larger as a computational task than today and would require significantly more power than is available with existing HPC technology. Hence a change of paradigm is needed regarding hardware, design of codes, and numerical methods. Various numerical innovative methods will need to be developed addressing numerical stability, accuracy, computational speed and flexibility to deal with more prognostic variables, and the interaction between resolved and unresolved dynamical and physical processes. The new numerical methods challenges will need to revisit choice of spatial discretization, the time stepping method and the treatment of boundaries.

The future modelling and observational challenges for atmospheric chemistry will include better: i) transport and dispersion of chemical species; ii) cloud microphysics, especially interaction with aerosols; iii) radiative transfer; and iv) turbulent fluxes in the boundary layer. The first is one of the most crucial requirements for the next generation of numerical schemes for global meteorology atmospheric composition models. The numerical schemes will need to have better conservation, shape-preservation and prevention of numerical mixing or unmixing. The latter is important since inaccurate mixing is similar to introducing erroneous chemical reactions. Eulerian flux-based schemes are suitable for mass conservation, but several semi-Lagrangian mass conservative schemes are now available.

In addition to cloud and convective processes we need to understand how radiation works to shape the water cycle and energy balance. Water and energy connect globally and then systematically in terms of finer and finer scales to the cloud microphysics level including cloud-aerosol interactions important for precipitation. There will be limited progress in environmental prediction unless a more accurate modelling of the water and energy budget is achieved.

An essential component of NWP is an ensemble prediction system to quantify the uncertainty in weather forecasts. Major advances have been made in designing ensemble prediction systems on the global and more recently for convective-scale forecasts. Particular challenges are associated with specifying the uncertainty in the initial conditions and in the representation of physical processes in the NWP model. The development of post-processing techniques and tailored forecast products are further priority research areas. Ensemble prediction systems can also be used to extend our knowledge and understanding of the processes that determine the evolution of weather systems and limit their predictability. The THORPEX Interactive Grand Global Ensemble (TIGGE) database has been particularly effective in this respect.

1.1.3 Interactions between Sub-systems

The demonstration that many components of the Earth-system (e.g., atmosphere, oceans, cryosphere, land-surface, hydrology, composition,) are influential for medium-range weather predictions is more and more evident (numerous references are available). Also analyses and predictions of these sub-systems, on a wide range of time-scales, have significant socio-economic benefits. Hence NWP is now evolving into numerical weather and environmental prediction. The trend to include various environmental interactions in atmospheric models, initiated in the 1970s, will continue. It is very likely that the models will be used increasingly to address problems of environmental emergencies and management of ecosystems. The potential for new applications linking the environmental models and the economy is vast. This will get even larger with the increasing realism of the sub-models representing chemical processes, hydrology, the biosphere, and ocean circulation.

To attain these objectives we will need to better understand fundamental processes that determine the two-way interactions between the atmosphere, land-surface, ocean, sea-ice, air composition and eco-systems.

The land surface and the atmosphere interact through the global water cycle (exchanges of precipitation and evaporation) and control high impact environmental events from regional to continental scales like floods and droughts. The latter can potentially be predicted because the land surface states vary more slowly than do the atmosphere. A better representation of the water cycle will open the way to more accurate prediction of floods and will most likely lead to better water management of large catchments such as the Great Lakes and St-Laurence river water levels. One of the major sources of error in hydrological predictions is due to uncertainties in the predicted rainfall.

The water cycle is closely connected to the energy cycle (e.g. latent heat flux and evapotranspiration) and the carbon cycle (through the vegetation transpiration and carbon uptake through photosynthesis). One challenging aspect is the chain of linkages between the surface processes, boundary layer and cloud formation that models must represents over hundreds square kilometers. If one sub-model is highly accurate but others are significantly in error, the overall simulation of land-atmosphere feedback will be poor. The utilization and interpretation of observations for calibration and validation to address such issue is challenging, especially to assess the long standing diurnal cycle problem. They are typically in situ measurements and area averages, like satellite pixels, which are smaller than the model spatial resolution or larger like catchment runoff. More accurate representation and validation of these processes in Earth-system models are crucial to close properly the water and energy budget and achieve eventually increase predictive skill.

Meteorology atmospheric composition modelling has developed significantly in the last decade for air quality applications like smog and pollen warnings, forecasting of hazardous plumes from volcanic eruptions, forest fires, oil and gas fires and dust storms. Mainly developed to account the effects of meteorology on air quality, they are also used more and more to understand better the possible feedbacks of the atmospheric composition on NWP predictive skill, especially by changing the radiation budget or ultimately by affecting cloud formation and precipitation. There is still a long way to go for near-real-time weather and chemical data assimilation to improve both weather and chemical weather forecasts, but the retrieval of satellite data and direct assimilation of radiances is likely to achieve this. Some encouraging results are emerging like the positive impact of assimilation of ozone on the wind fields.

Ocean-sea-ice-atmosphere interaction is one of the key challenges of weather and climate prediction from days to seasons. For example, there is evidence that the evolution of hurricanes on time-scales of 3-7 days can be significantly influenced by the presence of a coupled ocean in numerical prediction models. This and other societal needs has led NWP centres to add interactive components such as a coupling to an ocean-sea-ice circulation model even from day zero in weather predictions. An example is the demand for atmosphere-ocean-ice forecasts is being amplified by the increased economic activities in the Arctic. This is not without challenges like the low observational data density in the ocean, including sea-ice, makes data assimilation difficult and better air-sea exchange parameterisations at high wind speeds is needed. Also some consideration will be required for ensembles in coupled systems, and particularly to the potential for improving ensemble spread through perturbed ocean initialisations and/or perturbed ocean parameters.

Research in the last three decades on tropical modes of ocean-atmosphere interaction, like the El Nino/Southern Oscillation (ENSO) oceanic phenomenon and its complex interaction between the large scale tropical atmosphere and organised moist convection, has permitted significant advances in seasonal prediction. Similarly research in the intra-seasonal variability has point out another ocean-atmosphere interaction mode, the Madden-Julian Oscillation (MJO), as an important source of predictability. MJO modulates significantly the mid-latitude intra-seasonal variability through tropical and mid-latitude teleconnections, like the Canadian winter temperature and precipitation. Another example is the two-way link between the MJO and the North Atlantic Oscillation (NAO) modulates significantly weather regimes over Western Europe. This has important consequence in terms of the predictability of the global atmosphere.

1.1.4 Numerical prediction of the Earth System

The skill of global numerical weather predictions has significantly improved. These days' weather forecasts involve precise and reliable probabilistic numerical predictions estimating the range of likely future weather conditions. The advances in global Numerical Weather Prediction (NWP) made in the past decades are mainly due to:

- reducing numerical errors through more accurate and efficient numerical techniques and increased spatiotemporal resolution, enabled by increasing supercomputer capacity;

- improving the quality of the initial conditions by developing data assimilation methods that optimally combine the increasing number and variety of observations with prior information from forecasts;

- improving the representation of physical processes, using fundamental meteorological research on: clouds, convection, sub-grid scale orographic “drag”, surface interactions, aerosols, etc;

- enabling the design of reliable ensemble predictions through the inclusion of initial condition and model uncertainties such that probabilities can be estimated by using an ensemble of realizations.

World leading global forecasting systems in 2015 operate with around 20-50 ensemble members and a horizontal resolution in the range 13 to 50km with of order 100 vertical levels. We can currently predict large-scale weather patterns and regime transitions out to a month or more ahead and high-impact events, such as tropical cyclones, out to two weeks ahead. Under certain conditions, even sub-seasonal to seasonal forecast has some predictive skill. In a decade from now global NWP will approach convective-scale resolutions with more accurate quantity precipitation forecast.

An adequate representation of high impact weather phenomena such as severe summertime convection, intense localised wind, or winter weather requires higher resolution and a more accurate representation of key physical processes than can be achieved in current global forecasting systems described above. Regional NWP systems operated at km scale allow for a better description of physical processes leading to an improved description of the atmosphere such as a better representation of the interaction with the land surface and of the diurnal cycle. Furthermore, km scale resolution allows deep convection to be simulated explicitly rather than parameterised. Recognition of the high uncertainty associated with high impact weather has led a number of centres to run a convection-permitting ensemble rather than just a deterministic regional forecast. Challenges in regional NWP are associated with developing scale-aware parameterisations with a consistent coupling of different schemes, with dealing with partially-resolved processes such as shallow convection and turbulence, and with the design of initial-condition and model ensemble perturbations for convection permitting models.

As the NWP system skill increases more and more components of the Earth-system (e.g., atmosphere, oceans, composition, land surface, cryosphere) need to be taking in account to maintain progress. We are approaching a new era of environmental prediction where these geophysical sub-systems coupled to the atmosphere need to be better simulated not only for advancing weather prediction, but also to provide new forecasted variables (e.g. river flow and sea ice) with undeniable socio-economic benefits.

Overall demand has grown for many environmental prediction systems. As an example air quality can degrade with increases in population and industrial capacity, particularly in urban areas and megacities, which increases the need for air quality forecasts. Water management has also become a more important issue as the scarcity of potable water spreads and urban and river flooding effects more people as population densities have grown rapidly in areas at risk, such as coastal plains and river valleys.

Hence it will become increasingly important at convective-scale (and sub-kilometer scale) resolution to include a realistic representation of the effects of large cities for reliable prediction of the water cycle, energy budget and the atmospheric flows and dispersion in complex urbanized environments. New land cover databases are needed to describe the spatial distribution and variability of urban areas and a general classification method based on satellite imagery is needed. In this context, high-resolution numerical modellers will need to develop techniques for how to treat surfaces where the roughness elements are (much) taller than the lowest model level (typically 10 m for a convective-scale resolution model). It will also be necessary to develop a methodology to characterize the spatial and temporal distributions of anthropogenic heat emissions from large metropolitan areas. This will have to be tested over major world cities using detailed observations from urban field campaigns.

The development of more sophisticated forecasting systems from global to urban scale requires research into new approaches to verifying the forecast quality. Challenges are associated with verification of probabilistic forecasts, developing user-relevant forecast evaluation, accounting for uncertainty in observations, and developing appropriate methods for longer range forecasts.

1.1.5 Weather-related Hazards and Impacts

The seamless weather prediction system of the future must provide accurate and timely information on a range of time and space scales regarding the location, timing, and structure of weather-related hazards. This information can make an effective contribution to mitigating the impacts of weather-related hazards only if it is translated into products suitable for end users and communicated in a manner that allows it to be integrated directly into the decision making process. Different regions of the world are faced with different weather–related challenges, have different technological capabilities with regards to observations, nowcasting and NWP, and different socio-economic and cultural factors to consider. Furthermore, aspects such as growing population, increasing urbanization and increasing reliance on complex infrastructures and networks influence the demands on weather forecasting. These challenges must be taken into account as progress is made towards developing seamless high impact weather forecast systems.

In this context, the concept of seamless prediction includes the provision of consistent products and services irrespective of the method used to produce them and the lead times involved. The future high impact weather forecast system will combine observations, nowcasting techniques and probabilistic NWP using scientific and technological tools to deliver tailored output to the end-user. The role of the forecaster depends on both the weather situation and on local and regional needs and resources. Input from the human forecaster will focus on interpretation and decision making as well as on the creation and communication of final products. Automation will become increasingly important and require innovative scientific and technological developments.

Improvements in the provision of weather information must be translated into improved use of this information in in critical decision making. Challenges include understanding and quantifying weather impacts, accounting for and communicating forecast uncertainty, dealing with a wide range of stakeholder requirements, providing actionable information, and incorporating weather data and information into the decision-making process effectively. Research and development aimed at improving the decision-making process requires effective collaborations between a broad range of professionals in an interdisciplinary framework that brings physical and social scientists together. Particular focus should be given to societal impacts, working closely with forecast end users to better understand and quantify weather-related impacts, as well as developing strategies for communicating information that will enable end users to more effectively manage risk.

1.2 Challenges and Priorities for User, Application and Social Sciences

Despite all of the progress and advances in scientific understanding, monitoring, prediction, computing, telecommunications, and specialized services alluded to previously, major loss event statistics such as those offered in Figure X from Munich Re constantly remind us of the gaps between scientific knowledge and its beneficial application to both routine and complex weather-related problems facing society[1]. Describing, measuring, analysing, explaining and addressing these gaps is the subject matter for social and interdisciplinary scientists working in close collaboration with those affected by weather and related hazards, those charged with the responsibility of managing risks and consequences, and of course elements of the weather enterprise.

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[1] Interestingly this observation remains as valid in the 21st century as it was when initially identified in the 1940s (see White 1945, White et al. 2001)

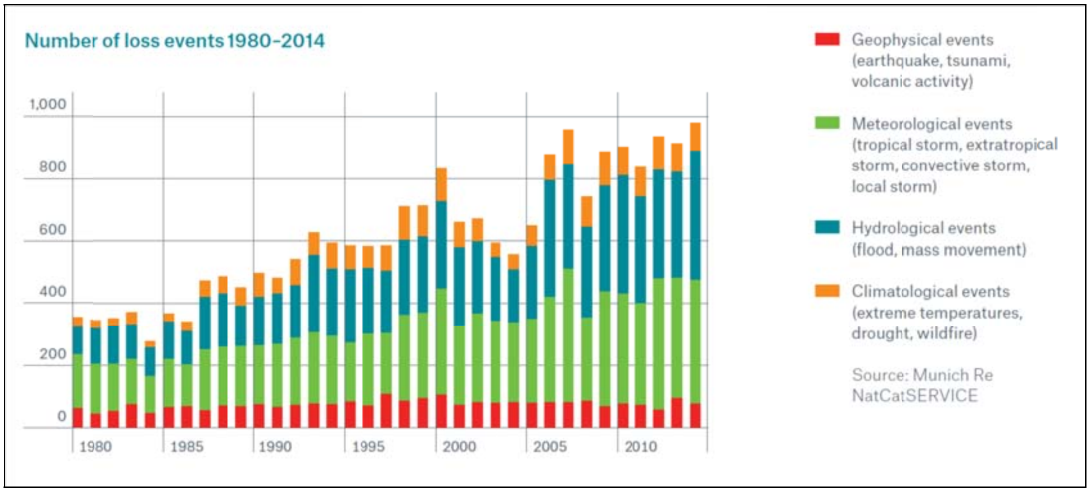

Figure 1. Number of loss events 1980-2014 (Munich Re, 2015)

The weather enterprise is the cumulative effort of individuals, businesses, and organizations to produce, communicate, interpret and apply knowledge concerning weather and its interactions with, and implications for, society for individual or collective benefit. It includes National Meteorological and Hydrometeorological Service (NMHS) organizations, the traditional source of weather observations, forecasts, and warnings, but is increasingly comprised of private enterprises and non-government organizations that provide, communicate, and tailor weather and related risk or impact information, advice and services to others in support of their decision-making.

Modern social science inquiry into aspects of the weather enterprise may be traced back to the human ecology and hazard traditions in geography (e.g., White, 1945; Burton et al. 1978), disaster orientations in sociology (e.g., Carr 1928, Fritz and Williams 1957, Quarantelli 1978) and anthropology (e.g., Wallace 1956, Tory 1978), and value-of-information research in economics and decision science (e.g., Thompson and Brier 1955, Lave 1963, Nelson and Winter 1964). The weather enterprise has also been taken up as the subject of psychology, social-psychology, and communication studies.

The contemporary state of social science research was on display through the presentations and remarks delivered by over 100 speakers in over 25 sessions of the User, Application and Social science (UAS) program of the WWOSC. The UAS touched upon a broad spectrum of research questions, methodological issues, and weather-sensitive issues, topics, and sectors. These included relatively mature application areas having well-developed relationships with service providers (e.g., energy, transportation, agriculture), emerging areas with tremendous benefit potential (e.g., health, disaster risk reduction and management), and sessions focused on under-studied topics critical to the future exploitation of weather-related knowledge (e.g., bridging disciplinary and practitioner boundaries, communication of weather and related risk information, future of the weather enterprise).

While not fully comprehensive, the material and opinions shared during and immediately following the WWOSC provided an impressive snapshot of reflections on social science achievements over the past decade and remaining challenges that serve as directions for future research and organizational change. A few of the more salient and widely supported ones are noted below. Given the breadth of UAS topics, more detailed and focused session summaries are being submitted to specific journals (see Jancloes et al., 2015, for a health session example) with a synthesis or collation to be developed for a future WMO publication.

1.2.1 Dissolving disciplinary, professional, and expert-public boundaries

The advancement receiving the strongest support from WWOSC participants related to improvements in understanding and working across disciplinary, professional, and expert-public boundaries. The epistemological wall that was perceived to have diminished the relevance or questioned the legitimacy of social science and substantive user engagement within the domains of meteorological research and NMHS operational communities prior to 2000 has been significantly eroded. In part, this change has been facilitated in a top-down manner by the recognition of the value of social sciences within the WMO and other international bodies (e.g., WMO 2015, ISSC and UNESCO 2013); national academies and professional associations, especially through their various meetings (e.g., American Meteorological Society, European Meteorological Society); large industries promoting and investing in weather-risk R&D (e.g., re-insurance); NHMS organizations, several of which regularly contract out or hire staff with social science expertise (e.g., Australian Bureau of Meteorology, UK Met Office, Finnish Meteorological Institute); and funding agencies which often require some level of involvement from social and applied sciences or justification of research in terms of anticipated societal benefit.

Even more crucial to this advancement has been the bottom-up involvement of weather-sensitive enterprises and organizations in jointly defining research problems and co-producing research (e.g., City of Toronto Health, or the collaboration between Deutscher Wetterdienst and University of Berlin – Weissmann et al. 2014); private sector expansion to develop and serve emerging weather information needs; formation of multi-disciplinary teams and programs at academic and other research institutes (e.g., NCAR-Societal Impacts Program, APEC Research Center for Typhoon and Society, International Research Institute for Climate and Society); and training, exchange, and visiting scholar programs that have explicitly encouraged communicating, learning and sharing across disciplines. Through programs such as WAS*IS (Demuth et al. 2007) and smaller-scale exchanges, scientists and practitioners trained in social or physical sciences are becoming familiar with the methods, concepts, limitations, and strengths native to multiple disciplines. This exposure, especially early on in a given career path and often maintained through social media connections, has opened new opportunities for the next generation of truly inter- or trans-disciplinary research and has provided essential capacity for NMHSs to begin extending their role, in collaboration with partners, into impact-based forecasting and risk communication. Significant organizational, funding, and other challenges remain to sustain and improve upon the progress made over the past decade, however, it is generally no longer acceptable to conduct large natural science projects without social, interdisciplinary, or applied elements.

1.2.2 An expanding volume of research

The number of researchers and volume of social and interdisciplinary science focused on weather and climate has expanded considerably over the past decade, a point reinforced by the large contingent of projects and applications represented at the WWOSC and by even a cursory review of the peer-reviewed literature. Perhaps as or more important, is the growing breadth of outlets in which this research is being published (e.g., Accident Analysis and Prevention, Applied Cognitive Psychology, Energy Economics, J of Ecological Anthropology, J of Risk Research, J of Urban Planning and Development, Tourism Management). While articles are still often targeted to the major meteorological journals such as the Bulletin of the American Meteorological Society, Meteorological Applications, Climate Change, or Climate Research—where social scientists were communicating with and to natural scientists—research is now finding a place in a greater range of disciplinary journals within social science which potentially entrains new social scientists into examining weather-related topics. New publications dedicated to the emerging space between the social sciences, meteorology and climatology (e.g., Weather, Climate and Society) are fostering multi- and interdisciplinary research. There remains a significant regional bias towards Europe and North America that must be addressed, both in terms of the study subject matter and the home institutions and agencies of the funded investigators. Clearly there is also a need to incorporate findings from non-English literature, conference proceedings, and other meetings.

1.2.3 Quality and framing of research

Many UAS participants noted that researchers were beginning to tackle more complex research questions with commensurate sophistication in study designs, methods, and novel data sources, often borrowing from other well-developed application fields (e.g., health promotion, transportation demand, behavioural economics). Certainly the significant progress that has been made in developing impact models with societal dimensions, for example for storm surge inundation, agricultural crop yields, electricity demand, wildfire propagation, and heat-related mortality, is laudable and a bold step towards the earth-system prediction initiative for the twenty-first century envisioned by Shapiro et al. (2010). A major challenge is to adequately deal with the dynamic nature of people and society and to test the underlying assumptions contained in such impact models. At an individual level, this means accounting for changing attitudes, beliefs, actions and behaviours of people upon which such models make hefty assumptions. At a macro level, even when well-understood, social and technological change coupled with shifts in the economic, political, and environmental landscape continuously alter the operating context thereby creating new risks and opportunities and demands for weather-related knowledge (e.g., renewable energy).

More importantly, however, such impact research is framed squarely within the structure, approaches, and questions of the physical sciences with an underlying assumed utility in more precise and accurate information. An equally significant advancement, but one needing further development, has been the reframing of the ‘weather’ problem using social science perspectives and concepts, including vulnerability, resilience, risk perception and communication, and various behavioural and decision theories. The notion that tools and techniques from economics, social psychology, evaluation and knowledge utilization research can be used assess, reflect upon, and improve the weather enterprise—and not just defend its budget allocation—has come. While the overall quality of weather-focused social science research has improved, there is also a general need over the next decade to expand the modest amount of critical and theoretical research which one would expect in a mature field of study.

1.3 AIMS OF THIS BOOK

In the long term, improvements in weather forecasting will continue along the lines denoted by the conference themes. This book reviews the different emerging research challenges related to the themes of the science program that will need particular attention in the future. The material presented in this book is based on white papers developed by the convenors of the individual sessions of the science programme. Each chapter reviews the state-of-the art for a particular theme and discusses future challenges that need to be addressed in the next decade so as to improve the seamless prediction of the earth system from minutes to months.

REFERENCES AND FURTHER READING

Burton, I., R.W. Kates, and G.F. White, 1978: The Environment as Hazard. Oxford University Press, New York.

Carr, L.J., 1932: Disaster and the sequence-pattern concept of social change, *American Journal of Sociology,* 38(2):207-218.

Demuth, J.L., E. Gruntfest, R.E. Morss, S. Drobot, and J.K. Lazo, 2007: Building a community for integrating meteorology and social science, *Bulletin of the American Meteorological Society,* 88(11):1729-1737. DOI: 10.1175/BAMS-88-11-1729.

Fritz, C.E. and H.B. Williams, 1957: The human being in disasters: A research perspective*, Annals of the American Academy,* 309:42-51.

ISSC and UNESCO, 2013. World Social Science Report 2013, Changing Global Environments. OECD Publishing and UNESCO Publishing, Paris.

Lave, L.B., 1963: The value of better weather information to the raisin industry, *Econometrica,* 31(1-2):151-164.

Munich Re, 2015,. Natural catastrophes 2014: Analyses, assessments, positions. Topics Geo. Munich Reinsurance, Munich.

Nelson, R.R. and S.G. Winter Jr., 1964: A case study in the economics of information and coordination the weather forecasting system, *Quarterly Journal of Economics,* 78(3):420-441.

Quarantelli, E. (ed.) 1978. Disasters: Theory and Research. Sage, London.

Thompson, J. C., and G. W. Brier, 1955: The economic utility of weather forecasts, *Monthly Weather*

Review, 83:249-253.

Wallace, A. 1956. Tornado in Worcester: An exploratory study of individual and community behavior in an extreme situation. National Research Council, Washington.

Weissmann, M., M. Göber, C. Hohenegger, T. Janjic, J. Keller, C. Ohlwein, A. Seifert, S.Trömel, T. Ulbrich, K. Wapler, C. Bollmeyer, H. Deneke, Initial phase of the Hans-Ertel Centre for Weather Research – A virtual centre at the interface of basic and applied weather and climate research. *Meteorologische Zeitschrift,* 23:193–208

White, G.F., 1945: Human adjustment to floods: A geographical approach to the flood problem in the United States. Department of Geography Research Paper No. 29, University of Chicago, Chicago.

White, G.F., R.W. Kates, and I. Burton, 2001: Knowing better and losing even more: The use of knowledge in hazards management, *Environmental Hazards,* 381-92.

WMO, 2015: Valuing Weather and Climate: Economic Assessment of Meteorological and Hydrological Services. World Meteorological Organization, World Bank Group, Global Facility for Disaster Reduction and Recovery, US AID, and Climate Services Partnership. WMO-No 1153. Geneva, Switzerland.