Annex 1 to Report by the Chair of the Scientific Advisory Panel

Scientific Advisory Panel

Science and Technology Vision Paper

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Contents

Executive Summary

The purpose of the WMO Scientific Advisory Panel (SAP) is to make recommendations and suggestions to WMO Members, the Executive Council and Congress on matters that are of relevance to the WMO research strategies and the optimal scientific directions to support the evolution of the WMO mandate. The SAP has worked in consultation with the other constituent bodies of WMO, including the Executive Council, the Research Board, INFCOM and SERCOM to develop the *SAP Science and Technology Vision Paper* which aims to inform WMO Members and constituent bodies on the scientific and critical challenges that could guide the development of the WMO mandate in the coming decades. The paper considers possible future demands and disruptors on existing weather, climate, water and environmental-related environment services (WCWES) and the emerging or existing capabilities that can help address these forthcoming challenges.

The paper anticipates there will be continuing demands for more accurate and relevant WCWES from users, with a greater focus on impacts and attribution of impactful weather, climate and water events to climate change driving further integration between disciplines, including social and economic sciences. Critical processes within the weather-climate-water system are currently not sufficiently well represented in Numerical Earth system Weather-to-Climate Prediction (NEWP) systems and global climate ensembles on the scale of a few kilometres (k-scale) will be required, along with other approaches, for us to meet these future requirements for accuracy and relevance. The digital revolution, increasing quantities of data, the growing role of the private sector, and a global move towards a carbon net zero economy will be important factors that will drive changes in the development of weather, climate, water and environmental-related services in the coming decades.

The importance of ensuring that future advances in global science can be translated into services with local impact cannot be over-emphasized, especially for low-income countries. Additionally, it will be crucial to nurture more opportunities to engage with the broad spectrum of users and stakeholders of climate information to provide training, advice, and support on how best to deploy the expertise and products for their own specific needs.

Exascale computing is a key future capability that will need to be developed through international cooperation if we want to meet future demands for greater accuracy in WCWES through improved resolution, complexity and ensemble size of NEWP systems. Beyond that, the opportunities fostered by quantum computing should be kept under review. Machine learning (ML) and artificial intelligence (AI) will potentially transform the value chain for WCWES, with global access to cloud computing potentially removing some of the barriers to exploiting large quantities of data.

Higher spatial and temporal resolution of observations will be needed to meet the future demands of global k-scale NEWP systems. Approaches to acquire and derive affordable complementary or “non-conventional” observations will need to be further researched and developed. Data assimilation systems will need to be designed to accommodate these novel observation sources and this critical dependency between observations and NEWP demands the integration of the development of comprehensive observations with multiscale models. Meanwhile, there remain important scientific challenges that need to be addressed within NEWP systems including the improved representation of dynamical, physical, and chemical processes; the interactions between the atmosphere and liquid and solid water components; and characteristics on the sub-km scale. The enabling of international cooperation in the field of weather, climate, water, and environment is considered one of WMO’s primary strengths and will be an essential strategy for delivering the benefits of global science advances to all. Finally, the importance of preparing our people to meet the challenges of the future in these new disciplines while not losing focus on traditional areas is stressed.

This paper makes a set of recommendations to WMO to prepare the community for the future. Considering that WMO is a success story for sharing observations, it now needs to initiate a “revolution” in Research and Development (R&D) coordination and knowledge sharing.

Recommendation 1: Major international climate R&D effort in the exploitation of global k-scale computing and Earth System observations. To meet future global needs for weather, climate, water, and environmental-related information, it will be necessary to develop global k-scale NEWP and climate modelling systems that run ensembles on climate timescales with environmental observational data sets and associated data analysis, including historical re-analyses. Such an endeavour will require close international collaboration between WMO Members to be realized. This collaboration should consider the technical questions of Exascale computing, exploit advances in information technology in order to enhance reliability and physical content, address the scientific challenges within NEWP systems as well as in the optimal application of observing systems. Strategies such as k-scale modelling, process studies, phenomenological studies and data sensitivity experiments would need to be core activities. The computing infrastructure should be environmentally sustainable with the development and implementation of a Net Zero strategy.

Recommendation 2: Bridge the gap between developing global science and delivering local impact. Investment in a quantum leap in global science to k-scale must incorporate equity to minimize perpetuating the disparity in service provision between high and low-income countries. Our global science endeavours must lead to positive impact in services in all countries, otherwise all that global investment would be in vain. Hence it will be crucial to work closely with those disciplines who collect and use socioeconomic data to understand WCWES impacts and develop relevant NEWP applications.

Recommendation 3: Develop a Digital Strategy. A digital strategy will help address the current and future challenges of the digital revolution and big data as well as enable the equitable exploitation of cloud computing, artificial intelligence, and machine learning. Without these approaches, it will become even more challenging for low-income countries to access and exploit the outputs arising from the scientific endeavours proposed in Recommendations 1 and 2.

Recommendation 4: Accelerate the development of attribution science and techniques. Detection and attribution products will become a key element of climate services demanded by policy and decision makers. As a result, WMO should promote the development of protocols and standards as attribution enters an operational phase. The underlying science requires observations and weather models and information to be produced in near real-time. WMO, therefore, should ensure leadership in fostering detection and attribution research, encourage appropriate observational and modelling capabilities around the world, particularly in vulnerable regions, and promote the standards and protocols required for attribution to enter an operational era.

Recommendation 5: Further development of quality assurance strategy for weather, climate, water and environmental-related services. With increasing numbers of weather, climate, water, and environmental-related service providers there is a need to further develop approaches to quality assurance of WCWES at the global and national level so that users can have confidence that the services they are consuming are scientifically robust for the purpose to which they are being put.

Recommendation 6: Work across agencies to enable closer integration of geophysical and social sciences to support better understanding of the impacts of weather, climate, water and environmental-related events. With users demanding services more focused on impacts of events, there is a need to integrate meteorology, hydrology, cryosphere and oceanography with other geophysical and social sciences to better understand and describe these impacts.

Recommendation 7: Develop education and training strategies to broaden expertise beyond traditional disciplines. A move towards more impact-based services and the use of new technologies will require a broader knowledge base for practitioners and those on the demand side, so weather, climate and water information can be effectively exploited for user benefit.

Recommendation 8: WMO, together with the National Meteorological and Hydrological Services (NMHSs), to provide leadership in the move towards Net Zero. WMO has the opportunity to (i) develop and implement a Net Zero strategy for its own operations in three important pillars of building management, working organization, and computing infrastructure, (ii) encourage and assist the NMHSs to develop their own plans to move to Net Zero and (iii) champion the pathway to Net Zero across the wider UN family.

1. Introduction

The purpose of the WMO SAP is to make recommendations and suggestions to the Executive Council and to Congress on matters that are of relevance to WMO research strategies and the optimal scientific directions to support the evolution of the WMO mandate. SAP was established as WMO's scientific 'think tank' to ensure the Organization retains its world-leading role as the go-to source for strong, expertly informed, and science-based advice in the future.

The SAP has worked in consultation with the other constituent bodies of WMO, including the Executive Council, the Research Board, INFCOM and SERCOM to develop a *SAP Science and Technology Vision Paper*. Consistent with the WMO Vision and Long-Term Goals set out in the WMO Strategic Plan[1], this Vision Paper aims to inform WMO Members on scientific and critical challenges that could guide the development of the WMO mandate in the fields of weather, climate, water, environmental and related social and economic sciences over the next two decades.

The success of WMO has always been dependent on international cooperation at the global and regional level to help address grand scientific and technical challenges and to ensure benefits are realized in all countries. As a result, this paper has a strong emphasis on international partnerships operating globally and within and across regions. In doing so, the vision encapsulates three principles from the UN Environment Programme (UNEP) – leave no one behind, ensure dignity and equality for all, and achieve prosperity within Earth's safe and restored operating space.

Recent decades have witnessed growing negative impacts of extreme weather, climate, water and related-environment events on humans and ecosystems driven, increasingly, by anthropogenic induced climate change and the demographic shifts of growing populations to more vulnerable areas. These impacts typically occur on regional and local scales but have far wider implications due to highly inter-connected globalized social and economic systems, and the complex inter-relationships of the Earth's climate. Furthermore, tipping points could be reached that have local, regional and global impacts that are poorly quantified.

The WCWES provided by WMO Members play an important role in enabling governments to enhance the environmental security of their citizens, by mitigating impacts and enhancing resilience to severe weather events, supporting the development of mitigation and adaptation strategies for climate change and helping to address issues of attribution, as well as supporting economic growth through best use of weather, climate and water intelligence. This importance has been recognized through the WMO Early Warnings for All Initiative, launched by the UN Secretary-General in March 2022 as a core deliverable in the UN's climate change adaptation plans, with the aim of ensuring easy and timely access to impact-based multi-hazard warnings for everyone on the planet by 2027[2].

Today's WCWES are built upon a global infrastructure constructed through decades of collective scientific and technical endeavour. The raw materials for these services are weather and climate predictions generated through numerical models, and observations of the Earth System from satellites and terrestrial-based systems. Each of those components – observations, prediction and service delivery – would not be possible without the expertise of skilled personnel such as research scientists, software engineers, technicians and operational meteorologists.

Weather-climate prediction systems have improved remarkably in the last 50 years with the weather prediction lead-time skill for many parameters improving at about a day per decade. This has been achieved by significant improvements in the observations, especially satellites, used to initialize and verify weather prediction models and increase our understanding of Earth System processes; advances in Earth System data assimilation; more sophistication in the

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[1] *WMO Strategic Plan 2020–2023* (WMO-No. 1225)
[2] *WMO Early Warnings for All: Executive Action Plan 2023–2027*

models themselves, through improved numerical methods and better representation of dynamical and physical processes and uncertainty. This has been underpinned by year-on-year advances in computing power that has enabled higher resolution and more complexity in Earth System modelling, yet progress has been slower for some challenging variables like precipitation, and extreme events in general.

Despite significant progress, climate models still have serious shortcomings in representing processes such as cloud formation and cumulus convection on scales that are finer than the grid of the model, with profound consequences for predictions of precipitation and related hydro-meteorological extremes. While regional weather prediction models can now be run at a scale of a few kilometres (so called k-scale) that permits the explicit representation of important convective processes, such as organized convection and the diurnal cycle, current computing constraints mean this remains outside the possibilities for global climate models. Hence, without a step change in available computing power, climate models cannot resolve the detailed structure and lifecycles of systems such as tropical cyclones, meso-scale convective systems and persistent blocking events, which drive many of the more costly impacts of climate change, nor resolve ocean currents that are fundamental to climate variability and regional climate change.[3] Furthermore, the new generation of models should be able to simulate processes presently not included or only approximately parametrized, and be able to provide more robust information on high-impact low-likelihood events, tipping points, and potentially irreversible changes in the climate system.

Meanwhile, there have been significant changes in the global economy and society that affect the future development of WCWES. The global population has doubled in the last 50 years leading to changes in urbanization and the number of people living in areas exposed to severe weather or climate change. Society is also increasingly vulnerable due to its dependence on global supply chains and national/regional infrastructure for water and energy security.

The digital revolution of the 21st century has changed how people demand, consume and act on information. The private sector remains an important player in the provision of observations and services and is increasing its role in the development and operation of parts of the meteorological infrastructure. The global climate emergency has increased the focus of policymakers on adaptation to climate change and its attribution, alongside mitigation strategies to reduce carbon emissions and their impacts. Therefore, the providers of weather, climate and water services need to consider these changes as they continue to evolve their services to remain relevant in this changing world.

Within the above context, this paper shall explore the scientific and technical challenges of the future by considering the following three questions in the subsequent sections:

- What do we see as the future demands and disruptors for WCWES?
- What are the existing and emerging capabilities that can help meet these future demands equitably?
- How should WMO move forward to meet these future challenges?

[3] Next generation climate models: a step change for net zero and climate adaptation (royalsociety.org)

2. Future demands and disruptors for WCWES

2.1 Demand for greater accuracy and local detail on the impacts of weather, climate, water, and environmental-related events in the context of a changing climate

Users demand improved accuracy and relevance from weather, climate, water, and related-environment services. They no longer wish to simply consume a weather forecast or climate scenario but are interested in the impacts of that event on their physical, social, and economic well-being. The requirement for increased accuracy, in terms of greater localization and reduced uncertainty, and better understanding of impacts has several important drivers on our scientific endeavour.

The first is improving the accuracy of NEWP systems and further quantifying the uncertainty inherent within their outputs. Storms, floods, droughts, and heatwaves, which cost us dearly, are generated by processes operating at kilometre scales, far finer than the typical granularity (50–100 km) of current climate predictions from NEWP systems. Their properties are shaped by larger-scale ocean and atmosphere circulations, but even here, our NEWP systems struggle at climate resolutions.

There are still substantial limitations regarding the representation of patterns and characteristics (frequency/intensity) of precipitation; of modes of variability such as El Niño Southern Oscillation (ENSO), Atlantic Multidecadal Oscillation (AMO), Madden-Julian Oscillation (MJO) and North Atlantic Oscillation (NAO) as well as monsoon dynamics; and of statistics of extreme events, for example associated with tropical storms and mid-latitude blocking. Uncertainty in how different components of the Earth System interact is hampered, in part, by a lack of co-located comprehensive observations across system interfaces. Particularly for more robust information on high-impact low-likelihood events, potentially irreversible changes and climate tipping points, this uncertainty represents a limitation.

Additionally, despite decades of enormous efforts by the community, biases in tropical convection and hence rainfall have remained stubbornly intractable. These have profound worldwide consequences – from the Hadley and Walker Circulations to the position and variability of mid-latitude jet streams and related weather patterns. This is because tropical convection is dominated by organized convective systems, operating at the kilometre-scale, in which the symbiotic relationship between thermodynamic heating and the kinematics of the system is crucial for their lifecycle.

These challenges limit the value of NEWP systems for impact studies and decision-making for future scenarios at regional and national levels. So, whether it be about the fidelity of the global circulation or about representing the fine-scale structure of rain-bearing systems or extremes, the current practice of working at tens of kilometres in climate prediction is untenable. Therefore, alongside increased sophistication, such as coupled atmosphere-ocean models, future NEWP systems will need to continue to improve the representation of physical (and chemical) processes at relevant scales by increasing their spatial resolution to k-scale. This will require a quantum leap in NEWP systems and in computational infrastructure. This will lead to a better representation of some of these modes of variability, using improvements that have been demonstrated within higher resolution NEWP models. WMO will have an important role in accelerating this by facilitating work at the boundary of weather and climate model development through fostering strategic international-regional to national collaborations.

Meanwhile, NEWP systems are moving inexorably to the use of ensembles by default, although further research work is required both upstream to optimize their configuration and downstream to make best use of the information which they can contain. Many challenges remain in providing skilful and reliable probabilistic forecasts, including consideration of how the uncertainties in one model component affect and interact with uncertainties in other components, and understanding the requirements for providing probabilistic forecasts for complex and/or rare events. However, this information will only be valuable if used. There must be an equal effort to support users in translating a spread of possibilities or probability of an event through effective communication and visualization to aid in decision-making, which often requires a yes or no action. All of the above requires major international research and development efforts to deliver NEWP systems on climate timescales at resolutions which can capture the critical processes. This is the primary driver behind Recommendation 1 but needs to be co-developed with Recommendation 6 because application of a system without value to the communities is worthless.

Secondly, understanding the impacts of weather, climate and water events requires integration with other geophysical and social sciences (see Box 1). For example, an extreme heat event could lead to wildfires, depending on environmental preconditions, such as soil moisture and forest management. This in turn leads to poor air quality in urban settings distant from the original event. The resultant health impacts on the population of both extreme heat and poor air quality will be dependent on behavioural and demographic factors. Hence, it can be expected that future users and policymakers may wish to receive holistic environmental services which capture the impacts of the weather-climate-water event, rather than specific or separate services from weather, climate or water agencies. This requires integration of different disciplines at the service level and at the modelling level: the impacts of flooding on coastal cities could be a complex combination of wind, waves, tides, surges and precipitation as well as how water flows are managed within that urban environment. This will require a more joined-up approach between natural and social scientific disciplines and is the principle behind Recommendation 6.

Box 1: Working with social and economic sciences to better understand weather and climate related impacts

Although social and economic sciences are not traditional disciplines of WMO, the integration of weather, climate, and environmental data with socioeconomic data provides the opportunity to predict and warn of the impacts of weather and climate on society. Therefore, it is desirable to collaborate closely with those disciplines who collect and use data on social vulnerability and resilience, human health, economic activities, infrastructure, land use, energy consumption, etc. to understand the impacts in those areas and develop relevant applications. Standards and protocols for the sharing of socioeconomic data are not nearly as advanced as those for sharing meteorological data, and privacy concerns also limit access to much relevant information, making it challenging to use those data for other purposes. Nevertheless, as the importance of social and economic sciences are increasingly recognized in understanding and improving peoples' responses to weather and climate advice and estimating and improving the socioeconomic benefit of weather information, NMHSs are finding it valuable to develop some in-house capability in this area.[4]

Finally, the attribution of extreme events to anthropogenic climate change is likely to become an important component of future climate services demanded by policy and decision makers to help understand how climate change is being manifested in weather, water, and environmental hazards and impacts. As this science rapidly advances, it will be important for WMO to provide leadership and guidance in how this science will continue to evolve. This science, in addition to k-scale counter-factual simulation with natural forcings, could depend also on real-time observational products and weather models to determine how much of a specific event can be attributed to anthropogenic climate change. Detection and attribution of high-impact weather/ climate/water/environmental events will require a very fine spatial scale and thus Exascale models need to be employed (see Recommendation 1). WMO, therefore, should ensure leadership in fostering detection and attribution research and encouraging appropriate observational and modelling capabilities around the world, particularly in vulnerable regions

[4] Acknowledgements to Beth Ebert, Bureau of Meteorology, Australia.

where extra efforts need to be made. Continued development and maturity of this area of science will increase the availability of this knowledge and the techniques in all countries.

2.2 Digital revolution and big data

In the past decade, there has been a dramatic transformation in how people receive information. The growth of personal devices in countries of all incomes across the globe means there is now an ability to reach individuals with weather information, and a desire from the user for information customized to their needs. In the UK, for example, the percentage of the public receiving their weather information through digital devices has increased from 37% in 2012 to 76% in 2020[5]. This change in user behaviour and expectations is a major opportunity for service providers and government agencies, as official warnings can now be delivered direct to members of the public. This demand places extra emphasis on the need for quality NEWP output as digital services are often driven without additional human intervention. Also, NMHSs have to develop appropriately agile strategies, perhaps in regional collaboration, to maintain an authoritative voice in a fast-changing market of many information providers, including the private sector.

Advances in modelling and from terrestrial and satellite observations, driven by the demand for more localized, comprehensive, accurate and timely information, require the meteorological community to manage much greater quantities of data than was ever previously envisaged.

There has been a step change in the availability of data on the environment. Information gathered from remote sensing, ground-based comprehensive observations (like Global Atmospheric Watch), sensor networks and low-cost devices can be brought alongside citizen science data, data mined from online sources (including social media), and synthetic data from simulation and prediction. Well-managed they will deliver unprecedented environmental insight, improved predictions and bespoke services. But this will require major investment in ‘big data’ systems, data analytics, machine learning, artificial intelligence including adequate human resources which could be a challenge particularly for middle to low-income countries. Some of these may be better achieved collectively at the regional scale to facilitate pooling of resources, and cloud computing could become an important enabler (see Section 3.3).

This challenge of rapidly expanding data volumes (also a result of the recently approved WMO data policy and Global Basic Observing Network (GBON)) will alter the way NMHSs manage data in the future. The combination of Geographic Information System (GIS)-type platforms together with Application Programming Interfaces (APIs) is potentially transformational. NMHSs will be able to provide users with the capability to access the data and produce their own service, allowing other sources of data to be utilized, such as demographic, economic and vulnerability data from other agencies. This will require novel approaches, in addition to equipping users with the required skills and provision of enabling infrastructure, to avoid new barriers for countries in exploiting global scientific outputs for local benefit. The challenges of big data and the digital revolution in service delivery are covered by Recommendation 3.

2.3 Global science having local impact

Maximizing the use of available weather forecasts, seasonal predictions and climate projections will require new ways of ensuring all countries, including low-income countries, can downscale products suitable for local sector risk reduction and resilience applications. Making more skilful NEWP forecasts at regional, local, and city specific levels timely, accessible and usable by all, by vulnerable communities, is a way to achieve a sustainable future. For WMO’s future science developments to build resilience and support global sustainability there will need to be equitable global participation in the conceptualization and development of environmental sciences for reliable and robust forecasting and prediction and delivery of services. Low-income countries will need to be positioned not just as recipients of information but as active participants in the new

[5] Source: Met Office Public Perception Survey 2020, Microsoft PowerPoint – PPS 2020_ Summary Report for Public Webpages – Read-Only (metoffice.gov.uk)

and envisaged science, development of the associated infrastructure and emerging innovative service delivery. Their participation should be meaningful and visible at the global, regional and national levels and should drive the future science agenda making research and innovation in the development of services and access to accurate, timely and relevant information a priority. This is a key challenge for delivery of the WMO Early Warnings for All Initiative and this requirement is included within Recommendation 2.

2.4 Private sector as an active player and quality assurance of services

The relationship between WMO and the meteorological private sector is a policy rather than a science issue, but it is acknowledged here as an important change in the future provision of weather, climate and water-related services and the supporting infrastructure. The WMO Open Consultative Platform white paper[6] describes how a closer partnership between government, academic and private sector bodies will be necessary to meet the scientific and technical challenges of weather and climate forecasting in the next decade.

One area where WMO should take a scientific leadership role is in the quality assurance of data, products and services. The white paper suggests that "WMO in partnership with private sector and academia, could come to an agreed methodology for validation of quality, and recognition and attribution of various providers". For example, open data policies infrequently include guidance on how to best use the data and WMO could provide guidance on how data should be created, used, and managed to ensure services have a sound scientific basis. This will be important for climate services where there is no means of objective real-time verification. WMO should consider how to help educate users to identify high scientific quality products, which may benefit the United Nations Framework Convention on Climate Change (UNFCCC) and national government agencies in charge of climate change adaptation policies, strategies and frameworks. The evaluation of services and products can also engage social sciences to assess whether people received and acted upon the intended message. Hence, it may be desirable to review the current methodology for verification to develop metrics which are more meaningful for the user. Recommendation 5 aims to address this driver.

2.5 Move towards a zero-carbon global world

The parties to the UNFCCC have, through the Paris Agreement of 2015, committed to hold global warming to well below 2 °C relative to pre-industrial values and to pursue efforts to limit it to below 1.5 °C. This stabilization requires the rapid reduction of greenhouse gas emissions, primarily CO_2, and to reach net zero carbon emissions before the middle of the 21st century. The remaining global emissions compatible with the warming limits decrease rapidly with every year of business-as-usual emissions and reaching the Paris targets becomes increasingly ambitious. This is why some pathways of greenhouse gas emissions scenarios, assessed by the Intergovernmental Panel on Climate Change (IPCC) in their latest reports, envisage negative carbon emission technologies to be employed in the coming decades. Depending on the availability and global scalability of such technologies, temporary overshoots of the Paris temperature limits may occur. Furthermore, it is crucial to ensure that natural carbon sinks are increasing.

As governments consider how best to mitigate global warming and its impacts in such circumstances, a debate emerges about ideas on geoengineering, particularly solar radiation modification. Any such climate intervention would create significant environmental, ethical, and social challenges that will require a comprehensive and inclusive scientific assessment. Such an assessment would have to consider global and regional changes that could be triggered by these interventions and their local and regional consequences for crucial resources such as water, ecosystem functioning, health, and livelihoods. In addition, it would need to investigate possible long-term commitments, risks, and unintended side effects in the atmosphere, from the surface

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[6] *WMO Open Consultative Platform White Paper #1 - Future of weather and climate forecasting* (WMO-No. 1263).

to the stratosphere, the land surface, the ocean, and the cryosphere. Furthermore, social, economic, developmental, governmental, and inter-generational issues associated with climate intervention must be addressed. In consequence, this issue concerns a range of UN organizations, and this calls for leadership which could be taken by WMO with its well-established links to a broad scientific community providing the necessary information.

Following the commitments in the framework of the Paris Agreement, strategies of governments towards a Net Zero economy have several consequences for NMHSs, as government bodies at the vanguard of weather and climate science and services. The growing energy demand of supercomputing may be in competition with increased computing needs in improving NEWP systems (see Recommendation 1). Also, a more environmentally sustainable approach to observing consumables, such as radiosondes, may be required. The new WMO Strategic Plan 2024–2027 includes objective 5.4 (environmental sustainability) that includes the commitment to achieve a sustainable, net zero and resilient world for all. Recommendation 8 builds upon strategic objective 5.4 but goes beyond through a strategy that encompasses computing infrastructure. New ways of collaboration could have positive benefits for diversity and inclusion in WMO business. WMO and the network of NMHSs could become strong voices within the UN family and in national government institutions in the move towards Net Zero.

The push to Net Zero will also open new markets for weather and climate services. As energy production shifts more towards renewables, weather, climate, water and related-environment information will become more valuable in siting and operating wind, solar and hydro power generation sites, while future energy security will be exposed to new risks from climate variability e.g. periods of low wind. This is an area for SERCOM to continue to explore.

3. Emerging and existing capabilities to help meet future needs

3.1 Exascale computing

Utilization of the next generation of computational technology will be essential for NEWP's future progress. The WMO Research Board has been developing a concept note for Exascale computing (see Box 2). Despite continued investment in supercomputing for weather and climate predictions it remains a constraint in unlocking the full potential of NEWP. Today, climate scientists and operational meteorologists have had to balance investments in resolution, complexity, ensemble size and timeliness in NEWP models to achieve the optimal outcome for the services they support. Taken together, a critical look must be taken at how best to achieve this quantum leap through coordinating global efforts for Earth System modelling and data analysis at the Exascale which is part of the motivation behind Recommendation 1.

Box 2: Exascale computing and other opportunities[7]

The ambition to substantially enhance Earth System-model spatial resolution to reduce the use of approximations for known physical processes to deliver increasing information on the water cycle, combined with data assimilation and the use of ensembles for improving uncertainty estimation leads to substantial computing and data requirements. These requirements are presently limited by the existence and affordability of extreme-scale computing and data handling infrastructures and their operation in ecologically sustainable environments. The computing and data handling challenges are nearly identical for weather and climate prediction but also value chain applications, and generic solutions can therefore benefit all areas simultaneously.

For achieving the required levels of predictive skill, science-to-service quality and user interaction with complex simulation and observation handling workflows as well as an investment in modern software infrastructures is required. This would allow exploitation of

[7] Acknowledgements to Peter Bauer, ECMWF.

diverse digital technologies across the entire range of data generation and information extraction, including smart sensors and networks but also data from the Internet of Things, edge and cloud computing, extreme-scale computing and big data handling, machine learning and new algorithmic frameworks in support of faster computing and more effective extraction of user specific information from vast amounts of data. The novel notion of digital twins for the Earth System comprises all these aspects leading to much enhanced levels of data quality and user interaction.

While novel technologies and related research programmes are increasingly being implemented in individual countries (e.g. Destination Earth in Europe) and – in selected cases – by commercial enterprises (e.g. NVIDIA Earth-2), there is a need for global, multinational coordination to maximize the return on investment, ensure that these developments benefit the entire community across high-income and low-income countries, and produce a step change for our predictive capabilities across all space and timescales. This requires a close science-technology co-design of systems and new levels of digital technology expertise being used in our community.

Looking further ahead, Quantum Computing is an exciting novel technology that could prove to be of value in weather and climate modelling and it will be wise for WMO to keep the progress of this technology under review and its applicability to weather and climate modelling as the technology matures (see Box 3).

Box 3: Quantum Computing[8]

Quantum computing was envisioned by Richard Feynman in the early 1980s when he said that this world is quantum and that it is essential that we start thinking about the quantum computer if we were to predict real life phenomena. In NEWP practice over the past 40 years, we have taken a classic route and it is only recently that many researchers in computer science have realized that quantum computers are excellent at solving very specific classes of problems with a predominantly probabilistic structure.

The emergence of quantum computing can lead to a significant increase of performance that will finally capture all crucial scales of motions from small-scale turbulence to planetary waves and provide realistic parameterizations of clouds and physical processes. Despite this daring perspective, there are still many open questions, both in the hardware and in the software domains. Until recently, quantum computers demonstrated their impressive performance only for a very specific class of quantum-friendly problems. There are, however, many possibilities to change the algorithms of the existing NEWP models, or parts of the forecast system, such as the data assimilation, to capitalize on the high performance of quantum computers. The concepts of graph theory, Feynman diagrams, and Feynman propagators will likely assist in the process of coding for quantum computers and some efforts in this direction are already underway. The central element in these efforts is a parallel discretization in time and space of the evolution equations of the atmosphere and ocean that can be computed directly on a quantum computer.

It is expected that the developments of the algorithms for quantum computing in NEWP will be completed in the years to come. The problem of the design of a large-scale quantum computer system with enough capability is much more difficult and still not solved but it is anticipated that the first reliable systems will appear within the next 5–10 years. This is supported by very optimistic announcements regarding dedicated quantum NEWP computers from various institutions.

[8] Acknowledgements to Janusz Pudykiewicz, Environment and Climate Change Canada.

3.2 Machine learning, Artificial Intelligence and Cloud Computing

Machine learning and AI algorithms have many potential applications in the WCWES value chain. Just one example is improving weather forecasts by helping remove model biases. Such approaches require reforecasting and observational data sets to act as training data for the algorithms. Many providers are already using these techniques within operational post-processing systems.

The WMO Research Board Task Team on Exascale, Data Handling, and Artificial Intelligence prepared a concept note on the use of AI and data exploitation in environmental modelling. The concept note identifies practical steps that WMO can take to support the community in developing strategies and plans to take advantage of the opportunities and tackle the challenges that are arising from the rapid research progress in this area (See Box 4).

Box 4: Research Board concept note on use of AI and data exploitation in environmental modelling[9]

Summary key points, and related recommendations, raised in the concept note:

- The rapidly evolving research creates an imperative for WMO Members to develop strategies and plans for adoption of AI methods in operational and production systems. WMO can support this by facilitating discussion between members.
- Data handling challenges are placing conventional workflows under increasing strain, creating an imperative for changes in approach. WMO can support this by facilitating discussion between members.
- While the combination of the use of AI methods and the expansion of the range of available data sets creates an opportunity for WMO Members to provide new services, there remain considerable practical barriers. WMO can support centres by facilitating efforts to elicit requirements, and by supporting the development of a coordinated roadmap to meet these requirements.
- The adoption of common standards and practice is essential to enable effective and efficient sharing of data and methods. WMO can support this through facilitating the development of guidance and standards and identifying a suitable body to take ownership of these.
- There is potential for public-private partnerships to deliver benefits through access to a combination of data, platforms, and methods. Existing WMO efforts to develop public-private partnerships provide the potential to develop this, in particular, in support of improving product delivery for low-income countries.

Cloud (or distributed) computing has the potential to democratize access to high powered computing capability. An on premise or shared national supercomputing capability would not be required to run NEWP, and large data sets can be managed within the "cloud" avoiding data handling issues. This could enable all countries, including low-income countries, to utilize the highest-quality weather and climate information. NEWP model providers and supercomputing vendors could work together to integrate multi-models (using multi-centres and at multiscale) in clusters with pre-optimization, then make those models available on the cloud as a service. Therefore, all countries could buy a cloud service to run NEWP systems or post-process global model output for their specific region in an affordable way, without the burden of future heterogeneous supercomputing, optimization of models and downloading massive amounts of

[9] Acknowledgements to Adrian Hines, Science and Technology Facilities Council,, UK.

data. The issues raised in this section are captured under Recommendation 3 and could be the way forward for the technical implementation of Recommendation 2.

3.3 Observation technologies and techniques

Good global and regional coverage of high quality, well-managed ground and space-based observations is essential for the weather, climate, water and environment enterprise: data assimilation to initiate and minimize errors in NEWP; verification of forecasts and service quality; short-timescale forecast services (“nowcasting”) and situational awareness; setting future predictions in the context of past events; detection of climate change, especially where non-linear impacts from rising temperatures are anticipated; and further understand the Earth System to aid NEWP development.

Unfortunately, in situ, high quality observation systems have decreased in number over the past 20 years in most regions of the world due to financial considerations. The most vulnerable areas, such as low-income countries, require well equipped and maintained stations that serve as early warning systems and as reference stations for complementary systems, private partnership networks, climate simulations and weather forecasts. Precipitation is particularly difficult to measure and reliable observations are not available with the required spatial density and high spatial-temporal resolution, which is a requirement if models are to be validated against observations.

As we move towards k-scale modelling, the density of observations will need to increase. While the idea of the GBON is to provide the basic surface-based observing network to support global NEWP modelling and climate analysis, it can never have the level of spatial and temporal coverage required for future applications. However, there are many complementary systems that help fill these gaps. Technological advances in low-cost communications and sensors – such as mobile phone networks, batteries, miniaturization (e.g. CubeSats) and embedded computing and data processing – offer significant potential for increased environmental monitoring. This requires understanding how to exploit mass-market sensors that are used for an alternative primary purpose and how to utilize opportunities presented by a highly connected, data-rich world – the so called “Internet of Things”.

In addition, there are many under-utilized in situ weather stations used for academic purposes. For example, many road agencies and agricultural and industrial enterprises maintain or contract out their own network, and members of the public may also have amateur observing equipment. While these observations may not meet WMO standards, if global or regional sharing arrangements could be agreed, they may add significantly to the overall system. The challenge of collating, storing and quality controlling these data, especially from “citizen scientists”, will require development and sharing of tools and expertise to use this potential resource globally. WMO will need to consider its approach to data quality and metadata standards as these complementary sources of data become commonplace.

Research and development in “non-conventional” observations will create further opportunities for complementing observing networks. Technological advances in low-cost communications and sensors – such as mobile phone networks, batteries, miniaturization (e.g. CubeSats) and embedded computing and data processing – offer significant potential for increased environmental monitoring. Information on meteorological variables can be extracted from systems designed for other purposes, including water vapour from Global Positioning System (GPS) signal delay, and from Mode S aeronautical transponder signals. Continued research in this area to explore new opportunities as new technologies arise may be crucial in attaining comprehensive and affordable data coverage while the availability and sharing of these observations should be facilitated under the WMO Unified Data Policy.

While these complementary observations may increase the spatial and temporal resolution of networks, there remains the challenge of what is the optimum balance of satellite, surface-based and other observations for any particular use case. Forecast sensitivity studies are a useful research tool in understanding the sensitivities and help target investment to maximize benefits. For NEWP, data assimilation systems will need to be designed to accommodate novel observation sources. This critical dependency between observations and NEWP necessitates any future global efforts for Earth System modelling and data analysis (see Section 3.1) should also include the integration of the development of comprehensive observations with multiscale models. For example, coupled prediction systems will have a need for co-located observations across system interfaces (e.g. the atmospheric boundary layer and ocean mixed layer) both for model development and evaluation, and forecast initialization. Alongside there is the need for global and comprehensive in situ observations, like Global Atmospheric Watch (GAW), data bases with open data access, metadata, quality monitoring, and high spatial and temporal resolution to meet the needs of WCWES. These comprehensive observations are crucial to understand the Earth System and to be able to answer research, societal and policy relevant questions, for now and the future. Because of the importance of observations, they are explicitly captured within Recommendation 1.

3.4 Evolving international frameworks

International cooperation is a strength of WMO. Many of our historic successes have come from working across national boundaries, pooling knowledge and resources, and providing advice and capability on the global, regional and national scale. This ability needs to be leveraged to its maximum extent to ensure that science and technology advances are translated into local beneficial impact, noting that many emerging technologies will be of greater value to society operating under regional and other evolving frameworks.

We have already identified that further global science collaboration will be necessary to fully exploit the opportunities enabled by Exascale supercomputing and observations. However, such global efforts can only deliver benefit at the local level if there also exist the mechanisms to enable all countries to exploit and utilize these advances in their weather, climate and water services. The WMO Global and Regional Climate Centres, NMHSs, and relevant local users' sector-based institutions need to work together in the co-designing, delivery of multidisciplinary research products and services, as well as in the development of the required local and regional capacity for seamless integrated modelling and downscaling capabilities.

There is an opportunity for WMO Regional Associations and regional institutions to take a more proactive role to ensure that global science is translated into local impacts. For example, regional WMO centres could work with the Global Framework for Climate Services (GFCS) on specific common service requirements that benefit NMHSs collectively within a region. Investment in infrastructure and skilled people will be critical for regional and national institutions. Working across and within international organizations and structures is critical to deliver all the recommendations.

3.5 Preparing our people

Advancing the skills of our people at all parts of the weather, climate and water value and knowledge-chain in a gender equal, diverse and inclusive way is essential both within the NMHS community and academia, especially in low-income countries.

Impact-based services require a new approach to education in the development and communication of services involving engagement with several disciplines beyond those of the traditional weather, climate and water enterprise. These include finance, risk management, and communication skills. In addition, training will be necessary in methodologies that usefully bridge these disciplines, such as whole systems thinking, and co-designed science and co-production of actionable knowledge to ensure that connections to affected sectors are made explicit. However, this must not be at the expense of education in traditional weather, climate and water disciplines.

The potential advances described in preceding sections have the potential to revolutionize the science underpinning environmental services. This demands engagement with emerging fields, especially innovators in computing and data science, machine learning, instrumentation development, autonomous and space-based platforms, and novel infrastructures (e.g. through smart phones). Application programming interfaces are revolutionizing the user experience and provide the potential for crowd-sourcing new forms of data and information in culturally appropriate ways.

Appropriately educated practitioners, researchers and teachers is critical, but similarly the receivers of their knowledge-based products and services – from policymakers and decision makers to communities – can benefit from an enhanced understanding of the value proposition of their national services, and of the benefits and limitations of services being delivered. Many decision makers are seeking salient and timely knowledge support, but often don't know what to ask for or how to interpret what they receive. This will become particularly important as advances in NEWP lead to more sophisticated and nuanced data sources, such as sub-km models and ensembles, which will require expert interpretation to extract relevant information for decision and policymakers. Recommendation 7 deals with the issues around people development.

4. Recommendations: How should WMO respond to meet these challenges?

The Vision Paper has attempted to identify the drivers, disruptors and enablers which will impact WCWES over the next two decades. This has identified scientific, technical and social imperatives which can be categorized as follows:

- The capabilities to advance the underpinning science such as new approaches to observations and improved representation of physical and dynamical processes will depend critically on the advent of global k-scale NEWP systems.

- New or emerging technologies to advance science and services, which include machine learning and AI, cloud computing, digital services and comprehensive observations.

- Approaches to ensure that science advances can be translated into improved and more user-oriented services. This requires international partnership, developing our people, further integration across other geophysical and social sciences to better understand impacts, and improved ways of handling increasing volumes of data.

To address these issues, the paper makes the following recommendations to the WMO Congress and Executive Council. The first three recommendations, if delivered successfully, can be thought of providing a "game-changer" for WCWES over the coming decades. The further five recommendations will complement and help enhance the benefits that will derive from the first three recommendations.

4.1 Major recommendations of the Vision Paper

Recommendation 1: Major international climate R&D effort in the exploitation of global k-scale computing and Earth System observations.

The development of global k-scale NEWP and General Circulation Model (GCM) systems running ensembles on climate timescales, with environmental observational data sets and data analysis is necessary to meet global future needs for weather, climate, water-related information particularly to address climate change mitigation and adaptation. The possibility exists today for predictions of the world's climate to be delivered by a new generation of global models that explicitly resolve k-scale phenomena, such as rain-bearing systems, ocean eddies, ice dynamics and land surface exchanges. Physical models operating on this scale are now being built at various national centres, but the scale of the scientific challenge of building a trustworthy, fully coupled k-scale climate-scale NEWP system, with all its non-linear interactions and feedbacks necessary to understand the long-term behaviour, as well as potential risks associated with high-impact low-likelihood events, tipping points and irreversibilities, is immense. Currently, there is no clear path for accelerating the development of this new generation of models into predictive systems capable of providing the quality of information needed to guide adaptation and guard against catastrophic changes.

To realize this global k-scale goal requires a quantum leap in the coordination and international collaboration between WMO Members. The collaboration needs to consider the technical questions of coordination of availability of Exascale computing; the scientific challenges of developing NEWP systems at k-scale; and in the optimal application and development of observing systems to underpin the modelling. Existing strategies such as model intercomparison studies and data sensitivity experiments would need to be core activities to assess the benefits of different NEWP model configurations for global k-scale climate simulation. Additionally, the future prospects for machine learning and quantum computing for NEWP systems will need to be continually re-assessed. It is anticipated that k-scale global re-analyses and climate simulations will be the basis to deliver ML based emulators to explore a broader space of the climate variability of adaptation/mitigation options.

The form of global collaboration will need to be agreed amongst Member States. It could take the form of a virtual global laboratory, a network of centres, or a pyramid structure. The collaboration should also focus on empowering select regional centres of excellence to build homegrown capacity that can enable effective participation and contribution to climate services and innovations that can match with expanding user-demands. In addition, the computing infrastructure should be environmentally sustainable with the development and implementation of a Net Zero strategy.

Existing initiatives and gaps

Work is underway in several centres on a regional or national basis to develop global models at the k-scale. For example, the European Commission is funding an initiative called Destination Earth (DestinE) between ESA, ECMWF and EUMETSAT to develop several "Digital Twins" of the Earth to monitor and simulate natural and human activity which will include k-scale global modelling. Other initiatives include DYAMOND (Dynamics of the Atmospheric general circulation Modelled on Non-hydrostatic Domains) and the World Climate Research Programme's (WCRP) Digital Earths Lighthouse Activity. As part of this activity, the WCRP hosted a k-scale modelling workshop[10] in October 2022 that produced several important scientific and technical recommendations to accelerate progress towards k-scale modelling. Additionally, the WMO Research Board has published a concept note on the potential of Exascale computing (see Section 3.1). This recommendation aims to accelerate these efforts by seeking a major coordinated global climate R&D effort rather than relying on disparate efforts mainly focused on high-income countries. This global effort would ensure that the fruit of this scientific research is available for all and by delivering this in hand with recommendations 2 and 3 below, we can ensure that all countries will benefit and can use this cutting-edge science in helping promote their sustainable development. Furthermore, GAW and several international initiatives (like Global SMEAR) and research infrastructures (like ICOS, ACTRIS, eLTER) can provide needed in situ data to verify models and also provide seamlessly new processes and feedbacks to NEWP systems.

[10] Report of the WCRP km-scale modeling workshop

Recommendation 2: Bridge the gap between developing global science and delivering local impact

The demand for greater accuracy and local detail on the impacts of weather, climate and water-related events in the context of a changing climate is increasing (Section 2.1). However, the benefits of this global investment will not be achieved without ensuring the output of this science is available for use in regional and national services. Thus, the second recommendation is to bridge the gap between developing global science and delivering local impact. We need to take an end-to-end approach beyond disciplines and sectors ranging from cutting-edge science to generation of societal benefits and from local to national, regional and international scales. The scientific collaboration will only help deliver the WMO vision if, at the same time, efforts are made to ensure that all WMO Members are able to exploit the improved science and capability in the delivery of their weather, climate, water, and related-environment services.

Investment in global science must incorporate equity to avoid perpetuating and enhancing the disparity in service provision between high and low-income countries. Our global science endeavours must lead to improved access and positive impact in services in all countries, otherwise all that global investment would be in vain. To promote the end-to-end approach, WMO should encourage related stakeholders, including public-private engagement (PPE, e.g. cloud service providers), to develop platforms where they can work together in interdisciplinary and transdisciplinary ways by making maximum use of data integration and analysis functions as common infrastructure and strengthening capacity building programmes. This could be achieved by, for example, encouraging the Regional Associations to consider necessary reorganization in order to have a more proactive role in facilitating regional collaboration in the development of future weather, climate and water-related services under the climatological and social commonality.

Key areas of focus should include:

- Co-designed multidisciplinary research for improving environmental forecast skill and reliability, across temporal and spatial scales.

- Improved observation (in quality and spatially), product and service information delivery.

- Developed scientific and institutional capacity from global to local scale.

- Provision of environmental services and user interface platforms with PPE (e.g. cloud services providers).

Existing initiatives and gaps

Recent, ongoing or planned WMO research activities with global reach but locally directed applications should inform a sustainable framework for deploying and maximizing global science for addressing local impacts. Examples include the World Weather Research Programme's (WWRP) HiWeather project and science to services research projects/pilots which have potential to translate into game-changing products and services that address local risks to climate extremes and socioeconomic impacts especially in more vulnerable developing countries.

The newly articulated WCRP Lighthouse Activities that include a better understanding of rapid-onset, high risk extreme events need to be developed within a framework that will leverage the cutting-edge science undertaken through pilot studies to be more translatable and transferable for improving solutions for local impacts.

The GFCS is also another WMO programme that set forth to not only create a user interface for mainstreaming climate services into critical socioeconomic sectors, from global to national level. Embedding new cutting-edge and innovative global science research and prediction within this framework could potentially ensure that global science contributes to improving national climate services, thus delivering local impacts.

A continual challenge for WMO has been that the work conducted within Regional Associations and Technical Commissions relies on volunteers and the limitations to both the numbers and skills of this resource make it difficult to deliver this pull-through of new science at the pace demanded by Members. The coordinated efforts envisaged in Recommendation 1 and funded by governments either directly or through international institutions must extend into the application of this science into services, especially for low-income countries, and hence ensure that this gap is bridged in a sustainable manner.

Recommendation 3: Development of a WMO Digital Strategy

This recommendation is a necessary pre-requisite for WMO to achieve the first two recommendations. WMO should develop a Digital Strategy with a focus on enabling effective access to ever-increasing volumes of data (through INFCOM) and utilizing digital approaches to service delivery (through SERCOM). The strategy should pay due regard to the opportunities afforded to weather, climate and water-related services by new technologies, including cloud computing and artificial intelligence/machine learning, and ensure that these are implemented in ways that help increase scientific equity between Members. In this way, Recommendation 3 becomes a mechanism to support the implementation of Recommendation 2.

Existing initiatives and gaps

WMO has been leading in the sharing of real-time meteorological data between Members for over-half a century, first through the Global Telecommunications System and more recently through the WMO Information System (WIS). The WIS saw the advent of a move to a “pull” rather than “push” methodology anticipating the cloud computing environment that is ubiquitous today. Within Europe, ECMWF and EUMETSAT have developed a “European Weather Cloud” to enable greater access to and manipulation of data, and several NMHSs are examining cloud solutions for their computing requirements. Given the likely quantities of data emanating from a global k-scale climate model, recommendations 1 and 2 can only be delivered with a holistic data sharing solution for facilitating scientific research and enabling the exploitation of the data within national services. While several centres and the private sector have been exploring the utility of AI and ML in NEWP systems and post-processing, through these recommendations these techniques should become more globally accessible and support Members in detecting extreme events and attributing to climate change.

4.2 Further recommendations

The following recommendations are considered critical and well aligned with WMO’s mission but do need urgent attention. They would complement the delivery of benefits from Recommendation 1 but are not as essential as recommendations 2 and 3 in achieving the quantum leap in weather, climate and water-related services envisioned in this paper. The exception is recommendation 8 which recognizes that if the science and services provided by our community are going to demand environmental policy changes from governments and communities then those science and services should themselves be delivered in an environmentally responsible way.

Recommendation 4: Accelerate the development of attribution science and techniques.

Detection and attribution products will become an element of climate services demanded by policy and decision makers. The underlying science requires observations and weather models and information to be produced in near real-time. WMO, therefore, should ensure leadership in fostering detection and attribution research and encouraging appropriate observational and modelling capabilities around the world, particularly in vulnerable regions.

To address future needs, attribution studies will need to be carried out rapidly, with high confidence, by independent experts using internationally agreed methodologies and definitions in order to avoid potential political and ethical biases. WMO can play a leadership role in not only advancing attribution research and addressing global data gaps, but also facilitating international agreement on appropriate methodologies and definitions and effectively communicating the potential uses of attribution science for society.

Existing initiatives and gaps

What is already being done: WCRP's Lighthouse Activity on Explaining and Predicting Earth System Change includes a Working Group on Integrated Attribution, Prediction and Projection. This Working Group aims to 1) establish and apply attribution methodologies to help explain multiannual to decadal changes in the climate system; and 2) design and build an operational capability using these attribution methods.

Recommendation 5: Further development of quality assurance strategy for weather, climate, water and related-environment services

Prospects for delivery of WCWES will continue to increase dramatically, including frequency of their updating in all aspects (monitoring and prediction, but also climate change projection) and variety of products. While private enterprise rests on a sound public sector, the "last mile" – getting the right message to the right user at the right time – is becoming a territory where a trustful collaboration between NMHSs and the private sector does not have acceptable alternatives. In terms of transparency and trust, with increasing numbers of service providers, WMO and NMHSs need to take the lead in developing approaches to provide quality assurance of services at the global and national level correspondingly. It is pivotal that users can have confidence that the services they are consuming are scientifically robust for the purpose to which they are being put. Quality assurance measures must be implemented at an international level with WMO playing a leading role in the endorsement of services. WMO, in partnership with other actors ideally under an international agreement, should develop a strategy for validation of quality and recognition and attribution of various products.

Existing initiatives and gaps

WMO has developed a number of quality management system approaches for aviation, climate, marine and hydrology sectors under the auspices of SERCOM. However, a quality management system does not necessarily assure the scientific integrity and quality of output and it is this aspect which requires further work to ensure that all users can benefit from the scientific advances that are expected to be seen in WCWES over the coming decades.

Recommendation 6: Work across agencies to enable closer integration of geophysical and social sciences to support better understanding of the impacts of weather, climate, and water events

With users demanding services more focused on impacts of events, there is a need to integrate meteorology, hydrology and oceanography with other geophysical, chemical, biological and social sciences, including socioeconomics, to better understand and describe these impacts, attract policy makers and civil society, and support their consensus building. This should be advanced at all levels (global, regional, national) with WMO having an objective to facilitate the further integration of weather, climate and water science and services to support the growing demand for relevant and timely information on environmental impacts. To achieve this objective, WMO strengthens data integration and analysis functions beyond disciplines and sectors and supports platform activities to encourage interdisciplinary and transdisciplinary cooperation. An initial focus on both fluvial flooding and impacts on urbanized coastal communities is seen as a priority.

Existing initiatives and gaps

Efforts to integrate meteorology, hydrology and oceanography with other geophysical and social sciences to better understand and describe the impacts of weather, climate, water, marine and related environmental hazards is a top priority for SERCOM with each of its six Standing Committees for services (Disaster Risk Reduction/public; aviation; climate; agriculture; hydrology; and marine/oceanography) and three Study Groups (Health; Energy and; Urban). These are closely coordinated at working and Secretariat levels and through the SERCOM Management Group to ensure that good practices are shared and the necessary integration is indeed taking place.

WMO has a long history of working with international organizations in partnership to co-sponsor and deliver programmes. Examples include, inter alia:

- Global Climate Observing System (GCOS) co-sponsored by WMO, IOC-UNESCO, UNEP and ICSU
- World Climate Research Programme (WCRP) co-sponsored by WMO, IOC-UNESCO and ISC
- IPCC co-sponsored by WMO and UNEP

The challenge is not to develop further bilateral or single sector/discipline partnerships but to start moving towards a genuine multi-hazard impact approach working across disciplines and with multiple partners. The WMO Early Warnings for All Initiative, launched in March 2022 by the UN Secretary-General as a core deliverable in the UN's climate change adaptation plans, is a cross-body initiative being led by SERCOM, with the aim of ensuring easy and timely access to (impact-based) multi-hazard warnings for everyone on the planet by 2027. Key to the success of this initiative is the need to work with all sectors including funding agencies, other UN bodies, the private sector and academia to address and integrate all components of the science (including social science), observations, modelling, technology, forecasting, services, and the communication value cycle to deliver warnings and advice that are useful, usable and used.

Recommendation 7: Develop training strategies to broaden expertise beyond traditional disciplines

A move towards impact-based services and the use of new technologies will require a broader knowledge base for practitioners, including those on the demand-side, for weather, climate, water, and environment information to be effectively exploited for user benefit. Broadening the knowledge of practitioners in the weather, climate, and water enterprise to include aspects of social sciences will be necessary to support the development and delivery of services which are more focused on impacts. This will likely require a different approach to training, increased incentivisation of cross-disciplinary research that informs teaching in concrete ways, and the development of new training strategies and skills in co-design and co-production of services. Training strategies should include definitions of climate experts, easy-to-access education tools, and courses like Climate University activities as well as pedagogical research to identify the best practices in education and knowledge transfer (Recommendation 2) and new items such as developing and utilizing early warning systems. Additionally, school and university teachers, different stakeholder groups, and climate experts should be included in the education systems. It is foreseen that NMHSs will implement these training strategies, where capacity exists, as well as regional bodies.

WMO should support an acceleration of knowledge sharing between supply-side and demand-side participants on interlinkages between sustainable development and disaster resilience via weather, climate and water. The aim will be to develop a greater appreciation of how users apply weather, climate and water information within their domain and for users to better understand the utility of that information, enhancing the pull-through of science improvements into impactful outcomes. To promote these two-way cooperative works, WMO should foster "Facilitators" who can identify local problems, provide professional advice, support consensus building, and lead the way toward resolving problems. Development of skills in applying new technologies – such as cloud computing, AI, Machine Learning, and low-cost and state of the art sensors – will be essential if the benefits of the game-changing recommendations are to be realized. The implementation of a WMO Digital Strategy (Recommendation 3) may be critical in this regard.

Existing initiatives and gaps

WMO should build on its existing training infrastructure, including the WMO Global Campus and other international initiatives like Climate University, in low-income countries and develop a framework for targeted training that can take advantage of anticipated advances in Exascale modelling, digital twinning, and other enabling technologies for customization of relevant information generated by new global science to improve local, impact-oriented, climate services. Intellectual twinning of expertise from high-income countries/advanced centres with low-income country experts in addition to the rethinking of partnerships among WMO institutions (lead by Regional Associations) in low-income countries with other regional and global actors.

Recommendation 8: WMO, together with NMHSs, provide leadership in the move towards Net Zero

WMO has the opportunity to (i) develop and implement a net zero strategy for its own operations in three important pillars of building management, working organization and computing infrastructure, (ii) encourage and assist the NMHSs to develop their own plans to move towards Net Zero and (iii) champion the pathway to Net Zero across the wider UN family. This is a new initiative within WMO, although several Members' NMHSs are already moving in this direction.

5. Conclusion

The *SAP Science and Technology Vision Paper* has set out several recommendations for how WMO, its Members, and the wider international community can address and meet the future demands for WCWES in a world impacted by climate change.

Weather prediction already provides a remarkable service to the world and will play an increasingly important role in delivering the UN call for everyone on Earth to be covered by early warning systems within five years. In comparison, climate prediction and services, especially related to adaptation, resilience, and loss and damage, are far less developed. As recent unprecedented events have demonstrated, urgent action is needed.

Within the next decade our goal should be the operational delivery of timely, reliable, and relevant information on future climate risks, especially for the most vulnerable nations, and to help secure a safe future for all people as well as the natural world on which we depend.

To achieve this goal underlying Recommendation 1: Major international climate R&D effort in the exploitation of global k-scale computing and Earth System observations, we should seek a new level of international collaboration that optimizes our resources around a common endeavour – to deliver a small set of world-class k-scale global climate models. These models will provide reliable and regularly updated predictions of our evolving climate risks, including local changes in daily weather patterns and damaging extremes, regional shifts in seasonal and longer-term climate variations, high-impact low-likelihood events, and abrupt regime shifts and tipping points. The international scientific workforce needs to be mobilized to bring together the range of skills from numerical methods, computational science, atmospheric and ocean sciences, terrestrial systems, data analytics and so on.

These efforts will need to be supported by dedicated Exascale computing and data facilities powered entirely by renewable energy sources to be aligned with Recommendation 8: Provide leadership in the move to Net Zero. These will provide a shared environment in which the development and evaluation of this new generation of models can be accelerated beyond current national efforts. The computational power to deliver this quantum leap to k-scale is realizable today with opportunities to shape next generation computer architectures around our needs.

Ultimately our mission must be to build operational k-scale climate prediction systems with time horizons from years to several decades. These systems will need to be initialized with the current state of the climate system through data assimilation, so we will need to strengthen the important links between numerical weather prediction centres and those delivering global observing systems. This will ensure an integrated approach between advances in observing networks and modelling systems, which should consider both operational and research networks, develop observing protocols, promote data flows, design new metrics for model evaluation and encourage greater data sharing between different institutions and disciplines.

This endeavour will facilitate the delivery of seamless and comprehensive data platforms for weather, climate, water, and environmental observation and re-analyses datasets, supported by novel global k-scale data assimilation capabilities. This will serve to underpin new and emerging needs by providing more robust detection and attribution of climate change for a much broader range of environmental parameters as proposed by Recommendation 4: Accelerate the development of attribution science and techniques.

This step change in climate modelling and predictive capabilities will offer the opportunity to transform operational climate data services. As discussed in Section 2.2, the data “avalanche” from k-scale models will mean a profound shift in how users interact with the predictions. Cloud-based data platforms and data management techniques used to store data and provide tools to turn model outputs into usable information, would realize part of Recommendation 3: Development of a WMO Digital Strategy. Close involvement with the information technology private sector will be essential. To ensure the integrity of climate data services, it will also be essential that they are informed by the deep understanding of NEWP systems performance and predictive skill as requested in Recommendation 5: Further development of quality assurance strategy for weather, climate, water and related-environment services. The goal is that these climate data services will provide authoritative sources of information for the benefit of all.

But even that is not enough. We need to work with users so that they can interact with such systems in ways that spur innovation in the use of this new level of climate information. Advances in data analytics and digital technologies offer new opportunities for evaluating and interrogating this new class of predictions and for delivering bespoke climate services that address each nation's need to quantify their risks entailed by local manifestations of global changes.

Currently, climate risk assessments are frequently done in a very fractured approach, with very little dialogue between the climate scientists, the producers of climate data and those who translate them into impacts. Recommendation 2 of this paper stresses the need to bridge the gap between developing global science and delivering local impact. Hence, translating climate data into actionable information by marrying climate predictions with sector-specific science and modelling systems, such as flood inundation, water resource management, crop production, renewable energy generation, etc., will be critical. There is also an urgent need for significant investment in interdisciplinary science for impacts and solutions, which takes a holistic, end-to-end approach from the core climate science and predictions to the 'on-the-ground' needs of the users. This is aligned with Recommendation 6 of the paper to enable closer integration of geophysical and social sciences.

This proposition for increased international collaboration on future climate risk should not be seen as an exclusive activity for those with the capability and resources to engage with world-leading science and technology. If this is to deliver for the world, then it must engage with and support all nations, whatever their competencies and needs. It should seek to build capability and expertise across all those whom it supports. To this end WMO needs to nurture more opportunities to engage with the broad spectrum of users and stakeholders of climate information to provide training, advice, and support on how best to deploy the expertise and products for their own specific needs. The success of this endeavour will require a continuing injection of new talent and the fostering of a new generation of cross-disciplinary researchers and practitioners. This would contribute to delivering Recommendation 7: Develop training strategies to broaden expertise beyond traditional disciplines.

Finally, in terms of outreach to the global community, and to ensure that WMO engages with and fosters the full breadth of science and technology required to deliver the *SAP Science and Technology Vision Paper,* it will need to instigate time-limited actions to bring together diverse groups of scientists to work together in an inter-disciplinary environment, supported by well-founded data facilities on topics that will enhance the capabilities of their home institutions. The two remaining recommendations of this report could be addressed through these proposed actions.

How some of these recommendations could be prioritized, refined, and implemented is not within the scope of this paper. This will be the choice of WMO and its Members, to decide the way forward for the *SAP Science and Technology Vision Paper*. Nevertheless, whatever approach is favoured, given the urgency of the challenges facing society and the potential now for accelerating and coordinating existing initiatives, work should start immediately to increase collaboration and cooperation between existing centres to enable the outcomes of scientific endeavour described in this paper to become reality.

Glossary

AI	Artificial Intelligence
AMO	Atlantic Multidecadal Oscillation
API	Application Programme Interface
AR6	IPCC Assessment Report Six
ENSO	El Niño Southern Oscillation
GAW	Global Atmospheric Watch
GBON	Global Basic Observing Network
GCM	Global Circulation Model
GFCS	Global Framework for Climate Services
GIS	Geographic Information System
GPS	Global Positioning System
IPCC	Intergovernmental Panel on Climate Change
MJO	Madden-Julian Oscillation
NAO	North Atlantic Oscillation
NEWP	Numerical Earth system Weather-to-Climate Prediction
NMHSs	National Meteorological and Hydrological Services
SAP	Scientific Advisory Panel
UNEP	United Nations Environment Programme
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNFCCC	United Nations Framework Convention on Climate Change
WCWES	Weather, Climate, Water and related-Environment Services
WHO	World Health Organization
WMO	World Meteorological Organization

Annex 2 to Report by the Chair of the Scientific Advisory Panel

Future Topics for 2023 and beyond

Surprises in the climate system: A need to inform climate services

1. The detailed high-resolution paleoclimatic records have demonstrated that perturbations in the Earth System can lead to abrupt, non-linear, often irreversible changes at local, regional and global scales. These will modify the background on which weather variability is experienced. The Earth System thus exhibits limited stability which is underscored by modelling studies of the coupled atmosphere-ocean-sea ice-land ice-vegetation system. Such changes encompass regime changes in atmospheric circulation, shifts in the hydrological cycle and in extreme weather statistics, ocean circulation changes, large-scale vegetation changes such as the extent of the boreal forest and the Amazon rainforest, monsoon systems and ice masses in Greenland and Antarctica. In the public, such changes are iconically referred to as crossing of tipping points, or surprises. A more impact-based term for such changes is HILL events, i.e., high-impact-low-likelihood events.

2. It is evident that the local and regional impacts of such surprises, or HILL events, could be large and could exceed changes that are normally anticipated in classical projection scenarios that are used by decision makers and climate services. The dynamical understanding of the non-linear coupled Earth System, however, is currently incomplete and far from being able to provide useful information for those that are potentially exposed to HILL events. Models using appropriate scenarios, however, would develop meaningful storylines which would be needed to assess risks associated with HILL events. While the proximity to tipping points may not be predictable now, such changes are often preceded by early warning signals in observable variables at specific locations. This would require both remote and in situ monitoring efforts, e.g., of critical ice streams in Greenland and Antarctica, of ocean circulation in the North Atlantic and in the Southern Ocean, of sea ice extent and of land surface properties. In addition to adaptation and mitigation required by the Paris Agreement, this provides an opportunity for societies to design prevention strategies and take protective measures for HILL events.

3. In order to provide better information for decision makers and more comprehensive climate services which include the possibility of surprises and their local and regional impacts, the following steps are proposed:

(a) The WMO SAP, in close collaboration with the WMO Research Board, designs a long-term strategy to improve the tools that could provide the information on impacts caused by abrupt, non-linear changes in the climate system that could materialize in the next few decades. A specific focus on HILL events in the forthcoming seventh assessment cycle of the IPCC would deliver important input into the development of this strategy.

(b) The WMO SAP builds the strategy on three pillars: (i) physical understanding of the non-linear interactions between the climate system components and their sensitivity to perturbations by analysing large ensembles of models; (ii) a hierarchy of models, from simple models able to explore the full range of plausible outcomes, to high-resolution climate models able to better represent small-scale processes that stabilize or destabilize the climate system on regional and global scales; and (iii) targeted observational systems that monitor changes at critical locations in the climate system where early warning signals are expected. Each of the three pillars has a strong link to the other strategic activities of the SAP.

(c) The SAP will suggest to WMO to strengthen links across the science and service areas within WMO. This would enable climate services to include HILL events into their strategies and open the door to link to other UN organizations such as UNEP, WHO, FAO, and others for whom knowledge on potential climate surprises and HILL events are equally relevant.

(d) The strategy would enable WMO and the scientific community to design: (i) new research foci, e.g. within WCRP; (ii) targeted observational campaigns to monitor early warning variables in the atmosphere, ocean and the cryosphere; (iii) experiments and simulations with a hierarchy of climate models, including a new generation of high-resolution climate models; (iv) a new generation of climate change scenarios, based on (iii) which include the effect of surprises in the climate system and which will provide essential information to climate services.

Big data in Earth sciences: Making it accessible for everyone

4. As technology advances, we're gathering more and more data from different sources, such as observations from land, ocean, and atmosphere, satellite images, and Earth system models. This "big data" helps us address important global issues like climate change, air quality, water and food supply, biodiversity, and more. However, the huge amount of data we collect also presents challenges in data quality, storage, management, and accessibility.

5. Big data is crucial for solving current and future problems, so we need to make it available and easy to use for everyone. Here's how we can do this:

(a) Encourage open data sharing and storage through platforms and structures that everyone can access. We should also use advanced AI and data mining techniques to better understand and use the data. It's important to make sure that people in developing countries have equal access to big data and its benefits, especially for weather, climate, and environmental services.

(b) Develop consistent measurement protocols and data standards to ensure the quality and reliability of the data we collect. With the increasing use of low-cost sensors, proper calibration systems are needed. We should also connect with existing standardization efforts, such as those by the European Committee for Standardization (CEN) and WMO.

(c) Create a network of supersites that takes the full advantage of the existing atmospheric and environmental observations conducted, for example, through harmonized infrastructures, such as WMO-GAW, ICOS, ACTRIS and eLTER and considering the benefits of co-location of the observation as implemented in advanced flagship stations like SMEAR stations. Further expansion is to include low-cost sensors and distributed observations to expand the spatial scale of the stations. As a whole, this would help gather data from different sources and improve our understanding of the Earth system.

(d) Under WMO's leadership, establish a global observatory for comprehensive data sets on weather, climate, water, and the environment. This would provide a real-world component for digital twins and help connect in situ observations, remote sensing, and multiscale model data.

(e) Improve big data access and use in developing and least-developed countries. To bridge the gap between high- and low-income countries, we need to address inequalities in infrastructure, skills, technology, and training. Support from WMO and public-private partnerships will be crucial in building effective data-sharing frameworks.

(f) Ensure seamless data flows for knowledge transfer, education, services, and addressing global challenges. This would lead to new scientific breakthroughs and societal benefits.

6. To truly benefit from big data, open access is essential. However, there are many barriers we need to overcome, such as a lack of documentation, misunderstandings, and technical difficulties. Building mutual trust, understanding user needs, and promoting open data access will enable us to make new discoveries and improve our world.

7. Finally, it’s not just about the volume of data, but also its quality and traceability. WMO, national meteorological organizations, and international research infrastructures play a critical role in ensuring data quality. Additionally, we need to consider the sustainability of data provision and access, such as through energy-efficient processing in data centres.

NEWP in support of clean energy transition and sustainable development and economies

8. Meteorological, hydrological and climate conditions influence a wide range of operational, tactical, and strategic decisions that guide the evolution of weather-sensitive social and economic activities over the course of a given day, week, season, year, decade or lifetime.

Examples include products and services designed to locate aquacultures in the most suitable environment, facilitate more efficient transportation of goods, or optimize clean energy production.

9. Increasingly, decisions must be made with greater consideration of the implications of anthropogenic climate change, resource depletion and degradation in terrestrial, aquatic and atmospheric environments, and inequities in the distribution of wealth and capacity to manage environmental, social and economic risks. For example, the development of sustainable infrastructure projects that require substantial initial investments, such as water catchment basins in drought-prone regions or renewable energy farms, should integrate reliable weather and climate information.

10. The foci of investment, scientific and technological advances in weather and climate centres cannot be agnostic to these concerns. There is a pressing urgency to explicitly position Numerical Earth system Weather-to-Climate Predictions (NEWP) as a catalyst for the growth, efficiency and successful transition of the global economy and society towards a more sustainable and equitable future. Existing or more easily produced information such as short-term renewable energy potential maps or basin water renewal time produced over-various present and future scenarios will be framed with sustainable development in mind.

11. Topic will further frame this focus, canvas Members to assess current efforts, and establish a set of priorities [economic sectors, regions] and measures of success.

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