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Article

Advancing Weather and Climate Forecasting for Our Changing World

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ABSTRACT: Our world is rapidly changing. Societies are facing an increase in the frequency and intensity of high-impact and extreme weather and climate events. These extremes together with exponential population growth and demographic shifts (e.g., urbanization, increase in coastal populations) are increasing the detrimental societal and economic impact of hazardous weather and climate events. Urbanization and our changing global economy have also increased the need for accurate projections of climate change and improved predictions of disruptive and potentially beneficial weather events on kilometer scales. Technological innovations are also leading to an evolving and growing role of the private sector in the weather and climate enterprise. This article discusses the challenges faced in accelerating advances in weather and climate forecasting and proposes a vision for key actions needed across the private, public, and academic sectors. Actions span (i) utilizing the new observational and computing ecosystems; (ii) strategies to advance Earth system models; (iii) ways to benefit from the growing role of artificial intelligence; (iv) practices to improve the communication of forecast information and decision support in our age of internet and social media; and (v) addressing the need to reduce the relatively large, detrimental impacts of weather and climate on all nations and especially on low-income nations. These actions will be based on a model of improved cooperation between the public, private, and academic sectors. This article represents a concise summary of the white paper on the Future of Weather and Climate Forecasting (2021) put together by the World Meteorological Organizations' Open Consultative Platform.

KEYWORDS: Climate prediction; Nowcasting; Operational forecasting; Seasonal forecasting; Numerical weather prediction/forecasting; Artificial intelligence

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Our changing world dictates the need for substantial forecast improvements in numerical Earth system and weather-to-climate prediction (NEWP). One challenge facing society as evidenced in daily news headlines is the increase in extreme weather events with, for example, in 2021, record-breaking cold in the U.S. Southern Great Plains, heat in the Pacific Northwest followed by wildfires, devastating flooding in Europe, Canada, Australia, and China, and rain-induced landslides in India. A statistical analysis from Munich Re's NatCatService 2019 database reveals that 1,383 weather-related natural disasters took place across the globe from 1980 to 1985 and the number grew to 4,020 registered events from 2013 to 2018 (Fig. 1). Human influence in extreme events was already shown in the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (AR5; IPCC 2013). Subsequently, the AR6 report concludes that a warming climate plays a role in increasing extremes in heat, drought, rainfall, wildfire, tropical cyclone intensity, and flooding (IPCC 2021). The need for improved weather and climate forecasts is also driven by this increase in extremes occurring against a backdrop of nonclimatic global trends that include biodiversity loss, unsustainable consumption of natural resources, degradation of ecosystems, human demographic shifts including rapid urbanization, social and economic inequalities, and a pandemic (IPCC 2022). For example, the dramatic loss of Arctic sea ice associated with a warming climate has also led to damaging shoreline erosion, changes in shipping routes, threats to national security, and damage to the Arctic ecosystem.

Currently, 19% of the world's population (1.47 billion people) face substantial risk of a 1-in-100-yr flooding event (Rentschler and Salhab 2020). While extremes in the climate system have a devastating effect on populations across the world, the impacts often fall disproportionately on low-income nations and marginalized populations as ~587 million people who face substantial risks from flooding are living on less than \$5.5[1] (U.S. dollars) per day (Rentschler and Salhab 2020).

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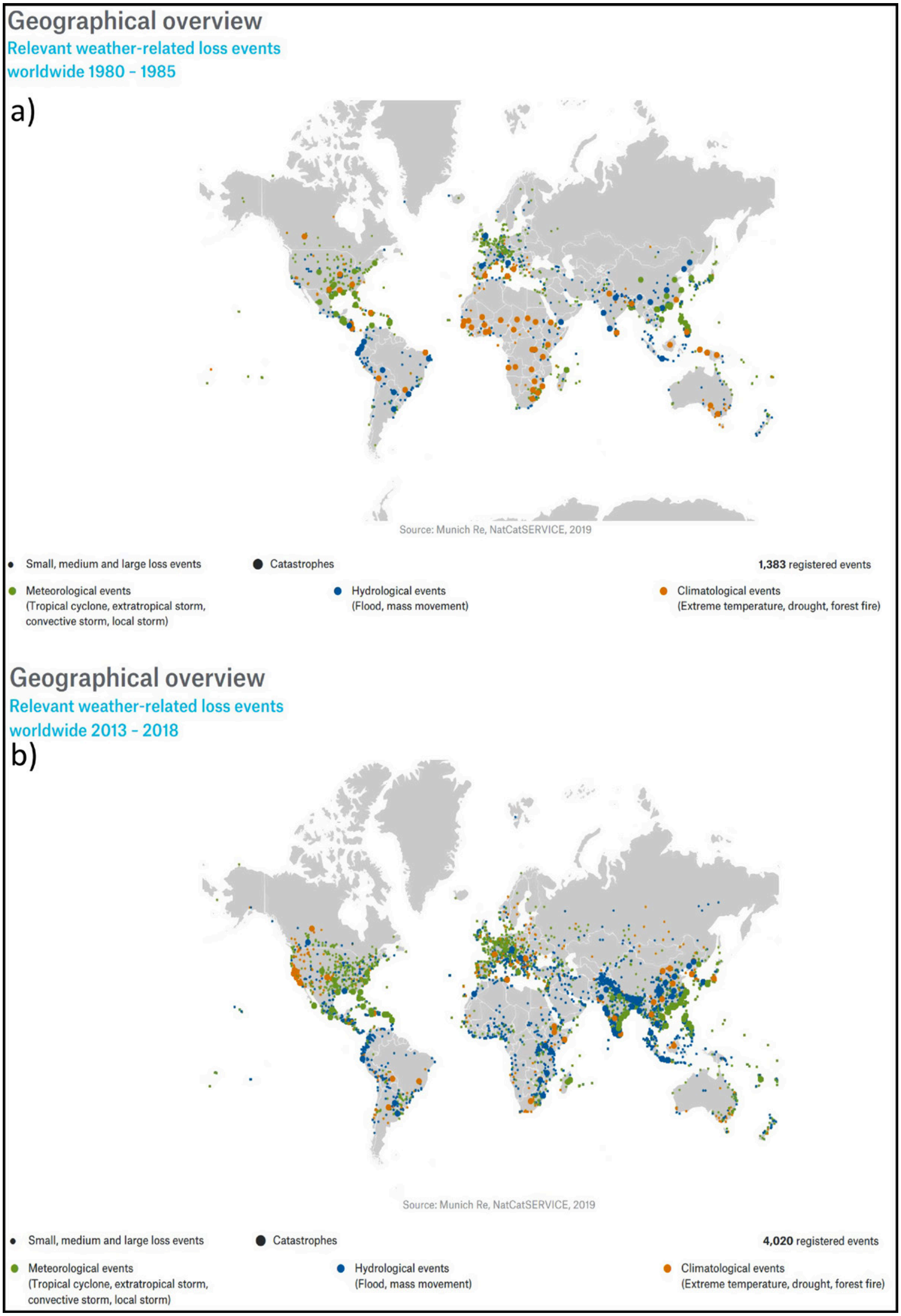
[1] The dollar amounts are defined in the cited publications, which span from 2017 to 2020. Given this relatively short time period, we did not attempt to standardize the amounts.


Geographical overview

Relevant weather-related loss events worldwide 1980 – 1985

a)

Source: Munich Re, NatCatSERVICE, 2019

Geographical overview

Relevant weather-related loss events worldwide 2013 – 2018

b)

Source: Munich Re, NatCatSERVICE, 2019

Fig. 1. Major weather- and climate-related loss events from the Munich Re, NatCatService, 2019 database plotted utilizing their online data access tools. For the periods (a) 1980–85 and (b) 2013–18. From keynote presentation by D. Parsons at InterMet Asia 2019.

Natural disasters also force a $520 billion (U.S. dollars) drop in consumption and drive ~26 million people into poverty each year (Hallegatte et al. 2017).

The importance of weather and climate risk–based decision-making to society is also increasing substantially with population growth and demographic shifts that include urbanization and movement to coastlines. For example, Majumdar et al. (2021) outlines the growing societal need for accurate and timely forecasts of flooding, heatwaves, and air pollution events in urban areas. The trends in urbanization are dramatic as the year 1800 only about 2% of the world's population lived in urban areas compared to ~55% in 2018 and projections of 68% in 2050 with 2.25 billion more urban residents added in Asia and Africa alone (United Nations 2019). These trends mean more people, assets, and essential services (e.g., power, water, transport, telecommunications, the internet) are exposed and vulnerable to weather, climate, water, ocean, and even space hazards. The demographic trends have resulted in a growth in the catastrophic events along coasts (Fig. 1) implying a clear need for highly localized, accurate, and frequently updated information, as well as tailored services for informed decision-making over multiple time scales. Meeting these needs will require a new level of collaboration between the stakeholders and user communities across the weather and climate enterprise.

Another driving force for the NEWP enterprise results from our global "just in time" manufacturing process that increasingly requires accurate, timely, and high-resolution forecasts of both detrimental events and routine day-to-day variations. These improved forecasts are needed since the components used in developing the final product are created and delivered as needed rather than created, shipped, and stored well in advance. A survey of 1,000 global executives in 15 countries by the IBM Institute for Business Value (IBV) in cooperation with Oxford Economics found that 93% of the executives felt that improved insight into weather variations would positively impact their revenue with estimates of growth in annual revenue exceeding $500 billion (U.S. dollars) (Orrell et al. 2018). This large economic impact is consistent with the study by Lazo et al. (2011) that found 3.4% of the U.S. gross domestic product is affected by routine variations in day-to-day weather.

These economic drivers have resulted in a growth in private sector companies providing targeted forecasts of weather variations from the time scale of minutes to climate risk and resiliency information spanning decades into the future. Policy debates around the future of the planet and society are intense in a world with significant global technological transformations and growing environmental risks. Such debates shape high demand and need for better weather and climate information and for services addressing the risks and socioeconomic impacts of the weather, climate, and water hazards.

Another factor in the debate on future directions of the NEWP enterprise is that we are living in the "decade of digital transformation" with increased reliance on data and information technology (IT). This reliance will profoundly change the organizations across the NEWP enterprise. These data opportunities coupled with the previously mentioned factors will drive increased competition between the public sectors and the growing private sector in providing specialized, targeted forecasts. However, investigation of this issue across eight diverse nations (World Bank 2020) suggests that defined cooperation between the public, private, and academic sectors will help meet the growing demands and need for forecasts, help sustain national meteorological and hydrological services (NMHSs), and foster economic development. Historical background on the U.S. prospective on these partnerships can be found in National Research Council (2003) report.

Objective and scope

The main objective of this paper is to provide a basis for informed decision-making by weather and climate enterprise stakeholders in planning their activities and investments in the NEWP enterprise during the coming decade. The weather and climate forecast enterprise involves various stakeholders from public, private, and academic sectors as shown in Fig. 2. The important drivers of the innovation cycle are highly qualified personnel, computational and observational infrastructures (in the middle of the figure), and increasing stakeholder and customer demand and need (on the circumference of the figure) for tailored and seamless weather and climate forecasting (localized, timely, precise, and accurate). Stakeholders and customers can push clockwise new initiatives (Fig. 2) at different positions in the innovation cycle: R&D, operation, and services. This paper will cover these three components of the innovation cycle: infrastructure, R&D, and operation. Stakeholders engaged in all three components will have to make strategic choices in the coming years, and some will struggle to keep up as technologies continue to combine and advance, and new ways of doing business appear quickly.

This paper summarizes the views, knowledge, and expertise of a group of scientists and practitioners from the public, private, and academic sectors that was produced under the leadership of WMO (Brunet et al. 2021). Our summary represents an update of the vision described over a decade ago in Shapiro et al. (2010). In addition, our approach of including input across these sectors allows us to go beyond the scientific vision described in Shapiro et al. (2010) through increased knowledge of the needs of society and economy. We do not attempt to dictate solutions to the many open questions on the future of weather and climate forecasting. Instead, we strive to improve the understanding of the ongoing R&D and to identify technological trends, and any possible impediments to progress. In this way, risks and

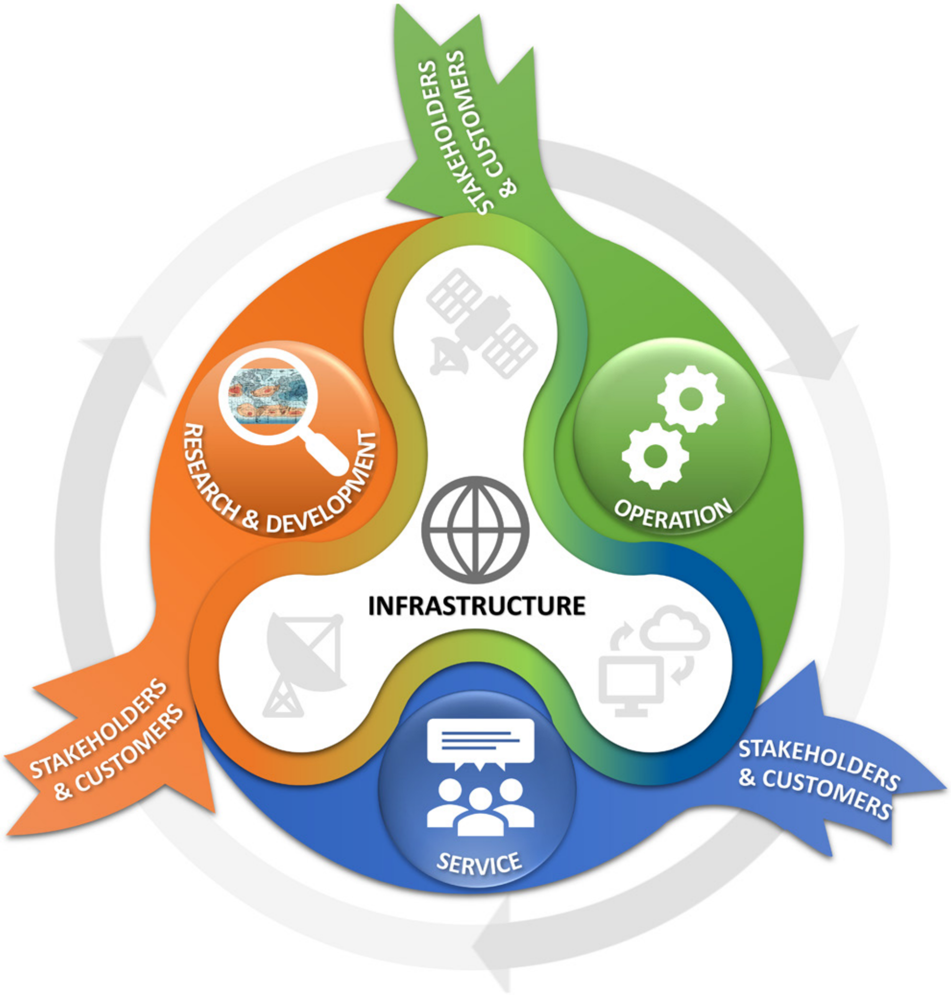


Fig. 2. **The innovation cycle: the public–private–academic engagement challenge taken from Brunet et al. (2021). The operations component is the creation of forecast and other products, while service is the delivery of these products to stakeholders and customers. Note that each sector can make contributions to the various components (i.e., research and development, operations, and service).**

opportunities for each stakeholder can be better assessed, and decisions on future organizational plans and investments can be better informed. Although our focus is on the future of weather and climate forecasting, we note that many of our recommendations are consistent with the priorities and targets of the Sendai Framework for Risk Reduction 2015–30 (UNISDR 2015) that had a greater emphasis on public health.

Weather and climate forecasting: Setting the scene

Brief history of NEWP. Significant progress has been achieved in NEWP over the past six decades through collaborative efforts by many institutions across the public, private, and academic sectors at national and international levels. There are several papers on the history of the highlights of NEWP developments (e.g., Pudykiewicz and Brunet 2008; Magnusson and Källén 2013; Bauer et al. 2015; Parsons et al. 2017; Benjamin et al. 2019; Bock et al. 2020; Ritchie et al. 2022) with our summary of highlights provided in the "Major milestones in operational weather and climate forecasting" sidebar. While weather prediction systems were initially designed to provide useable information on time scales covering hours to days, NEWP forecasts

Major milestones in operational weather and climate forecasting

- 1861: Met Office weather forecast services using telegraphs established by FitzRoy
- 1873: Working toward global meteorological observatories and international data sharing with the foundation of the International Meteorological Organization in Vienna
- 1900–22: Birth of numerical weather prediction (NWP) with the work of Abbe (1901), Bjerknes (1904), and Richardson (1922)
- Early 1920s: Onset of statistical climate prediction and global atmospheric teleconnection insights pioneered by Walker
- 1950: First computer NWP forecast on Electronic Numerical Integrator and Computer (ENIAC) by Charney et al. (1950)
- 1960 onward: Satellite-based meteorological observations and telecommunications at the forefront of technological innovations since the launch of *TIROS-1* (first weather satellite)
- 1960s onward: Emergence of general circulation models for climate research and forecasting
- 1962: Establishment of the World Weather Watch (WWW) program with its three main components (Global Observing System, Global Telecommunication System, and Global Data-Processing System)
- 1963: Lorenz's seminal work on chaos initiated atmospheric predictability theory and paved the way to numerical ensemble prediction in the 1980 and 1990s
- 1969: Launch of the Global Atmospheric Research Program (GARP) led by Charney
- 1969 onward: Global NWP innovations since the first global spectral NWP simulation by Robert
- 1975: Federation of global NWP R&D effort in Europe with the foundation of the European Centre for Medium-Range Weather Forecasts (ECMWF)
- 1979: First GARP Global Experiment, to gather the most detailed observations ever of the global atmosphere
- 1980: World Climate Research Programme (WCRP) established under the joint sponsorship of the World Meteorological Organization (WMO) and the International Council for Science (ICSU) currently the International Science Council
- 1980s onward: Development of coupled ocean–atmosphere climate models
- 1992: Operational implementation of ensemble prediction systems at ECMWF and the National Centers for Environmental Prediction (NCEP)
- 1993: The Intergovernmental Oceanographic Commission of UNESCO became a cosponsor of WCRP
- 1995–97: Global reanalyses developed by NASA, NOAA–NCAR, and ECMWF fostering the use of NWP analyses in climate monitoring
- 1997: Ground-breaking numerical prediction advances in the use of multiple sources of Earth system observations with the introduction at ECMWF of four-dimensional data assimilation
- 1998: World Weather Research Programme (WWRP) established by the WMO
- 2002: Earth Simulator, Japan—A landmark supercomputer investment for climate, weather, and geophysical research
- 2002: Met Office began use of high-resolution, convective allowing model for operational prediction

- 2004: WMO establishes the 10-yr THORPEX program to accelerate improvements in the skill in global NWP models
- 2005: First operational assimilation of cloud and precipitation affected satellite data at ECMWF
- 2007: A great step forward for weather and climate Earth system forecasting with 3,000 Argo oceanic floats in global operation
- 2008 onward: Dealing with prediction uncertainty in data assimilation with ensemble data assimilation techniques
- 2008: First successful launch and application of CubeSat technology by University of Toronto for atmospheric profiling of column integrated CO_2, atmospheric humidity, and electron density
- 2013: First global simulations with subkilometer-scale horizontal resolution conducted using the Nonhydrostatic Icosahedral Atmospheric Model on the K supercomputer
- 2013: Cloud computing first used for regional NWP applied to user needs
- 2014: Agreement reached in the ECMWF system between the annual average of the ensemble spread and error in increasing the reliability of ensemble forecasts
- 2015: Development of a 40-member ensemble for the atmospheric component of the Community Earth System model
- 2018 onward: Introduction of coupled ocean/sea ice models to global NWP systems (e.g., leading to improved medium-range prediction of Arctic cyclones)
- 2018 onward: Acceleration in the development of convolution neural networks and other machine learning approaches for accelerating computing, advancing model physics, and weather and climate forecasts
- 2020 onward: Joint weather and climate community initiatives toward global convection resolving models through the use of exascale computing

now extend from minutes and hours to seasons, years, and even decades on spatial scales ranging from urban to planetary for different components of the Earth system. The achievements are remarkable; for instance, the ability of NEWP models to predict variations in the 500 hPa height field generally improves at a rate of a day per decade (e.g., Bauer et al. 2015) so that the midlatitude 5-day weather forecasts today are as accurate as 1-day forecasts 40 years ago. The advances in Earth system modeling are another outstanding achievement that encompasses understanding and predicting the atmosphere and its chemical composition, the oceans, land/sea ice, and other cryosphere components as well as the land surface, including surface hydrology and wetlands, lakes, and human activities. On short time scales, Earth system forecasting needs to include phenomena that result from the interaction between one or more components (e.g., ocean waves, tides, sea ice, and storm surges). On longer time scales, the Earth system also includes terrestrial and ocean ecosystems, the carbon and nitrogen cycles and slowly varying solar and cryosphere components (e.g., large continental ice sheets and permafrost).

These advances in operational weather forecasting and climate predictions began well before computers were utilized to produce forecasts (see “Major milestones in operational weather and climate forecasting” sidebar). Subsequently the success of the first numerical prediction by Charney et al. (1950) launched a spectacular trend of innovations in NEWP over the following seven decades. Routine, real-time forecasting with NEWP started in the mid-1950s and was introduced in operation in the 1960s. Improved observational coverage, the advent of satellite observations, the steady growth of computer power, and breakthroughs in the theory of Earth system coupled processes all underpinned a successful story of weather forecasting in the NEWP era.

The high cost of NEWP, including the capital investment for computers and their running and maintenance costs, as well as resources needed in R&D, meant that the most developed nations had the highest concentration of major developments. Nonetheless, exemplary cooperation and knowledge sharing with scientists from many countries and institutes has nurtured advancement of NEWP. European countries undertook a strong collaborative move with the establishment of the European Centre for Medium-Range Weather Forecasts (ECMWF) in 1975 as an intergovernmental organization. International cooperation has also been supported by our professional societies (e.g., American Meteorological Society, Royal Meteorological Society, the American and European Geophysical Unions) and government agencies funding field campaigns and focused research efforts.

Progress in NEWP is often illustrated by the improvement in the horizontal and vertical resolution of operational models even in global modeling systems (e.g., Skamarock et al. 2012; Miyamoto et al. 2013; Stevens et al. 2019). There has been an almost 40-times increase in the horizontal resolution of global numerical weather prediction (NWP) models (from about 400 km in the early 1960s to less than 10 km in 2020); in addition, regional fine-mesh models have reached 1 km in resolution. In the vertical direction, from the early one- and three-layered quasigeostrophic models, today's models utilize more than 130 levels, reaching an altitude of about 80 km. The role of the private sector in NEWP has evolved significantly from their initial role as a provider of infrastructure (observation instruments, telecom and supercomputer ecosystems) and primarily producing value-added products based in part on NMHS forecast data. In many countries, the private sector plays a significant, if not leading, role in communicating and interpreting weather information to the public and providing specific weather forecasts tailored for use by governments and businesses. The private sector activities have also grown to include providing global satellite-based measurements, targeted high-resolution modeling, and climate risk products utilized by corporations and governments. These climate risk products are obtained by combining historical observations of extremes with the output of ensemble-based climate models from research institutions, downscaling with high-resolution models, and artificial intelligence approaches.

WMO role. Obtaining the observations to initialize NEWP models requires data sharing across national boundaries. The WMO has played a critical role in fostering data sharing and furthering the progress of weather and climate forecasting. In cooperation with partners in the 1960s, the WMO established the World Weather Watch (WWW) program composed of the Global Observing System, the Global Telecommunication System, and the Global Data-Processing and Forecasting System (GDPFS), coupled with the Meteorological Applications Programme. The result was a global set of observational and forecast data that were shared among WMO member states and territories serving as the foundation for development of the spectrum of user-oriented applications and services.

The global observing system is changing, however, to include observations from CubeSat satellite systems, drones, vehicle-borne systems, microwave links, airborne Mode-S systems, social media hazard data, low-cost 3D printed weather stations, urban in situ and enhanced air quality systems, and other systems (e.g., Majumdar et al. 2021). To meet the growing demand and need for observations useful to NEWP within this changing observing system, the WMO has launched a new Unified Data Policy (https://public.wmo.int/en/our-mandate/what-we-do/observations/Unified-WMO-Data-Policy-Resolution). This new policy encompasses WMO-relevant Earth system observations (e.g., weather, climate, hydrology, atmospheric composition, cryosphere, and space weather) with urging for a clear commitment to free and unrestricted exchange of relevant data. Despite the movement toward data sharing, open access to regional measurements (e.g., mesonets, radar data), research datasets, and archives of observations taken by the private sector often remains a challenge. Such limitations can hamper both scientific research and efforts to improve NEWP forecasts.

Today, the WMO GDPFS includes an elaborate system of global and regional centers, including nine World Meteorological Centres (WMCs) and 11 Regional Specialized Meteorological Centres (RSMCs) with geographical specialization (Fig. 3). Various centers are tasked with production of analyses and other data assimilation products, global deterministic and ensemble NWP; limited-area deterministic and ensemble NWP; nowcasting; various

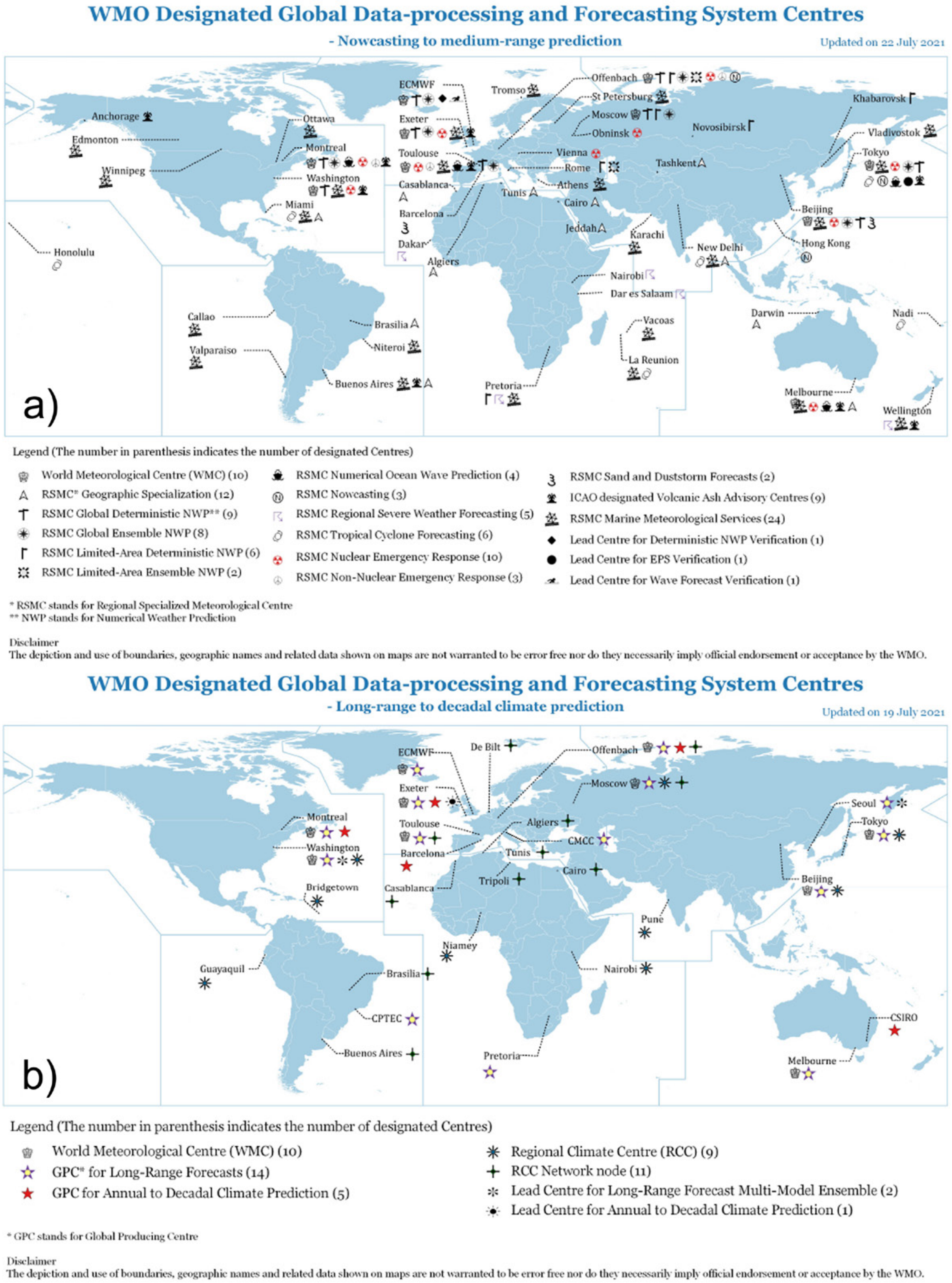


Fig. 3. WMO-designated (a) GDPFS centers for nowcasting and weather forecasting (up to 30 days) and (b) long-range and climate forecasting (over 30 days) (WMO 2019a,b,c).

specialized forecasting activities (e.g., tropical cyclones); atmospheric transport and dispersion modeling (nuclear and nonnuclear); atmospheric sandstorm and dust storm forecasting; numerical ocean wave prediction; aviation forecasting; and so forth. In addition, 13 centers are designated as Global Producing Centres for Long-Range Prediction (monthly to seasonal),and four centers as Global Producing Centres for Annual to Decadal Climate Prediction.

The WMO technical commissions were instrumental in facilitating international collaboration and knowledge sharing. The World Weather Research Programme (WWRP) and the

World Climate Research Programme (WCRP)[2] have been at the forefront of scientific efforts underpinning progress in NEWP development and in research-to-operation transition. The WWRP and WCRP contributions span nowcasting (e.g., Majumdar et al. 2021), global NWP (e.g., Parsons et al. 2017), polar prediction (e.g., Rabier et al. 2010), and climate projections (e.g., Brasseur and Carlson 2015; Wake 2019) including the Coupled Model Intercomparison Project (CMIP) (Meehl et al. 2000; Eyring et al. 2016; Bock et al. 2020). WWRP and WCRP collaboration has also been valuable particularly on subseasonal to seasonal time scales at the weather–climate interface (e.g., Brunet et al. 2010; Vitart 2017).

Challenges and opportunities in the coming decade: Recommendations

Operational weather forecasting based on numerical prediction systems has continuously improved over the past few decades. The usefulness of NEWP forecasts has been pushed to lead times beyond 10 days for some weather phenomena including for high-impact events such as midlatitude snowstorms in North America. However, the steady progress has been at a slower pace for some forecasted elements, like quantitative precipitation, where more efforts are needed that span from observational needs and model improvements to communication of forecasts (e.g., Balmaseda et al. 2020; NOAA 2020). This section highlights some key messages and recommendations that were discussed in Brunet et al. (2021), although we note that the helpful comments of the reviewers and additional discussions between the authors have provided us with some new perspectives. As such guidance must account for uncertainties and society's ability to use weather and climate forecasts, we emphasize optional ways of development and additional considerations (e.g., economic, operational) that may need to be applied in decision-making.

Policy changes. In our changing world, the ever-growing need for weather and climate services has meant the value of information is becoming better understood and appreciated (e.g., Orrell et al. 2018). The market growth for NEWP is stimulating a variety of new business models that may fit diverse national and transnational frameworks, improve the quality and access to information, and contribute to the robustness and efficiency of the requisite underpinning activities like environmental monitoring and research. Improved coordination and collaboration among the public and private sectors of the weather and climate enterprise, with strong engagement of academia, will accelerate the achievement of the vision for improving skill over the coming decade. While technological advances and open data policies have enhanced collaboration between these sectors, improved coordination and collaboration remains a fundamental need with the degree of cooperation varying substantially across different countries (World Bank 2020). The expectation is that each sector will continue in its most relevant roles; at the same time, new potential synergies need to be effectively promoted and implemented.

On the policy side, prevailing free and open data sharing among countries and institutions led by the WMO has facilitated progress including the establishment of the Global Basic Observing Network (GBON) in which the basic surface-based observing network is designed, defined, and monitored at the global level for international exchange. The increased availability and adoption of forecast-driven tools for weather- and climate-informed decision-making, especially by the commercial sector, has facilitated major progress. The need and demand for decision-support tools in our "just in time economy" is growing rapidly. These needed decision-support tools are a challenge as the transport of materials for manufacturing often requires both accurate high-resolution, short-range forecast for components arriving by trucks and rail to long-range forecasts for overseas shipping. However, in some areas, policies implying commercial or other barriers to accessing important datasets need to be removed to accelerate progress for detailed forecasts across these time scales. In addition to commercial

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[2] The WCRP includes cosponsorship of by the WMO, the International Science Council (ISC), and Intergovernmental Oceanographic Commission (IOC) of UNESCO (IOC-UNESCO), while the WWRP is an international program of the WMO.

restrictions, regional observations (e.g., mesonets, radar) are often not shared widely. This challenge of balancing open data versus protecting commercial licensing has been with the weather enterprise for many years (e.g., National Research Council 2003).

Research and development. The general framework for R&D in NEWP has long been to better utilize NEWP forecast data to meet society's needs while striving to reach the theoretical limits of predictability (i.e., Lorenz 1963). Defining this theoretical limit remains a challenge since the Earth system contains both slowly varying components (i.e., sea surface temperature, soil moisture, snow cover, sea ice) that can aid predictive skill (Krishnamurthy 2019) and highly nonlinear, rapidly changing phenomena such as convection that can produce both large local errors and significant errors downstream on the jet stream due to the modification of Rossby wave packets (e.g., Rodwell et al. 2018). Efforts to advance predictive skill include increasing high-performance computing (HPC) capacity; improving observational instrumentation providing more accurate data with higher temporal and spatial resolutions; advanced dynamical cores and better representation of complex physical processes; better model initialization through the utilization of expanding satellite observations (e.g., both from government agencies and occultation and other observations from commercial vendors), taking advantage of novel new measurement strategies such as crowd-sourced data (e.g., Hintz et al. 2019), rainfall from cell phone tower attenuation (e.g., Overeem et al. 2013), and the improved utilization of polarimetric radar measurements as models move to kilometer scale (Zhang et al. 2019), and more effective data assimilation methods; and use of ensembles to represent uncertainty in the initial state and model processes.

The Brunet et al. (2021) report describes the R&D challenges that need to be met to accelerate weather and climate forecasting in response to the needs of our changing world. These challenges include the need to advance predictability, dynamical and physical modeling (see "Some predictability, dynamical, and physical modeling challenges" sidebar) and

Some predictability, dynamical, and physical modeling challenges

Significant outstanding challenges remain in terms of weather and climate predictive skill:

- Midlatitude weather regime transitions at the week 3 to week 4 time range
- Teleconnections between tropical phenomena (e.g., the Madden–Julian oscillation) and midlatitude synoptic-scale weather patterns at the monthly range
- Seasonal-scale sea ice cover and thickness predictions, and the different trends observed in the Arctic and Antarctic
- Large-scale patterns of precipitation and midlatitude circulation changes in climate change projections
- Deep-ocean circulation and ice sheet sensitivity to change in climate models
- Convective precipitation beyond the short range
- Closure of the water and energy cycle

Model and data assimilation shortcomings include the following:

- Major uncertainties associated with parameterizations of key processes such as deep convection, orographic drag, cloud microphysics (and aerosol interactions), thermodynamic and dynamic coupling with Earth surfaces, including land, waves, snow, and sea ice, and their impact on global circulation
- Limited understanding of the possible feedbacks of atmospheric composition on NEWP predictive skill and climate simulations
- Mismatching fluxes at the land–atmosphere, ocean–atmosphere, and ocean–sea ice–atmosphere interfaces
- Insufficient and incomplete treatment of systematic and random errors in data assimilation and ensembles
- Insufficient use of diagnostic methods for tracing key sources of model error back to their roots in weather and climate models

Source: WMO (2015)

catalyzing innovations in numerical prediction system design like artificial intelligence (AI) and machine learning (ML) techniques to help advance observing and prediction strategies with topics of current and future interest shown in the "Potential major breakthroughs from ML" sidebar. The reader is also referred to summary articles on the current and future directions of relevant ML and AI research (e.g., McGovern et al. 2017; Wang et al. 2019; Mansfield et al. 2020; NOAA 2021). Since these approaches could prove valuable to forecasting on time scales from nowcasting to climate resiliency with benefits to both the public and private sectors, collaboration across the private, public, and academic sectors would prove beneficial. Addressing these challenges at the national level will require NMHSs to engage more in community-based modeling, data initiatives, and the R&D consortia. The importance of working closely with users and the opportunities for private–public partnerships should be recognized and promoted. Confederating R&D activities and intercountry collaborations will help scale core NMHS technology and capability development. The WMO has been effective in involvement in broad collaborative R&D topics relevant to advancing NEWP (i.e., Future Earth and Integrated Research on Disaster Risk, projects of the International Science Council, Risk Kan) and could play a major role in bringing NEWP advances to assist in addressing the sustainable development issues, disaster impacts–responses, and other relevant topics.

Reaching these goals must also include addressing the funding challenges often impeding R&D progress relevant to advancing weather and climate forecasting including (i) developing and refining strategies to advance interdisciplinary collaboration relevant to NEWP, (ii) sustained funding strategies (i.e., >5 years) and supporting research that lies between fundamental process studies and efforts to transition applied research to operation,

Potential major breakthroughs from ML

The use of ML will lead to significant progress over the whole range of "classical" modeling, data assimilation and postprocessing algorithms in the coming decade. It can be applied at each step of the weather forecasting process. Examples of topics relevant to NEWP can be found in the ESA–ECMWF Workshop: Machine Learning for Earth System Observation and Prediction (www.ml4esop.esa.int). Current and future research topics and potential advantages of utilizing ML include the following:

- Improve the utilization of observing systems, allowing forward planning of maintenance activities, improved quality control, and intelligent filling of data gaps
- Advance the ability to input information from complex observing systems into models' data assimilation by providing better compression rates, which will significantly increase the precision and speed of forward operators
- Help better estimate model and observation errors in data assimilation through combining hybrid ML and data assimilation techniques
- Allow incorporation of further complex subgrid physical parameterizations, or training subgrid parameterizations on data provided by higher-resolution models like large-eddy simulation models
- Advance postprocessing of numerical variables by allowing incorporation of nonlinear correlations
- Estimate impacts by combining ML, model output, and further observations or statistically relevant data
- Advance nowcasting and improve rainfall estimation by applying ML to radar observations
- Use of ML approaches to detect and forecast severe weather such as tornadoes, large hail, and damaging winds
- Detect regimes where forecast failures are more likely to occur by combining ML with observations, model initial conditions, and forecast output
- Explore whether ML is a computationally efficient tool to replace the NWP forecast approach

A wide range of open-source AI and ML frameworks (e.g., TensorFlow and PyTorch), together with well-known programming languages like Python or C++, can support the development of these applications. Therefore, it becomes possible to tackle large-scale problems with the advent of dedicated accelerators. Cloud infrastructures provide easy access to accelerator hardware. If meteorological data are readily available, small- and medium-sized enterprises can develop successful applications, especially if they bring together expertise from different disciplines.

(iii) fostering collaborations between weather and climate researchers to advance forecasting at weather–climate interface and other problems of mutual benefit (e.g., physical parameterizations), (iv) supporting international R&D collaborations considering that the NEWP is a global enterprise, and (v) developing efforts aimed at improving the utility of weather and climate data by society.

Toward improved systems for forecasting

INVESTMENT STRATEGIES. Improved forecasts and better utilization of forecast information will require investments in the global observing system, especially for sparsely populated parts of the world and oceans where the boundary layer and lower troposphere are often poorly sampled. Public investments in an accessible observational network will benefit all enterprise stakeholders, including the private sector and academia. Investments will also be needed in the supercomputing capability that is necessary to create weather and climate information of high accuracy, resolution, and reliability to address growing societal needs. These investment strategies must recognize the critical role of the private sector in creating the instrumentation for observational networks and the computational infrastructure. Hence, these investments should be accompanied by collaborations between the weather and climate enterprise, computer scientists, and industry on what changes need to be undertaken in the design of supercomputers, ML, and data sharing. Investments in observational networks should be coordinated with NEWP system development (e.g., determination of the likely forecast improvement from a proposed observing strategy, timely development of data assimilation systems) to significantly and efficiently improve forecasts and maximize the impact of observations on forecast skill.

An integrated system-of-systems approach should be used with considerations of scope, complementarity, and cost–benefit analysis across all space and time scales. The role of the WMO will continue to be important for improved coordination of investments and broadening the participation of the private and academic sectors. The private sector can help make the case to funders and development agencies to meet these key computing, observational, and R&D needs including advancing state-run long-term observations, reference networks, and data sharing.

CHANGING ROLES. There will be some notable shifts in roles, functions, and performance requirements for the NEWP enterprise stemming from the expected breakthroughs in technology and research developments. The development/improvement of climate models would benefit from coordination with efforts to advance weather prediction with global weather models evolving in the years to come to explicitly represent convection. R&D efforts to overcome fundamental limitations in physics parameterization are accelerating and would benefit from collaboration between the weather and climate communities. Efforts to develop a unified single model system (e.g., Côté et al. 1998a,b) across a range of time scales (nowcasting to centennial) and spatial scales (convective-scale to climate system Earth modeling) should be accelerated since such systems are possible (i.e., Met Office strategy since 1990), desirable, and perhaps even necessary for accelerating forecast advancements.

The ECMWF model of international cooperation may need to be expanded and replicated to a certain extent to other regions, which will allow consolidation of human resources and expertise, and optimization of running costs. Such a regional approach could be successful only with strong political support for national-based regional institutions and scientists to build capacity and consideration of existing regional climate centers. This approach is a task and challenge for WMO in cooperation with other relevant international organizations, including development agencies. Private–public engagement could be a guiding principle to ensure partnerships, availability, and usability of skilled regional/local products.

THE CHALLENGES OF BIG DATA. Numerous segments of society are facing challenges in transporting, storing, and utilizing large datasets and NEWP is at the forefront of this big data challenge. The scope of this challenge is evident in Bauer et al. (2015), which noted that 10^7 observations are incorporated each day into operational weather prediction systems that produce 10 TB of model output per day. Increases in observational datasets (e.g., crowd sourcing, advanced satellite observations), the movement of NEWP systems to ensembles operating at high resolution (1–3 km), and attempts to observe and predict more components of the Earth system will only increase the difficulty humans and our technology face in handling these datasets. This big data challenge will pose a key dilemma for the NWEP enterprise and for society.

High-resolution global ensemble modeling systems will continue to be run operationally only by those organizations having access to very significant supercomputing capabilities. Currently many NMHSs and private sector entities are operating their own regional modeling systems. The quality and small-scale details of these new global models will likely exceed locally run models operating with limited computational resources. Thus, local models may appear to be a waste without adding value to freely available high-resolution global models.

One option is the downscaling of forecast data from the global ensembles into useful products, including the use of AI, which would be highly valuable for the various national impact sectors, especially for low-income countries. This approach will require using the reforecast data from the global ensembles and training scientists from NMHSs in applying these approaches to local scales in their own countries with national observations utilized to optimize the calibrations. This shift might be one of the most disruptive changes of the coming decade requiring advanced planning and change management. The dissemination and utilization of ECMWF and North American Ensemble Forecast System forecasts by many NMHSs and private organizations are showing the viability of such an option.

Implementing NEWP systems with postprocessing, production, and visualization in the cloud may offer a more sustainable and cost-effective approach. Such an approach could benefit nations and offer improved cooperation and burden/benefit sharing between public and private partners. Certain competencies and financial resources will be needed with an emphasis on maximizing scalability (e.g., cloud-based software solutions that can be customized and redeployed to assist countries with similar needs).

Progressing together with low-income nations. The importance of quality observations to global prediction means that stabilizing the national observing networks in low-income countries and ensuring their long-term maintenance to provide standard-quality observational data are of paramount importance. One striking element of addressing this situation is that the massive investments (estimated as billions of dollars) through various development assistance projects, engaging numerous development funding agencies, have often provided disappointingly low impacts on local capacity. Some analysts pointed out that the main reason for such a failure is that the development funds were spent mostly on equipment such as automatic weather stations, communication systems, computers to run NEWP, and weather radars (widely not utilized after delivery due to maintenance problems). Unfortunately, less attention is often given to the longer-term success of these investments, which requires planning and funding to maintain and sustain instrumentation, improve communication systems and service delivery, capacity building including training and retaining staff, access to and utilization of observations and forecast products from the WMO and major operational centers, engagement with the private and academic sectors, and advanced data management systems (e.g., Snow et al. 2016; Rogers et al. 2019).

In addition, partnerships between the private, public, and academic sectors has recently been shown to be useful in fostering development and building and sustaining the NEWP enterprise (World Bank 2020). The WMO, in collaboration with development agencies, needs to play an enlarged role in supporting low-income countries to contribute effectively and sustainably to their national observational programs as components of the global observing system. Fortunately, many players in the weather enterprise well understand the need for a paradigm change in the provision of development assistance. As an example, WMO has recently established the Systematic Observations Financing Facility (SOFF) to provide financial and technical support for the implementation and sustained operation of GBON for low-income countries.

Regarding NEWP, as mentioned previously, a more efficient path might be to invest available resources to serve national purposes through building sustainable expertise and computation infrastructure for accessing and utilizing available data from international sources like high-resolution global model products. Sharing observations and the best global and regional prediction datasets with low-income countries is consistent with obligations of every WMO member. There is currently a marked inequality in the availability of weather and climate forecast information in low-income countries, and insufficient capacity to produce and utilize such information to save lives and bring socioeconomic benefits.

Hence, it is vital that all countries have the expertise and technical capability to utilize the highest-quality weather and climate information. NEWP model providers and HPC vendors could work together to integrate multimodels (using multicenters and at multiscales) in HPC clusters with preoptimization, then make those models available on the cloud as a service. Rather than buying HPC and running a NEWP model, the low-income countries could buy cloud service to run NEWP systems or postprocess global model output for their specific region in an affordable way, without the burden of future heterogeneous HPC, optimization of models, and downloading massive amounts of observational data. In this regard, we note the progress and success of Copernicus, Earth on AWS, Google Earth Engine, and other ventures to make data more accessible.

A closer strategic alignment among low-income countries and enhancing regional meteorological cooperation is essential. Scientists from low-income countries can contribute to the development of global NEWP systems. When a NEWP system does not perform well for a specific high-impact event, regional scientists need to be able to study the factors that the forecast had issues with and make recommendations on how to improve the global forecast system. These international collaborations will also act as a catalyst for technical capacity building, engendering improvements in education and infrastructure. International collaborations have been shown to be a catalyst in furthering research productivity across the low-income and developed nations of the world (e.g., Wagner et al. 2015) and will therefore accelerate innovation across the entire NEWP enterprise. Thus, global cooperation would improve regional capacity in meteorological disaster monitoring, prediction, and early warning and help to achieve sustainable development of the global economy and society. An excellent model to build on is three International Desks (i.e., African, South American, and Tropical) at NOAA's National Centers for Environmental Prediction. This program hosts ~20 visitors each year with its in-residence training program and also includes on-site training via workshops, and follow-up training through distance learning.

NEWP services also require investment in academic institutions in low-income countries to carry out targeted research, scientific consulting, and training of future expert forecasters and communicators. It is critical that efforts to grow a cross-national, multigenerational community of scholars consider rethinking the way experts teach, research, publish, and influence across the whole multidisciplinary domain of weather and climate forecasting. Targeted funding opportunities would prove beneficial, and we note that for U.S. researchers efforts aimed at advancing education, training, and/or forecasting in low-income nations would contribute to meeting the broader impact components of NSF grants. Collaborations between educational institutions within low-income nations and between universities in developed and low-income countries would also be advantageous in enhancing education and training. Increasing partnerships between academic institutions and those working on development activities relevant to the NEWP enterprise (e.g., WMO, World Bank, U.S. Agency for International Development) are likely to be beneficial. Finally, as noted in World Bank (2020), cooperation between the private, public, and academic sectors also greatly contributes to long-term advances in the NEWP enterprise and training the next generation.

Finally, we note that a disproportionately large impact of weather and climate extremes and other high-impact events fall on the poor and those living in the low-income nations of the world (e.g., Hallegatte et al. 2017; Rentschler and Salhab 2020). Insights from scientists around the world in the selection of research problems aimed at reducing these large detrimental impacts would advance observational, modeling, and postprocessing strategies and reduce the large detrimental impacts. Success in this approach requires that the societal needs and research findings be shared with and fed back to the primary forecast centers to obtain improvements in new operational cycles. Established frameworks and forums, such as the WMO Regional Climate Centres, Regional Climate Outlook Forums, and the WWRP and WCRP should exploit their full potential in this endeavor including a focus on translating these advances with organizations focused on a more sustainable and equity future (e.g., START, IRDR, Future Earth).

Conclusions

The decade 2021–30 will be the decisive period for realization of the 17 United Nations Sustainable Development Goals and targets outlined in the Sandei Framework. Most of these goals have links with the changing environment—climate change, water resources, and high-impact weather and environmental events. The desired outcomes in all areas require enhanced resilience, which is also the main call of the WMO Vision 2030 (WMO 2019b). The advances expected in weather forecasting and climate prediction during this decade will support those ambitious goals by enabling a next generation of weather and climate services that help people, businesses, and governments to better mitigate risks, reduce losses, and materialize opportunities from the new intelligence of highly accurate and reliable forecasts. These advances will also help assess systemic risks arising from the long-term evolution of weather and climate high-impact events, variability, and change across time and space.

This paper has shown the major challenges of and opportunities in each of the first three components of the innovation cycle (see Fig. 2): infrastructure, R&D, and operation. Several key factors will determine the success and effectiveness of future progress in NEWP, including open data access, ability for near-real-time data processing and transmission, monitoring data and forecast quality, quick and focused dissemination to users, and advances in societal decision-making. Some of these factors are common to the three components of the innovation cycle (infrastructure, R&D, and operation), but their implication and logic can be different, such as sharing data policies or HPC requirements for R&D and operation. It has been emphasized that the only way to address these challenges and enable the uptake of the technological and scientific achievements is through inclusive public, private, and academic partnerships.

Acknowledgments. The contributors to this white paper express their great sadness on the tragic demise of two of contributors to this article with major input to the “Challenges and opportunities in the coming decade: Recommendations” section. *Prof. Laban A. Ogallo* passed away in November 2020. Prof. Ogallo was one of the pioneers of climate science in Africa whose research contributions include playing a lead role in the identification of leading modes of climate variability, such as the decadal variability mode. He was a recipient of the WMO Award for the Encouragement of Young Scientists. The second colleague was *Netatua Pelesikoti*, the first Pacific Islands woman to become a lead author of an IPCC report. She was the director of the Climate Change Division at the Secretariat

of the Pacific Regional Environment Programme for more than 7 years and a consultant to the World Bank. In 2019, she became a member of the International Scientific Advisory Panel for the World Meteorological Organization She sadly passed away in Tonga in late 2020.

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