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Advancing Research for Seamless Earth System Prediction

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ABSTRACT: Whether on an urban or planetary scale, covering time scales of a few minutes or a few decades, the societal need for more accurate weather, climate, water, and environmental information has led to a more seamless thinking across disciplines and communities. This challenge, at the intersection of scientific research and society's need, is among the most important scientific and technological challenges of our time. The "Science Summit on Seamless Research for Weather, Climate, Water, and Environment" organized by the World Meteorological Organization (WMO) in 2017, has brought together researchers from a variety of institutions for a cross-disciplinary exchange of knowledge and ideas relating to seamless Earth system science. The outcomes of the Science Summit, and the interactions it sparked, highlight the benefit of a seamless Earth system science approach. Such an approach has the potential to break down artificial barriers that may exist due to different observing systems, models, time and space scales, and compartments of the Earth system. In this context, the main future challenges for research infrastructures have been identified. A value cycle approach has been proposed to guide innovation in seamless Earth system prediction. The engagement of researchers, users, and stakeholders will be crucial for the successful development of a seamless Earth system science that meets the needs of society.

https://doi.org/10.1175/BAMS-D-17-0302.1
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Supplemental material: https://doi.org/10.1175/BAMS-D-17-0302.2

In final form 9 August 2019

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Fundamental changes in the environment, an ever-growing global population, especially in vulnerable regions like coastal zones, and rapid changes in technologies create new challenges and opportunities. At the same time, natural events with high impact (e.g., resulting from hydrometeorological hazards or air pollution) continue to reveal the vulnerability of people and the infrastructures they rely on. Making society more resilient to the impacts of such events, whose characteristics may be amplified under a changing climate, requires a coordinated research effort and new investments to build the observing and prediction systems of the future. To enable all nations of the world to benefit, the scientific and technical knowledge and advancements need to be made more accessible and usable through international efforts, such as undertaken by the World Meteorological Organization (WMO).

Fig. 1. Participants of the Science Summit, held 20–22 Oct 2017 at the World Meteorological Organization's headquarters in Geneva, Switzerland. A full list of participants is provided in the online supplement.

With a focus on establishing the organization's future research agenda, the Commission for Atmospheric Sciences (CAS) of the WMO convened in October 2017 for the Science Summit on Seamless Research for Weather, Climate, Water, and Environment. More than 120 scientists (Fig. 1) from 47 countries participated in this conference, which aimed to garner the scientific community's views and share knowledge and strategic thinking (see supplement for further information about the Science Summit). The presentations, panel discussions, and breakout groups in World Cafes (Fig. 2 and supplement) focused on seamless prediction of the Earth system and on how science can serve society. Identifying key challenges and requirements for future infrastructure, innovation, and resources and the sustainable development of science were on the agenda (Hov et al. 2017). Here we highlight the key outcomes of the Science Summit and the discussions it sparked, together with the requirements that are needed to implement successfully the future seamless Earth system science agenda.

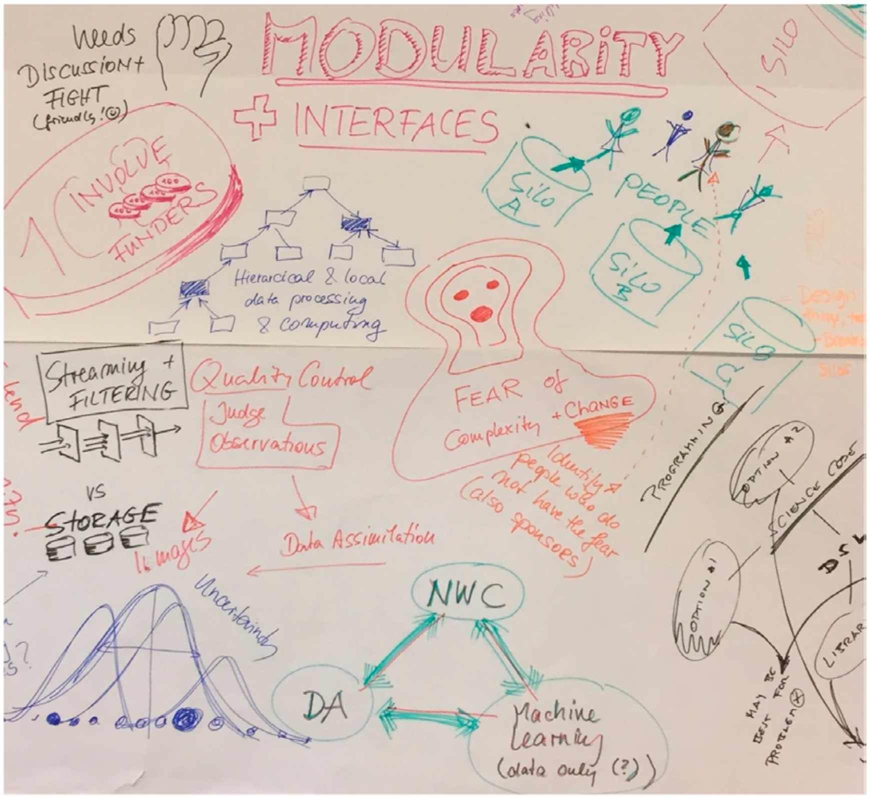

Fig. 2. An impression of the discussion in the World Cafe. This setup allowed all attendees of the Science Summit to participate and express their views and vision, both verbally and by drawing on the table cloths.

Seamless prediction and science for society

The Earth system is characterized by complex nonlinear physical, chemical, and dynamical processes acting on a vast range of spatial and temporal scales (e.g., Lucarini et al. 2014). The memory of the Earth system components and the associated coupled processes (e.g., ocean–atmosphere, land–atmosphere, ocean–ice–atmosphere, atmospheric composition, air quality) act as seamless sources of predictability. Mitigating and adapting to the impacts of weather extremes and changing environmental conditions requires detailed information on all relevant scales, and tailored predictions for a broad variety of user needs. These demands can only be addressed through a seamless approach to Earth system science that encompasses the processes acting on the various scales and in all compartments of the Earth system—including human-induced changes—and their interactions (see sidebar; Shapiro et al. 2010; Nobre et al. 2010). Advancing Earth system observation, analysis, and prediction capabilities as an international community, and providing valuable information to the benefit of society, was postulated by Shapiro et al. (2010) as our grand challenge for the future.

A definition of seamless prediction. The original usage of "seamless" (Palmer et al. 2008) referred to predictions across the range of weather and climate time scales. Since then, the definition has evolved toward the idea of predicting "the spatial–temporal continuum of the interactions among weather, climate, and the Earth system" (Brunet et al. 2010, p. 1398).

In 2015, WMO and the World Bank compiled an economic assessment of meteorological and hydrological services, conceptualizing the connections between the production and delivery of those services into a value chain (WMO 2015). This value chain links the production and delivery of these services to user decisions and to the outcomes and values resulting from those decisions. The main components are observation, modeling, forecasting, and services delivery. This approach strengthens the role of user needs in the development of weather and climate products. At the same time, however, it does not include feedback and co-design mechanisms that would put user needs at the heart of the research and development phase. The value cycle approach (Day 1999) extends the idea of a value chain, originally developed in an economic context (Porter 1985), by adding interactions with users to the process. Such a value cycle approach provides a useful means to guide Earth system science and ensure its societal benefit. The generation and delivery of weather and climate services can be depicted in such a value cycle (Fig. 3). This encompasses the production (observing, modeling, forecasting) of information, the dissemination to users (ways of provision, communication, and tailor-made products), perception and decision-making, and the outcomes and values. The interaction with the users is essential for the exploration of "what works" in terms of relevance, quality, and impact. The processes connecting those steps along the cycle and the feedback between them are essential for its functioning. For instance, it allows one to explore how new technologies may help to enhance forecast products or methods like climate downscaling.

Our definitions

Earth system

Following Shapiro et al. (2010), the Earth system encompasses 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, it includes phenomena that result from the interaction between one or more components, such as ocean waves and storm surges. On longer time scales (e.g., climate), the terrestrial and ocean ecosystems, including the carbon and nitrogen cycles and slowly varying cryosphere components (e.g., the large continental ice sheets and permafrost), are also part of the Earth system (Brunet et al. 2015).

Global Weather Enterprise

Following Thorpe and Rogers (2018, p. 2003): "The term Global Weather Enterprise (GWE) has been coined to describe the totality of activities by individuals and organizations to enable weather information to be created and provided to society…The enterprise includes the full value chain of scientific research, observations of the Earth system, numerical models encoding the laws of physics applied to the system, supercomputing to integrate the models and observations, weather and hydrological forecasts from hours to weeks and potentially months ahead, and business-specific products and services enabling economic benefit and jobs to be created. The health of the whole enterprise strongly depends on the strength of each component."

Extending the concept of seamless prediction to draw on expertise from social sciences together with users' knowledge and experience will help to improve the development of knowledge and services. Nowadays, we thus expand the initial definition of seamless prediction to consider also the need of users, stakeholders, and decision-makers for information that is continuous and consistent despite the different sources from which the information is generated. This seamless prediction approach thus encompasses all compartments of the Earth system, including human-induced modifications and their consequences, but also all elements of the value cycle.

Seamless Earth system science, guided by the value cycle approach (Fig. 3), will allow us to understand better and simulate more completely the inherent feedbacks and to generate and deliver user-specific information on changes in the Earth system, over minutes to centuries in time, and local to global scales in space. Further, it will enable an assessment of the resulting benefits to society.

The need for such a seamless prediction approach that considers inherent feedbacks is underpinned by the fact that human activities like water management or various other climate policies can directly modify the very system that we want to predict. Two examples of why such interactions need to be considered to allow for the best possible predictions across a wide range of applications are given below.

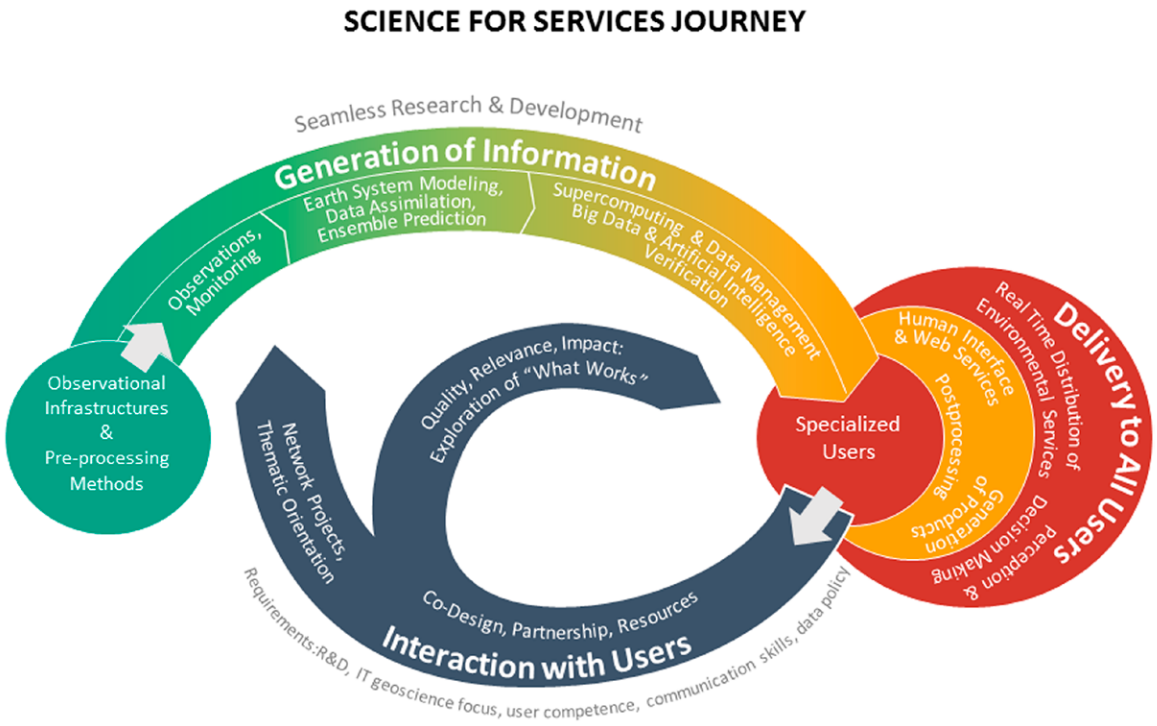

Fig. 3. Technical developments on seamless Earth system science need to go hand in hand with informed advancement of observations, monitoring capabilities, and advanced assimilation and Earth system modeling and other prediction methods, which are the backbone of existing meteorological services. This sketch of the value cycle identifies the fundamental bricks of our system and details the interfaces along the value cycle. It encompasses the generation of information (observations and their infrastructure, modeling, forecasting; green to yellow), postprocessing, the generation of products and suitable interfaces (yellow), an the dissemination to users (red) and the perception and decision-making. The interaction with users (gray), for example, through co-design of projects, is essential for the exploration of user-oriented services.

1) Depending on the availability of water resources and their management on subseasonal time scales, stakeholders might decide to mitigate the impact of a heat wave by modifying urban microclimates through water buffers and green spaces or irrigating surrounding fields. This, in turn, may feed back through surface fluxes on to the local and mesoscale weather patterns (e.g., Grimmond et al. 2010; Steenbergen et al. 2011; Shepherd 2013; Oke et al. 2017; Chen and Jeong 2018).
2) On longer time scales, we also have to consider changes in land use, such as urbanization, deforestation, expansion, or reduction of agricultural land, as well as construction of infrastructure, including photovoltaic and wind power plants. The associated change in surface albedo and roughness will locally influence water and energy surface fluxes of the Earth system and may lead to regional influences on weather patterns (e.g., Erickson 1992; Baidya Roy et al. 2004; Pielke 2005).

In this framework, accelerating improvements in prediction and services requires comprehension of the complexity of the technological and human dimensions of the value cycle together with the interactions, synergies, and feedbacks between the various components of the Earth system. This integrated approach broadens the Earth system science's traditional approach to include socio-economic themes.

Meeting the needs of society. Tackling and reducing risks of natural hazards and disasters depends increasingly upon interdependencies between people, their environment, and hazards (Paton and Johnston 2006; Eiser et al. 2012). For example, Barros et al. (2014) analyzed nearly 4,000 stream gauge records in the eastern and southeastern United States. They reported increases of one order of magnitude in the specific flood discharge for high-frequency events (e.g., the 2- and 10-yr return period) in counties with large increases in population density between 1990 and 2010 according to the U.S. census, and in particular in the Houston area. Using population density as an indirect metric of urbanization (lifeline infrastructure and increase in paved areas in new developments), and thus landscape hardening, this implies reduced conveyance and storage capacity in the downstream network for the same weather event or risk level. Given that a one-order-of-magnitude increase in the specific flood discharge was found for such high-frequency events in Houston already, then much worse conditions should be expected for extreme low-frequency events, such as Hurricane Harvey in 2017.

Take the general case of a tropical cyclone forecast to make landfall in an urban area. Based on a probable landfall forecast, authorities have to monitor water storage of dams surrounding the area and the drainage system status across the city, and reconcile the timeliness of all information sources. Their operational decisions then feed back into the system behavior. For example, releasing water from a reservoir to prevent dam failure may result in magnifying the flood threat. To improve the prediction of such events, and thus increase resilience, the coupled natural and infrastructure drainage systems and contributing areas need to be represented in models with a high level of granularity. A continuous monitoring of system changes in land use, population density, and drainage systems, especially in upstream contributing areas, will allow the representation in models to be updated on a regular basis.

Introducing land use and other anthropogenic effects allows us to predict the impacts of extreme weather events more effectively (impact-based forecasting). The step forward is to ensure the timeliness, granularity, and flexibility of the information that is required for successful decision-making processes. For instance, traffic management (road, airports, railways, etc.) in an urban area during and after landfall of a tropical cyclone needs high granularity (i.e., resolution, level of details) of information, but also flexibility in providing details at required time intervals.

A co-design approach. It is important to ensure flexibility in the development of products and services while also maintaining standards for quality. Only a co-designed approach that involves all relevant parties will allow this novel service provision based on seamless Earth system information to work. Expanded services require more collaboration among disciplines, sectors, and organizations.

The energy sector provides examples of where scientific progress improves functionality and service delivery through a co-design approach. At present, the world is undergoing a global energy transition with increasing shares of energy derived from renewable energy systems that are intrinsically weather and climate dependent (REN21 2017; IEA 2019; Siefert et al. 2017). Ramps in wind or photovoltaic power production occur due to their weather-dependent capacity. They threaten the security of energy supply if not predicted with the required accuracy. Power plant and grid operators must incorporate these energy sources into existing fossil fuel–dominated power grids and manage their variable weather-dependent outputs based on tailored predictions. These challenges result in new definitions of high impact weather—such as the occurrence or non-occurrence of low stratus clouds that strongly affect solar power production—that must be considered by scientists and forecast providers.

A secure and economic integration of renewable energy sources thus relies on accurate forecasts of the potential power production, and these in turn on improved weather forecasts, including an estimate of forecast uncertainty. The energy sector requires data for multiple time scales to respond to current user needs. Further, it uses data for infrastructure planning and for responding to future energy demands. The value cycle approach could help facilitate the integration of user's needs into the science planning, thus becoming a concrete tool for co-design.

Future infrastructure

Earth system sciences are extremely data and compute intensive. They are increasingly a big data problem, involving a huge number of different kinds of observations and diverse modeling and data processing outputs. A new machine learning frontier is bridging between outputs and sector-specific services. Turning these opportunities and challenges into a benefit for society requires a paradigm shift in scientific methodologies and a strengthening of collaboration across different sectors. Science that serves society requires planning to ensure that resources—financial, technical, physical, organizational, and human—can meet future requirements.

Earth system computing and machine learning. Advances in numerical weather prediction since the 1950s and in climate predictions and projections more recently have gone hand in hand with progress in scientific computing and observational capabilities. Meeting societal needs requires simulating finer scales with more complex physical processes, assimilating more data, coupling models for the different compartments of the Earth system, and running large ensembles to produce more accurate and reliable forecasts, while also providing information about their uncertainty. This has resulted in research and operational centers using some of the largest high performance computing (HPC) systems worldwide. The steady increase of skill obtained with more complex forecasting systems run on increasingly larger HPC facilities and the availability of new diverse and extended observational datasets for data assimilation (e.g., from modern satellite systems), has led to what is known as a “quiet revolution” in numerical weather prediction (Bauer et al. 2015).

Moving to high-resolution, complex, and probabilistic Earth system analysis and forecasting systems will, however, require substantially more computing and data handling resources. Contrary to the reliance on the steady microprocessor performance development in the past, these need to be provided by a concerted effort between mathematical, algorithmic, and programming environment developments, taking also into account affordable electric power levels. Further, the developments should focus on more heterogeneous, specialized hardware options (Lawrence et al. 2018), like different kinds of processors, and explore artificial intelligence methods where applicable (Dueben and Bauer 2018). These challenges receive worldwide attention currently and spawn significant funding programs, for example, through the Future and Emerging Technology High-Performance Computing program of the European Commission, the Department of Energy Exascale Earth System Model effort in the United States, and comparable large-scale science–technology programs in Japan and China.

Substantial advances have been made in the assimilation of traditional and new types of data into models, using them for the development of verification methodologies, as well as for the generation of nowcasting and other prediction products. New developments in data assimilation, like ultra-rapid data assimilation algorithms, allow the gap between forecasts from nowcasting and numerical weather prediction to be closed and can form the base for seamless prediction from minutes to hours.

Machine learning and big data techniques provide new possibilities to complement and expand on our seamless prediction system, in particular for very short time decision-making problems (time scale of minutes). Information (e.g., about road conditions) can be shared instantaneously and processed by smart networks (e.g., interconnected cars), issuing an automatic warning to the full network.

The emerging wealth of data further provides the chance to add inductive, data-driven science to theory-driven, deductive science (Hey et al. 2009). Additional opportunities arise for multidisciplinary research that can enrich service provision using seamless Earth system information by providing visual analytics and appropriate storylines. Storylines can help to make information about possible developments of the Earth system and their impact more comprehensible to users (Hazeleger et al. 2015). In such a storyline approach, numerical models can, for example, be used to create a set of physically plausible realizations of an extreme weather event in an altered climate and the possible impacts. Instead of probability information, which often suffers from uncertainties in model simulations, this event-oriented approach provides a set of possible development scenarios, which might be more accessible to some users (Shepherd et al. 2018). Tapping into the potential of these technological opportunities to further enhance our seamless Earth system prediction capabilities needs supporting scientific virtual or physical infrastructures that facilitate their exploitation (e.g., regional research center network, monitoring capacity in least developed countries and small island developing states, computing facilities and high-speed connectivity). Capitalizing the full benefit of these new types of data, methods, and systems for our prediction approaches remains an ongoing challenge, however, requiring continuous investments in research, infrastructure, and human resources.

The data management issue. The increasing volume of data, both from observations and models, may make data handling and transfer computationally unaffordable or even infeasible and thus result in immobility of data. New data-management models are required, such as moving from existing centralized data storage, processing, and analysis systems to more distributed systems or cloud-based solutions. Big data approaches must be applied to large spatiotemporal data such as gridded forecasts, satellite imagery, and large volumes of nonconventional observations of weather or the environment (Lu et al. 2016). Future distributed infrastructure should build on modular components of formats, methods, and systems, including the full chain from observation operators to retrieval and nowcasting algorithms, data assimilation components, numerical models, monitoring and alert systems, exchange formats, verification, diagnostics, quality control, and intercomparison tools. In this case, maintenance of observational systems and data management are critical elements to ensure the sustainable development of knowledge and science for society.

Accessibility of observations. The availability and accessibility of observations is key to skillful predictions and is indispensable for developing, maintaining, and further enhancing the skills of our prediction systems. That is why a long tradition of standardizing and sharing data, starting from the late nineteenth century, has developed in the meteorological community (Pudykiewicz and Brunet 2008). It is recognized that weather forecasting is a shared, global challenge that must be addressed collectively. Under the auspices of WMO, the worldwide access and exchange of observational data from national networks and the fleet of national and international satellites has therefore been organized in an efficient way.

In this context, the highest priority should be given to ensuring data availability and the best possible exchange of information. All relevant observations must be available to improve nowcasting, for assimilation into multiscale models, and to ensure long-term monitoring of essential climate variables. Earth system data—because of their essential role for the security of society and environmental disaster prevention—thus need to be Findable, Accessible, Interoperable, and Reusable (FAIR; Wilkinson et al. 2016).

Improved collaboration in the Global Weather Enterprise. As new players are entering the field, the infrastructure and management culture of this data exchange need to be modernized. These new players, including commercial data service providers, are generating and providing observations of our environment, or creating their own prediction systems. One example can be found in the development and management of sensor systems, where a transition is underway from solely sparse public sector data sources using high cost, but well-characterized and standardized equipment and mobile monitoring, to the use of blended data that includes lower-cost sensors deployed by public and private actors. More non-conventional data will become available, for example, from mobile phones, cars, and other internet-connected devices, most of which will be owned by private companies or individuals. This results in increasing volumes of data in the public domain of varying quality, provenance, and reliability, supplied by a much wider range of sources. On the one hand, this opens up the opportunity for advancing prediction systems and for the production of improved user-tailored products. On the other hand, this requires a policy on data usage and sharing, for example, following the FAIR concept mentioned above, and the means to ensure interoperability of systems and methods with data from other science disciplines or sectors.

Collaboration among the private and public sectors and partnerships in the context of the Global Weather Enterprise (Thorpe and Rogers 2018) are vital to ensure that as much of these data as possible are available to as many people as possible, including full accessibility for research purposes. At the same time, these data and technologies must be used in ways that ensure decisions are made based on information that is of the right quality for the task at hand (Lewis and Edwards 2016). An open question is how the growth of private-sector capabilities can strengthen and not weaken the overall investment on the value cycle, and the continuous improvement and availability of Earth system information. Companies with a weather-oriented business recognize that this capability has to be built on the public investment in the global observing system, in models and tools that form the bedrock of their operations, and in long-term atmospheric research (Thorpe and Rogers 2018). The development of public–private partnerships further necessitates a clear definition of the roles of the different players in providing information. This applies in particular to warnings and other information that are highly critical for the society. Such a policy and mutual agreement among all players involved could be crucial to prevent unplanned breakdowns in the provision of essential Earth system data for the benefit of society. Thus, WMO is promoting a dialogue among different players to ensure a coordinated growth of the Global Weather Enterprise.

Nurturing scientific talents

An innovative and diverse workforce is needed to advance seamless Earth system science. Developing science guided by the value cycle requires an interdisciplinary approach and mind-set alongside the capability to work in depth in individual disciplines. The technical side of the value cycle requires expertise in aspects of data handling and understanding emerging technologies, in computational sciences, in managing and improving infrastructure, developing and running coupled prediction models, and various other components. Developing products for end-users, improving the information provided for decision-making, and considering aspects of vulnerability and risk in predictions requires a consideration of risk communications, behavioral sciences, and economic aspects. Early exposure to and training in an interdisciplinary scientific approach is essential in building the links between natural and social sciences.

There are various challenges that the new generation of scientists encounter during their career, which may vary for different regions in the world. Access to data, tools and infrastructure, and scientific publications, as well as the possibility to attend conferences and workshops and thus to interact with the international research community, are examples. These may apply in particular to scientists in developing countries (Dike et al. 2018), but also to scientists at under-resourced universities and research institutions. The development of cloud-based solutions to provide access to data and tools could be a means to foster research worldwide. Together with improvements in information technology and research infrastructure within developing countries and an investment plan for highly qualified human resources, these new solutions might help to prevent researchers from moving to other countries because they expect a better support for their research (Polcher et al. 2011).

The development and retention of scientific talents could benefit from the development of scientific educational hubs, both virtual and real. There is a need to connect people in academia, government, and the private sector, facilitating the improvement of both local and global research collaborations and providing an open forum for broader participation. Three examples from Africa for such an approach are given here. The Science for Weather Information and Forecasting Technology (SWIFT; https://africanswift.org/) project is jointly funded by research and development funds, through the U.K.'s Global Challenges Research Fund Africa. SWIFT aims to enhance the weather prediction capability from hourly to seasonal time scales in four African countries. The project connects universities and forecasters from the United Kingdom with those in Senegal, Ghana, Nigeria, and Kenya to maintain and further increase local research capacities. It works with forecast users from various sectors toward tailored provision of weather forecasts and improved response to high-impact weather events. The recently established East African Institute for Fundamental Research (EAIFR; https://eaifr.ictp.it/) in Rwanda, a partner of the International Centre for Theoretical Physics, addresses the need in Rwanda and the region for MScs and PhDs in various areas of physics, both fundamental and applied. The African Institute for Mathematical Sciences, a pan-African network of centers of excellence, offers a structured Master's in mathematical sciences and focuses on scientific training, cutting-edge research, and public engagement. One important component of any of these actions is ensuring fluent and sustained connections among scientists from developed and less developed countries and from different sectors. This would benefit science as a whole.

The gender disparity in the scientific, technological, engineering, and mathematics (STEM) disciplines is another factor that may limit access to the full potential of an emerging generation of scientific talents. Although not fully understood yet, the gender disparity may be attributed to conscious and unconscious gender biases, education systems and society, challenges in work–life balance, lack of long-term career opportunities in academia, attitudes about career choice, and a lack of role models. Aspects of harassment, marginalization, and isolation might further add to the gender disparity. An in-depth analysis of the factors resulting in gender disparity is beyond the scope of this paper. UNESCO (2017) provides a more detailed assessment, together with examples from research and practice on how encourage women and girls to pursue a career in STEM.

Working to break down the barriers described above and to create opportunities that foster future scientific talents with an interdisciplinary education are key to supporting an emerging generation of scientists. As future leaders in the field it is in their hands to progress the work toward a seamless Earth system science that will benefit governments, institutions, and society.

Innovation and resources

Our environment has a widespread and important impact on many industries, including energy, transportation, public health, and agriculture. Organizations in all these industries are using Earth system data to inform their operations, planning, and decisions. In a science-driven inquiry framed by real-world problems, there is a growing interaction between science and applications. The proposed seamless Earth system science will advance scientific knowledge of the system itself, improve predictive capabilities, and foster policy-oriented research. It will also enable the provision of products and services at all time scales and to all sectors and applications, and will hence facilitate the transition to a seamless provision of Earth system information.

The way we organize science and its connection with stakeholders needs to change if we are to develop a more flexible system tailored for answering emerging and urgent societal requirements, expressed in the Paris Agreement of 2015 (UNFCCC 2015), the 2030 Agenda for

Sustainable Development (UN 2016), or the Sendai Framework for Disaster Risk Reduction (UNISDR 2016). Research requires a balanced approach, combining long-term activities that will support continuous improvement alongside short-term innovation for targeted challenges. Both are needed to progress toward the longer-term goal of seamless Earth system prediction. The implementation of a feedback loop along the value cycle (see sidebar) and across the interfaces will help to ensure a continuous interaction between users, operations, and science. As an example, in the satellite sector, scientists who are designing the satellite observing system, those who are developing products, and the user community work together to determine how satellite data can better inform decision-making (Brown and Escobar 2019). In this value cycle framework innovation can be promoted by focusing research activities, improving access to interdisciplinary datasets and tools for application development, and mobilizing resources around key societal needs.

Recommendations

From the discussions during the Science Summit and beyond, a number of recommendations emerged as cornerstones to shape the WMO research agenda for the years to come.

- A better integration between the needs of stakeholders, decision-makers, and other users, and the implementation of seamless Earth system prediction, must be facilitated. Science has to work together with users to explore ways of integrating data from different observing systems, models, and other prediction products, as well as from the different compartments of the Earth system to enable the provision of information that is accurate, smooth, and consistent across time and space scales.
- A mechanism must be developed for a rolling review of user requirements that will help shape priorities in Earth system science and involve user groups through effective feedback mechanisms, interdependencies, and mutual trust. To ensure that our developments meet the increasing demands of users and society for more sophisticated, integrated services, this mechanism must be based on a continuous exchange of information between the science and user communities. This is the prerequisite for co-designing the development of new and user-oriented services. The implementation of a value cycle, with well-defined connections at the interfaces along the cycle, is seen as a promising approach to realize the concept of co-design.
- The focus on emerging technologies and methodologies, like new observing platforms, lower-cost sensors, artificial intelligence, "extreme" (exabyte and further) data management, and supercomputing must be strengthened. The increasing availability of a vast amount of data opens up new opportunities for improving predictions and services. At the same time, new challenges emerge when it comes to the diversity of data sources, to aspects of data handling, or to recent developments in supercomputing. Fruitful collaborations between computing experts and industry could thus help explore new ways of creating seamless Earth system predictions. As a pioneering endeavor, the international ExtremeEarth initiative (www.extremeearth.eu/) aims at bringing together academia, private companies, and operational centers to drive future developments in large-scale computing and data-intensive methodologies. Together with these emerging technological opportunities comes the need to implement strategies to ensure that the information provided is of the right quality and content to allow well-informed decision-making.
- New policies on data management and use must be developed, taking into account the growing field of Earth system information providers. The different contributors to the Global Weather Enterprise from the public, private, and academic sectors need to cooperate even more fully than in the past if the seamless approach to Earth system prediction is to become reality.

- The education of scientists, particularly in developing regions, must be fostered, in order to exploit the full potential of the seamless Earth system prediction worldwide. Building academic training around the concept of the value cycle presented in this paper would be a first priority for better linking the academic community to WMO operational activities. The emerging opportunities of online communication tools to broaden access to training and information sharing and the establishment of educational hubs should improve accessibility to scientific resources and bring the global research community closer together.
- An international coordinating mechanism must be established that ensures the development of basic and applied themes of the seamless Earth system prediction, combined with a strong link to the different regional needs. Regional dedicated networks for interconnecting academic and operational institutions are needed for the most vulnerable regions. These networks should elaborate the relevant scientific questions that need to be addressed to make regions more resilient to environmental extremes, and international bodies and organizations (e.g., WMO, the International Science Council, Intergovernmental Oceanographic Commission of UNESCO, the Belmont Forum, and FutureEarth) should facilitate this together.

These recommendations guided the research and operation dialogue at the 2019 WMO Congress, ensuring effective connections of Earth system science with societal needs, paving the way to the development of seamless Earth system prediction capabilities. Engaging researchers, users, and stakeholders in advancing seamless Earth system science will be crucial to ensure that the delivery of information about the changing environment addresses the needs of society.

Acknowledgments. The authors of this paper (the organizers, keynote speakers, and panelists of the Science Summit) would like to express their sincere appreciation to the contribution from all participants (see supplement for a full list of participants). Their active engagement during plenary discussions and the World Cafe sessions was essential for the final outcome and for the recommendations to World Meteorological Congress. We further thank the WMO staff for supporting all aspects of the meeting, as well as the Republic of Indonesia for their effort in planning the meeting, which had to be moved to Geneva on a short-hand notice, due to a volcanic eruption. Our sincere thanks also go to three anonymous reviewers who provided very encouraging and valuable feedback on previous versions of the manuscript, which helped to significantly enhance the clarity and message of this paper. VD acknowledges the support of CAS International Cooperation program (Grant 134111KYSB20160010) and the CAS-TWAS President Fellowship for his PhD study. VL acknowledges the support received by the Horizon 2020 Projects CRESCENDO (Grant 641816) and Blue Action (Grant 727852).

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