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Advancing research for seamless Earth system prediction

Article

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Advancing Research for Seamless Earth System Prediction

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Capsule Summary: The WMO convened the "Science Summit on Seamless Research for Weather, Climate, Water, and Environment" to guide the Commission for Atmospheric Sciences (CAS-17) on future scientific research needs and requirements.

Abstract

Whether on an urban or planetary scale, covering timescales 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 amongst 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.

Body Text

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 hydro-meteorological 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).

With a focus on establishing the organization's future research agenda, the Commission for Atmospheric Sciences (CAS) of WMO convened in October 2017 for a Science Summit. 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 online supplement for further information about the Science Summit). The presentations, panel discussions and breakout groups in World Cafes (Fig. 2, and online 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.

Seamless Prediction and Science for Society

The Earth system is characterized by complex non-linear 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 (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 towards the idea of predicting "the spatial-temporal continuum of the interactions among weather, climate and Earth system" (Brunet et al., 2010).

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 et al. 2015). This value chain links the production and delivery of these services to user decisions and to the outcomes and values resulting from those

167 decisions. The main components are observation, modeling, forecasting, and services delivery.
168 This approach strengthens the role of user needs in the development of weather and climate
169 products. At the same time, however, it does not include feedback and co-design mechanisms
170 that would put user needs at the heart of the research and development phase. The value cycle
171 approach (Day 1999) extends the idea of a value chain, originally developed in an economic
172 context (Porter 1985), by adding interactions with users to the process. Such a value cycle
173 approach provides a useful means to guide Earth system science and ensure its societal benefit.
174 The generation and delivery of weather and climate services can be depicted in such a value
175 cycle (Fig. 3). This encompasses the production (observing, modelling, forecasting) of
176 information, the dissemination to users (ways of provision, communication and tailor-made
177 products), perception and decision making, and the outcomes and values. The interaction with the
178 users is essential for the exploration of "what works" in terms of relevance, quality and impact. The
179 processes connecting those steps along the cycle and the feedback between them are essential for
180 its functioning. For instance, it allows to explore how new technologies may help to enhance forecast
181 products or methods like climate downscaling.
182 Extending the concept of seamless prediction to draw on expertise from social sciences
183 together with users' knowledge and experience will help to improve the development of
184 knowledge and services. Nowadays, we thus expand the initial definition of seamless prediction
185 to consider also the need of users, stakeholders and decisions makers for information that is
186 continuous and consistent despite the different sources from which the information is generated.
187 This seamless prediction approach thus encompasses all compartments of the Earth system,
188 including human-induced modifications and their consequences, but also all elements of the
189 value cycle.

190 Seamless Earth system science, guided by the value cycle approach (Fig. 3), will allow us
191 to understand better and simulate more completely the inherent feedbacks and to generate and
192 deliver user-specific information on changes in the Earth system, over minutes to centuries in
193 time, and local to global scales in space. Further, it will enable an assessment of the resulting
194 benefits to society.
195 The need for such a seamless prediction approach that considers inherent feedbacks is
196 underpinned by the fact that human activities like water management or various other climate
197 policies can directly modify the very system that we want to predict. Two examples of why such
198 interactions need to be considered to allow for the best possible predictions across a wide range
199 of applications are given below.
200 1) Depending on the availability of water resources and their management on sub-
201 seasonal time scales, stakeholders might decide to mitigate the impact of a heat
202 wave by modifying urban microclimates through water buffers and green spaces
203 or irrigating surrounding fields. This in turn may feed back through surface fluxes
204 on to the local and mesoscale weather patterns (e.g., Grimmond et al. 2010;
205 Steenbergen et al. 2011; Shepherd 2013; Oke et al. 2017; Chen and Jeong 2018)
206 2) On longer time scales, we also have to consider changes in land use, such as
207 urbanization, deforestation, expansion or reduction of agricultural land, as well as
208 construction of infrastructure, including photovoltaic- and wind power plants. The
209 associated change in surface albedo and roughness will locally influence water
210 and energy surface fluxes of the Earth system and may lead to regional influences
211 on weather patterns (e.g., Erickson, 1992; Baidya Roy et al. 2004; Pielke 2005).

212 In this framework, accelerating improvements in prediction and services requires
213 comprehension of the complexity of the technological and human dimensions of the value cycle
214 together with the interactions, synergies and feedbacks between the various components of the
215 Earth system. This integrated approach broadens the Earth system science´s traditional approach
216 to include socio-economic themes.
217
218 *Meeting the needs of society*
219 Tackling and reducing risks of natural hazards and disasters depends increasingly upon
220 interdependencies between people, their environment and hazards (Paton and Johnston 2006;
221 Eiser et al. 2012). For example, Barros et al. (2014) analyzed nearly 4,000 stream gage records in
222 the eastern and southeastern United States. They reported increases of one order of magnitude in
223 the specific flood discharge for high-frequency events (e.g. the 2- and 10-year return period) in
224 counties with large increases in population density between 1990-2010 according to the US
225 census, and in particular in the Houston area. Using population density as an indirect metric of
226 urbanization (lifeline infrastructure and increase in paved areas in new developments), and thus
227 landscape hardening, this implies reduced conveyance and storage capacity in the downstream
228 network for the same weather event or risk level. Given that a one order of magnitude increase in
229 the specific flood discharge was found for such high-frequency events in Houston already, then
230 much worse conditions should be expected for extreme low-frequency events such as Hurricane
231 Harvey in 2017.
232 Take the general case of a tropical cyclone forecast to make landfall in an urban area.
233 Based on a probable landfall forecast, authorities have to monitor water storage of dams
234 surrounding the area and the drainage system status across the city, and reconcile the timeliness

235 of all information sources. Their operational decisions then feed back into the system behavior.
236 For example, releasing water from a reservoir to prevent dam failure may result in magnifying
237 the flood threat. To improve the prediction of such events, and thus increase resilience, the
238 coupled natural- and infrastructure drainage systems and contributing areas need to be
239 represented in models with a high level of granularity. A continuous monitoring of system
240 changes in land-use, population density and drainage systems, especially in upstream
241 contributing areas will allow the representation in models to be updated on a regular basis.

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

248 *A co-design approach*

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

253 The energy sector provides examples of where scientific progress improves functionality
254 and service delivery through a co-design approach. At present, the world is undergoing a global
255 energy transition with increasing shares of energy derived from renewable energy systems that
256 are intrinsically weather and climate dependent (REN21 2017; IEA 2017; Siefert and Hagedorn
257 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 timescales 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

281 Advances in numerical weather prediction since the 1950s and in climate predictions and
282 projections more recently have gone hand in hand with progress in scientific computing and
283 observational capabilities. Meeting societal needs requires simulating finer scales with more
284 complex physical processes, assimilating more data, coupling models for the different
285 compartments of the Earth system and running large ensembles to produce more accurate and
286 reliable forecasts, while also providing information about their uncertainty. This has resulted in
287 research and operational centers using some of the largest high performance computing (HPC)
288 systems worldwide. The steady increase of skill obtained with more complex forecasting systems
289 run on increasingly larger HPC facilities and the availability of new diverse and extended
290 observational datasets for data assimilation (e.g., from modern satellite systems), has led to what
291 is known as a 'quiet revolution' in numerical weather prediction (Bauer et al. 2015).
292 Moving to high-resolution, complex and probabilistic Earth system analysis and
293 forecasting systems will, however, require substantially more computing and data handling
294 resources. Contrary to the reliance on the steady micro-processor performance development in
295 the past, these need to be provided by a concerted effort between mathematical, algorithmic and
296 programming environment developments, taking also into account affordable electric power
297 levels. Further, the developments should focus on more heterogeneous, specialized hardware
298 options (Lawrence et al. 2018), like different kinds of processors, and explore artificial
299 intelligence methods where applicable (Dueben and Bauer 2018). These challenges receive
300 worldwide attention currently and spawn significant funding programs, for example through the
301 Future and Emerging Technology High-Performance Computing program of the European
302 Commission, the Department of Energy Exascale Earth System Model effort in the US, and
303 comparable large-scale science-technology programs in Japan and China.

304 Substantial advances have been made in the assimilation of traditional and new types of
305 data into models, using them for the development of verification methodologies, as well as for
306 the generation of nowcasting- and other prediction products. New developments in data
307 assimilation, like ultra-rapid data assimilation algorithms, allow the gap between forecasts from
308 nowcasting and numerical weather prediction to be closed and can form the base for seamless
309 prediction from minutes to hours.
310 Machine learning and big data techniques provide new possibilities to complement and
311 expand on our seamless prediction system, in particular for very short-time decision making
312 problems (time scale of minutes). Information (e.g., about road conditions) can be shared
313 instantaneously and processed by smart networks (e.g., interconnected cars), issuing an
314 automatic warning to the full network.
315 The emerging wealth of data further provides the chance to add inductive, data-driven
316 science to theory-driven, deductive science (Hey et al. 2009). Additional opportunities arise for
317 multidisciplinary research that can enrich service provision using seamless Earth system
318 information by providing visual analytics and appropriate storylines. Storylines can help to make
319 information about possible developments of the Earth system and their impact more
320 comprehensible to users (Hazeleger et al. 2015). In such a storyline approach, numerical models
321 can e.g. be used to create a set of physically plausible realizations of an extreme weather event in
322 an altered climate and the possible impacts. Instead of probability information, which often
323 suffers from uncertainties in model simulations, this event-oriented approach provides a set of
324 possible development scenarios, which might be more accessible to some users (Shepherd et al.
325 2018). Tapping into the potential of these technological opportunities to further enhance our
326 seamless Earth system prediction capabilities needs supporting scientific virtual or physical

327 infrastructures that facilitate their exploitation (e.g., regional research center network, monitoring
328 capacity in least developed countries and small island developing states, computing facilities and
329 high-speed connectivity). Capitalizing the full benefit of these new types of data, methods and
330 systems for our prediction approaches remains an ongoing challenge, however, requiring
331 continuous investments in research, infrastructure and human resources.

332 *The data management issue*

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

345 *Accessibility of observations*

346 The availability and accessibility of observations is key to skillful predictions and
347 indispensable for developing, maintaining and further enhancing the skills of our prediction
348 systems. That is why a long tradition of standardizing and sharing data, starting from the late
349 19th century has developed in the meteorological community (Pudykiewicz and Brunet 2008). It

350 is recognized that weather forecasting is a shared, global challenge that must be addressed
351 collectively. Under the auspices of WMO, the worldwide access and exchange of observational
352 data from national networks and the fleet of national and international satellites has therefore
353 been organized in an efficient way.

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

360 *Improved collaboration in the Global Weather Enterprise*

361 As new players are entering the field, the infrastructure and management culture of this
362 data exchange need to be modernized. These new players, including commercial data service
363 providers, are generating and providing observations of our environment, or creating their own
364 prediction systems. One example can be found in the development and management of sensor
365 systems, where a transition is underway from solely sparse public sector data sources using high
366 cost, but well-characterized and standardized equipment and mobile monitoring, to the use of
367 blended data that includes lower cost sensors deployed by public and private actors. More non-
368 conventional data will become available, for example, from mobile phones, cars, and other
369 internet-connected devices, most of which will be owned by private companies or individuals.
370 This results in increasing volumes of data in the public domain of varying quality, provenance
371 and reliability, supplied by a much wider range of sources. On the one hand, this opens up the
372 opportunity for advancing prediction systems and for the production of improved user-tailored

373 products. On the other hand, this requires a policy on data usage and sharing, e.g. following the
374 FAIR concept mentioned above, and the means to ensure interoperability of systems and
375 methods with data from other science disciplines or sectors.
376 Collaboration among the private and public sectors and partnerships in the context of the
377 Global Weather Enterprise (Thorpe and Rogers 2018) are vital to ensure that as much of this data
378 as possible are available to as many people as possible, including full accessibility for research
379 purposes. At the same time, these data and technologies must be used in ways that ensure
380 decisions are made based on information that is of the right quality for the task at hand (Lewis
381 and Edwards 2016). An open question is how the growth of private sector capabilities can
382 strengthen and not weaken the overall investment on the value cycle, and the continuous
383 improvement and availability of Earth system information. Companies with a weather-oriented
384 business recognize that this capability has to be built on the public investment in the global
385 observing system, in models and tools that form the bedrock of their operations, and in long-term
386 atmospheric research (Thorpe and Rogers 2018). The development of public-private partnerships
387 further necessitates a clear definition of the roles of the different players in providing
388 information. This applies in particular to warnings and other information that are highly critical
389 for the society. Such a policy and mutual agreement among all players involved could be crucial
390 to prevent unplanned breakdowns in the provision of essential Earth system data for the benefit
391 of society. Thus, WMO is promoting a dialogue among different players to ensure a coordinated
392 growth of the Global Weather Enterprise.
393
394
395 **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,

419 government, and the private sector, facilitating the improvement of both local and global
420 research collaborations and providing an open forum for broader participation. Three examples
421 from Africa for such an approach are given here. The "Science for Weather Information and
422 Forecasting Technology (SWIFT)[1]" project is jointly funded by research and development funds,
423 through the UK's Global Challenges Research Fund Africa. SWIFT aims to enhance the weather
424 prediction capability from hourly to seasonal timescales in four African countries. The project
425 connects universities and forecasters from the UK with those in Senegal, Ghana, Nigeria and
426 Kenya to maintain and further increase local research capacities. It works with forecast users
427 from various sectors toward tailored provision of weather forecasts and improved response to
428 high-impact weather events. The recently established East African Institute for Fundamental
429 Research (EAIFR) [2] in Rwanda, a partner of the International Centre for Theoretical Physics,
430 addresses the need in Rwanda and the region for MScs and PhDs in various areas of physics,
431 both fundamental and applied. The African Institute for Mathematical Sciences, a pan-African
432 network of centers of excellence, offers a structured Master's in mathematical sciences and
433 focuses on scientific training, cutting-edge research and public engagement. One important
434 component of any of these actions is ensuring fluent and sustained connections amongst
435 scientists from developed and less developed countries and from different sectors. This would
436 benefit science as a whole.

437 The gender disparity in the scientific, technological, engineering and mathematics
438 (STEM) disciplines is another factor that may limit access to the full potential of an emerging
439 generation of scientific talents. Although not fully understood yet, the gender disparity may be
440 attributed to conscious and unconscious gender biases, education systems and society, challenges

[1] More information on SWIFT is available at https://africanswift.org/
[2] More information on EAIFR is provided at https://eaifr.ictp.it/

441 in work-life balance, lack of long-term career opportunities in academia, attitudes about career
442 choice, and a lack of role models. Aspects of harassment, marginalization and isolation might
443 further add to the gender disparity. An in-depth analysis of the factors resulting in gender
444 disparity is beyond the scope of this paper. UNESCO (2017) provides a more detailed
445 assessment, together with examples from research and practice on how encourage women and
446 girls to pursue a career in STEM.
447 Working to break down the barriers described above and to create opportunities that
448 foster future scientific talents with an interdisciplinary education are key to supporting an
449 emerging generation of scientists. As future leaders in the field it is in their hands to progress the
450 work toward a seamless Earth system science that will benefit governments, institutions and
451 society.
452
453 **Innovation and Resources**
454 Our environment has a widespread and important impact on many industries,
455 including energy, transportation, public health, and agriculture. Organizations in all these
456 industries are using Earth system data to inform their operations, planning and decisions. In a
457 science driven inquiry framed by real-world problems, there is a growing interaction between
458 science and applications. The proposed seamless Earth system science will advance scientific
459 knowledge of the system itself, improve predictive capabilities, and foster policy oriented
460 research. It will also enable the provision of products and services at all timescales and to all
461 sectors and applications, and will hence facilitate the transition to a seamless provision of Earth
462 system information.

The way we organize science and its connection with stakeholders need 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 towards the longer-term goal of seamless Earth system prediction. The implementation of a feedback loop along the value cycle (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, inter-dependencies, 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 (http://www.extremeearth.eu/) aims at bringing together academia, private companies and operational centers to drive future developments in large-scale computing and

509 data intensive methodologies. Together with these emerging technological
510 opportunities comes the need to implement strategies to ensure that the information
511 provided is of the right quality and content to allow well-informed decision making.

512 • New policies on data management and use must be developed, taking into account the
513 growing field of Earth system information providers. The different contributors to the
514 Global Weather Enterprise from the public, private and academic sectors need to co-
515 operate even more fully than in the past if the seamless approach to Earth system
516 prediction is to become reality.

517 • The education of scientists, particularly in developing regions, must be fostered, in
518 order to exploit the full potential of the seamless Earth system prediction worldwide.
519 Building academic training around the concept of the value cycle presented in this
520 paper would be a first priority for better linking the academic community to WMO
521 operational activities. The emerging opportunities of online communication tools to
522 broaden access to training and information sharing and the establishment of
523 educational hubs should improve accessibility to scientific resources and bring the
524 global research community closer together.

525 • An international coordinating mechanism must be established that ensures the
526 development of basic and applied themes of the seamless Earth system prediction,
527 combined with a strong link to the different regional needs. Regional dedicated
528 networks for interconnecting academic and operational institutions are needed for the
529 most vulnerable regions. These networks should elaborate the relevant scientific
530 questions that need to be addressed to make regions more resilient to environmental
531 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 will guide the research and operation dialogue at 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.

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555 **References**

556 Barros, A. P., Y. Duan, J. Brun, and M. A. Medina, 2014: Flood nonstationarity in the SE and
557 Mid-Atlantic regions of the United States. *J. Hydrol. Eng.*, **19**,
558 https://doi.org/10.1061/(ASCE)HE.1943-5584.0000955.

559 Bauer, P., A. Thorpe, and G. Brunet, 2015: The quiet revolution of numerical weather prediction.
560 *Nature,* **525**, 47–55, https://doi.org/10.1038/nature14956.

561 Baidya Roy, S., S. W. Pacala, and R. L. Walko, 2004: Can large wind farms affect local
562 meteorology? *J. Geophys. Res.*, **109**, D19101, https://doi.org/10.1029/2004JD004763.

563 Brown, M. E., and V. M. Escobar, 2019: NASA's Early Adopter Program links satellite data to
564 decision making. *Remote Sens*., **11**, 406; https://doi.org/10.3390/rs11040406

565 Brunet, G., S. Jones, and P. M. Ruti (Eds.), 2015: *Seamless prediction of the Earth system: From*
566 *minutes to months*. WMO-No. 1156, 483pp, https://library.wmo.int/pmb_ged/wmo_1156_en.pdf.

567 Brunet, G., and Coauthors, 2010: Collaboration of the weather and climate communities to
568 advance subseasonal-to-seasonal prediction. *Bull. Amer. Met. Soc*., **91**, 1397-1406,
569 https://doi.org/10.1175/2010BAMS3013.1.

570 Chen, X. and S.-J. Jeong, 2018: Irrigation enhances local warming with greater nocturnal
571 warming effects than daytime cooling effects. *Environ. Res. Lett.,* **13**, 024005,
572 https://doi.org/10.1088/1748-9326/aa9dea.

573 Day, G. S., 1999: *The market driven organization: Understanding, Attracting, and Keeping*
574 *Valuable Customers*. Free Press, 285 pp.

575 Dike, V. N. and Coauthors, 2018: Obstacles facing Africa's young climate scientists. *Nature*
576 *Climate Change,* **8**, 447–449, https://doi.org/10.1038/s41558-018-0178-x.

577 Dueben, P. D. and Bauer, P., 2018: Challenges and design choices for global weather and
578 climate models based on machine learning. *Geosci. Model Dev.*, **11**, 3999-4009,
579 https://doi.org/10.5194/gmd-2018-148.

580 Eiser, J. R., A. Bostrom, I. Burton, D. M. Johnston, J. McClure, D. Paton, J. van der Pligt, and
581 M. P. White, 2012: Risk interpretation and action: A conceptual framework for responses to
582 natural hazards. *Int. J. Disaster Risk Red.,* **1**, 5-16, https://doi.org/10.1016/j.ijdrr.2012.05.002.

583 Erickson, C.L., 1992: Prehistoric landscape management in the Andean highlands: Raised field
584 agriculture and its environmental impact. *Popul. Env*., **13:4**, 285-300,
585 https://doi.org/10.1007/BF01271028.

586 Grimmond, C. S. B. and Coauthors, 2010: Climate and more sustainable cities: Climate
587 information for improved planning and management of cities (producers/capabilities
588 perspective). *Procedia Environ. Sci.,* **1**, 247–274, https://doi.org/10.1016/j.proenv.2010.09.016.

589 Hazeleger, W., B. J. J. M. van den Hurk, E. Min, G. J. van Oldenborgh, A. C. Petersen, D. A.
590 Stainforth, E. Vasileiadou and L. A. Smith, 2015: Tales of Future Weather. *Nat. Climate*
591 *Change*, **5**, 107-114, https://doi.org/10.1038/nclimate2450.

592 Hey, T., S. Tansley, and K. Tolle, 2009: *The Fourth Paradigm: Data-intensive Scientific*
593 *Discovery*. Microsoft Research, 287pp.

594 Hov, Ø., D. Terblanche, G. Carmichael, S. Jones, P. M. Ruti and O. Tarasova, 2017: Five
595 priorities for weather and climate research. *Nature,* **552**, 168–170,
596 https://doi.org/10.1038/d41586-017-08463-3.

597 IEA, 2017: World Energy Outlook 2017 – Executive Summary. International Energy Agency, 13
598 pp,

599 http://www.iea.org/publications/freepublications/publication/WEO_2017_Executive_Summary_
600 English_version.pdf

601 Lawrence, B. N., and Coauthors, 2018: Crossing the chasm: How to develop weather and climate
602 models for next generation computers? *Geosci. Model Dev.,* **11**, 1799-1821,
603 https://doi.org/10.5194/gmd-11-1799-2018.

604 Lewis, A. C. and P. Edwards, 2016: Validate personal air-pollution sensors, *Nature*, **535**, 29-31,
605 https://doi.org/10.1038/535029a.

606 Lu, S., X. Shao, M. Freitag, L. J. Klein, J. D. Renwick, F. J. Marianno, C. M. Albrecht, and H .
607 F. Hamann, 2016: IBM PAIRS curated big data service for accelerated geospatial data analytics
608 and discovery. *IEEE International Conference on Big Data*, 5-8 Dec 2016, Washington, D.C.,
609 USA, https://doi.org/10.1109/BigData.2016.7840910.

610 Lucarini V., R. Blender, C. Herbert, F. Ragone, S. Pascale, and J. Wouters., 2014: Mathematical
611 and physical ideas for climate science. *Rev. Geophys*. **52**, 809-859,
612 https://doi.org/10.1002/2013RG000446.

613 Nobre, C., and Coauthors, 2010: Addressing the complexity of the Earth system. *Bull. Amer.*
614 *Met. Soc*., **91**, 1389-1396, https://doi.org/10.1175/2010BAMS3012.1.

615 Oke, T., G. Mills, A. Christen, and J. Voogt, 2017: *Urban climates*. Cambridge University Press.
616 https://doi.org/10.1017/9781139016476.

617 Paton, D. and D. M. Johnston, 2006: *Disaster resilience: An integrated approach*. Charles C
618 Thomas Springfield Pub Ltd., 344 pp.

619 Pielke Sr., R. A., 2005: Land use and climate change. *Science*, **310**, 1625-1626,
620 https://doi.org/10.1126/science.1120529.

621 Polcher, J., and Coauthors, 2011: AMMA's contribution to the evolution of prediction and
622 decision-making systems for West Africa. *Atmos. Sci. Lett*., **12**, 2-6,
623 https://doi.org/10.1002/asl.320.

624 Porter, M. E., 1985: *The Competitive Advantage: Creating and Sustaining Superior*
625 *Performance*. Free Press, 592pp.

626 Pudykiewicz, J. and G. Brunet, 2008: The first hundred years of numerical weather prediction.
627 *Large-Scale Disasters: prediction, mitigation and control*. M. Gad-El-Hak, Ed., Cambridge
628 University Press, 427-446.

629 REN21, 2017: Renewables 2017 Global Status Report. Renewable energy policy network for the
630 21st Century Secretariat, Annual Report, 302pp, http://www.ren21.net/wp-
631 content/uploads/2017/06/17-8399_GSR_2017_Full_Report_0621_Opt.pdf.

632 Rogers, D. P., and Coauthors, 2010: Health and climate – opportunities. *Procedia Env. Sci.*, **1**,
633 37-54, https://doi.org/10.1016/j.proenv.2010.09.005.

634 Siefert, M., R. Hagedorn, A. Braun, J. Dobschinski, R. Fritz and G. Good, 2017:
635 Abschlussbericht EWELINE – Erstellung innovativer Wetter- und Leistungsprognosemodelle für
636 die Netzintegration wetterabhängiger Energieträger. Final Report of EWELINE Project (in
637 German), 298 pp, https://doi.org/10.2314/GBV:1000941604.

638 Shapiro, M. A., and Coauthors, 2010: An Earth-system prediction initiative for the 21st century.
639 *Bull. Amer. Meteor. Soc.*, **91**, 1377-1388, https://doi.org/10.1175/2010BAMS2944.1.

640 Shepherd, J.M., 2013: Impacts of urbanization on precipitation and storms: Physical insights and
641 vulnerabilities. *Climate Vulnerability*. R. Pielke, Ed., Elsevier, 109-125,
642 https://doi.org/10.1016/B978-0-12-384703-4.00503-7.

643 Shepherd, T.G., and Coauthors, 2018: Storylines: an alternative approach to representing
644 uncertainty in physical aspects of climate change. *Climatic Change*, **151**, 555-571,
645 https://doi.org/10.1007/s10584-018-2317-9

646 Steenbergen, F., A. van Tuinhof, and L. Knoop. 2011: Transforming lives transforming
647 landscapes. The Business of Sustainable Water Buffer Management. Wageningen, The
648 Netherlands: 3R Water Secretariat, 112 pp,
649 http://www.hydrology.nl/images/docs/ihp/nl/2011.08_Transforming_Landscapes.pdf.

650 Thorpe, A., and D. Rogers, 2018: The future of the Global Weather Enterprise. *Bull. Amer.*
651 *Meteor. Soc.,* **99**, 2003–2008, https://doi.org/10.1175/BAMS-D-17-0194.1

652 UN, 2016: Transforming our world: The 2030 agenda for sustainable development. A/RES/70/1,
653 United Nations, 41 pp,
654 https://sustainabledevelopment.un.org/post2015/transformingourworld/publication

655 UNESCO, 2017: Cracking the code: Girls' and women's education in science,
656 technology, engineering and mathematics (STEM). United Nations Educational, Scientific and
657 Cultural Organization, 85 pp, https://unesdoc.unesco.org/ark:/48223/pf0000253479.

658 UNFCCC, 2015: Report on the structured expert dialogue on the 2013–2015 review. Rep.
659 FCCC/SB/2015/INF.1, U.N. Framework Convention on Climate Change, 182 pp,
660 https://unfccc.int/resource/docs/2015/sb/eng/inf01.pdf

661 UNISDR, 2016: Sendai framework for disaster risk reduction 2015–2030. United Nations
662 International Strategy for Disaster Reduction, 37 pp,
663 www.preventionweb.net/files/43291_sendaiframeworkfordrren.pdf.

664 Wilkinson, M. D., and Coauthors, 2016: The FAIR Guiding Principles for scientific data

management and stewardship. *Sci. Data,* **3**:16001, https://doi.org/10.1038/sdata.2016.18.

WMO, World Bank, United States Agency for International Development, and Global Facility for Disaster Reduction and Recovery, 2015: Valuing Weather and Climate: Economic Assessment of Meteorological and Hydrological Services. World Meteorological Organization, WMO-No. 1153, 308 pp, https://library.wmo.int/doc_num.php?explnum_id=3314.

Sidebar1: The value cycle approach to seamless Earth system science and the Global Weather Enterprise

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.

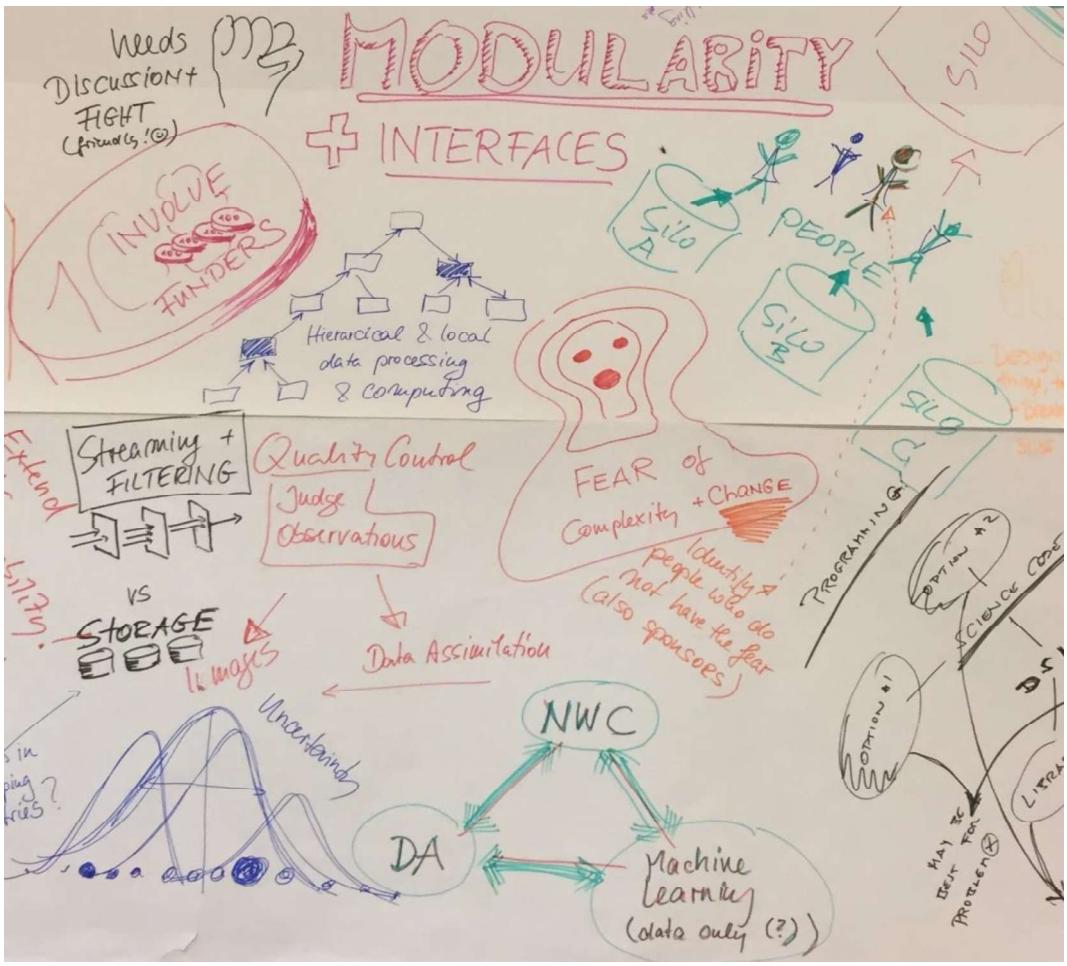
Global Weather Enterprise:

Following Thorpe and Rogers (2018): "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."

693

694 Figure 1: Participants of the Science Summit, held from 20 – 22 October 2017 at the World
695 Meteorological Organization's headquarters in Geneva, Switzerland. A full list of participants is
696 provided in the online supplement.

697



698

699 Figure 2: An impression of the discussion in the World Cafe. This setup allowed all members of
700 the Science Summit to participate and express their views and vision, both verbally and by
701 drawing on the table cloths.

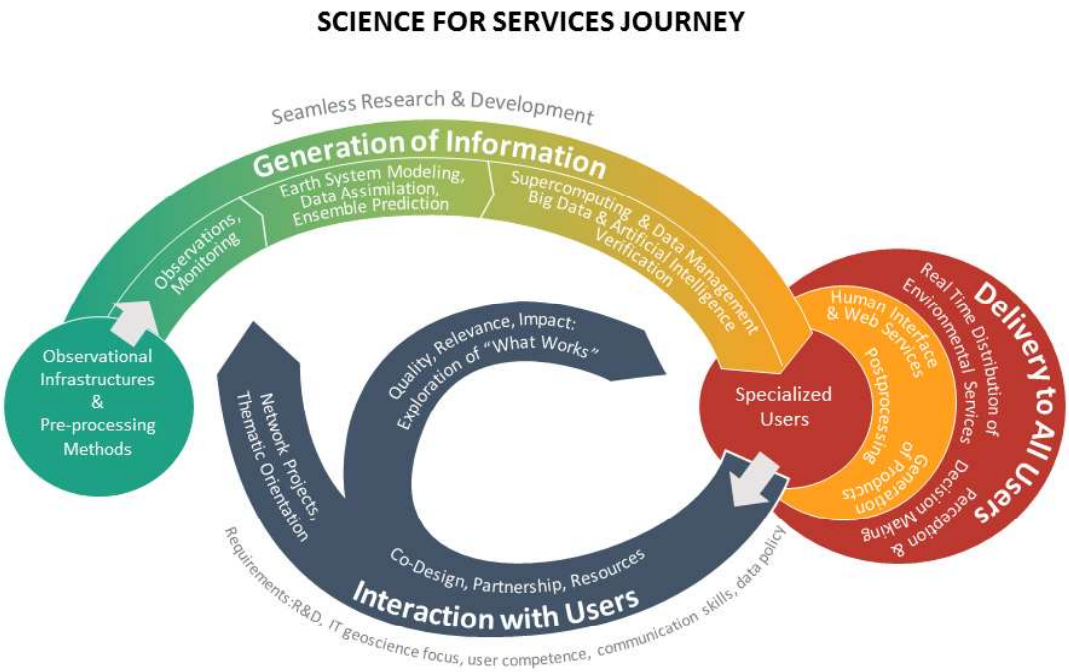


Figure 3: Technical developments on seamless Earth system science need to go hand in hand with informed advancement of observations, monitoring capabilities and advanced assimilation and Earth system modelling and other prediction methods, which are the backbone of existing meteorological services. This 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, modelling, forecasting; green to yellow), postprocessing, the generation of products and suitable interfaces (yellow), as well as the dissemination to users (red) and the perception and decision making. The interaction with users (gray), e.g. through co-design of projects, is essential for the exploration of user-oriented services.