GEWEX QUARTERLY

WCRP World Climate Research Programme

UNESCO United Nations Educational, Scientific and Cultural Organization | Intergovernmental Oceanographic Commission

World Meteorological Organization

International Science Council

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GEWEX is a Core Project of the World Climate Research Programme on Global Energy and Water Exchanges

A History of BSRN from a Founder's Perspective

The Baseline Surface Radiation Network (BSRN) Station at Ny-Ålesund, Svalbard, Norway, one of the longest-serving BSRN stations. See *Ohmura* on pg. 12 for more on the genesis and history of BSRN.

Inside This Edition

Commentary: GEWEX Science Plan for 2021–2030

Xubin Zeng and Jan Polcher
GEWEX Scientific Steering Group (SSG) Co-Chairs

Under the brilliant leadership of Graeme Stephens, who finished his term as the GEWEX Scientific Steering Committee Co-Chair in May 2021, GEWEX completed the review of the significant progress it has made in the past three decades. Also under Graeme's leadership, following the Science and Applications Traceability Matrix approach usually used for National Aeronautics and Space Administration (NASA) satellite missions, GEWEX has finished its draft Science Plan for 2021-2030. Its three goals are described below.

Goal #1: Determine the extent to which Earth's water cycle can be predicted. This Goal is framed around making quantitative progress in addressing questions related to fast reservoirs (atmosphere and land surface), flux exchanges, and precipitation extremes.

Goal #2: Quantify the inter-relationships between Earth's energy, water, and carbon cycles to advance our understanding of the system and our ability to predict it across scales. This Goal is framed around making quantitative progress in addressing questions related to forcing-feedback understanding, atmospheric boundary layer process representation, understanding circulation controls, and land-atmosphere interactions.

Goal #3: Quantify anthropogenic influences on the water cycle and our ability to understand and predict changes to Earth's water cycle by addressing questions related to anthropogenic forcing of continental scale water availability, water management influences, and variability and trends of water availability.

For its new direction in the next decade, GEWEX will include the coupling of energy and water cycles with the carbon cycle, with a focus on process understanding in order to enhance our ability to observe and predict them. Another direction is the inclusion of human activities in the Earth system in order to close the water and energy cycle over continents. These two goals are closely linked, as most of the water management occurring in the world is for the benefit of agriculture and thus also impacts the carbon cycle.

Our enhanced observational capabilities [e.g., NASA and the European Space Agency (ESA)'s designated observables] and spatially-refined models (e.g., through exascale computing) will require confronting and merging new techniques in order to access unobservable parameters in the system or determine the state of reservoirs not easily accessible through the current observational systems.

The close collaboration of GEWEX with operational weather and hydrological services allows us to better formulate societal needs in terms of environmental monitoring and prediction and ensures that the scientific topics we propose will promote wiser management of the environment and adaptation to changing resources.

Because Earth's water cycle is both central to and integrative of most WCRP activities, GEWEX is expected to be core to the five cross-cutting Lighthouse Activities (LHAs; see page 4) recently established by WCRP:

- The Digital Earths LHA will integrate Earth observations with kilometer-scale global and regional modeling, and GEWEX will contribute its model development capabilities and the regional expertise (through the regional hydroclimate projects).
- For the Explaining and Predicting Earth System Change LHA, GEWEX's contribution will focus on the processes linked to latent and sensible energy exchanges in the atmospheric and continental reservoirs.
- GEWEX's knowledge on the recent trends in the energy and water cycle and the coupling of these cycles with the carbon cycle will contribute to the Safe Landing Climates LHA.
- GEWEX's efforts in bringing together scientific communities in various regions of the world around trans-disciplinary regional projects will contribute to the My Climate Risk LHA.
- GEWEX's efforts in developing and organizing trainings, workshops, and summer schools will contribute to the WCRP Academy LHA.

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Navigating Academic Waters Workshop and Bystander Training

Julia Guimond

H3S Chair, National Science Foundation (NSF) Postdoctoral Fellow, Dalhousie University

To many students and early career researchers, the academic job application process can seem daunting and mystifying. This summer, to help unpack the application process, the American Geophysical Union (AGU) Hydrology Section Student Subcommittee (H3S) teamed with the Consortium of Universities for the Advancement of Hydrologic Science, Inc. (CUAHSI) to host a five-week cyber workshop series that discussed major components of the academic job application process. Every Thursday in July and into August, four panelists joined us to speak about a new aspect of applications, from finding the right positions to conquering the interview, and even what a tenure-track position entails. Weekly sessions included a one-hour Q&A with four panelists followed by smaller breakout discussions. The series, titled "Navigating Academic Waters: The Academic Job Application Process", had record numbers with over 400 people registered and often over 100 weekly attendees.

Are you on the job market but missed this series? Not to worry! CUAHSI is posting all Q&A sessions on its YouTube channel (*https://www.youtube.com/user/CUAHSI*), and a series write-up will follow shortly. Watch H3S's website (*https://agu-h3s.org*) for more details.

Additionally, H3S is holding a bystander training workshop on Thursday, November 18, 2021 from 1–4pm EST/10–1pm PST. This event, run by the National Science Foundation's ADVANCEGeo program and sponsored by the AGU Hydrology Section, will train participants how to identify and address harassment and exclusionary behaviors in the workplace. Registration links will be posted on H3S's website (*https://agu-h3s.org/*) and on H3S's Twitter (*@AGU_H3S*). Space is limited.

With the AGU Fall Meeting abstract deadline already behind us, H3S is looking forward to a number of town halls for early career researchers. Posts on H3S events at the AGU Fall Meeting will be announced on the H3S website in the coming weeks.

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YESS Contribution to Recent International Scientific Events

Valentina Rabanal[1], Carla Gulizia[2], Faten Attig Bahar[3], and the YESS Executive Committee

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Over the past few months, the Young Earth System Scientists (YESS) community has taken part in several international events. Among those was the Sustainability Research and Innovation Congress 2021 (SRI2021, *https://sri2021.org/*). Three YESS members–Felix Donkor, Gaby Langendijk, and Faten Attig Bahar–were selected as SRI2021 Conference Early Career Champions (*https://sri2021.org/selected-early-career-champions-announced/?fbclid=IwAR0hcZuxxpHs5_3tFEIP23XEVKoRCwe5sabhT57qI-PDHmAEHocWdqTOMfU*). Gaby Langendijk contributed to Plenary 4 of the Congress, "*To 2030 and beyond: Insights from the 2023 Global Sustainable Development Report and SRI2021 Early Career Champions*", and Faten Attig Bahar hosted a session (*https://sri2021.org/the-economics-of-the-water-energy-land-food-nexus-how-to-contribute-to-restoration-goals/*) on the economics of the water-energy-food nexus. The World Climate Research Program (WCRP) Climate Research Forum for Europe and Western Asia (*https://www.wcrp-climate.org/crf-events/ewa-june-2021*) was held online on June 9th, 2021, and Gaby Langedijk, a former YESS Executive Committee (ExeCom) member, was among the invited panelists representing the YESS community.

During the quadrennial WMO Global Atmosphere Watch (GAW) Symposium, YESS organized a panel discussion on capacity building and young scientists. The panel examined the challenges with entraining early career researchers in atmospheric composition measurements and research, and explored possible solutions to overcome these barriers, among other topics. YESS member Julie Nicely was the session convener, and Faten Attig Bahar shared her perspective as a panelist. The event was open to everyone, and over 40% of the registered participants worldwide indicated that they were early career researchers (ECRs).

Last but not least, YESS was also invited by the WCRP Joint Scientific Committee to participate in its annual meeting (*https://www.wcrp-climate.org/jsc42-about*). The event was held virtually between June 28th and July 2nd, 2021. The YESS Community was represented by the former ExeCom member Gaby Langendijk, ExeCom member Shipra Jain, and YESS officer Valentina Rabanal. The event was a great opportunity for YESS to take part in the different breakout sessions and contribute to discussions on science gaps, engagement of ECRs, diversity, and scientific partnerships. We would like to thank WCRP for the opportunity to be present in this event and for its continuous support to the YESS Community.

The WCRP Lighthouse Activities

Detlef Stammer[1], Helen Cleugh[2], and Narelle van der Wel[3]

[1]Chair, WCRP Joint Scientific Committee; [2]Vice-Chair, WCRP Joint Scientific Committee; [3]World Climate Research Programme, Geneva, Switzerland

The World Climate Research Programme (WCRP) has developed five new activities that aim to make critical near-term progress towards meeting WCRP's Vision, Mission, and four Scientific Objectives, as outlined in the WCRP Strategic Plan 2019–2028 (*https://www.wcrp-climate.org/about-wcrpx/overview/wcrp-strategic-plan-2019-2028*). The WCRP Lighthouse Activities (Fig. 1) are designed to be ambitious and transdisciplinary (integrating across WCRP and collaborating with partners) so that they can rapidly advance some of the new science and technologies, and institutional frameworks, that are needed to manage climate risk and meet society's urgent need for robust and actionable climate information more effectively.

To do this, the Lighthouse Activities will need to draw on WCRP's core scientific and technical capabilities, and strategic partnerships. Their scope encompasses building new knowledge of the Earth's climate system, its near-term predictability and longer-term trajectories, through to harnessing emerging technologies to better simulate the Earth system via a digital "twin", as well as exploring new approaches for managing climate risk that start with the decision context and user needs.

The science plans of the Lighthouse Activities were approved at the 42nd Session of the WCRP Joint Scientific Committee in July 2021. Here, we explain the objectives and plans of each of the Lighthouse Activities.

Explaining and Predicting Earth System Change

The formulation of robust policies for mitigation of, and adaptation to, climate change require a quantitative understanding of how and why specific changes are unfolding in the Earth system, and what might happen in the future. A quantitative explanation of observed changes–through robust process-based detection and attribution–is also fundamental to specifying confidence in climate assessments, predictions, and projections. However, this capability is very immature. The WCRP Lighthouse Activity on Explaining and Predicting Earth System Change will address this gap. Its overarching objective is to "design, and take major steps toward delivery of, an integrated capability for quantitative observation, explanation, early warning, and prediction of Earth System change on global and regional scales, with a focus on multi-annual to decadal timescales." Its goals are to:

- Assess and improve persistent errors in climate models and reanalyses of historical observations
- Build an integrated operational capability to attribute and predict multi-annual to decadal changes in the climate system and provide quantitative attribution statements to support World Meteorological Organization (WMO) forecasts and State of the Climate reports, a key component of which will be large ensemble single forcing simulations for the historical period
- Establish a methodology for assessing the adequacy of and recommending improvements to observational networks and modeling systems to capture early indicators and the full evolution of these changes in the climate system
- Provide quantitative assessments of current and future hazards, underpinned by robust process understanding
- Seek to maximize the value to users of the advances achieved, e.g., through the development of an international open-access multi-model archive of seasonal-to-decadal hindcasts and forecast data, and through case studies employing co-design of decision-relevant products

***Figure 1**. The five new Lighthouse Activities*

The Lighthouse Activity has three main themes:

1. Observing and modeling Earth system change
2. Integrated attribution, prediction, and projection (including early warning and the potential for abrupt change)
3. Assessment of current and future hazards

Initial activities of this Lighthouse Activity include a Workshop on Attribution of Multi-annual to Decadal Changes in the Climate System (*https://wcrp-epesc.sciencesconf.org/*) that takes place in September 2021 and the publication of several related papers. Longer-term deliverables include established methodologies for novel case study application, an international open-access multi-model archive of seasonal-to-decadal hindcasts and forecast data, improved capabilities for prediction of multi-annual to decadal changes in the climate system and their impacts on hazards, and quantitative assessments of the current risk of specific hazards and future risk under defined scenarios, supported by process-based understanding of the drivers of changing risk. These activities will build on the multi-annual forecasts that are now routinely issued on the WMO Lead Centre for Annual to Decadal Climate Prediction website and in the WMO Global Annual to Decadal Climate Update.

For more information, please see the draft Explaining and Predicting Earth System Change Science Plan (2021) (*https://www.wcrp-climate.org/epesc*).

My Climate Risk

The My Climate Risk Lighthouse Activity aims to develop and bring into the mainstream a "bottom-up" approach to regional climate risk, which starts with the requirements of decision-makers. The term "risk" in this context means the combination of hazard, vulnerability, and exposure that is particular to a given regional context. By developing a new framework for assessing and explaining regional climate risk using all the available sources of climate information (observations, reanalyses, model simulations, better understanding, etc.), climate information will be made meaningful at the local scale. Whilst any application of the framework will inevitably be specific and tailored to local concerns, the framework itself will be generic, hence flexible and applicable across a range of region types [large scale, urban, typical Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX) region, etc.] and therefore provide much-needed support for the development of climate services. At the same time, the Lighthouse Activity will identify needs to be addressed by the WCRP Core Projects and other Lighthouse Activities (one example could be on the implications of model biases). My Climate Risk will primarily use a case-study approach, in the form of labs (communities of practice), where labs are understood to be dynamic, exploratory, transdisciplinary environments, and not physical infrastructure. Labs will be explored in partnership with a few regional hubs and will cover timescales that are meaningful to the decisions being considered.

The initial step will be to work with interested organizations from around the world on a series of workshops on local to regional climate risk to explore whether the topics raised and stakeholders involved would benefit from collaborating with the My Climate Risk Activity and would be good candidates for the overarching risk framework. The first of these workshops, Storying Climes of the Himalaya, Andes, and Arctic: Anthropogenic Water Bodies, Multispecies Vulnerability, and Sustainable Living (*https://www.icimod.org/event/storying-climes-of-the-himalaya-andes-and-arctic-anthropogenic-water-bodies-multispecies-vulnerability-and-sustainable-living/*), will take place online in October in collaboration with the Himalayan University Consortium. Further workshops and associated publications are being planned. My Climate Risk recently held a session (*https://sri2021.org/my-climate-risk/*) at the Sustainability Research and Innovation (SRI) Congress in June 2021 and has a special session planned at the American Geophysical Union (AGU) Fall Meeting in December 2021.

For more information, please see the draft My Climate Risk Science Plan (2021) (*https://www.wcrp-climate.org/my-climate-risk*).

Safe Landing Climates

The Safe Landing Climates Lighthouse Activity is an exploration of the routes to "safe landing" spaces for human and natural systems (Fig. 2). It will explore future pathways that avoid dangerous climate change while at the same time contributing to the United Nations Sustainable Development Goals (SDGs), including those of climate action, zero hunger, clean water and sanitation, good health and well-being, affordable and clean energy, and healthy ecosystems above and below water. The relevant time scale is multi-decadal to millennial.

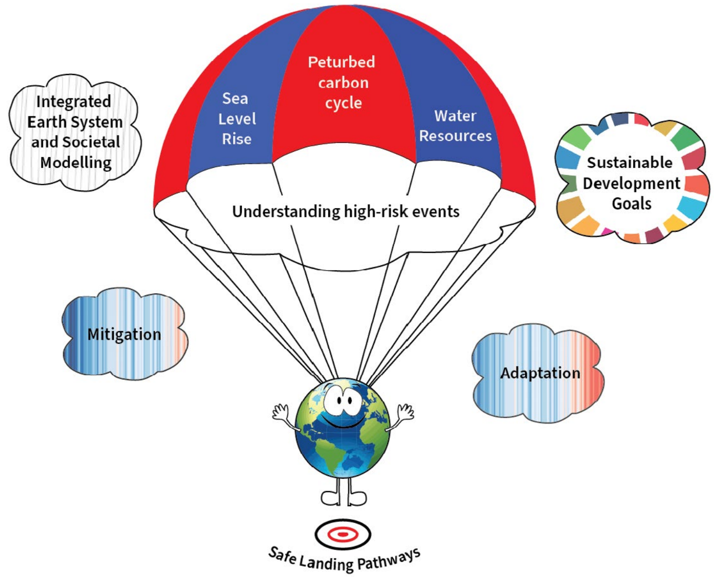

Figure 2. *Schematic of the Safe Landing Climates Lighthouse Activity*

Safe Landing Climates has five scientific themes:

1. Safe landing pathways: what climate trajectories and destinations are safe and unsafe, and for whom? The objectives of this theme are to define safe landing climate pathways and landings, preserve habitability and food security, and identify adaptation limits. The theme aims to foster analytic, modeling, and model-data fusion tools that enable representing and estimating large-scale climate risks, including cross-system feedbacks (climate, biosphere, and society).
2. Understanding high risk events: what are the risks from low-probability, high-impact events? The objectives of this theme are to enhance our understanding of highly uncertain planetary risks (such as large carbon release, ice shelf and ice sheet collapse, high equilibrium climate sensitivity, regime shifts, multiplicative compound hazards, large-scale extreme events, fireball Earth, and biome collapse), facilitate the incorporation of uncertain risks into future projections, and identify adaptation limits and determine whether risks can be avoided (or caused) by climate mitigation or geoengineering efforts.
3. Perturbed carbon cycle: how will the carbon cycle change in the future? The objectives of this theme are to determine the climate implications of carbon dioxide removal (including bioenergy with carbon capture and storage)

while maintaining food and water supply, preserving biodiversity, and limiting ocean acidification. The theme will also assess the possible contribution to mitigation by methane, nitrous oxide, etc.; evaluate the risk of surprises or rapid changes in greenhouse gases due to land sources; determine the implications for allowable greenhouse gas emissions under the Paris Agreement; and build an understanding of the coupled carbon-energy-water cycle.

4. Water resources: how will major reservoirs of water change in the future? The objective of this theme is to identify the long-term redistribution of water in land-based natural systems or reservoirs, including glaciers and tropical rainforests, due to climate change and direct human activity (e.g., deforestation, agriculture). This theme will identify thresholds of tolerance and risk of collapse, and integrate physical climate, social and economic sciences, and local and indigenous knowledge. It will also assess the implications of mitigation and adaptation scenarios, including solar radiation management and geoengineering or climate intervention.

5. Sea level: how will the habitability of our coasts change in the future? The objectives of this theme are to quantify "acceptable" sea level rise and its irreversibility, estimate the impact of storm surges and hurricanes on low elevation land, communities, and ecosystems, and assess the potential for adaptation. The theme will facilitate the interaction of modeling efforts across spatial scales from global to coastal, and will foster the interaction and co-production between sea-level experts and coastal planners worldwide.

The Safe Landing Climates Lighthouse Activity is planning a discussion series (*https://www.wcrp-climate.org/slc-events-opportunities/slc-tipping-points-discussion*) and workshops in 2021 and 2022, including a science session at the AGU Fall Meeting in December 2021.

For more information, please see the draft Safe Landing Climate Science Plan (2021) (*https://www.wcrp-climate.org/safe-landing-climates*).

Digital Earths

The Digital Earths Lighthouse Activity will carry out research activities that support the establishment of integrated interactive digital information systems that provide information on the past, present, and future of our planet. In this case, "integrated" means that the system combines all elements required to describe the coupled Earth system as well as models of human systems so that the impacts of a changing Earth on such systems can be estimated. Digital Earths systems may exist at both global and regional scales and there may be interim systems that act as stepping stones towards full Digital Earths systems.

The initial objectives of Digital Earths are to:

- Establish a global research network with expertise in ultra-high-resolution (kilometer-scale or finer) of the global Earth system and its individual components

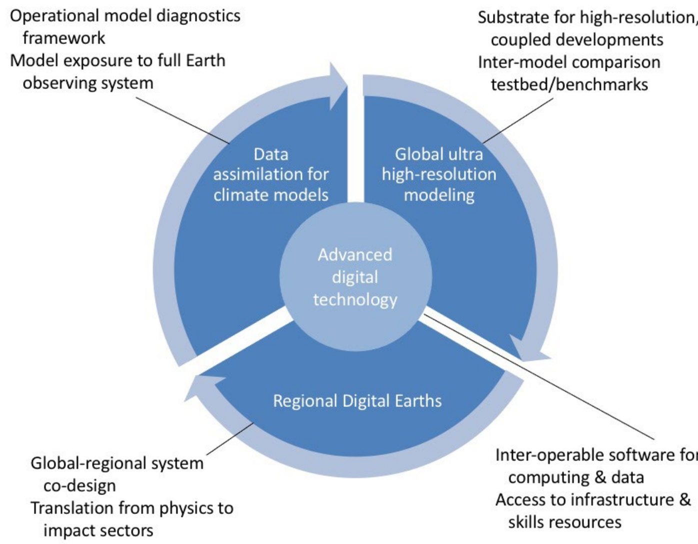

***Figure 3**. The four themes of the Digital Earths Lighthouse Activity*

- Establish an active research community in data assimilation for climate that builds on the existing numerical weather prediction (NWP) and reanalysis efforts and significantly expands them to fulfill the needs of Digital Earths applications
- Support the establishment of both global and regional Digital Earths demonstration projects across the globe and provide a collaborative network for their development
- Enable the above by optimally exploiting extreme-scale computing and data handling resources through interoperable software infrastructures

Digital Earths is founded on an ideal blend of models and observations. The activity will push the co-development of ultra-high-resolution Earth system modeling and the exploitation of billions of observations with digital technologies from the convergence of novel high-performance computing (HPC), big data, and Artificial Intelligence (AI) methodologies. The Lighthouse Activity will provide open access to data, methodologies, and software. The work of Digital Earths will be developed through national and international consortia, such as the Destination Earth consortium in Europe. The role of the Digital Earths activities within WCRP is to support such initiatives by providing fundamental science and technology developments.

The four major areas of activity (Fig. 3) in which WCRP must play a leading role are:

1. Global coupled ultra-high-resolution modeling
2. Data assimilation for climate
3. Regional digital Earths systems
4. Advanced digital technology

Although the fourth area of activity on advanced digital technology is not an area of core expertise in WCRP, the successful implementation of Digital Earths science depends on strong connections to existing expertise in this space. The aim is that in ten years from now, Digital Earths systems developed with the support of WCRP science will be delivering open-access actionable climate information for the globe in a fully-shared framework.

The Digital Earths Lighthouse Activity plans several workshops and at least one white paper in 2021 and 2022. It also intends to establish a kilometer-scale modeling coordination group and a WCRP-wide Task Force to identify opportunities for the application of Digital Earths outputs and to propose demonstration projects of their potential utility.

For more information, please see the draft Digital Earths Science Plan (2021) (*https://www.wcrp-climate.org/digital-earths*).

WCRP Academy

The WCRP Academy's mission is to equip current and future climate scientists with the knowledge, skills, and attributes required to tackle the world's most pressing and challenging climate research questions. The Academy's activities will promote and advance lifelong learning opportunities and global equity in climate science training. It will measure its success by the scope and diversity of the global climate research community that engages with the Academy as well as its ability to improve global access to high-quality climate science training and professional development without prohibitive costs to the trainee.

The WCRP Academy's objective is to determine the requirements for climate research education and build enabling mechanisms. One mechanism is an online marketplace for climate science training, which connects training providers and climate scientists who are seeking training (Figure 4). This will be both inward facing, which aims to consolidate and support WCRP training activities, and outward facing, which will bring together an even broader range of training opportunities. The Academy will also identify training gaps and advocate for those needs to be met.

To build the Academy marketplace, the science team will work with WCRP core activities, including the other Lighthouse Activities, and established climate education providers, including universities. There will be an annual training stocktake survey to ensure that the Academy continues to meet the needs of the climate science community by asking what education and training in climate science is available now, what and where the gaps are, and what support the Academy can provide for online climate science and related training opportunities. The first WCRP Academy Training Stocktake Survey (*https://www.wcrp-climate.org/academy-survey*) will be open until 26 November 2021.

The Academy has a special session planned as part of the AGU Fall Meeting 2021 and is planning a workshop as part of the International Conference on Southern Hemisphere Meteorology and Oceanography (ICSHMO) Conference in February 2022.

For more information, please see the draft WCRP Academy Science Plan (2021) (*https://www.wcrp-climate.org/academy*).

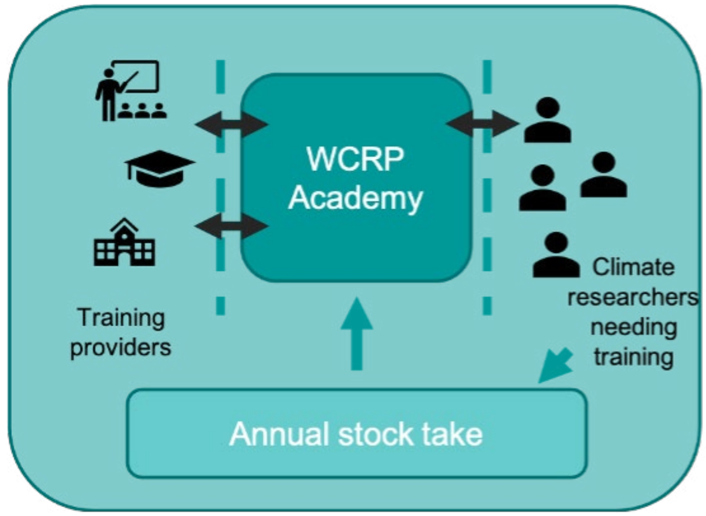

Figure 4*. Schematic of the WCRP Academy Marketplace*

Next Steps

The Lighthouse Activities will now start to implement their science plans, which are still evolving. Initial activities are being planned, but at the same time, the science teams will continue to connect with partners to ensure that ongoing planning is part of a larger international effort. The implementation of the Lighthouse Activities will start with the science teams convening discussions and workshops to identify specific actions that will work towards their objectives and to build communities.

There will be many opportunities to become involved in the Lighthouse Activities and to participate in events being planned. As well as the opportunities already mentioned in this article, the science teams of the Lighthouse Activities will evolve in the next year, with an emphasis on creating groups that have the expertise needed, that are geographically and gender diverse, and that include all career stages. While each Lighthouse will have two co-chairs and a core team responsible for the scientific direction of the Activity, each will necessarily have a slightly different structure, tailored to respond to the specific mission and objectives. How the Lighthouse Activities organize themselves will be somewhat flexible and may change as these ambitious projects find the best path forward. The success of these Activities will mean that in a decade from now, we will have made some giant strides in our understanding of climate science and of the risks and opportunities of a changing climate. At the same time, we will work from the research side to ensure that all decision makers, from the heads of governments to the village farmer, have the climate information they need, when they need it, in a form that they can easily access, use, and understand.

Acknowledgement

The Lighthouse Activities overviews are largely drawn from their draft Science Plans and we thank Nico Caltabiano and the Lighthouse Activity Chairs for their comments on this article.

The GEWEX INTENSE Crosscut: Advancing Scientific Knowledge of Climate Change Impacts on Short-Duration Rainfall Extremes

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Since the release of the Intergovernmental Panel on Climate Change (IPCC) 5th Assessment Report, an enormous international effort has produced multiple studies that have advanced scientific knowledge of climate change impacts on short-duration rainfall extremes (Fowler et al., 2021b). The INTElligent use of climate models for adaptatioN to non-Stationary hydrological Extremes (INTENSE), a Crosscutting Project (Blenkinsop et al., 2018) of the Global Energy and Water Exchanges (GEWEX) Hydroclimatology Panel, led the effort, with the European Research Council (ERC) providing the core funding (Fig. 1). Prior to this crosscut, there was a lack of understanding around changes to short-duration (sub-daily) rainfall extremes, although it was known that climate models project a general intensification of extreme rainfall during the 21st century on continental to global scales, consistent with observed trends (Westra et al., 2013; Fischer et al., 2016). Short-duration rainfall extremes are especially hazardous and are often responsible for fatalities (Archer, 2018), as they lead to flash floods, landslides, and debris flows that occur with little warning (Fadhel, 2018), as seen recently in the devastating floods in the UK, Belgium, Germany, and China.

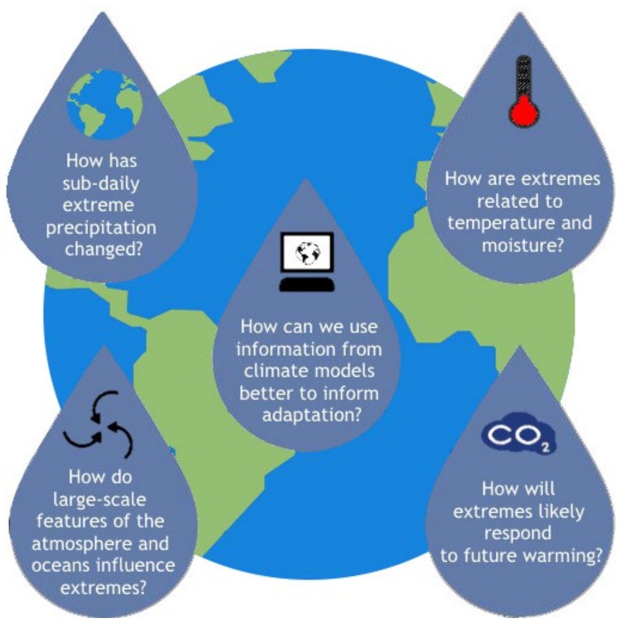

Figure 1*. The INTENSE project's key questions (Fig. 1 in Fowler et al., 2021c)*

The INTENSE crosscut has led to a huge increase in knowledge on the subject, now detailed in "Chapter 11: Extremes" of the IPCC Working Group I (WGI) 6th Assessment Report (AR6) and in a special issue of the *Philosophical Transactions of the Royal Society* following a Discussion Meeting at the Royal Society in February 2020 (Fowler et al., 2021a) where a number of experts discussed the state-of-the-art in this research field and how to address remaining gaps. These advances range from the development of convection-permitting models (CPMs) and idealized model experiments (e.g., O'Gorman et al., 2021) to the collection and assessment of precipitation observations. INTENSE also led an effort to collect and quality-control sub-daily precipitation across multiple continents [the Global Sub-Daily Rainfall (GSDR) data set, Lewis et al., 2019]. This recent work has provided a global assessment of observed extreme rainfall characteristics, enabled access to rainfall extreme metrics for impact researchers, and provided a platform for the exploration of the role of storm dynamics in state-of-the art climate models. However, gaps still remain, and these are explored in a perspective piece (Fowler et al., 2021c) in the special issue.

INTENSE was the first major international effort to focus on sub-daily rainfall extremes, enabling substantial advances in quantifying historical changes and providing improved physical understanding for regional projections (Fig. 1) (Blenkinsop et al., 2018). The project collected the GSDR, a global database of sub-daily precipitation data from a number of countries and from global data sets, comprising observations from >25,000 gauges (Lewis et al., 2019). INTENSE also developed robust methods to perform quality control checks on the sub-daily data (Blenkinsop et al., 2017), and open-source Python codes will soon be available from Lewis et al. (in revision). The GSDR was used to develop UK-wide gridded 1 km resolution hourly precipitation products (Lewis et al., 2018), to establish blended gauge-radar data sets (Yu et al., 2020), and to examine the ability of hourly gauge data to capture hourly rainfall extremes (Lengfeld et al., 2020). The global data set was used, together with reanalyses and remotely-sensed products, to produce global 0.1° daily and 3-hourly precipitation probability distribution climatologies for 1979–2018 (Beck et al., 2020). These add to existing merged products as a key resource for the community to validate climate model outputs (Prein et al., 2015) and provide a significant platform for future development. INTENSE also produced the first global climatology of hourly rainfall extremes (Barbero et al., 2019a) and is further developing a set of global sub-daily extreme precipitation indices for use by the community, including for climate model evaluation, which we hope to make available in 2022. The quality-controlled gauge data and derived data set of indices will be hosted by the German meteorological service (Deutscher Wetterdienst, DWD), though the availability of the former will be limited due to licensing arrangements with data providers. Efforts are also underway to identify a mechanism for ongoing maintenance and updating to ensure their long-term legacy through long-term funding.

The GSDR has also been used to characterize current short-duration extremes and, by linking with CPM simulations, better understand drivers of change. Trend analyses in the UK (Kendon et al., 2018) and U.S. (Barbero et al., 2017) have shown that trends in winter extremes have emerged first in hourly precipitation for both magnitude and frequency statistics, and that these can in part be linked to rising temperatures. Similar work over The Netherlands has shown that most hourly precipitation extremes are part of large-scale circulation systems, with considerable forcing from larger scales (Loriaux et al., 2017). Large-scale drivers of hourly precipitation extremes were explored further by linking these to atmospheric circulation patterns over Europe (Darwish et al., 2020; Blenkinsop et al., 2015), the U.S. (Barbero et al., 2019b), Australia (Moron et al., 2019), India (Moron et al., 2021), and globally (X.F. Li et al., 2020). Analyses have also established the large-scale precursors of small-scale storms in CPMs over the UK (Chan et al., 2018). Results suggest that large-scale stability is skillful in predicting the occurrence of extremes in a 1.5 km CPM. Missed events show some common features: they tend to have lower convective fraction and may be related to orography or coastal convergence.

INTENSE also examined CPM simulations for the UK and Europe. Very high-resolution CPM simulations (e.g., Kendon et al., 2014) explicitly simulate km-scale motions in convective storms and how these change with global warming, but do not yet resolve turbulent cloud dynamics. CPMs substantially improve the simulation of local storm dynamics (Prein et al., 2015), e.g., the diurnal cycle of convection (Ban et al., 2014), orographically-enhanced extreme precipitation (Bartsotas et al., 2017), spatial structure of rainfall and duration-intensity characteristics (Ekström and Gilleland, 2017; Kendon et al., 2012), and hourly and sub-hourly precipitation intensities (Chan et al., 2014a,b). For the scaling relationship between hourly extreme rainfall and daily temperature through day-to-day temperature variation–the "apparent" scaling (Bao et al., 2017)–we found that CPMs show a peak in heavy rainfall rates during warm days but decreasing rates on the hottest days, as also seen in observations Chan et al., 2016a), with scaling relations similar between observations, control, and future climates (Lenderink et al., 2021). Scaling relationships between temperature and precipitation for sub-hourly precipitation were found to be similar to scaling for hourly precipitation (Chan et al., 2016b). A review of existing projections made with CPMs for different regions and from different modeling groups showed where projections are robust across model resolution (Prein et al., 2021) and where convective (km) scale models are needed for accurate projections (Kendon et al., 2017). CPMs were also used to explore whether storm profiles change in a warmer climate. Results over Northern Europe suggest that storms become more intense (Lenderink et al., 2019), longer in duration, and more slow-moving (Kahraman et al., 2021), but with the storm profile not changing in shape (Chan et al., 2016b). This is similar to results from radar observations, where storms were found to become more intense and larger in size with warming (Lochbihler et al., 2017). It also corroborates work with CPMs over the U.S. (Prein et al., 2017), but is different than storm profile changes identified in observations in Japan (Utsumi et al., 2011) and Australia (Wasko and Sharma, 2015; Wasko et al., 2016), which found intensification of the storm core but smaller size and duration of storms with warming. The seasonality of intense hourly events was also found to change with global warming, with more events in autumn months in Europe (Chan et al., 2020). Challenges and outlook for CPMs are detailed in (Kendon et al., 2021) in the special issue.

INTENSE also evaluated the potential usefulness of temperature-scaling for projections of changes to precipitation extremes and flood extremes (see, e.g., Wasko, 2021). Heavy rainfall extremes are intensifying with warming at a rate generally consistent with the increase in atmospheric moisture, for accumulation periods from hours to days (Ali et al., 2018). Studies have indicated the need for a moisture component in temperature-scaling (Barbero et al., 2018; Lenderink et al., 2018) and that sub-daily precipitation extremes are in some regions increasing at faster rates than would be anticipated with warming, at up to three times what would be expected from atmospheric moisture increases alone (Guerreiro at al., 2018). The project also established at least some of the mechanisms for enhancement of intensities from local in-storm effects (Lenderink et al., 2017) and from urbanization (Y. Li et al., 2020). This means that at regional scales, the temperature-scaling of sub-daily extreme precipitation intensities is more consistent with Clausius-Clapeyron, but at local scales, it might be larger (Ali et al., 2021). It is still uncertain what this will mean for future projections of changes to precipitation intensities, due to the unknown effect of large-scale circulation changes (Lochbihler et al., 2017), but evidence is emerging that sub-daily rainfall intensification is related to an intensification of flash flooding, at least locally (Prein et al., 2017).

Much progress has been made within INTENSE. Improvements in observations and the advent of CPMs has led to considerable advances in the comprehension of thermodynamic drivers of changes and their impacts on peak intensities, with much clearer understanding of the potential role of relationships between day-to-day temperature variabilities and precipitation (scaling) in projecting extremes. Progress has also been made on the understanding of changes to storm spatial structures and profiles with warming, with considerable evidence of changes from climate change. Considerable improvement has been made in the understanding of local dynamical enhancements causing super-CC scaling, such as latent heat release, enhanced vertical uplift, and moisture convergence. Less well understood is the moderating role of large-scale circulation on thermodynamic changes and the climate change impacts on small-scale cloud dynamics (i.e., turbulence) and cloud microphysics and their effects on changing extreme precipitation. Recommendations for scientific progress are made in Fowler et al., 2021c.

Finally, to make this ever-increasing understanding useful to decision-makers, the international community must rethink language, headline messages, and communication mechanisms as well as experimental design (Evans et al., 2013). Better understanding of the impacts of global warming on sub-daily (particularly hourly to 3-hourly) extreme precipitation is crucial for societal adaptation (Westra et al., 2014), through the management of the water environment (Orr et al., 2021). Connections must be bridged between the atmospheric science community (e.g., climate modelers) with the hydrologic

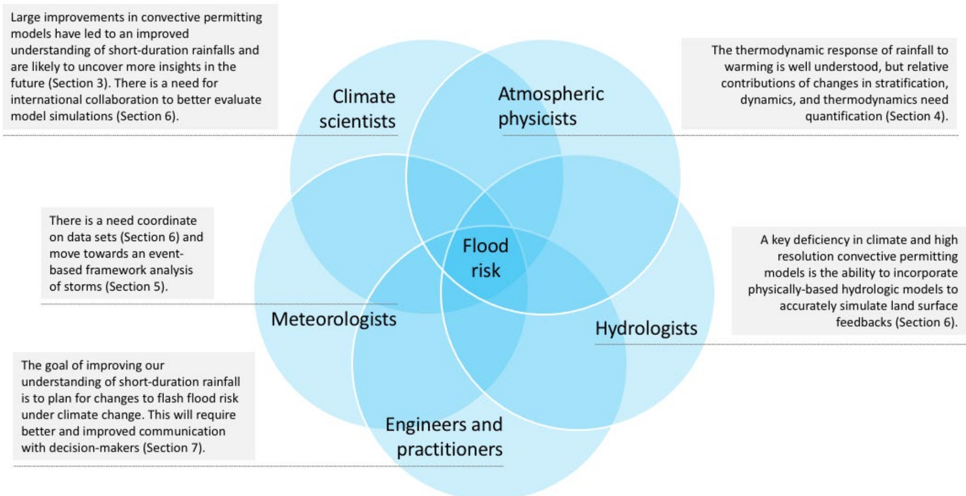

***Figure 2**. The INTENSE Project culminated in bringing together experts across multiple disciplines at the Royal Society, London to discuss recent advances in understanding climate change impacts on short-duration rainfall extremes and what is required to make further advances in the field. This diagram is conceptual only and aims to illustrate the crossovers between disciplines in a general sense. It is not to designed to be accurate in the placement of the Venn diagram circles (Fig. 3 from Fowler et al., 2021c).*

and climate impacts communities (Fig. 2). Recent advances in atmospheric modeling allow us to tackle questions of how this will change flood risk. However, our current understanding is limited to changes in extreme precipitation; this is only part of the story when we are interested in future flooding. For example, although some instances exist of translation of current state-of-the-art model results into flood design guidance (e.g., Dale et al., 2017; Dale, 2021), this is still in its infancy (see a review in Wasko et al., 2021). To enable better decision-making, we may need to change our current approaches to include alternative modeling strategies such as storylines (Shepherd et al., 2018) and "plausible worst case" scenarios. This type of information is key to informing climate adaptation strategies in water management (Orr et al., 2021).

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The Baseline Surface Radiation Network: A Personal History from a Network Founder

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By Way of Introduction

The Global Baseline Surface Radiation Network (GBSRN), now the Baseline Surface Radiation Network (BSRN), emerged through loosely-exchanged discussions sometime between 1986 and 1988 around a seminar presentation of radiation held at the National Aeronautics and Space Administration (NASA) Langley Research Center in Hampton, VA. Dr. John DeLuisi of the National Oceanic and Atmospheric Administration (NOAA), Dr. Charles Whitlock and Dr. William Rossow of NASA, and myself from the Swiss Federal Institute of Technology in Zürich (ETH Zürich) were all involved. The starting point was no more than discussing and lamenting the missing or disorganized measurements of radiation at the Earth's surface. John came to this from the perspective of long-term environmental monitoring needs, while the gentlemen from NASA were looking for accurate ground-truth measurements to compare to satellite observations. I always needed precision radiation measurements at the surface, but was plagued by a prejudice among academics that measurements are not the realm of scientists and should be left for technicians. Whatever the awareness of the need might be, the missing trustworthy radiation measurements at the Earth's surface were hindering progress in atmospheric science. With coffees in hand, we all agreed on this point. It was fortunate that Dr. Whitlock did not forget this conversation, and invited us to a meeting with half a dozen interested colleagues who came together to try and answer the question of what could be done to remedy this situation. Dr. Anatoly Tsvetkov, the new director of the World Radiation Data Center in Leningrad, also attended. For the time being, I will dwell on the approach from the ETH side. I trust that there were similar preparations at NOAA and NASA.

The Situation at ETH Zürich

Energy flow is one of the fundamental processes at play in the climate system. This area is called energy balance climatology and was led by two pioneers, Academician Michail Budyko of the Soviet Union, and Prof. Julius London of the U.S. The graduate-level textbooks of my generation were written based on one of these works or both. For example, one of the most widely read textbooks, *Physical Climatology* by William Sellers, is entirely based on the Budyko energy balance climatology, which is best summarized in the 1963 publication, *Atlas of Energy Balance of the Earth*. While the London energy balance was made based on physical calculations, the Budyko climatology was largely based on the empirical calculations derived from meager observations. The reality was that there was not an abundance of actual measurements. An inquiry formed during my time as a student centered on asking how accurate these climatologies are. The only way to evaluate the quality of the Budyko and London climatologies was to compare the calculated energy fluxes against the measured fluxes. Energy fluxes can be thought of at any level of the atmosphere, but work first concentrated on the Earth's surface, as the major energy conversion happens there and we also live close to it. There are at least eleven flux components altogether that make up the energy balance at Earth's surface. Of the eleven, there is one component that is the most widely observed, solar global radiation. This component is also best standardized for observation. With this overview in mind, I started to contact the data sources, mostly national meteorological services, and engaged universities and research institutions. At the beginning, I had to collect the data in this manner. There was at that time only one international organization that collected and archived two components worldwide: the World Radiation Data Center (WRDC) in Leningrad, financed by the World Meteorological Organization (WMO). The data exchange with WRDC was painful, a typical case of an institution swallowing data without returning them. It was called a data cemetery and a data blackhole. Nevertheless, it was a soothing feeling to know that there was such a data center safeguarding the observation results. I managed to purchase all data publications from WRDC, to find that the WRDC had only solar global radiation and net radiation. One had to locate the data through one's own effort. To create another data source for global data collection, I surveyed publications with students on summer vacations by going through about fifty journals where we could potentially find original data for any of the energy balance components. This survey was very productive. It gave us not only the data, but also clues as to who was doing their own measurements. At night and on holidays, I started to standardize the data and enter it into our computer. In about half a year, certain features started to emerge from this first-stage data collection. There was a systematic difference between the established climatologies by Budyko and London and the actual measurements. The measured solar global radiation, the major energy source at the Earth's surface, was smaller than the published climatologies. How can one reconcile such a difference? These outstanding pioneers did an enormous amount of work; they couldn't be wrong. It might be that the measurements were wrong, that perhaps the instruments were not accurate, etc. This discrepancy became the gateway leading to the discoveries of the missing (solar) absorption of the atmosphere, and global dimming. If the problem existed for just one component, solar global radiation, then what was the situation with other components, which are much more difficult to measure, such as sensible heat flux and latent heat of evaporation? The amount of data collected at this stage was admittedly not so large, and I decided to scan the published measured fluxes. The strict rule I applied at the beginning of data collection is that the fluxes to be archived must be measured by instrument, without any computation involved, because the objective was to check the quality of calculated values. At the same time, I decided to open the data collection to the scientific and engineering communities, as the archive would continue to grow. The first "customer", so to speak, requesting the data was Prof. Yale Mintz at the University of California, Los Angeles. I was rather moved to know that such a theoretician and the initiator of one of the early general circulation models (GCMs) was thinking of the need to compare the results of computation against measurements too. In general, the GCM community, however, remained aloof towards the observed fluxes.

BSRN scientific and technical meeting of 2004, held at the British Met. Office in Exeter. From left, Dr. Alexander Mannes, Vice Director of Israel Meteorological Service; Dr. Ellsworth Dutton, NOAA, Project Manager BSRN; Dr. Anatoly Tsvetkov, Diretor, World Radiation Data Center; Dr. Jean Olivieri, Station Scientist, BSRN station at Carpentras, France; Prof. Atsumu Ohmura, ETH Zürich, Director, World Radiation Monitoring Centre

The archive grew and I named it the Global Energy Balance Archive (GEBA). It remained a shoelace project, not officially funded. Data collection was not a strong selling point in the university environment, and the effort was still a night and weekend engagement. In the mid-1980s, Prof. Hans-Jürgen Bollé (at that time the president of the International Association of Meteorology and Atmospheric Physics, or IAMAP, which is now called the International Association of Meteorology and Atmospheric Sciences, or IAMAS) visited me from the Free University of Berlin. He thought that GEBA should have an official status, which would make my data-collecting and fundraising efforts easier. He presented GEBA at the World Climate Research Programme (WCRP)'s Scientific Steering Committee meeting of 1986 to gather support, and if possible, acceptance of GEBA as one of the WCRP projects. The proposal was rejected by an American delegate who claimed that satellite-based remote sensing could produce more accurate and homogenous energy fluxes at the Earth's surface. This statement was seconded by a Russian member, although with a more reserved tone. During the Cold War, there was an unwritten agreement between the two superpowers that each side would not reject the other side entirely, but keep communication through a strategically insensitive channel like meteorology, hence WMO. The proposal fell victim to this agreement. Prof. Bollé did not lose time and went to the World Climate Programme (WCP) office, and managed to obtain the support, so that GEBA was made a WCP-Water Project, A-7. GEBA continued until it became a part of WCRP at a later stage.

The GEBA effort consciously avoided the data of the stations whose data were published by WRDC. It was thought that if needed, these data could at any time be transferred from WRDC to GEBA. It did not work this way. During the Cold War, the digital data transmission from the Soviet Union to even a neutral country like Switzerland turned out to be next to impossible. As Academician Budyko was a frequent visitor to Geneva, I asked him to carry the WRDC fluxes in a magnetic tape and he kindly agreed, but it never happened. At this stage, I launched a mini project of the summer vacation to scan all volumes of the World Radiation Data Center Monthly Report. The task was not trivial, as the World Radiation Monthly Report (WRMP) was a poor-quality offset print. The best IBM scanner could not manage the job. Since ETH is also an engineering school, we made a scanner with the highest resolution available at that time. A student whose hobby was making electric guitars helped me a great deal. However, the scanned and digitized numbers and letters had to be frequently corrected. The quality of the original print was such that often, 4 and 1 were confused when only a part of the type was in print. There was also frequent confusion between 3 and 8. Eventually a correction software was developed. By this time, I had a quality control program for screening GEBA data. I applied the quality control program to the WRDC data to find a very high frequency of error. The frequency of the Leningrad data error was 2%, instead of 0.2% of the GEBA error rate. I asked Academician Budyko if the Leningrad team applied any quality control to the data. Budyko surprised me by responding that they didn't check the accuracy of the incoming data. I asked why, and his answer was that quality control was not a Slavic concept. He, however, gave me extremely important information on the unit of the Leningrad energy fluxes. When it is the unit of energy per area per year, it does not pose great difficulty, but a flux per month is a trickier proposition. A month can be 31 or 30 days or even 28 or 29 days long. This difference could easily introduce a deviation of up to 10% in fluxes, a large error. According to Budyko, the month in "per month" in all his publications meant 30.4 days. This principle was used in all Voeikov Main Geophysical Observatory publications, including the widely-used 1963 publication of the World Atlas.

Budyko was succeeded by Dr. Anatoly Tsvetkov as director of the WRDC. He introduced many improvements in WRDC working procedures, including providing internet access to the WRDC data. He asked if we could give him the GEBA quality control program, and I agreed instantly. I was more than happy that the WRDC data would undergo quality-check procedures. We are working in coordination. Both data sets, however, continue to be different. WRDC deals with a part of irradiances, solar global and net radiation, while GEBA will register all energy fluxes so long as the observation lasted for more than one month. WRDC is basically a passive data center, in the sense that it assimilates the donated data, while GEBA will hunt down any existing and hidden data sets. WRDC has radiation data starting from 1963, per the agreement with WMO, while GEBA will dig into measurements from older years. The oldest date of quality-assured continuous measurement is the solar global radiation from July 1922 in Stockholm.

A Drive for a New Radiation Network

I come back to the stage of GBSRN preparation. In the course of 1987, John DeLuisi, Charles Whitlock, and I made the idea of establishing a new precision radiometric network somewhat more concrete, and approached the Joint Scientific Committee of WCRP. The WMO, in support of our effort, nominated Mr. Roger Newson to act as the secretary. Some alterations were necessary before the formal proposal was presented. As global coverage with such a demanding operation was found unrealistic, the "G" of "GBSRN" was dropped. A plan was formally proposed in October 1988 for the establishment of an international Baseline Surface Radiation Network (BSRN) with the following goals: 1) to provide Earth's surface irradiances for validating satellite-based estimates of the surface radiation budget and radiation transfer through the atmosphere, 2) to provide the irradiances to validate and improve radiation codes of climate models, and 3) to monitor long-term changes in irradiances at the Earth's surface.

To reach these goals, it was necessary to assure uniform adherence to the highest achievable accuracy, a standardization of the observational procedure, and the development of calibration methods throughout the entire network. Consequently, a sustained effort for developing more accurate and stable instruments, more reliable weather protections, and more uniform calibration procedures is considered to be a necessary component of BSRN activities. It was also thought to be important to carry out radiometry concurrently with measurements of the relevant atmospheric characteristics, such as temperature, water vapor, ozone, aerosol, and clouds. The network was initially proposed to consist of about 20 strategically-located sites. A working group for the implementation of the project was formed in 1989. The group included established scientists and engineers from the fields of instrument development, field observation, remote sensing, theory of radiation, radiation modeling, and radiation parameterization for GCMs. The group was charged with the following tasks: 1) to identify the sites and the organizations to carry out the observations; 2) to formulate the observational requirements and procedures, including the identification (development if necessary) of the instruments, the installation of the instruments, and the calibration processes; and 3) to develop the data administration scheme, which includes quality control, permanent archival, and data dissemination. The group proposed John DeLuisi to act as the project manager, and myself to establish the data center. As the selection of the instruments was completed, we found it necessary to create an observation manual to achieve BSRN quality. For this purpose, all working group members contributed, and the task of writing the manual was entrusted to Dr. Bruce McArthur of the Canadian Meteorological Service.

The group worked hard to start the project as soon as possible, and it began on January 1st, 1992. A slight disappointment was that only five stations began their observations, although other four stations joined within that year.

Currently, some 62 stations are active and regularly forwarding monthly data to the Archive Centre. More than 62 stations began the observations, but for various reasons, activities were terminated at several stations. Radiation measurement doesn't require quite the same degree of engagement as, for example, temperature measurement. It requires theory, experience in precision measurements, common sense necessary in all field activities, and above all, personal interest. The only way to continue this sort of monitoring work is to institutionalize the whole system by infusing stations into an existing stable organ, like a government. This is only partially successful. The best solution is to see the stations within a national weather service, or a similar national research institution. The

Three generations of BSRN Archive directors: from left, Prof. Atsumu Ohmura, ETH Zürich (1992–2007); Dr. Gert König-Langlo (2007–2017), Alfred Wegener Institute; and Dr. Amelie Driemel (2017–present), Alfred Wegener Institute

station in many cases is placed under responsibility of a scientist, who is doctorated in some field of radiation.

When the network started functioning, no matter how modest the beginning might have been, it was a great joy for all who worked on this goal. As time went by, the network evolved, and more spectral radiometry was added at most stations. This was a necessary and constructive development, especially for evaluating the role of aerosols. Another change to the network happened in 1993, when I received a call from the WMO representative, Mr. Roger Newson. This was a most mysterious happening, about one year after the happy start of the network. He surprised me by stating that the project manager, Dr. John DeLuisi, had to be changed. I had to demand the reason. The answer was that WMO was not happy with the way that BSRN was managed, and further, John was transferring the know-how developed within the BSRN community to the Surface Radiation Budget Network (SURFRAD). I was fully aware of the SURFRAD preparation within the U.S. SURFRAD is also a project aiming at providing high quality irradiances measured at the surface, but with stress on aerosols. Both SURFRAD and BSRN could complement each other, and in academic communities, there is no complication when skills developed by a group are transferred to another. Naturally, it would have been nicer if such a transfer was made explicit, but one shouldn't be too rigid about this sort of matter. Roger's call was less a consultation on the matter and more a declaration that the project manager must be changed, and he wanted my support. The new manager also had to be an American. So, Ellsworth Dutton was introduced to me. Of course, I knew him as we worked on similar scientific problems. I had only a slight reservation because Ells had just received his doctorate and experience-wise, fell short in comparison with the established DeLuisi. But he turned out to be an excellent administrator, and also acted fairly. For certain technical matters, he offered unique ideas. So, for the rest of the 15 years, we worked in harmony. Still, I am sometimes caught by the question as to what happened in 1993 in Boulder.

One of the unique and productive mechanisms of BSRN is the bi-annual Scientific and Technical Meeting, attended by all station scientists and experts in the theories of radiation, modeling, instrument engineering, and IT. By bringing together different specialists from a wide spectrum of knowledge and experience, the meeting was so productive that the project made enormous strides in measuring accuracy during the first several years. Quality checks of the data were made both at the stations and the data center in Zürich. This double-checking was another reason for the high accuracy and the quality homogeneity of the BSRN irradiances. The price of this meticulousness was the long period of time needed before releasing the data with the BSRN guarantee. It took almost a month between the observation and its publication. In the meantime, an unexpected request came from the European Centre for Medium-Range Weather Forecasts (ECMWF) to make faster access possible, so that the BSRN irradiances could be integrated into the forecast. A happy reasoning was that when they carried out comparative experiments for the forecast, with and without BSRN irradiances, the results were improved by integrating the BSRN irradiances. Ells and I did not want to compromise the data quality in favor of time. The solution was to make a second channel for the data release for forecast purposes. This second channel was made possible by releasing the real-time data directly from each station to ECMWF. The whole operation became more complicated as time went by, but this was probably not unavoidable. At my formal retirement from ETH in 2007, the data center, which was then called the World Radiation Monitoring Centre (WRMC), was formally transferred to the chair of Prof. Peter Lemke at the Alfred Wegener Institute (AWI) in Bremerhaven. The center was ably managed by Dr. Gert König-Langlo until his retirement in 2017, upon which the responsibility was put in hands of Dr. Amelie Driemel. At the same time, the BSRN Centre was made an independent group from the retiring Prof. Lemke as a constituent of AWI.

BSRN achieved its initial objectives very well by supplying first-class ground-truth for satellite remote sensing, and contributed tremendously to improving radiation computations both in the long- and short-wave ranges. This contribution is clearly recorded in the progress of the global energy balance presented in the Intergovernmental Panel on Climate Change (IPCC) assessment reports over the last 30 years. Further, the BSRN network is successfully monitoring the increasing incoming long-wave irradiance at all sites, which provides unshakable proof that the cause of ongoing warming is due to the increasing infrared (IR) from the sky. The recent developments in BSRN and GEBA are summarized in Driemel et al. (2018) and Wild et al. (2017).

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Essential Water Variables (EWVs): Ensuring Data for Water Cycle Research and Water Sustainability Applications

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A number of data sets are required for describing water in all its forms, and understanding and predicting the global water cycle and its many impacts on the human and natural environments. Emphasizing certain variables as "essential" focuses attention on ensuring the availability, accessibility, adequacy, and quality of observations that underpin these critical applications.

Defining Essential Water Variables (EWVs)

Early studies that sought to test the balance of the global water cycle (Fig. 1) found it difficult to assemble observationally-based data sets that covered all aspects of the water cycle, and discovered important imbalances among available data sets (e.g., Schlosser and Houser, 2007; Trenberth et al., 2007). GEWEX emphasized this issue early on, focusing on water-related data sets, including precipitation, clouds, and surface vapor flux. At the same time, the Group on Earth Observations (GEO) was finding that many of the Societal Benefit Areas it defined required water data. This work led to a study of the requirements across many applications (GEO 2010) and a summary of priority data sets (GEO 2012). The needs analysis showed a huge range of spatial and temporal resolution, accuracy, and data latency needs across the different applications for essentially every variable. At the same time, the Integrated Global Water Cycle Observations (IGWCO) group had been formed to advance such data sets. IGWCO became a GEO Community of Practice and subsequently associated with the GEO Global Water Sustainability (GEOGloWS) activity. IGWCO led an extensive review of the state of the different variables (GEO 2014; Lawford et al., 2021) that formalized the concept of EWVs. One key result was that the different variables had very different levels of maturity, resolution, coverage, and availability. The implication is that the user needs, as previously surveyed, cannot all be satisfied with the current state of observations, with strong variations in status across the different variables, particularly given the specific observational limitations that affect the different variables. Subsequently, surface water extent and water use/demand were added to reflect additional important priorities in addition to the original quantitative water cycle variables.

Current Status

The current list of EWVs is given in Table 1. Besides the "primary" EWVs, it is recognized that a set of "supplementary" EWVs is needed to help complete the information that the formal list of "primary" EWVs should provide. For example, when the surface water extent EWV is layered with the elevation, topographic, and bathymetric information, total surface water volume can be calculated.

Primary EWVs	Supplemental EWVs (apply to water and related disciplines)
Precipitation	Surface meteorology
Evaporation and evapotranspiration	Surface and atmospheric radiation
Snow cover (including snow water equivalent, depth, freeze thaw margins)	Water vapor and clouds
Soil moisture/temperature	Permafrost
Groundwater	Land cover, vegetation, and land use
Runoff/streamflow/river discharge	Elevation/topography/bathymetry and geological stratification
Lake/reservoir levels, water storage, and aquifer volumetric (or mass) change	Surface altimetry
Surface water extent	Bathymetry
Mass balances of glaciers and ice sheets	Surface radiation
Water quality	Aerosols
Water use/demand (agriculture, hydrology, energy, urbanization, others)	Atmospheric radiation

***Table 1**. Current list of primary and supplemental EWVs. Adapted from Lawford et al., 2021.*

This relatively compact list addresses the water information needs that are called out in a wide range of international activities, programs, and stated objectives and goals, including:

- Aichi Convention on Biological Diversity
- Framework Convention on Climate Change
- GEO Flagships, Initiatives, Community Activities, and heritage Societal Benefit Areas
- Ramsar Convention on Wetlands
- Sendai Framework for Disaster Risk Reduction
- United Nations Sustainable Development Goals

While some of the applications are "obvious", such as Water for Agriculture/Forestry (UN SDG 15), the need for water information extends much further, such as Health and Disease Warnings/Control (UN SDG 3, 15).

Obtaining and assembling the necessary input data, retrievals, and analyses is a multi-faceted enterprise scattered across disparate agencies and organizations around the world. Note that each variable has particular observational requirements and applicable instrumentation. One key fact is that both in situ and remote observing systems are badly needed to create the best record of the different variables. In some cases, such as water quality variables, in situ sampling is still the primary data source, although remote sensing is helpful for global coverage of selected parameters such as algal blooms and total suspended solids. Variables such as soil moisture, precipitation, and surface water extent are examples where satellite data are gener-

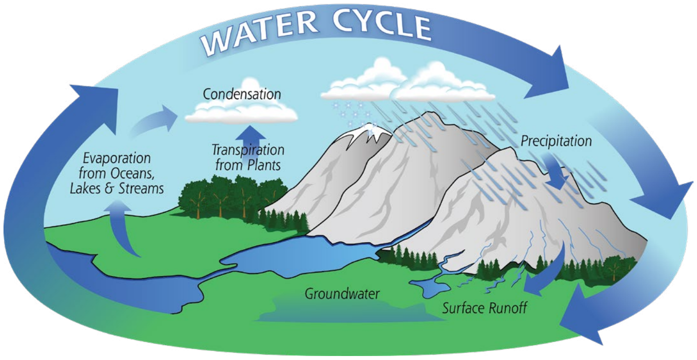

***Figure 1**. Simplified diagram of Earth's water cycle. Credit: NASA GPM; https://gpm.nasa.gov/resources/images/diagram-water-cycle*

ally useful, while in situ data are still required both as tie points and validation for the satellite data. A second key fact is that the large-scale averages that satisfy some applications, such as climate monitoring, cannot be fulfilled by a correspondingly coarse set of observations. For example, precipitation is intermittent and highly variable in time and space, so the observations need to be recorded on a correspondingly fine scale, then accumulated and averaged. This is particularly true as climate studies turn to examining extreme events, which tend to be smaller-scale by definition. A third key fact is that these observing systems require consistent funding and institutional stability to both a) deliver information in near-real time for warning and prediction applications, and b) sustain these observations for decades to build the data record that climatological studies require. This challenge extends from basic meteorological and hydrological stations, particularly in developing countries, to the constellations of satellites that require ongoing replenishment and continued funding. Support by the science, modeling, and applications communities for the priority of these observational data sets and the underpinning observational systems is required by the various agencies to determine the configuration and level of service that are necessary. As such, and given the critical importance of water information to GEWEX, support by GEWEX for the EWVs and the requisite observing systems is of ongoing importance.

Accessing the complete set of available EWV data sets is still challenging. The GEO Data Portal (https://www.geoportal.org/) provides a directory service that points to the data sets submitted to the system. However, it is still up to the users to understand, retrieve, and manipulate each data set. Many applications users lack the expertise or resources to carry out these steps, leading to the "valley of death" between data sets and end users. The GEOGloWS European Centre for Medium-Range Weather Forecasts (ECMWF) Streamflow Service (https://geoglows.ecmwf.int/), being led by J. Nelson (Brigham Young University), provides one example of an end-to-end data-to-information display system that also provides an Application Programming Interface (API) that allows (relatively) easy creation of new data displays. Another example of a site that provides both data access and tools is the AmeriGEO DataHub (https://data.amerigeoss.org/). A more general issue that remains is that, when multiple data sets are computed for the same variable, different data sets have strengths and weaknesses that vary by region, as well as by different design goals. Non-specialists need advice about the fitness for use of the different data sets for their particular work, but this is not generally available. One first step toward this is shown in the listings of publicly-available precipitation data sets posted on the International Precipitation Working Group website (https://www.isac.cnr.it/~ipwg/data/datasets.html), together with some introductory material (https://www.isac.cnr.it/~ipwg/data.html) and an assessment currently underway. As with the observational systems and data sets, feedback from the science, modeling, and applications communities, including GEWEX, on the priority of these next steps past simply providing access to the basic data is required by the various agencies to determine the configuration and level of service that are necessary. More specifically, GEWEX and the research community should benefit from the developing data services that systematize access to water data. As these develop, work by GEWEX researchers to use and evaluate the usability and quality of the products could be a fruitful interaction with GEOGloWS.

A final wrinkle is that many GEO activities have developed lists of essential variables, some of which duplicate variables in the EWVs. It is not yet resolved how GEO can best address this issue. Can a single standard be defined by each variable's experts that satisfies the entire range of GEO activities? And how does that potential standard interact with the existence of current (and future) multiple data sets for the same variable?

Summary

EWVs provide a compact list of the variables on which observational agencies and activities should focus to adequately support the water information needs of the science, modeling, and applications communities. As such, community support for the continuation, modernization, and expansion of the relevant observational systems is key to ensuring the ongoing supply of quality EWV information. For the most part, users currently must discover and handle data sets individually in order to create displays and decision-support information. It remains a challenge to provide the data in convenient, accessible, curated ways that allow users to focus on data use. Providing data in convenient, accessible, curated ways that allow users to focus on data analysis and application remains a challenge. The GEWEX community should see improved access and coverage, and is invited to help accelerate these developments by supporting the EWV development.

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Meeting/Workshop Reports

The Seventh Aerosols-Clouds-Precipitation-and-Climate (ACPC) Workshop

Virtual Meeting
24–29 May 2021

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The Aerosols-Clouds-Precipitation-and-Climate (ACPC; *http://www.acpcinitiative.org*) initiative organized its seventh annual meeting from 24–29 May 2021 to discuss progress towards understanding the role of aerosol perturbations on clouds and precipitation. This was also the second virtual meeting following a successful first virtual meeting last April 2020 due to the COVID-19 pandemic. This year's event was organized into two broad themes aligned with the two ACPC working groups, aerosol effects on low clouds (with a focus on "natural laboratories"; see below) and aerosol effects on deep convective clouds [with a focus on the TRacking Aerosol Convection interactions ExpeRiment (TRACER); see below]. During each session, working group members gave updates on ongoing research activities and roadmaps, and participants from around the globe presented their progress on aerosol effects on both low and deep clouds, using a hierarchy of modeling and observational approaches.

The low cloud group had sessions focusing on shallow clouds and a day of sessions devoted to "opportunistic experiments", sometimes called "natural laboratories". Opportunistic experiments are aerosol perturbations in the environment (natural or anthropogenic) that can be used as analogs for anthropogenic changes to aerosols.

On the first day of the meeting, the low cloud sessions featured numerous talks about different types of observations and using different scales of modeling. There was a great deal of discussion about the interaction of cloud dynamics with aerosols and how relatively small fluctuations in the dynamics of the boundary layer (e.g., gravity waves, free-tropospheric stable layers) can trigger cloud microphysical transformation. Coupling between clouds and rain is another example of a process strongly modulating aerosol-cloud interactions. The coupling of cloud responses to meteorology makes it difficult to prove causality in observations, and in many cases, even detection and attribution using models is very challenging. In some cases, short-duration, high-resolution simulations may not be representative of continuous emissions into distinct environments due to the differences in rapid and slow timescale responses. We discussed the modeling of shallow clouds, from Large Eddy Simulations (LES) to the global scale, to attack similar problems and case studies using observations and different modeling scales to understand processes, as well as deficiencies in models. This could also link ACPC efforts with other modeling work such as the Aerosol Comparisons between Observations and Models (AeroCom) project and bring together existing results with new cross-scale work.

The second day of low cloud sessions focused on opportunistic experiments. There is a review paper on these different experiments for understanding aerosol-cloud interactions (Christensen et al., submitted; Fig. 1). Many presentations focused on using models and observations of different scales to examine ship tracks and shipping lanes, which are a prime candidate for linking the small scale to large scale models. The relatively short timescales of ship tracks were demonstrated to exert larger aerosol indirect radiative cooling compared to cloud systems, which are fully adjusted (Glassmeier et al., 2021). New observational developments in this area at the track (Gryspeerdt et al., 2021) and corridor level (Diamond et al., 2020) will be pivotal in future work targeting this problem from geostationary satellite observations. Targeted periods and cases approached from different scales would have the capacity to make significant progress and link the process level to global scale forcing from aerosol-cloud interactions (ACI). Finally, the session closed with focus on two other types of experiments: long-term trends in anthropogenic emissions that can be correlated with cloud properties (e.g., Cao et al., 2021), and recent changes in aerosols due to the COVID-19 pandemic (Gettelman et al., 2021).

The deep cloud sessions focused on building on previous efforts in the comparison and evaluation of the representation of aerosol-convection interactions in cloud resolving models, extending to aerosol impacts on severe storms and other hazardous weather, and exploring aerosol effects in additional climate regimes around the globe. In the end, the deep cloud group discussed the ACPC deep clouds roadmap for the next 3 years, which is centered on the preparations for the upcoming TRACER experiment and partner field campaigns in the Houston, Texas region, which have been delayed due to COVID-19 safety concerns.

The simulation results from the ACPC model intercomparison project of the 19 June 2013 convective cloud case in

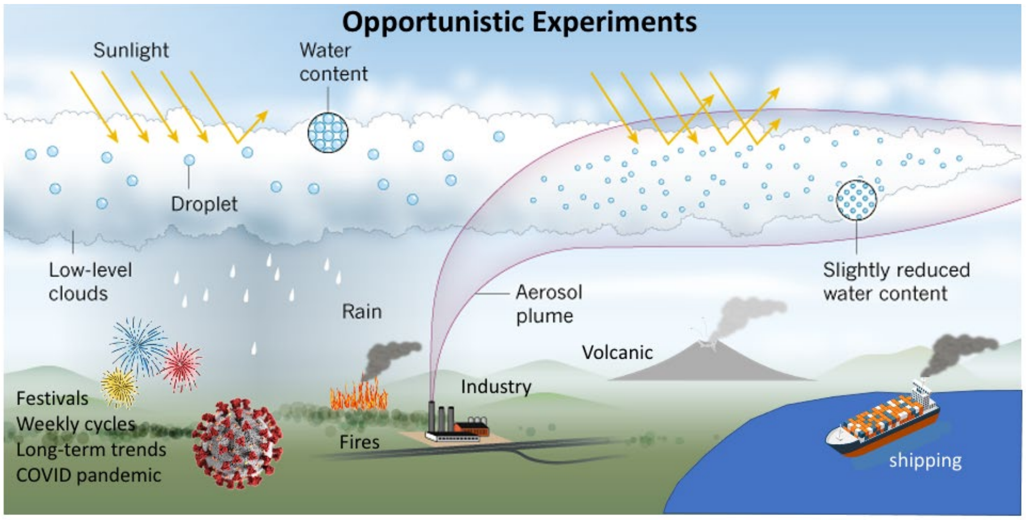

***Figure 1**. Conceptual diagram showing examples of the aerosol effect on boundary layer liquid clouds from some prominent natural laboratories. From Christensen et al. (submitted).*

Houston, Texas (Marinescu et al., 2021) are being used to refine and inform observational sampling techniques to better define the links between updraft dynamics and microphysics. Composites of simulated convective cells are also being used to identify changes in microphysical quantities related to interactions with aerosols (Hu et al., 2019). Instrument simulators are then being applied to quantify the impacts of these changes on the measurements from remote sensing instruments.

Another focus of the deep cloud sessions was advancing the understanding of the impacts of aerosols on severe convective storms and hurricanes. A series of connected studies showed that aerosols from wildfires and urbanization can enhance the occurrence of large hail (e.g., Lin et al., 2021; Zhang et al., 2019). Li et al. (2021) further show that the cloud condensation nuclei effect on hail is even larger than the initial meteorological perturbations based on a large number of ensemble simulations. Pan et al. (2020) found that aerosols can efficiently modulate tropical cyclone intensity and precipitation near rainbands and that industrial aerosol sources in Houston enhanced precipitation amounts by 110% during Hurricane Harvey (2017). However, the simulations of Cotton and Walko (2021) showed no discernible such aerosol effect.

Geostationary satellites remain an important tool for elucidating the impacts of aerosol on convection. Analysis of Meteosat observations over the equatorial Atlantic Ocean and African continent showed increases in cloud-top temperature, convective lifetime, and total precipitation with increasing aerosol concentrations, particularly over land regions (Pan et al., 2021). Using Himawari-8 observations over China, Chen et al. (2021) showed that aerosol impacts on convection and hail are modulated by megacities and complex topography. Studies for the regions in India, China, and the Amazon reported significant impacts of aerosols on deep convective clouds and the deep convective cloud processing of aerosol precursors.

Modeling and analysis of the synoptic, mesoscale (e.g., sea-breeze, urban heat island), and cloud environment in the Houston area continues in preparation for TRACER. This includes work on the use of machine learning techniques to define dominant synoptic regimes, modeling of sea breeze and urbanization impacts on convective characteristics, environmental modulation of aerosol impacts on tropical sea breeze convection, and instrument simulators to identify the most promising radar-based cell-tracking criteria for deployment during the TRACER campaign. Ongoing and future ACPC activities as described in an updated ACPC deep convection roadmap (*http://acpcinitiative.org/Docs/ACPC_DCC_Roadmap_2021.pdf*) are aimed at comparisons of cell-tracking algorithms applied to observations and model output and first light identification of "golden cases" for detailed modeling and analysis during TRACER and constraining using observational data collected during the field campaign.

The ACPC scientific steering committee (SSC) approved its Terms of Reference, which will guide the rotation of its leadership, including co-chairs and members of the SSC. The rotation of SSC members will start this fall. The next ACPC meeting is planned for April 2022, and a hybrid meeting format is proposed, including both a physical meeting and a virtual component. All colleagues interested in ACPC topics are cordially invited to join the initiative.

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Global Water Futures Shows Important Scientific Progress and Outcomes at Its 4th Annual Open Science Meeting

Virtual Meeting
17–19 May 2021

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Canada and the world are facing immense water-related threats from climate warming, environmental change, and human actions. Cold regions supply much of the world's freshwater and are undergoing rapid change with an increasing occurrence of extreme events. Finding solutions for how to best forecast, prepare for, and manage water futures in the face of dramatically increasing risk is a global imperative. *Global Water Futures (GWF): Solutions to Water Threats in an Era of Global Change* (www.globalwaterfutures.ca) is a Canadian-led initiative over seven years (2016–2023) that involves over 380 scientists from 18 Canadian universities and 39 federal and provincial government agencies, as well as many collaborators and stakeholder partners from across Canada and internationally. GWF's overarching goal is to deliver risk management solutions—informed by leading-edge water science and supported by innovative decision-making tools—to manage water futures in Canada and other cold regions, with a focus on 1) improving disaster warning and developing forecasting capacity to predict the risk and severity of extreme events, 2) predicting water futures through the use of big data and improved numerical models to assess change in human and natural land and water systems, and 3) informing adaptation to change and risk management through governance mechanisms, management strategies, and policy tools and guidance. In Canada, GWF focuses on large (and often transboundary) river basins spanning the country, and key ecological, climatological, and physiographic regions that are representative of the scientific and societal issues faced globally, especially within cold regions.

GWF builds upon several decades of Canadian contributions to the GEWEX project. This began in the 1990s with the Mackenzie GEWEX Study, focusing on the Mackenzie River Basin between 1994 and 2005. In 2012, the Saskatchewan River Basin (SaskRB) Regional Hydroclimate Project (RHP) was approved and was expanded in 2014 to include the Mackenzie Basin. This broader RHP for western Canada mirrored the Changing Cold Regions Network, running from 2013 to 2018. This effort was further expanded in scientific and geographic scope with the GWF program, which since 2018 has contributed to GEWEX as a fully operational RHP—the only current RHP for North America (see https://gwf.usask.ca/documents/gewex-global-water-futures-proposal_submit_2018.pdf).

Last year, GWF reached a milestone with its mid-term point of its 7-year program. GWF continues to make scientific and institutional progress despite the challenges of the pandemic; has launched its full suite of transdisciplinary and transformative projects and teams; implemented a co-developed Indigenous community water research strategy; developed an innovative virtual approach to linking science and art; and is implementing an ambitious equality, diversity, and inclusion (EDI) strategy. GWF is working with its community of users to make important advances that enhance water security for Canadians and address some of the world's most important and pressing water problems. A comprehensive report on the scientific strategy and progress was released and provides more detail (*https://gwf.usask.ca/outputs-data/midterm-report-2020.php*).

Over 1,000 GWF members and partners met online in the second year of the global pandemic for GWF's 4th Annual Open Science Meeting (GWF2021), held May 17–19, 2021. This brought together the GWF community to share our advances in knowledge, connect with users and partners, provide updates on co-developed water solutions, and discuss the actions needed to secure a sustainable water future. GWF2021 offered a variety of virtual programming to enable shared learning and insightful discussions through key events, including keynote talks, panels, and an interactive poster session. These were complemented by parallel sessions, networking, social activities, and workshops for GWF's Young Professionals. The meeting's programming was designed to engage both researchers and stakeholders in two-way learning and exchanges.

View the posters and recordings of the plenaries and parallel sessions on the GWF2021 website: *https://www.gwf2021.com/*. The meeting was organized around five major themes and five cross-cutting challenges, as follows:

Theme 1	Theme 2	Theme 3	Theme 4	Theme 5
Climate-driven changes of water environments in cold regions	From anthropogenic pressures to ecosystem services	Turning research into policy and management solutions	Innovation in water science and technology	Knowledge co-creation with Indigenous communities

Cross-cutting challenges and opportunities
Transferable knowledge and tools
Predictive modeling and forecasting
(Big) data science and management
Social, economic and health determinants and impacts
Stakeholder engagement and knowledge mobilization

Within this framework, the meeting included four plenary sessions (three keynote speakers and 10 panelists), 14 parallel sessions (75 presentations and talks, 92 GWF speakers, and 15 external speakers), and 131 poster presentations. It was a unique experience to have parallel sessions in a virtual science meeting, but this worked very well as sessions were recorded and available for viewing the same day. Poster presenters were assigned "live chat" times when they were available on a Zoom chat to interact with viewers and respond to questions and comments.

The topics covered were varied and diverse, including: permafrost landscapes; vegetation in arctic ecosystems; SARS-CoV-2 (COVID-19) wastewater surveillance and variant detection; river discharge and water quality prediction, flood forecasting and modeling for water reservoir management; remote sensing of water resources; sensors for water monitoring; best practices in Indigenous community water research; climate modeling and future climate projections; advances in water resources modeling; water valuation; economic value of water quality and behaviors; big data and artificial intelligence; next-generation data science; Indigenous water governance and justice; groundwater in cold regions; aquifer recharge and baseflow trends; sustainable urban water management; agriculture, crops, and hydrology; wetlands and ecosystem services; water quality modeling and nutrient legacy; and advancing access to clean water in Indigenous communities.

Parallel Sessions

Day 1 – Monday, May 17	Day 2 – Tuesday, May 18	Day 3 – Wednesday, May 19	
The Vulnerability and Resilience of Northern Ecosystems to Change	Mechanistic Modeling under Future Climates	Groundwater as a Cause and Cure of Water Insecurity	Theme 1
From Fish Toxicology to Covid Monitoring		Managing Urban Water Challenges in a Changing Climate	Theme 2
From Modeling to Management, Policy & Practice–Case Studies from Global Water Futures	Valuing Canada's Water Resources and Aquatic Ecosystem Services	Water and Agriculture	Theme 3
Sensors and Observations	Innovations in Data Science	Improved Tools for Prediction of Water Futures	Theme 4
Best Practices in Indigenous Community Water Research	Indigenous Water Governance and Justice	Co-creating Research to Advance Access to Clean Water in Indigenous Communities	Theme 5

List of parallel sessions of the GWF2021 meeting

The GWF2021 meeting represented an important event to bring the program together and synthesize results, and clearly showed the progress being made. GWF has improved the scientific underpinning to support disaster warning from floods, droughts, and water quality degradation episodes, and, through new code and computer technologies, is delivering state-of-the-art prediction systems. These prediction systems now require integration and implementation. GWF has made scientific progress in diagnosing the varied dimensions of changing water futures under climate and ecosystem change and in response to water resource development and has built the models that can predict this change. Now it is time to synthesize our assessment of water futures and to deploy those models to predict change and impacts on people, the environment, and the economy.

GWF has worked with over 450 users to develop transdisciplinary solutions to managing water-related risk in a wide variety of sectors, communities, and regions. Now we need to:

- Share, evaluate, compare, and contrast those solutions;
- Work with our users on the implementation and institutionalization of a solutions-based, equitable, inclusive, and evidence-informed approach to achieving water sustainability for Canada; and,
- Contribute to global water solutions through our international partnerships.

The final two years of the GWF program are now underway and we look forward to completing the project objectives and synthesizing the science behind recent extreme events in Canada such as the 2021 heat wave and subsequent drought, wildfires, glacier melt, and flooding and to linking hydrological models to water resource, health, and water use modeling with policy-informing model scenarios developed in consultation with users across Canada. The expansion of international and continental activities of GWF holds great promise for the future.