Advancing Understanding of Urgent Gaps and Needs in Atmospheric Science
Key Insights from the Climate, Weather, and Water Forum

Lujia Zhang, Yurong Song, Tat Fan Cheng, and Mengqian Lu

KEYWORDS:
Water resources; Extreme events; Climate change; Data quality control; Numerical analysis/modeling

Climate, Weather, and Water Forum 2023
What: Participants from around the world, including international researchers, local Hong Kong government officials, and representatives from industrial communities, gathered to review and discuss pressing challenges, positive solutions, and potential opportunities related to climate change, extreme weather events, and water sustainability issues.
When: 5–7 June 2023
Where: Hong Kong, China

https://doi.org/10.1175/BAMS-D-23-0245.1
Corresponding author: Mengqian Lu, mengqian.lu@ust.hk
In final form 14 September 2023
© 2023 American Meteorological Society. This published article is licensed under the terms of the default AMS reuse license. For information regarding reuse of this content and general copyright information, consult the AMS Copyright Policy (www.ametsoc.org/PUBSReuseLicenses).
Climate, weather, and water are interconnected and influence each other to form our shared Earth. Climate change is happening worldwide and accelerates with the continuous emission of heat-trapping greenhouse gases into the atmosphere, as highlighted by the latest Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR6; IPCC 2023). The altered climate system has led to an increase in the frequency and intensity of extreme weather events and the alteration of the global water cycle. From devastating wildfires and floods to extreme heatwaves and droughts, the consequences of a rapidly changing climate are being felt all around the world. According to a recent report from the World Meteorological Organization (WMO), tremendous mortality (2.06 million deaths) and economic losses [$3.64 trillion (U.S. dollars)] were incurred during the 11,072 climate, weather, and water-related disasters throughout the past half century (World Meteorological Organization 2021). Foreseeing that these hazards will exert even more adverse impacts on the sustainability of humanity in a changing climate, the theme designated for World Meteorological Day 2023, “The Future of Weather, Climate, and Water Across Generations,” underscores the pressing need to address the challenges posed by climate change and to develop sustainable strategies for water and weather-related practices that can benefit future generations. The brief overview and agenda of this forum are available here: https://cemlu.people.ust.hk/CWF2023.html.

The Hong Kong University of Science and Technology hosted a forum from 5 to 7 June 2023 to address emerging threats from the changing climate, extreme weather, and the depleting availability of clean water. The forum aimed to reduce uncertainty and anxiety for the next generation that inherits the world by facilitating a dialogue among scientists, engineers, students, public and private enterprises, and government entities. Figure 1 highlights the forum participants, topics, and main contents. As a special administrative region of China, the Hong Kong government agencies [Hong Kong Observatory (HKO); Civil Engineering and Development Department (CEDD); Water Supplies Department (WSD); Environmental Protection Department (EPD); Drainage Services Department (DSD)] possess a high degree of autonomy, collaborating with each other to efficiently deal with various extreme disasters, e.g., prevention from tropical cyclone (TC) hazards, water resources scheduling, and infrastructure planning under climate change. Communication with the pragmatic government could bridge the gap between research and application. The forum was attended in person by about 100 participants and featured a total of 29 talks and 31 poster presentations, including 13 invited talks that lasted 45 min each and 16 contributed talks that lasted 15 min each. Approximately half of the attendees are students or in the early stages of their research careers.

The 2.5-day forum focused on three key purposes: deepening our understanding of physical mechanisms of Earth science (day 1), examining the impacts and challenges of climate change (day 2), and exploring technological advances in modeling and observations (day 3). Each morning session featured three invited experts, followed by a panel discussion, aimed at encouraging the sharing of unique insights and experiences and brainstorming questions related to the talks. Contributed talks were arranged during the afternoons of the first and...
second days, while a poster session was held on the first day afternoon, with the posters remaining up for the duration of the workshop. The participants’ contributions addressed key problems and strengthened our understanding of atmospheric science from data, modeling, and scientific recognition perspectives. In accordance with this framework, the following parts will present the summarized contents separately for clarity and coherence.

**Scientific highlights**

The enumeration and discussion of modifications in weather and climate extremes in the context of climate change have been pursued to foster an enriched comprehension and evoke innovative solutions (Easterling et al. 2000). Among the notable focal areas of investigation, heat-related perils, water-related vulnerabilities, and the compound hazards have emerged as prominently significant themes interconnected with the domain of extreme events. The observed increases in frequency, intensity, and duration of heatwaves are projected to continue with global warming (Barriopedro et al. 2023). More specifically, nighttime and compound (daytime and nighttime) heatwaves demonstrate more substantial increases in frequency compared to daytime heatwaves across most regions of the globe (Wu et al. 2023), with urbanization significantly contributing to this phenomenon (Ma and Yuan 2021). In the ocean, the occurrence probabilities of the duration, intensity, and cumulative intensity of most documented, large, and impactful marine heatwaves have increased more than twentyfold as a result of anthropogenic climate change (Laufkötter et al. 2020). The change in the heat leads to the difference in the water cycle. The Arctic’s rapid warming is influencing extreme...
precipitation in the Northern Hemisphere, which is associated with a negative Northern Hemisphere annular mode (Liu et al. 2021). Warming temperatures in the west of the United States also have led to less snow and more winter rain, creating more persistent low- to no-snow conditions. These conditions led to a significant event—the evacuation of 188,000 residents below the already-damaged Oroville Dam spillway in February 2017 in California’s Sierra Nevada (Haleakala et al. 2023). Furthermore, there are significant increasing trends in flash drought frequency, duration, and intensity for most of China during 1961–2016. Warmer temperatures and vegetation greening increase evapotranspiration and decrease soil moisture and explain 89% and 54% of the increasing frequency of flash drought, respectively (Zhang et al. 2022).

In light of our awareness of the imminent hazards posed by these extreme events, the imperative to delve into the physical mechanisms driving such extremes becomes even more pressing. Extreme precipitation is found to be facilitated by increased precipitation efficiency, caused by reflecting the accelerated rate of recycling of precipitation-total cloud water in regions of strongly reduced outgoing longwave radiation, associated with colder anvil cloud tops (Lau et al. 2023). While noteworthy progress has been achieved in the exploration of thermodynamic aspects, the comprehension of dynamic processes lags behind (Barriopedro et al. 2023). Recent studies in teleconnections have shed light on the organization of clustered extreme events, potentially bridging the existing gap in our understanding. For instance, the Asian–North American teleconnection is found linking clustered extreme precipitation from India to Canada and the circumglobal teleconnection is responsible for the Yangtze River valley heatwaves in 2022 (Tang et al. 2023; Wang et al. 2022). Endeavors are undertaken to mitigate the uncertainties encompassing the intricate physical processes, with the explicit objective of enhancing the forecast’s credibility. For example, internal variability dominates the uncertainty of tropical Pacific sea surface temperature zonal gradient change and accounts for over 80% at the end of the twenty-first century (Dong et al. 2021), which can lead to a better understanding and reduction of uncertainty in future projections through successfully isolating internal variability. The notable uncertainty in climate sensitivity can also be attributed, in part, to cloud feedback mechanisms. Efforts to mitigate this uncertainty encompass a multifaceted approach that combines empirical observations, theoretical modeling, and computational simulations (Ceppi and Nowack 2021). Notably, advancements in our understanding of radiative impacts attributed to tropical upper-level clouds have emerged as a pivotal contributor in diminishing the uncertainty associated with cloud feedback (Kang and Choi 2023). These findings have the potential to serve as a valuable source of improved climate projections and extreme weather forecasts.

More accurate and realistic modeling
The key challenge in modeling lies in how to adeptly harness physical mechanisms discovery to fine-tune models and enhance predictive accuracy. Within the diverse spectrum of model tasks, the refinement of nowcasting performance emerges as a focal point of scientific efforts. Even when performed on a supercomputing platform, numerical weather prediction (NWP) models are still struggling to provide skillful kilometer-scale nowcasting (i.e., up to 6 h ahead based on the WMO definition) at an updating cycle of tens of minutes, which is a typical duration for short-lived, localized extreme weather events (Zhang et al. 2023). Artificial intelligence and machine learning (AI/ML) methods are given a high hope for improving nowcasting by a number of forum speakers, considering their capability in capturing nonlinear processes. NowcastNet has succeeded in implementing a physically constrained, radar-image-based neural network framework to simplify the numerical computation of advective and convective processes while reproducing the complex structure of extreme precipitation at lead times up to 3 h (Zhang et al. 2023). The Pangu-Weather model, implemented as three-dimensional...
deep networks, achieves stronger deterministic forecast results on reanalysis data across all tested variables compared to the world’s leading NWP system. These breakthroughs reaffirm the feasibility of integrating AI/ML in bridging the computational gap in nowcasting highlighted in the forum.

Subseasonal-to-seasonal (S2S) forecast is another forefront challenge in numerical modeling. It refers to a time scale of 14–90 days which is too long for weather forecasting but too short for seasonal prediction driven by slowly varying sea surface temperature anomalies (Robertson and Vitart 2019). A satisfactory S2S prediction therefore presents “windows of opportunity” for optimizing resource management. However, rainfall prediction skills plunge significantly at a lead time beyond a fortnight. This could be the result of the inherent unpredictability of extratropical variabilities and model deficiencies in reproducing teleconnections (de Andrade et al. 2019). Hence, even with the source of predictability harnessed from the Madden–Julian oscillation (MJO), a prominent intraseasonal variability in the tropics with a periodicity of ~20–70 days, promising skill of medium-range forecasting would still be limited to a narrow belt of the tropics (Liu et al. 2022). Other potentially important sources of S2S predictability include soil moisture, snow cover, stratosphere-troposphere interaction, as well as ocean conditions, yet their S2S predictability is to be fully understood and harnessed (Robertson and Vitart 2019). Beyond delving into the origins of predictability, a consensus among the speakers materialized in recognition of the ongoing imperative of advancing data assimilation in better harnessing the power of observation data to initialize numerical models for medium-range prediction. In resonance with the speakers’ endorsement of employing AI/ML technology to bridge the gap in S2S prediction, recent success has been realized through a prize challenge campaign initiated by the WMO, wherein the application of deep learning models has demonstrated a modestly heightened skill level in S2S forecasts for the 2-m temperature and precipitation compared to a benchmark forecast relying on simple bias correction (Vitart et al. 2022). Furthermore, the strategic incorporation of AI/ML technology, exemplified by entities such as ChatGPT, stands poised to potentially evolve into an Earth science–oriented GPT and significantly contribute to the realms of model assessment, parameterization, and the progressive evolution of our scientific comprehension of S2S forecasts.

Model formulation is often simplified despite the recognition of a fully coupled, highly complex Earth system. As most of the global climate models (GCMs) share more or less the same dynamics (i.e., the prognostic equations) at a grid-resolving scale, their predictive power is largely limited to how well the subgrid-scale physics (e.g., phase changes of water molecules, and the mass, momentum, and heat transfers from turbulence and friction) are represented based on physical parameterizations (Bauer et al. 2015). While advances in these parameterizations would require intense field observations for validation of physical theories, recent success in improving numerical prediction has been achieved by convection-permitting, kilometer-scale simulations using the state-of-the-art global cloud-resolving Energy Exascale Earth System Model (E3SM) in small-scale, extreme event simulations, such as mesoscale convective systems (Feng et al. 2023) and derechos (Liu et al. 2023). Such a framework explicitly resolves convection at small scales and produces more physically robust results than convective parameterization schemes that are often prone to errors such as misrepresentation of the precipitation diurnal cycle (Liu et al. 2023).

The participants further advocated for the comprehensive integration of land-atmosphere-ocean interactions within the framework of Earth system modeling. Illustrative instances were presented wherein hydrological modeling had been performed in a decoupled mode, thereby disregarding the intricate interplay and feedback mechanisms existing between land surface conditions and the atmosphere. This affects not only streamflow and flood forecasts, but also the fidelity of the simulated extreme weather
Efforts to enhance observational data credibility

The utilization of credible and sufficient observational data is imperative for researchers to conduct precise disaster assessments and clear mechanism diagnoses. Among three primary platform types, airborne, spaceborne, and land-based acquisition of data directly within the storm through aircraft plays a pivotal role in attaining realistic information. The Intensity Forecasting Experiment (IFEX), initiated by the National Oceanic and Atmospheric Administration (NOAA), has undertaken the collection of airborne data encompassing both TCs and pre-cyclonic disturbances (pre-TCs) spanning the period from 2005 to 2020, with a total of 728 flight missions (Rogers et al. 2013a). The precious observational data pertaining to atmospheric dynamics serve to delineate the inner-core structure and intensity fluctuations of TCs (Rogers et al. 2013b). As an exemplification, airborne data play a crucial role in explicating a development step of the rapid intensification process: the low-level spinup underneath the midlevel vortex results in the vertical alignment of the vortex column (Stone et al. 2023). The data are also proven valuable for analyzing the precipitation characteristics of TCs. Specifically, the convective downdrafts, subsidence in the upshear quadrants, and lateral advection of midtropospheric dry air are three potential factors that can impede the symmetrical distribution of TC precipitation (Nguyen et al. 2017). The forthcoming mission of IFEX is poised to encompass a comprehensive spectrum of forecast challenges and knowledge gaps, encompassing all phases of the TC life cycle, rather than being confined solely to the rapid intensification stage. Additionally, the mission will extend its scope to encompass a broader exploration of TC structure and associated hazards beyond the realm of TC intensity.

Satellite observations represent an efficacious and convenient approach to acquiring Earth data. The HT-1 satellite group, launched in March 2023 by Piesat Information Technology Co., Ltd., signifies a pioneer as the world’s foremost distributed interferometric SAR satellite system using a four satellite “cartwheel” formation configuration comprising four satellites. This satellite constellation effectively enhances global land topographic mapping, imaging observations, and deformation monitoring, thereby contributing substantively to the investigation and preemptive mitigation of ground subsidence, collapses, landslides, and other related disasters. HT-1 marks the inaugural stride in the realization of the “Nvwa Constellation” initiative, an endeavor conceived to achieve seamless global coverage via high-resolution remote sensing, real-time observation capabilities, and navigation augmentation functions. This monumental undertaking envisions the development and construction of over 100 satellites, culminating in the establishment of a robust backbone network for the transmission of spaceborne remote sensing information—a monumental stride toward the realization of the overarching project’s objectives. The commercial enterprise strives to establish global real-time interconnected remote sensing capabilities and a subsequent service platform, enabling the provision of abundant and valuable Earth data for academic research. Concurrently, academia contributes expertise and innovation that can benefit the industry. Collaboration between academia and industry presents novel opportunities to safeguard our shared Earth amid a changing climate. Data assimilation is a solution to the issue of dealing with various data types resulting from numerous observational data sources. By optimally combining models and
observations, data assimilation can enhance the accuracy of forecasts and maximize the benefits derived from observations (Federico et al. 2022). For example, Doppler wind lidar (DWL) data have a positive impact on numerical simulations of typhoons in terms of their formation, track, and intensity. Compared with the three-dimensional variational method, a four-dimensional variational data assimilation system is deemed to be more promising for assimilating the DWL data (Pu et al. 2010). Combined assimilation of DWL wind profiles and tail Doppler radar radial velocity achieves better analysis in terms of hurricane vortex representation, providing better hurricane track and intensity forecasts (Li et al. 2022). In addition, the assimilation of the NASA Cyclone Global Navigation Satellite System (CYGNSS) ocean surface winds has great potential to improve hurricane track and intensity simulations through improved representations of the surface wind fields, hurricane inner-core structures, and surface fluxes. The assimilation of the superobbed CYGNSS data seems to be more effective in improving hurricane track forecasts than thinning the data (Zhang et al. 2017), especially for the weak phase of a hurricane (Cui et al. 2019).

Key insights and future directions

- **Different models serve distinct purposes with their advancements.** Coarse-resolution, computational-saving models help us look at large and climate scales while the time-consuming fine models could achieve the simulation of extreme events. Additionally, the widespread development of AI models has demonstrated their significant potential in reducing prediction times. Therefore, there does not exist an absolute categorization of inherent goodness or badness among different model types. Rather, the optimal selection of models, guided by the specific problem and the desired outcome, serves to maximize their inherent value and efficacy.

- **A notable gap exists between the scientific discovery and its practical application.** Despite the extensive discoveries made regarding Earth’s mechanisms across various temporal and spatial scales, the effective applications of these findings into improving more accurate short-term to long-term forecasts remains an ongoing challenge. Furthermore, the communication and collaboration between scientists and stakeholders regarding the application of state-of-the-art knowledge are insufficient. In addressing water-related issues, such as the imperative for agriculture to adapt to changing drought and flood conditions under global warming, research endeavors focused on precise estimation of groundwater and water resource management could assume a significance in addressing the issue at hand.

- **Interdisciplinary integration bolsters the development of Earth sciences.** The significance of interdisciplinary endeavors within the realm of Earth sciences, exemplified by the intersection of atmospheric and oceanic sciences, has garnered widespread recognition. Technological advancements across diverse disciplines have also contributed to the progress of Earth science. The relentless evolution of electronic chips has engendered the emergence of formidable radar and satellite systems, thereby equipping Earth scientists with the means to access data of heightened reliability. Consequently, to promote the development of Earth science research, it is essential to foster broader collaborations with experts from various disciplines, depending on the specific objectives of the research.

The forum exemplifies a high level of diversity and fosters wide communication, thus facilitating concrete endeavors toward promoting peaceful coexistence with our Earth. For example, Professor Mengqian Lu is initiating a project about managing the water–energy–carbon nexus stemming from the focused items mentioned above with local and international participants of the forum. The forum convenes on an annual basis in Hong Kong, serving as
a source of inspiration for subsequent topics. Building upon this forum, the upcoming one will introduce more topics, specifically focusing on the assessment of Earth’s carbon footprint and the utilization of AI in scientific research.

**Acknowledgments.** We extend our heartfelt gratitude to all the participants of the forum for their enthusiastic contributions and active engagement, which were the foundation of the event’s success. We would also like to express our appreciation to the Hong Kong University of Science and Technology, Truth Capital, and Beijing PIESAT Information Technology Co., Ltd., for their generous financial support. We acknowledge Dr. Robert Rogers from the National Oceanic and Atmospheric Administration for reading this summary of the forum and verifying the accuracy of its contents.
References


