GEWEX QUARTERLY

WCRP World Climate Research Programme

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

World Meteorological Organization | International Science Council

Vol. 34, No. 2 | Quarter 2 2024

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

Special Edition: 9th GEWEX Open Science Conference
We look forward to seeing you in Sapporo!

Water · Climate | 水 · 気候

9th Global Energy and Water Exchanges Open Science Conference
Sapporo, Japan | 7–12 July 2024

SCAN ME

Commentary

Xubin Zeng[1], Jan Polcher[1], and Peter van Oevelen[2]
[1]GEWEX SSG Co-Chair; [2]Director, International GEWEX Project Office

With close to 900 attendees from across the globe, the upcoming 9th Global Energy and Water Exchanges Open Science Conference (9th GEWEX OSC) will be the largest gathering of the GEWEX community in the program's 30+ year history. Organized by GEWEX together with Hokkaido University and the Science Council of Japan, this meeting will celebrate the history and future of GEWEX as well as the contributions of the Japanese research community, all against the backdrop of Sapporo.

The OSC will be preceded by the Early Career Researcher (ECR) Workshop with 50 participants selected on the quality of their current research, with science talks, training, discussions, and site visits. This is also part of GEWEX's efforts in capacity development.

The OSC programming will start on Sunday, 7 July with a Space Agency Day to facilitate the interactions between space agencies and scientists, particularly ECRs. It will feature talks from the space agencies of China, South Korea, and Brazil for the first time, along with talks from space agencies that have been GEWEX partners for a long time, including the National Aeronautics and Space Administration (NASA), European Space Agency (ESA), Centre National d'Etudes Spatiales (CNES), Japan Aerospace Exploration Agency (JAXA), and European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT). Four parallel breakout sessions will follow, with agency representatives and scientists discussing how measurements are made and integrated in Earth system modeling for precipitation, surface water level and snow depth, clouds and aerosols, and solar and longwave radiation.

The Conference itself will begin the next day, 8 July, and runs to Friday, 12 July with poster and oral presentations for 30 different sessions that splinter off from the three overarching themes of water, climate, and the Anthropocene; extremes and risks; and water, energy, and carbon processes. Each day's program will start with two to three keynote speeches to set the stage.

To strengthen the interaction between science and stakeholders and accelerate the transition from science to applications, for the first time for GEWEX OSCs, there will be stakeholder sessions each day from Monday to Thursday that will be organized by five agencies of the Japanese government: the Ministry of Land, Infrastructure, Transport, and Tourism; the Ministry of Agriculture, Forestry and Fisheries; the Ministry of Environment; the Japan Science and Technology Agency; and the Japan International Cooperation Agency. The themes include: flood risk assessment and flood control efforts, challenges facing agricultural production infrastructure development, climate resilience, and addressing global issues with partner countries. To facilitate the interaction between scientists and stakeholders, live translation between English and Japanese will be provided.

The OSC will also be the occasion for the celebration of 150 Years of the Indian Meteorology Department through the Monsoon Session and for the centennial celebration of atmospheric science education and research in China through sessions under the Atmospheric Processes Topic.

GEWEX has set up the GEWEX Lifetime Contribution Award to honor colleagues who have contributed in a substantial way to GEWEX research and/or the community over the span of their career. Only one to two people are selected by GEWEX's Scientific Steering Group before each OSC, about every four years. The first two recipients of this exceptional award are Jack Kaye and Toshio Koike. They will be honored during the OSC banquet. Furthermore, as reported in prior GEWEX Quarterlies, GEWEX has set up the GEWEX Ambassadors Award to honor colleagues who have contributed a significant amount of their time and energy to GEWEX and who can continue to promote GEWEX in the broadest sense. The two recipients from 2023, Christa Peters-Lidard and Andrew Pitman, will also be honored during the OSC banquet.

Besides the science and applications programs of the OSC, local and regional tours (including those related to conference themes) have also been organized during and after the OSC.

To get you in the spirit of the conference, this special *GEWEX Quarterly* issue has a wide selection of GEWEX related and relevant research short papers. We hope for a fruitful conference!

Table of Contents

Early Career Researcher (ECR) Workshop "Extremes in the water cycle and risks to society: Understanding 'actionable' information in hydroclimate research"

Lucía M. Cappelletti[1], Carla Gulizia[1], Valentina Rabanal[2], Javed Ali[3], and Gerbrand Koren[4]

[1]Centro de Investigación del Mar y la Atmósfera–UBA/CONICET, Argentina; [2]Argentinian National Meteorological Service (SMN Argentina), Argentina; [3]University of Central Florida, Orlando, FL, USA; [4]Copernicus Institute of Sustainable Development, Utrecht University, Utrecht, The Netherlands

Three ECR networks, the Young Earth System Scientists (YESS) community, the American Geophysical Union Hydrology Section Student Subcommittee (AGU-H3S), and the Japanese community of young researchers, are organizing an ECR Workshop on "Extremes in the water cycle and risks to society: Understanding 'actionable' information in hydroclimate research". This event will take place in Sapporo, Japan, between 4–6 July 2024, in the context of the 9th Global Energy and Water Cycle Open Science Conference (GEWEX OSC).

The workshop outcomes will be presented during the 9th GEWEX OSC and will provide feedback for writing a white paper describing the ECR perspective on research challenges and opportunities related to three overarching topics:

1. Extremes in the water cycle and risks to society,
2. Understanding "actionable" information in hydroclimate research, and
3. Emergent issues: Artificial Intelligence/Machine Learning (AI/ML) applications in the water-energy nexus and climate intervention in the water and energy cycle.

During the first and second days, the selected participants will discuss the three main topics in breakout sessions that will be galvanized by two invited experts: Dr. Monica Morrison from the National Center for Atmospheric Research (NCAR) in the U.S., an expert on the philosophy of science, values in science, and climate science; and Dr. Yohei Sawada of the Institute of Engineering Innovation at the University of Tokyo, an expert on hydrometeorological disaster prediction and data assimilation.

A special half-day session will be held on the third day of the workshop. It will be dedicated to ECRs exchanging with experts from the Japan Aerospace Exploration Agency (JAXA) and the National Aeronautics and Space Administration (NASA) space agencies on understanding satellite observations for climate extremes and the water cycle from space. This session will include presentations on the technical and operational aspects of satellite operation and a hands-on lab activity aiming to explore further resources, products, and tools. In addition, there will be space for discussion and consideration of the current status, future professional development, and the enhancement of career prospects for ECRs.

The workshop is expected to provide an inspirational, informative, and exciting environment for the ECR attendees, giving them the opportunity for networking, exchanging perspectives on the workshop's three overarching topics, learning novel tools regarding satellite products and resources, and developing their academic/professional career to the next stage. Further information about the workshop is available at https://www.gewexevents.org/meetings/gewex-osc2024/ecr/workshop/.

In addition, there will be a Space Agency Event, organized by GEWEX and various space agencies, on Sunday, 7 July. Participation is open to all those who have registered for the conference.

Jack Kaye and Toshio Koike are the First Recipients of the GEWEX Lifetime Contribution Awards

After 30+ years of history of the Global Energy and Water Exchanges (GEWEX) project, the GEWEX Scientific Steering Group (SSG) has decided to set up an exceptional award to honor colleagues who, over the span of their career, have contributed in a substantial way to GEWEX research and/or the community. Only one to two people are selected before each GEWEX open science conference, about every four years. This is as much an honor to GEWEX (and the international research community on energy and water cycles) as an honor to the awardees.

After a rigorous discussion and voting procedure during GEWEX's SSG meeting in Budapest in late April 2024, GEWEX is happy to announce that Drs. Jack Kaye and Toshio Koike have won the first Lifetime Contribution Award! This award will be presented during the banquet of the Open Science Conference in July 2024 in Sapporo, Japan.

Jack Kaye is the Associate Director for Research in the Earth Science Division of NASA's Science Mission Directorate. He is responsible for NASA's research and data analysis program to study the Earth system using satellites, aircraft, surface-based measurements, and computer models. He received his Ph.D. in theoretical physical chemistry at the California Institute of Technology in 1982. He was named as a Fellow by the American Meteorological Society in 2010, by the American Association of the Advancement of Science in 2014, and named as an honorary member of the Asia Oceania Geoscience Society in 2015. He also received the NASA Distinguished Service Medal in 2022.

Ever since its inception, GEWEX has made the strategic decision to closely connect with space agencies for water and climate science and applications. The continuous support from NASA for the International GEWEX Project Office has been foundational to the long-term success and organizational efficiency of GEWEX. This support has been enabled through Jack's vision and leadership. Furthermore, various NASA Earth Science Research and Analysis programs led by Jack have supported numerous GEWEX-related disciplinary and interdisciplinary projects. Finally, Jack has provided insightful strategic advice to GEWEX leadership throughout the years on GEWEX activities and its interaction with agencies.

Toshio Koike is the Director of the International Centre for Water Hazard and Risk Management (ICHARM) under the auspices of United Nations Educational, Scientific and Cultural Organization (UNESCO) and hosted in Japan. He received his Doctor of Engineering from the University of Tokyo in 1985 where he was also professor from 1999 to 2017. His main research interests are the water cycle and climate sciences and their applications to water resources management using remotely-sensed information. His main efforts have been data integration to fusion the various sources of information on the water cycle. For his research efforts Toshio has received various recognitions including the science award from the Japan Society of Hydrology and Water Resources in 2015.

As chair of the GEWEX Hydroclimate Panel, Toshio has been key in bringing about collaborations between the various continental scale experiments with his Coordinated Enhanced Observing Period (CEOP) concept. Ensuring that all regional campaigns report in near real time to a central server all the observations made with their densely-instrumented observatories has been key. The data could then be compared to single column output from weather analysis and satellite products to obtain a global picture of the near surface processes at key locations around the world. This concept lives on within GEWEX's current regional hydroclimate projects and in particular the GEWEX Land/Atmosphere Feedback Observatory (GLAFO), which continues to confront in situ measurements, satellite derived products, and meteorological analysis.

GEWEX/WCRP Calendar

For the complete Calendar, see http://www.gewex.org/events/

3–5 July 2024—2024 GEWEX Hydroclimatology Panel (GHP) Meeting—Sapporo, Japan

6 July 2024—2024 GEWEX Data and Analysis Panel (GDAP) Meeting—Sapporo, Japan

6 July 2024—2024 GEWEX/Global Land-Atmosphere System Study (GLASS) Panel Meeting—Sapporo, Japan

6–7 July 2024—Groundwater Workshop—Sapporo, Japan

7–12 July 2024—9th Global Energy and Water Cycle Open Science Conference—Sapporo, Japan

13–21 July 2024—COSPAR 2024 45th Scientific Assembly—Busan, Korea

15–16 July 2024—International Symposium on Energy and Water Exchanges in Land-Atmosphere Interactions—Busan, Korea

1–6 September 2024—15th Annual Catchment Science Summer School—Birmingham, UK

2–6 September 2024—International School on Satellite Meteorology (ISSM)—Naples, Italy

14–19 October 2024—2024 Annual Workshop of the International Network for Alpine Research Catchment Hydrology (INARCH)—Lanzhou and Zhangye, China (*By Invitation Only*)

14–16 October 2024—ESA Water Vapour Climate Change Initiative (WV_cci) 2nd User Workshop—Jülich, Germany, and Online

28–30 October 2024—Micro2Macro: Origins of Climate Change Uncertainty Workshop—Laramie, WY, USA and Online

Precipitation in a Changing Climate: What Can We Do as a Research Community?

Xubin Zeng[1] and Ruby Leung[2]

[1]University of Arizona, Tucson, AZ, USA; [2]Pacific Northwest National Laboratory, Richland, WA, USA

Precipitation, the product of many multiscale interacting processes, is a critical component of the water cycle. Through the diabatic heating associated with condensation and evaporation, precipitation is a major driver of atmospheric circulation (e.g., monsoons). Precipitation also has a direct connection to society and the environment. For instance, many high-impact weather events are strongly linked to precipitating storm systems. Among the 28 confirmed weather/climate disaster events in the United States during 2023 with losses exceeding $1 billion each (Figure 1), 26 were associated with precipitation, while the remaining two were due to a lack of precipitation (one drought event and one wildfire event). Furthermore, there has been a remarkable increase in the number of such events in the U.S. (after the consumer price index adjustment); for example, from the annual average of 8.5 events in 1980–2023 versus 20.4 events for the most recent five years (2019–2023).

For these reasons, precipitation has already received much attention. For instance, precipitation has been emphasized by numerous national and international projects, including GEWEX (Stephens et al., 2023). Nevertheless, the robust observation, modeling, and prediction of precipitation over land and oceans remain one of the fundamental challenges in weather and climate research (Douville et al., 2022). The question is: what can we do as a research community? Discovering the silver bullet as a magic solution to this complex problem is unlikely; instead, making sustained progress through observations, understanding, and modeling while leveraging emerging technologies and high-performance computing will lead to a quiet revolution, just like the case for numerical weather prediction (Bauer et al., 2015). Indeed, this is the strategy of the Global Precipitation EXperiment (GPEX)—a new World Climate Research Programme (WCRP) Lighthouse Activity (*https://www.wcrp-climate.org/gpex-overview*)—and some of the ideas discussed below come from GPEX.

Precipitation is produced by complex moist processes and their multiscale interactions with atmospheric dynamics and other components of the Earth system. Precipitation must be characterized by multiple metrics, including intensity, frequency, amount, duration, type, hydrometeor size and distribution, and extremes, as well as more advanced metrics such

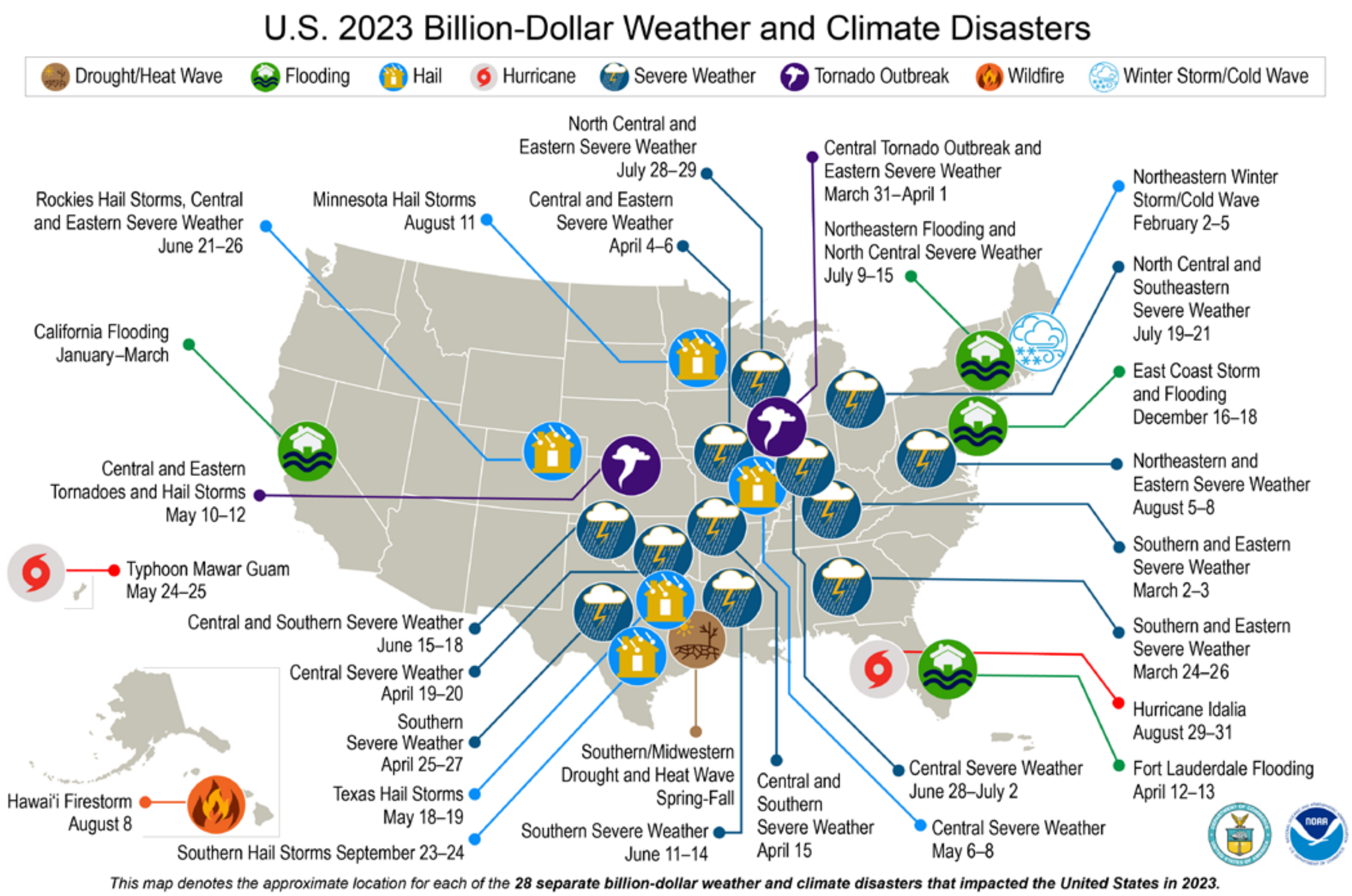


***Figure 1.** U.S. 2023 billion-dollar weather and climate disasters, as documented at https://www.ncei.noaa.gov/access/billions/.*

as precipitation spatial and temporal coherence, its relationship with the environments, and its association with different storm types (Leung et al., 2022). To understand precipitation processes and evaluate model prediction of precipitation, we need high-quality global and regional precipitation data sets. Such data sets already exist but they differ from each other; e.g., for extreme precipitation and for how precipitation relates to other variables such as sea surface temperature (Roca et al., 2021).

For high-quality global data sets with ~5km and 10-min resolutions, satellite remote sensing, surface-based rain gauge and radar measurements, and innovative data fusion are needed. In particular, open access of all precipitation and related measurements from all countries, e.g., via the coordination of World Meteorological Organization, is crucial. To ensure high-quality measurements of precipitation rate, type and hydrometeor size distribution, a baseline surface precipitation network over land, similar to the long-term baseline surface radiation and atmospheric aerosol networks, will accelerate progress. For each site, comprehensive high temporal resolution (10 min or less) precipitation hydrometeor size distribution and phase measurements can be used to calibrate other measurements, improving the overall quality of the global precipitation data sets. Precipitation data uncertainty can be further constrained by considering the balance of the water cycle over river basins, as emphasized by GEWEX (Rodell et al., 2015).

To better understand precipitation processes, we need field campaigns with comprehensive measurements over different regions. Data from prior field campaigns already provide a significant resource for synthesizing our knowledge about precipitation and informing future campaign design to fill critical gaps. Indeed, the 1974 Global Atmospheric Research Programme (GARP) Atlantic Tropical Experiment field campaign (GATE) data over the tropical Atlantic Ocean from half a century ago are still widely used for process understanding. More importantly, GPEX is planning the World Climate Research Programme (WCRP) Years of Precipitation with globally-coordinated field campaigns over land, ocean, and ice for 2–3 years. These field campaigns will focus on several key phenomena responsible for extreme precipitation events and their interactions across scales, including atmospheric rivers, mesoscale convective systems, tropical cyclones, and monsoons.

Besides field campaigns, existing and new satellite measurements are required for global coverage. For instance, the three-dimensional distribution of horizontal atmospheric wind vectors (referred to as 3D winds) is an integral part of the Earth system. 3D winds interact with clouds, convection, and precipitation, and they transport heat, moisture, momentum, aerosols, and trace gases. Zeng et al. (2024) recently proposed Vientos—a new satellite mission concept that combines two or more passive water vapor sounders with Doppler wind lidar to measure 3D winds. The need for 3D wind observations is highlighted by the inconsistencies in reanalysis estimates, particularly under precipitating conditions. Recent studies have shown that 3D winds can be retrieved using water vapor observations from two polar-orbiting satellites separated by 50 minutes, with the help of advanced optical flow algorithms. These winds can be improved through the incorporation of a small number of co-located higher-accuracy measurements via machine learning. The Vientos concept would enable simultaneous measurements of 3D winds, temperature, and humidity, and hence is expected to have a significant impact on process understanding, weather prediction, and other applications. As an illustration, Galarneau et al. (2023) used the 3D winds, temperature, and humidity (from reanalysis) to compute the three ingredients (atmospheric instability, humidity saturation deficit, and the differential divergence between the lower and upper troposphere) and use them to understand and predict the preconditions for organized convection.

One purpose of the field campaigns and data analysis is to better understand the sources of precipitation errors in weather and climate models and hopefully reduce model errors to improve predictions and projections of precipitation at different temporal and spatial scales. One approach is to organize model intercomparisons specifically designed for diagnosing model precipitation biases using field campaign observations. For instance, the GEWEX/ Global Atmospheric System Studies (GASS) precipitation diurnal cycle model intercomparison project (Tang et al., 2022) investigated the interactions between convection and environmental conditions, processes that control nocturnal convections, and the transition from shallow to deep convection on a diurnal time scale using the Department of Energy Atmospheric Radiation Measurement (DOE ARM) data over the Southern Great Plains in the United States and over the central Amazon. Their results provide long-term statistical insights in which physical processes are essential in climate models to simulate the diurnal cycle of precipitation.

A very useful tool for precipitation simulation and prediction is km-scale (storm-resolving) modeling. The benefit is obvious, as it does not need to explicitly parameterize deep convection—which represents one of the most important uncertainties in global modeling. Global km-scale modeling has become more feasible with the progress in model software engineering for graphics-processing units and computational technology. The U.S. Department of Energy modeling team won the inaugural Gordon Bell Prize for Climate Modelling in 2023 by demonstrating an efficient and performance-portable implementation of a global storm-resolving model to run on an exascale supercomputer, which become the first model to break the one-simulated-year-per-day barrier for realistic storm-resolving simulations with a horizontal grid size < 5km (Taylor et al., 2023). Rapid advances are also being made on several fronts such as intercomparison of global storm-resolving models (Stevens et al., 2019), coupling of such models with eddy-resolving ocean models (Hohenegger et al., 2023), and use of these models to provide insights on changes in convection and precipitation extremes in response to global warming (Cheng et al., 2022). Besides global storm-resolving modeling, regional km-scale modeling and global modeling with regional refinement at km-scale are also useful tools for precipitation research. For example, at more affordable computational cost, they have been used to understand the impact of climate change (Prein et al., 2017) and human activities such as urbanization and irrigation (Li et al., 2022) on storms and precipitation.

At the same time, we need to recognize, and seek solutions to, potential weaknesses of km-scale atmospheric modeling: km-scale modeling still does not resolve shallow convection, turbulence, cloud microphysics, and other atmospheric processes. Therefore, significant biases still persist in these km-scale models. Furthermore, the large data volume and high demand for computing power make km-scale models difficult to diagnose and calibrate. On the other hand, these models are resolving processes at scales more comparable to those of satellite and field measurements, so they offer new opportunities to utilize observations for model development as well as to inform observing system design, e.g., through observing system simulation experiments (Zeng et al., 2020). There are also opportunities for developing new metrics for precipitation predictions/projections to meet the needs of users and the decision support community.

A robust understanding of how precipitation has changed in the past and will change in the future requires advancement in theory and understanding. While the thermodynamic aspect of mean and extreme precipitation changes is quite well understood, especially at global scale, significant gaps exist in the dynamical aspect and the process-level understanding of clouds and convection, which are connected closely with regional changes that have direct consequences on people and society. Observations and modeling are invaluable for seeding ideas for theories and for falsifying hypotheses. A hierarchy of models connecting theory-inspired simple models on one end to realistic coupled, high-resolution models on the other end is particularly useful for understanding precipitation in a changing climate. Adding machine learning (ML) models and explainable artificial intelligence (AI) in the model hierarchy opens new opportunities to utilize data from both observations and model simulations in more ways for scientific discovery.

Moving forward, bringing about the convergence of several ingredients will fuel more rapid progress in better understanding and predicting precipitation in a changing climate. These ingredients include: (1) the development of comprehensive field campaign data and global gridded data from surface-based measurements and satellite remote sensing to paint a more accurate and complete picture of precipitation and associated processes, (2) the integration of models with observations and breakthrough technology in computing and AI/ML to support hypothesis-driven research and advancements in prediction and projection, and (3) last but not least, the scientists—from both the Global North and the Global South —that make real progress possible through their innovation and creativity.

References

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

Cheng, K.-Y., and Coauthors, 2022. Impact of warmer sea surface temperature on the global pattern of intense convection: Insights from a global storm resolving model. *Geophys. Res. Lett.*, 49, e2022GL099796. https://doi.org/10.1029/2022GL099796

Douville, H., and Coauthors, 2022. Water remains a blind spot in climate change policies. *PLOS Water* 1(12): e0000058. https://doi.org/10.1371/journal.pwat.0000058

Galarneau, T.J., X. Zeng, R.D. Dixon, A. Ouyed, H. Su, and W. Cui, 2023. Tropical Mesoscale Convective System Formation Environments. *Atmos. Sci. Lett.*, 24 (5), e1152. https://doi.org/10.1002/asl.1152

Hohenegger, C., and Coauthors, 2023. ICON-Sapphire: simulating the components of the Earth system and their interactions at kilometer and subkilometer scales. *Geosci. Model Dev.*, 16, 779-811. https://doi.org/10.5194/gmd-16-779-2023

Leung, L.R., and Coauthors, 2022. Exploratory precipitation metrics: Spatiotemporal characteristics, process-oriented, and phenomena-based. *J. Clim.*, 35(12), 3659-3686. https://doi.org/10.1175/JCLI-D-21-0590.1

Li, J., Y. Qian, L.R. Leung, Z. Feng, C. Sarangi, Y. Liu, and Z. Yang, 2022. Impacts of large-scale urbanization and irrigation on summer precipitation in the mid-Atlantic region of the United States. *Geophys. Res. Lett.*, 49(8). https://doi.org/10.1029/2022GL097845

Prein, A.F., R.M. Rasmussen, K. Ikeda, K., C. Liu, M.P. Clark, and G.J. Holland, 2017. The future intensification of hourly precipitation extremes. *Nat. Clim. Chang.*, 7(1), 48-52. https://doi.org/10.1038/nclimate3168

Roca, R., and Coauthors, 2021. The Joint IPWG/GEWEX Precipitation Assessment. WCRP Report 2/2021, 125 pp. https://www.wcrp-climate.org/WCRP-publications/2021/Joint_IPWG-GEWEX_Precipitation_Assessment_web.pdf

Rodell, M., and Coauthors, 2015. The observed state of the water cycle in the early 21st century. *J. Climate*, 28, 8289-8318. https://doi.org/10.1175/JCLI-D-14-00555.1

Stephens, G.L., and Coauthors, 2023. The first 30 years of GEWEX. *Bull. Amer. Meteor. Soc.* 104(1), E126-E157. https://doi.org/10.1175/BAMS-D-22-0061.1

Stevens, B., and Coauthors, 2019. DYAMOND: the DYnamics of the Atmospheric general circulation Modeled On Non-hydrostatic Domains. *Prog. earth planet. sci.*, 6(1), 1-17. https://doi.org/10.1186/s40645-019-0304-z

Tang, S., and Coauthors, 2022. Long-term single-column model intercomparison of diurnal cycle of precipitation over midlatitude and tropical land. *Q. J. R. Meteorol. Soc.*, 14, 641-669. https://doi.org/10.1002/qj.4222

Taylor, M.A., and Coauthors, 2023. The Simple Cloud-Resolving E3SM Atmosphere Model Running on the Frontier Exascale System. In *Proceedings of the International Conference for High Performance Computing, Networking, Storage and Analysis*, pp. 1-11, https://doi.org/10.1145/3581784.3627044

Zeng, X., and Coauthors, 2020. Use of observing system simulation experiments in the U.S. *Bull. Amer. Meteorol. Soc.*, 101, E1427–E1438. https://doi.org/10.1175/BAMS-D-19-0155.1

Zeng, X., and Coauthors, 2024. Vientos - A new satellite mission concept for 3D wind measurements by combining passive water vapor sounders with Doppler wind lidar. *Bull. Amer. Meteorol. Soc.* 105(2), E357–E369. https://doi.org/10.1175/BAMS-D-22-0283.1

A 60+ Year Perspective of Advancement of Science Results from Studies of the Earth's Radiation Budget from Space and a Proposal for the International ERB Consortium

Thomas H. Vonder Haar[1] and Peter Pilewskie[2]

[1]Department of Atmospheric Science and CIRA, Colorado State University, Fort Collins, CO, USA; [2]Laboratory for Atmospheric and Space Physics/Department of Atmospheric and Ocean Sciences; [2]University of Colorado Boulder, Boulder, CO, USA

Introduction

From the late 1950's International Geophysical Year experiment to the upcoming National Aeronautics and Space Administration (NASA) Libera Mission, there has been and will continue to be a steady gain of science results and knowledge of Earth's Radiation Budget (ERB) from Space. This paper identifies seven key ERB observing periods or Eras with their technologies, satellite observations, and examples of new results. Key science information from ERB observations ranging from required poleward energy transports through global cloud radiative forcing to Earth's Energy Imbalance will be discussed.

As one of the most fundamental Essential Climate Variables (ECVs; see Bojinski et al., 2014), measurements of the ERB, its regional variation, and trends are required to inform our understanding of Earth's climate. They are also required for climate model development and improvement. They provide closure to the energetic system of atmospheric and oceanic circulations on our planet.

For the next Era of ERB measurement and analysis progress into the 2030s, we propose actions by a new International ERB Consortium (IERBC) to develop a 6 to 12 member constellation carrying innovative state-of-the-art ERB instruments. The IERBC is proposed for design, implementation, and periodic review by GEWEX of the World Climate Research Programme (WCRP). The Consortium members will include government agencies, non-governmental organizations, universities, and private sector businesses collaborating in this environmental initiative vital for complete understanding of Earth's climate and its change.

The First Era of Earth Radiation Budget Scientific Studies–Pre-Satellite

Early in the 20th century, several scientific leaders completed research to gain the first estimations of the ERB. These studies were based upon the available, sparse climatological data sets collected in the Northern Hemisphere. Surface reports of clouds, temperature, and moisture formed the majority of the early climatologies. The expanding network of temperature (and some water vapor) profiles from balloon-borne radiosondes greatly aided computation of solar and infrared radiation profiles in the atmosphere with the aid of physically-based radiation charts and nomograms. Surface albedo measurements were made over land, ocean, and snow using contemporary radiometers of various design. Low cloud albedos were measured from higher terrain looking down at clouds in valleys. Estimates of the "top of the atmosphere" total solar irradiance (TSI, commonly called the solar constant at the time) were based on surface (including mountain top) radiometric measurements extrapolated to space with astronomical methods and climatological data.

Seasonal and annual values of ERB were obtained within latitude zones of the Northern Hemisphere. Global ERB values such as albedo were generally estimated by assuming the seasonal Southern Hemisphere ERB values were reciprocals of those in the Northern Hemisphere despite the known differences in surface features. Despite the many assumptions and data voids, some estimated values for the Earth's global albedo were:

- Dines: 50% in 1910
- Simpson: 43% in 1928
- Lettau: 34% in 1954
- London: 32–33% in 1957 (see Stephens et al., 2015 and Kandel, 2012 for more historical details)

The difference between these pre-satellite estimates of albedo and lower values from the first satellite measurements reported by Vonder Haar and Suomi (1971) of 29 +/- 1% is very significant from an Earth energy perspective as discussed below. The difference between early estimates and the first satellite measurements has been attributed primarily to uncertainty in cloud amount and reflectance in the pre-satellite data, especially in large areas of the tropics.

Early Satellite ERB Measurement Era 2

The call for new scientific experiments for U.S. participation in the International Geophysical Year (IGY) in the late 1950s coincided with the emergence of the U.S. civil space program. Verner Suomi and Robert Parent from the University of Wisconsin received a small U.S. IGY grant to develop thermistor bolometer radiometers to measure the ERB from the experimental Explorer satellites. In October 1959, a successful radiometer launch, small experimental tape recorders, and a crude system of data receiving ground sites resulted in the collection of the first nighttime spectrally-integrated Infrared portion of ERB measurements. For several months, segments of orbital data were collected and compared to weather maps and ground-based cloud observations.

This proof-of-concept for satellite ERB data led to flights of similar radiometers aboard three Television Infrared Observation Satellite (TIROS) weather satellites in inclined orbits and two experimental satellites launched into the first near polar sun-synchronous orbits. Improved onboard data recording and radiometer technology as well as satellite stabilization provided the first day and nighttime measurements of both solar and infrared components of the global ERB with global coverage over many seasons (Vonder Haar and Suomi, 1971). Radiometer calibration occurred at each terminator crossing as the radiometers viewed the Total Solar Irradiance. Figure 1 shows some of the early and unexpected science results.

The satellite measurements found a warmer and darker Earth, especially in tropical regions. This gave information about increased poleward energy transport required by the atmosphere–ocean system and initiated considerable related research for the next several decades. In addition, observation that the Northern and Southern Hemispheres had nearly the same albedo despite their different land and ocean distributions remains a research area today (see, for example, Rugenstein and Hakuba, 2023).

ERB Era 3 from Nimbus Measurements

Motivated by the scientific method requirement of reproducibility of new results, the research community looked to ERB measurements from four of the seven new NASA Nimbus spacecraft to validate and expand upon the results from the first satellites in Era 2.

Nimbus was a large, advanced satellite with three axis stabilization and large payload capacity flying in a sun synchronous local noon/midnight orbit. A five-channel scanning radiometer for ERB on Nimbus 3 soon returned data showing the albedo of 30% and equator to pole gradients of net radiation very similar to the Era 2 results. Several years later an improved ERB/TSI instrument package on Nimbus 7 produced even more significant results. It collected nearly 10 years of continuous ERB data, allowing studies of interannual ERB variations including those due to the El Niño-Southern Oscillation (ENSO). Higher spatial resolution of the scanning ERB radiometers also allowed important regional ERB results over the poles, large deserts, and large semi-permanent cloud systems. It also verified the earlier satellite results of the warmer and darker Earth than thought in the pre-satellite era. House et al., 1983 and Kidder and Vonder Haar, 1995 provide additional details about the first three Eras of ERB.

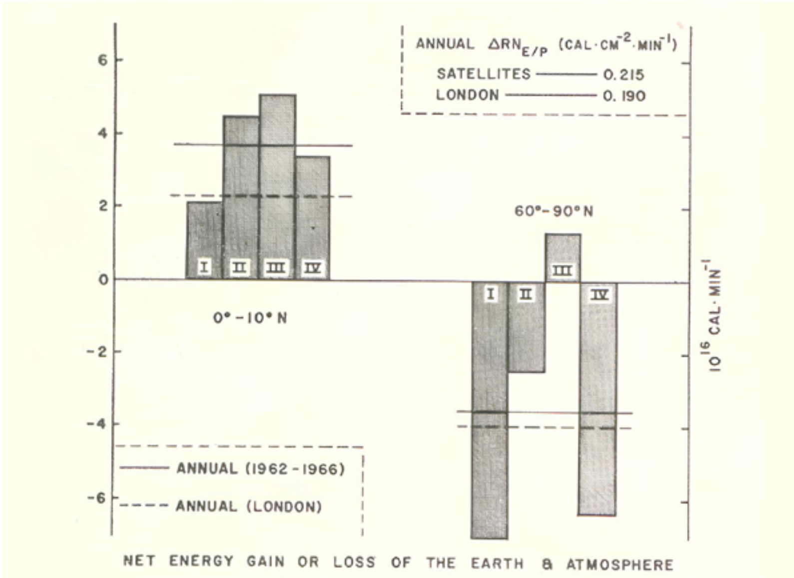


FIG. 2. Mean annual and seasonal energy exchange with space, measured from satellites during 1962–66, for two latitude zones. Bar graph represents seasonal values (I = Dec., Jan., Feb.; II = Mar., Apr., May; etc.). $\Delta RN_{E/P}$ is the net radiation gradient between equator and pole.

***Figure 1**. First results from Era 2 ERB observations from space (Vonder Haar and Suomi, 1971). Note: 1 cal/cm2-min = 698 W/m^2*

***Figure 2**. The ERBE Constellation launched in 1984*

Of special importance for full ERB understanding, the small electrical substitution radiometer "cavity" on Nimbus 7 made the first daily measurements from space of the TSI reaching Earth. This measurement, long awaited in geophysical science, is discussed further in the Era 7 section of this article.

Era 4 and the ERBE Constellation

The Earth Radiation Budget Experiment (ERBE) was a major NASA Earth Science Mission designed to continue and expand upon the groundbreaking Nimbus ERB results from Era 3. The first of a three satellite constellation carrying the same ERB instrument (ERBI) was launched in October, 1984 (Figure 2). A prelaunch computer simulation was used to assess the ERB diurnal variability that would be measured from the inclined orbit in combination with two other satellites in separate sun synchronous orbital planes.

The new ERBI was the product of a four-way competition among instrument incubator radiometer designs. It was a combination of two of the proposals and its sensor suite included an advanced scanning radiometer and wide and medium field of view (FOV) electrical substitution radiometers, which measured both solar and infrared outgoing radiation from Earth as well as the incoming total solar irradiance.

ERBE measurements overlapped and compared well with the latter years of Nimbus 7 ERB and, once again, the lower global albedo and the additional energy gained in tropical areas was confirmed. A new result from the scanning radiometers showed the cloud radiative forcing effect for the first time. It was found that on average clouds cool Earth, imparting a -20 W/m² forcing on the Earth system (Harrison et al., 1990). The ERBE results were also used extensively in the design and improvement of radiation and cloud representation in climate models where cloud-radiative forcing and feedback is studied today. In addition, the long lifetime wide FOV radiometers on the small ERBS satellite provided almost 20 years of data for decadal ERB studies and a welcome overlap with the Clouds and the Earth's Radiant Energy System (CERES) measurements in ERB Era 5.

ERB Era 5 with More than 20 Years of CERES Data

NASA's continued ERB measurement program, CERES, developed, launched, and analyzed ERB data from six radiometers on three research satellites and three operational weather satellites from the late 1990s through the present. This > 20-year record also overlapped with the latter years of ERBE measurements, thus continuing the ERB climate data continuity record of great scientific and environmental value (Figure 3).

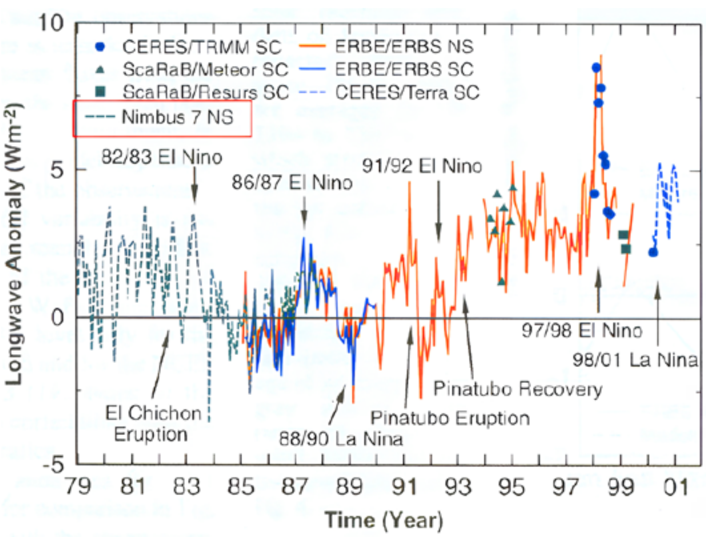


***Figure 3**. An ERB multi-decadal continuity record for 20N to 20S from 1979–2001 (Wielicki et al., 2002)*

The CERES radiometer is an improved version of the scanner on ERBE that, by design for continuity, uses nearly the same radiometer and technology on all instruments that were flown during two decades. It has been primarily flown on satellites in the 1330 local time sun-synchronous orbital plane.

A very large number of scientific papers have been published using ERB measurements from CERES and ERBE (see Kandel, 2012 for a synopsis of references). They include those ranging from ERB variability due to cloud and atmospheric changes through studies of changes in ERB during short-term variations in Earth's climate. One of the most cited recent papers (Loeb et al., 2021) shows the variations of ERB with correlative Ocean Heat Content observations from profiling buoys, thus providing a first estimate of global Earth Energy Imbalance (EEI) over a 14-year period.

ERB Era 6: The Upcoming Launch of the Libera Mission

The Libera Mission, named for the daughter of Ceres in Roman mythology, will provide continuity of the CERES ERB observations from space. Libera's attributes enable a seamless extension of the ERB climate data record. Libera will acquire integrated radiance over the CERES broad spectral bands in the shortwave (0.3 to 5 µm), longwave (5 to 50 µm), and total (0.3 to beyond 100 µm) and adds a split-shortwave band (0.7 to 5 µm) to provide deeper insight into shortwave energy deposition. Libera leverages advanced detector technologies using vertically aligned black carbon nanotubes (VACNT) with closed-loop electrical substitution radiometry to achieve radiometric uncertainty of approximately 0.2% [see Figure 4 showing ERB detectors developed by the Sources and Detectors Group at the National Institute of Standards and Technology (NIST), Boulder, and the Laboratory for Atmospheric and Space Physics, University of Colorado Boulder; see Harber et al., 2023, for details on the Libera radiometers]. Libera will also employ a wide FOV camera to provide scene context and explore pathways for separating future ERB missions from complex imagers. Libera will fly on the National Oceanic and Atmospheric Administration (NOAA)'s operational Joint Polar Satellite System-4 (JPSS-4) satellite, which is scheduled to launch in 2028.

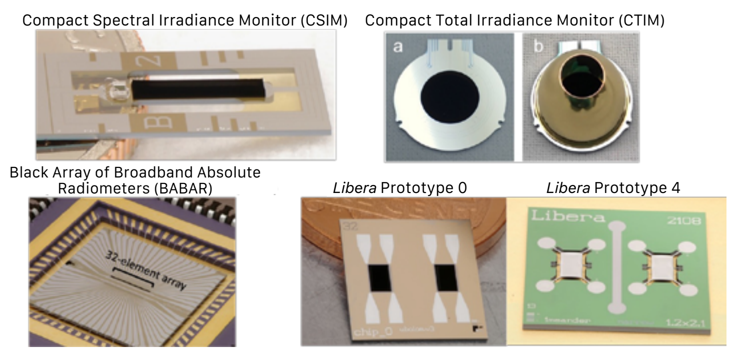


***Figure 4**. VACNT ESRs for ERB measurements*

The Libera science objectives associated with continuity and extension of the ERB data record are to identify and quantify processes responsible for ERB variability on various times scales. Beyond data continuity, Libera's new and enhanced observational capabilities will advance our understanding of spatiotemporal variations of radiative energy flow in the visible and near-infrared spectral regions. They will also enable the rapid development of angular distribution models to facilitate near-IR and visible radiance-to-irradiance conversion.

The 7th ERB Era–The Future

A high priority for this ERB continuity initiative (IERBC) is to continue the 46 years of TSI reaching Earth (Figure 5). In order to assess the flow of outgoing Earth radiation and monitor Earth's energy imbalance, we must also monitor and understand both the TSI and its spectral components as a fundamental driving variables for ERB.

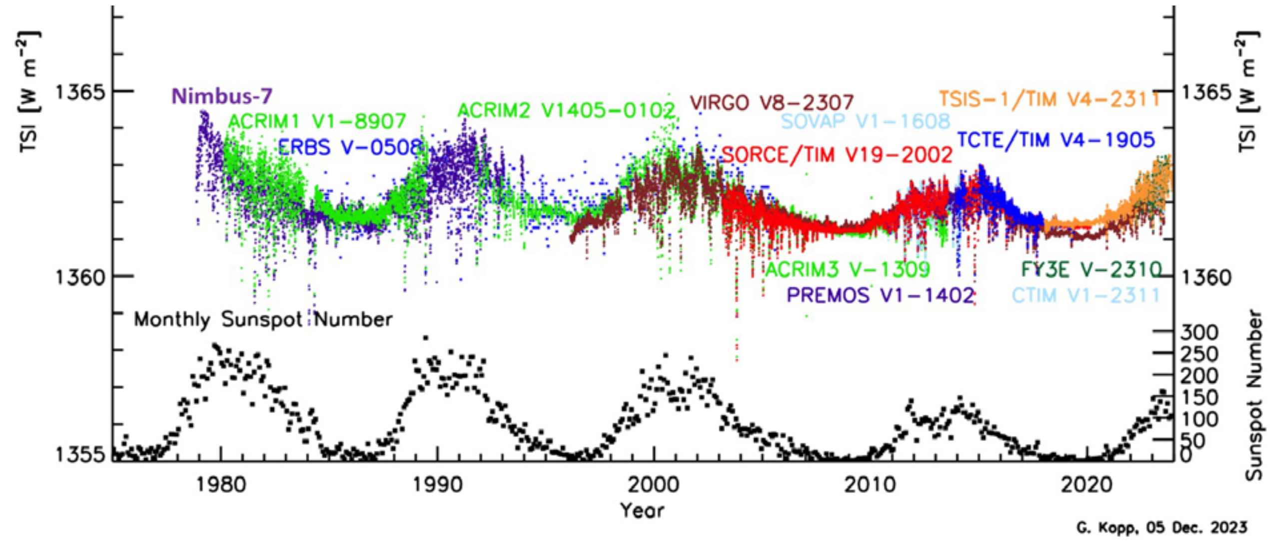


Figure 5. *The TSI record since 1978 on a comment calibration scale. From* https://spot.colorado.edu/~koppg/TSI/

An early challenge for IERBC is to plan an Earth observing system to measure the diurnal component of the global ERB. Several options exist, but only the plausible IERBC satellite constellation is considered here. It is based upon experience with the ERBE three-satellite constellation of Era 4.

Given the Libera class instrument's high accuracy, the remaining uncertainty in ERB understanding arises from incomplete measurement of the reflected solar energy and infrared energy changing throughout the day. This diurnal ERB variation arises from changing cloud and temperature conditions and varies with season and location. A selected small constellation of ERB instruments can remove this ERB uncertainty. The constellation of measurements is well within the space system capabilities of today.

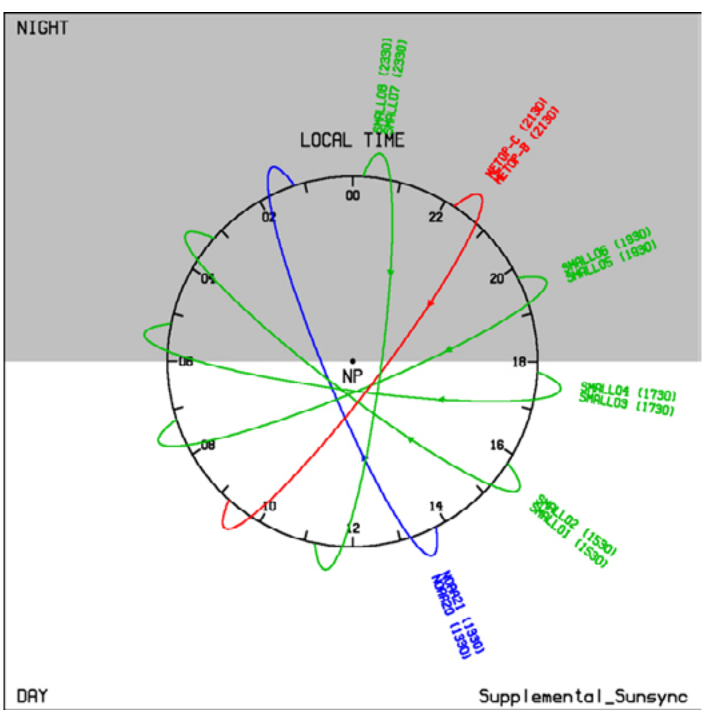


Figure 6. *Kidder et al., 2022: the S3C constellation of orbital planes*

For example, Figure 6 from Kidder et al., 2022 illustrates a Supplemental Sun-Synchronous Constellation with six orbital planes (S3C). Two of the six orbital planes are already populated with NOAA (1330) and Metop (2130) satellites. Completing the constellation for hourly ERB observations would require four launches of two satellites each. A host of international government agency and private sector organizations can fill this role using operational program or research satellites. This is likely to be the most efficient and cost-effective way to achieve hourly observations for the global ERB.

Satellite ERB measurements using the radiant power method are described above in all previous ERB Eras. However, in Era 7, it is possible that these radiometric methods can be complemented by an independent physical method measuring the radiation pressure from Earth affecting the orbits of specially-designed satellites. This geodetic satellite approach was first discussed in the 1990s and is one of the topics of a recent EEI Workshop (Meyssignac et al., 2023).

In summary, we suggest the future ERB measurements will best be attained and analyzed by an International Earth Radiation Budget Consortium (IERBC). This cohort of governmental agencies, non-government organizations, universities, and private sector businesses will design, implement, and analyze the 7th Era of ERB observations.

The International Radiation Commission, WCRP, GEWEX, and the World Meteorological Organization have more than four decades of successful experience with such international space observing system collaborations from the International Satellite Cloud Climatology Program (ISCCP; Rossow, 2022). It serves as a model and provides lessons learned for the IERBC.

Acknowledgements

We thank John Forsythe, Xubin Zeng, and Hong Chen for their contributions and appreciate support from the Libera Science Team.

References

Bojinski, Stephan, M. Verstraete, T.C. Peterson, C. Richter, A. Simmons, and M. Zemp, 2014. The Concept of Essential Climate Variables in Support of Climate Research, Applications, and Policy. *Bull. Amer. Meteor. Soc*. 95. 1431–1443, 10.1175/BAMS-D-13-00047.1

Harrison, E.F., P. Minnis, B.R. Barkstrom, V. Ramanathan, R.D. Cess, and G.G. Gibson 1990., Seasonal variation of cloud radiative forcing derived from the Earth Radiation Budget Experiment. *J. Geophys. Res*., 95(D11), 18687–18703. doi:10.1029/JD095iD11p18687

Harber, D., K. Catani, J. Gieseler, R. Haun, N. Kruczek, J. Sprunk, N. Tomlin, C. Yung, J. Lehman, M. Stephens, T. Kampe, S. Collins, J. Peterson, H. Latvakoski, C. Monte, M. Hakuba, and P. Pilewskie, 2023. The Libera Mission: Bringing Next-Generation Technology to an Established Climate Data Record. 15th International Conference on New Developments and Applications in Optical Radiometry (NEWRAD 2023), 11–15 Sep. 2023, NPL, Teddington, UK

House, F.B., A. Gruber, G.E. Hunt, and A.T. Mecherikunnel, 1986. History of satellite missions and measurements of the earth radiation budget (1957–1984). *Rev. Geophys.* 24: 357–377

Kandel, R., 2012. Understanding and Measuring Earth's Energy Budget: From Fourier, Humboldt and Tyndall to CERES and Beyond. *Surv Geophys* 33: 337-350. DOI 10.1007/s19712-011-9162-y

Kidder, S., T. Vonder Haar, and S. Miller, 2022. Revisiting the Earth's spectral radiance shell concept for a constellation of small environmental satellites. 25th AMS Conference on Satellite Meteorology, Oceanography and Climate, poster #177, Madison, August 2022. For orbital equations: Kidder, S. and T. Vonder Haar, 1995. *Satellite Meteorology, An Introduction*. Chapt. 2, Elsevier e-books

Loeb, N.G., et al., 2021. Satellite and ocean data reveal marked increase in Earth's heating rate. *Geophys. Res. Let*., 48, 13. doi.org/10.1029/2021GL093947

Meyssignac, B., et al., 2023. First earth energy imbalance assessment WCRP-ESA workshop summary and recommendations executive brief. ESA Publication, *http://doi.org/10.5270/wcrp-esa-eeia-2023.final_report_brief*

Rossow, W., 2022. History of the International Satellite Cloud climatology Project. World Climate Research Programme Publication No: 06/2022, *https://mars.gmu.edu/items/9d5f4c38-7c8d-45b1-b629-2a901d82e9b3*

Rugenstein, M., and M. Hakuba, 2023. Connecting hemispheric asymmetries of planetary albedo and surface temperature. *Geophys. Res. Let.* 50, e2022GL101802. *https://doi.org/10.1029/2022GL101802*

Stephens, G., D. O'Brien, P. Webster, P. Pilewskie, S. Kato, and J.-L. Li, 2015. The Albedo of Earth. *Rev. Geophys*. 53. 10.1002/2014RG000449

Vonder Haar, T., and V. Suomi, 1971. Measurements of the Earth's radiation budget from satellites during a five-year period: Extended time and space means. *J. Atmos. Sci.* 28, 3, 305–314

Wielicki, B.A., et al., 2002. Evidence for large decadal variation in the tropical mean radiative energy budget. *Science* 295: 841–844

Regional Evaluation of Water and Energy Cycles in Contemporary Reanalyses

Michael G. Bosilovich[1], J. Brent Roberts[2], Michael Mayer[3,4], and Franklin R. Robertson[2]

[1]Global Modeling and Assimilation Office, NASA GSFC, Greenbelt, MD, USA; [2]Emeritus, NASA MSFC, Huntsville, AL, USA; [3]Research Department, European Centre for Medium-Range Weather Forecasts, Reading, UK; [4]Department of Meteorology and Geophysics, University of Vienna, Vienna, Austria

Background

The motivating mission of GEWEX has been to improve the understanding of the Earth's water and energy cycles across time and spatial scales from past to the future (Stephens et al., 2023). The regional aspect is particularly important, as the climate, variability, and extremes become more uncertain but crucially important to adaptation and mitigation, not to mention understanding. The GEWEX Hydroclimatology Panel's (GHP) Regional Hydroclimatology Projects (RHP) have evolved to provide intensive research efforts in many regional basins, not just in the areas of basic hydrology and climate research, but also along themes of much broader science and societal benefit.

Important tools for weather and climate research are atmospheric retrospective analyses (reanalyses), where models are continually confronted by observations to determine the state of the weather through data assimilation, and the background model enables a spatially and temporally continuous data record. During data assimilation, the modeled state fields are adjusted toward the observations, which adds a tendency in the state budgets that is not related to the physical processes in the atmosphere. While this tendency can be related to the observational analysis (e.g., Bosilovich et al., 2017), it has also been interpreted as an imbalance (Trenberth et al., 2011). Roads et al., 2002 evaluated GEWEX regional projects' (at that time termed Continental Scale Experiments) water and energy budgets in the National Centers for Environmental Prediction (NCEP) Reanalysis II, paying particular attention to the observational influence, solved for as a residual.

In the present study, we use the methods laid out in Roads et al., 2002 to evaluate the more modern atmosphere reanalyses' water and energy budgets. As a starting point, we focus on the Mississippi River Basin (MRB), as it is well-instrumented and at the geographic center of a new GEWEX Regional Hydroclimate Project, called Humans and Hydroclimate in the United States (H2US). In addition, the Amazon basin is also included as another point of comparison to the previous effort of Roads et al., 2002) The intent is to, in time, expand to the other current RHPs, especially those less well-instrumented. Likewise, for this paper, we focus on the regional water budget and will expand to the energy budget in the course of the project.

Data

Most of the current reanalyses provide the physical component terms required to assess atmospheric water and energy budgets. However, for closure in reanalyses, one must also consider the influence of the analysis of water vapor observations. In the Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2), the analysis increment tendency is explicitly archived (Bosilovich et al., 2017). For the European Centre for Medium-Range Weather Forecasts (ECMWF) Reanalysis, Version 5 (ERA5), the analysis increment has been computed from the difference of the background forecast and analysis (by co-author M. Mayer). Following the notation in Roads et al., 2002, the atmospheric regional water budget can be written:

$$\partial Q/\partial t=E+MC-P+RSQ \qquad (1)$$

Where Q represents the vertically-integrated and regionally-averaged total column water, which changes from the surface evapotranspiration (E), precipitation (P), and moisture flux convergence (MC). RSQ is a term arising in atmospheric models and represents nonphysical terms. Specifically, these can include imbalances that arise from model numerics and the analysis of observations.

When available to evaluate the impact of assimilation, the residual term will be assessed as RSQ=RSQ` + QANA where QANA is the analysis increments and RSQ' represents any remaining residual elements.

The reanalyses considered here include: Japanese Reanalyses for Three Quarters Century (JRA3Q, Kosaka et al., 2024), ERA5 (Hersbach et al., 2020), MERRA-2 (Gelaro et al., 2017), and the NCEP Reanalysis II (NCEPR2, Kanamitsu et al., 2002). While NCEPR2 is representative of the late 90s technology, it provides a connection back to the Roads et al., 2002 work. The NCEPR2 total tendency of water, total column water, and moisture convergence were computed from the 6-hourly NCEPR2 analysis fields on pressure levels. The analysis increments for JRA3Q and NCEPR2 were not available, so the RSQ term combines these with any numerical residuals.

While we are interested in the current state of budget closure, we also include observations as a reference, when possible, such as the Global Precipitation Climatology Project (GPCP) version 3.2 (Huffman et al., 2023), a merger of remotely-sensed and station gauge observations for a reference precipitation. The Global Land Evaporation Amsterdam Model (GLEAM) algorithm derives evaporation from remotely-sensed observations, soil water availability modeling, and the Priestley-Taylor equation. The integration for the reanalyses budget terms in the MRB and Amazon were determined from a basin mask used in the Global Modeling and Assimilation Office (GMAO) Catchment land surface model, based on Shuttle Radar Topography Mission (SRTM) elevation and Pfafstetter codes (reducing the resolution to each of the reanalyses' native resolution, courtesy of Randy Koster and Qing Liu).

Results

Mean Atmospheric Water Budget

A first glimpse of the reanalyses regional budgets is presented in Table 1, including as many of the terms of the water budget equation as is possible with each system time averaged for the 2000–2020 period (chosen for the presence of some observations, and also for increased number of assimilated observations). For MRB, the reanalyses generally represent the mean precipitation in comparison to GPCP, though a persistent high bias against GLEAM evaporation is present, and NCEPR2 evaporation bias is apparent. The moisture convergence for each of the reanalyses is reasonably close, presumably owing to the reliable radiosonde network in and around the MRB, where MC is related to observed state fields, but noting that P and E rely on model parameterizations. The NCEPR2 residual occurs as a response to the high bias in evaporation. Over the long period, ERA5, JRA3Q, and MERRA-2 residuals or analysis increments are small here.

MRB	MERRA-2	ERA5	JRA3Q	NCEPR2	OBS
TPW	17.5	17.0	16.4	17.3	16.9 (AIRS)
P	2.57	2.32	2.61	2.52	2.43 (GPCP3.2)
E	1.92	1.89	1.95	2.64	1.65 (GLEAM)
MC	0.60	0.42	0.56	0.61	
RSQ	0.00	0.08	0.10	-0.73	
QANA	0.06	-0.08			

Amazon	MERRA-2	ERA5	JRA3Q	NCEPR2	OBS
TPW	46.7	45.8	44.0	43.5	45.4 (AIRS)
P	6.90	6.51	7.38	6.05	6.06 (GPCP3.2)
E	3.86	3.49	4.12	3.93	3.72 (GLEAM)
MC	2.02	3.12	2.87	1.63	
RSQ	0.01	0.06	0.40	0.49	
QANA	1.02	-0.17			

***Table 1**. 2000–2020 time and area average water balance terms (units are mm d^{-1}) for the Mississippi River Basin (MRB, top) and Amazon River Basin (bottom). Total precipitable water (TPW, mm) is included for a reference. Observed data also provide a reference (with the source of the observation noted in the table). Analysis increments were not readily available for JRA3Q and NCEPR2, so their residuals would include the analysis increment and any residual.*

The Amazon's tropical climate has a more active water cycle than MRB, but observations here are much more sparse. The more recent reanalyses overestimate the precipitation, while the reanalysis evaporation estimates bracket the GLEAM evapotranspiration. There is also a wide range of Amazon moisture convergence among the reanalyses. The magnitude of the residuals/increments have increased (except for NCEPR2), with MERRA-2 having a substantial increase in the analysis increment. So, while it appears there is some improvement in closure for the Mississippi River Basin, the Amazon still exhibits significant closure difficulties.

Interannual Variations and the Annual Cycle

To explain more of the water cycle, we expand the comparison to consider the interannual variations (monthly mean time series, with a 12-month running mean applied) and the mean

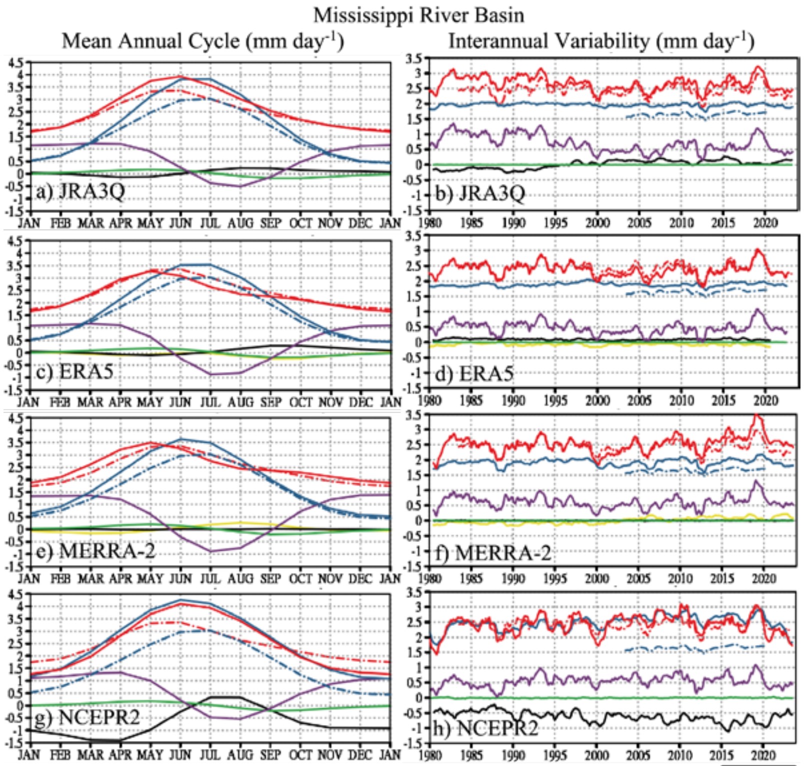


Figure 1*. Mississippi River Basin water cycle representation of the annual cycle (left, 2000–2020) and interannual variability (12 month running means, right) for JRA3Q (a,b), ERA5 (c,d), MERRA-2 (e,f) and NCEPR2 (g,h). The dashed lines are GPCP v3.2 (red) and ERA5-Land evaporation (blue). Units are mm day*$^{-1}$*.*

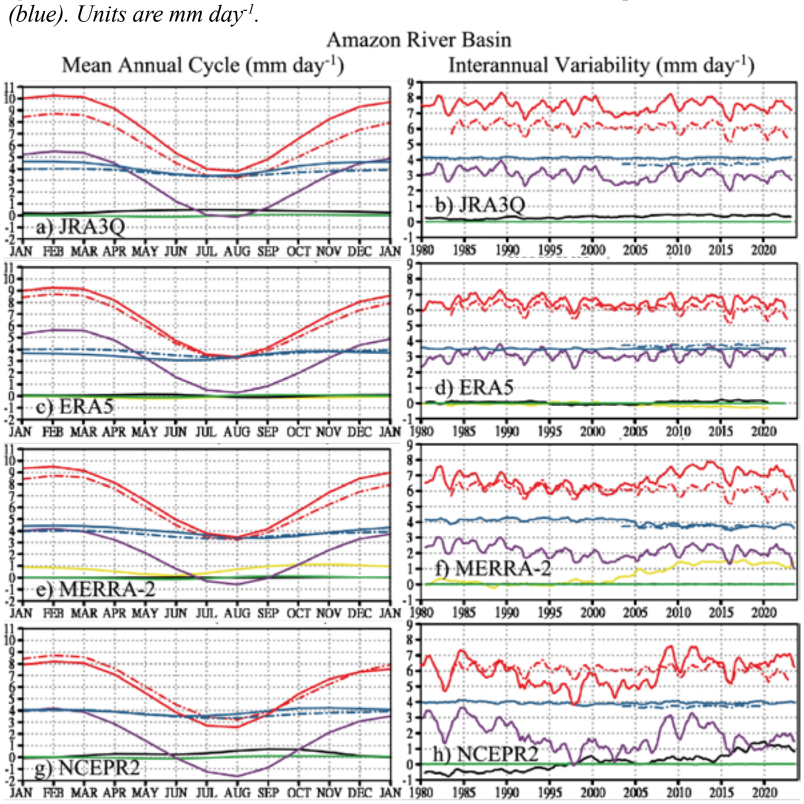


Figure 2*. Amazon Basin water cycle representation of the annual cycle (left) and interannual variability (12 month running means, right) for JRA3Q (a,b), ERA5 (c,d), MERRA-2 (e,f) and NCEPR2 (g,h). The dashed lines are GPCP v3.2 (red) and ERA5-Land evaporation (blue). Units are mm day*$^{-1}$*.*

cycle (2000–2020) in Figure 1 for MRB. These can show which season, time of the 40+ year record, where biases or change points occur. For example, the overestimate of the evaporation in NCEPR2 appears to be across the annual cycle, while the others increase evaporation during the warmer months. All the reanalyses seem to exhibit subtle phase shifts in the precipitation compared to GPCP. Even with these phase shifts, the moisture convergence annual cycles and interannual variations appear quite similar, likely related to the quality of the radiosonde record. There are apparent correlations in the interannual variations of precipitation with moisture convergence. However, JRA3Q precipitation and moisture convergence are elevated prior to the mid-1990s. This appears to be related to a corresponding increase in RSQ. While the residuals/increments seem relatively stable over the modern satellite period in the MRB, JRA3Q does seem to show a trend in the residual comparing the 1980s with the 2000s. A similar though smaller trend is apparent in the MERRA-2 analysis increments. The large negative NCEPR2 residual here seems related to the persistent high bias of evaporation.

The time variations in the Amazon differ among the reanalyses (Figure 2). Though JRA3Q and ERA5 moisture convergence is similar in the wet season, JRA precipitation and evaporation cycling is stronger. ERA5 water cycle variability appears quite stable through the 40+ year period, though there tends to be larger increments later in the period than earlier. MERRA-2 encounters a significant increase in the water vapor increments at ~2003, and while there are some variations in the moisture convergence, the precipitation bias in MERRA-2 looks to be related to the analysis increments. For NCEPR2, the mean annual cycle of the water budget terms seems well behaved, but the downward dip in moisture convergence and precipitation in the middle of the record appears to be an exaggerated version of that in MERRA-2 including a similarly significant trend in the residual term.

Monthly Anomaly Statistics

While the previous discussion begins to grapple with the differences among reanalyses, there is more to these long time series. Specifically, when we have reference observations, statistics can provide further insight. We have computed anomaly correlations and standard deviations from the monthly anomaly time series for 2000–2020 (starting in 2003 for GLEAM v3.6b evaporation), presented as Taylor diagrams (Figure 3; Taylor, 2001). These statistics generally demonstrate the ability of the reanalyses to replicate the temporal patterns of the reference anomalies by the closeness to the reference point. It should be noted that these statistics do not represent the spatial information. For MRB precipitation, the reanalyses show a strong comparison to the GPCP observations. NCEPR2

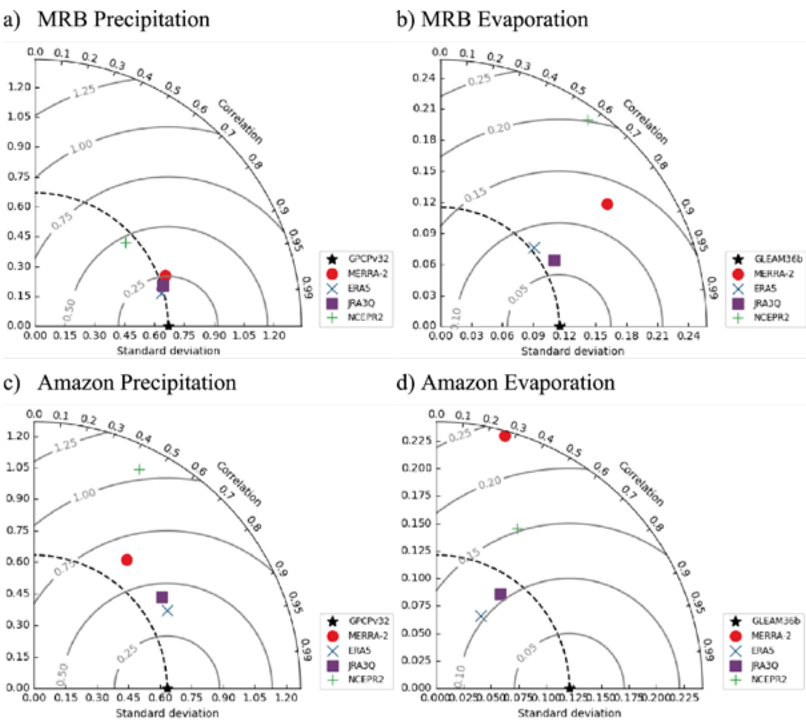


Figure 3. Taylor diagrams of the monthly time series comparisons to a) GCPC version 3.2 precipitation and b) GLEAM version 3.6b for land evaporation of the Mississippi River Basin (and c,d are the same respectively for the Amazon Basin). The time series for the standard deviation and correlation are monthly anomalies from the 2000–2020 mean annual cycle, such that this represents the pattern comparison of the time series. Root mean square difference is represented by the concentric contours from the reference point.

correlation misses some of the variations, but has comparable variance. This likely results from the control of precipitation by moisture convergence, and the assimilation of abundant observations. Evaporation is more model dependent, and we find a larger separation of the reanalyses, with the more recent reanalyses closer to the GLEAM observations. In the Amazon, as noted previously, there are some differences in the reanalyses' moisture convergence, and so, a large separation in the precipitation statistics in comparison with GPCP. However, it is an encouraging sign that the newer (and higher resolution) reanalyses are closer to the observed reference. The Amazon evaporation statistics yield an important result and benefit from delving deeper into the data. While it is not so clear in the range of Figure 2f, the MERRA-2 variations in evaporation are much larger and not synced with GLEAM 3.6b, which the time correlation emphasizes. The 2005 jump in evaporation is related to the observation-corrected precipitation used to force the MERRA-2 land surface and relates to a significant decrease in available rain gauges (Reichle et al., 2017). The shifts substantially reduce the evaporation anomaly correlation determined for Figure 3d (newer GMAO systems correlate better with both GLEAM and ERA5). Otherwise, we see the latest reanalyses closer to the observed reference.

Summary and Further Work

This initial review of only two major basins is intended to gauge the progress of reanalyses' regional quality and closure since Roads et al., 2002. Improvements generally hold, especially for ERA5 and JRA3Q, though biases and residuals can still play significant roles in the quality at the regional scales, and careful analysis can demonstrate errors. In the near future, we anticipate expanding this evaluation to consider the energy balance and more regions, especially those related to current GEWEX RHPs. In addition, larger-scale continental regions to compare with other water and energy closure optimizations should provide improved reference data (e.g., Rodell et al., 2015, and L'Ecuyer et al., 2015) than single observation data sets. While reanalyses typically produce the flux terms of water and energy, atmospheric transport and convergence are not always available, and as Roads et al., 2002 encountered with NCEPR2, are not easily computed from the available states' output files. Generally, regional studies are best done with users in and familiar with the regional climate, but these researchers may not have access to hourly state fields to compute fluxes and divergence. We encourage reanalysis developers to include the complete budgets from their systems, especially the analysis increments which allow quantifying how evolving observation system uncertainties interact with model physics biases as well as differing assimilation strategies (e.g., 3D vs. 4D-Var, incremental updating), as it is important to explicitly demonstrate the influence of the analysis on the regional balances.

Acknowledgments

This work was funded through the NASA Energy and Water Cycle Studies Program. MERRA-2 has been developed and funded through the NASA Modeling and Analysis Program.

ERA5 divergence fields were taken from an offline effort (Mayer et al., 2021a,b).

JRA3Q data was the 1.25 degree coarse resolution data: https://search.diasjp.net/en/dataset/JRA3Q.

NCEPR2 is available at: https://downloads.psl.noaa.gov/Datasets/ncep.reanalysis2/.

MERRA-2 precipitation and evaporation are available from GMAO, 2015a and the moisture convergence, analysis increment, and total column water are available from GMAO, 2015b.

GPCP v3.2 is available at Huffman et al., 2022. GLEAM 3.6b (Martens et al., 2017) is available at https://www.gleam.eu/.

References

Bosilovich, M.G., F.R. Robertson, L. Takacs, A. Molod, and D. Mocko, 2017. Atmospheric Water Balance and Variability in the MERRA-2 Reanalysis. *J. Climate*, 30, 1177–1196. https://doi.org/10.1175/JCLI-D-16-0338.1

Gelaro, R., and Coauthors, 2017. The Modern-Era Retrospective Analysis for Research and Applications, Version 2 (MERRA-2). *J. Climate*, 30, 5419–5454. https://doi.org/10.1175/JCLI-D-16-0758.1

Global Modeling and Assimilation Office (GMAO), 2015a. MERRA-2 tavgM_2d_flx_Nx: 2d,Monthly mean,Time-Averaged,Single-Level,Assimilation,Surface Flux Diagnostics V5.12.4, Greenbelt, MD, USA, Goddard Earth Sciences Data and Information Services Center (GES DISC), Accessed: January 22, 2024, 10.5067/0JRLVL8YV2Y4

Global Modeling and Assimilation Office (GMAO), 2015b. MERRA-2 tavgM_2d_int_Nx: 2d,Monthly mean,Time-Averaged,Single-Level,Assimilation,Vertically Integrated Diagnostics V5.12.4, Greenbelt, MD, USA, Goddard Earth Sciences Data and Information Services Center (GES DISC), Accessed: January 22, 2024, 10.5067/FQPTQ4OJ22TL

Hersbach, H., and Coauthors, 2020. The ERA5 global reanalysis. *Q J R Meteorol Soc*. 146, 1999–2049. https://doi.org/10.1002/qj.3803

Huffman, G.J., R.F. Adler, A. Behrangi, D.T. Bolvin, E.J. Nelkin, G. Gu, and M.R. Ehsani, 2023. The New Version 3.2 Global Precipitation Climatology Project (GPCP) Monthly and Daily Precipitation Products. *J. Climate*, 36, 7635–7655. https://doi.org/10.1175/JCLI-D-23-0123.1

Huffman, G.J., A. Behrangi, D.T. Bolvin, and E.J. Nelkin, 2022. GPCP Version 3.2 Satellite-Gauge (SG) Combined Precipitation Data Set. Edited by Huffman, G.J., A. Behrangi, D.T. Bolvin, E.J. Nelkin, Greenbelt, Maryland, USA, Goddard Earth Sciences Data and Information Services Center (GES DISC), Accessed: January 22, 2024, 10.5067/MEASURES/GPCP/DATA304

Kanamitsu, M., W. Ebisuzaki, J. Woollen, S. Yang, J.J. Hnilo, M. Fiorino, and G.L. Potter, 2002. NCEP–DOE AMIP-II Reanalysis (R-2). *Bull. Amer. Meteorol. Soc.*, 83, 1631–1644. https://doi.org/10.1175/BAMS-83-11-1631

Kosaka Y., and Coauthors, 2024. The JRA-3Q reanalysis. *J. Meteor. Soc. Japan*, 102, 49-109. https://doi.org/10.2151/jmsj.2024-004

L'Ecuyer, T., and co-authors, 2015. The Observed State of the Energy Budget in the Early 21st Century. *J. Climate*, 28, 8319–8346. doi: http://dx.doi.org/10.1175/JCLI-D-14-00556.1

Martens, B., D.G. Miralles, H. Lievens, R. van der Schalie, R.A.M. de Jeu, D. Fernández-Prieto, H.E. Beck, W.A. Dorigo, and N.E.C. Verhoest, 2017. GLEAM v3: satellite-based land evaporation and root-zone soil moisture. *Geosci. Model Dev.*, 10, 1903–1925. doi: 10.5194/gmd-10-1903-2017

Mayer, J., M. Mayer, and L. Haimberger, 2021a. Consistency and Homogeneity of Atmospheric Energy, Moisture, and Mass Budgets in ERA5. *J. Climate*, 34, 3955–3974. https://doi.org/10.1175/JCLI-D-20-0676.1

Mayer, J., M. Mayer, L. Haimberger, 2021b. Mass-consistent atmospheric energy and moisture budget monthly data from 1979 to present derived from ERA5 reanalysis. Copernicus Climate Change Service (C3S) Climate Data Store (CDS). doi: 10.24381/cds.c2451f6b (Accessed May 19, 2022)

Reichle, R.H., Q. Liu, R.D. Koster, C.S. Draper, S.P.P. Mahanama, and G.S. Partyka, 2017. Land surface precipitation in MERRA-2. *J. Climate*, 30, 1643–1664. doi:10.1175/JCLI-D-16-0570.1

Roads, J., M. Kanamitsu, and R. Stewart, 2002. CSE Water and Energy Budgets in the NCEP–DOE Reanalysis II. *J. Hydrometeor.*, 3, 227–248. https://doi.org/10.1175/1525-7541(2002)003<0227:CWAEBI>2.0.CO;2

Rodell, M., and Coauthors, 2015. The Observed State of the Water Cycle in the Early 21st Century. *J. Climate*, 28, 8289–8318. doi: http://dx.doi.org/10.1175/JCLI-D-14-00555.1

Stephens, G., J. Polcher, X. Zeng, P. Van Oevelen, G. Poveda, M. Bosilovich, M.H. Ahn, G. Balsamo, Q. Duan, G. Hegerl, and C. Jakob, 2023. The First 30 years of GEWEX. *Bull. Am. Meteorol. Soc.*, 104(1), pp.E126–E157

Taylor, K.E., 2001. Summarizing multiple aspects of model performance in a single diagram. *J. Geophys. Res.*, 106(D7), 7183–7192. doi:10.1029/2000JD900719

Trenberth, K.E., J.T. Fasullo, and J. Mackaro, 2011. Atmospheric Moisture Transports from Ocean to Land and Global Energy Flows in Reanalyses. *J. Climate*, 24, 4907–4924. https://doi.org/10.1175/2011JCLI4171.1

Back to the Drawing Board? Modeling Land Surface Fluxes and Their Coupling with the Atmosphere

Nathaniel Chaney, Anne Verhoef, Kirsten Findell, Gab Abramowitz, John Edwards, Nicholas Parazoo, Joseph Santanello, Volker Wulfmeyer, Yunyan Zhang, Yijian Zeng, Souhail Bousetta, Laura Condon, Hyungjun Kim, David Lawrence, Xianhong Meng, Vimal Mishra, Patricia Lawston-Parker, Joshua Roundy, Gert-Jan Steeneveld, and Asaminew Teshome

GLASS Panel Members

For 24 years now, the key objective of the GEWEX Global Land Atmosphere Systems Study (GLASS) Panel and its collaborators has been to improve understanding and modeling of land-atmosphere interactions and feedback (Van den Hurk et al., 2011; Stephens et al., 2023; Yin et al., 2023), including under conditions of climate change (Hsu and Dirmeyer, 2023). As part of the coupled land-atmosphere system, the vertical exchanges of water, energy, and carbon via land surface turbulent fluxes remain a key lynchpin that together with lateral fluxes of water enable the interactions of land with the wider Earth system. With that in mind, one of the key focuses of the GLASS Panel and the scientific community it represents remains to improve the representation and modeling of surface fluxes in land models, as this has direct implications for weather prediction, seasonal forecasts, drought and flood monitoring, and climate prediction, among others. One of the main motivations here is to reduce systematic errors in weather and climate models (Frassoni et al., 2023).

Over the past decade, the GLASS Protocol for the Analysis of Land Surface models (PALS) Land Surface Model Benchmarking Evaluation Project (PLUMBER) project, now in its second phase, has brought to light the underwhelming performance of contemporary land models in the modeling of turbulent surface fluxes when compared to data-driven approaches (Best et al., 2015; Abramowitz et al., 2024). These empirical approaches have provided a unique opportunity to benchmark our land models, to understand the level of predictive skill that can be achieved given the available land parameters and atmospheric driving data. As exemplified in Figure 1, there is ample room (and need) for growth and improvement in the modeling of surface turbulent fluxes in land models. This is especially true for sub-daily fluxes, which are arguably the most important given their critical role in the development of convection and soil-vegetation-atmosphere feedbacks, for example.

Given that one of the primary motivations behind the development of physically-based land models has been, and still is, to model surface turbulent fluxes, the GLASS Panel argues that it is time to go back to the drawing board to ensure that the modeling of these fluxes meets expectations (Abramowitz et al., 2024). To be more direct, the most important thing that land models are supposed to provide for coupled systems in the Earth system is the one thing in which they continue to underwhelm; this is wholly unacceptable and presents itself as an urgent challenge that should become a key focus of the community moving forward.

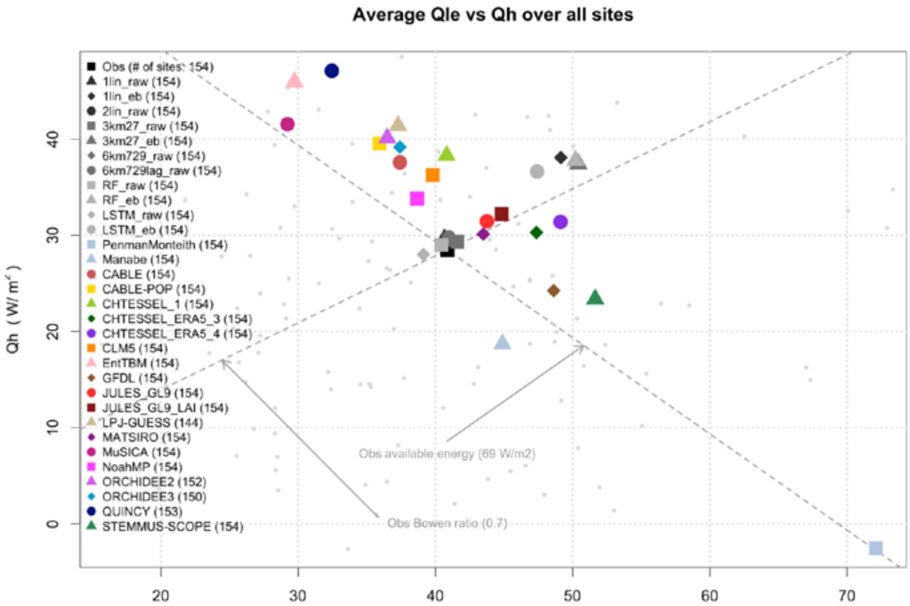


Figure 1. Average latent heat flux (Qle) versus average sensible heat flux (Qh) averaged over 154 eddy covariance sites over the globe. Dashed lines show observed constant values of average available energy (Qle+Qh) and average Bowen ratio (Qh/Qle) across the sites, using raw (as opposed to energy balance corrected) flux data. Light grey dots in the background represent individual site averages. Adapted from Abramowitz et al., 2024.

To determine how to move forward, it is important to first understand how we got here in the first place. One of the Achilles heels of physically-based land models is that they are still mostly a series of intertwined conceptual parameterizations (Fisher and Koven, 2020; Blyth et al., 2021), and they also suffer from a host of numerical issues (Clark et al., 2021). Uncertainties in process representation as well as errors in input data, of both the static (e.g., parameters) and dynamic (e.g., meteorological forcing) kind, are compounded, thus leading to limited added value when increasing complexity. We are effectively taking legacy parameterizations that have a series of hard-wired assumptions and then we are trying to either modify these schemes or bolt on others, when in reality, the path forward is most likely going back to the drawing board and leveraging contemporary data, process understanding, and new data analysis tools such as Machine Learning (ML) to construct the next generation of models.

As an example, let's consider Monin-Obukhov Similarity Theory (MOST). The community has been reluctant to move beyond this approach due to its inherent simplicity in being able to back out turbulent fluxes from mean gradients and (near-)surface properties; this makes the MOST approach ideal to calculate surface fluxes within Earth system models. However, its underlying assumptions of the absence of subsidence, independence from entrainment, quasi steady-state turbulent statistics and horizontal homogeneity of land surface over the footprint and of the mean flow statistics are known to be problematic in strongly stable or unstable boundary layers, complex orographic regimes, highly heterogeneous landscapes, and complex canopies (Stiperski and Calaf, 2023). These challenges will likely continue to be exacerbated as these models continue to move towards higher spatial and temporal resolutions. Figure 2 illustrates an example of the limitations of MOST when compared to observations and data-driven models.

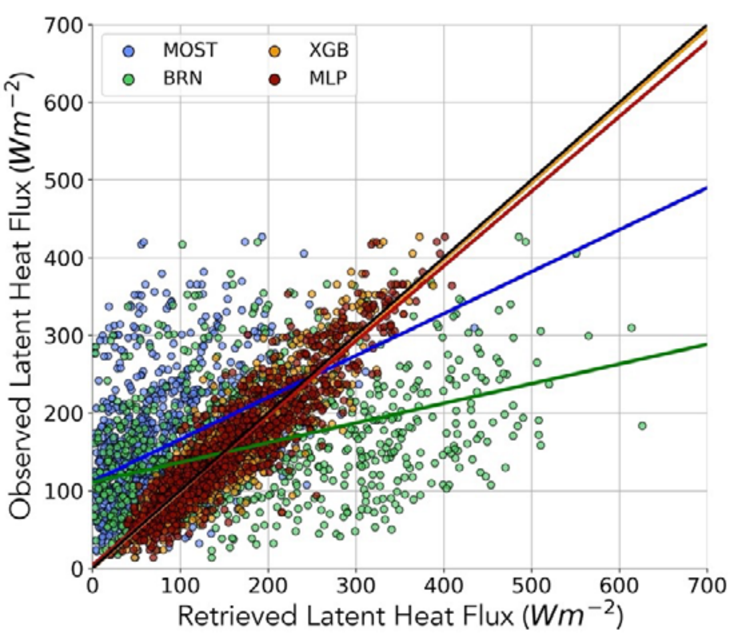


Figure 2. Comparison between observed and simulated latent heat flux at three flux towers from the Land-Atmosphere Feedback Experiment (LAFE) campaign at the Atmospheric Radiation Measurement (ARM) Southern Great Plains (SGP) site in Oklahoma in 2017. MOST (Monin-Obukhov Similarity Theory), BRN (Bulk Richardson Number), XGB (Extreme Gradient Boosting), MLP (Multilayer Perceptron). Adapted from Wulfmeyer et al., 2023.

Another example is how soil and vegetation, in particular their "structure" and processes, are portrayed in land models, particularly from a spatio-temporal point of view (Blankenship et al., 2018; Rahmati et al., 2023). This is important as the soil-vegetation system plays a fundamental role in the surface energy, water, and carbon balance (and in the flux exchanges of their component fluxes), including via its radiative properties (e.g., albedo), hydrological properties (e.g., vegetation interception capacity or soil infiltration capacity) and aerodynamic properties (roughness and displacement heights), that ultimately together determine the evaporative fraction, among others. For instance, vegetation parameters like leaf area index (LAI) and vegetation albedo are still often predefined and their seasonality kept constant in time; here the absence or inadequate implementation of interactions between soil and vegetation is a glaring deficiency. Additionally, crucial below-ground processes, such as coupled heat and water flow, remain unaccounted for, and soil parameters remain static despite the dynamic influence of the soil aggregate life cycle (e.g., via soil- and land-management activities) on soil structure and pore-size distribution, and ultimately on soil hydro-thermal properties (Weber et al., 2023). Therefore, a paradigm shift is imperative in the treatment of soil hydraulic and thermal theory within land models. Although progress has been made in the representation of vegetation dynamics and plant hydraulics, a more fundamental bottom-up revisiting of the soil-vegetation (hydraulic) system is necessary to properly connect all the components of the system (Vanderborght et al., 2023). This is also important when we want to assimilate satellite observables, which are often strongly dependent on plant turgor and leaf water content, and related variables such as leaf angle and color. This will ultimately allow us to construct a digital twin of the soil-plant system (Zeng and Su, 2024).

Similarly, the spatial representation in land models remains another key source of uncertainty. Spatial heterogeneity over the land surface can play a defining role; these heterogeneities include static heterogeneities such as land cover/type, soil types and textures, vegetation type; dynamic heterogeneities with different temporal and spatial scales such as those caused by soil moisture recharge by precipitation; and human activities such as deforestation and urban expansion, which often change surface albedo and surface roughness too. Although these processes and features have been historically assumed to be mostly spatially independent from one another in land models, in reality, they are often intricately connected. For example, soil moisture and soil thermal space-time patterns are strongly influenced by the topography, geology, soils, and vegetation. This in turn leads to spatial organization of surface fluxes, which in turn can trigger re-circulations between disparate landscape features and, interestingly, further break down MOST's planar homogeneous assumption (Simon et al., 2021; Tian et al., 2022).

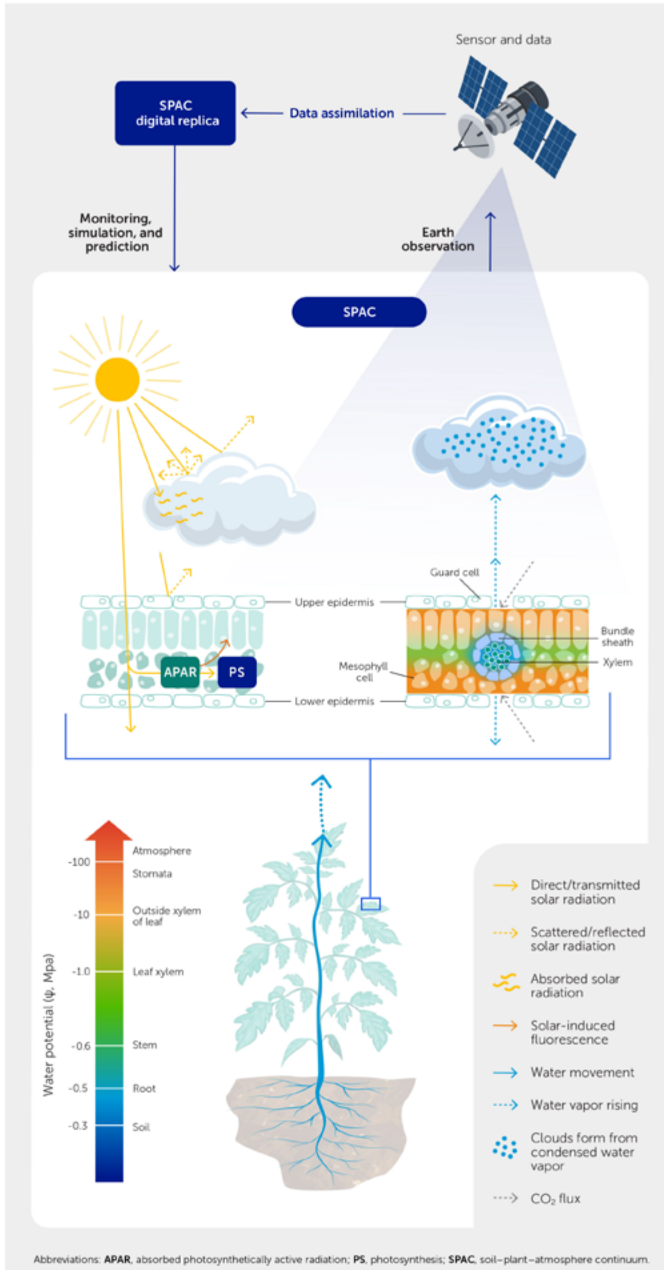


***Figure** 3. A digital twin of the soil-plant-atmosphere continuum (SPAC) augmented with Earth Observation (SPACEO). The SPACEO digital twin consists of three pillars: EO-collected data, the capability for assimilating such data (i.e., data assimilation), and a digital replica of the SPAC system. Adapted from Zeng and Su, 2024.*

We acknowledge that we have only scratched the surface of land model process deficiencies in this article. However, even if we identified all the challenges, the question remains how we move forward. One method is to take the more classical approach of building conceptual parameterizations from scratch that can leverage current and near-future process understanding and data availability and that are more tailor made for present-day applications (i.e., higher temporal and spatial resolutions). Land models with enhanced modularity and interoperability can be a fruitful way forward here (He et al., 2023). Another contemporary approach is to move towards Machine Learning with physics constraints (e.g., mass and energy conservation); indeed, ML approaches were explored in the PLUMBER-2 experiments and illustrate what is possible when all the data available are used to assemble cross-site self-consistent models (Abramowitz et al., 2024). Hybrid approaches that combine physics-based models with Machine Learning approaches are also a promising avenue to explore, especially in cases where temporal extrapolation is important (e.g., climate prediction) and data sparsity remains a weakness.

Finally, we would like to emphasize that benchmarking and evaluation systems need to be central to future redevelopment of surface flux parameterizations; if not, we risk falling into the same traps that have hindered the community. Following PLUMBER-2 and building on efforts such as the International Land Model Benchmarking project (ILAMB, Collier et al., 2018), we envision a portable evaluation system that can leverage surface flux observations and can be used by land modeling groups across the globe. Beyond surface observations, it will also be critical to leverage observations of the surface layer and the planetary boundary layer (wind, temperature, and moisture profiles) such as those emerging in the GEWEX Land-Atmosphere Feedback Observatory (GLAFO) network (Wulfmeyer et al., 2020). The new observation systems' synergy will provide data for studying entrainment, replacing MOST, and for assessing the surface flux linkages to the fully coupled (land-atmosphere) process chain. Furthermore, these evaluation systems need to consider both the temporal and spatial scale of the model performance. Narrowing down the temporal and spatial scales at which prediction breaks down will be instrumental in pinpointing what processes are working and which are not, and how this varies for different environments. As illustrated in Figure 3, effectively leveraging data from satellite remote sensing that are closely tied to the surface energy, water, and carbon balance (e.g., land surface temperature and solar induced fluorescence) will be a unique asset to accomplish this goal.

References

Abramowitz, G., A. Ukkola, S. Hobeichi, J. Cranko Page, M. Lipson, M. De Kauwe, S. Green, C. Brenner, J. Frame, G. Nearing, M. Clark, M. Best, P. Anthoni, G. Arduini, S. Boussetta, S. Caldararu, K. Cho, M. Cuntz, D. Fairbairn, C. Ferguson, H. Kim, Y. Kim, J. Knauer, D. Lawrence, X. Luo, S. Malyshev, T. Nitta, J. Ogee, K. Oleson, C. Ottlé, P. Peylin, P. de Rosnay, H. Rumbold, B. Su, N. Vuichard, A. Walker, X. Wang-Faivre, Y. Wang, and Y. Zeng, 2024. On the predictability of turbulent fluxes from land: PLUMBER2 MIP experimental description and preliminary results. *EGUsphere* [preprint], https://doi.org/10.5194/egusphere-2023-3084.

Best, M.J., G. Abramowitz, H.R. Johnson, A.J. Pitman, G. Balsamo, A. Boone, M. Cuntz, B. Decharme, P.A. Dirmeyer, J. Dong, M. Ek, Z. Guo, V. Haverd, B.J.J. van den Hurk, G.S. Nearing, B. Pak, C. Peters-Lidard, J.A. Santanello, Jr., L. Stevens, and N. Vuichard, 2015. The Plumbing of Land Surface Models: Benchmarking Model Performance. *J. Hydrometeorol.*, 16(3), 1425-1442. https://doi.org/10.1175/JHM-D-14-0158.1.

Blankinship, J.C., A.A. Berhe, S.E. Crow, et al., 2018. Improving understanding of soil organic matter dynamics by triangulating theories, measurements, and models. *Biogeochemistry* 140, 1–13. https://doi.org/10.1007/s10533-018-0478-2

Blyth, E.M., V.K. Arora, D.B. Clark, et al., 2021. Advances in Land Surface Modelling. *Curr Clim Change Rep* 7, 45–71. https://doi.org/10.1007/s40641-021-00171-5

Clark, M.P., R. Zolfaghari, K.R. Green., S. Trim, W.J.M. Knoben, A. Bennett, B. Nijssen, A. Ireson, and R.J. Spiteri, 2021. The numerical implementation of land models: Problem formulation and laugh tests. *J. Hydrometeorol.*, 22(6), 1627–1648. doi: 10.1175/JHM-D-20-0175.1

Collier, N., F.M. Hoffman, D.M. Lawrence, G. Keppel-Aleks, C.D. Koven, W.J. Riley, et al., 2018. The International Land Model Benchmarking (ILAMB) system: Design, theory, and implementation. *J. Adv. Model. Earth Syst.*, 10, 2731–2754. https://doi.org/10.1029/2018MS001354

Fisher, R.A., and C.D. Koven, 2020. Perspectives on the future of land surface models and the challenges of representing complex terrestrial systems. *J. Adv. Model. Earth Syst.*, 12, e2018MS001453. https://doi.org/10.1029/2018MS001453

Frassoni, A., and coauthors, 2023. Systematic Errors in Weather and Climate Models: Challenges and Opportunities in Complex Coupled Modeling Systems. *Bull. Amer. Meteorol. Soc.*, 104, E1687–E1693. https://doi.org/10.1175/BAMS-D-23-0102.1

He, C., P. Valayamkunnath, M. Barlage, F. Chen, D. Gochis, R. Cabell, T. Schneider, R. Rasmussen, G.-Y. Niu, Z.-L. Yang, D. Niyogi, and M. Ek, 2023. Modernizing the open-source community Noah with multi-parameterization options (Noah-MP) land surface model (version 5.0) with enhanced modularity, interoperability, and applicability. *Geosci. Model Dev.*, 16, 5131–5151. https://doi.org/10.5194/gmd-16-5131-2023.

Hsu, H., and P.A. Dirmeyer, 2023. Soil moisture-evaporation coupling shifts into new gears under increasing CO_2. *Nature Comm.*, 14, 1162. doi: 10.1038/s41467-023-36794-5

Rahmati, M., D. Or, W. Amelung, et al., 2023. Soil is a living archive of the Earth system. *Nat Rev Earth Environ* 4, 421–423. https://doi.org/10.1038/s43017-023-00454-5

Simon, J.S., A.D. Bragg, P.A. Dirmeyer, and N.W. Chaney, 2021. Semi-coupling of a field-scale resolving land-surface model and WRF-LES to investigate the influence of land-surface heterogeneity on cloud development. *J. Adv. Model. Earth Syst.*, 13(10), e2021MS002602

Stephens, G., and Coauthors, 2023. The First 30 Years of GEWEX. *Bull. Amer. Meteorol. Soc.*, 104, E126–E157. https://doi.org/10.1175/BAMS-D-22-0061.1

Stiperski, I., and M. Calaf, 2023. Generalizing Monin-Obukhov similarity theory (1954) for complex atmospheric turbulence. *Phys. Rev. Lett.*, 130(12), 124001

Tian, J., Y. Zhang, S.A. Klein, R. Öktem, and L. Wang, 2022. How does land cover and its heterogeneity length scales affect the formation of summertime shallow cumulus clouds in observations from the US Southern Great Plains? *Geophys. Res. Lett.*, 49(7), e2021GL097070

Van den Hurk, B., M. Best, P. Dirmeyer, A. Pitman, J. Polcher, and J. Santanello, 2011. Acceleration of land surface model development over a decade of GLASS. *Bull. Amer. Meteorol. Soc.*, 92, 1593–1600. https://doi.org/10.1175/BAMS-D-11-00007.1

Vanderborght, J., D. Leitner, A. Schnepf, V. Couvreur, H. Vereecken, and M. Javaux, 2023. Combining root and soil hydraulics in macroscopic representations of root water uptake. *Vadose Zone J.*, 00, 1–22. https://doi.org/10.1002/vzj2.20273

Yin, Z., K.L. Findell, P. Dirmeyer, E. Shevliakova, S. Malyshev, K. Ghannam, N. Raoult, and Z. Tan, 2023. Daytime-only mean data enhance understanding of land–atmosphere coupling. *Hydrol. Earth Syst. Sci.*, 27, 861–872. https://doi.org/10.5194/hess-27-861-2023

Weber, T.K.D., L. Weihermüller, A. Nemes, M. Bechtold, A. Degré, E. Diamantopoulos, S. Fatichi, V. Filipović, S. Gupta, T.L. Hohenbrink, D.R. Hirmas, C. Jackisch, Q. de Jong van Lier, J. Koestel, P. Lehmann, T.R. Marthews, B. Minasny, H. Pagel, M. van der Ploeg, S.F. Svane, B. Szabó, H. Vereecken, A. Verhoef, M Young, Y. Zeng, Y. Zhang, and S. Bonetti, 2023. Hydro-pedotransfer functions: A roadmap for future development. *EGUsphere* [preprint], https://doi.org/10.5194/egusphere-2023-1860.

Wulfmeyer, V., F. Späth, A. Behrendt, L. Jach, K. Warrach-Sagi, M. Ek, D.D. Turner, C. Senff, C.R. Ferguson, J. Santanello, T.R. Lee, M. Buban, and A. Verhoef, 2020. The GEWEX Land-Atmosphere Feedback Observatory (GLAFO). *GEWEX Quarterly* 1, www.gewex.org/gewex-content/files_mf/1583952472Feb2020.pdf

Wulfmeyer, V., J.M.V. Pineda, S. Otte, M. Karlbauer, M.V. Butz, T.R. Lee, and V. Rajtschan, 2023. Estimation of the surface fluxes for heat and momentum in unstable conditions with machine learning and similarity approaches for the LAFE data set. *Bound.-Lay. Meteorol.*, 186(2), 337–371.

Zeng, Y., and Z. Su, 2024. Digital twin approach for the soil-plant-atmosphere continuum: Think big, model small. *Front. Sci.* 2, ISSN=2813-633, DOI=10.3389/fsci.2024.1376950

Introduction to the Earth Observation Satellite Program of Korea

Myoung-Hwan Ahn[1] and Sun-Gu Lee[2]

[1]Climate and Energy Systems Engineering, Ewha Womans University, Seoul, Korea; [2]Satellite Application Division, Korea Aerospace Research Institute, Daejeon, Korea

Introduction

The history of South Korea's satellite program began on 11 August 1992, with the launch of the first Korean Institute of Technology Satellite (KITSAT, Our Star) from the Guiana Space Centre in French Guiana, South America. The satellite, developed by the Satellite Technology Research Center at the Korea Advanced Institute of Science and Technology with technology transferred from the University of Surrey in the UK, marked South Korea's entry into the league of countries possessing artificial satellites. Following this, in September 1993, KITSAT-2, developed with domestic technology, was launched. In 1996, the nation formally adopted a mid-to-long-term basic plan for space development, propelling the development of practical satellites. Presently, the plan has evolved, establishing a Space Development Promotion Plan every five years at the governmental level. The most recent plan, established in 2023, covers areas on launch vehicles, satellites, and utilizations.

Among these programs, the Earth observation satellite segment aims to expand satellite utilization services by providing customized satellite information focused on user needs in areas such as weather and climate monitoring, oceans, the environment, agriculture and forestry, disaster management, communications navigation, and land management. It also seeks to establish a government-wide satellite information utilization support system. To achieve this, the program is advancing large-scale projects like geostationary satellite programs, low Earth orbit satellite programs, and microsatellite programs. Additionally, a project is underway to construct the Korean Positioning Satellite (KPS) system, comprising eight geostationary satellites, and the potential use of geophysical variables obtained from this system is being explored. This review introduces programs related to observation satellites.

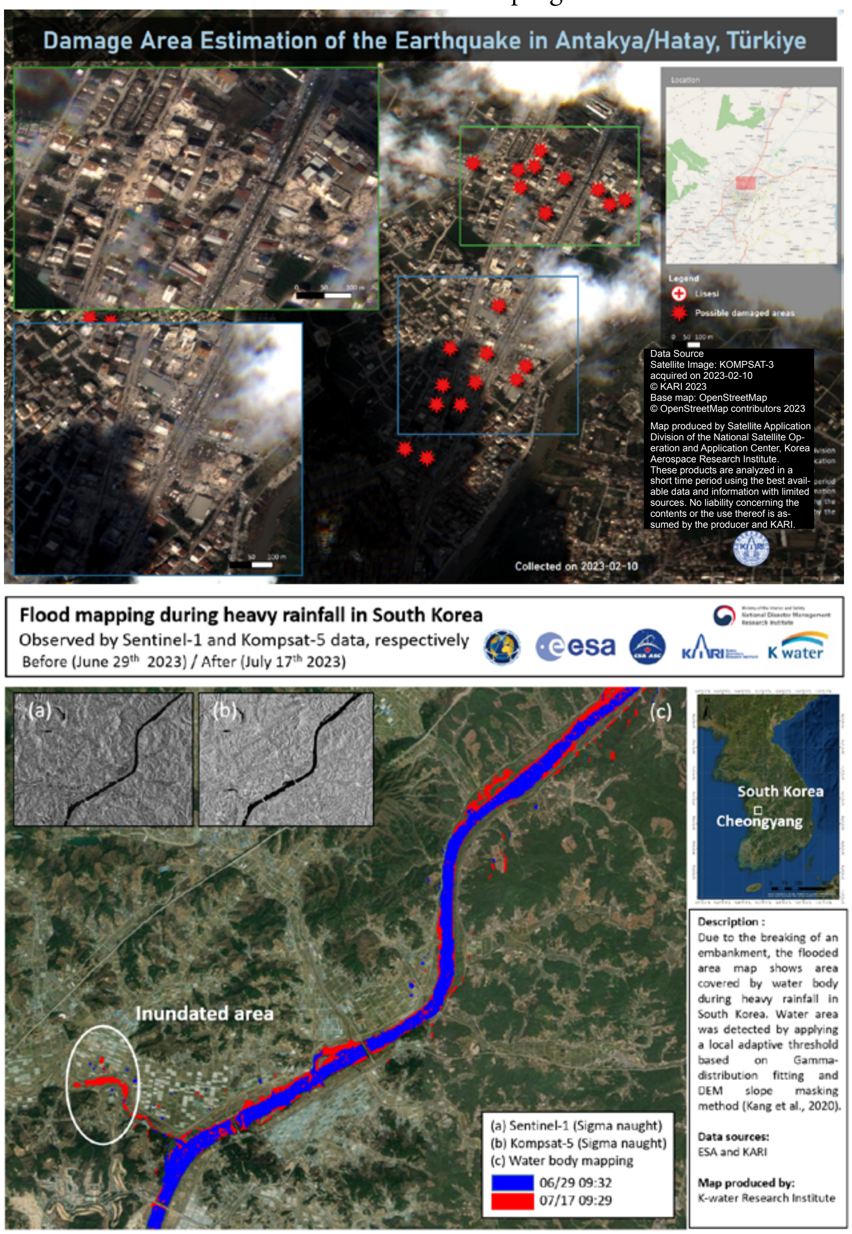


Figure 1. Damage area estimation of the earthquake in Turkey (top), flood mapping during heavy rainfall in South Korea (bottom) through International Charter (https://disastercharter.org)

KOrean Multi-purpose Practical SATellite (KOMPSAT) Program

The KOMPSAT program operates to secure ultra-high-resolution images (visible, infrared, microwave spectrum) mainly demanded for public needs (precision observation, disaster response, national security, etc.). To date, five KOMPSAT satellites have been launched, with three currently operational. The first satellite, dubbed as Arirang 1, was developed for three main purposes: mapping the Korean peninsula, ocean observation, and scientific experiments. It was successfully launched in December 1999 with a high-resolution panchromatic electro-optical camera with a spatial resolution of 6.6m, a multispectral ocean observation camera with a spatial resolution of 1km, a high-energy particle detector, and an ionospheric measurement sensor. The second satellite, a domestically-developed Earth observation satellite launched in July 2006, was designed for large-scale disaster monitoring and response, precision numerical mapping domestically and abroad, monitoring ocean pollution and red tides, agricultural disaster monitoring, and natural resource exploration, equipped with a 1m-class multispectral optical satellite. The third satellite,

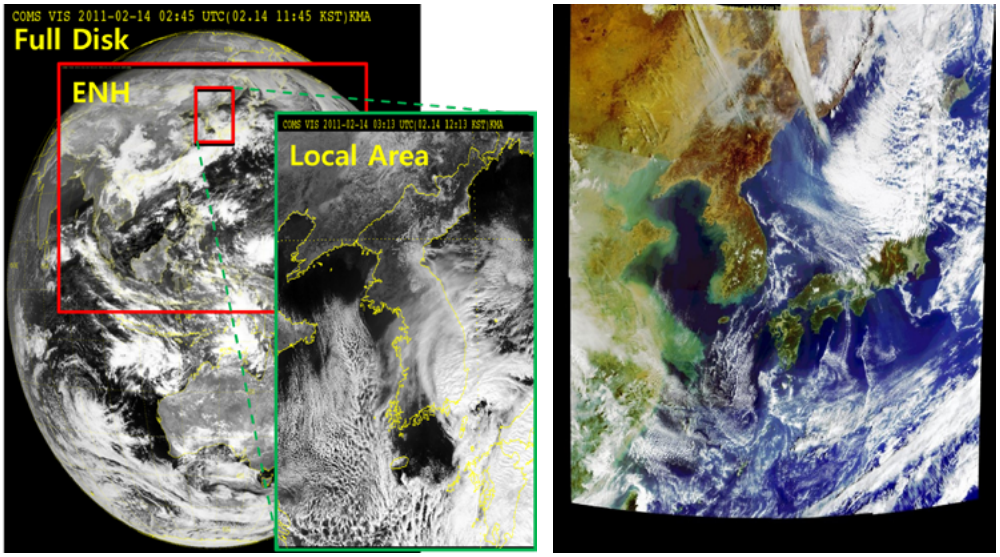


***Figure 2**. Example of images from GK-2A/AMI (left) and GK-2B/GOCI-2 (center)*

launched in May 2012, featured a 0.7m-class electro-optical camera, marking its significance as the country's first sub-meter-class optical satellite. Based on the design of the third, the 3A satellite launched in March 2015 carries the Advanced Earth Imaging Sensor System-A (AEISS-A), enabling the highest resolution optical imaging to date at 0.5m-class and making South Korea the second country after the USA to provide images under 50cm. It also has significance as the first publicly-disclosed Earth observation satellite equipped with a mid-infrared sensor, capable of detecting terrestrial heat regardless of night or weather conditions to observe fires, volcanic activity, and urban heat island effects.

Thus, the multi-purpose practical satellites, encompassing optical and imaging radar satellites and infrared observation capabilities, are operated complementarily as a series of low-Earth orbit Earth observation satellites, fulfilling the national demand for satellite information. Currently, the development of the 6th satellite, enhancing imaging radar performance, and the 7th and 7A satellites, equipped with precision optical and infrared sensors, is underway. The plan is to launch optical and infrared sensor-equipped 7th, 7A, 7B, imaging radar sensor-equipped 8th, and optical and infrared observation 9th satellites sequentially by 2028 for continuous mission performance. Through the International Charter, a global cooperation program involving 17 space agencies worldwide, multi-purpose practical satellite images are provided during significant disasters like the Quirguistão earthquake, floods in the Korean peninsula, and bushfires in Australia (Figure 1).

Other Low Earth Orbit Programs

The Compact Advanced Satellite 500 program encourages private sector-led development and utilization of satellites using a standard platform (500kg class), capable of accommodating various domestic payloads such as optical cameras, image radars, microwave radiometers, and hyperspectral imagers. The platform has been developed by the Korea Aerospace Research Institute (KARI) and the satellite system as well as payload technology are transferred to the private sector for the satellites listed below. This approach significantly reduces the development time and cost of satellites. The first and second satellites are aimed at land management and spatial information utilization, with the first already launched and operational in 2021, and the second completed and awaiting launch. The third satellite focuses on science and technology, the fourth on agriculture and forestry, and the fifth on water resources, all currently under development. Additionally, to meet requirements such as rapid disaster response, development is ongoing for a cluster of small satellites (100kg class) and related utilization systems, planning for a test unit launch in 2024, followed by launches of five units in 2026 and another five in 2027, aiming for a total of 11 units operating in a cluster.

Geostationary Satellite (GEO-KOPMSAT; GK) Program

Geostationary satellites, orbiting about 36,000km above the equator, are predominantly used for Earth observation and telecommunications relay. South Korea's geostationary satellite program includes the Cheollian observation satellite series and the newly proposed KPS program.

The Cheollian series is a geostationary satellite program responding to the continuous operational demands (weather, ocean/environment, telecommunications, etc.) of both public and private sectors. The first satellite, launched in June 2010, was designed for communications, ocean, and weather missions. The second satellite, for enhancing weather mission capabilities and succeeding the tasks of GK-1, is comprised of twin satellites for weather and space weather observation (GK-2A) and for ocean and environmental observation (GK-2B) (Table 1, Figure 2). GK-2A was successfully launched on December 5, 2018, and is currently operational, providing real-time data (Chung et al., 2020). Its weather observation capabilities have significantly improved in terms of resolution, observation cycle, and the number of observation channels, enhancing weather forecasting accuracy and the ability to monitor and predict meteorological changes in Korea and the Asia region. GK-2B, launched on 18 February 2020 for environmental and ocean observation, has also seen a significant improvement in resolution over GK-1, with its new environmental payload, the Geostationary Environment Monitoring Spectrometer (GEMS), monitoring transboundary air pollutants like aerosol and trace gases around the Korean Peninsula multiple times a day (Kim et al., 2020).

For further detailed information and data access on GK-2A's weather data, visit the Meteorological Satellite Center website (*https://nmsc.kma.go.kr/enhome/html/main/main.do*). For envi-

Satellite Sensor	GK-2A (Oct 2018)	GK-2B (Feb 2020)	
	AMI	GEMS	GOCI-2
Purpose	Atmospheric monitoring & retrievals	Retrieval of trace gases & aerosol properties	Ocean monitoring & retrievals
Spectral region	0.47-13.3 μm (VNIR-IR)	300-500 nm (UV-VIS, FWHM < 0.6 nm)	380-900 nm (UV-VNIR)
Spectral Channel	16 (3 VIS, 3 NIR & 10 IR)	Hyperspectral spectrum (Δ = 0.2 nm)	13 (12 VNIR & 1 wide)
Spectral resolution	1 km (VIS), 2 km (IR)	3.5 × 8 km^2	0.25 km
Observation area	Full disk (10 min.) Enhanced NH (10 min) Local area (2 min)	5°S-45°N, 75-145°E (1 hour)	25-50°N, 110-150°E (1 hour)

Table 1*. Specifications of Geo-Kompsat-2 satellites for weather, ocean, and environment applications (AMI: Advanced Meteorological Imager; GEMS: Geostationary Environmental Monitoring Spectrometer; GOCI: Geostationary Ocean Color Imager)*

ronmental payload data from GK-2B, the National Environmental Satellite Center provides details at its website (*https://nesc.nier.go.kr/en/html/index.do*), and ocean payload data can be found at the National Ocean Satellite Center's website (*https://nosc.go.kr/eng/main.do*). These satellites continuously support South Korea's ability to independently provide accurate weather services, ocean observation, and environmental monitoring, establishing a foundation for the next-generation satellite communication systems.

Summary

The Earth observing satellite program of Korea, mostly based on the national plan, is a comprehensive initiative aimed at developing and deploying a wide range of satellites for various applications, enhancing the country's capabilities in space observation and utilization. Through continuous development and cooperation with international space agencies, South Korea aims to expand its satellite technology and applications, providing critical data for disaster response, environmental monitoring, and more. With continuous growth and openness of the data, GEWEX activities could benefit in the areas of atmospheric processes and climate change (weather, ocean, and environmental satellites such as GK programs), water cycles and energy fluxes (ocean, land surface, and environmental satellites), water and energy extremes (disaster monitoring, land surface observation, weather and environmental satellites), as well as land-atmosphere interactions and water cycle dynamics.

References

Chung, S.R., M.H. Ahn, K.S. Han, et al., 2020. Meteorological Products of Geo-KOMPSAT 2A (GK2A) Satellite. *Asia-Pacific J Atmos Sci*, 56. *https://doi.org/10.1007/s13143-020-00199-x*

Kim, J., U.K. Jeong, M.H. Ahn, et al., 2020. New Era of Air Quality Monitoring from Space: Geostationary Environment Monitoring Spectrometer (GEMS). *Bull. American Meteorol. Soc.*, 101, pp. E1-E22. *https://doi.org/10.1175/BAMS-D-18-0013.1*

Indian Satellite Missions and Data Products Relevant to GEWEX Decadal (2023–2032) Goals

Atul Kumar Varma
Former Group Director, Atmospheric and Oceanic Sciences Group at the Space Applications Centre, Indian Space Research Organisation (ISRO), Ahmedabad, India

South Asia is witnessing the effects of climate change in terms of rising events of temperature extremes, heat waves, intense precipitation, agricultural and ecological droughts, etc., which in turn cause cascading adverse effects on the availability of potable water and agricultural, livestock, and aquaculture productivity. The effects of climate change on some ecosystems, which include the impacts of hydrological changes resulting from the retreat of glaciers and changes in the mountain and Arctic ecosystems driven by permafrost thaw, are approaching irreversible (*https://www.ipcc.ch/assessment-report/ar6/*). In view of the changing climate and associated impacts on Earth's water cycle and the relationships among Earth's energy, water, and carbon cycles, GEWEX formulated a decadal plan (the GEWEX Science Plan 2023–2032, *https://gewex.org/gewex-content/uploads/2022/11/GEWEX-science-plan-v8.pdf*) to address these issues.

In order to contain global warming, at the 26th United Nations Climate Change Conference (COP26) held in Glasgow, Scotland, in 2021, India committed to achieving net zero emissions by the year 2070. Containing climate change requires continuous monitoring and model simulations and projections. Therefore, with these objectives, India planned a number of satellite missions, and many of them address the objectives of the GEWEX Science Plan.

INSAT-3DS

It is the third in the geostationary Indian National Satellite System (INSAT)-3D series of meteorological satellites launched on 17 February 2024. Presently, three of the INSAT-3D series of satellites, INSAT-3D, -3DR, and -3DS, are in orbit. These satellites carry two identical meteorological payloads: a six-channel imager operating at visible, short infrared, mid-infrared, water vapor absorption, and thermal infrared bands, and a 19-channel sounder operating at visible (1 band), shortwave infrared (6 bands), midwave infrared (5 bands), and longwave infrared (7 bands) bands. The operational products from INSAT-3D satellites include precipitation, outgoing longwave radiation, water vapor, sea surface temperature, land surface temperature, layer precipitable water, total precipitable water, atmospheric thermodynamic indices, etc. (Figure 1).

EOS-06/OCEANSAT-3

Oceansat-3 launched on 26 November 2022 in a sun-synchronous orbit, and carries a Ku-band radar scatterometer, a 13-narrow-band Ocean Color Monitor operating in visible and near infrared bands, a 2-band Sea Surface Temperature Monitor (SSTM), and an Advanced Research and Global Observation Satellite (ARGOS) data receiver/transmitter. All onboard

INSAT-3DS : Operational Products

Imager

S. No.	Geophysical Parameter	Code
1	Clear Sky Brightness Temperature	CSBT
2	Cloud Mask	CMK
3	Hydro Estimator	HEM
4	Improved IMSRA	IMC
5	Outgoing Longwave Radiation	OLR
6	Sea Surface Temperature	(NLSST/1DVAR)
7	Cloud Properties	CTP/CTT
8	Upper Tropospheric Humidity	UTH
9	Land Surface Temperature	LST
10	Total Precipitable Water	TPW
11	Fog	FOG
12	MIR Reflectance	REF
13	Snow	SNW
14	Insolation	INS
15	Land Surface Albedo	LSA
16	Net Effective Radiation	NER
17	Atmospheric Correction	TOA/BOA

S. No.	Geophysical Parameter	Code
18	Cloud Microphysics	CMP
19	Smoke	SMK
20	Forest Fire	FIR
21	Atmospheric Motion Vectors	IRW, WVW, MRW, VSW
22	Wind Derived Products (WDP)	WDP
23	Merged Wind Products	IRW_MERGED WVW_MERGED
24	High Resolution Winds	VSW_HR
25	Full Disc Winds	IRW_FD, WVW_FD
26	GOES Precipitation Index	GPI
27	Aerosol Optical Depth	AOD
28	Potential EvapoTranspiration	PET_DLY
29	Short Wave Radiation Over Ocean	SWR
30	5 day composite winds	5DCW
31	Actual EvapoTranspiration	AET
32	Land Surface Albedo (Daily/15-Day Composite)	LSA

Sounder

L1B Product

1. Clear Sky Brightness Temperature (CSBT)

Operational Geophysical Profiles

2. Temperature Profiles
3. WV Profiles
4. Surface Skin Temperature
5. Total Ozone

Derived products

6. Geo Potential Height (at 40 pressure levels)
7. Total Precipitable Water
8. Layer-1 (1000-900 hPa) Precipitable Water
9. Layer-2 (900-700 hPa) Precipitable Water
10. Layer-3 (700-300 hPa) Precipitable Water
11. Lifted Index
12. Wind Index
13. Dry Microburst Index
14. Maximum Vertical Theta-e

Cloud Properties

15. Cloud Top Temperature
16. Cloud Top Pressure
17. Cloud effective Emissivity

Figure 1*. Figure shows operational products from INSAT-3D/3DR/3DS satellites (disseminated from* https://mosdac.gov.in/*)*

instruments, except SSTM, are currently operational. The scatterometer provides global wind vectors and sea ice extent at 12.5km resolution. Scatterometer winds are operationally assimilated in the Numerical Weather Prediction models, and to force ocean wave and circulation models for simulating sea state.

RISAT-1A

The Radar Imaging Satellite (RISAT)-1A/Earth Observation Satellite-04 (EOS-04) satellite launched on 14 February 2022 carries a C-band synthetic aperture radar. In addition to providing very high-resolution imaging (3–50 meters), for the interest of the GEWEX community, RISAT-1A also provides mapping and characteristics of land and sea ice, glacial lakes, water bodies, soil moisture, flood inundation, flood plain zonation, river morphology, early warning of glacial lake outbursts, etc.

Forthcoming Satellite Missions

- A joint National Aeronautics and Space Administration (NASA)-ISRO Synthetic Aperture Radar (NISAR) satellite with an L and S-band Synthetic Aperture Radar (SAR) is expected to be launched later in 2024. NISAR will provide unique observations at multiple angles, polarizations, and interferometric measurements (InSAR) from the repeat passes.
- Ensuring continuity of the C-band SAR measurements, RISAT-1B is expected with the launch of a new satellite later in 2024.
- Continuity of the Oceansat-3 measurements is expected with the launch of a similar Oceansat-3A satellite later in 2025.
- A joint ISRO and Centre national d'études spatiales (CNES) Thermal infraRed Imaging Satellite for very High-resolution Natural resources Assessment (TRISHNA) mission is expected to be launched by 2026. This will provide thermal infrared measurements at 57m resolution over land. It is aimed to provide various crop parameters including evapotranspiration, soil wetness, crop water requirement, and snow/cryosphere parameters and processes.
- India has proposed a G20-SAT on a collaborative basis among G20 nations to enable space-based observations of various variables that affect environment and climate change. This satellite may be realized in the next 2–3 years.

Data Products, Services, and Their Dissemination

Satellite data products and services are provided through the Meteorological and Oceanographic Satellite Data Archival Centre (MOSDAC, *https://mosdac.gov.in/*), Visualisation of Earth Observation Data and Archival System (VEDAS, *https://vedas.sac.gov.in/*), and BHOONIDHI (*https://bhoonidhi.nrsc.gov.in/*) data portals. All the satellite data products and value-added products and services (e.g., weather forecast, nowcast, sea state forecast, etc.) are available from these data portals. There are also many special data sets of interest to the GEWEX community available through these portals. One example is an ISRO-Japan Aerospace Exploration Agency (JAXA) jointly-developed precipitation product for the Indian subcontinent, referred as the GSMaP_ISRO product, which is disseminated from the MOSDAC portal (*https://mosdac.gov.in/gsmap-isro-rain*). Other products, such as atmospheric integrated water vapor from ground-based global navigation satellite system (GNSS) receivers, river discharge, and water level of inland water bodies from satellite altimetry are provided through the MOSDAC portal. Other services of interest to the GEWEX community, such as short-range forecasts of heavy rain, lightning, monsoons and cyclones; image/statistical model-based nowcasts of cloudburst and heavy rain; and near-real time observations of heavy rain, fog and atmospheric optical depth, soil wetness index, and soil moisture are disseminated through MOSDAC. The VEDAS portal hosts and facilitates data dissemination for various themes such as agriculture, forestry, desertification, wetland, snow and glacier, coastal zone studies, marine ecosystem, polar science, and hydrology.

A Constellation of Satellites with Ka-band Radars and Microwave Sounders for an Unprecedented Look at Earth's Atmosphere

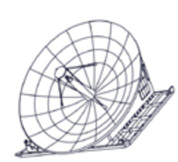
Ethan Nelson, Natasha McGrady, and Stelios Flampouris
Tomorrow.io, Boston, MA, USA

Advancing weather and climate prediction faces significant challenges, including a lack of rapidly refreshing global observations of the vertical structure of precipitation. The National Academies 2018 Decadal Survey recognized that the increased frequency and resolution of such precipitation observations are paramount for better understanding and modeling global energy fluxes and water cycles. Tomorrow.io's constellation of 28 satellites, equipped with a mix of Ka-band radars and microwave sounders, will begin to close this observation gap within the next three years.

In early 2023, two separate pathfinder satellites (see Figure 1) were launched, Tomorrow-R1 and Tomorrow-R2, equipped with a fixed-pointing Ka-band radar on the SpaceX Transporter-7 and -8 missions. These satellites utilize an 85kg Evolved Expendable Launch Vehicle (EELV) Secondary Payload Adapter (ESPA)-class bus, making them much larger than a cubesat, but smaller than most spaceborne cloud or precipitation radars deployed to date like GPM DPR. The radar instruments provide a sub-5km ground footprint, 250m vertical resolution, and high measurement sensitivity near 10dBZ; the antenna has the ability to alter pointing geometry about each axis. With the pathfinders, the space readiness of our software-defined radar—a fully adaptive and pulse-to-pulse reconfigurable digital intermediate frequency transceiver—has been demonstrated while also increasing the number of precipitation-sensing instruments deployed in space.

Parameter	Value
Transmit frequency	35.5-36 GHz
Instantaneous bandwidth	500 MHz
Transmit power*	16 W
Transmitter duty cycle	30%
Noise figure*	8 dB
Antenna diameter	1.2 m
Antenna gain	50.3 dB
Antenna beam width (FWHM)	0.51°
Antenna max side lobe level	-25 dB
Orbit altitude	500 km
Horizontal footprint (at nadir)	4.5 km
Instrument duty cycle (orbit avg)	40%

*Referenced to the antenna interface port



Spacecraft bus:

- 85 kg bus based on Astro Digital's Corvus-XL unit
- High-speed Ka-band downlink for payload data
- UHF and S-band uplink
- ~300 W solar panel power generation

***Figure 1**. Specifications of the Pathfinder satellite and radar instrument*

To maximize observational opportunities on the pathfinder missions, a complex radar tasking logic tree for prioritization of science data collection has been developed. This system points the antenna toward high-value precipitating targets such as tropical cyclones and frontal systems to maximize the payload collections while minimizing the power expended. The pathfinders are nearing completion of initial instrument testing and calibration, but they have already made numerous precipitating event radar collections, ocean scattering estimates, and radiometer mode observations.

The core component of the precipitation algorithm is a density regression neural network trained on dual-frequency Ku-/Ka-band radar (DPR) and microwave imager retrievals from the Global Precipitation Measurement (GPM) mission core observatory satellite (Olsen et al., 2022; Pfreundschuh et al., 2022). Supplemented with an attenuation estimate (surface reference technique) as well as collocated global model data, it leverages the information from the Ka-band observations in the trained neural network to derive both surface variables and full profiles of hydrometeor information. After the neural network, an optimal estimation algorithm uses a forward model simulator to iterate the neural network output and physically constrain the ultimate solution.

The full offering of products includes: level 1C data (1C-GEOPROF) with vertical profiles of geolocated radar reflectivity and surface normalized radar cross sections; auxiliary data (AUX) with global model and reanalysis data collocated and subsampled to match the radar profiles; and level 2A data (2A-PRECIP), which contains both the neural network and optimal estimation output with profiles of ice and water content, surface precipitation rate and regime, profiles of hydrometeor diameter, and confidence intervals for each variable (with an example provided in Figure 2).

Our next generation of satellite radars, slated for initial launch in late 2025, will also implement a novel electronically-scanning antenna that can steer the radar beam in the satellite's cross-track plane–similar to GPM DPR payloads but with drastically reduced system size, weight, and power. This will provide precipitation mapping observations between -20 and +20 degrees off-nadir, which from the planned orbital altitude of 550km, results in a 400km swath, or about 60% greater than DPR. The increased swath width and satellite count relative to the single GPM core observatory platform will greatly increase the spatiotemporal coverage of global precipitation by radar, providing high resolution observations of three-dimensional storm structure with an elevated refresh rate.

To maximize cost efficiency while also providing broader environmental regime context about precipitation, a constellation of microwave sounders is also being developed, which are an evolution of the Time-Resolved Observations of Precipitation structure and storm Intensity with a Constellation of Smallsats (TROPICS) cubesat sounder. Specifically, the sounders will capture microwave radiance over 12 spectral bands, including temperature and water vapor channels, with a 2200km wide swath and 15km resolution at nadir. The first pair of sounders are planned for launch in the second half of 2024.

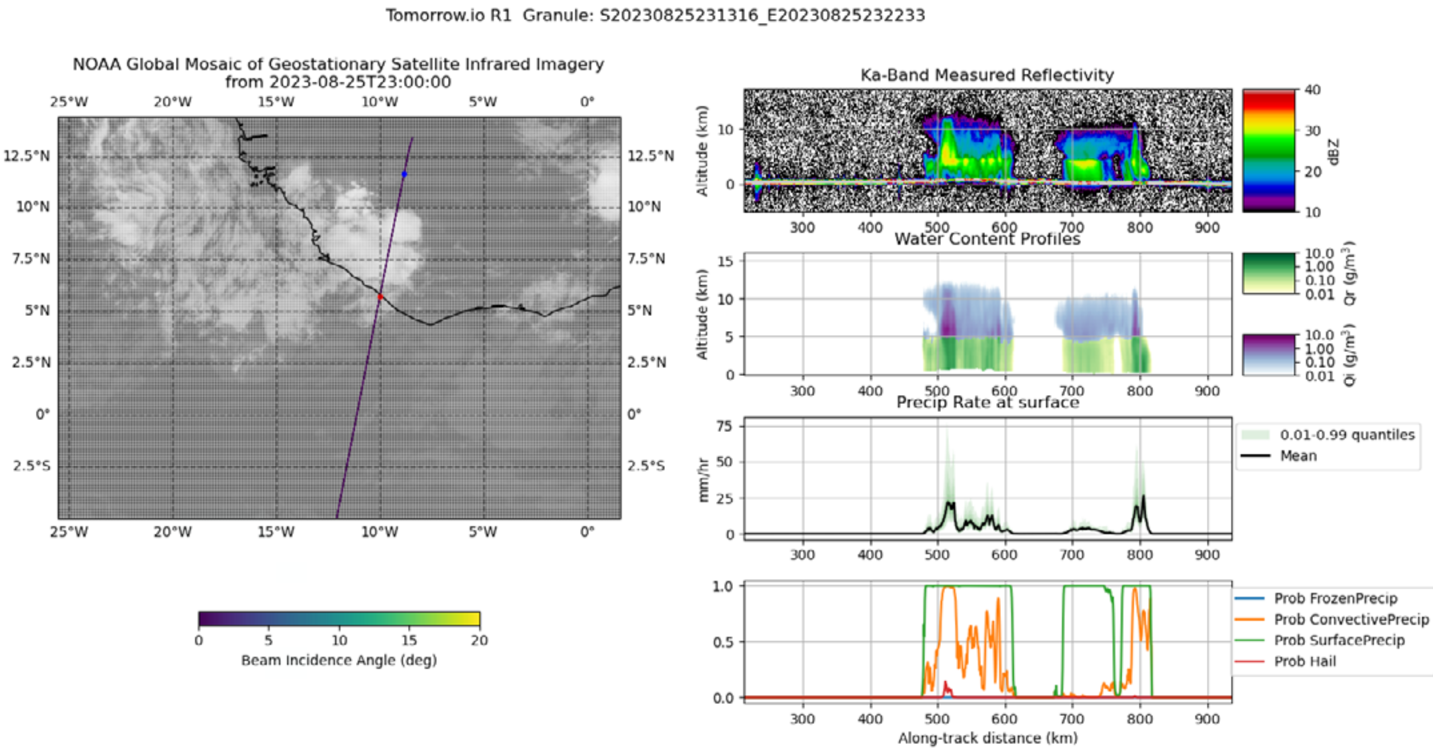


***Figure 2**. A compilation of L1C-GEOPROF and L2A-PRECIP products for an intersection with a convective system over Equatorial West Africa. Left: the ground footprint of the radar plotted over near-simultaneous 10.8 micron imagery from Meteosat 11. The curtain plot boundaries are indicated by the blue and red dots. Top right: Ka-band reflectivity curtain plot from Tomorrow-R1. Upper middle right: neural network-derived ice and water content profiles. Lower middle right: neural network-derived surface rainfall rate mean and quantiles. Bottom right: probability values for precipitation presence and classification.*

In tandem, we are actively developing the scientific algorithm processing chain for the microwave sounders. The planned data set includes: 1B calibrated individual sensor brightness temperature; 1C constellation-intercalibrated brightness temperatures; 2A constellation-intercalibrated, uniform resolution and view angle brightness temperatures; 2B temperature and humidity vertical profiles; 2B high resolution surface precipitation rates, integrated ice and water paths, and echo top heights; and 2B tropical cyclone intensity estimates.

The combination of the sounders and radars in the constellation will provide a planned global revisit rate of 1 hour and an expected 15 minute latency, leading to an unprecedented view of precipitation happening in near real time across the full globe. This near real time data set is expected to drive short-term regional and global forecasts of precipitation with greater accuracy than current systems. The sounder observations will also be assimilated into traditional numerical weather prediction models for improved medium-range forecast skill.

In addition, these observations retrospectively will enable better quantification of the character of global precipitation and, ultimately, improve the collective and integrated understanding of Earth's energy and water cycles. As part of the data production, a database of collocated observations with reanalysis products, ground observations, and other satellite-based sensors will be developed for machine learning and analysis.

For more information, interested users can visit our landing page for satellite data at https://www.tomorrow.io/satellite-data/ to view sample offerings of the radar data sets and to subscribe for updates as more algorithms and satellites come online. We currently have active partnerships with four universities and research organizations for development and validation activities, but we encourage interested scientists and researchers to also contact relevant program contacts at federal agencies to express interest in this data. By partnering with relevant agencies and additional organizations in the future, we hope to empower further scientific investigation of our planet's weather and climate.

References

National Academies of Sciences, Engineering, and Medicine, 2018. *Thriving on Our Changing Planet: A Decadal Strategy for Earth Observation from Space*. Washington, DC: The National Academies Press. https://doi.org/10.17226/24938

Olsen, W.S., and the GPM Combined Radar-Radiometer Algorithm Team, 2022. *GPM Combined Radar-Radiometer Precipitation Algorithm Theoretical Basis Document (Version 7)*. https://gpm.nasa.gov/sites/default/files/2023-01/Combined_algorithm_ATBD.V07_0.pdf

Pfreundschuh, S., P.J. Brown, C.D. Kummerow, P. Eriksson, and T. Norrestad, 2022. GPROF-NN: A neural-network-based implementation of the Goddard Profiling Algorithm. *Atmos. Meas. Tech.*, 15, 5033-5060. https://doi.org/10.5194/amt-15-5033-2022

9th Global Energy and Water Exchanges Open Science Conference

Sapporo, Japan | 7–12 July 2024

Water • Climate | 水 • 気候

Preliminary Program Overview

For the full program, including updates, please visit
https://www.gewexevents.org/meetings/gewex-osc2024/program/

Side Meetings and Pre-Conference Programming

3–5 July 2024: 2024 GEWEX Hydroclimatology Panel (GHP) Meeting

4–6 July 2024: Early Career Researcher (ECR) Workshop on "Extremes in the water cycle and risks to society: Understanding 'actionable' information in hydroclimate research"

6 July 2024: 2024 GEWEX Data and Analysis Panel (GDAP) Meeting

6 July 2024: 2024 GEWEX/Global Land-Atmosphere System Study (GLASS) Panel Meeting

6–7 July 2024: Groundwater Workshop

7 July 2024: PLUMBER2 Meeting

7 July 2024: Space Agency Event

11 July 2024: CLIVAR/GEWEX Monsoon Panel Meeting

Plenary Sessions and Keynote Speakers At-A-Glance

	8 July	9 July	10 July	11 July
Plenary Session Concept	Flood risk assessment and flood control efforts using climate change impact prediction Review of research by Prof. Syukuro Manabe and its impact on GEWEX*	Challenges facing agricultural production infrastructure development under climate change and responses	Climate resilience—toward science-based adaptation practices	JST and JICA's SATREPS Program: Addressing global issues with developing countries—progress and prospects of international joint research projects on climate change and water supported by the Government of Japan
Speakers	**Jack Kaye**, Associate Director, NASA (9:00-9:10) **Riko Oki**, Director, JAXA (9:10-9:20)	**Yukiko Hirabayashi** Shibaura Institute of Technology (9:00-9:30)	**Stefan Uhlenbrook** WMO (9:00-9:30)	**Toshio Koike** ICHARM (9:00-9:30)
	***Yasuhiro Yamanaka** Hokkaido University (9:20-9:35) ***Kirsten Findell** GFDL (9:35-9:50)	**Daniel Klocke** Max Planck Institute (9:30-10:00)	**Hiroyuki Kusaka** University of Tsukuba (9:30-9:50) **Naota Hanasaki** National Institute for Environmental Studies (9:50-10:10)	**Huiling Yuan** Nanjing University (9:30-10:00)
	Takashi Koyari Parliamentary Vice Minister of MLIT (9:50-10:00) **Eiichi Nakakita** Kyoto University (10:00-10:20)	**Laura Condon** University of Arizona (10:00-10:30)	**Amadou Gaye** WCRP (10:10-10:30)	**Krishnan Raghavan** WCRP (10:00-10:30)

9th Global Energy and Water Exchanges Open Science Conference

Sapporo, Japan | 7–12 July 2024

Preliminary Program Overview

For the full program, including updates, please visit
https://www.gewexevents.org/meetings/gewex-osc2024/program/

Monday, 8 July 2024

08:30-09:00	Opening ceremony
09:00-10:30	Plenary
10:30-11:00	Coffee break
11:00-12:30	Parallel sessions
	Session 29 - Advances in flood research, its prediction, impact assessment, and mitigation strategies
	Session 3 - Regional hydroclimate systems research
	Session 6 - Organization of convection: From process understanding to high-impact weather and lightning warning
	Session 13 - The mountain and cold region (cryosphere) water cycle
	Session 18 - Observing the water cycle from space
12:30-14:00	Lunch and poster viewing
13:15-17:15	Stakeholder session (Ministry of Land, Infrastructure, Transport and Tourism) - Flood risk assessment and flood control efforts using climate change impact prediction
13:15-15:15	Stakeholder session - Water cycle changes over Asia: From attribution to adaptation how to communicate advanced information on climate and hazard projections to the general public
15:45-17:45	Stakeholder session - Initiatives taken by the Tokyo Metropolitan Government against flood and storms considering climate change
14:00-15:30	Parallel sessions
	Session 29 - Advances in flood research, its prediction, impact assessment, and mitigation strategies
	Session 6 - Organization of convection: From process understanding to high-impact weather and lightning warning
	Session 13 - The mountain and cold region (cryosphere) water cycle
	Session 18 - Observing the water cycle from space
15:30-17:30	Coffee break and poster viewing
16:00-17:30	Core poster viewing time
17:30-19:00	Session 3 - Regional hydroclimate systems research
	Session 13 - The mountain and cold region (cryosphere) water cycle
	Session 18 - Observing the water cycle from space
19:00-21:00	Welcome reception

9th Global Energy and Water Exchanges Open Science Conference

Sapporo, Japan | 7–12 July 2024

Preliminary Program Overview

For the full program, including updates, please visit
https://www.gewexevents.org/meetings/gewex-osc2024/program/

Tuesday, 9 July 2024

08:30-10:00	Plenary
10:00-10:30	Coffee break
10:30-12:00	Parallel sessions
	Session 29 - Advances in flood research, its prediction, impact assessment, and mitigation strategies
	Session 5 - Understanding precipitation and the Global Precipitation Experiment (GPEX)
	Session 9 - Leveraging land surface temperature in land atmosphere interactions and evapotranspiration
	Session 23 - Human-climate-water nexus, and water security, management, and sustainability
	Session 19 - Novel observation methods for closing observational gaps in the water, energy, and carbon cycles
12:00-13:30	Lunch and poster viewing
13:00-17:00	Stakeholder session (Ministry of Agriculture, Forestry and Fisheries) - Challenges facing agricultural production infrastructure development under climate change andresponses
13:00-15:00	Stakeholder session - Advancements and future directions of risk evaluation methodologies on water disaster considering climate change
15:30-17:30	Stakeholder session - Examples of practitioners' efforts on climate change and river basin disaster resilience and sustainability by all
13:30-15:00	Parallel sessions
	Session 29 - Advances in flood research, its prediction, impact assessment, and mitigation strategies
	Session 20 - Observational and modeling initiatives for the Asian Monsoon Field Campaign (AsiaPEX and AMY-II)
	Session 23 - Human-climate-water nexus, and water security, management, and sustainability
	Session 19 - Novel observation methods for closing observational gaps in the water, energy, and carbon cycles
15:00-17:00	Coffee break and poster viewing
15:30-17:00	Core poster viewing time
17:00-18:30	Parallel sessions
	Session 14 - Understanding energy and water cycles in the troposphere and stratosphere via data and modeling
	Session 20 - Observational and modeling initiatives for the Asian Monsoon Field Campaign (AsiaPEX and AMY-II)
	Session 5 - Understanding precipitation and the Global Precipitation Experiment (GPEX)
	Session 23 - Human-climate-water nexus, and water security, management, and sustainability
	Session 19 - Novel observation methods for closing observational gaps in the water, energy, and carbon cycles

9th Global Energy and Water Exchanges Open Science Conference

Sapporo, Japan | 7–12 July 2024

Preliminary Program Overview

For the full program, including updates, please visit
https://www.gewexevents.org/meetings/gewex-osc2024/program/

Wednesday, 10 July 2024

08:30-10:00	Plenary
10:00-10:30	Coffee break
10:30-12:00	Parallel sessions
	Session 8 - Cloud processes: From cloud development to dynamic interactions
	Session 25 - Addressing the challenge of cascading and compound events
	Session 10 - Monsoons (**special session celebrating 150 Years of IMD**)
	Session 24 - Heatwaves and droughts in present and future climate
	Session 7 - Atmospheric boundary layer and land atmosphere interactions
12:00-13:30	Lunch and poster viewing
13:00-17:00	Stakeholder session (Ministry of Environment) - Climate Resilience - Toward ScienceBased Adaptation Practices
13:00-15:00	Stakeholder session - Risk assessment and adaptation to water/soil compound disasters in climate change-vulnerable regions
15:30-17:30	Stakeholder session - Challenges by local governments and stakeholders towards social implementation of climate change mitigation and adaptation measures
13:30-15:00	Parallel sessions
	Session 8 - Cloud processes: from cloud development to dynamic interactions
	Session 4 - Emerging techniques and technology: From climate modification to AI
	Session 24 - Heatwaves and droughts in present and future climate
	Session 7 - Atmospheric boundary layer and land atmosphere interactions
15:00-17:00	Coffee break and poster viewing
15:30-17:00	Core poster viewing time
17:00-18:30	Parallel sessions
	Session 25 - Addressing the challenge of cascading and compound events
	Session 24 - Heatwaves and droughts in present and future climate
	Session 10 - Monsoons (**special session celebrating 150 Years of IMD**)
19:00-21:00	Banquet

9th Global Energy and Water Exchanges Open Science Conference

Sapporo, Japan | 7–12 July 2024

Preliminary Program Overview

For the full program, including updates, please visit
https://www.gewexevents.org/meetings/gewex-osc2024/program/

Thursday, 11 July 2024

08:30-10:00	Plenary
10:00-10:30	Coffee break
10:30-12:00	Parallel sessions
	Session 26 - Predictability and prediction of extreme events
	Session 12 - Water and climate in urban and/or coastal environments
	Session 15 - Monitoring and modeling of water, energy, and carbon processes across scales
	Session 16 - Novel monitoring, modelling, and benchmarking towards improved process understanding and prediction of land-atmosphere interaction
	Session 17 - Climate extremes: Documentation and observations
12:00-13:30	Lunch and poster viewing
13:00-17:00	Stakeholder session (JST and JICA) - JST and JICA's SATREPS program: Addressing global issues with partner countries— Progress and prospects of international joint research projects on climate change and water supported by the Government of Japan
13:00-15:00	Stakeholder session - Civil Engineering Research Institute's efforts to understand the impact of climate change on disasters and the environment in snowy and cold regions, and adaptation measures of climate change
15:30-17:30	Stakeholder session - Initiatives to resolve social problems related to water and climate at Hokkaido University
13:30-15:00	Parallel sessions
	Session 26 - Predictability and prediction of extreme events
	Session 27 - Early warning of climate and disaster risk management
	Session 16 - Novel monitoring, modelling, and benchmarking towards improved process understanding and prediction of land-atmosphere interaction
	Session 17 - Climate extremes: Documentation and observations
15:00-17:00	Coffee break and poster viewing
15:30-17:00	Core poster viewing time
17:00-18:30	Parallel sessions
	Session 26 - Predictability and prediction of extreme events
	Session 27 - Early warning of climate and disaster risk management
	Session 12 - Water and climate in urban and/or coastal environments
	Session 15 - Monitoring and modeling of water, energy, and carbon processes across scales
	Session 1 - Groundwater Resources, Sustainability, Modeling and Observations

9th Global Energy and Water Exchanges Open Science Conference

Sapporo, Japan | 7–12 July 2024

Preliminary Program Overview

For the full program, including updates, please visit
https://www.gewexevents.org/meetings/gewex-osc2024/program/

Friday, 12 July 2024

08:30-10:00	Parallel sessions
	Session 11 - Coupled human-Earth system modeling
	Session 28 - Generating climate information for smaller-scale decision-making
	Session 2 - The Earth's water, energy and carbon cycles studies
	Session 22 - Km-scale regional and global modeling – Advancements, opportunities, and challenges
	Session 21 - Land-atmosphere interactions and climate predictability, including subseasonal to seasonal (S2S)
10:00-10:30	Coffee break
10:30-12:00	Parallel sessions
	Session 11 - Coupled human-Earth system modeling
	Session 28 - Generating climate information for smaller-scale decision-making
	Session 2 - The Earth's water, energy and carbon cycles studies
	Session 22 - Km-scale regional and global modeling – Advancements, opportunities, and challenges
	Session 21 - Land-atmosphere interactions and climate predictability, including subseasonal to seasonal (S2S)
12:00-12:30	Coffee break
12:30-14:00	Closing ceremony

Poster Sessions for Each Day

Monday	Tuesday	Wednesday	Thursday
Session 02	Session 05	Session 04	Session 01
Session 06	Session 09	Session 07	Session 12
Session 13	Session 14	Session 08	Session 15
Session 18	Session 19	Session 10	Session 16
Session 21	Session 20	Session 11	Session 17
Session 29	Session 23	Session 22	Session 26
	Session 29	Session 24	Session 26
		Session 25	Session 30
		Session 28	