GEWEX QUARTERLY

World Climate Research Programme

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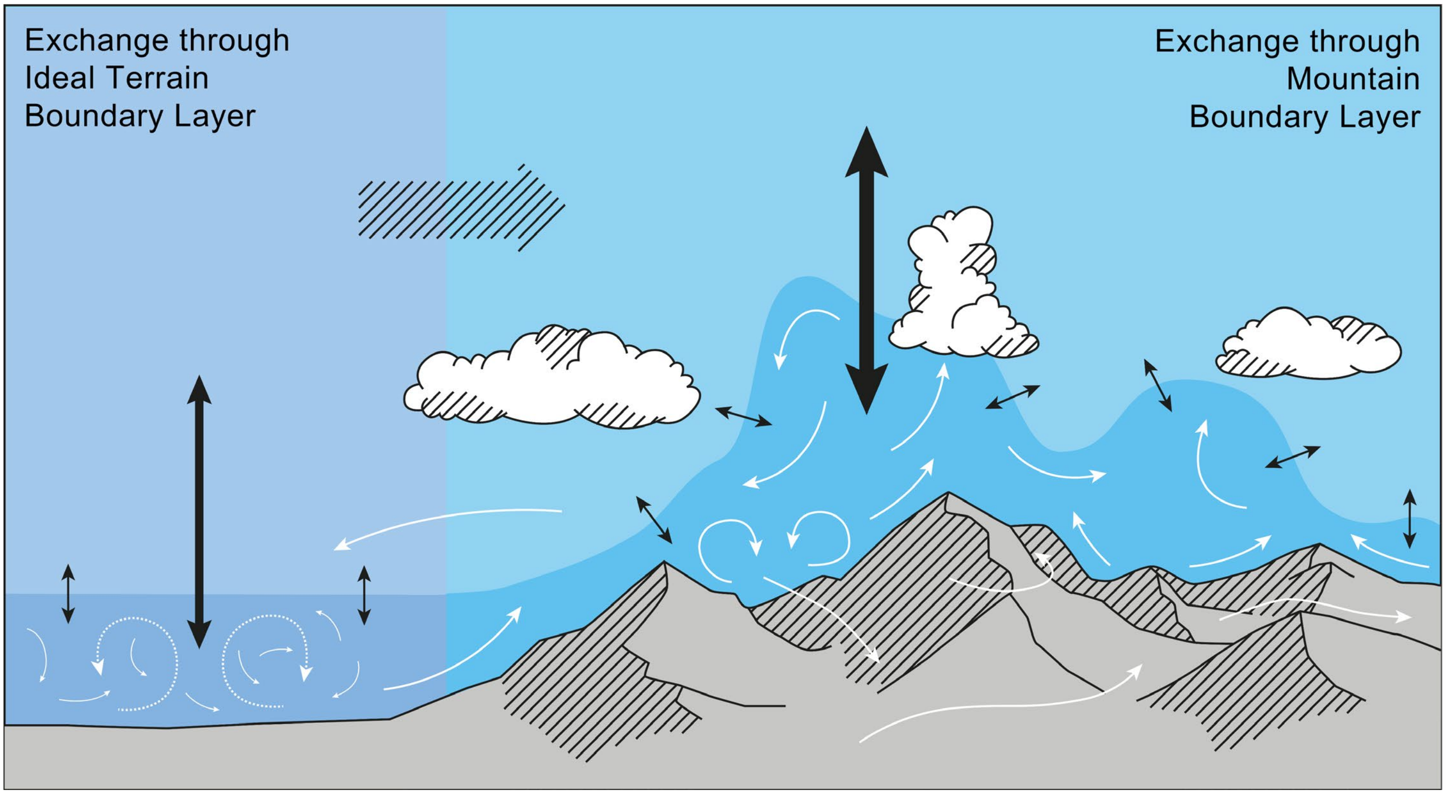
GEWEX is a Core Project of the World Climate Research Programme on Global Energy and Water Exchanges

TEAMx: A Joint Research Initiative Focused on Atmospheric Transport and Exchange Processes over Mountains



Obtaining representative measurements in mountainous terrain is a major challenge. This sketch shows exchange processes that determine the transfer of energy, mass, and momentum between the surface and atmosphere over flat terrain and over mountains. A wide range of exchange processes are relevant over mountainous terrain, including turbulent mixing, local breeze systems, gravity wave propagation, and moist convection. On average, vertical exchange with the free atmosphere (thick black arrows) is believed to be more intense over mountains than flat terrain. Image from Serafin et al. (2020); see Ward et al. on page 12.

Inside This Edition

Commentary

Peter van Oevelen
Director, International GEWEX Project Office

This quarterly edition brings you the unfortunate news of the passing of several of our GEWEX community members. Both Bruno Rudolph, former head of the Global Precipitation Climate Center (until 2006) and head of the Department for Hydrometeorology at the Deutsche Wetterdienst (2006–2013), and Eric Wood, a Professor of Engineering at Princeton University (1976–2019), have been highly supportive of GEWEX. Eric was, for me, as he has been to so many in our community, a great source of support, a soundboard, and a friend. I will surely miss him, his love of good food and wine, and certainly his sometimes-prickly sense of humor. Included in this edition is an in memoriam for Gail Skofronick-Jackson, the National Aeronautics and Space Administration (NASA) program manager who passed away unexpectedly in August. I express my deepest sympathy to the families of Eric, Bruno, and Gail and wish them strength in dealing with their loss.

This edition of the *GEWEX Quarterly* also features a short report of the GEWEX 33rd Scientific Steering Group Meeting. This year, the meeting focused on the future scientific direction of GEWEX (Phase 4: 2022–2032) as well as the World Climate Research Programme (WCRP)'s reorganization and GEWEX's role in that. On the latter aspect, we plan to include a short summary article in upcoming *Quarterly* issues of the latest status of each of the WCRP Light House Activities (LHAs) and how GEWEX can and should contribute. This *Quarterly*, we feature the Digital Earths LHA, providing an overview of this ambitious and exciting activity.

A few articles are presented on new, or relatively new, activities in GEWEX: the Multi-scale Transport and Exchange Processes in the Atmosphere over Mountains–Programme and Experiment (TEAMx), the Land surface Interactions with the Atmosphere over the Iberian Semi-arid Environment (LIAISE) campaign, and the Aerosol Cloud meTeorology Interactions oVer the western ATlantic Experiment (ACTIVATE). Due to COVID-19, the LIAISE campaign was postponed from 2020 to 2021, and as it turned out, this year's weather conditions, contrary to last year's, were nearly perfect! And on that good note I'd like to end: sometimes, we do get lucky!

3rd Pan-GASS Meeting

Understanding and Modeling Atmospheric Processes (UMAP 2022)

In-Person Event

25–29 July 2022 | Hyatt Regency Monterey, CA, USA

GASS Global Atmospheric System Studies

About

Hosted by the Lawrence Livermore National Laboratory, UMAP 2022 aims to bring together weather and climate scientists, including both observationalists and modelers, to discuss the key issues of atmospheric science.

The purpose of the conference is to discuss progress in understanding atmospheric processes and representing them in models, coordinate current GASS initiatives, and plan future projects.

Information and Registration

For detailed information and to register and submit your abstract, please visit the UMAP 2022 website at https://bit.ly/3DOBgTe.

Call for Abstracts

For each of the four main themes outlined below, we are calling for studies relying on process-oriented diagnostics, modeling, and new observational data, applied to enhance our understanding and modeling capabilities of atmospheric processes and their coupling with the surface. The four main themes are:

- Organization of shallow and deep convection
- Surface-atmosphere interactions and the boundary layer
- Cloud systems and associated processes (microphysics, physics, dynamics, radiation)
- Towards global km-scale modeling and Digital Twins of the Earth System

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H3S Applications are Now Open for 2022–2024 Members

Julia Guimond

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

The American Geophysical Union (AGU) Hydrology Section Student Subcommittee (H3S) is now accepting applications to join our team! The application is open through December 31, 2021 and can be found at our website (*https://agu-h3s.org*).

H3S is a dynamic, inspiring, and supportive group of students and early career scientists in water-related fields. As a group, we strive to increase professional development opportunities, diversity, and inclusivity among students and early career scientists in the wider AGU and hydrology communities. We do this through cyber seminars, networking events, researcher highlights, AGU Fall Meeting town halls and events, and conversations with section leadership. We strongly encourage all students and early career scientists to apply–that includes undergraduate students and postdocs! Each position lasts for two years and requires up to 10 hours per month.

Please don't hesitate to reach out to H3S with questions–email us at *h3s.agu@gmail.com*. And please share the application with any person that may be interested!

In Memoriam: Dr. Bruno Rudolf

Dr. Bruno Rudolf, the former head of the Global Precipitation Climatology Centre (GPCC), passed away in June of this year at the age of 72. Dr. Rudolf led GPCC, which collects and analyzes in situ land surface precipitation data, from 1989 to 2006. He steered the formation of GPCC and guided it into the well-respected data center it is today. GPCC is a GEWEX Hydroclimatology Panel (GHP) Global Data Center and reports at the annual GHP meetings, and it also contributes to the GEWEX Data and Analysis Panel (GDAP) and to the Global Climate Observing System (GCOS). Dr. Rudolf's contributions to and leadership of GPCC and later the Deutscher Wetterdienst (DWD) Department of Hydrometeorology have left and will continue to leave a lasting impact on his colleagues. As a scientist, Dr. Rudolf will be missed for his wealth of ideas and careful approach when dealing with the complexities of precipitation data measurements, their quality control, and related user-specific applications. As a person, Bruno will be missed for his subtle humor and his love of jazz music.

Sources

"Obituary for Dr. Bruno Rudolf." Andreas Becker. Deutscher Wetterdienst. *https://www.dwd.de/EN/ourservices/gpcc/memorial/memorial.html?nn=495490&lsbId=353848.*

YESS Thrives in the International Scientific Community

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

[1]University of Carthage, Tunisia Polytechnic School, Al Marsa, Tunis, Tunisia; [2]Centro de Investigaciones del Mar y la Atmósfera (CIMA/CONICET-UBA), Buenos Aires, Argentina; [3]Servicio Meteorológico Nacional (SMN-Argentina), Buenos Aires, Argentina

YESS community representation in the international scientific community continues to increase. We proudly announce the new appointments of YESS members Faten Attig Bahar and Gaby Langendijk to the Future Earth Governing Council, and Jo-Ting Huang-Lachmann to the Future Earth General Assembly. The Future Earth Governing Council (*https://futureearth.org/about/who-we-are/governing-council/*) is the elected, operational decision-making structure working on behalf of the Assembly. It oversees the strategic and scientific direction of Future Earth and supports timely decision processes to advance Future Earth's agenda, strategies, activities, and structures.

Furthermore, an open call was jointly organized by YESS and the Analysis, Integration, and Modeling of the Earth System (AIMES, *https://aimesproject.org/*) initiative, a global research project of Future Earth. Yuhan Rao, YESS Executive Committee member, was appointed as a member of the AIMES Scientific Steering Committee.

YESS co-organized the second Global Atmosphere Watch Training and Education Centre (GAWTEC, *https://www.gawtec.de*) webinar series, focused on reactive gases. The webinar series comprised seven events between September and November 2021. More details about the YESS-GAWTEC webinar series can be found at *https://www.yess-community.org/gawtec-webinar-series/*.

The GEWEX Global Atmospheric System Studies Panel (GASS) will hold its 3rd Pan-GASS Meeting, Understanding and Modeling Atmospheric Processes (UMAP 2022), from 25–29 July 2022 in Monterey, CA, USA. An Early Career Researcher (ECR) competition is being organized and those ECRs using either the DYnamics of the Atmospheric general circulation Modeled On Non-hydrostatic Domains (DYAMOND) or U.S. Department of Energy Atmospheric Radiation Measurement (DOE ARM) data sets are invited to submit their contributions and participate in the competition by 31 January 2022. More info can be found at *https://www.gewexevents.org/events/3rd-pan-gass-meetingunderstanding-and-modeling-atmospheric-processes/ecr-competition/*.

In Memoriam: Eric Wood

Dennis Lettenmaier[1], Justin Sheffield[2], Ming Pan[3], and Craig Ferguson[4]

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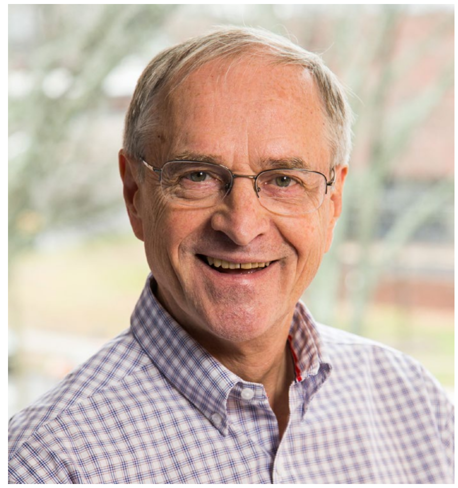
Eric F. Wood, who was well known to the GEWEX community for his work in land surface hydrology, passed away November 3, 2021. He graduated in civil engineering from the University of British Columbia in 1970. He received his doctorate, also in civil engineering, from the Massachusetts Institute of Technology (MIT) in 1974. One of his dissertation papers on selection of flood frequency models received the American Geophysical Union (AGU) Hydrologic Sciences Award in 1977. He spent two years at the International Institute for Applied Systems Analysis (IIASA) in Laxenburg, Austria, and joined the faculty at Princeton University in 1976, where he spent his entire academic career before retiring in 2019. Eric received many honors, including the European Geosciences Union (EGU) Dalton Award (2007), the American Meteorological Society (AMS) Jule G. Charney Award (2010), an honorary doctorate from Ghent University (2011), the EGU Alfred Wagener Award (2014), the AGU Robert E. Horton Award (2017), as well as being named a fellow of the Royal Society of Canada (2013) and the U.S. National Academy of Engineering (2015). Early in his career, Eric's research was in the area of systems analysis as applied to hydrology–a field that was much in vogue in the 1970s. His early work resulted in papers in the late 1970s on the role of parameter uncertainty in deterministic hydrologic predictions, hydrologic network design, and Kalman (and related) filtering approaches to hydrological forecasting, among many others. By the mid-1980s, however, he recognized that the hydrologic landscape was changing with the evolution of hydrology as a branch of Earth science rather than engineering. A groundbreaking series of papers in the late 1980s and early 1990s with Beven, Famiglietti, Sivapalan, and Band examined how the hydrologic response of catchments scaled with drainage area and advanced the concept of Representative Elementary Areas.

In the 1980s and 1990s, two parallel trends motivated the evolution of his research. The first was the coming-of-age of hydrologic remote sensing. While the use of remote sensing to characterize land cover and land use dates at least to the 1970s, pathways by which remote sensing could provide insights into hydrological processes remained elusive. When planning for NASA's Earth Observing System (EOS) began in the 1980s, Eric recognized that remote sensing could provide measurements (and hence process insights) at scales larger than the relatively small catchments to which most hydrological models were then applicable. He participated in a number of remote sensing field campaigns (the first of which was the First ISLSCP Field Experiment–FIFE–in the late 1980s) intended to better understand how remote sensing observations, especially of soil moisture, could be related to in situ observations. Eric would go on to serve on the National Aeronautics and Space Administration (NASA)'s Advanced Microwave Scanning Radiometer for EOS (AMSR-E), Global Precipitation Measurement (GPM), Soil Moisture Active Passive (SMAP), and ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station (ECOSTRESS) Science Teams. By 2010, his group had developed the first long-term consistent NASA satellite records of evapotranspiration and soil moisture as part of the NASA Making Earth Science Data Records (ESDR) for Use in Research Environments (MEaSUREs) Program.



Eric F. Wood, 1947–2021

The second trend that motivated Eric's research was the recognition that the models of the land surface being used in weather and climate models were too rudimentary to represent land-atmosphere interactions properly. Early work with hydrological parameterizations implemented by Ezio Todini in collaboration with Chinese scientists led to adoption of aspects of Todini's Arno model into what became the Variable Infiltration Capacity (VIC) macroscale hydrology model. The VIC model–the modern version of which traces to Xu Liang's dissertation work at the University of Washington, and later as a postdoc with Eric–was intended for applications at the scale of large continental river basins (and even globally).

In the 1990s, GEWEX initiated its first Continental Scale Experiment, the GEWEX Continental Scale International Project (GCIP), the domain of which was the Mississippi River basin. The VIC modeling structure was well suited to GCIP's goals, and implementation over the Arkansas-Red River basin (the first of four Large Scale Areas, or LSAs, within GCIP) allowed for direct comparisons of evapotranspiration between land surface models and atmospheric water budgets. The Arkansas-Red basin was also the focus of a Project for Intercomparison of Land Surface Parameterizations (PILPS) multi-institutional collaboration led by Eric in the late 1990s. The PILPS effort was notable for its focus on model improvement, rather than the "beauty contests" that had characterized earlier model intercomparison efforts.

A key aspect of the VIC model as it evolved at the University of Washington and Princeton was that the model source code was freely available. That, in turn, led to its widespread use internationally. The model played a prominent role in the North American Land Data Assimilation System (NLDAS) and in

Attendees of the Eric Wood Symposium at Princeton, June 2016

many projects led by Eric and his group. For example, Pan and Wood developed a novel water-balanced constrained remote sensing data assimilation system using VIC and the 2012 Sheffield et al. *Nature* paper used a long-term VIC simulation to show that there has been little change globally in the frequency and severity of droughts over the last 60 years. VIC was also used to: reconstruct droughts over the U.S., China, and India among many other regions; study the decline of snowpacks in the Western U.S.; produce hydrological projections of climate change impacts; and provide real-time flood and drought monitoring, and seasonal hydrological forecasts. Despite the fact that the primary paper describing the VIC model (Liang et al., 1994) was published over 25 years ago, it has typically been cited about 200 times per year in the recent past.

About 10 years ago, Eric became interested in the possibilities for much higher-resolution application of hydrological models than has been the case in the past. Hydrologists typically have felt bound by the effective spatial resolution of gridded data sets of precipitation and other variables used to force models like VIC. At best, inter-station distances of stations with long-term records in the developed world are 10–20 km, and the distance is much larger over remotely populated or low-income regions of the globe. Hence, the argument goes, there is no point in macroscale hydrological modeling at scales much smaller than about 10 km. Eric's 2011 paper (with other attendees of a workshop that he hosted) advocates a rationale for "hyper-resolution" land surface models (which it defines as exceeding about 1 km spatial resolution globally) of Earth's terrestrial water, energy, and biogeochemical cycles. The paper, now cited over 50 times per year, has spawned an entire field of research that investigates not only the nuances of large-scale hydrological processes that are only manifested at high spatial resolutions, but also the computational methods and data sets that are needed to support such efforts.

As an educator, Eric had a huge impact on the professional development of his 35 Ph.D. students, as well as many (an almost certainly greater number of) post-docs, research staff, visitors, and advisees at other institutions. In an interview with Siva Sivapalan, as part of the EGU History of Hydrology project, he was asked about his students. He responded: "There are two parts. One is that the students [have to be] very bright to start with. Second is that they need…to be taught how to do research. If you look at the early paintings of Picasso, [he] started out doing classical portraits. He didn't wake up and say I am going to do Cubism! You have to teach someone how to do research, it is a learned skill." Eric emphasized creativity, focusing on one's strengths, and selecting good research problems. He held everyone he worked with to the very highest standards; he convened his group meetings on Fridays at 4PM, often making the attendees late to Departmental Happy Hour.

Finally, some personal reflections: Eric was, shall we say, a complicated personality, and surely there were some who were put off by him. He didn't suffer fools gladly; at a meeting some decades back, after a speaker pontificated on some point with which he didn't agree, he was heard to say, "If I wanted a sermon I'd go to church." But he worked tirelessly to advance the careers of all whom he thought were deserving. These were not only his own students and close associates, but in many cases, he wrote in support of hydrologists (not to speak of other Earth scientists) with whom he had no direct connection. In a few cases he wrote for people who'd felt offended by his comments–and they never knew that they were the beneficiaries of his support.

From those of us who worked with him, it was an honor and a privilege. Eric, we will miss you.

References

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Wood, E.F., et al., 2011. Hyperresolution global land surface modeling: Meeting a grand challenge for monitoring Earth's terrestrial water. *Water Resour. Res.*, 47, W05301. doi:10.1029/2010WR010090.

In Memoriam: Gail Skofronick-Jackson

Jack Kaye[1], Scott Braun[2], Sandra Cauffman[1], George Huffman[2], Dalie Kirschbaum[2], and Aaron Piña[1]

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It is with great sadness that we report the death of Gail Skofronick-Jackson, manager of the National Aeronautics and Space Administration (NASA)'s Atmospheric Dynamics research program, due to a tragic accident while deployed on a NASA airborne field campaign in St. Croix, U.S. Virgin Islands on September 7, 2021. Dr. Skofronick-Jackson spent her 24-year professional career at NASA as a researcher and manager. In St. Croix, she was the leader of NASA's Convective Processes Experiment–Aerosols and Winds (CPEX-AW), designed both to study tropical convection and its relationship to underlying meteorological conditions and to provide complementary calibration/validation information for the European Space Agency (ESA) Aeolus satellite.

Dr. Skofronick-Jackson was born in Madison, WI, and grew up in Tallahassee, FL, where her father was a physics professor. She was one of four siblings, all of whom grew up to become engineers. Gail got her B.S. in Electrical Engineering (EE) from Florida State University (FSU) and then went to the Georgia Institute of Technology, where she received both her M.S. and Ph.D., also in EE. After receiving her Ph.D. in 1997, she joined the Goddard Space Flight Center (GSFC) in Greenbelt, MD, where she conducted research on precipitation processes using microwave remote sensing.

Dr. Skofronick-Jackson became involved in NASA satellite programs, especially the Tropical Rainfall Measuring Mission (TRMM) and then subsequently the Global Precipitation Measurement (GPM) mission. Over time, her responsibilities grew so that by the time of its launch in 2014, she was the GPM Project Scientist, working closely with the Project Manager to oversee its successful implementation and coordinating the science with NASA's international partners. She played a key role in overseeing the development of retrieval algorithms for the mission and the development and implementation of calibration/validation plans for GPM. In particular, the higher orbital inclination of GPM and the presence of the Japan Aerospace Exploration Agency (JAXA)-provided dual-frequency radar allowed for studies of snow, which was her primary scientific passion. Dr. Skofronick-Jackson played a leadership role in field campaigns conducted both before and after launch, such as the GPM Cold Season Precipitation Experiment (GCPEX) in 2012, for which she was the instrument scientist for the Conical Scanning Millimeter-wave Imaging Radiometer (CoSMIR) instrument aboard the NASA DC-8.

At GSFC, she also rose through the ranks to become the Chief of the Mesoscale Atmospheric Processes Laboratory. In that role, she provided direction, guidance, and supervision to a group of civil servants, contractors, and cooperative agreement personnel, and was widely recognized as a supportive and nurturing manager, a good friend and colleague, a dynamic speaker on behalf of her science and missions, and as an outstanding role model for the growing cadre of early career scientists at GSFC.

Dr. Skofronick-Jackson transferred to NASA Headquarters in 2018 to manage the Weather and Atmospheric Dynamics program. In this role, she led the development of CPEX-AW, including overseeing the solicitation and selection of investigator teams, coordinating planning with ESA, and replanning due to the COVID-19 pandemic, which required the mission to be postponed from 2020 to 2021. Dr. Skofronick-Jackson served as program scientist for several NASA missions and instruments, including GPM, the Cyclone Global Navigation Satellite System (CYGNSS), Aqua/Atmospheric Infrared Sounder (AIRS), the Time-Resolved Observations of Precipitation structure and storm Intensity with a Constellation of Smallsats (TROPICS) mission, the Lightning Imaging Sensor aboard the International Space Station, as well as the Investigation of Microphysics and Precipitation for Atlantic Coast-Threatening Snowstorms (IMPACTS) airborne campaign focused on her beloved snow science. She was also playing a lead role in the development of plans for the Planetary Boundary Layer component of the Incubation effort called for by the National Academies in their 2018 Decadal Survey for Earth Science.

Dr. Skofronick-Jackson was an active and engaged resident of McLean, Virginia, where she lived with her husband David and two children, Marina and Matthew. She was especially engaged in her "McLean Moms Run This Town" running community and she was an active member of the Foundry United Methodist Church in Washington, DC. She was a Fellow of the Institute of Electrical and Electronics Engineers (IEEE) and helped create the Women Mentoring Women Initiative within the IEEE Geoscience and Remote Sensing Society. As a loyal alumna of FSU, she maintained her involvement in the university and was well-recognized in the community. In 2014, she received the FSU "Grad Made Good" Award and in 2015 was the FSU Summer Commencement speaker. In 2017, she was a featured speaker in the Tallahassee Scientific Society Speakers Series. To help continue her work in support of students entering STEM disciplines, a scholarship fund has been set up at FSU for students studying science and electrical engineering; information about the fund can be found at *https://spark.fsu.edu/GailSkofronickJackson*.

At the memorial service held to commemorate her life on November 14, 2021, she was posthumously awarded NASA's Exceptional Service Medal for her many accomplishments.

The WCRP Digital Earths Lighthouse Activity–An Opportunity for the GEWEX Community

Christian Jakob[1], Peter Bauer[2], Sandrine Bony[3], Daniel Klocke[4], Kirsten Findell[5], Anne Verhoef[6], Francina Dominguez[7], Ali Nazemi[8], and Jan Polcher[9]

[1]Monash University, Melbourne, Australia; [2]European Centre for Medium-Range Weather Forecasts, Reading, UK; [3]Centre National de la Recherche Scientifique, Sorbonne University, Paris, France; [4]Max Planck Institute for Meteorology, Hamburg, Germany; [5]Geophysical Fluid Dynamics Laboratory, Princeton, NJ, USA; [6]University of Reading, Reading, UK; [7]University of Illinois at Urbana-Champaign, Urbana and Champaign, IL, USA; [8]Concordia University, Montréal, QC, Canada; [9]Laboratoire de Météorologie Dynamique du CNRS/IPSL, France

What Are the Goals of the Digital Earths Lighthouse Activity (LHA)?

The vision of Digital Earths is to build global interactive digital information systems that describe the past, present, and future states of planet Earth.

The LHA mission is to carry out frontier research activities within the World Climate Research Programme (WCRP) that enable the implementation of this vision in one or more international or national systems to generate and disseminate information of direct relevance for climate information stakeholders.

What Do We Need to Make It Happen?

Fig. 1 provides a schematic overview of the ingredients and connections in a Digital Earths information system. The systems are informed by the needs of society and draw on the latest developments in computing and data capabilities. In doing so, they combine Earth System Models (ESMs) at resolutions that explicitly resolve convectively-driven storms, ocean eddies, river basins, sea ice leads, and glaciers with data assimilation and data fusion techniques that take advantage of Earth observations at both weather and climate timescales. The systems fully integrate climate impact models and, where necessary or desirable, couple them to the more traditional ESM components to enable feedbacks. Designing and implementing what are effectively Digital Twins of planet Earth will have to go hand in hand with developments of high-performance computing and data handling systems and the exploitation of the ever-evolving observation systems.

From Fig. 1, it is evident that success requires both the design and execution of new research activities within WCRP as well as the building of new collaborations with partners outside the WCRP family. At a minimum these activities must include:

- The design of storm/eddy/river basin/sea-ice leads/glacier-resolving ESMs
- The further development of data assimilation systems for climate
- The extension of our modeling capabilities beyond the traditional Earth system through the inclusion of new components, including those representing human systems.

What Are the Main Activities of the Digital Earths LHA?

Based on the above considerations, the Digital Earths LHA will be built around three major activities, each of them focused on one of the three activity areas above.

Global to Regional Modeling of the Earth System at Storm/Eddy/River Basin/Sea-Icea Leads/Glacier-Resolving Scales

This activity aims to build global and regional fully-coupled models of the climate system at ultra-high resolution as a core component of any Digital Earths information systems. Its initial focus will be on modeling the physical climate system as a foundation for the future expansion to the full Earth system (see next activity). Both regional and global modeling activities are central to developing the model innovations required, creating the opportunity for a global and regional modeling alliance within and beyond WCRP. The unprecedented increase in resolution driven by both scientific considerations, such as the elimination of the need to parameterize deep convection in the atmosphere and by society's need to manage the environment, will fundamentally challenge the way we currently model the Earth system. These challenges will reach well beyond just the computational realm. Moving to kilometer scales will invalidate key assumptions currently made in virtually all ESM components and processes assumed to be negligible in current ESMs may start to dominate and need to be represented.

Enabling Modeling Capabilities beyond the Traditional Earth System

This activity targets adding new components to traditional ESMs, all the way from detailed hydrological models to water and land management models to socio-economic impact models. Its goal is to establish a physical-impact science alliance that enables the co-design of physical Earth system approaches and that defines and implements success metrics in the use of Digital Earths systems by society. Likely first steps could be the co-design of a range of demonstration projects covering global and regional foci and new downscaling strategies that would represent the diversity of impact sectors that benefit from Digital Earths systems. Learning from and enhancing existing regional modeling activities will pave the way for a comprehensive integration of the new model components into global Digital Earths systems as they mature in their representation of the physical Earth system.

Data Assimilation for Climate

Data assimilation methods have been shown to be an optimal approach to exploit the rich and yet incomplete set of

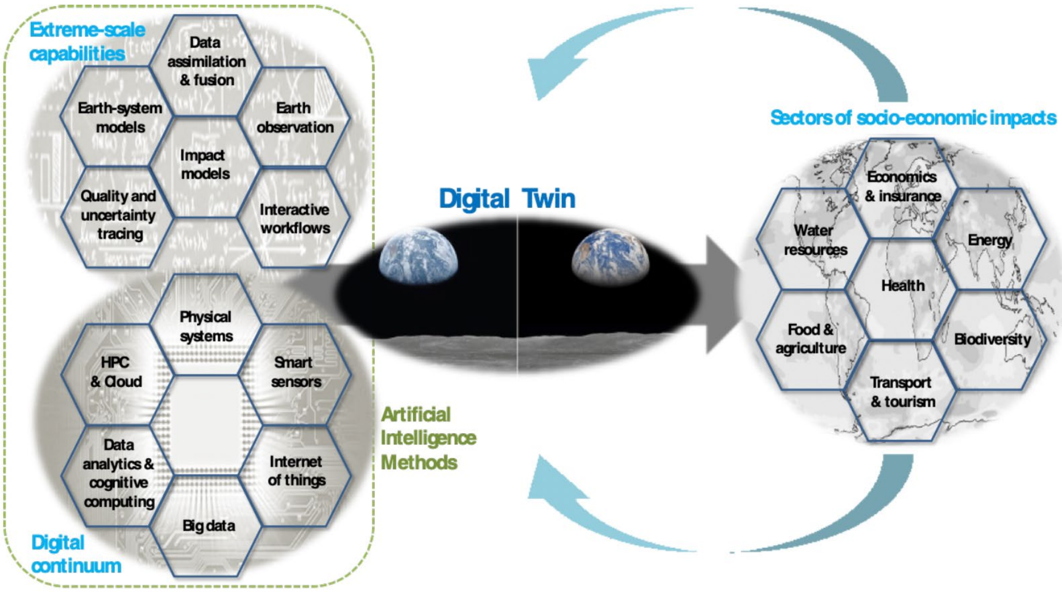

***Figure 1**. Schematic of Digital Earths*

observations of the Earth system for a comprehensive and consistent description of the state of the system at any given time. Many current data assimilation efforts have their roots in creating initial conditions for prediction with little to no regard given to fundamental constraints that are critical to climate research, such as energy or water conservation. With few exceptions, even the more climate-oriented and very successful reanalysis systems are deeply rooted in the initial condition generation paradigm. Furthermore, current data assimilation methodologies have serious limitations (linearity, degrees of freedom, computational costs) that will need to be overcome when including fast processes acting at small scales; when fully interfacing Earth-system components such as atmosphere, oceans, sea ice and land; and when integrating new information beyond the physical system. In short, extending data assimilation to climate prediction/projection in an operational framework whilst approaching kilometer-scale model resolutions at the same time requires nothing less than a paradigm shift in how this highly-successful methodology is used and how climate models are assessed. As existing efforts in data assimilation are largely concentrated in numerical weather prediction (NWP) and climate centers focused on initialized weather and climate prediction, the most important first task of the Digital Earths LHA is to create a climate data assimilation community by bringing together existing climate, NWP, reanalysis, and observational groups to plot a course for this critical, and yet under-appreciated, research area.

Collaboration Opportunities between the Digital Earths LHA and GEWEX

Atmospheric Modeling

The Global Atmospheric System Studies (GASS) Panel and its predecessor, the GEWEX Cloud System Study (GCSS), have pioneered the development and use of process models together with observations for process understanding and parameterization development. These models were able to produce realistic simulations of cloud systems and later, with increased domain size, even organized mesoscale clouds systems. They became the basis for the atmospheric components of the now-emerging new class of storm-resolving climate models. Through its expertise in process understanding and evaluation using fine-scale models and observations, GASS will provide guidance for the development of storm-resolving physical models of the atmosphere, and will promote the open analysis of the new global storm-resolving climate model simulations by the scientific community. In addition to being directly involved in the LHA modeling activities, GASS will also continue to carry out process studies with models run over smaller domains, which will directly inform the development of the parameterizations still required in the modeling system envisaged, such as those of turbulence and cloud microphysical processes. Maintaining the long-term successful collaboration with the working Group on Numerical Experimentation (WGNE), GASS is looking forward to meeting the new challenges that the ambitious goals of the Digital Earths LHA provide.

Land Surface Modeling

The Global Land-Atmosphere System Studies (GLASS) Panel has been WCRP's main body for process-oriented land surface modeling and model improvements since its inception. Findings, products, and recommendations from many GLASS projects have fed and will continue to feed into ESM capabilities in WCRP and their extension to kilometer scale resolution will provide foundational efforts for the Digital Earths LHA. The challenges of modeling the land surface at such high spatial resolution are significant, but the long-term experience in projects like the Soil and Water (SoilWat) Initiative, which has the aim to improve the representation of soil and subsurface processes in climate models and improve parameterization of soil hydraulic and thermal properties, or the Local Land-Atmosphere Coupling (LoCo) Project, which focuses on the interaction of the land surface with the atmosphere at local scales, have equipped us with the necessary tools to meet these challenges.

GLASS also has significant experience in benchmarking with the International Land Model Benchmarking (ILAMB) and

Protocol for the Analysis of Land Surface models (PALS) Land Surface Model Benchmarking Evaluation (PLUMBER) projects. Both provide tools for the systematic analysis of land- and Earth system model simulation of land variables and surface climate, using both flux tower data and Earth Observation (EO) data as their benchmarking material, that undergo regular updates as new observing systems come online. They will become instrumental in assessing the new generation of very high-resolution models.

Finally, in collaboration with the GEWEX Hydroclimatology Panel (GHP), GLASS is also beginning to tackle representations of human involvement in and management of the Earth system, as in the recently-established GLASS-GHP Irrigation project.

Regional Modeling and Stakeholder Interactions

The strong experience in regional modeling and stakeholder interaction in the Regional Hydroclimatology Projects (RHPs) coordinated by GHP provides GEWEX with an excellent platform for the integration of regional models into LHA activities. Several of the RHPs have already begun to build and exploit ultra-high-resolution regional modeling for their research, including the Global Water Futures (GWF), ANDEX, and USTARS projects. GHP also plans to make a fundamental contribution to better understanding of precipitation generation in mountainous terrain, a challenge for current climate models.

GHP also aims to contribute to pioneering the integration of new components beyond the physical Earth system in the Digital Earths LHA framework. The GHP Crosscutting Projects that are currently under construction around some important human activities and/or impacts that have not been yet represented in ESMs, most notably Irrigation, Water Resource Management, and Floods, provide an excellent opportunity to demonstrate the utility of such components and study their effect on the overall ESM performance. GHP can also play a key role in evaluating the new Digital Earth ESMs in the often topographically-complex regions of its RHPs by using the observations collected in them.

Summary

The Digital Earths LHA, with its three activities in i) storm/eddy/river basin/sea-ice leads/glacier-resolving Earth System Models (ESMs), ii) the extension of ESMs to incorporate the human system, and iii) data assimilation for climate, provide a rich set of opportunities for the GEWEX community to engage. A small initial set of these are outlined in this article. Both the Digital Earths LHA and GEWEX teams are looking forward to interacting with the readership of this newsletter to engage in the design and execution of research activities that drive our ability to describe and predict the Earth at the level of detail that society requires to make knowledge-based decisions in mitigating and adapting to climate change.

New Efforts in Improving Numerical Aspects of Atmospheric Physics Parameterizations

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Atmospheric physics parameterizations in a regional or global model describe the ensemble effects of small-scale processes that are unresolvable by the computational mesh, e.g., radiation, convection, turbulence, cloud microphysics, and aerosol life cycle. Parameterizations play a crucial role in determining the fidelity of numerical weather and climate predictions. Model errors associated with parameterizations can arise from missing or inadequate representation of physical processes (which leads to "structural" errors) and from the spatial and temporal discretization of the integro-differential equations describing the physics (which leads to numerical errors). Most research to date on parameterizations has focused on structural errors and their dependency on spatial resolution. Much less attention has been paid to the time integration algorithms used for individual processes and for process coupling. The traditional mindset was that structural errors overwhelm the inaccuracies introduced by discretization. While this might have been the case in older models, the fast-growing complexity and process-level details in current models have brought new challenges.

To efficiently identify sources of time integration error in global atmospheric general circulation models (AGCMs), Wan et al. (2015) carried out ensembles of 1-hour simulations using the Community Atmosphere Model, the predecessor of the atmosphere component of the Energy Exascale Earth System Model. The model's time-step size was varied by three orders of magnitude to quantify the rate at which the numerical solution approached the reference solution when temporal resolution was increased, i.e., the so-called time-step convergence rate. While the evaluation of convergence is a routine exercise in computational fluid dynamics and many other computational sciences, the study by Wan et al. (2015) was the first one to apply it to a full-fledged global AGCM in its "operational" configuration. Not surprisingly, when time-step size was varied, the physics parameterizations were found to cause substantially larger changes in the numerical results than the mesh-resolved fluid dynamics. Disconcertingly, convergence towards the reference solution in the full model appeared to be substantially slower than theoretical prediction, suggesting the computational cost associated with higher temporal resolution could not provide the expected accuracy gain.

The work by Wan et al. (2015) has triggered philosophical discussions. Given the empirical and pragmatic nature of parameterizations, is it meaningful and practical to expect theoretically-predicted convergence rates? Would differences in short-term convergence behavior matter for long-term climate simulations? An interdisciplinary team of atmospheric

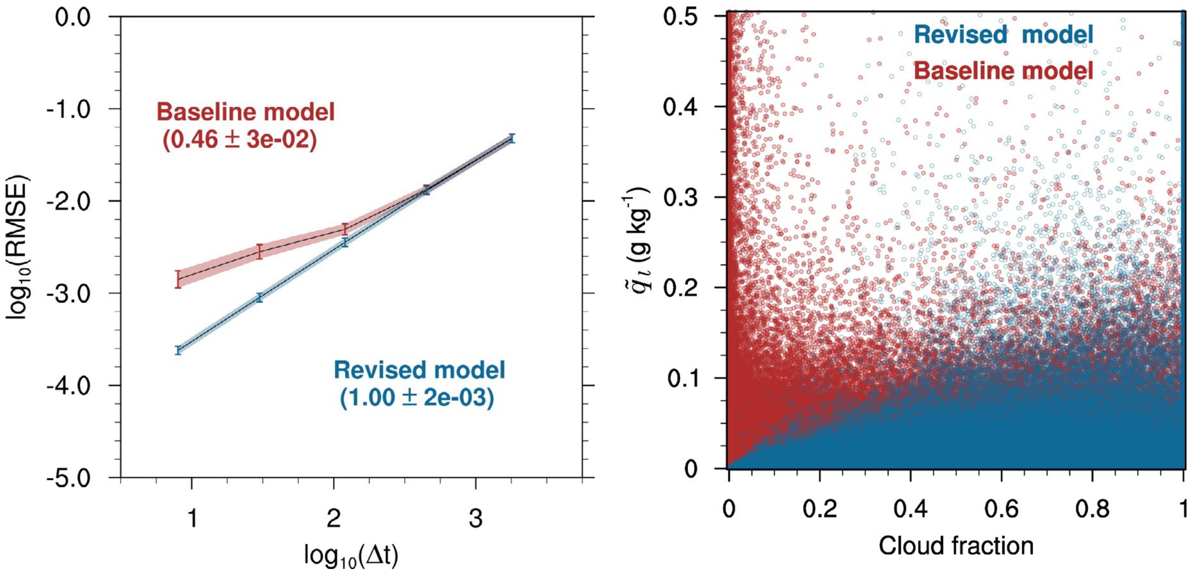

***Figure 1**. Left: global mean, mass-weighted time integration error in air temperature (y-axis) and solution self-convergence rate (numbers in parentheses showing mean ± one standard deviation) in 1-hour simulations carried out with different time-step sizes (x-axis) using a simplified global model with a dynamical core and a large-scale condensation parameterization. Color shading shows the spread of six ensemble members. Red and blue correspond to results obtained from the baseline and revised model, respectively. Right: scatter plot showing instantaneous in-cloud water mixing ratio against cloud fraction in individual grid cells in simulations performed with 450 s time steps. The baseline simulation shown in red contains a large number of grid cells with close-to-zero cloud fraction (x-axis close to the origin) and high in-cloud water mixing ratio (y-axis). The simulation using the revised model does not show this pathology. More details can be found in Wan et al., 2020.*

scientists and applied mathematicians used a simplified cloud parameterization to shed light on answers to these questions (Wan et al., 2020; Vogl et al., 2020). In Fig. 1, a baseline model is shown to have a convergence rate of 0.46, which substantially deviates from the theoretical value of 1. The direct cause of the behavior turns out to be a significant number of grid cells associated with zero cloud fraction but high in-cloud water mixing ratio (Fig. 1, red circles in right panel), which is nonphysical. The pathology is addressed at its root by revisiting the physical concept, employing rigorous mathematical derivations to avoid inadvertent oversimplification, and carefully choosing numerical methods (Fig. 1, blue). Improved short-term convergence is found to have systematic impacts on the long-term mean climate simulated by a full-fledged climate model (Wan et al., 2020; Vogl et al., 2020).

Inconsistencies caused by simplifications and approximations are common in atmospheric models. Additional examples often requiring ad hoc, after-the-fact manipulations of a simulation include contradictions between particle mass and number concentrations in cloud and aerosol parameterizations as well as mismatches between different moments of the probability distribution of subgrid-scale variations in turbulence parameterizations. The impacts of such issues have not been thoroughly investigated. Time-step convergence tests combined with physical understanding of the intended physics might provide an effective path forward.

While the two studies by Wan et al. (2020) and Vogl et al. (2020) focused on a simplified cloud parameterization, the research team has extended its work to a sophisticated turbulence and cloud parameterization currently used in several major global climate models. The team is also exploring other methods for identifying and reducing time integration errors related to parameterizations in AGCMs (Wan et al., 2021) and developing new ways for solving stochastic differential equations (Stinis et al., 2020). The goal of the interdisciplinary collaboration between climate modelers and mathematicians is to help improve the numerical accuracy and computational efficiency of the current and next-generation atmospheric models.

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Opinion: The Role of GEWEX in Moving the Needle on the Resiliency of Society to Flooding

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As the world grapples with the health and economic impacts of COVID-19, the impacts of climate extremes are magnifying the suffering of individuals around the world. Of the climate extremes, flooding impacts more people than any other natural hazard and the destructive flash floods of recent months have been a reminder of their devastating impacts on lives, property, and critical infrastructure. Increasing populations, changes in the climate system, expansion of built infrastructure, and sea level rise threaten to further increase flooding impacts and losses around the world over the coming decades.

Given the strong connection between flooding and the global water and energy cycles, who better than GEWEX to directly address the alarming societal impacts of floods that occur on continental scales? In order to stay relevant and connected to societal needs in a changing climate, we need to tackle the primary drivers of floods, including climatic and terrestrial drivers across different scales and regions. This can be achieved by facilitating and focusing research on flood-generating mechanisms that control the magnitude, frequency, and seasonality of extreme flows. This includes extreme rainfall characteristics, but also less obvious mechanisms including soil moisture-dependent rainfall excess, saturation excess, snowmelt, and rain-on-snow events that are significant contributors to flood mechanisms and responses in many regions. The continental-scale classification of dominant flood-generating mechanisms will help emphasize the disparity in timing and variability between extreme rainfall and flooding and has the potential to transform flood prediction and risk assessment.

Dominant flood-generating mechanisms are expected to change in a warming climate, particularly in cold regions (Berghuijs et al., 2019) due to increased temperatures that affect snow dynamics and potentially alter the magnitude of snowmelt flooding (e.g., Regonda et al., 2005; Hall et al., 2014). Cold regions are also expected to experience an increase in convective precipitation under future warming, which might starkly increase the risk for flash flooding (Chernokulsky et al., 2019). Warmer temperatures also tend to increase precipitation extremes that potentially increase the risk of flood-generating rainfall (e.g., Trenberth et al., 2003; Westra et al., 2013; Kendon et al., 2014; Fowler et al., 2021). However, climate-driven changes in flood generation mechanisms are not well-understood and difficulties still exist in disentangling the climatic component from substantial natural variability and direct human impacts on flood hydrographs. Changes in the timing and earlier occurrence of (spring) peak flow rates in snowmelt- and glacier-fed rivers have been observed and reported. In some regions where snowmelt is the preliminary driver of flood-generating mechanisms, the time of peak high flow has shifted from spring to winter. Rapid snowmelt from rain-on-snow events causes a potential flood threat and significant disruption to the water cycle. This necessitates a precise understanding of changes in flood hazards and the underlying driving mechanisms for predicting future changes.

While evidence suggests that current flood modeling approaches particularly for real-time assessment are meaningful and useful (e.g., Sukovich et al., 2014), their outcomes rest heavily on imprecise and subjective expert opinion; there is an overestimation in their probabilistic simulation for setting robust evidence-based thresholds for impact studies (e.g., Palmer, 2012). Due to the limited scope of many modeling frameworks, it is still a challenge to model the complexities and nonlinear nature of flooding, particularly under non-stationary conditions (climate change, human interface; see Philips et al., 2018). Many flood modeling systems were designed to model the land surface and atmospheric drivers over a limited range of runoff generation mechanisms as well as river routing schemes (e.g., superposition of flood waves in the main channel and its tributaries). However, flooding occurs due to compound mechanisms, particularly in low-elevation areas on the coast where intense rainfall, inland flooding, and storm surge co-occur simultaneously or successively.

Most importantly, the majority of current flood modeling systems rely too strongly on single deterministic forecast models, small ensemble flood models, or a combination of the two. The limitations of these modeling approaches are threefold. First, their scope is limited to systematically considering modeling alternatives needed for model evaluation and improvement. Such modeling approaches provide context but cannot adequately capture spatial and temporal variability of maxima, geometry of the drainage system, model parameters, and surface and sub-surface flow interaction and processes. Second, most existing flood models cannot adequately represent physical-systematic processes across different spatial configurations, such as grids versus hydrologic response units (HRUs), to improve simulation and to demonstrate the scaling behavior of physical processes involved in flood generation mechanisms. Finally, many models do not adequately characterize model sensitivity and uncertainty. Thus, there is a lack of insight into systematic errors and evaluation of multiple model representations (hypotheses) for flood generation and routing. More broadly, those approaches are limited in their scope to separate the model physics from the numerical solution (e.g., subroutines) and in their capacity to adjust model parameters.

A frontier in flood modeling and mechanistic understanding involves implicitly representing the variability of flood events using both physical details as in the bottom-up approach (distributed physically-based models), and subgrid-scale heterogeneities as in the top-down approach (conceptual models). Scaling up/down the flood generation mechanisms to larger/smaller catchments, determining the sensitivity of runoff to climate and land use changes, and improving the representation of rapid surface flow through the use of multiple rainfall-runoff schemes would be beneficial to understanding the destructive effects of flooding. Combining these strengths will also allow us to identify areas "at-risk" to flooding across a range of catchment types (e.g., urban vs. rural vs. coastal) and regions.

As noted, understanding flood generation mechanisms and their impacts on the water cycle will be challenging and will require expertise well beyond GEWEX and the World Climate Research Programme (WCRP). It should include, but not be limited to, the World Meteorological Organization (WMO)'s strengthening efforts in hydrology and the expertise in the International Association of Hydrological Sciences (IAHS) communities, for example. Nevertheless, we must start a flood crosscutting initiative and bring in other perspectives and knowledge across science and engineering disciplines. There are a number of activities ongoing within the GEWEX community that the flood initiative could contribute to. A prime example of a beneficiary could be Regional Hydroclimate Projects (RHPs) such as the Asian Precipitation Experiment (AsiaPEX). AsiaPEX focuses on understanding Asian land precipitation over diverse hydroclimatological conditions to better predict the extremes for disaster reduction and sustainable development.

The GEWEX vision for a flood crosscutting initiative should focus on overcoming barriers in designing appropriate modeling architectures to represent rapid rainfall-runoff processes and mechanisms within Earth system models across current and future flood-prone regions. Furthermore, GEWEX needs to identify proper strategies to ensure scientific understanding of historical floods and translate that knowledge into future projections to enable prediction of the processes governing the probability, occurrence, and impacts of flood-generating rainfall. Strengthening flood monitoring and warning systems to advance our understanding, risk assessment, and modeling capabilities should be encouraged. How potential flooding and flood risk will change under climate change should be discussed and communicated broadly. These strategies will push GEWEX to remain vigilant and communicate those ever-growing risks and vulnerabilities and help the creation of a worldwide resilience network to continue global conversation and dialogue among regions and communities.

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TEAMx: A Joint Research Initiative Focused on Atmospheric Transport and Exchange Processes over Mountains

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Multi-scale Transport and Exchange Processes in the Atmosphere over Mountains–Programme and Experiment (TEAMx)

TEAMx is an international research program dedicated to improving the understanding of atmospheric transport and exchange processes over mountains, evaluating how well these are represented in weather and climate models, and improving model performance to provide more reliable information for societal applications. In mountain regions, the exchange of energy, mass, and momentum between the Earth's surface and the atmosphere is extremely complex. Multitudes of physical processes with vastly different controls interact across a wide range of spatial and temporal scales. This situation is dramatically different from the assumptions used in developing most of our observational and modeling tools that are largely based on more ideal terrain. In mountainous areas, the validity of these assumptions is often questionable, if not clearly problematic, which could potentially lead to large errors in the output of weather and climate models, and therefore in the applications relying on these data. Considerable errors must be expected in predictions that do not accurately account for complex terrain and its effects–with wide-reaching implications for the surface energy balance (Fig. 1), the global carbon budget, the mass balance of glaciers, and long-range transport of pollutants, to name a few. An important example of reducing errors in predictive capability is the substantial improvement in weather forecasts following the inclusion of orographic drag. Furthermore, exchange processes over mountainous regions largely determine the availability of water for both the mountain and downstream populations. Observing, understanding, and modeling processes relevant for water availability in and downstream of mountain areas is one of the main reasons that TEAMx is a cross-cutting project of the GEWEX Hydroclimatology Panel (GHP).

Despite the importance of mountainous regions, their inherent complexity presents major challenges to our means of studying them. Fortunately, recent advances in instrument technology and modeling capabilities offer new means to tackle the challenges of complex mountain environments. The TEAMx Memorandum of Understanding (currently signed by 29 partners from ten countries) sets out these considerations and calls for considerable international effort to address these challenges.

TEAMx will use state-of-the-art measurement and modeling techniques to study a wide variety of mountain-related phenomena across a range of scales and the interactions between

Figure 1. Preparation for the TEAMx Observational Campaign: work on one of the long-term surface energy balance towers in highly complex terrain in the Inn Valley Target Area, Austria, one of three target areas in TEAMx. Photo courtesy of Ivana Stiperski, University of Innsbruck.

these scales. A major observational campaign involving large-scale deployment of in situ and remote sensing instruments from both ground-based and airborne platforms will be closely integrated with coordinated model evaluation and development studies combining a hierarchy of tools from large eddy simulations to regional climate models. Compared to previous internationally-coordinated atmospheric research programs in mountainous terrain, such as the Alpine Experiment (ALPEX: Global Atmospheric Research Programme, 1986) or Mesoscale Alpine Programme (MAP: Bougeault et al., 2001), TEAMx will investigate smaller-scale processes (with a focus on near-surface exchange) and how these small-scale processes are influenced by and interact with larger-scale processes.

Specific research questions as well as the broader scientific motivation behind this bottom-up initiative is outlined in the TEAMx White Paper (Serafin et al., 2020), which was delivered following the First TEAMx Workshop in Rovereto, Italy, in August 2019. The White Paper summarizes the current state of knowledge on mountain meteorology and mountain climate from a series of recent review papers specially commissioned for the journal *Atmosphere* (Zardi and Rotach, 2021). TEAMx research topics are organized into six working groups on *Atmospheric Chemistry*, *Mountain Boundary Layer*, *Mountain Climate*, *Orographic Convection*, *Surface-atmosphere Exchange*, and *Waves and Dynamics*, each with more specific aims. TEAMx events, projects, and working groups bring together different communities interested in mountain research along with more applied scientists so that new knowledge gained can be used to benefit society in various ways. This interdisciplinary approach will overcome the lack of communication traditionally found between the mountain weather and mountain climate communities.

A Joint Experiment with Coordinated Field Campaign and Modeling Activities

Obtaining representative measurements in mountainous terrain is a major challenge due to the extremely high spatiotemporal variability of the surface and atmosphere, and a wide range of transport and exchange processes that occur in three dimensions and span multiple scales (Fig. 2, see cover). Multiple repeat observations are needed at several sites to capture mesoscale to regional-scale variations, while spatially-distributed observations are needed in areas of interest to capture microscale to local-scale variations and allow process studies. Such a campaign demands a large amount of instrumentation, and hence a major international collaborative effort is required.

Researchers and specialized instrumentation from all over the world will be brought together in a joint field campaign: the TEAMx Observational Campaign (TOC), which will take place from spring 2024 to spring 2025. The whole campaign will span one year and will include two Extended Observation Periods (EOPs), one in summer and one in winter. These two EOPs will allow a range of processes to be investigated, including thermally-driven circulations in summer and snow-related processes in winter. The main study region is the European Alps, and three target areas have been identified for more detailed study: the Inn Valley in Austria, the Adige Valley in northern Italy, and the alpine foreland in southern Germany. These target areas have been selected based on the availability of existing long-term measurements (important for closing the gap between field campaign and climate timescales) and local knowledge gained through previous research, as well as the objectives of TEAMx. Through TEAMx, additional long-term monitoring sites are also being established in the alpine region, improving coverage of observations. TEAMx operates an open data policy, so all TEAMx data sets will be available for use by the wider community.

To supplement the existing observations and monitoring networks, a considerable amount of additional instrumentation will be installed during the TOC: a dense network of meteorological and air quality monitoring stations will provide information on near-surface conditions; numerous eddy covariance stations over a range of surface types (including urban and glacier) will provide information about near-surface turbulent exchange processes; and a variety of remote sensing instrumentation, radio-soundings, and aircraft measurements will provide atmospheric profiles and offer insights into the valley atmosphere and conditions aloft. The range of equipment deployed will enable new instruments (and new combinations of instruments) as well as novel retrieval processes to be tested and evaluated against more traditional techniques. A detailed plan describing the TOC is currently being revised following discussion at the Second TEAMx Workshop, which was held online in May 2021 and brought together 180 TEAMx researchers.

TEAMx numerical modeling experiments will involve idealized, semi-idealized, and real-terrain simulations, from large eddy simulations to regional climate modeling. In order to capture processes in mountainous terrain, higher-resolution simulations are generally needed, which gives rise to various issues (e.g., numerical stability in steep terrain, availability of spatial data sets, a disconnect between the representativeness of point measurements and model grid points, the grey zone of turbulence). The numerical modeling plans within TEAMx are currently being drafted and will include current best-practice recommendations for dealing with these issues, as well as a summary of known model biases over complex terrain.

Some of the modeling activities most relevant to GEWEX include assessing and improving downscaling algorithms for precipitation in complex terrain, development of improved snow depth models, and a convection-permitting model intercomparison that will explore processes affecting orographic convection and help ensure that models provide accurate results for the right reasons. High-impact weather events such as flash floods, landslides, avalanches, air quality events, downslope windstorms, and convective storms are especially relevant in mountainous areas, yet they are difficult to predict. TEAMx will conduct targeted research into specific physical processes relevant to extreme weather to understand how predictive capability is currently limited and develop improved parameterizations.

A cornerstone of TEAMx is the close links between observations and modeling. As such, the TEAMx Experimental Plan is being developed from a dual perspective of both observation and modeling and, critically, the need to integrate and assimilate the two. Plans for the field campaign involve an exceptional range of cutting-edge instrumentation that will help to provide a three-dimensional characterization of the atmosphere and insight into processes across multiple scales. At the same time, a variety of state-of-the-art modeling studies (1 m large eddy simulations; 1 km climate simulations; idealized, semi-idealized and real-terrain simulations) will be used to investigate processes that cannot be measured directly, to extend the coverage of instrumentation, and to conduct careful experiments to investigate the controls on particular processes. The TOC will provide an unparalleled data set for model evaluation and development. At the same time, modeling will be used to help design the campaign and to assist interpretation of new observation methods (e.g., the accuracy of lidar retrievals). Operational forecasts will be provided to help decision-making during the campaign.

One of the main TEAMx objectives concerns the translation of scientific knowledge into critical information for applications. Although the current priorities are planning and securing funding for the experimental (observational and modeling) activities, these plans are being developed with applications in mind. In May 2020, the *TEAMx Programme and Applications* webinar (*http://www.teamx-programme.org/splinter-meeting/*) included contributions on hydrology, avalanche warning, aviation meteorology, urban air quality, and renewable energy, among others, and several of the presentations at the Second TEAMx Workshop were on applied topics (such as wind energy, air quality, ecology, and hydrology) relevant to the TEAMx Target Areas. As the program develops and new science emerges, we anticipate closer and closer links with climate services.

Current Activities

With less than three years until the TOC, the TEAMx community is busy making preparations: writing proposals to secure funding, conducting preliminary studies (e.g., Adler et al., 2020), surveying field sites and, in some cases, conducting work on already-funded TEAMx projects. TEAMx Working Groups meet regularly to discuss plans for the experimental work or review current knowledge. In preparation for the TOC, a climatology of convective initiation over the study region has been conducted based on lightning data, with a second in preparation using radar data.

If you are interested in finding out more or joining the TEAMx effort, please contact the program coordination office (helen.ward@uibk.ac.at) or visit the TEAMx website (*http://www.teamx-programme.org/*).

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Airborne Platforms to Advance NASA Earth System Science Priorities: Assessing the Future Need for a Large Aircraft

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At the request of the National Aeronautics and Space Administration (NASA), the U.S. National Academies established a committee of experts and conducted a consensus study to provide guidance about future needs for airborne platforms to achieve Earth system science research goals. Released in May 2021, *Airborne Platforms to Advance NASA Earth System Science Priorities: Assessing the Future Need for a Large Aircraft* (NASEM, 2021) examines the combination of suborbital airborne platforms (piloted aircraft, uncrewed airborne systems, and balloons) that can best contribute to meeting priority science questions identified in the latest National Academies' 2017 decadal survey of Earth science applications from space (NASEM, 2018). Emphasis was placed on identifying the emerging questions that can be best addressed with large aircraft similar to the Douglas DC-8-72 (hereafter DC-8) in NASA's current fleet.

A major focus of NASA's integrated Earth system science research strategy is the ongoing collection of Earth observations through satellites, suborbital airborne platforms, and surface measurements. Together, data from those observations inform societally-relevant decisions ranging from weather prediction to the management of air pollution to the assessment of sea-level rise.

***Figure 1**. Conceptual diagram of the range of Earth observation platforms to support integrated Earth system science research*

This report focuses on six of the priority research areas identified in NASEM (2018) in which airborne platforms are used to undertake research: coupling of the water and energy cycles; physics and dynamics for improving weather forecasts; air quality and atmospheric chemistry—chemistry coupled to dynamics; ecosystem change—land and ocean; sea-level rise in a changing climate and coastal impacts; and surface dynamics, geological hazards, and disasters. For each area, the committee considered the role of large and small aircraft; the types of variables to be measured; the contribution of newly-available airborne platforms; and the support that airborne platforms provide for satellite calibration and validation, computer model testing, instrument development, and workforce training and development.

The report also emphasizes interdisciplinary science to meet societal needs, and includes two examples where a large aircraft can be leveraged: 1) extreme precipitation and flooding, and 2) wildfire events. These examples highlight emerging societal applications that require advancing understanding, prediction, and decision-making on topics spanning multiple disciplines, and are timely subjects given the prevalence of these events and their widespread impacts across the globe today.

A large aircraft that has the DC-8–like combination of long duration, heavy lift, multiple ports, and cruising ability at all altitudes from Earth's planetary boundary layer up to about 12.5 km provides unique value to Earth system science research. Necessary attributes for such a large aircraft include the capacities to take simultaneous, co-located measurements; access remote regions of the Earth; enable new approaches for multi-instrument and air-deployable payloads; support instrument development and people to operate those instruments onboard; calibrate and validate space-based remote sensing observations in widespread locations; provide capacity to examine unexpected environmental events; and to engage and train the next generation of Earth system scientists. These attributes and further suggestions take the form of six recommendations to NASA.

Recommendation 1: NASA should acquire, maintain, and operate a large aircraft as part of its aircraft fleet in order to address priority questions developed for the 2017 Earth Science and Applications from Space Decadal Survey to support satellite calibration and validation, computer model testing, instrument development, and workforce training and development.

Recommendation 2: To meet NASA objectives, a new large aircraft must have characteristics comparable to or better than those of the DC-8 in terms of payload capacity, altitude and distance ranges, instrument sampling port versatility, instrument integration, and durability.

A new large aircraft is a necessary member of the NASA fleet, but is only one contributor to the array of airborne platforms needed to address Earth system science objectives (See Fig. 1). Airborne platforms with diverse specifications of payload, range, altitude, onboard pilot, and operational flexibility form a complementary fleet that can meet a wide range of mission objectives, often in collaboration with the fleets of other research agencies, private organizations, and other countries.

Recommendation 3: NASA should continue operating a diverse array of airborne platforms in addition to a large aircraft, as part of the broader government, university, and commercial fleet, in order to meet the evolving airborne needs for advancing Earth system science research.

The inherent complexity of the Earth system, emerging questions resulting from a foundation of disciplinary knowledge, and rapid Earth system changes observed today highlight the need for growth in interdisciplinary research to meet societal needs. The report encourages NASA to proactively seek proposals involving innovative approaches for using a large aircraft to accomplish interdisciplinary and surface remote sensing research, in addition to new disciplinary research. Doing this will increase the impact that a large aircraft can have on achieving NASA's Earth system science research goals.

Recommendation 4: NASA should continue to solicit large aircraft requests that span the breadth of NASA Earth science, especially encouraging those for interdisciplinary science across the interfaces of Earth system components with integrated multi-instrument payloads and novel strategies for remote sensing and in situ observations.

Future advancement of NASA Earth system science research depends on the continual emergence of early-career scientists to develop new measurement concepts, make measurements, and eventually take over field study leadership roles. A large aircraft is an important facility for attracting, training, and developing a diverse workforce and engaging the public because it provides the space to accommodate additional passengers beyond the core scientists and crew needed to carry out missions.

Recommendation 5: NASA is encouraged to build on the training and outreach opportunities it has established using the DC-8 and use a future large aircraft to expand its efforts to attract, develop, and train the next-generation workforce, with particular emphasis on diversity, equity, and inclusion, to foster the capacity to conduct international Earth system science research, and to inform the public.

Recommendation 6: NASA is encouraged to continue building on its use of the large aircraft capacity to enable scientists with next-generation measurement concepts, especially early-career scientists, to become active participants in Earth system science research, even beyond airborne science research.

Download the full report or our 4-page report highlights (*https://www.nap.edu/catalog/26079*) for more information.

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A Second Career for the "COMET" Supercomputer: Petascale Computing to Support Research and Prediction for Western Weather and Water Extremes, from the Ocean to Atmospheric Rivers, Precipitation, Hydrology, S2S and Use of Community Models

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Supercomputing is both a major resource and a limitation in the science and prediction of weather, water, and climate. For instance, it represents the capacity to explore new processes, numerical methods, resolutions, and ensemble sizes, and yet there are so many promising directions to pursue that the amount of computing power available for use in our field is a major constraint on innovation. This paper summarizes a two-pronged approach to this dilemma: (a) repurposing a used supercomputer and (b) focusing it on a specific topic, i.e., the science and prediction of water cycle extremes and their cascading impacts in the Western United States, especially their major driver: atmospheric rivers (ARs) and the associated precipitation and runoff.

The program described below is led by the Center for Western Weather and Water Extremes (CW3E) at the Scripps Institution of Oceanography of the University of California San Diego, in partnership with the San Diego Supercomputing Center (SDSC). It is supported by state and federal water agencies.

The focus on water cycle extremes is driven by the fact that water management, flood control, and wildfire are major challenges in the Western United States and all are driven by too much or too little precipitation. In the West, these extremes are heavily influenced by AR storms that produce both beneficial water supply and hazards; for example, 25–50% of annual precipitation is provided by ARs, while 84% of all flood damage in the West (up to 99% in key areas) is associated with ARs. However, AR landfall forecast position errors can exceed 200 km at even 1-day lead time and yet many watersheds are <100 km across, which contributes to large flood forecast errors and issues such as the 2017 Oroville Dam spillway incident and presidential disaster declarations in 2020 and 2021 due to landfalling ARs in the Pacific Northwest. Combined with the rise of wildfires and deadly post-wildfire debris flows, such as Montecito (2018), the need for better AR forecasts is urgent.

The mission of CW3E is to provide 21st century water cycle science, technology, and outreach to support effective policies and practices that address the impacts of extreme weather and water events on the environment, people, and the economy of Western North America. To fulfill it, CW3E has reached an agreement with SDSC that provides the Center with exclusive access to the SDSC's petascale "Comet" supercomputer—which can perform nearly three quadrillion operations per second and has a storage of 12 Petabytes, thanks to a newly-purchased filesystem by CW3E. For reference, the computer will carry out over one billion core hours of work over three years, which is roughly equivalent to one year of the National Science Foundation's well-known "Cheyenne" supercomputer. This will enable CW3E researchers and collaborators to leverage Comet's computing resources, which are substantially larger than what typically is available for the development of a regional numerical weather prediction system. The goal is to significantly improve weather and hydrological forecasts to enhance the decision-making process associated with reservoir management over California, which could result in increased water supply and reduced flood risk over the region.

The CW3E Supercomputing Advisory Group (CSAG) includes scientists from CW3E and SIO, as well as recognized experts from the National Centers for Environmental Prediction (NCEP), European Centre for Medium-Range Weather Forecasts (ECMWF), National Center for Atmospheric Research (NCAR), Jet Propulsion Laboratory, University of Arizona, University of Colorado at Boulder, and Northern Illinois University. The CSAG operates as a directed research effort to aid CW3E in the selection of allocation requests. Projects are recommended by CW3E members plus CSAG and use a variety of community models and an array of promising technical approaches.

Some of the ongoing computational projects include CW3E's large ensemble (200 members), run at high-resolution (9 km horizontally, 60 vertical levels) based on CW3E's version of the Weather Research and Forecasting model ("West-WRF"), which is tailored to improve forecasts of ARs and extreme precipitation over the West; testing of the NCEP's experimental Global Forecast System v16 and its limited-area regional modeling capability; a high-resolution (2 km, 100 vertical level) 40-year reanalysis based on West-WRF downscaling of ECMWF Reanalysis Version 5; nature runs with NCAR's Model for Prediction Across Scales to perform predictability studies; high-resolution, high-top subseasonal-to-seasonal ensemble predictions with NCAR's Community Earth System Model Version 2; high-resolution hydrodynamic modeling for flood and inundation risk analysis with the University of Bristol's LISFLOOD-FP; and ocean-atmosphere coupled modeling experiments with the Massachusetts Institute of Technology's general circulation model (ocean) and WRF (atmosphere).

The program is well underway, producing unique modeling outputs relevant to water cycle extremes. CW3E solicits requests semiannually from center members, affiliates, and collaborators for use of Comet's computing resources. Stay tuned for future announcements (*https://cw3e.ucsd.edu*), including potential opportunities to participate.

Updates on the International Land Surface Interactions with the Atmosphere over the Iberian Semi-Arid Environment (LIAISE) Field Campaign

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Introduction

The overall objective of the Land surface Interactions with the Atmosphere over the Iberian Semi-arid Environment (LIAISE) project is to improve the understanding of land-atmosphere-hydrology interactions in a semi-arid region characterized by strong surface heterogeneity owing to contrasts between the natural landscape and intensive agriculture. It is known that irrigation can potentially impact the local atmospheric boundary layer (ABL) characteristics, thereby modifying near surface atmospheric conditions within and downwind of irrigated areas (e.g., Lawston et al., 2020) and potentially the recycling of precipitation. The understanding of the impact of anthropization and its representation in models have been inhibited due to a lack of consistent and extensive observations. In recent years, land surface and atmospheric observation capabilities have advanced while irrigated surfaces have been increasing, leading to a renewed need for dedicated field campaigns over contrasting (climate) regions. For example, the Great Plains Irrigation Experiment (GRAINEX) in the summer of 2018 focused on the impact of irrigation on coupled surface-atmosphere processes over a mesoscale region in eastern Nebraska (Rappin et al., 2021). In this paper, we present a summary of the LIAISE field campaign intensive phase, which took place over the Catalan counties of Urgell and Pla d'Urgell within the Ebro basin in northeastern Spain this summer (after a one year delay owing to the COVID-19 pandemic). In contrast to the GRAINEX experimental zone, LIAISE is located in a semi-arid hot, dry Mediterranean climate, with a very sharp delineation between a vast, nearly continuous intensively-irrigated region and the generally much more dry rain-fed zone to the east of the study domain. There are discussions underway to further expand this irrigated zone owing to its economic importance, but there is an urgent need to improve the prediction of the potential changes to the regional water cycle since water resources are limited (most of the water comes from reservoirs located in the Pyrenees Mountains to the north). The consensus of current climate projections predicts a significant warming and drying over this region in upcoming years. The science questions and main objectives of the LIAISE project were described in Boone et al. (2019); thus, this paper focuses on a short summary of the intensive field campaign this past summer.

Salient Weather Features

An intensive observation period (IOP) was defined a priori as being a relatively clear day characterized by a well-mixed atmospheric boundary layer with weak synoptic scale forcing so that surface-induced local to regional scale circulations are most likely to be present and detectable. In late July, synoptic scale winds are typically light and from the west, and a thermal (heat) low pressure area generally forms over the region with daily maximum temperatures in the mid-to-upper 30s °C, though it is not unusual for them to be upwards of 40–42 °C for several-day periods. This thermal situation has a strong impact on surface winds. Formation of some shallow cumulus is possible, but moist convection, if present, is generally confined to the surrounding mountain ranges. Owing to the proximity to the Mediterranean Sea to the east, sea breeze (SB) formation is quite frequent, but its inland progression is slowed by the presence of the Catalan pre-coastal and coastal ranges that separate the Ebro basin from the sea. The intensity of the westerlies and strength of the heat low are also contributing factors to the SB front propagation and intensity. Generally speaking, the SB front usually arrived sometime between 16:00 and 19:00 local time over the study zone with the dry zone sites impacted earliest. The SB passage was seen in the observations as a low level wind shift (to winds with a significant easterly component) over the entire region, while in the east, horizontally-scanning lidar observations also revealed a significant increase in low-level moisture with its arrival. The sea breeze generally coincided with a collapsing ABL in the late afternoon. Days with a predicted early arrival of the SB were not designated as IOPs during the daily briefings. Finally, one rain event did occur on July 26, which was associated with the passage of a synoptic scale trough: local precipitation totals of around 30 mm were recorded over the irrigated zone; however, the convective cells propagated to the northeast and the dry zone received relatively little rainfall, thereby reinforcing the wet-dry zone contrast during the subsequent days of the SOP.

Observing Period Strategy

The observation strategy consisted of three periods:

1. The long observation period (LOP) monitored slowly-evolving land surface state variables (such as soil moisture, crop evapotranspiration, and temperature) and relatively autonomous surface flux measurements at five sites characterized by different but regionally-representative land cover types, covering the growing season of summer cultivars (ending in October or November).

2. The special observation period (SOP) occurred from July 15–29, when contrasts between irrigated and natural surfaces are generally at or near their maximum. Intensive surface-based and airborne measurements of the atmospheric boundary layer were made, along with intensive ecophysiological observations and remotely-sensed high spatial resolution mesoscale measures of surface variables from aircraft and unmanned aerial vehicles (UAVs). Two additional local-scale energy budget and soil moisture sites were added for the SOP, since they were used to evaluate remote sensing data from aircraft.

3. IOPs were defined as days within the SOP for which sufficiently good meteorological conditions occurred to justify the full complement of measures mentioned in item 2). Fortuitously, the weather during the SOP was nearly ideal and enabled 11 IOP days.

Forecast Support/Decisions

A daily briefing was held each morning (09:00 to 12:00 local time), which consisted of a review of the previous day's scientific activities and potential technical issues, a forecast briefing, and a final discussion to propose an IOP day 2 days in advance, to confirm 1 day in advance and potentially to cancel it on the morning of the IOP (in the case of a significant and poorly-anticipated degradation of weather conditions or technical issues). Daily forecast briefings were provided by a team of forecasters from the Meteorological Service of Catalonia (SMC) and three students from the Météo-France National Meteorological School (ENM). Forecasts were based on operational model outputs from a version of the Weather Research and Forecast (WRF) model used by the SMC, the European Center for Medium Range Prediction (ECMWF), Research Actions from small to large scales (ARPEGE) and Application of Research at the Operational Mesoscale (AROME) models. The operational WRF-ARW configuration uses grid nesting with a cascade from 9 to 3 km spatial resolution, but outputs from a research version running at 1.5 km was also used. AROME (the domain covers most of Spain) is run operationally at 1.3 km. The other two models are global (resolutions less than about 10 km over the area). These forecasts were used to coordinate aircraft flight timing and paths, the different surface-based atmospheric monitoring operations, and for coordination with different teams making surface measurements for calibration and evaluation of data from airborne sensors.

Aircraft

Eight flights were made on IOP days by the French Office of Aircraft Instrumented for Environmental Research (SAFIRE) ATR-42, which consisted of two legs. During the first leg, the goal was to explore the properties of the convective boundary layer and measure the turbulence (at five vertical levels ranging from 300 m to several km in altitude) over roughly 15 km transects within both the irrigated and rain-fed zones. In the second leg, 16 km transects crossing between the two zones at a constant height for which airborne high spatial resolution measures were made of atmospheric state variables (Fig. 1), soil moisture, vegetation water content, photosynthesis and biomass from the GNSS-R dual polarization airborne instrument (the Global navigation satellite system Reflectometry Instrument, GLORI), and solar-induced fluorescence (SIF) from the HyPlant imaging spectrometer. NASA flew the Scanning L-band Active Pas-

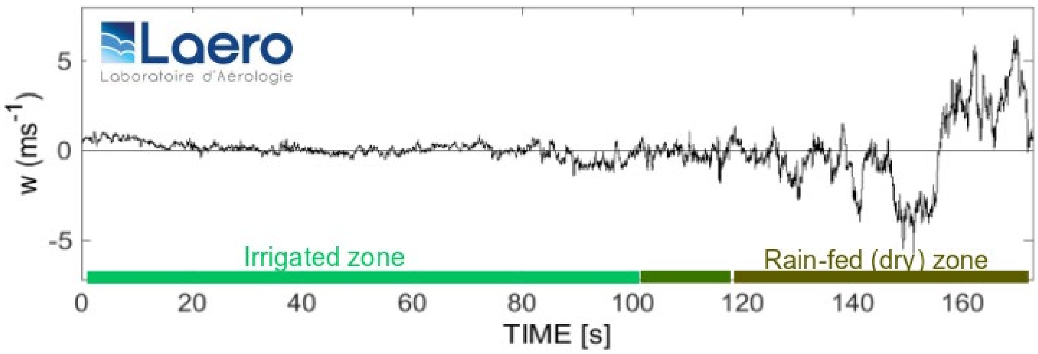

***Figure 1**. Vertical velocity measured by the ATR32 on July 21 at a height of 1240 m moving from NE to SW across the irrigation transition to rain-fed surfaces starting at 13:47 UTC (on the left).*

sive (SLAP) sensor on a B200 King Air to provide soil moisture over both irrigated and non-irrigated zones. Most flights were low altitude (300 m), providing a unique opportunity for small 100x200 m footprints. Two flights were at medium altitude (~800 m) to provide wider context. Data products will include passive brightness temperature, active backscatter coefficient, and soil moisture (from the passive). Thermal infrared (IR) data will also be available. Nine science flights were conducted, and conditions were favorable, including observations of irrigation events and precipitation followed by a dry down. A third aircraft, the Flying Laboratory of Imaging Systems (FLIS) airborne infrastructure operated by Czechglobe, performed five successful flights: visible and near-infrared and longwave infrared hyperspectral imaging sensors were utilized for data acquisition of target areas under different viewing angles. The study was focused mainly on research of the Bidirectional Reflectance Distribution Function (BRDF) effect.

The drone activities in July 2021 had four top priorities: a) analysis of the vegetation activity by SIF imaging (six flights), b) identification of stress situations of the vegetation by multispectral and thermal imaging (26 flights), c) meteorological vertical profiling of wind, temperature, and humidity (36 flights), and d) supporting flights providing high-precision maps and digital elevation models (5 flights). Some of the flights, i.e., the SIF flights, were closely correlated to manned aerial flights. The drones proved to be a valuable and complementary tool with respect to the ground-based and other airborne (balloons, manned aircraft) systems and instruments.

Surface Network

The study zone covered approximately a 30x30 km square (Fig. 2), which is divided by a boundary (from southwest to northeast) between the irrigated and rain-fed zone (southeastern part). Seven observing sites were installed with nine surface energy budget (SEB) observing stations (one site, Mollerussa, included three SEB stations over different vegetation types) and two weighing lysimeters in apple trees. All of the SEB stations used eddy covariance to compute turbulent fluxes in addition to including the main components of the surface radiation balance. The study zone location allowed the project to benefit from the dense local meteorological station and radar data from SMC, along with an existing extensive observation site run by the Institute of Agrifood Research and Technology (IRTA) and SMC in Mollerussa. Three of the locations were over cultivars within the irrigated zone, three were located within the dry zone (one was drip irrigated), and the final location is a lake within the irrigated zone. Leaf-level and canopy-level ecophysiological data were collected for five vegetated SEB sites. Field scale turbulence estimates from scintillometers were made at three of the sites. Finally, two of the sites (La Cendrosa and Els Plans) were complemented by extensive measurements of the lowest part of the atmosphere using captive balloons, frequent radio-sounding releases, UHF wind profilers, and lidars. Ecophysiological measurements were conducted both at leaf- and canopy level at all of the field sites within the LIAISE domain with the objective of: providing vegetation-specific parameters for land surface models, providing leaf-level and canopy-level traits as ground-truth for remote sensing and eddy covariance measurements, quantifying diurnal patterns in leaf-level transpiration in response to drought stress, and quantifying partitioning of evaporation versus transpiration and photosynthesis versus soil respiration. A summary of the sites is given below where wet zone and dry zone indicate sites within the irrigated or rain-fed parts of the study domain, respectively.

La Cendrosa Site: Irrigated Alfalfa (Wet Zone)

The La Cendrosa supersite was irrigated just before and once during the SOP using the flood/gravity method. The crop was cut just before the start of the SOP, and was ready for cutting by the end with a height of about 70 cm. A 50 m mast was installed with a SEB station that measured meteorological variables at three levels and enabled turbulent flux computations at two. A distributed temperature-sensing Raman scattering optical cable was also mounted along the tower and across the field which provided high frequency temperature measurements every 12–25 cm. A laser scintillometer was installed for estimating parcel-scale sensible heat flux. Hourly radiosondes (up to ~3 km) and tethered balloon flights (at levels ranging from 50 to 600 m) were carried out on IOP days roughly from sunrise through early evening, and a total of 152 radiosondes were released. A UHF wind profiler (wind and certain turbulence measures from 200 m to 3000 m) and a vertical profiling lidar (40 to 250 m) were in operation throughout the SOP. A Parsivel2 disdrometer was also installed near the 50 m mast. A great deal of ecophysiological measures at the plant and leaf level were made, which included in situ measurements of vegetation fluorescence (passive and active fluorescence and gas exchange), CO_2 assimilation (A-PAR), stomatal conductance,

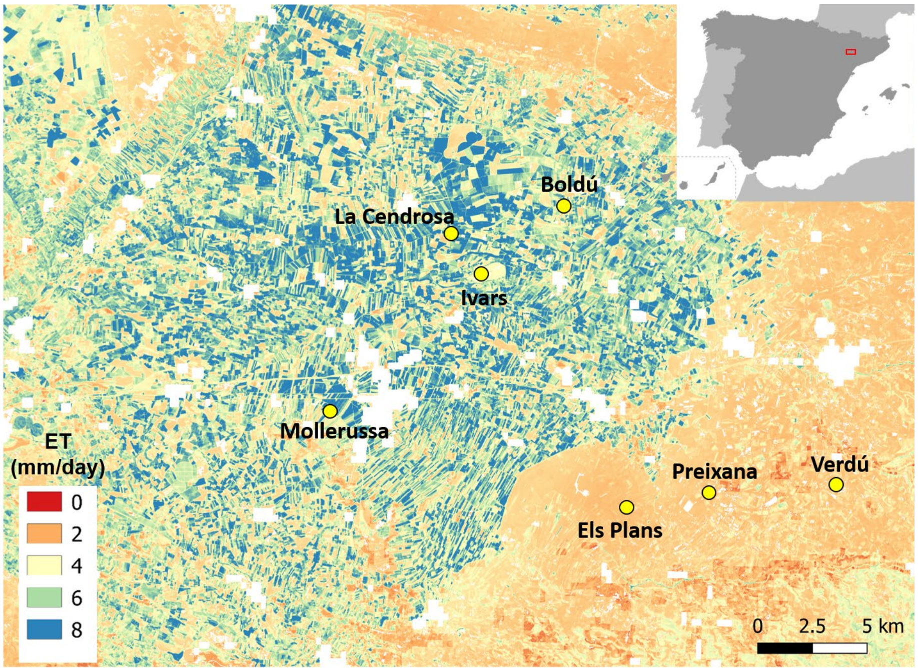

Figure 2. The LIAISE study zone in Catalonia (NE Spain) with surface site locations plotted over a map of crop evapotranspiration corresponding to 17th July 2021, obtained through a Two-Source Energy Balance (TSEB) model using images from Sentinel-2 and Sentinel-3. Prepared by IRTA.

photochemical yield, fluorescence (fraction of absorbed photosynthetically active radiation, or F-PAR), chlorophyll content, vegetation height, leaf reflectance, leaf area index, and water and carbon isotopes. SIF was also observed remotely from UAVs with RGB and multi-spectral instruments.

Els Plans Site: Winter Crops and Seasonal Bare Soil (Dry Zone)

At the Els Plans supersite, a naturally rain fed area, a 50 m mast was deployed and included meteorological parameters and flux measurements at a number of heights, surface canopy measurements and subsurface moisture, surface temperature, and thermal imaging. On 7 IOP days, boundary layer profiles were made between sunrise and 19:00 local time. On 4 evenings, the soundings were extended to 23:00 local to capture the ABL evening transition. A total of 116 radiosonde releases were achieved to a maximum height of 8 km. The evening transition soundings were extended into the stable boundary layer by deployment of a tethered balloon. Finally, a lidar setup was installed near this site, pointing northward with a swath across the transition zone between the irrigated and rain-fed zones which provided measures of state variables and turbulent fluxes. A series of soil evaporation experiments were made, for example, by small mobile lysimeters.

Ivars Site: Lake (Wet Zone)

The lake has a surface of approximately 1x2 km, and is on the order of 1–2m deep. A floating SEB station was anchored near the center of the lake during the entire LOP. Lake water temperature measurements at depths of 5, 10, 30, 50, 100, and 150 cm were measured, along with periodic measures of lake turbidity. Two screen-level meteorological measurement stations were installed on opposite sides of the lake in proximity to an optical large aperture and a microwave scintillometer (operational during the SOP). Turbulent flux measurements over the lake can thereby be compared with those from the floating SEB station. Finally, several UAV flights were made to map the surrounding topography for high resolution modeling studies.

Preixana Site: Almond Orchard (Dry Zone)

A SEB station was installed in a rain-fed almond tree grove near Preixana within the dry zone. The measurement of the turbulent fluxes is done from the top of a scaffolding 2 m above the trees. The system was complemented by soil temperature and moisture measurements.

Mollerussa Site: Irrigated Apple Orchard, Corn Field and Short Grass (Wet Zone)

The Mollerussa site is located at the IRTA experimental facility, southwest of the town, and includes three separate SEB stations each over contrasting vegetation types and two weighing lysimeters. Here, there was a particular focus on evapotranspiration (ET) estimates (contributing directly to the GEWEX ET initiative: Cuxart et al., 2019). The first site is within a drip-irrigated apple orchard irrigated under two different irrigation strategies (full-irrigation and stressed) during the IOP campaign. A SEB station was installed over the weighing lysimeter located in the fully-irrigated part of the orchard in order to give ET estimates using two different approaches. Two sets of soil sensors were deployed on both sides of the irrigation line, each consisting of temperature measurements at multiple levels and a heat flux plate and a water content reflectometer just below the soil surface. Infrared temperature sensors were also installed above apple trees in order to monitor continuous canopy transpiration. An automatic weather station from the SMC network is maintained a few meters north of the apple orchard, and a second SEB station was installed within an irrigated cornfield. Finally, for the LIAISE campaign, a complete SEB station was installed over a well-irrigated short grass surface to monitor the so-called reference ET0. An optical microwave scintillometer was set up to provide field scale turbulent fluxes. The lower atmosphere was monitored using a radio acoustic sounding system (RASS) sodar to provide vertical profiles of the wind and virtual temperature between 40 and 300 m above the ground, and a UAV made lower atmospheric profiles. Several flights were also conducted with an UAV equipped with multispectral and Thermal-IR cameras in order to evaluate the performance of the thermal-based Two-Source Energy Balance (TSEB) model for estimating daytime ET and its partitioning components. Numerous ecophysiological measurements were also made, many the same as at La Cendrosa; however, several specific experiments were designed to contrast certain processes over well-irrigated versus sparsely-irrigated plots, such as stomatal conductance at the apple orchard.

Verdú Site: Irrigated Vineyard (Dry Zone)

A SEB station was installed over a vineyard near the town of Verdú. The objective of this experiment is to provide flux, vegetation, and soil moisture measurements for use in an improved version of the Food and Agricultural Organization Irrigation and Drainage Paper No. 56 (FAO-56) model for rank tree crops (in collaboration with the European Space Agency). The vineyard row spacing is 4 m with no vegetation cover on the inter-row. The soil is very shallow (about 50 cm) and stony. The monitoring system includes a 4-band net radiometer, three soil heat flux plates, two SKYE Normalized Differential Vegetation Index (NDVI) sensors, three soil moisture sensors (5, 20 and 40 cm) on the row, and one surface soil moisture sensor on the inter-row. Three weather variables are also monitored: rainfall, temperature, and relative humidity. The experiment was supported by a weekly field survey of soil moisture and vegetation porosity.

Boldú Site: Multiple Irrigated Crops (Wet Zone)

A network of soil moisture sensors has been installed over different crops at Prat de Boldú in collaboration with a local irrigation consulting company, SAF-Sampling. The goal of this experiment is multi-purpose: first, to test an innovative low-cost soil moisture monitoring network; second, to provide validation data for the estimation of soil moisture by GLORI and the Sentinel-1 algorithm; and third, to improve an algorithm of irrigation retrieval from satellite data. In agreement with the Cooperative of Ivars, a network of two gateways and 14 soil moisture stations were installed. The site is characterized by cereal crops (barley, wheat, maize), vegetables (peas, broccoli), fodders (alfalfa), and apple trees. The irrigation methods are flooding, sprinkler (pivot, ramp, and full cover), and drip irrigation on broccoli. In addition, a full SEB station was installed in a corn field within the area that was flood-irrigated.

Perspectives

Data processing is ongoing, and data will be continuously uploaded to the LIAISE database (LIAISE-DB) maintained by Data and Services for the Atmosphere (AERIS). Currently, select quicklook images from the field campaign can be viewed at *https://liaise.aeris-data.fr/products/*, but over upcoming months and in 2022, processed data will be continuously updated. Simulations from modeling studies will also be contributed to the database in upcoming years. Field data will have an embargo period of three years; however, researchers may contact the LIAISE science principal investigators for specific instruments to obtain data sooner for research purposes on an individual basis. The data distribution policy is modeled after the GEWEX-supported Hydrological cycle in the Mediterranean Experiment (HyMeX) experiment and a final version will be posted on the LIAISE website by the end of 2021. It is planned that LIAISE data will be used for several planned GEWEX initiatives studying the regional scale water and energy cycles in upcoming years (Best et al., 2020). The LIAISE multi-mesoscale-model intercomparison project (*http://turbulencia.uib.es/intercomp_liaise/*) will contribute directly to the ongoing GEWEX ET initiative (Cuxart et al., 2019) and other LIAISE community modeling projects. The data also has the potential to help improve the retrieval of hydrology-related variables: at least two European Space Agency funded projects have plans to use the data set in order to improve our knowledge on the downstream impact of irrigation by water management agencies. More information on the project, workshop presentations, and information on the field campaign can be found at *https://www.hymex.fr/liaise/index.html*.

Two sites are being maintained over the longer term in order to cover the dry down, which was missed in 2021 due to travel restrictions. The Met Office 50 m mast will be deployed from June 2021 to July 2022, capturing the evolution of the surface and near-surface conditions over a 13-month period, including very dry conditions during the summer months, and soil moisture dry-down in the spring. Specific stable ABL experiments are also planned for the spring of 2022. The ET0 station and the RASS will also remain at Mollerussa for several years to complement research being done at IRTA and SMC.

Finally, a series of outreach actions have been planned in the Lleida region. During the campaign, presentations were made to local groups involved in viticulture, and classes were offered to a local high school (that graciously hosted the LIAISE forecast briefings) on land-surface interactions with emphasis on the objectives and results from the LIAISE campaign. A press conference was organized at IRTA during the SOP and interviews were presented on Catalan and Spanish television networks, and project summaries were published in regional and national newspapers and in Spanish agritech publications. More comprehensive outreach efforts are anticipated for 2022 led by IRTA and in conjunction with the first post-campaign LIAISE workshop.

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Cold Region Precipitation Consistency and Emerging Synergistic Earth Observations

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Precipitation is vital for life, and quantifying its amount and distribution is critical for sustainable development and for understanding the current state of Earth's climate and future changes through its important role in the energy balance of the planet (Trenberth et al., 2009; Stephens et al., 2012; L'Ecuyer et al., 2015). Recognizing its importance, significant efforts have been devoted to developing and assessing precipitation products using observations from rain gauges, satellites, or a combination of them, and some of these efforts are discussed in the recent *Joint International Precipitation Working Group (IPWG)/GEWEX Precipitation Assessment* report (Roca et al., 2021).

Yet, there are several areas where current precipitation products face challenges, partly due to limited observational capabilities and sensitivity of the instruments, limited understanding of the precipitation processes, and imperfect retrieval methods. Among these challenging areas are precipitation estimation in high latitudes and cold regions, especially over snow and ice surfaces. In such situations, in situ observations are also limited or face major uncertainties. This is more critical for snowfall due to wind-induced undercatch, which can result in up to 300% underestimation (Legates and Willmott, 1990). Efforts have been made to correct for local or regional gauge undercatch (Rasmussen et al., 2012; Grossi et al., 2017; Kochendorfer et al., 2017), but global implementations of these corrections require major assumptions and come with large uncertainties (Legates and Willmott, 1990; Fuchs et al., 2001). This has motivated the use of other synergistic Earth observing instruments that can potentially help with precipitation assessment and consistency studies, but so far they have been underutilized.

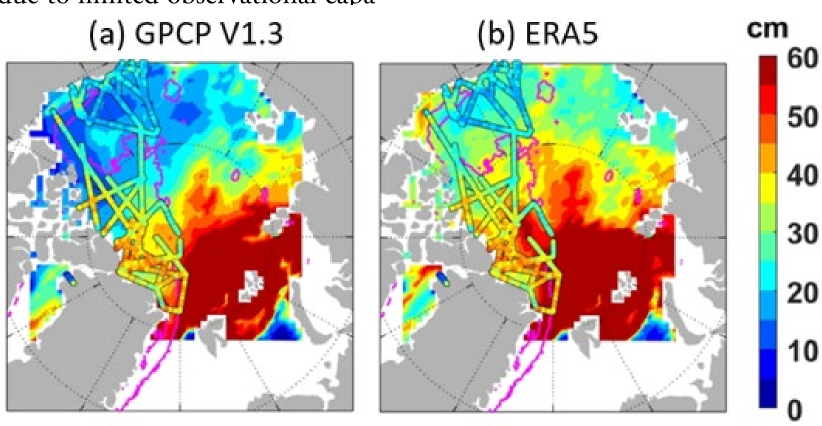

Figure 1. *Spatial distribution of Arctic sea ice snow depth reconstructed from satellite [Global Precipitation Climatology Project (GPCP)] and reanalysis [European Centre for Medium-Range Weather Forecasts (ECMWF) Reanalysis v5 (ERA5)] precipitation estimates in 2012. Observed snow depths from OIB are shown with flight paths. Figure from Song et al. (2020) with slight modifications*

Over a time span of subfreezing temperatures, changes in snow height [or snow water equivalent (SWE)] and snow mass can provide valuable insights into the amount of falling snow that has been difficult to retrieve from satellites. Changes in snow height and mass are signatures of snowfall accumulation on ground that can be quantified using synergistic Earth-observing instruments from space. Observation of snow depth can provide an estimate of the net snowfall accumulation after accounting for snow density, sublimation, redistribution due to wind, and melt losses between the two survey dates. Sublimation and snowfall redistribution are complicating terms, but are typically small and can be approximated by regional models or reanalysis. Melt losses are also negligible at subfreezing temperatures. Below we provide few examples of such opportunities.

Using fine scale observation of snow depth and careful approximation of snow density, changes in SWE from the Airborne Snow Observatory (ASO, Painter et al., 2016) have been used to quantify snowfall accumulation in cold mountain environments in the western U.S. and to assess snowfall accumulation from satellite-based precipitation products (Behrangi et al., 2018). At larger scales, SWE and snow depth can be obtained from individual or combinations of microwave radiometers (e.g., GlobSnow; Luojus et al., 2021), radars (e.g., Sentinel-1; Lievens et al., 2019), or innovative interpolation of in situ data (Zeng et al., 2018) with reasonable accuracy (Song et al., 2021; Panahi and Behrangi, 2020). Clearly, this approach has its limitations for low-quality SWE products (Gonzalez and Kummerow, 2020).

In cold months, vast areas of high latitude oceans are covered by sea ice, where almost no in situ observations of precipitation exist and the current precipitation products are highly uncertain (Song et al., 2020). However, measurement of the snow depth on sea ice is an active area of polar research and significant progress has been made, partly because the snow layer on Arctic sea ice regulates the surface heat balance and rate of ice growth through its insulating effect (Maykut and Untersteiner, 1971). Snow depth is also required to determine sea ice thickness from satellite altimetry (Kwok et al., 2017).

The ultra-wideband radar system on NASA's Operation IceBridge (OIB) airplane has made it possible to measure snow depth on sea ice (Brucker and Markus, 2013; Kwok et al., 2017) and compare it with snowfall accumulation from satellite (Song et al., 2020) or reanalysis (Blanchard-Wrigglesworth et al., 2018) products using proper snow density values and by tracking sea ice (DeRepentigny et al., 2016) (Fig. 1). Satellite altimetry can also potentially be used to produce spatially and temporally more-complete observations of snow depth on sea ice than those offered by OIB. Ice, Cloud, and land Elevation Satellite 2 (ICESat-2) together with CryoSat-2 should make it possible to extend snow depth estimations over the entire Arctic sea ice mass using differences in freeboard heights ob-

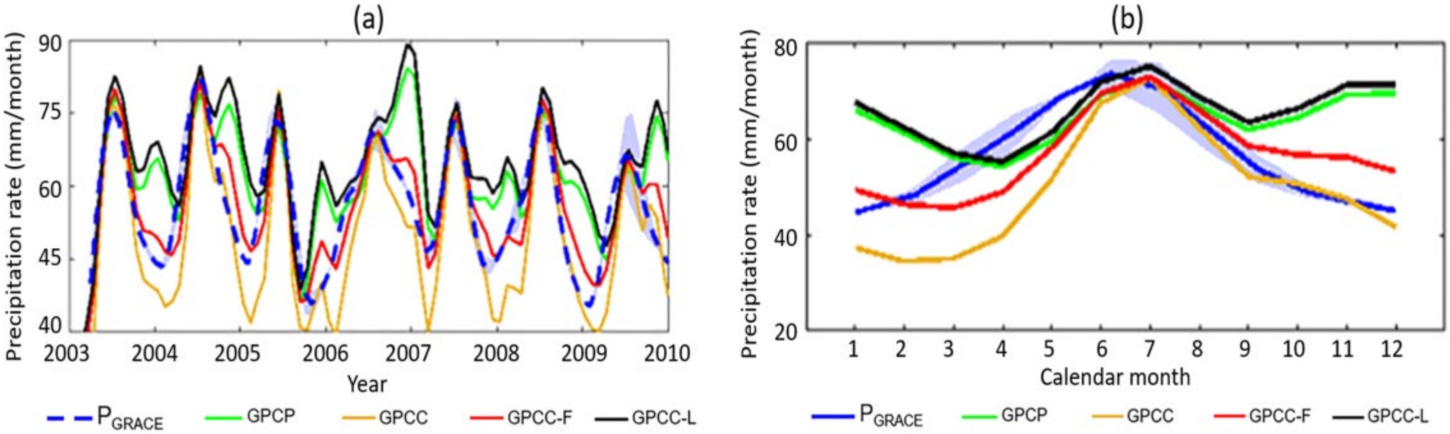

***Figure 2**. (a) Time series of monthly mean precipitation rates calculated from GRACE and comparison with the Global Precipitation Climatology Centre (GPCC) full data monthly (V7) (Schneider et al., 2017) with no correction for gauge undercatch, monthly GPCP V2.3 (Adler et al., 2018), GPCC corrected with Legates and Willmott (1990) gauge undercatch correction factor (GPCC-L), and GPCC corrected with Fuchs (2001) gauge undercatch correction factor (GPCC-F) over the Volga basin in Russia. (b) Monthly multiannual (2003–2010) mean precipitation rates. The shaded area around the GRACE-based precipitation rates represent upper and lower bounds of evapotranspiration estimates. Figure from Behrangi et al. (2019) with slight modifications*

served by the two instruments (e.g., Kwok et al., 2020). Upon acheiving quality snow depth estimates, unique opportunities exist to assess precipitation products over sea ice, where other alternatives are limited or non-existent.

By utilizing the mass signature of snow and measuring its changes, it is also possible to estimate snowfall accumulation. The Gravity Recovery and Climate Experiment (GRACE) (Tapley et al., 2004) and GRACE Follow-On (GRACE-FO) missions have made it possible to quantify changes in snow mass over sufficiently large areas after accounting for other terms in the water budget equation. In cold months, large areas in high latitudes remain frozen and lateral flows are often negligible. Therefore, estimation of snowfall accumulation mainly requires estimates of mass change, sublimation, and snow redistribution, and the latter two are often small. Lateral flows can also be ignored in endorheic (or closed) basins that retain water and allow no outflow to rivers or oceans.

By using GRACE mass change measurements in endorheic basins of High Mountain Asia, it was found that both satellite and gauge products can miss about 50% or more of precipitation in winter (Behrangi et al., 2017). By focusing on a basin with observed streamflow, it is also possible to solve a mass budget equation and calculate precipitation amount using GRACE observations and assess gauge undercatch correction factors (Figure 2). A similar concept can be applied to Antarctic basins where considerable ice discharge (flow of solid ice into the ocean) exists. Ice discharge has been computed with relatively good accuracy (Gardner et al., 2018) by combining a comprehensive record of recent changes in Antarctic-wide ice flow, calculated by applying novel feature-tracking methods to hundreds of thousands of Landsat images, with optimized flux gate definitions and an earlier mapping of surface velocity (Rignot et al., 2011).

Using ice discharge and GRACE mass change observations, it has been shown that about two thirds of snowfall accumulation maybe missed over Antarctica by the current constellation of satellites used for precipitation estimation (Behrangi et al., 2020). The insights gained from GRACE observations of snow mass changes have also been used to assess gauge undercatch correction factors that can be as much as a factor of three (Behrangi et al., 2018). Without correction for gauge undercatch, global land precipitation can be underestimated by about 6–10%, depending on the approach used for correction (Ehsani and Behrangi, 2021). It is worth mentioning that the GRACE-based estimate of snowfall accumulation in cold regions could potentially complement other existing remote sensing methods because it is based on a completely independent technique (gravimetry versus radiometry) with no need for empirical parameterizations and large assumptions for snowfall microphysics, surface cluttering and emissivity, ground-based calibration, and correction for gauge undercatch. Furthermore, it does not miss precipitation occurring between two satellite overpasses. However, the analysis needs to be done at a relatively coarse scale due to the limited spatial resolution of GRACE observations (e.g., 300 km).

Here, we have only described a few examples to demonstrate how synergistic Earth observing systems (radiometry, altimetry, Gravimetry, and in situ; Fig. 3) can collectively add insights to the quantification of snowfall accumulation in cold regions. However, the concept of utilizing the strength that each Earth observing system provides and using that to assess or complement existing products goes beyond that presented here. With multiple Earth observing systems flying currently or in the future, recognition and integration of their individual strengths and their complementary role in determining the components

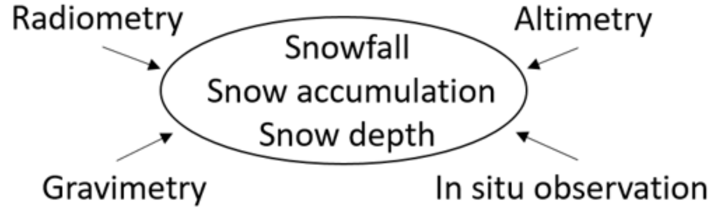

***Figure 3**. Synergistic observations for quantifying snow*

of the water and energy cycle seems to be a reasonable path forward that can help advance our understanding of the Earth system. Perhaps the next generation of instruments and products can collectively provide solutions to what seems to be difficult to achieve using a single type of instrument, or this approach can help gain a more realistic knowledge of the current uncertainties in quantifying the water and energy cycle components.

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Understanding Aerosol-Cloud-Meteorology Interactions Using Two Coordinated Aircraft

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In response to the large uncertainty in simulating weather and climate owing to the complex interactions between aerosol particles, clouds, and meteorology, the NASA Aerosol Cloud meTeorology Interactions oVer the western ATlantic Experiment (ACTIVATE) project is building an unprecedented airborne data set over the western North Atlantic Ocean. Advancing knowledge of aerosol-cloud interactions requires immense amounts of data covering a wide range of aerosol, cloud, and meteorological conditions to be able to disentangle the impacts of meteorology (e.g., winds, humidity) and aerosol particles on cloud behavior. ACTIVATE is deploying two aircraft (HU-25 Falcon and King Air) based out of NASA Langley Research Center (LaRC), with a goal of 150 joint flights between the two planes over three years (2020–2022). Flights span months ranging from November–March and May–September. After the first two years of flights, a total of 82 joint flights have been executed, including another 11 science flights with a single aircraft. Some of these flights were coordinated with the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) and Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) satellites, in addition to flights above surface-based remote-sensing monitoring networks near Hampton, Virginia. The third year of flights will occur from November 2021 to June 2022, with planned operations including secondary bases in Bermuda and the northeast U.S. to extend the spatial extent of the data set. Data are being publicly archived at *https://www-air.larc.nasa.gov/missions/activate/index.html*.

A highlight of ACTIVATE is the vertical synchrony of the two aircraft that fly in tight spatial coordination to offer detailed, simultaneous, and systematic measurements of aerosol particles, clouds, and meteorology (Fig. 1). The HU-25 Falcon (low-flyer) flies in the boundary layer where the clouds of interest are sampled, providing in situ measurements of trace gases, aerosol particles, clouds, and meteorology below, in, and above clouds. The King Air (high-flyer) flies at ~8–9 km to characterize atmospheric properties in the column underneath the plane with the Research Scanning Polarimeter (RSP) and the High Spectral Resolution Lidar-2 (HSRL-2). Dropsondes are also deployed from the King Air to measure profiles of atmospheric state parameters. ACTIVATE uses these advanced remote sensors to assess and advance aerosol and cloud retrieval capabilities to study aerosol-cloud interactions. The joint deployment of these remote sensors will addi-

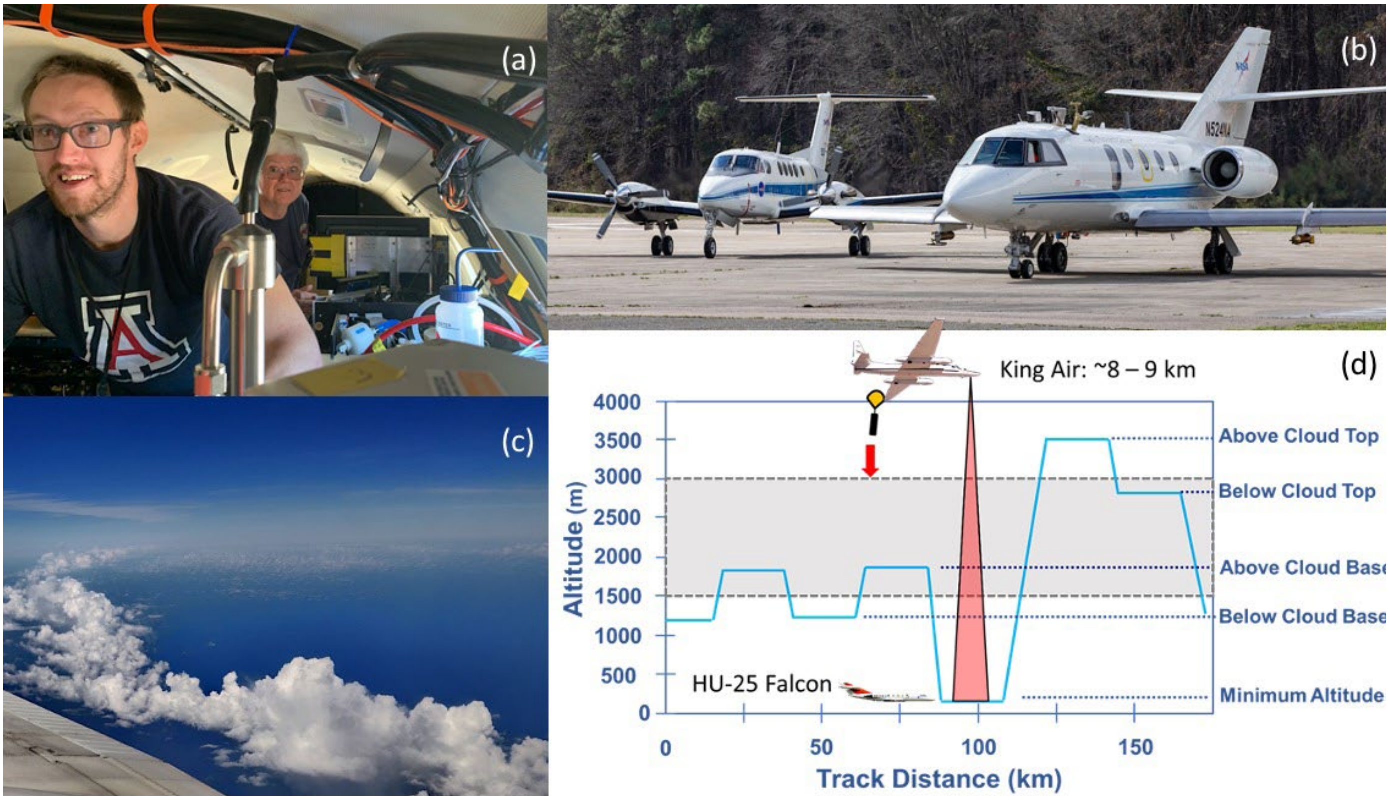

Figure 1. *(a) HU-25 Falcon flight scientists Ewan Crosbie and Edward Winstead preparing for an ACTIVATE science flight (credit: Johnathan Hair, NASA LaRC). (b) The NASA LaRC King Air (left) and Falcon (right) on the tarmac before a science flight (credit: David Bowman, LaRC). (c) Photograph from the King Air of boundary layer clouds being examined by the ACTIVATE campaign (credit: Taylor Shingler, LaRC). (d) Schematic of how the two coordinated aircraft do statistical sampling of aerosol-cloud-meteorology parameters during research flights, with the King Air flying aloft and the Falcon conducting legs at various altitudes below, in, and above clouds (credit: Andrea Corral, University of Arizona).*

tionally help assess current (e.g., CALIPSO) satellite measurements and can help the NASA Atmosphere Observing System (AOS, formerly ACCP) assess how such satellite and suborbital measurements can be used to address the National Academies 2017 Decadal Study recommendations for the aerosol and cloud designated observables.

In addition to building and archiving a valuable airborne data set, the ACTIVATE team is active in data analysis and modeling activities targeting three major objectives:

1. quantify relationships between aerosol particles, cloud condensation nuclei, and cloud drops and reduce uncertainty in model parameterizations of cloud droplet activation;
2. improve process-level understanding and model representation of factors governing cloud micro/macro-physical properties and how they couple with cloud effects on aerosols; and
3. assess advanced remote sensing capabilities for retrieving aerosol and cloud properties related to aerosol-cloud interactions. Early results from ACTIVATE science data analysis have been documented in 30 peer-reviewed publications.

Of particular interest during wintertime flights are cold air outbreak conditions, as climate models struggle to simulate the post-frontal clouds associated with these conditions. Summertime conditions are marked by higher aerosol concentrations, including the influence of biomass-burning emissions from the western U.S. and dust from North Africa, and lower cloud droplet number concentrations as compared to the winter.

To encourage data usage, the ACTIVATE team held a public data virtual workshop on 20–21 October 2021, attracting ~70 participants from different countries. The purpose of the workshop was to increase awareness of publicly-available ACTIVATE data and foster collaboration with scientists outside the ACTIVATE science team. The science team provided an overview of the mission and data products, and discussed a pair of case study flight days to provide a deep look into the campaign's data and philosophy. Ample time was left for discussion and a question and answer session. Pre-recorded materials were provided online to guide anyone interested in the data set. The project description and publications are available at *https://activate.larc.nasa.gov/*. Data access and data workshop materials (including pre-recorded materials and a recording of the workshop's two days) are all available at *https://www-air.larc.nasa.gov/missions/activate/docs/data_workshop/Oct2021.html*.

Meeting/Workshop Reports

33rd Meeting of the GEWEX Scientific Steering Group

Virtual Meeting
3–6 May 2021

Peter van Oevelen[1], Jan Polcher[2], Xubin Zeng[2], and Fernande Vervoort[3]

[1]Director, International GEWEX Project Office; [2]Co-Chair, GEWEX Scientific Steering Group; [3]Scientific Officer, International GEWEX Project Office

This short report documents the proceedings of the 33rd Session of GEWEX Scientific Steering Group (SSG-33), the annual meeting of scientists who guide the formation of GEWEX's scientific program as well as the Chairs and Co-Chairs of the GEWEX Panels. This SSG-33 was originally planned to be hosted by the Seoul National University in Seoul, South Korea. Unfortunately, the meeting had to be moved to an online setting due to COVID-19 and ultimately took place on May 3–6, 2021. The full meeting report can be found at: *https://www.gewex.org/gewex-content/uploads/2021/12/GEWEX-SSG33-report_V2.pdf*.

In addition to the GEWEX Scientific Steering Group (SSG) members and GEWEX Panel Co-Chairs, delegates from collaborating organizations attended the meeting, including representatives from the U.S. Department of Energy (DOE); the European Space Agency (ESA); the Japan Aerospace Exploration Agency (JAXA); the National Aeronautics and Space Administration (NASA); the National Oceanic and Atmospheric Administration (NOAA); the U.S. Global Change Research Program (USGCRP); the United Nations Educational, Scientific and Cultural Organization (UNESCO); the World Climate Research Programme (WCRP); WCRP's core programs and working groups, and other partners of GEWEX.

The attendees reviewed the progress of GEWEX and its four Panels for the year 2020 and discussed the program's relevance today and in the years to come. They also examined how to continue to support international climate research collaborations and links with other relevant climate research organizations and our sponsors. Emphasis was put on how to engage with the new structure of the World Climate Research Programme (WCRP) and its new Light House Activities as well as the two new core projects, Earth System Modeling and Observations (ESMO) and Regional Information for Society (RIfS). This is an ongoing discussion that we will continue to report on in the *GEWEX Quarterly*.

All four GEWEX Panels reported a wide range of activities organized in 2020, despite the unprecedented circumstances brought about by the pandemic. Activities ranged from continued operations such as installing new Panel members and activity monitoring to the startup of new projects and initiatives, and the development and marketing of products and the organization of online meetings and workshops. Ongoing projects are advancing mostly according to plan or have ended successfully. Working groups in all four Panels have published articles in major scientific journals, have articles under review at this time, or both. Discussions on how to proceed, what is lacking, other possible topics to explore, and dialogues on existing or possible obstacles resulted in new action items and recommendations.

As of June 17, 2020, the support required to meet the obligations and responsibilities of the International GEWEX Project Office (IGPO) has been taken over by George Mason University under the Center for Ocean-Land-Atmosphere Studies (COLA) in the Department of Atmospheric, Oceanic and Earth Sciences. We are grateful for both the support from NASA as well as George Mason University and look forward to continued successful operations.

In anticipation of Phase IV (2023–2032) of GEWEX, a "Science and Applications Traceability Matrix" (SATM) is being assembled with input from all SSG and Panel members. The GEWEX SATM will provide traceability from WCRP strategies to core science, defined metrics, applications, and programs. It will serve as the backbone of, and provide direction to, the revision of the GEWEX strategic science plan and science questions for the coming years. A first draft of this plan was presented at the meeting, discussed, and overall very well received. The latest version of this plan can be found at: *https://www.gewex.org/gewex-content/uploads/2021/10/GEWEX-science-plan-v7.pdf*.

We thank all participants who attended and made this meeting successful, despite the online format and the necessary engagement taking place often outside of working hours due to the truly global character of our program.

GEWEX QUARTERLY

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