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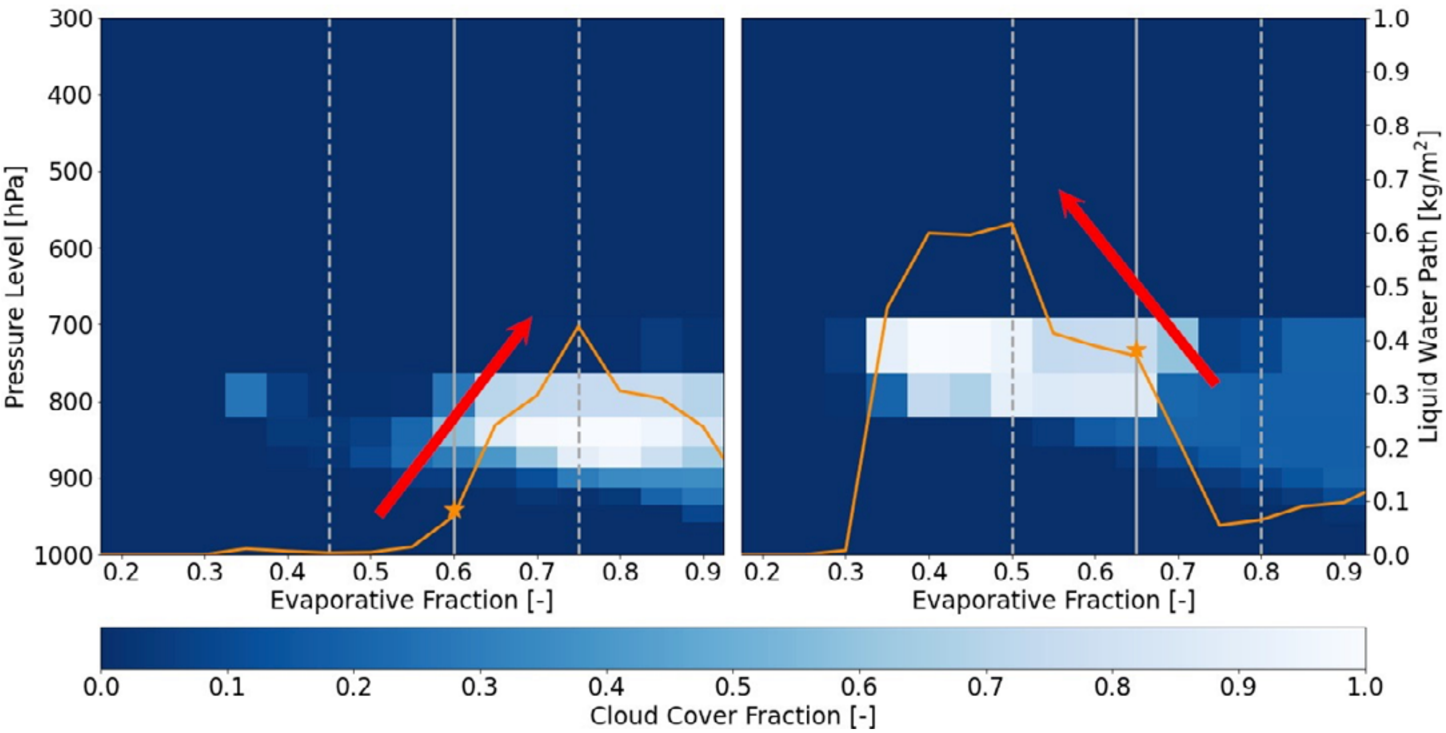
GEWEX is a Core Project of the World Climate Research Programme on Global Energy and Water Exchanges

Addressing Organized Spatial Heterogeneity of Land-Atmosphere Interactions on Sub-Grid Atmospheric Convection in Models



This figure shows cloud cover fraction (shading) and liquid water path (orange line) from an ensemble of single column model simulations representing a range of prescribed surface evaporative fractions (x-axis). Solid gray line represents the evaporative fraction from analysis over the Atmospheric Radiation Measurement-Southern Great Plains (ARM-SGP) site on two different days in summertime, with dotted grey lines representing a sensitivity window of +/- 0.15. Left panel shows an afternoon with positive feedback; increasing evaporative fraction leads to increasing cloud within the sensitivity window. Right panel shows an afternoon with negative feedback; decreasing evaporative fraction leads to increasing cloud within the sensitivity window. Adapted from Hay-Chapman, 2023. For more, see Chaney et al., page 8.

Inside This Edition

Commentary

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International research collaboration can take many forms and can be done for a variety of reasons. GEWEX, under the auspices of the World Climate Research Programme (WCRP), has as its mission to observe, understand, and model the hydrological cycle and energy and carbon fluxes in the Earth's atmosphere at and below the surface. As such, we support the international weather, climate, and hydrological research communities. Because we are not a funding organization, we support these communities by developing research agendas; promoting, cultivating, and executing new research activities; and organizing and extending relevant research communities. It is important to note that these activities have an international character and are not solely a national endeavor. We do this primarily by bringing researchers together through meetings (either in person or virtual) and providing a platform to collaborate, exchange ideas, and find resources to support these endeavors.

So far, this is all very well, but what does it take to have a successful international research collaboration? Can we be more specific, and what are the possible metrics to define progress and success? In the previous *GEWEX Quarterly*, the commentary focused on the lessons learned from the first 30 years of GEWEX as described in Stephens et al., 2023. That is a good starting point to take stock of what has been achieved and might provide us with some insights into exploring possible metrics for the future success of our activities. That would be focusing entirely on the research itself, but not the community. Hence, another approach is to survey the community and ask members if they are satisfied, and to what extent, with what the program does and offers. You could also look at the diversity and inclusivity of the community. Of course, these approaches are not mutually exclusive!

If you have read John Doerr's *Measure What Matters* (Doerr, 2018), you should be familiar with objectives and key results (OKRs). A crucial element in that approach is quantifiability, so OKRs can be consistently compared to show progress. Regardless of whether the objectives are quantitative or qualitative, one should try to define metrics that can be measured objectively. In addition, it is important to make clear the priorities of the various goals and objectives and have a good understanding of how to weigh their relative importance. The overall outcome is always subjective, though; what is deemed successful according to one criterion might be a complete failure according to another, and how these are weighed is often very much based upon personal experience and background. It is up to us to define success! A good example here can be our Regional Hydroclimate Projects (*https://www.gewex.org/panels/gewex-hydroclimatology-panel/regional-hydroclimate-projects-rhps/*). These projects are to be run and led from within the region, and hence, even if they have raised sufficient resources, performed research, and made great progress, they are not deemed successful if this was done ultimately under leadership from outside the region and primarily with researchers who are not local.

So why the above? With GEWEX having a new research plan (*https://www.gewex.org/gewex-content/uploads/2022/11/GEWEX-science-plan-v8.pdf*) for the next 10 years, we want to be proactive in making sure we deliver; we should be clear on what can be expected and inclusive in our actions and thinking. So think about this, and do not be surprised if this comes up in your next Panel or activity meeting!

I would like to conclude with congratulating our two new GEWEX Ambassadors, Christa Peters-Lidard and Andy Pitman, and I look forward to their contributions. I hope you enjoy this edition of the *GEWEX Quarterly*.

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Doerr, J., 2018. *Measure What Matters: How Google, Bono, and the Gates Foundation Rock the World with OKRs*. Edmonton, Portfolio Publishing.

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New GEWEX Ambassadors

Based on statements provided by Christa Peters-Lidard and Andy Pitman

GEWEX is proud to announce the 2023 GEWEX Ambassadors: Dr. Christa Peters-Lidard and Prof. Andy Pitman. Dr. Peters-Lidard, Director of the Sciences and Exploration Directorate at the National Aeronautics and Space Administration (NASA) Goddard Space Flight Center, remembers first coming across GEWEX at a workshop as a graduate student, then joining the GEWEX Land Atmosphere System Study (GLASS) Panel as a member in 2004. While project lead of the NASA Unified Weather Research and Forecasting (NU-WRF) project, she became involved in the Local Coupling (LoCo) group. NU-WRF coupled the community WRF model to the Land Information System (LIS; *http://lis.gsfc.nasa.gov*) and enabled multiple planetary boundary layer schemes and multiple land surface models to interoperate, aiding the LoCo undertaking of gaining a clearer understanding of coupled processes in models. A series of publications on LoCo metrics and analysis, led by Joe Santanello, followed, addressing the last unexamined subset of model intercomparison projects in the GLASS Panel.

Dr. Peters-Lidard points out that "GEWEX activities have had a profound impact on land surface modeling and data assimilation research and applications. By promoting integrated Earth system research under GEWEX, along with other WCRP projects and programs, our community has been at the forefront of addressing some of the most pressing questions in climate change research, mitigation, and adaptation." She has contributed to the evaluation, intercomparison, and evolution of land models within the GLASS Panel and beyond.

Prof. Pitman, Director of the Australian Research Council (ARC) Centre of Excellence, notes that his research and GEWEX's mission overlap in significant ways: "my career has focused on understanding and modeling the Earth's water cycle and energy fluxes at, and below, the surface and in the atmosphere–the core objective of GEWEX." He has served on the GEWEX Scientific Steering Group (SSG) and along with Jan Polcher, Paul Dirmeyer, and Taikan Oki, worked to establish the GLASS Panel, which he also chaired for several years. His first contribution to GEWEX was in 1990, when he co-led the Project for the Intercomparison of Landsurface Parameterization Schemes (PILPS) with Ann Henderson-Sellers, which could perhaps be called the first model intercomparison project (MIP). Prof. Pitman was also involved in the Global Soil Wetness Project (GSWP) and the Protocol for the Analysis of Land Surface Models (PALS) Land Surface Model Benchmarking Evaluation Project (PLUMBER). His interest in the topics that animate GEWEX have resulted in a greater understanding of and focus on land processes.

We are grateful to Prof. Pitman and Dr. Peters-Lidard for their roles in shaping GEWEX involvement in land model improvement. Thank you for your commitment and leadership!

YESS in Action: Advancing Earth System Science through Collaboration and Innovation

Faten Attig Bahar[1], Javed Ali[2], Gerbrand Koren[3], Yuhan Rao[4], and the YESS Executive Committee
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YESS is delighted to announce the election of its 2023–2024 Executive Committee (ExeCom) members and Regional Representatives. The ExeCom plays a vital role in maintaining an overview of and guiding YESS activities, and serves as the contact point for communication within the YESS community and with external partners. The Regional Representatives actively support the work of the community by sharing experiences, special interests, and information from their region, and act as the contact point for specific regional questions, activities, and tasks. Please meet the new generation of YESS executives here: *https://www.yess-community.org/2023/04/03/yess-elections-2023-results/*.

YESS is also excited to invite researchers across all career stages to join a community discussion on balancing data-intensive and foundational climate research activities. This discussion will be a side meeting to be held at the World Climate Research Programme Open Science Conference 2023 (WCRP OSC 2023) and is inspired by the recent paper "Are we at risk of losing the current generation of climate researchers to data science?" published in AGU Advances. For more information and to participate, please visit: *https://wcrp-osc2023.org/side-event-th09*.

And finally, YESS is proudly announcing that our ExeCom member Faten Attig Bahar was one of the co-authors and chair at the launch webinar of a new World Meteorological Organization (WMO) guide. This document assists countries, particularly their National Meteorological and Hydrological Services, on how to use weather, water, and climate data and science to develop national plans for the net-zero energy transition. The guide is an update of the Global Framework for Climate Services (GFCS) "Energy Exemplar" and was compiled under the aegis of the WMO Study Group for Integrated Energy Services (SG-ENE), part of the Commission for Weather, Climate, Water and Related Environmental Services and Applications (SERCOM), with contributions from some of the leading experts in the field. This recent publication channeled the expertise of nearly 50 authors and provides guidelines and examples of integrated weather and climate services from across the globe, which are essential to accelerate the transition towards net zero emissions. The webinar recording is available here: *https://app.swapcard.com/event/launch-webinar-of-the-wmo-best-practices-for-integrated-weather-and-climate-services-in-support-of-net-zero-energy-transition/planning/UGxhbm5pbmdfMTIyMzQ0MA==*.

A New ESA Precursor Project on River Discharge

Sylvain Biancamaria[1], Alice Andral[2], Silvia Barbetta[3], Malik Boussaroque[4], Luca Brocca[3], Beatriz Calmettes[2], Stefania Camici[3], Paolo Filippucci[3], Laetitia Gal[4], Gilles Larnicol[5], Julien Lefebve[1], Simon Munier[6], Fabrice Papa[1], Adrien Paris[4], Vanessa Pedinotti[5], Nicolas Taburet[2], Angelica Tarpanelli[3], Elena Zakharova[7], Clément Albergel[8], and Jérôme Benveniste[9]

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Rationales for River Discharge Essential Climate Variable

River discharge is the main land freshwater influx to the ocean (Milliman and Farnsworth, 2013) and plays an important role in the continental part of the water cycle. It is both affected by, and impacting, human activities. As all components of the water cycle, river discharge will be increasingly affected by climate change. To better understand these changes and for adaptation of human societies, having access to climatic-long time series of river discharge is crucial. Thus, the Global Climate Observing System (GCOS) identified river discharge as an Essential Climate Variable (ECV) (GCOS, 2022).

For multiple reasons (remote locations difficult to monitor, decreasing number of gauges worldwide, gauge data withholding, etc.), the internationally-available in situ gauge networks are very heterogeneous both in space and time, as illustrated by the Global Runoff Data Center (GRDC, *https://www.bafg.de/GRDC/*) river discharge database. They have been declining since the middle of the 20th century (Milliman and Farnsworth, 2013), and this is especially true for transboundary basins. Lack of in situ river discharge observations in the last few decades is particularly important in some parts of Africa, South America, and Asia. Therefore, current global databases do not provide a full synoptic observation of water fluxes on land, which impacts our knowledge of the inland water cycle and our capacity to close the water budget (Dorigo et al., 2021). With the increasing number of Earth Observation (EO) satellites, it became feasible to complement our capacity to observe and infer causes of continental freshwater variability using the global information from these satellites.

A New ESA Climate Change Initiative (CCI) Precursor Project to Complement River Discharge Observations with Satellite Data

More than half of the ECVs listed by GCOS (2022) can benefit from EO satellites (*https://climate.esa.int/en/esa-climate/esa-cci/Objective/*). This is why the European Space Agency (ESA) has launched, developed, and sustained the Climate Change Initiative (CCI) for over a decade, to realize the full potential of the long-term global EO archives. Current CCI projects correspond to 27 ECVs, but some ECVs are still to be developed, such as river discharge. Therefore, ESA is funding the "CCI River Discharge precursor project" (*https://climate.esa.int/en/projects/river-discharge/*), a new feasibility study to investigate the possibility of complementing current in situ observation of river discharge with satellite EO over a long period of time.

There is currently no satellite instrument able to directly measure river discharge. Instead, satellite measurements of river hydrological variables can be used indirectly to estimate it, using, for example, in situ discharge and parameterization. Satellite radar nadir altimeters observe water surface elevation (not water depth) along the satellite ground track, with multiple missions launched since the 1990s. These measurements are provided at the intersection of the satellite ground track with the water bodies. As with in situ data, the relation between satellite water elevation and in situ discharge over a common period can be used to derive discharge from satellite altimetry observation after the end of the in situ time series. Despite these missions not having all been on the same orbit tracks and having different sensor characteristics, this wealth of data should allow long-term observations of water level variations for rivers. Moreover, multispectral sensors, specifically in the near infrared (NIR) band, are also able to detect the variability of river dynamics. The ratio between the reflectance of a dry pixel and a wet pixel is expected to represent river flow variation. The large advantage of the multispectral sensors is the sub-daily temporal resolution, even if they cannot penetrate clouds, which impacts their time sampling.

Objective of the Precursor Project and Link with GEWEX

As a proof-of-concept, this project is not yet global, but aims at complementing in situ discharge observations from 2002 to 2022 at different locations over at least 15 river basins. These targets will cover different climatic zones from the tropics to the Arctic, different drainage areas from 50,000 km^2 to the Amazon basin, and different levels of human activities and in situ observations. The user requirements document for the river discharge product, based on interviews of some ECV users in a spirit of co-design, has just been finalized.

Given the role of river discharge in the water cycle and its potential impact on the closure of the water mass balance, connections between the ESA CCI River Discharge project with GEWEX activities are multiple. River discharge is highly dependent on precipitation and makes a connection between the atmosphere and ocean; thus, our products would contribute to the GEWEX Data and Analysis Panel (GDAP). The Global Land-Atmosphere System Studies (GLASS) Panel should benefit from new CCI River Discharge data for land surface model assessment. We are open to receiving advice from the GEWEX Hydroclimatology Panel (GHP) on locations that need more observations. Access to our basin scale discharge estimates should interest GHP. We are eager to interact with crosscutting projects such as the new "Advancing global surface water science for local benefits" project (led by Cédric David, Jet Propulsion Lab).

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The Need for SIF within Integrated Carbon-Water Cycle Assessments

Nicholas Parazoo[1], Alexander Norton[2], and Jennifer Johnson[3]
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Global carbon and water cycles, and their interactions with vegetation, are the foundation for understanding and modeling the Earth as a physical system (NASEM, 2018). It is therefore imperative to track changes in carbon, water, and vegetation if we are to understand climate-driven changes in the Earth system. The National Aeronautics and Space Administration (NASA) and other space agencies have more observations now on carbon, water, and vegetation than we have had at any point in human history. Long-term observations of total water storage show diverse regional responses in the Earth's freshwater supply to human and natural forces (Rodell et al., 2018). Such large-scale changes to water supply are likely to affect global vegetation function and carbon storage through carbon-water cycle coupling, which can amplify land-atmosphere feedbacks. Likewise, global observations of atmospheric CO_2 and derived land-atmosphere carbon exchange (Schimel and Schneider, 2019) show diverse seasonal and regional patterns of vegetation CO_2 uptake (Liu et al., 2021), including contrasting tropical responses to El Niño temperature and precipitation anomalies (Liu et al., 2017).

Satellite records are also increasingly demonstrating the presence of vegetation-carbon-water interactions and feedback mechanisms across global ecosystems over short and long time-scales. For example, the global CO_2 growth rate is strongly sensitive to observed interannual variations in terrestrial water storage through interactions between soil water and net biosphere exchange of carbon (NBE) (Humphrey et al., 2018). Variations in photosynthetic carbon uptake by gross primary production (GPP) can explain up to 30% of the variations in rainfall in the dry tropics (Green et al., 2017), and can trigger wet season onset in southern Amazon rainforests (Wright, 2017), through coupled changes in evapotranspiration (ET)-driven atmospheric moisture availability. Warming-induced earlier vegetation activity in northern extratropical forests can stimulate enhanced GPP in spring and summer, but at the expense of soil water through increased ET (Wolf et al., 2016; Liu et al., 2017). Hidden legacy responses of vegetation and carbon to soil water (Peylin et al., 2016; Bloom et al., 2020) have important consequences for interpreting natural vs. anthropogenic influences on global CO_2 growth rates.

Quantitative understanding of GPP and ET is needed to improve our understanding of carbon-water interactions and their response to climate. Numerous methods have been proposed to quantitatively estimate GPP and ET using various combinations of field and satellite measurements with mechanistic and data-driven models. These methods have led to important advances, but have historically been hindered by lack of direct measurement at leaf and ecosystem scale, reliance on satellite vegetation reflectance, and modeling uncertainties, as evidenced by conflicting results between bottom-up and top-down estimates (Anav et al., 2015; Pascolini-Campbell et al., 2020; Kaushik et al., 2020). Satellite observations of far red solar induced fluorescence (SIF) (Parazoo et al., 2019) and land surface temperature (LST) (Schimel and Schneider, 2019) provide direct probes of key ecosystem processes of GPP and ET and their dynamic interaction with climate (e.g., Smith et al., 2020), and are not subject to many of the retrieval issues associated with vegetation indices. Moreover, newer satellites such as the Tropospheric Monitoring Instrument (TROPOMI) and the Geostationary Operational Environmental Satellite (GOES) have dramatically improved the spatial sampling and frequency of SIF and LST (Köhler et al., 2018; Doughty et al., 2020; Chen et al., 2021), providing unprecedented opportunities for characterizing how carbon and water fluxes covary at daily to sub-daily time scales, and studying their change with climate (e.g., Lin, et al., 2019; Xiao et al., 2021).

Recent successes in passive remote sensing of SIF have spurred the development and integration of canopy-level fluorescence models in global terrestrial biosphere models (TBMs). The fluorescence-capable TBMs describe key processes related to the absorption of sunlight, leaf-level fluorescence emission, scattering, and reabsorption throughout the canopy. The SIF signal originates from chlorophyll *a* molecules inside the leaves of plants (Fig. 1). Following the absorption of light by photosynthetically active pigments, excitation energy in a leaf has one of three fates: photochemistry, dissipation as heat, or re-emission as chlorophyll fluorescence. Physiological processes inside the leaf regulate photochemistry and heat dissipation in order to balance the energy supply from absorbed light with energy demand by downstream processes, primarily photosynthetic CO_2 fixation. Chlorophyll fluorescence responds dynamically to these regulatory processes, thus providing a non-invasive probe into photosynthesis, a tool used for decades in plant research. The relationship between the quantum yield of chlorophyll fluorescence and electron transport (Genty et al., 1989) was originally introduced into TBMs with an empirical approach (van der Tol et al., 2014), and more recently with a mechanistic approach (Johnson and Berry, 2021). Following emission from chlorophyll *a*, fluorescence photons are scattered and partially re-absorbed within the canopy, with a proportion escaping and able to be detected by spectrometers. SIF is therefore closely linked to the absorption and scattering properties of the canopy and by photosynthetic regulation processes. The interaction of fluorescence with photochemistry at the leaf and canopy scales provides novel opportunities to diagnose and constrain model simulations of GPP and related processes, through direct comparison to and assimilation of SIF observations.

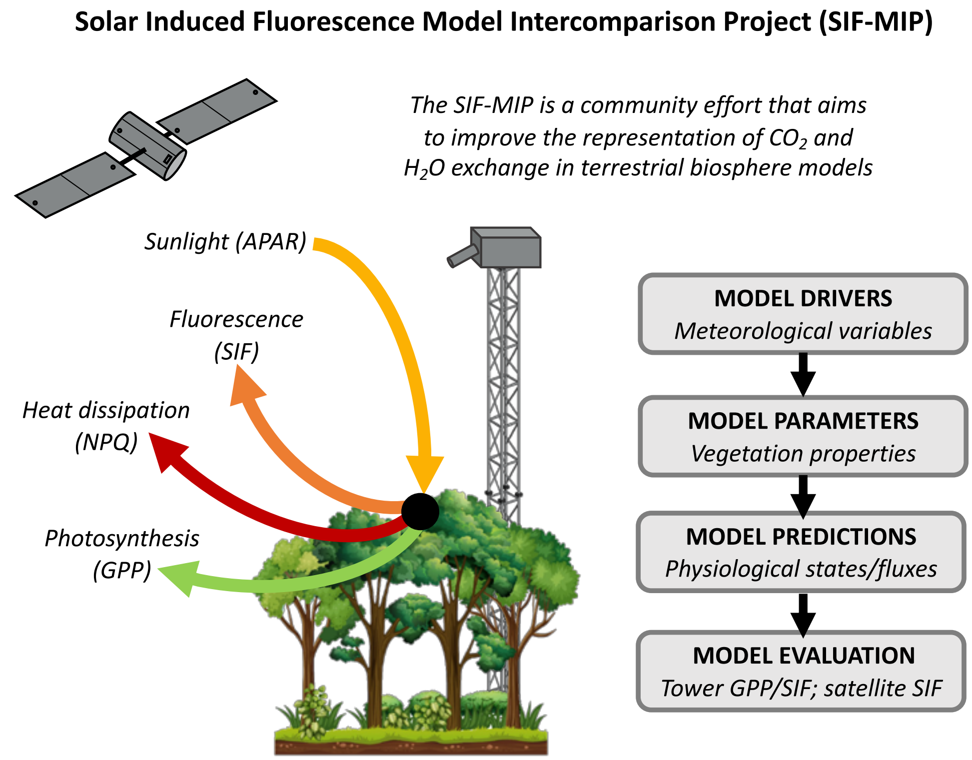

***Figure 1**. Schematic representation of SIF-MIP. SIF-MIP uses tower and satellite observations with increasingly sophisticated models to improve the representation of carbon-water cycle interactions in terrestrial biosphere models.*

The SIF model intercomparison project (SIF-MIP), depicted in Fig. 1, focuses on targeted assessments of simulations from an ensemble of process-based TBM-SIF models, forced with local meteorology and analyzed against tower-based continuous far-red SIF, and net and gross carbon and water exchanges. The basic protocol focuses on single point simulations across surface towers equipped with instruments that measure SIF, carbon, and water flux simultaneously, using prescribed model inputs, designated model outputs, within model experiments (e.g., with/without data assimilation, different process representation), and spin-up and data constraints (e.g., prescribed vegetation) at principal investigator discretion. The objective of SIF-MIP is to first summarize the site-level state-of-the-art in TBM-SIF modeling, and ultimately advance underlying equations and parameters to better match variations in fluorescence and photosynthesis across a range of environments, setting the stage for regional- to global-scale analysis, and model-data integration.

Phase 1 of SIF-MIP (Parazoo et al., 2020) focused on a subalpine evergreen needleleaf forest in Colorado, USA, and summarized the state-of-the-art according to seven independently developed models from international partners in the USA, Europe, China, and Australia. The models were generally well-constrained in simulating photosynthetic yield, but strongly divergent in absorbed sunlight, absolute gross primary production and fluorescence, and light responses. This study indicated a strong need for more mechanistic modeling of leaf and canopy level processes, including heat dissipation (non-photochemical quenching) and leaf-to-canopy radiative transfer. Phase 2 of SIF-MIP, currently underway, has expanded the scope of study in terms of time and spatial scale; number of free running, data assimilation, and radiative transfer models; and integration of new mechanistic capabilities.

The next step for SIF-MIP, and the carbon-water community as a whole, is finding integrated value in the diverse and unique observations that makes them most useful to the science community. Key to this effort is the use of model-data fusion systems, which can help reconcile different satellite data sets and uncertainties in both models and data, systematically retrieve otherwise unobserved quantities (i.e., not directly observed from spaceborne sensors) such as biosphere and hydrologic state (soil water, biomass) and fluxes (GPP, ET), and more accurately estimate C and H_2O cycle interactions, fluxes, budgets, and trends. Previous efforts which have successfully assimilated SIF within a TBM have either used a linear-scaling approach, which assumes a linear relation between SIF and GPP at some spatio-temporal scale and that SIF relates to biophysical parameters in the same way as GPP (e.g., MacBean et al., 2018; Bloom et al., 2020), or a process-based approach, which simulates SIF explicitly using process-based models (e.g., Norton et al., 2019; MacBean et al., 2022). While the linear approach is effective at capturing the coarse resolution controls on the carbon-water cycle, the community is working toward a process-based approach that will be more effective at capturing the non-linear interactions between absorbed sunlight, SIF, and GPP at finer resolutions. Harmonizing SIF and multiple other independent satellite data sets in the Earth observation record through model-data fusion provides critical quantitative understanding of inferred interactions as highlighted above, and has improved our ability to detect and predict positive or negative feedbacks in carbon and water cycles.

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Coupling Land and Atmosphere Sub-grid Parameterizations (CLASP)

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Although there have been notable advances in Earth system models (ESMs) over the past decades, the predictability of clouds and convective precipitation remains a key weakness (Balmaseda et al., 2020). This is in large part due to the coarseness of the grid size (~25–100 km grid resolutions) and the necessary continued reliance on sub-grid parameterizations. This challenge is especially true for land-atmosphere (L-A) interactions, where the unresolved sub-grid spatial scales (100–5000 m) can influence the depth of the atmospheric boundary layer, convection initiation, and the spawning of secondary circulations (Simon et al., 2021). Environments where organized spatial heterogeneity over the land surface are known to play a pivotal role include complex terrain, strong soil moisture gradients, urban environments, irrigated farmlands, and land cover mosaics (Ntelekos et al., 2008; Shao et al., 2013; Kustas and Albertson, 2003; Timmermans et al., 2008; Bertoldi et al., 2013).

Even though the importance of surface heterogeneity in the sub-grid coupling of the land and atmosphere has been known for years, its representation in ESMs remains vastly oversimplified. While the past few decades have seen the development of increasingly sophisticated sub-grid parameterizations for both the land surface [e.g., tiling schemes (Koster and Suarez, 1992; Chaney et al., 2018; Lawrence et al., 2019)] and the atmosphere [e.g., turbulence closure schemes (Golaz et al., 2002; Siebesma et al., 2007)], these widely-used approaches generally only interact via sub-grid spatial means of surface states and fluxes (e.g., evaporation); in other words, the role of organized spatial heterogeneity of L-A interactions on sub-grid atmospheric convection remains mostly ignored in contemporary ESMs. The ongoing Coupling of Land and Atmosphere Subgrid Parameterizations (CLASP) project is addressing this persistent challenge.

CLASP began in 2019 as a Climate Process Team (CPT) in the United States funded by multiple federal agencies including the National Oceanic and Atmospheric Administration (NOAA), National Aeronautics and Space Administration (NASA), and the Department of Energy (DOE). To date, the project has combined observation-oriented experimentalists, process modelers, process diagnosticians, theoreticians, and Earth system/climate model developers from five modeling centers, two academic centers, and the GEWEX community. *The primary objective of CLASP is to parameterize sub-grid heterogeneous exchanges between the land and atmosphere and to characterize its implications for surface climate, variability, and extremes*. The schematic in Figure 1 illustrates the complex sub-grid L-A interactions (e.g., secondary circulations) that CLASP aims to first parameterize in ESMs and then explore their impact on the global climate system. Below we provide an overview of the previous and ongoing efforts within CLASP.

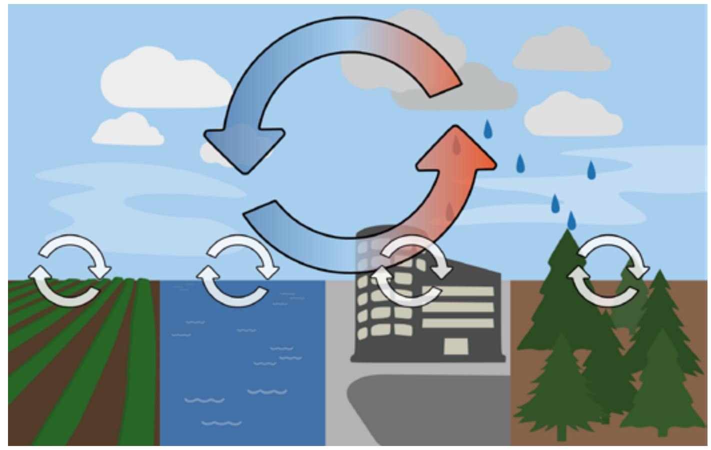

***Figure 1**. The existing approach to sub-grid coupling of the land and atmosphere in Earth system models involves the atmosphere effectively only interacting with the surface via sub-grid spatial means of states and fluxes. CLASP is addressing this weakness by developing, implementing, and evaluating parameterizations that enable the modeled sub-grid heterogeneity of the land surface (i.e., tiling schemes) to influence the corresponding sub-grid atmosphere more directly. Surface driven secondary circulations are an example of a process that the CLASP parameterizations aim to represent.*

To inform CLASP's parameterization efforts, one key focus has been to leverage large eddy simulations (LES) to understand when and where sub-grid heterogeneity over the land surface will play a noticeable role in the atmospheric response. To this end, LES experiments were performed over the Southern Great Plains site in Oklahoma (Simon et al., 2021). As shown in Fig. 2, organized spatial heterogeneity in surface fluxes can lead to a large increase in simulated turbulent kinetic energy (TKE) and liquid water path (LWP). Ninety-six additional LES experiments on different days and with differing surface heterogeneity patterns have confirmed these results—appreciable spatial heterogeneity of sensible heat fluxes during shallow convection days can lead to the development of mesoscale circulations which, in turn, can aid and enhance cloud development. The CLASP LES results have brought to light the importance of focusing CLASP's parameterization efforts on representing land-driven secondary circulations as this process can, at times, dramatically alter the timing, intensity, and spatial organization of sub-grid atmospheric convection.

Parallel to the LES efforts, CLASP has focused its parameterization efforts on two distinct approaches: 1) more fully leveraging the simulated tile-level surface heterogeneity of states and fluxes to define the time-varying surface boundary conditions of turbulence closure schemes and 2) using the modeled sub-grid surface heterogeneity to inform the size, velocity, and intensity of sub-grid buoyant plumes. The

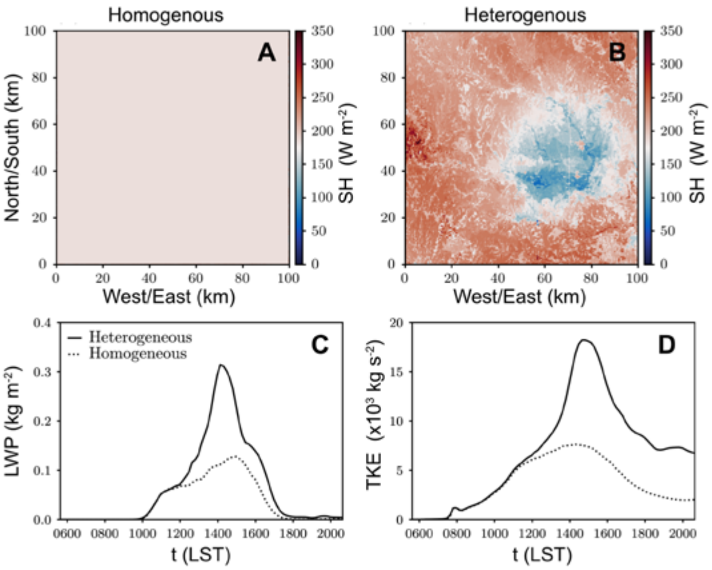

***Figure 2**. LES experiments are run for 9/24/2017 over a 100 km domain over the Southern Great Plains (SGP) site in the United States. The experiments are run at a 100-m resolution using simulated surface latent heat and sensible heat fluxes. The heterogeneous experiment (b) uses the surface fields "as is" while the homogeneous experiments (a) use the spatial mean (mimicking the ESM sub-grid coupling). The differing response is summarized via time series of liquid water path (LWP) (c) and turbulent kinetic energy (TKE) (d). Adapted from Simon et al., 2021.*

first parameterization approach emerged from the realization that the surface boundary conditions of turbulence closure schemes [e.g., Cloud Layers Unified By Binormals (CLUBB); Golaz et al., 2002] only leverage the spatial means of fluxes and states calculated from the sub-grid tiling schemes over the land surface; the higher-order surface moments (e.g., temperature variance) are then backed out from the grid-level fluxes and states (Huang et al., 2022). Efforts within the National Center for Atmospheric Research Community Earth System Model (NCAR CESM) and DOE Energy Exascale Earth System Model (E3SM) in this area have leveraged the work of Machulskaya and Mironov, 2018 to parameterize all the higher-order surface moments directly at the tile level and then aggregate these to compute the grid-scale effective value; these moments are then used as the surface boundary conditions for the turbulence closure scheme. Although this approach is more coherent and consistent than the previous one, the end result has yet to show appreciable changes in the atmospheric response, and it certainly appears to be unable to represent the effect of secondary circulations (Fowler et al., 2022).

The second parameterization approach has focused on how the surface heterogeneity impacts the strength and intensity of buoyant plumes. In this case, for both the NOAA Geophysical Fluid Dynamics Laboratory coupled model (GFDL CM4) and NASA Goddard Earth Observing System Model, Version 5 (GEOS-5), the team has been exploring how the mass flux component of the eddy-diffusivity mass-flux (EDMF) scheme (Siebesma et al., 2007) can be leveraged to account for the effects of surface heterogeneity. In the case of CM4, preliminary results show an appreciable sensitivity of the global climate when using this approach. Furthermore, this approach is especially interesting as parameterizing the impact that surface heterogeneity has on buoyant plumes is more closely connected to the process that drives the secondary circulations in LES; however, the interconnectivity between the warm and cold patches that secondary circulations transmit are still lost in this approach. To address this discrepancy, another approach using two column sub-grid atmospheres, one column over a warm patch and another over a cold patch, connected by a parameterized circulation, is being explored (see Fig. 3). Preliminary results indicate that this approach can qualitatively reproduce the enhancement in cloud production found when using the same heterogeneous surfaces in the LES experiments (Waterman et al., 2023).

Finally, to evaluate the emerging parameterizations, efforts are ongoing to determine the appropriateness of the existing land-atmosphere coupling metrics [e.g., the Local Land-Atmosphere Coupling (LoCo) project; Santanello et al., 2018] to quantify the role of surface heterogeneity in atmospheric response. One important result that has emerged from this work is the importance of computing diagnostics at high temporal frequencies; the results can vary substantially when computed using coarser time scales (Yin et al., 2022). This is especially important given the LES results that illustrate the critical role of the diurnal cycle on the effect of sub-grid surface heterogeneity on convection. Furthermore, it is unclear how useful metrics computed from sub-grid spatial mean vertical profiles will be to diagnose the sensitivity of sub-grid heterogeneity in the atmosphere. As shown in Fig. 4 (see cover), one promising approach to understand the sensitivity of a given atmosphere to surface heterogeneity is to explore how a range in evaporative fraction impacts cloud cover fraction and liquid water path (Hay-Chapman and Dirmeyer, 2023). In addition, other novel metrics being explored include leveraging existing global land surface temperature data from satellite remote sensing to evaluate the simulated space-time sub-grid patterns of land surface temperature in the tiling schemes.

Looking to the future, CLASP recently became a project of the Global Land-Atmosphere System Studies (GLASS) Panel within GEWEX, enabling the project to continue beyond the original US-centered CPT that will conclude this summer. As CLASP is more fully integrated into GLASS and the larger GEWEX community, the team is excited to expand collaborations with previous and ongoing efforts within GEWEX. Within GLASS, we are excited to both leverage the measurements emerging from the GEWEX Land/Atmosphere Feedback Observatory (GLAFO) project as well as to work in tandem with them to develop new measurement systems and coupling metrics that are more suitable to diagnose both the heterogeneity over the land surface as well as the response in the atmosphere. We are also looking forward to working with the Soil and Water (SoilWat) initiative to more fully understand how heterogeneities (and uncertainties) in soil hydraulic and thermal properties are connected to the response of the atmosphere to surface heterogeneities. Among other ongoing efforts within GEWEX, one especially exciting route is to leverage the data collected via the Land surface Interactions with the Atmosphere over the Iberian Semi-arid Environment (LIAISE) campaign in 2022. The stark spatially-organized con-

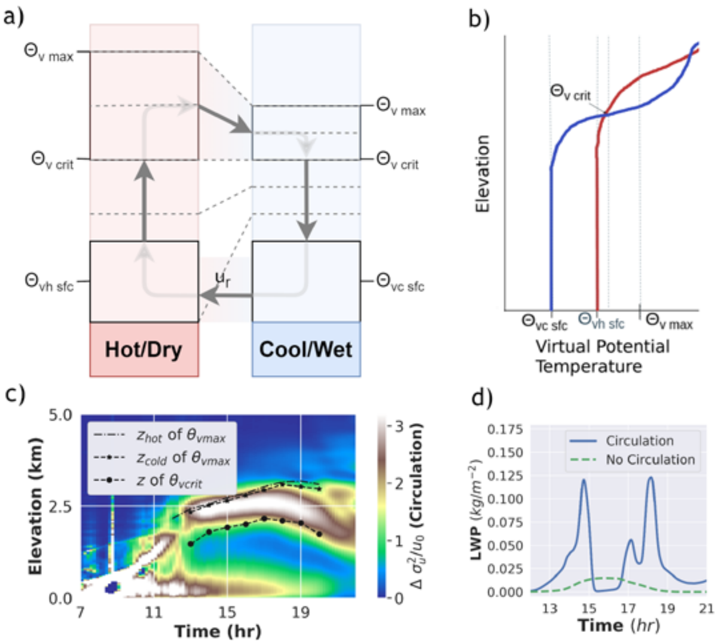

Figure 3. *a) Schematic of the parameterized circulation between two CLUBB columns with key virtual potential temperature limits shown. b) Illustration of idealized virtual potential temperature profiles for two columns, with key virtual potential temperature limits in a) shown. c) Difference in normalized (u'^2) profile in time between the heterogeneous and homogeneous LES. High values indicate potential advection from a circulation. The elevation of the virtual potential temperature limits used to define the two-column modeled circulation, as shown in a) and b), are plotted here. d) LWP through time for a two-column simulation with (blue) and without (green) a modeled circulation.*

trasts in states and surface fluxes seen in LIAISE between irrigated and non-irrigated regions are ideal to further explore via a hierarchy of models (e.g., LES, mesoscale, and single column models) the response of the atmosphere over physical environments with dramatically different degrees of water availability.

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Recent Development of the Asian Precipitation Experiment (AsiaPEX) toward the Collaborative Observation-Modeling Initiative

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As reported by the *GEWEX Quarterly* in 2020 (Terao et al., 2020), we launched the Asian Precipitation Experiment (AsiaPEX, *http://iceds.cc.kagawa-u.ac.jp/asiapex/*) in May 2019 as the successor to the GEWEX Asian Monsoon Experiment (GAME; Yasunari, 2001) and the Monsoon Asian Hydro-Atmosphere Scientific Research and Prediction Initiative (MAHASRI; Matsumoto, 2018). The first AsiaPEX conference was successful, confirming our research objective of understanding terrestrial precipitation over diverse hydroclimatological conditions to improve predictions, disaster reduction, and sustainable development across Asia. Currently, AsiaPEX is listed as a prospective Regional Hydroclimate Project (RHP), and is expected to be a full RHP after a review of its science plan.

In this short report, we provide information on the recent developments in AsiaPEX activities. In particular, our science steering group published a review paper on this project in the *Bulletin of the American Meteorological Society* (*BAMS*) (Terao et al., 2023), in which we discussed the key approaches of AsiaPEX and further proposed an initiative for an observation and modeling campaign named the Asian Monsoon Year (AMY)-II. We hope that this report will stimulate international research on hydroclimatological systems in Asia.

Recent Activities of AsiaPEX

Just after the first AsiaPEX conference, the COVID-19 pandemic occurred worldwide. However, we continued several regional research projects and exchanged study outcomes even during this difficult time.

The Himalaya PRECipitation Study (HiPRECS), a field experiment focusing on precipitation and its variability over the southern slope of the Himalayan range, and the South Asian Hydro-Meteoro-Climatological Observation Network (SOHMON), a field experiment focusing on the Northeastern Indian subcontinent, have been ongoing and extending collaboration with Asian countries. Several papers have been published on these studies (Fujinami et al., 2021; Sugimoto et al., 2021; Hirata et al., 2023; Murata et al., 2020).

The last research exchange before the COVID-19 pandemic was the Second Workshop on the Extreme Severe Storm and Disaster Mitigation Strategy (ESSDMS2 Workshop), February 27–29, 2020, and the AsiaPEX/South Asia (South Asia) Workshop, March 1–2, 2020, at the Central University of Rajasthan in Rajasthan, India. These workshops provided the basis for activities in South Asian countries to date. Subsequently, Dr. Terao was invited to the Workshop of the South Asian Meteorological Association (SAMA) as a speaker on September 4, 2021, and September 2, 2022. During the latter, because international border controls had partly relaxed, Dr. Terao was able to visit Nepal and attend lectures at Tribhuvan University in Kathmandu. At the Seventh World Meteorological Organization International Workshop on Monsoons (IWM-7) held on March 22–26, 2023, several core members of AsiaPEX were invited to deliver recent research outcomes. Scientific discussions were conducted over several conference sessions. The Special Session at the Meteorological Society of Japan (MSJ) Spring Meeting (in Japanese) was held on May 19, 2021. Session AS28 of the Asia Oceania Geosciences Society (AOGS) Meeting, held August 3–6, 2021, which included a poster session, was one of the five most popular sessions in AOGS2021. The proposed session at the Annual Meeting of the Japan Society of Hydrology and Water Resources was held on September 16, 2021. A session at the 2022 Japan Geoscience Union Meeting, "Multiple scale structures and their interactions in Asian monsoon system", took place on May 23, 2022, in Chiba, Japan, both in person and online. Joint sessions with the Third Pole Experiment (TPE) were continuously conducted and planned during the AOGS. In the upcoming general spring meeting of the Meteorological Society of Japan, core members of AsiaPEX will join one of the main programs, the symposium on Asian monsoons, as panelists.

Discussion and Publication of AsiaPEX Review Paper

During the COVID-19 pandemic, the Science Steering Group (SSG) of AsiaPEX continued its discussions. This group was formed through a workshop called "Decadal Challenges in Asian Monsoon Process Studies" at Nagoya University in Nagoya, Japan, September 2–5, 2019. Our SSG comprised 31 researchers from India, China, South Korea, the Netherlands, the USA, and Japan. Following this discussion, they drafted a review paper and submitted it to *BAMS*. Prof. van Oevelen from GEWEX joined, and the paper was accepted in December 2022 (Terao et al., 2023).

The AsiaPEX review paper emphasizes the importance of a bottom-up research design to understand the hydroclimatological systems characterized by interactions within fine-scale hydroclimatological land–atmosphere coupling processes occurring at the bottom. It further describes the strategy using the following six approaches:

1. the observation and estimation of the variations and extremes in Asian land precipitation;
2. process studies of Asian land precipitation with respect to diverse land–atmosphere coupling;
3. understanding and predicting variability in the Asian monsoon from subseasonal to interdecadal time scales;
4. high-resolution land surface hydrological modeling and monitoring, which incorporate the impacts of water withdrawal, agriculture, vegetation, and cryosphere;
5. field campaigns for coordinated observations and modeling initiatives; and
6. the detection and projection of climate change impacts on the regional precipitation across Asia.

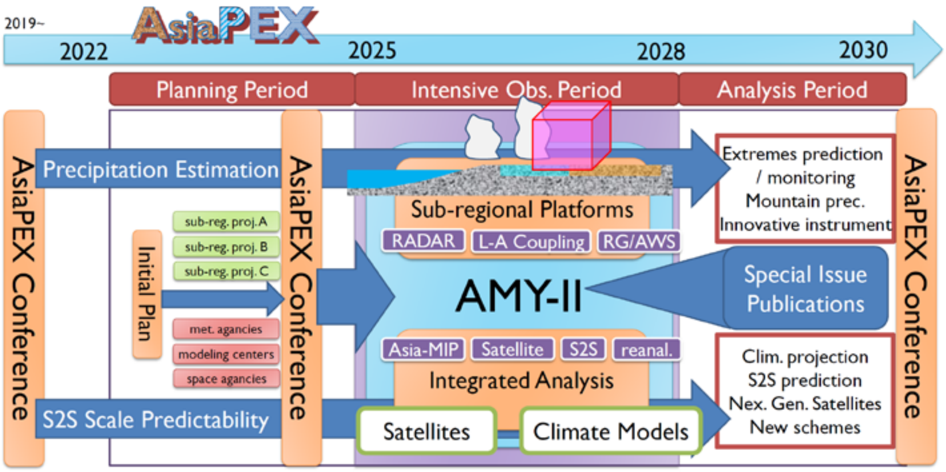

***Figure 1.** Conceptual figure for AMY-II. Our intensive observation period (IOP) will be scheduled within the period from 2025 to 2028. From Terao et al. (2023).*

Based on this understanding, the researchers discussed the strategies for observational studies, process studies, modeling studies, and field campaigns. The most prominent content in this review is the proposal for the international field campaign Asian Monsoon Year (AMY)-II, which will be explained in the following section.

AMY-II Field Campaign

A review paper proposed an integrated observational and modeling initiative called AMY-II. The target of this initiative is the variability in the Asian hydroclimatological system at the continental and subseasonal to seasonal (S2S) spatiotemporal scales, prioritizing land–atmosphere coupling processes (Fig. 1). Based on the lessons learned from GAME, MAHASRI, Asian Monsoon Years (AMY; Matsumoto et al., 2017), Year of Maritime Continent (YMC; Yoneyama and Zhang, 2020; Hattori et al., 2017; Yokoi et al., 2017), and the outcomes of recent activities in AsiaPEX (e.g., Ogino et al., 2017; Mateo et al., 2014; Hanasaki et al., 2014; Fujinami et al., 2021; Sugimoto et al., 2021; Teramura et al., 2019; Lin et al., 2018; Takaya et al., 2021), the review suggested two next steps that should be the key aspects of AMY-II:

1. the subregional process-oriented coordinated observation platforms at scales of tens to hundreds of kilometers with collaborative observations and
2. integrated analysis using global modeling, reanalysis, and remote sensing data set that can be underpinned by sub-regional observation platforms.

A more comprehensive proposal for AMY-II will appear this year, and the intensive observation period will be organized within the period from 2025 to 2028. At the GEWEX Open Science Conference, which is planned for July 2024 in Sapporo, we will organize a discussion session on this opportunity.

We hope to collaborate with many researchers interested in Asian hydroclimatology and its impact on global society.

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Meeting/Workshop Reports

The GEWEX Integrated Product Workshop

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The evaluation of global climate data records related to water and energy fluxes is often complicated by assumptions in satellite algorithms that lead to state dependent errors in impact assessment studies. These errors are notoriously difficult to quantify, as their dependence on state variables is rarely understood. The GEWEX Integrated Product Workshop, held from April 11–13, 2023, attempted to make progress in this area by focusing on consistency, closure, and the underlying processes from both a satellite and a land model perspective. The workshop was thus intended not simply to map the components of the terrestrial water cycle, but also to explore how consistent it is as a function of state variables, including soil moisture, land surface temperature (LST), turbulent fluxes, the boundary layer, clouds, and precipitation processes. While the ultimate objectives are global, the focus will be on using well-instrumented, ground-based sites such as the ARM facility in Oklahoma as well as GEWEX Hydroclimatology Panel (GHP) and GEWEX Land-Atmosphere Feedback Observatory (GLAFO) sites to guide the assessment and provide the additional high resolution physical information needed to develop a fuller understanding of the relevant processes.

The first sentences of the meeting description above are perhaps key to understanding the primary focal areas of the discussions: "The evaluation of global climate data records related to water and energy fluxes is often complicated by assumptions in the satellite algorithms that lead to state dependent errors. These errors are notoriously difficult to quantify as their dependence on state variables is rarely understood". What this means in practice is that while efforts have been made to close the global water and energy budgets, one cannot simply select a region of interest (e.g., 5°x5° or 10°x10°) and close the water and energy budgets with any confidence (or skill). There are also significant time dependences to the closure. Experts representing atmospheric and land surface observations and modeling were thus invited to explore ways in which to use high resolution models and observations to determine what processes, meteorological background, and land conditions and dynamics, separately and combined, affect our ability to upscale the local observations and models to a global framework. The meeting also sought to clarify what needs to be better understood to enable the translation across scales and approaches, including an identification of primary sources of errors and uncertainties in making these translations to a global scale.

The following points summarize key findings from the individual group and plenary discussions held over the course of the two-and-a-half day meeting.

1. On the Global and Regional Water and Energy Budgets

The consensus of the meeting was that the exact numbers behind the typical water and energy diagrams, whether at global or watershed scales, were in themselves not as relevant as often assumed. Instead, the "lack of closure" at the space and time scales regularly studied was really an indicator that our assumptions, models, or observations lacked critical processes, or process scales, needed to be better understood before the products could be used with confidence. Thus, water and energy budget closure should not necessarily be pursued for its own sake, but rather constitute useful stress tests for the quality of data used in Earth system studies – whose space and time scales also dictate the space and time scales at which closure should be studied. The scale challenge is particularly acute because the budget closure over land at high resolution is even more challenging due to possible human impacts on the water and energy cycle. **Recommendation**: much can still be learned from integrated closure studies at different spatial and temporal domains as part of ongoing Earth system studies. If closure studies are incorporated into routine science and validation plans, they will help account for dominant sources of uncertainty at different scales, express the suitability of individual products for integrated studies, and help identify new approaches for using data from the most appropriate observations.

2. On Linking of Surface and Atmospheric Models with Observations

While there was considerable discussion about the need to better understand the differences of how the land-atmosphere interface is handled by atmospheric and land surface models, much discussion was devoted to the need for consistent definitions of critical variables, such as soil properties (e.g., temperature and moisture). Because soil properties are 3-dimensional and relevant processes differ depending on space and time resolutions, soil properties can become tunable parameters. This has prevented fundamental progress in better process understanding. A specific example is the controls on the partitioning between surface sensible and latent heat fluxes, which are often assigned, but may depend critically on light rain or other factors. There are now observational concepts, such as GLAFO, as well as highly-instrumented sites, including those in the U.S. Department of Energy (DOE) Atmospheric Radiation Measurement (ARM) portfolio, that can be leveraged to gain new insights into mechanisms controlling the connections between soil properties and land surface fluxes. This would allow for connecting models and data in a more meaningful way without funding entirely new field experiments dedicated to closure. **Recommendation:** the upcoming DOE ARM Third Mobile Facility (AMF3) Campaign to the Southeastern U.S. will provide measurements of land-surface fluxes, atmospheric boundary layer profiles of wind, thermodynamics, and turbulence parameters that could be leveraged for in-depth process studies. There was a consensus that AI/machine learning (ML) techniques, trained at heavily-instrumented measurement sites, would provide the most feasible mechanism for expanding upon measurements in other locations. In addition, there is significant opportunity for "natural experiments" where interannual climate variability, wildfires, plant infestations or the heavy-handed land use change by humans have radically altered the landscape during a period of observations. Before and after conditions can partially mimic the manipulation of conditions that can help diagnose models. A unique opportunity exists across the African continent. The continent has diverse climates, land use conditions, and climate seasonality, and the landscape has seen multiple disturbances during the period of record. Given long records of high-quality satellite data, the situation is well suited for finding "natural experiments" related to surface water and energy balance and their coupling. We recommend that future GLAFO installations consider a transect across sections of Africa. Historic measurement campaigns including the African Monsoon Multidisciplinary Analysis (AMMA) and the associated ARM deployment to Niamey may also be valuable for this analysis.

Attendees of the GEWEX Integrated Product Workshop

3. On Improvements in Soil Temperature Measurements

Soil temperature is critical for determining atmospheric boundary layer properties; however, there remain significant uncertainties in measuring this parameter from satellites. There was a sense from the discussion that more could be done to describe the diurnal cycle of soil temperature under clear sky but the real challenges come when trying to estimate soil temperature under cloudy skies. Microwave techniques present challenges both because of relatively large horizontal footprints and ambiguity with surface emissivity, which in turn depends on the soil moisture. **Recommendation**: microwave instruments may be useful but require more research to separate emissivity from land surface temperature.

4. On Improvements in Soil Moisture Measurements and Their Model Representation

Because of the critical nature of soil moisture in connecting the land surface to the planetary boundary layer and thus to clouds and convection, there was discussion about the need to simultaneously consider soil states as well as surface fluxes in our models. Because land models were developed at a time when soil moisture observations were sparse, the requirement that models capture the dynamics of fluxes (e.g., evapotranspiration, runoff, percolation, etc.) at the same time that they accurately capture the dynamics of the soil moisture state variables was not usually invoked. One challenge is that satellite observations cannot provide soil moisture profile measurements beyond 5–10 cm, nor the hydraulic and textural soil properties, and soil temperature or heat flux that are nearly as critical to characterize as the near surface value. Progress, however, will be limited unless land hydrology models get both the fluxes and the states right, which is realistically only possible by assimilating surface soil moisture in models or by using in-situ observations. **Recommendation**: while no direct measurement approaches were offered, there was a sentiment that indirect approaches using platforms such as Unmanned Aerial Systems (UASs) would be highly beneficial due to their ability to capture data of soil moisture and the diurnal cycle of temperature over long time periods at landscape scales. These data, together with high quality precipitation, could be used to train algorithms to infer soil moisture, plant water use, and surface heat fluxes, as well as temperature and soil profiles in a less direct, but more holistic observing approach. Preference should be given to conducting these fine-scale studies at locations that also measure surface–atmosphere fluxes.

5. On the Co-variability of Hydrologic Parameters

Integrating points 1–4 above, there was much discussion on the utility that may be gained by not treating variables as individual silos, but that the co-variance of many of the water and energy parameters and variables is often an extremely powerful tool in model development and verification that is currently not sufficiently exploited. Models have built-in processes that often govern the co-variability between, for instance, precipitation, soil moisture profiles, surface fluxes, boundary layer depth, and the temporal response of the land surface temperature. Observing the co-variability of land surface and boundary layer parameters, from which causal relationships within and between states and fluxes of energy and water can be inferred, can thus shed significant light on model performance validation and parameterization development, and potentially identify any significant structural issues for model improvements. Like the water and energy budget closure mentioned in point 1, these studies need to be cognizant of the spatial and temporal scales being studied, as both the processes, and thus the parameter co-variabilities, are generally a function of the scale being investigated. Often such co-variabilities or relationships may be piece-wise valid under certain atmospheric and/or land surface regimes. ML and AI methodologies, and particularly causal inference and explainable AI, are likely powerful tools to explore these co-variabilities. **Recommendation**: based on co-located simultaneous measurements at supersites, such as DOE ARM and GLAFO observatories, diagnostics of such co-variability being developed by GLASS Local Coupling (LoCo) project diagnostics [e.g., mixing line diagram, planetary boundary layer-lifting condensation level (PBL-LCL) deficit, Convective Triggering Potential–Humidity Index diagrams], should be encouraged as useful diagnostics at all sites.

6. On the Spatial/Temporal Scales of Greatest Impact

While all scales are important, it was felt that the time scales that have not been sufficiently explored from a current observing capability were the sub-seasonal to seasonal (S2S) scales (i.e., 3 weeks up to 2 years). For regional predictions at these scales, models are more or less in climate prediction mode and suffer more from incorrect processes than from initial conditions beyond sea surface temperature (SST) and soil moisture that can be verified by observations. Given that all models involved in the S2S scales are global, this is likely the scale at which satellite products can have a direct impact on verifying water cycle processes that can then be directly used to evaluate model processes. The representation of the larger global processes can be further enhanced by verifying these at high resolution sites scattered around the globe (e.g., U.S. DOE ARM sites that provide boundary layer height data), which must be considered in conjunction with satellite observations in order to make significant progress. **Recommendation**: satellite observations relating the co-variability of SST and soil moisture on relevant processes for S2S predictions should be encouraged, as they may lead to rapid advances forecasting these important applications.

7. On Sustained and Future Observational Needs

Many of the participants found that programs such as the National Aeronautics and Space Administration (NASA) Energy and Water Cycle Study (NEWS) (and similar programs elsewhere that seek to integrate the water and energy cycles) were particularly effective at focusing on the opportunities above and moving the field forward with only limited resources. Because the discussions never assumed increased funding but rather focused on increased efficiencies possible through collaborations and leveraged activities, the focus here reflects this. There are many collaborations where other programs would greatly benefit from more NEWS type activities if integrated into their programs instead of standing alone.

Three measurements were specifically mentioned as being critical for the activities highlighted here: (a) data continuity for current water cycle missions, particularly of soil moisture and precipitation, for understanding the evolution of the water and energy cycles; (b) expansion of measurement concepts such as the GEWEX Land-Atmosphere Feedback Observatory[1], to observe the feedbacks at a number of representative locations (e.g., AMF3 Southeastern U.S. campaign[2]); and (c) expansion of new technologies, such as UASs, to provide finer-scale observations not possible from other platforms to capture diurnal cycles of parameters such as soil moisture and LST at landscape scales that could then be used to evaluate high-resolution models, evaluate satellite retrievals if conducted across a network of sites, and explore new scaling approaches.

[1] *https://www.gewex.org/gewex-content/uploads/2022/12/221003_GLAFO_White_Paper.pdf*

[2] *https://www.arm.gov/capabilities/observatories/bnf*

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