A GEWEX US-RHP FOR FOOD, ENERGY, AND WATER SECURITY IN THE ANTHROPOCENE

A SUMMARY PROPOSAL

to the World Climate Research Programme's (WCRP) Global Energy and Water Exchanges (GEWEX) Project for a Regional Hydroclimate Project (RHP) Over the Conterminous U.S.

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Affinity Group: The development of this plan was supported by, and with contributions from the 146 other current members of the US-RHP Affinity Group. See Appendix B.

"How can we know the dancer from the dance?"

-- W. B. Yeats (Among School Children)

I. Introduction

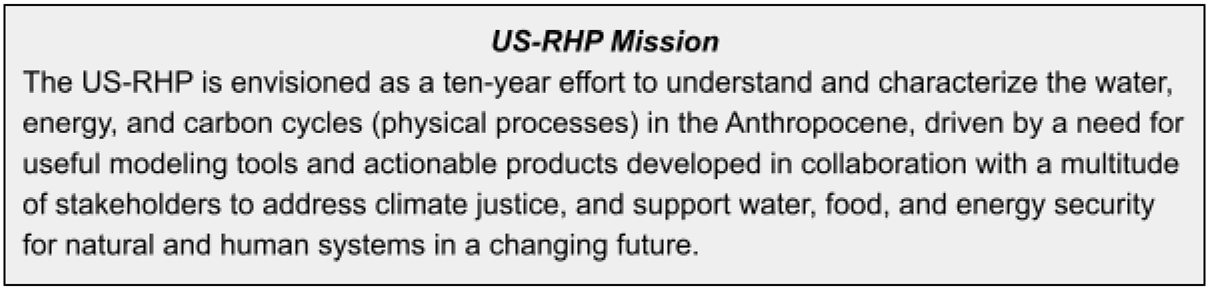
What is a GEWEX Regional Hydroclimate Project (RHP)?

> *RHPs are generally large, regionally-focused, multidisciplinary projects that aim to improve the understanding and prediction of that region's weather, climate, and hydrology.*[1]

Since the Global Energy and Water Exchanges (GEWEX) Continental-Scale International Project (GCIP) in the 1990s and the GEWEX Americas Prediction Project (GAPP) in the 2000s, the GEWEX community has sought to organize a new RHP in the United States that evolves and builds from these earlier experiments, and speaks directly to the dynamically evolving Earth systems challenges we face. This document is a Summary Proposal for a new Regional Hydroclimate Project (RHP) over the Conterminous United States (CONUS). The dual functions of this document are to provide a basis to become a GEWEX Initiating RHP[2], as well as to work towards alignment with US Agencies so that these Agencies might better meet their respective missions and the RHP can identify support to execute and bridge these activities: the whole is greater than the sum of its parts.

Land Acknowledgement:
The authors of this plan recognize that we live and work on lands that are, and have been, inhabited by many Indigenous peoples. Their place-based knowledge systems are as sophisticated and rich as those from the Western science traditions that many of us practice. These indigenous knowledge systems have the benefit of being rooted in place for millenia. This project is committed to engaging respectfully and sincerely with Indigenous people and communities, and to embracing and integrating their contributions. The US-RHP recognizes that we have a long way to go to build trust and relationships to create and sustain these efforts.

1.1 A New Regional Hydroclimate Project in the United States



US-RHP Mission

The US-RHP is envisioned as a ten-year effort to understand and characterize the water, energy, and carbon cycles (physical processes) in the Anthropocene, driven by a need for useful modeling tools and actionable products developed in collaboration with a multitude of stakeholders to address climate justice, and support water, food, and energy security for natural and human systems in a changing future.

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[1] https://www.gewex.org/panels/gewex-hydroclimatology-panel/regional-hydroclimate-projects-rhps/

[2] RHP Criteria: https://www.gewex.org/gewex-content/uploads/2016/03/RHP_criteria_FnlSep2013.pdf

Goals associated with this mission include:

1. Improve understanding of factors that enhance the production of actionable hydroclimate modeling tools and products
2. Improve understanding of how the development and application of hydroclimate modeling tools can advance equity and climate justice alongside food, water, and energy security, in awareness and support of ecosystem health and sustainability
3. Understand hydroclimate predictability at subseasonal to seasonal (S2S) to decadal scales, how predictability may be changing and what risks that poses for society, and how best to harness and improve our predictive skill with observations, methods, and models
4. Improve understanding of physical and dynamic mechanisms and human interventions that underlie the water-energy-food nexus and interaction and associated impacts on socio-economic factors, particularly under extreme weather in a changing climate
5. Identify impacts of anthropogenic changes in climate, land use, water use, and water management on water and energy across scales
6. Quantify critical and unknown hydrologic stores (groundwater, rock/soil water, snowpack) and fluxes (evapotranspiration)
7. Improve understanding of hydrologic variability at multiple, coupled scales
8. Understand the critical linkages associated with compound and cascading extreme events
9. Understand how changes in climate and catchment physical condition co-evolve and cascade from the atmosphere to the land surface, shaping catchment susceptibility to extremes
10. Broaden participation in multidisciplinary hydroclimate science, observation, modeling, and applications research
11. Co-create usable data, tools, and case studies with and for educational and community users

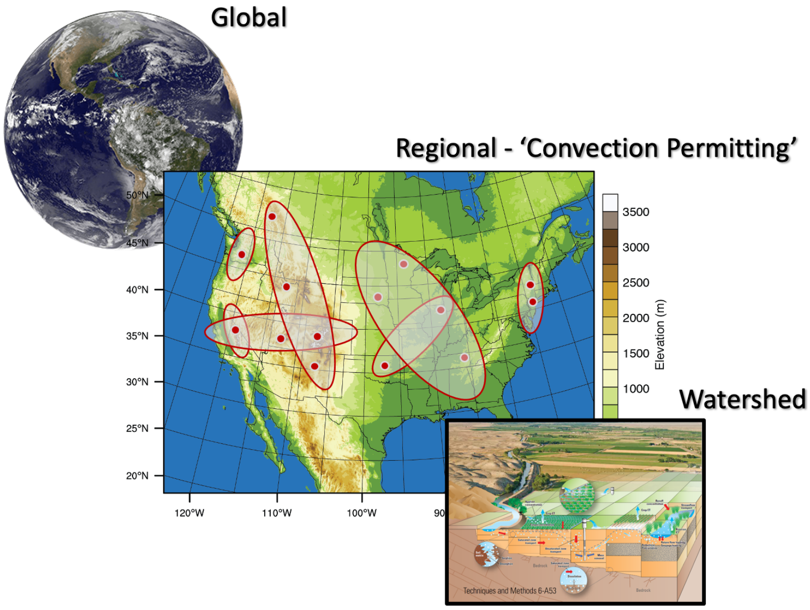
"Imperatives" driven by these goals:

1. Quantify and narrow the gap between models and nature (observations) using an uncertainty framework; identify components in modeling and observations that are needed to take imperative actions. Closing the water balance from headwater catchments to the continental-scale by fusing observations and models
2. Improve methodologies and tools to understand and address a changing hydroclimate; tools are needed that represent the full complexity and coupled interactive nature of physical, biogeochemical, ecological, and socio-economic processes at the appropriate spatio-temporal scales, which lead to multiple cascading impacts and/or crises
3. Integrate data intelligence and analytics systems (machine learning) within Earth system physical approaches
4. Determine the surface water, energy, and carbon budgets over the CONUS and within river basins with greater fidelity in a rapidly changing world
5. Integrate social, behavioral, economic, natural, physical, and indigenous science and knowledge and learn from that integration to improve interdisciplinary, convergent research and the production of actionable knowledge

6. Create a “digital twin” of the CONUS (build-out the “knowledge chain”)
7. Integrate research and outreach to inform understanding of current hydrological extremes
8. Improve knowledge, observational monitoring, and modeling capabilities for compound hydroclimate extremes (e.g., drought-heatwave-wildfire, rainfall-flood-storm surge) and their societal impacts
9. Understand the compound impacts of wildfires on water quality and the timing and magnitude of runoff in catchments
10. Collaborate with diverse potential users of hydroclimate models and tools, including Indigenous and other communities that have been historically under-represented in research, to coproduce usable hydroclimate models and tools and learn from these collaborative efforts to iteratively improve coproduction
11. Build a diverse, inclusive community of scholars, professionals, and practitioners to broaden participation in multidisciplinary hydroclimate modeling and applications research to enable a convergent science approach
12. Broaden accessibility of coproduced data, tools, and case studies for educators and community users

Defining “Regional” – Our Geographic Scope

The rather expansive focus of the US-RHP is the CONUS. The CONUS encompasses a wide range of geomorphologies, land uses and land cover, weather phenomena, and localized climates. The CONUS also interacts with, and is influenced by global phenomena such as dynamical processes (e.g. El Nino/La Nina, teleconnections), climate change, and large scale events (dust storms, volcanic eruptions, etc.). Thus there will be a range of modeling activities that span spatial and temporal scales: from the global to the regional (CONUS in this sense) to the hyperlocal (e.g. a watershed). These modeling efforts will be supported by sub-regional focal studies, driven by observational campaigns, which are optimally coordinated into transects that leverage existing as well as new assets. This is illustrated in the figure below.

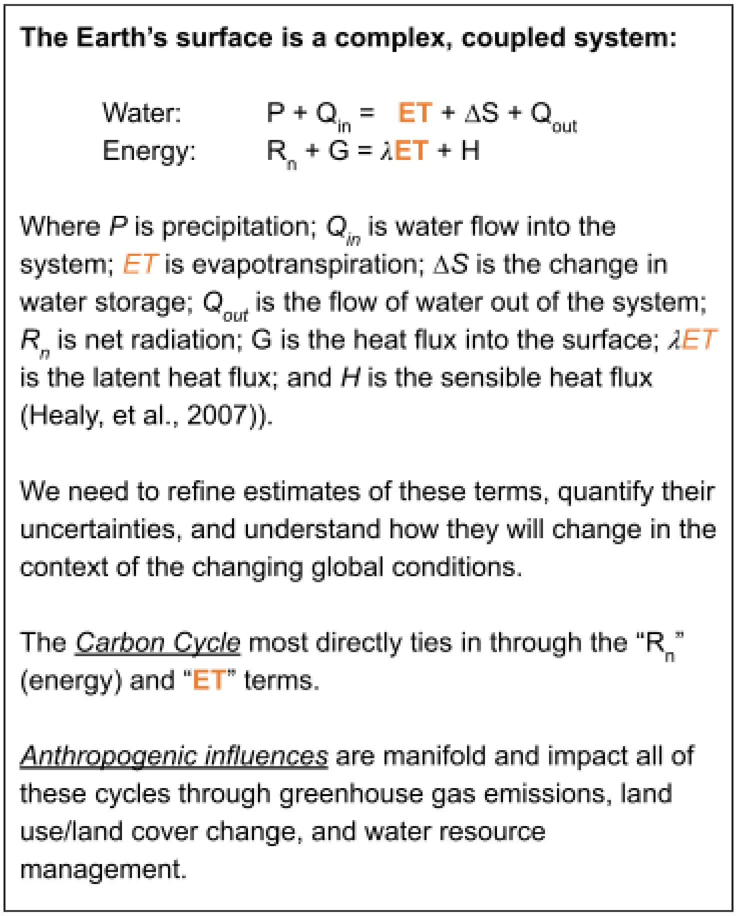


The map in the center of this figure prescribes our definition of CONUS for the purposes of the US-RHP, and notionally illustrates the idea of observational “transects” (the gray ellipses are not actual or even proposed transects, they are simply possible ones for illustrative purposes). It should be noted that the initial bounding box for the US-RHP represented by this map is partly informed by geographic scope of what can be modeled today at finely-resolved scales (~4 km resolution) over climate time scales (multiple decades). The “Global” inset indicates how the CONUS scale activities are supported by global monitoring (e.g. satellites) and modeling of the weather, water and climate systems. The and “Watershed” inset represents the processes that are locally dominant, and may require finer scale modeling and/or more intensive observations. But the Regional domain is the link that ties it all together.

1.2 Motivation

Humans live, work, eat, sleep and play on the Earth’s surface. Indeed, processes on, below, above, and through the Earth’s land surface are critical for all of life on Earth, and exert a fundamental influence on the physical and biogeochemical processes of the Earth. Due to the scope and scale of human activity, we are now the dominant driver of change in these systems such that many now consider us to be in a new geological epoch called the Anthropocene. For example, there is concern that we will drive the system to a climatic tipping point (IPCC, 2022; McIntyre, 2023), and we are now witnessing the sixth great mass extinction (Ceballos, et al., 2015; Cornford, et al., 2023).

The last time that there were any comprehensive land-atmosphere studies in the U.S., were GCIP running from 1993 to 2000 and GAPP running from 2001 to 2007. Since these first RHPs, the rest of the world has conducted numerous RHPs and the U.S. is lagging behind. Now is the time for a new large coordinated effort focused on land-atmosphere processes. This calls for an RHP that reflects the physical realities presented by the Anthropocene that are unique to our geography, and that integrates and represents the human dimensions that exert a strong influence on the natural systems.



The Earth’s surface is a complex, coupled system:

Water: $P + Q_{in} = \mathbf{ET} + \Delta S + Q_{out}$

Energy: $R_n + G = \lambda \mathbf{ET} + H$

Where *P* is precipitation; Q_{in} is water flow into the system; *ET* is evapotranspiration; ΔS is the change in water storage; Q_{out} is the flow of water out of the system; R_n is net radiation; G is the heat flux into the surface; λET is the latent heat flux; and *H* is the sensible heat flux (Healy, et al., 2007)).

We need to refine estimates of these terms, quantify their uncertainties, and understand how they will change in the context of the changing global conditions.

The *Carbon Cycle* most directly ties in through the “R_n” (energy) and “**ET**” terms.

Anthropogenic influences are manifold and impact all of these cycles through greenhouse gas emissions, land use/land cover change, and water resource management.

Why do we need an RHP over the CONUS now?

The Science Case

- Despite advances GCIP and GAPP, our analyses (model + observations) cannot close the water and energy balances over the US
- Our models are “outstripping” the observations (e.g., Lundquist et al., 2019), but are the models right? We are now capable of modeling the

CONUS at “high” resolutions (km grid spacing) over multiple decades. Land-surface models are becoming capable of reflecting processes on smaller scales (catchments to hillslopes, e.g. see Fan et al., 2019)

  - Simultaneously emerging observational capabilities [e.g., the GEWEX Land Atmosphere Feedback Observatory (GLAFO) and the United States Geological Survey (USGS) Next Generation Water Observing System (NGWOS)] should be used to validate and improve these models
  - In places we now have sufficiently extensive and long historical time series of observations to use for model development. Developments of improved observation capabilities and model representation need to be better linked (co-developed)
- Given the rapidity and scale of change in the Earth system, we need models capable of representing the carbon, energy and water cycles with greater fidelity and at the proper time and space scales to enable actionable and convergent science
- We need action now as a community to close the energy, water, and carbon balances in regional human-natural systems to address the pressing science questions of the day
  - One important reason to close these balances is to understand the errors and uncertainties in all of the terms in the coupled water-energy-carbon cycles (see text box above): which leads to the question, which processes do we describe and predict appropriately and accurately, and which we do not?
  - In Section 2 we identify some of these pressing questions (no one project can address all of them). Underlying these questions are a growing population and changing demographics, aging infrastructure, a changing climate, and stressed and imperiled ecosystems.

The Programmatic Case

The whole is much greater than the sum of its parts!

- *Leveraging:* No one agency or entity can do it all
- *Focus:* As noted, there has not been a major land-atmosphere project in the US for a long time, and gaps in knowledge put food, water, and energy security and sustainability at risk. The US-RHP will provide an impetus to conduct this work and be a focal point to enable advancements in this area
- *Engagement:* the US-RHP is an agent for “Open Science.” It brings the international community to the table, and provides a mechanism to engage and coordinate the academic community and others in the enterprise. It provides an effective venue for stakeholder engagement and mechanism for coproduction of actionable science
- *Economy of scale:* Agencies are focussed on their respective missions (as they should be); the US-RHP can help to coordinate and integrate these investments into a greater whole and provide a more efficient and effective use of taxpayer dollars

Alignment with GEWEX Goals

The efforts proposed by the US-RHP are aligned with the GEWEX Science Plan (2021), which identifies three science goals, all of which are addressed in multiple ways by this project:

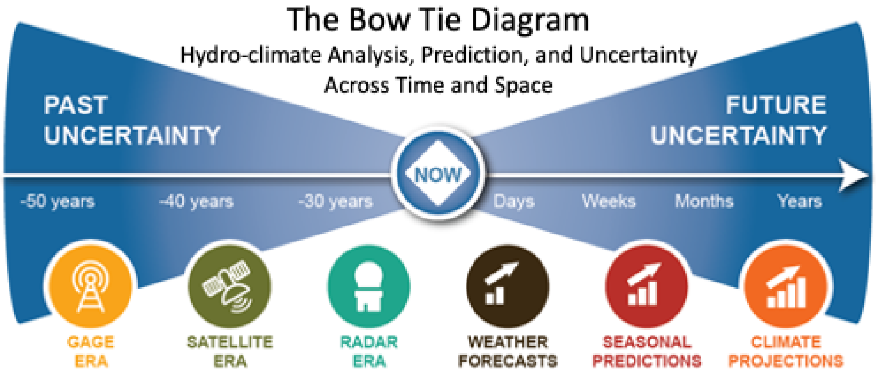
Goal #1: To determine the extent to which Earth's water cycle can be predicted. This Goal is framed around making quantitative progress on three related areas: the fast reservoirs of water, flux exchanges with the Earth's main reservoirs of water, and precipitation extremes.

Goal # 2: Quantify the inter-relationships between Earth's energy, water, and carbon cycles to advance our understanding of the system and our ability to predict it across scales.

Goal # 3: Quantify anthropogenic influences on the water cycle and our ability to understand and predict changes to Earth's water cycle.

In Summary

One of the primary drivers for this project is to reduce the uncertainty in our ability to measure, predict and understand the coupled water, energy and carbon cycles:



The US-RHP is an opportunity to develop a coordinated, holistic response to hydroclimate change. In the past several years, the US has witnessed hydroclimate events that are without historical precedent (e.g., heat extremes, droughts, fires, relentless coastal storms, flooding, and record snowfalls), and the number of such events are growing. Yet the environmental science community often responds in a disjointed way, as there is no established mechanism to provide the needed coordination and synthesis. The US-RHP would create a flow of information that is sustained, coordinated, and actionable to the agencies and user communities, as these events and their aftermath unfold. This would help address and align the sizable gaps between the physical and human hydroclimate knowledgebase across the community. It is an opportunity to engage and coproduce science with Indigenous scientists and knowledge holders, in order to develop a more comprehensive and complete understanding of our changing hydroclimatic system. It is also an opportunity to center ideas about engagement, equity, and climate justice in knowledge coproduction and application, to broaden participation in multidisciplinary hydroclimate modeling, observations, and applications research, and to make actionable outputs more accessible and usable to educators and community users.

Lastly, this will be *a living document and process* that will continue to evolve with community input.

II. US-RHP Scientific Strategy

This section outlines a scientific strategy for the US-RHP. This section, and indeed the entire plan, is the product of a sustained effort of the US-RHP Affinity Group (161 members as of this writing). The Affinity Group discussed and drafted the “Goals” and “Imperatives” defined above. We then identified eight thematic research areas to advance. These are: Human Dimensions, Mountain Hydroclimate, Land-Atmosphere Processes and Coupling, Impactful Extremes, Organized Convection and Precipitating Systems, Advancing Observational Systems, Coastal Processes and Coupling[3], and the Digital Earth for the U.S (DEUS). Seven Working Groups[3] were formed for each theme, who identified the gaps (motivation), core science questions, and activities for their respective topics, and considered the implied scope.

2.1 Human Dimensions

Motivation/Thematic Gaps

We make choices in how humans are included in continental scale models and aggregate measures (e.g., human response to hydroclimatic stress or human impacts on hydroclimatic systems, assessments of climate and environmental justice), and these choices have implications for both the reliability and usability of hydroclimate science that are not well understood. Relatedly, while scholarship on environmental and climate justice has grown exponentially, less well understood is how assessments of environmental and climate risks at broad spatial and temporal scales may result in actionable insights on hydroclimatic impacts on disenfranchised or marginalized populations.

Human activities significantly modify hydrological and land surface processes in a variety of ways and at multiple scales such as through water diversion, storage, irrigation, and vegetation and soil management (Lu et al. 2018). While large scale hydrological models have begun to incorporate human impacts on the hydrological cycle, critical challenges remain including better incorporating human water management information and systems into these models (Blair & Buytaert 2016; Wada et al. 2017) and measurements to enhance the production of actionable hydroclimate knowledge for communities.

Most studies of actionable knowledge are retrospective, aimed at understanding the production of actionable knowledge that fits the needs of a particular community or knowledge user (Lemos et al. 2014, Timofeyeva-Livezey et al. 2015, Vogel et al. 2016). Longitudinal studies of how science becomes actionable are less common (Kirchhoff et al. 2015, Lemos et al. 2019), as are studies of actionable knowledge at broad spatial or temporal scales (VanderMolen et al. 2019). Critical questions remain about how we 1) bridge our understanding of what makes hydroclimate and integrated carbon-water-food-energy knowledge actionable from continental to local scales, and 2) whether known strategies that improve the production of actionable knowledge at local scales—such as early and ongoing engagement to co-create

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[3] Coastal Coupling and Processes thematic research area remains to be determined. The AG recognizes the importance of this activity but does not currently have the capacity to establish a Working Group on this topic, though we remain open to the notion.

knowledge—will work at scale, e.g., when the scale of the science and the scope of the scientific enterprise are much bigger. Finally, while there are emerging studies on the production of actionable knowledge with Indigenous and other communities that have been and continue to be underrepresented in research (Kalafatis et al. 2019), more research is needed regarding approaches that may improve reciprocity and building (and repairing) relationships with these communities (Tachera 2021).

These gaps in understanding lead to the science questions noted below.

Science Questions

1. How do we include humans and human alterations of hydrologic processes (e.g., population characteristics, water and land use, adaptive behavior, practices, transbasin diversions, local knowledge) in continental scale models and aggregate measures?
2. How does the scale of the science and the scope of the scientific enterprise affect our ability to produce actionable knowledge, particularly with emphasis on Indigenous and other communities that are under-represented in research?
3. How can we improve transparency and communication of scientific research to improve reciprocity and build (or repair) relationships with Indigenous and other communities?

Key Activities

- **End-use case studies/best practices:** Work with model developers and potential users of model outputs and insights to develop end-to-end use cases that illustrate best practices for the entire process from question identification and refinement to data identification, scenario development, and modeling, and co-creation of outputs (e.g., platforms or tools or summary documents) for communicating actionable information to decision makers.
- **Science of actionable knowledge:** Conduct ethnographic or observational studies to track how question identification, data identification, scenario development and modeling, and co-created outputs are used by communities and are revised over time in response to community feedback. These studies would improve our understanding of how interaction between modelers and potential users shape the information/models, how perceptions about the data/information/outputs changes over time (e.g., usability, reliability, legitimacy, etc.), how understanding (both modelers' understanding of user needs and users' understanding of modeling) changes over time, and more.
- **Experimentation:** Conduct experiments to understand trade-offs in how human activities and human behavior are included in continental scale models; including both non-intentional interventions (usually at the global scale) as well as intentional ones such as water management (which are usually at a more local/regional scale). This will also include multiple model-generated data studies that examine how adaptive behaviors, human practices, and other human characteristics can best be represented in the model and how these behaviors interact with changes in hydroclimate (e.g., rates of decomposition may reflect farmer tilling behavior, which may be further shaped by changes in hydroclimate; Graham et al. 2021).

- **Science of Engagement:** Conduct ethnographic or observational studies to understand what engagement and research practices improve reciprocity and repair relationships with Indigenous communities. This activity may require building and sustaining relationships between information producers and users known to facilitate actionable knowledge production and use (Lemos et al. 2012).
- **Data Adequacy and Management of Misuse:** In the context of generating actionable knowledge it is important to assess whether information and data (whether model derived, observational, or from any other source or process) are adequate-for-purpose, especially when new applications deviate from the intended research purposes of the data. Data and the tools and processes that produce the data have an origination, and are meant to serve a certain research purpose within a certain context. Assessing, documenting, and communicating the adequacy for different purposes of data products is necessary to prevent the possibility of misuse or misapplication of these products. In actionable science contexts, this can have harmful consequences if the information is informing how resources are allocated or plans for adaptation, resilience or management are made. In this project we will attend to questions of how to best provide adequacy-for-purpose information to users to manage the risk associated with the misuse of information outside of its origin context and purposes.

Geographic Scope/Regions

- For local level actionable knowledge production, we intend to focus on four different subregions and four different potential end user groups. The subregions will be selected to maximize the range of biophysical features involved in the RHP, and potential end user groups will represent a range of different communities, prioritizing underrepresented groups in hydroclimate research including Indigenous communities, migrant communities, coastal communities, agricultural communities, and low-income urban communities.
- For national or regional scale actionable knowledge production, we intend to work with regional policy or decision makers such as, for example, the regional energy utility, regional water (or water-energy) utility or authority, agricultural extension officers or United States Department of Agriculture (USDA) administrators, Tribal leaders, elected officials, or others who hold similar decision making roles.

2.2 Mountain Hydroclimate

Motivation/Thematic Gaps

Water from mountainous watersheds in the Western United States serves as a critical resource for that arid region, providing 85 billion cubic meters of water (Richter et al, 2020) to a region inhabited by 80 million people and supporting myriad uses, including agriculture, municipal and industrial supply, hydropower, navigation, ecosystems and recreational activities (Raff et al, 2013, Siirila-Woodburn et al. 2021, Sturm et al. 2017). Because of this societal relevance, the last three to four decades have seen large federal- and state-level investments in research and development by researchers, operational groups, and stakeholders to support the operation, management, and planning of US water and emergency resources. This investment has produced multiple datasets, methods, and models to enhance our understanding of the behavior and vulnerabilities of our watersheds and dependent water applications (e.g. Lukas et al., 2020).

However, despite these investments and capabilities, gaps remain in our knowledge of this important resource. While our estimates of Western US hydroclimate processes are reasonably well-constrained and understood at coarse time and spatial scales, applications and model evaluations demand increasingly high-resolution descriptions of the functioning of watersheds and their sensitivity to the impacts of climate and land use change and water demands. Describing watershed-level hydroclimatology with greater space-time granularity adds a layer of uncertainty that becomes difficult to untangle from our physical understanding, given our current modeling systems.

To a large degree, this is because at these high spatial and temporal scales, our quantitative estimates of precipitation in mountainous terrain suffer from uncertainties large enough to confound our model evaluation (Lundquist et al. 2019, Bytheway et al. 2020). These precipitation estimates are typically either based on in situ point observations (approximately 30K sites for the US), are ground-based-radar- or satellite-derived (with coverage issues and/or large measurement uncertainties), or distributed with horizontal resolutions of 4 km or higher (e.g., AORC, 2021). Hydrological observations are either point-based or based on satellite remote sensing, with various limitations: for example, in situ soil moisture measurements are limited spatially to a few thousand locations across the US and temporally to a few decades (Quiring et al. 2016), current satellites only estimate soil moisture in the top ~5 cm of the soil (e.g., Champagne et al. 2016; Entekhabi et al. 2010, Kerr et al. 2012), and satellite gravimetry offers estimates of changes to water in deeper soils, but at coarse spatial resolution and limited accuracy (Chen et al. 2022). While spatial representation of highly heterogeneous variables like soil moisture is a challenge across the US, the challenge is greatest in the complex terrain.

To support these information needs, we must both densify and expand our observational network, including new and more spatially- and temporally-distributed observations not only of precipitation, but also for other surface meteorological variables and hydrological variables. Even for precipitation, a critical variable, there are scientific and technical limitations to achieving this objective: i.e., ground-based radars suffer from blockage from complex terrain, satellite-based estimates struggle with retrievals over the heterogeneous mountainous terrain, and installing a dense enough network of in situ measurements to capture the heterogeneity is resource-intensive. Addressing this gap for short periods of time is possible; for example, the Seeded and Natural Orographic Wintertime clouds: the Idaho Experiment (SNOWIE) field campaign used the Doppler on Wheels (DOW) radars to well-sample precipitation in the Payette Mountains of Idaho (Tessendorf et al. 2019), and the SnowEx field campaign organized coincident field, airborne, and tasked remote-sensing observations (Durand et al. 2017, https://snow.nasa.gov/campaigns/snowex). However, a network capable of observations for extended periods and across larger watersheds requires resources that exceed those available for typical scientific field campaigns.

There are also opportunities to improve our quantitative consensus on the fate of mountain precipitation (i.e., either into storage terms like snowpack, soil moisture, or groundwater, or into fluxes like runoff and evapotranspiration). Uncertainties in surface meteorology (e.g., precipitation, temperature, wind speeds, humidity, and other variables) propagate into uncertainties in hydrologic variables, and these uncertainties must also be quantified in efforts to face this challenge. An improved understanding of precipitation partitioning at the surface (into snowpack formation, infiltration, or runoff) and dependent subsurface processes is needed. That is, even when we have good quantitative estimates of how much precipitation falls across a given watershed, knowing how much of that precipitation fell as snow versus rain remains highly uncertain (Jennings et al. 2018); subsequently our estimates of snowpack evolution are impacted by this precipitation uncertainty as well as being poorly constrained by snowpack observations (Wrzesien et al. 2018, McCrary and Mearns 2019). Recent years have exhibited runoff deficits that are unexpectedly large given observed precipitation and snow deficits (Lehner et al. 2017, Abatzoglou et al., 2021). Recent streamflow deficits in the Colorado River Basin have been attributed to warming air temperatures, decadal variation in precipitation and possibly secondary feedbacks such as the influence of snow albedo on near surface air climate (Milly and Dunne 2020), or the effects of dust on rates of snowmelt (Painter et al. 2018). A full suite of high-quality, distributed observational datasets to use in refining our understanding of these phenomena is lacking, however. This has led the community to call for significant improvements in observational networks for all aspects of the water balance (Kampf et al. 2020).

These uncertainties make model evaluation in complex terrain exceptionally challenging, a challenge exacerbated by the inability of models to represent the scales of the heterogeneity of these regions. This impacts weather and water models used to make predictions across timescales, including convection-permitting weather forecast models (e.g., Bytheway et al. 2020), and becomes more problematic as model resolution coarsens. On longer timescales, global climate models, which serve as our current tools for generating climate projections, operate at scales too coarse to represent complex terrain and the mesoscale and microscale processes. Many of the uncertainties associated with anthropogenic hydroclimatic change are even larger in complex terrain because of the interaction between large scale climate and the terrain, and these uncertainties cannot be addressed, narrowed, or resolved due to our glaring gaps in observational networks in this terrain.

Finally, progress on these scientific gaps in our understanding of mountain hydroclimate is slowed by insufficient investment in collaborations between federal, state, and local agencies and the research community. Many of the aspects of mountain hydroclimate science challenge reside in different portfolios of the different agencies' missions. One example of this can be found for the Colorado River Basin. On the federal side, official Colorado River Basin forecasts on seasonal (S2S) time-scales could better leverage improvements from operational sub-seasonal to seasonal climate efforts, modern methods for assimilating Earth observations (e.g., for snow and soil moisture variables), and new hydrology and land modeling development efforts from the Earth system science community.

For centennial-scale hydroclimate projections used by state and local agencies in planning, the last two decades have seen the development of extensive datasets, research literature, and agency guidance at various levels (particularly federal and state; e.g. Lukas et al., 2020, Reclamation, 2021). Agencies such as the US Army Corps of Engineers and local utilities such as Denver Water are evolving from the qualitative use of future hydroclimate scenarios to more quantitative uses in planning and design. Yet science questions and uncertainties remain in multiple areas, including identifying the best approaches for selecting and using future climate projections from general circulation models (GCMs) and Earth system models (ESMs), for interpreting their results in the face of random internal model variability, for downscaling their outputs to local climate, and for implementing hydrologic and land models that can robustly simulate climate-forced changes in water availability.

Science Questions

The above gaps in mountain hydroclimate lead to several pressing science questions surrounding mountain hydroclimate, its representation in models, and its prediction. Below, we highlight primary and secondary questions stemming from each of the thematic gaps identified in the section above.

1. What are the dominant sources of uncertainty in mountain hydrometeorology for state estimates, and sources of predictability on various predictive timescales?
    a. How do uncertainties in our estimates of mountain meteorology propagate into uncertainties in hydrologic variables (runoff, snow accumulation and melt, soil moisture, groundwater, evapotranspiration)?
    b. How do uncertainties in the hydrological state of the land surface effect the atmospheric boundary layer (and vice versa)?
    c. How can we reduce prediction uncertainties and improve predictive skill?
    d. These uncertainties stem from both deficiencies in our observational networks (leading to inaccurate and uncertain state estimates) and from incomplete use of our observational constraints in predictions (i.e., unrealized predictive potential). What's the optimal investment in the observation and prediction infrastructure to make the largest improvements in predictive skill?
    e. How can information from stakeholders be used, both in terms of their needs, but also in terms of their experiential knowledge of these systems, which is rarely incorporated into mountain hydrometeorology prediction in spite of its value in capturing the salient processes that influence mountain hydrometeorology?
2. What are the most significant impacts to mountain hydroclimate under anthropogenic climate change?
    a. How does precipitation over mountain barriers shift in response to changes in temperature and land use changes, and how does that impact the water balance in different watersheds?
    b. How does evapotranspiration in mountain basins respond to anthropogenic climate change?
    c. How do characteristics of mountain snowpack change in response to anthropogenic climate change, and what are the implications for mountain hydrology?

        i. What will this mean for the timing of runoff, if the areas that currently hold snow longest providing late season melt, have the greatest shift in timing of melt?
        ii. Will the shift to warmer temperatures result in more melt, less sublimation, and/or more condensation on the snow surface?
        iii. How will climate change impact blowing snow (via both sublimation and spatial distributions)?
        iv. How will sub-canopy snow change in response to increased canopy longwave radiation and/or increased snow interception?
    d. How will widespread montane land cover change, such as that through wildfire, aridification, or forest mitigation practices, affect fundamental hydrological processes?
3. What constitutes sufficient scientific support infrastructure for mountain hydrometeorology that ensures all federally-funded observations, modeling, and scientific insights from satellite- to field-scale activities are readily accessible for researchers?
    a. What are the optimal observational strategies for a given process; in terms of types of instrumentation, density (number), and siting (location)?

Key Activities

Science question 1 and Science question 3:

- Observations of precipitation amounts and types, at high enough spatial/temporal resolution to quantify “how much water falls” for at least a few large western US basins
- Very dense network of precipitation gauges (can be simple tipping buckets for rain only) and snow depth sensors for a solid precipitation proxy, particularly at high altitudes where few precipitation measurements exist at present. Low density network of snow pillows (solid state) or small double fence intercomparison reference (SDFIR) with Geonor-type precipitation gauges to estimate new snow density
- Observations of snowpack from airborne LiDAR mapping and new in situ observations above tree line
- Observations of canopy snow interception
- Installation of “gap-filling” radars and atmospheric measurements in mountains, e.g. cloud radars and Doppler LiDAR
- A comprehensive evaluation of observations of evapotranspiration in complex terrain, including potentially under-utilized satellite-based opportunities
- Full energy balance (EB) sites using either bulk aerodynamic method or eddy covariance (EC) for turbulent fluxes would be ideal. It depends on specific purpose for EB measurements, but multi-year (≥3 years) would be necessary to capture inter-seasonal/inter-annual variability
- Western US hydrometeorology prediction testbed: a strategy to create an organized focus of effort for evaluation of alternatives (methods, observational data, models)
- Case Studies, especially end-to-end studies or those integrated to work with climate/hydro/management agencies

  - e.g., the current National Center for Atmospheric Research (NCAR)-Reclamation-Missouri Basin River Forecast Center (MBRFC)-Northern Water project to develop better retrospective and real-time forcings for modeling and forecasting in the Big Thompson River basin through fusion of public observation networks, proprietary observations (OneRain), and Rapid Refresh (RAP)/High-Resolution Rapid Refresh (HRRR) forecast systems, in ensemble mode. These forecasts impact the operation of the Colorado-Big Thompson (CBT) project.

Science question 2:

- High-resolution modeling experiments to elucidate the mechanisms of orographic precipitation response to anthropogenic climate change
- Advancing snow modeling capabilities to explicitly simulate key mountain snowpack features at snow-drift resolving scales (<100m)
- Intermediate-scale ensemble modeling experiments to allow for characterizing model uncertainties and support model-observation fusion
- Model-observation fusion experiments (reanalyses, digital twin)

Geographic Scope/Regions

The Intermountain West region of the United States is the primary focus of the questions and efforts outlined in the Mountain Hydroclimate thematic research area. That said, what is learned from these efforts will improve our understanding and ability to model and predict hydro-meteorological processes and states, and may be applied in other geographic areas as well. Furthermore, resources and community priorities can shift and/or expand the geographic scope as necessary.

2.3 Land-Atmosphere Processes and Coupling

Motivation/Thematic Gaps

There are several knowledge gaps in our understanding of, and ability to quantify, land-atmosphere (L-A) interactions and their impacts over the US:

1. There is a lack of knowledge about the role that L-A coupling plays in influencing the evolution of US hydroclimate extremes on S2S to decadal timescales (and even for short to medium range weather timescales). Some examples include: S2S drought propagation (superimposed on decadal megadrought), wildfire responses to droughts, and the impact of precipitation extremes and rain-on-snow events on flooding. This is because detailed process-level mechanisms of how L-A interactions and planetary boundary layer (PBL) processes control the local and regional weather/climate systems are still not fully clear, and observations of these processes often lack spatial resolution or coverage to ameliorate these uncertainties. This thereby limits our ability to improve modeling capabilities of S2S predictions and longer-term climate projections of the US hydroclimate extremes.
2. There is a lack of knowledge about how L-A feedback affects the coupled snowpack-drought-fire-heatwave system in the US, particularly under climate change. Several key questions include how declining snowpack driven by warming will affect the

evolution of droughts and fires and hence feed back to regional hydroclimate systems. These processes also play a critical role in energy-water-carbon coupling.
3. There is a lack of knowledge in understanding how land use land cover (LULC) change will alter L-A interactions and hence the US hydroclimate under climate change. Several key aspects are not well understood, including impacts of human land management practices on weather/climate, bio-energy and food security, urbanization effects on regional extremes, and fire effects on L-A coupling and ecohydrology. In many cases, land surface models (LSMs) lack adequate realization of physical processes. These important but unresolved issues hinder a better understanding and prediction of the food-water-energy nexus.

Science Questions

To fill in the knowledge gaps, we propose three core science questions:

1. What roles do local and regional L-A interactions play in controlling the evolution and prediction of US hydroclimate extremes on S2S timescales?
    a. What are the L-A processes affecting the S2S predictability of hydroclimate extremes?
    b. What are the roles of the local/regional L-A interactions versus large-scale circulation patterns in controlling S2S hydroclimate predictions?
    c. How will hydroclimate predictions benefit from enhanced model representations and surface data assimilation related to L-A interactions?
    d. How will US L-A coupling hotspots shift under climate change and how will these shifts exacerbate or dampen regional hydroclimate extremes?
    e. What are the roles of land-atmosphere interactions in translating extreme precipitation to floods?
2. What are the L-A feedback mechanisms controlling interactions between snowpack, drought, heatwave, and fire in the US, and how will they respond to changing climate?
    a. How will declining snowpack and shifts from seasonal to ephemeral snow affect drought and fire, and what are the processes coupling these phenomena?
    b. How do drought and fire impact seasonal snowpack evolution, and how will their interactions change in a warming climate?
    c. What key L-A coupling processes control how drought exacerbates the frequency and intensity of fire and heatwaves?
    d. What will be the hydrologic impact of declining snowpack and induced changes in frozen soils?
3. How will LULC change affect local/regional hydroclimate through L-A interactions under climate change?
    a. How will agricultural management impact US crop yields, food security, and bio-energy in a coupled atmosphere-surface water-groundwater system, particularly during droughts?
    b. How will US urbanization affect regional hydroclimate conditions and extremes through L-A interactions under climate change?
    c. How will land cover perturbation due to wildfires change and respond to L-A interactions and hydroclimate over the Western US?
    d. How will longer-term shifts in ecohydrology due to land surface disturbance and climate interventions related to landscape changes modify or be modified by L-A feedbacks?

Key Activities Needed

Addressing those questions will require expansion of our current ability to observe and model coupled processes between the land subsurface, surface, PBL, and free troposphere. There are several existing observational resources that we can leverage. For example, there are existing satellite missions to measure terrestrial hydroclimate, including soil moisture [e.g., Soil Moisture Active Passive (SMAP), Soil Moisture and Ocean Salinity (SMOS), the European Space Agency (ESA) Climate Change Initiative (CCI)], terrestrial water storage [e.g., Gravity Recovery and Climate Experiment (GRACE), GRACE Follow On (GRACE-FO), Surface Water and Ocean Topography (SWOT)], vegetation cover and fire signal [e.g., Monitoring Trends in Burn Severity (MTBS), Moderate Resolution Imaging Spectroradiometer (MODIS), Visible Infrared Imaging Radiometer Suite (VIIRS)], plant temperature [e.g., ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station (ECOSTRESS)], and snow cover [e.g., Interactive Multisensor Snow and Ice Mapping System (IMS), MODIS]. Snow water equivalent (SWE) and snow depth are more challenging to capture with current remote sensing capabilities, especially in mountainous and forested regions. As Earth observing missions are phased out over time, new missions with equivalent variables will need to come online in order to maintain a consistent long-term record of a changing climate. While spaceborne missions are planned and executed over a long period of time, the modeling, observations and science conducted under the US-RHP, could support and inform these efforts.

Ground observations will also be critical, such as the existing AmeriFlux for carbon and energy fluxes, Snow Telemetry (SNOTEL) for SWE and snow depth, and the Soil Climate Analysis Network (SCAN) for soil moisture and soil temperature. Some existing field campaigns can be exploited, including the Department of Energy Atmospheric Radiation Measurement (DOE ARM) site and Holistic Interactions of Shallow Clouds, Aerosols, and Land-Ecosystems (HI-SCALE) campaign in the Southern Great Plains (SGP), the DOE Surface Atmosphere Integrated Field Laboratory (SAIL) and National Oceanic and Atmospheric Administration (NOAA) Study of Precipitation, the Lower Atmosphere and Surface for Hydrometeorology (SPLASH) in the East River Watershed along with the longer-term Rocky Mountain Biological Laboratory and East River Watershed Function Scientific Focus Area (SFA), the National Aeronautics and Space Administration (NASA) SnowEx, the National Science Foundation (NSF) Critical Zone Collaborative Network (CZNet), and National Ecological Observatory Network (NEON), the USGS Next Generation Water Observing Systems (NGWOS), and the proposed GEWEX Land Atmosphere Feedback Observatories (GLAFOs) effort.

Given the heterogeneity of surface processes and coupling with the atmosphere, additional observations are needed. Measurements of PBL quantities are needed to improve model parameterization of turbulence. This would require an expansion of flux tower networks in mountainous and diverse climate regions, where GLAFOs could provide valuable data. More cross-canopy measurements could be critical for better understanding below-canopy turbulence, canopy-radiation interaction, and canopy snow interception. L-A interactions have been under-studied in cold climates, so an expansion into such regions would be critical. Currently, most surface snow observations are located at mid-elevations in the Western US, while additional observations are needed at lower-elevation ephemeral snow regions and very high elevations.

Recently, atmospheric and land models have been enhanced to better represent L-A coupling, such as the coupled canopy-snow-soil system and biogeochemical cycles/ecosystems. Current LSMs and coupled weather/climate models can capture key features of L-A interactions. Regional/global high-resolution (convection-permitting) models have demonstrated their great usefulness to capture L-A interaction, particularly for the diurnal cycle and over complex terrain. In addition, data assimilation has been applied to further enhance the representation of L-A coupling and its impacts on weather/climate. Overall, combining convection-permitting models that are enhanced in physical parameterizations with observations through data assimilation and adding model isotopes/tracers will be particularly useful for understanding and modeling L-A interactions.

Current model uncertainties in processes related to L-A interaction call for better representations of processes like groundwater, frozen soil, plant hydraulics, fires, canopy turbulence, wetland, irrigation, crop evolution, biogeochemical cycles, and ecosystem evolution. Existing model parameters may need to be updated and optimized according to specific applications. In addition, enhancements and new physics introduced to offline LSMs do not always produce improved results in coupled weather/climate models. This is motivation to have a Hierarchical System Development (HSD) approach for model improvement, where systematic testing (from individual model element to fully-coupled model) is necessary. In addition, there is a strong need for better model input datasets such as soil texture, land use and vegetation types, and groundwater table depth. A model intercomparison initiative for L-A interactions across scales will be useful. Also a collaborative effort of synthesizing existing model input datasets will be beneficial. Moreover, detailed process-level studies are needed to better understand those processes and then enhance model physics. A strongly-coupled data assimilation system for atmosphere and land components is also needed.

Focused Geographic Scope/Regions

We highlight a few geographic regions where expanded L-A coupling research needs to be done. Snow-fire-drought relationships are critical to understand in the Western US. Here we could leverage regions related to existing field campaigns [e.g., SAIL, SPLASH, SnowEx, DOE East River Watershed, NSF Critical Zone Observatories (CZO)]. Expansion of flux towers into mountains will also allow us to better understand turbulence in complex terrain and within-canopy coupling. Additionally, the Northern Great Plains could be a key focus area, as potentially large shifts in local L-A coupling may occur in a warmer climate. This region has a notable cold season that is lacking at the ARM Southern Great Plains (SGP) site, such that coupling in cold/snow conditions could be examined. Finally, we could propose to expand the GLAFO proposed sites to help enhance US-RHP activities.

Potential Stakeholders

- Federal agencies such as NOAA [e.g., Weather Program Office (WPO) and Climate Program Office (CPO) programs], DOE [e.g., Environmental System Science (ESS) and Atmospheric System Research (ASR) programs], USDA, and NASA [Terrestrial Hydrology Program (THP) and Interdisciplinary Research in Earth Science (IDS) programs], who would be interested in improving the understanding and modeling of the role that L-A interactions play in S2S and decadal forecasts of fire, drought, and extreme events under climate change
- Local water and fire resource managers, who will provide useful information to guide the research focus of this working group (WG), while the deliverables (improved knowledge and modeling tools) will in turn benefit them in making better decisions in resource management
- General public: educational outreach to distribute improved knowledge among the general public will help to better cope with extreme events and better protect public life and property

Inter-WG Synergies and Connections

- Our foci on L-A coupling in snow-fire-drought interactions and hydroclimate extremes are closely related to those of the Mountain Hydroloclimate and Impactful Extremes WGs
- The study of L-A interactions could benefit from collaboration with the Organized Convection and Precipitating Systems WG, since L-A interaction is directly coupled to convection (e.g., in SGP)

- This WG can connect to the Coastal Processes and Coupling WG, where L-A-ocean feedbacks are important in controlling coastal processes (e.g., hurricane impacts on coastal cities)
- L-A coupling hotspots identified by this WG will be able to guide the Advancing Observational Systems WG to better set up future measurement networks and observing systems, where those observations will in turn help understand L-A interactions in those key hotspot areas
- This WG can work with the Human Dimensions WG to better understand the socio-economic consequences of the proposed scientific issues, while the Human Dimensions WG could provide guidance for the key areas that require a higher priority of scientific investigation, such as implementing anthropogenic processes into our models

2.4 Impactful Extremes

Motivation/Thematic Gaps

Weather and climate-related extreme events, are often comprised of significant environmental forcings coupled with socioeconomic characteristics that produce serious impacts and hazards. From heatwaves to flooding to drought and severe cold, impactful extremes have touched all aspects of society across North America, and in many cases, have yielded severe economic losses, depleted ecological resources, and loss of life. Further, there is growing evidence that extreme events are connected both spatially and temporally with other extreme events and outcomes. For example, drought in the west can lead to desiccation of the ecosystem and subsequent wildfires. However, during transitions to excessive precipitation (e.g., via an enhanced monsoon or atmospheric river events), significant rainfall upon burn scars can lead to flash flooding, slope failure, and debris flows. Such “cascading” events can produce multiple hazardous outcomes that occur at varying temporal periods. In addition, compound events such as drought and heatwaves can occur simultaneously, threatening agriculture and water resources while stressing the electrical grid.

Scientifically, impactful extremes pose numerous challenges. Broadly, it can be non-trivial to determine the best way to define a given extreme event for different locations and seasons. For a given type of extreme, there can be many definitions (e.g., Perkins and Alexander 2013). The choice of baseline climatology period can also affect the quantification of extremes (Dunn et al. 2022). It is also unclear whether current definitions for extreme events are appropriate to apply to future climate projections. It may be beneficial to consider non-gaussian distributions for defining and forecasting extremes. Finally, as society adapts, the relative severity of certain impacts may decrease, so there is a need to determine how to quantify impacts across timescales (explore links with the Human Dimensions Working Group).

Understanding the precise mechanisms driving impactful extremes is also an important problem. There are often both local and remote influences driving extreme events, and disentangling these can be a challenge. Limits to relevant observational networks, such as evapotranspiration and streamflow, can further exacerbate this challenge. Of particular importance is understanding the mechanisms driving compound and cascading events, and the heightened societal impact and feedback these can have (Raymond et al. 2020; explore links with the Human Dimensions Working Group).

Predictability is another major challenge with impactful extremes. While some types of extremes have the potential to be predicted on S2S times scales (e.g., Vitart and Robertson 2018), there are still many open questions regarding main drivers of prediction skill, and how well these are currently simulated. It is crucial to establish sources of predictability for impactful extremes on timescales ranging from sub-seasonal to decadal or longer timescale projections.

Science Questions

1. How should impactful extreme events be defined spatially and temporally in a non-stationary climate, and how can current definitions be applied to future climate projections?
2. What are the primary physical mechanisms associated with different impactful extreme events, and what is the role of climate change in driving extremes in the present and future climate?
3. What are the sources of predictability for different types of extreme events at various prediction timescales, and how well do current models represent these sources?

Key Activities

Science question 1:

- Case studies on sensitivity of quantification of and trends in extremes to different definitions and thresholds
- Impacts-based assessments of extreme events–particularly compound/cascading events

Science question 2:

- Case studies of extreme events including water and energy budgets leading up to and during the event
- Large-ensemble experiments to explore the role of forced climate change in extreme events

Science question 3:

- Examination of S2S reforecasts to identify times and places where extremes are predictable
- Modeling experiments to test the impact of resolution, initialization on predictability of extremes

The GEWEX/Impact of Initialized Land Temperature and Snowpack on Sub-seasonal to Seasonal Prediction (LS4P) project is an opportunity to collaborate and coordinate on Impactful Extremes, and cross-cuts other thematic research areas, notably the Land-Atmosphere Processes and Coupling and Mountain Hydroclimate sections. Recent research in GEWEX/LS4P has identified that the land temperature in the Rocky Mountains has a significant impact on downstream regions, in particular for the Great Plains during the spring and summer, with implications for droughts and floods (Xue et al., 2018). GEWEX/LS4P has also demonstrated the importance of high-mountain land temperatures for S2S prediction, again with implications for floods and droughts (Xue et al., 2021, 2022). These issues will be investigated further by the GEWEX/LS4P Phase-II project, which will continue to focus on the effect of land temperatures in the Rocky Mountains on North and Central American summer droughts and floods.

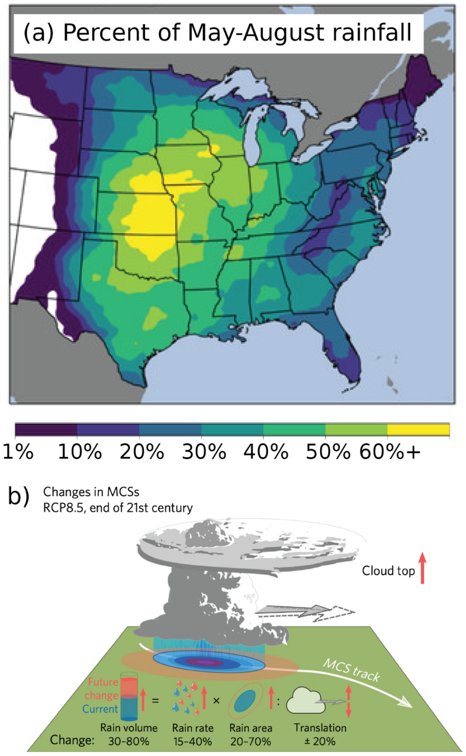
Geographic Scope/Regions

Extremes affect all areas of the CONUS, so there is a broad geographic scope to the science questions. However, there is a particularly pressing need to understand the mechanisms and impact of extremes in urban areas.

2.5 Organized Convection and Precipitating Systems

Motivation/Thematic Gaps

Convective rainfall provides the large majority of precipitation for the heavily populated and critical agricultural regions of the US Midwest, Southeast, and Eastern US, with mesoscale convective systems (MCSs) contributing most of that precipitation (i.e., Fritsch et al. 1986, Haberlie and Ashley 2019). A major challenge of the hydroclimate scientific community arising from locales that experience organized convection and rely on it for their livelihood is improved prediction of MCSs from weather, S2S, to climate timescales. Changes in precipitation amounts, frequencies, and intensities will impact the availability of water resources as well as the effect of extreme events (flood/drought), with each of these variables having overlapping and distinct impacts on society and the intensively managed landscapes in the eastern two-thirds of the USA. MCSs, which have scales of 100-1000 km, can be forced by their atmospheric environments, local land surface conditions, and heterogeneities (including topography, soil moisture, and vegetation dynamics). MCSs have a lifetime of hours to days and can produce severe weather hazards including heavy local- to regional-scale rainfall, producing both pluvial and riverine flooding (Schumacher and Rasmussen 2020; Hu et al. 2021; 2022). Atmospheric circulation patterns and local land surface heterogeneity and memory can establish forcings and feedbacks that can modify sources of water and energy, modifying circulations and moisture transport, changing the precipitation arising from organized convective systems on intraseasonal to interannual timescales (i.e., Wolters et al. 2010, Alter et al. 2017, Klein and Taylor 2020, Matus et al. 2023).



(top) Percentage of rainfall from organized convection during May-August (Haberlie and Ashley 2018); (bottom) Diagram showing potential simulated changes in mesoscale convective system rainfall under a worst case forcing scenario (Prein et al. 2018).

The lifecycle and behavior of continental organized convection have been observed in a number of intensive field campaigns [Preliminary Regional Experiment for STORM-Central (PRE-STORM; Cunning 1986), 1985, to Plains Elevated Convection at Night (PECAN), 2015].

These campaigns have primarily focused on atmospheric dynamic processes; however, some have focused additionally on land-atmosphere interaction processes [International H2O Project (IHOP; Weckwerth et al. 2004), 2002, to the Remote Sensing of Electrification, Lightning, and Mesoscale/Microscale Processes with Adaptive Ground Observations (RELAMPAGO), 2018]. Observational campaigns have enabled key advances in improving the representation of convective systems in models; however, they typically collect data and examine only selected “golden cases,” making it difficult to generalize their behavior to the long-term climate and its change. Additionally, the instrumentation deployed in those campaigns may be insufficient to characterize key processes that could be used to understand regional hydroclimate and its feedbacks. Opportunities now exist due to 1) new capabilities in the remote sensing of wind and water vapor from satellites, isotopic observations, ground and airborne LiDAR, and soil moisture monitoring from passive microwave sensor mobile radars, 2) vastly expanded capabilities to measure water vapor isotope ratios to elucidate hydroclimate processes, and 3) the establishment of longer-term regional-scale observatories that are able to observe the processes and coupled interactions arising from organized convection across spatial and temporal scales.

In addition to detailed process-oriented field campaigns, models must be used to address key scientific questions related to hydroclimatic variability and change and to the impacts of organized convection, as well as quantities important for prediction of organized convection. However, the representation of impactful quantities related to the variability of rainfall amounts, frequency, and intensity in the current climate and how it may change in the future are some of the most uncertain of all climatic variables in reanalyses and models (IPCC 2022). Improvements in those models used to understand local-to-regional hydroclimatic variability and change associated with MCSs have been hampered by observational or reanalysis-based datasets that were too coarse in resolution or contained large uncertainties in representation of organized convective processes or other coupled components of the water cycle, including coupling with land surface processes of water and energy fluxes and transport, subsurface groundwater processes, planetary boundary layer, and cloud-radiative feedbacks. Thus, efforts are needed to create high spatial and temporal resolution datasets to estimate geophysical variables that include coupled components of the water and energy cycles including human interventions (e.g., irrigation) on spatial (km to regional) and temporal scales (minutes to days) relevant to the lifecycle of organized convective systems.

Prediction of the impacts of organized convection relies on models that can represent the multi-scale nature of convection, which has components that operate on the convective (m) to synoptic (1000 km) spatial scales. Due to the high computational cost of representing convective scale processes, organized convection is not explicitly represented in current generation global climate models or models used to produce reanalysis products, and must be parameterized (i.e., Randall et al. 2003). Typically, schemes are developed to assess convective processes at the grid scale, which inherently cannot represent mesoscale processes critical for MCS organization and lifetime, producing biases in precipitation accumulation and rate (e.g., Prein et al. 2021). Increased computational capabilities in recent years have enabled the use of higher resolution convection permitting models (CPMs), which are able to explicitly represent key processes such as convective mass flux, mesoscale circulations associated with convective organization such as convectively-generated cold pools and gravity waves, and interactions between these phenomena and surface-radiation and cloud-radiation feedbacks on convective systems (Prein et al. 2020). Additionally, km-scale models are needed to realistically simulate shallow groundwater dynamics in the central US, which has a profound impact on MCSs and the hydroclimate of the region (Barlage et al. 2021). We are still some time away from CPMs being routinely used for global climate change simulations (Jacob et al. 2022), but the continued improvement of CPMs in representing organized convection is a critical avenue for reducing uncertainties in regional hydroclimate projections. To that end, regional CPMs based on limited area models and global models with regional refinement (e.g., Hagos et al. 2018; Liu et al. 2023) have enabled the projection of hydroclimate hazards into the future using GCM downscaling and "pseudo-global warming" (PGW) approaches.

While these models enable a significant leap in representing the hydroclimate impacts of organized convection, biases exist as a function of the models' spatial scale (i.e., Prein et al. 2021), as well as their own parameterizations of cloud microphysics, turbulence, and planetary boundary layer and surface parameterizations. Additionally, CPMs typically simulate the natural water cycle, and anthropogenic impacts such as irrigation, land management practices, or aerosol emissions on the regional hydroclimate are not well understood. Model improvements can be realized through model intercomparisons (i.e., Feng et al. 2023), as well as direct model-observational comparisons of water- and energy-related geophysical variables. Thus, further evaluation and improvement of the representation of processes in CPMs is a necessary step in understanding and predicting hydroclimate in the US. In addition, frameworks, model intercomparisons, and evaluation datasets at high resolution will be needed to advance hydroclimate modeling capabilities, as well as assess risks associated with hydroclimate extremes to various key sectors such as agriculture and food security, urban sustainability, and human health.

Science Questions

1. What are the sources and limits of predictability for the initiation, growth, and track of organized convective systems and precipitation? To what extent are they connected to atmospheric, land, ocean, and coupled processes locally and remotely? To what extent do these limits impact our ability to predict changes and extreme events of precipitation from organized convection from local to regional spatial scales and weather to seasonal-to-subseasonal to climate change timescales?

2. What are the shortcomings of models in representing organized convective systems, extreme precipitation, and societal impacts of precipitation from organized convection?

3. What are the potential climate change effects on organized convection, and how do these operate in different convective regimes (atmospheric and surface forcing differences)?

Key Activities

Our specific goals are to understand how predictability of convective precipitation depends on the interactions and feedbacks between 1) convective regime (i.e., strongly vs. weakly forced organized convection); 2) horizontal water transport in the atmosphere (low-level jets, atmospheric rivers), surface and subsurface transport (runoff and lateral ground water transports); 3) land surface persistence/memory, inhomogeneities in the land surface and moisture; 4) PBL interactions with convection-land surface processes and feedbacks and the diurnal cycle; 5) external forcing, i.e., teleconnections, aerosols/wildfire (direct and indirect effects), snowpack/ice cover.

To do this, we will use a combination of observations and modeling:

- **Observations**
  Supplement existing long-term observations with regional-scale observing networks (such as Ameriflux and NEON, or the proposed GLAFO concept) and targeted field campaigns with atmospheric and cloud scanning and profiling instrumentation able to observed coupled sub-surface, surface, PBL, and tropospheric processes. Extending observations focused on surface-planetary boundary layer processes to also study the cloud and precipitation processes within organized convection – observing the coupled column from the subsurface to the top of the troposphere through using existing and field campaign observations with mobile facilities and aircraft in situ and remote sensing of convection and its surface and atmospheric environment. Emphasis on coordinating focused/coordinated observational datasets from satellites, improved high-resolution reanalysis in the atmosphere, and land surface assimilating remote sensing data from clouds and soil moisture to close the water and energy budgets on a regional scale during organized convective events across meteorological and surface forcing regimes. We will include novel data analysis approaches such as cloud tracking and Lagrangian moisture tracking in the atmosphere and land surface. Oxygen and hydrogen isotope observations in the atmosphere, precipitation, and surface and subsurface water bodies will provide estimates of origin, fluxes, and residence times of moisture in the system. These observations will provide an important lens through which to investigate water-cycle processes and place constraints on existing model estimates of these same quantities.

  Intensive surface/atmosphere observing campaigns would focus on low-level jets, the effects of soil moisture heterogeneity on PBL structure, and structures of and dynamic processes within the resulting convection. An aircraft campaign would target convective events over their lifecycle from pre- to post-convection, with surface based in situ and remote sensing of the atmospheric profile and targeted in situ and remote sensing from aircraft measurements.

- **Modeling**
  We will perform hierarchies of ensemble/regional and global GCM, CPM, and high-resolution large eddy scale (LES) simulations across space and timescales and rigorously perform model evaluations and model intercomparisons. We will focus on the

models' representation of precipitation and precipitation extremes, cloud-radiative interactions, and interactions with the land surface from organized convection at different timescales. Our goal is to identify what processes need to be improved. We will also critically evaluate how well models represent precipitation and extremes for use in risk assessments.

We will establish best practices for performing simulations and analyses for organized convection, and unify theoretical/idealized approaches with observational and modeling approaches. In addition to model-observation and model-model comparisons, new techniques such as moisture tagging and isotope analysis, available or available soon in climate (i.e., CESM, E3SM) and km-scale (i.e., WRF) models and land surface models (Noah-MP and WRF-Hydro) will enable quantitative analysis and attribution of changes in the organized convection hydroclimate. We will coordinate with WCRP programs such as the Digital Earths Lighthouse Activity to enable scientific collaborations with the international research community. We also need to emphasize transferability of our research to other CPM modeling systems that are not used in the U.S.

Models will allow us to improve S2S predictability and project changes in organized convection in a changing climate and understand how changes in organized convection link to long-term trends in circulation, thermodynamics, and land use change. Are there theoretical constraints on changes for organized convection under changes in circulation and climate? Can such constraints provide for new parameterization development? What are the implications of these changes on economic and social factors such as agricultural productivity, engineering design, and hazards? We will strive to develop and improve end-to-end risk assessment tools for hydroclimate extremes associated with organized convection.

In addition to traditional modeling, we will use machine learning techniques to test whether machine learning can break the convective parameterization improvement deadlock.

Geographic Scope/Regions

The targeted region includes the Great Plains to the East Coast. Impacts are different across rural and urban areas and across different regions of the Midwest, Southeast, and East Coast, and agricultural applications, water resource availability and societal risks are important factors in these regions. An approach across these different areas would encompass assessing the predictability and impacts to broad sectors of the US, including agriculture, infrastructure, engineering and water resources, the general public, under-resourced, underserved, and vulnerable groups in rural and urban settings.

Inter-WG Synergies and Connections

- We will work in close collaboration with the Land-Atmosphere Process and Coupling WG on the land processes that can affect convection with special emphasis on soil moisture and groundwater. We will work towards improved S2S prediction and climate change projections.

- Organized convection often produces impactful extremes in terms of flash and riverine flooding as well as severe weather impacts. We will work with the Impactful Extremes WG to facilitate process-oriented examination of how organized convection creates impactful hydroclimate events.
- We will work with the Advancing Observational Systems WG to facilitate observational systems that will fully capture the spatiotemporal scales and relevant processes related to organized convection and its interactions with the land surface across relevant regions
- Interactions with the Human Dimensions WG will enable the impacts of Organized Convection and Precipitating Systems on stakeholders who are impacted by hydroclimate processes and multi-scale variability in regional hydroclimate associated with organized convection.

2.6 Advancing Observational Systems

We anticipate that much of our progress will be based on improving our observational capabilities. Simply put, we cannot expect to simulate and understand how the future will evolve, if our models do not accurately and correctly represent the natural systems they are simulating. This fact cannot be established without comprehensive observational data of sufficient quality and quantity.

Motivation/Thematic Gaps

The US-RHP approach to observations is inherently a cross-cutting strategy. It underpins everything that we will do, anchoring this work in reality. It is key to process understanding, it is needed to develop and improve our models, it is the basis for model evaluation and validation, and it is the basis for data assimilation. Observations are not limited to the physical realm, though different in nature, they are also required for work under the human dimension theme. Required observations span in situ monitoring networks, as well as ground-, airborne-, and space-based remote sensing. The project will take advantage of existing satellites, operational infrastructure and networks, as well as leveraging ongoing and planned field campaigns. But we also expect that the US-RHP will spur innovation, promote and employ new strategies and technologies, and increase the density and longevity of observations. To this end, we envision proposing new field campaigns (e.g. to form transects), based on requirements and findings from this and other projects, as well as advocating for and deploying novel observational strategies such as GLAFO.

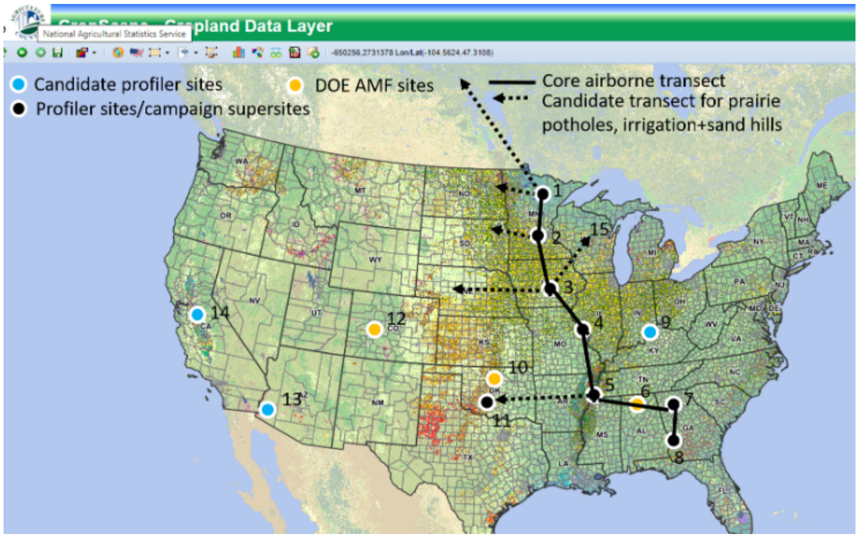
Science Questions

Beyond the extensive observational challenges and needs identified in all of the other thematic research areas in Section 2, additional overarching questions are posed here. The following is borrowed from and informed by a concept paper entitled “*Scoping of a next-generation NASA calibration/validation strategy to meet preeminent ecohydrological monitoring and modeling* *challenges*”[4].

1. How can we best observe, analyze, and model the impacts of human land management (i.e., agriculture, wind and solar farms, deforestation, urbanization) on subsurface - surface - atmosphere coupling of water-energy-carbon cycle processes, and do these impacts represent a significant source of subseasonal-to-seasonal hydroclimatic predictability?
    a. What is the impact of landscape-scale surface energy flux partitioning on planetary boundary layer height, clouds, and precipitation across diurnal and seasonal cycles?
    b. How do critical zone processes influence evapotranspiration, streamflow, and their short and long-term climate patterns?
    c. What is the partitioning of evapotranspiration between transpiration and evaporation, and what is the partitioning of streamflow between subsurface runoff and groundwater?

Envisioned Outcomes

- A network of centers for Coupled Earth System Observation and Modeling will be established, where coupled refers to natural-human, water-energy-carbon, and land-atmosphere-ocean. Centers will operate one or more fixed long-term (i.e., 5-10 year) core land-atmosphere feedback observatories along a south-north river valley corridor from Georgia to Minnesota with transects addressing critical landscape features and processes. Instrumentation will be tailored to key-in/correspond to satellite radiance measurements and land and atmospheric model states and parameters. Core observatories span gradients in temperature, precipitation, groundwater depth, snow class, and vegetation hardiness. Private, state, and federal ground networks supplemented with airborne campaigns will span and extend the core sites. The most cost effective core observatories will constitute build-outs of existing partner sites, such as USDA Long-Term Agroecosystem Research, DOE AmeriFlux, NOAA Climate Reference Network, NSF NEON, US Forest Service Experiment Forest, and state mesonets. One or more NSF-requestable core



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observatories (i.e., Lower Troposphere Observing System) will be available to onboard/train new partners and cover opportunistic events (e.g., post-wildfire, drought, flood).

- The NASA data repository with consistent quality assurance and control processing will tie-in and cohost data from international GLAFO network partners. This will be coordinated with and/or linked to the US-RHP Hub and DEUS.
- Multi-agency centers will train the next generation of observational and modeling experts to leverage new and conventional multiscale and multivariate in situ, unmanned aerial systems, airborne, and satellite data. Joint land- and airborne/satellite-based retrieval testbeds will be established for diurnal planetary boundary layer thermodynamic profiles. NASA THP and Terrestrial Ecology Program (TEP) collaborative science will advance our understanding of critical ecohydrologic processes.
- Holistic observational datasets (e.g., large-scale forcing data for driving single-column, cloud-resolving, and large-eddy simulation models) will support the next generation of hierarchical Earth system model development over a range of climatic regions. The centers will specifically develop harmonized land and atmospheric data assimilation schemes for use within strongly-coupled modeling systems, including those employed in subseasonal-to-seasonal hydrologic forecasting.

This is a good example of the US-RHP transect strategy to support and enable coordinated, sub-regional intensive studies. As noted, our modeling efforts are pushing the limits of our measurements to develop and drive them. Hence more comprehensive observations have the potential to advance our understanding and ability to predict how the water, energy and carbon cycles are changing. Each of the other working groups have identified specific observational needs that will need to be addressed.

Key Activities

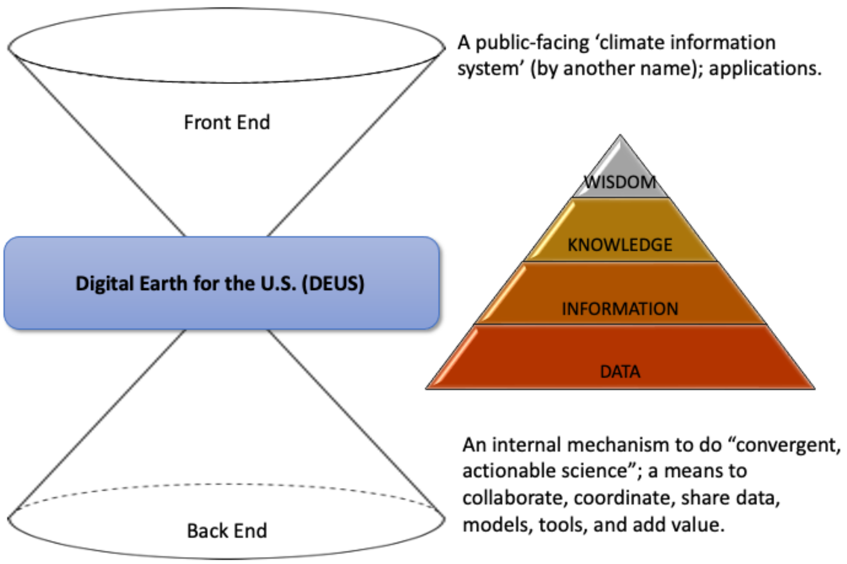
Some initial activities will be to identify observational requirements for the project, and then to assess and compile available resources. This will then allow the US-RHP team to develop a detailed plan and strategy that will propose innovative new observational strategies and instrumentation; field campaigns; and new/leveraged long-term observational networks.

2.7 Coastal Processes and Coupling

To be considered: Coastal processes and coupling was identified as an area of importance and interest, but the US-RHP does not currently have a working group associated with this theme, as there was insufficient capacity to establish one. There are a number of efforts within the United States that could be leveraged and/or coordinated with but this remains to be determined at this time.

2.8 Digital Earth for the US (DEUS)

The Digital Earth for the US (DEUS) is conceived of as a regional digital twin of the state of the natural water, energy, and carbon cycles over the US, and how these cycles impact human and natural systems in a changing world. This is in alignment with the WCRP Digital Earths Lighthouse Activity. It is in part about building the knowledge value chain: data → information → knowledge → wisdom. It embraces open data and science practices that bridge the social dimensions, stakeholders, and the “hub and halo” concept, among other things. It is an integrating framework. While ambitious it is not unprecedented (e.g. Bauer, Stevens, and Hazelleger, 2021).



Motivation/Thematic Gaps

Essentially all aspects of the science and applications discussed previously require significant amounts of coordinated and integrated data. Collaboration within and between the groups will require sharing of data, and perhaps also new data development. To this end, we propose the Digital Earth of the United States (DEUS) as a way of integrating data from a wide range of sources, including satellite data, weather data, and models (reanalyses and dynamical downscaling), to create a comprehensive picture of the United States regional weather and hydroclimate. The information system will advance open science, connection to applied users, and further human dimensions.

The science plans and questions in this document require a prediction and analysis system of the scale of an integrated Digital Earth to effectively meet the needs identified:

- Human dimensions need an integrated system, a digital Earth so there is coupling from data to predictive modeling to human systems and decision making and back again (since changing a human system changes the physical data input)
- Mountain hydroclimate requires high resolution at the watershed scale in the atmosphere, and snow-drift resolving scales for the land
- Land Atmosphere processes and coupling require consistent coupled modeling of the land and atmosphere with detailed data for processes
- Extremes require an efficient system that can run at scale for predictive modeling
- Organized convection requires a coupled modeling system with a hierarchy for the atmosphere
- Advancing observational systems and uncertainty implies a model-data fusion and a system where the hydroclimate and its uncertainty can be predicted, and then the Digital Twin can help fill in gaps in the existing observing network and figure out where better observations could constrain uncertainty (Gettelman et al. 2022)

Science Questions

DEUS will facilitate the interdisciplinary science components of the RHP and also connections between the science and societal applications and human dimension. Explaining science and making it openly accessible to everyone is a fundamental goal of this aspect of the US-RHP.

Quantified uncertainty is difficult in data assimilation and modeling. Through evaluations and intercomparisons we will use the DEUS to assess the collected observations, data assimilation, model simulation, and projections to best provide understanding of the quality of the RHP data, a crucial requirement for broad adoption and use of the data in societal applications.

1. What are current risk factors for flooding in the US? How will they change under climate extremes?
2. What strategies can be used to adapt human systems (including agriculture) to the new water environment under climate change and to be resilient to water stress?
3. How do we integrate the sub-regional studies, as-well-as the physical, social and Indigenous sciences, into a scalable and flexible system that will be used for diverse purposes at a national scale? Defining and designing a digital twin is a substantial research and development activity in its own right.

These are huge questions with already lots of specific work happening. A goal of developing a digital Earth for US hydrology is to couple data of the physical and human system with transient weather and climate data and predictions to enable predictions of hydrology across a number of scales. A system should build on existing models, and attempt to couple them together, probably starting with some targets in the areas outlined in other areas of this science plan.

The system will also couple to models of the human system so active human hydrology can be accounted for. Key in this is partnering with stakeholders.

Key Activities

- Build a data management framework (combination of a data center and distributed centers)
- Support interdisciplinary sciences coordination and collaboration
- Conduct stakeholder engagement and collaborations (e.g., water resource managers, urban and transportation planners, Indigenous communities and institutions)
- Foment education and information exchange
- Support actionable convergent science

Geographic Scope/Regions

Recognizing that what happens in the US is integrally tied to a tightly coupled, global dynamical system, at the outset we will not limit the geographic scope of DEUS. Initial inclusivity, even for global data, will enhance the potential for understanding. For example, the atmospheric circulation in the Pacific Ocean, even to the tropics, can have an influence on the regional weather and climate across the United States.

That said, the focus of DEUS is principally the US land surface over the CONUS, and the natural and human systems that drive it. This requires interactions with the regional and global atmosphere and regional land surface. Ideally, such a system would have a global component (as described). DEUS will be driven by fields produced from a variety of modeling systems operating over a range of time and space scales: from global Earth system models, to higher resolution regionally refined systems, down to very detailed and highly refined hillslope/neighborhood scale processes. These products will be supported by a variety of observations spanning on the ground in situ, as well as ground-, airborne-, and spaceborne remote sensing. Furthermore, geospatial scientists will add layers of human and natural information. The goal will be to provide the data and information at the highest possible resolution, with as much fidelity as resources permit.

While the framework will be anchored in a global system and focused on the CONUS, the concept should allow extension to (e.g., OCONUS) and/or further refinement over other regions of interest for detailed study of localized effects: such as a river basin, a specific ecosystem, or a city and its surrounding catchment. Ideally a DEUS system would have scalable complexity. DEUS priorities could be refined based on areas outlined in the plan above:

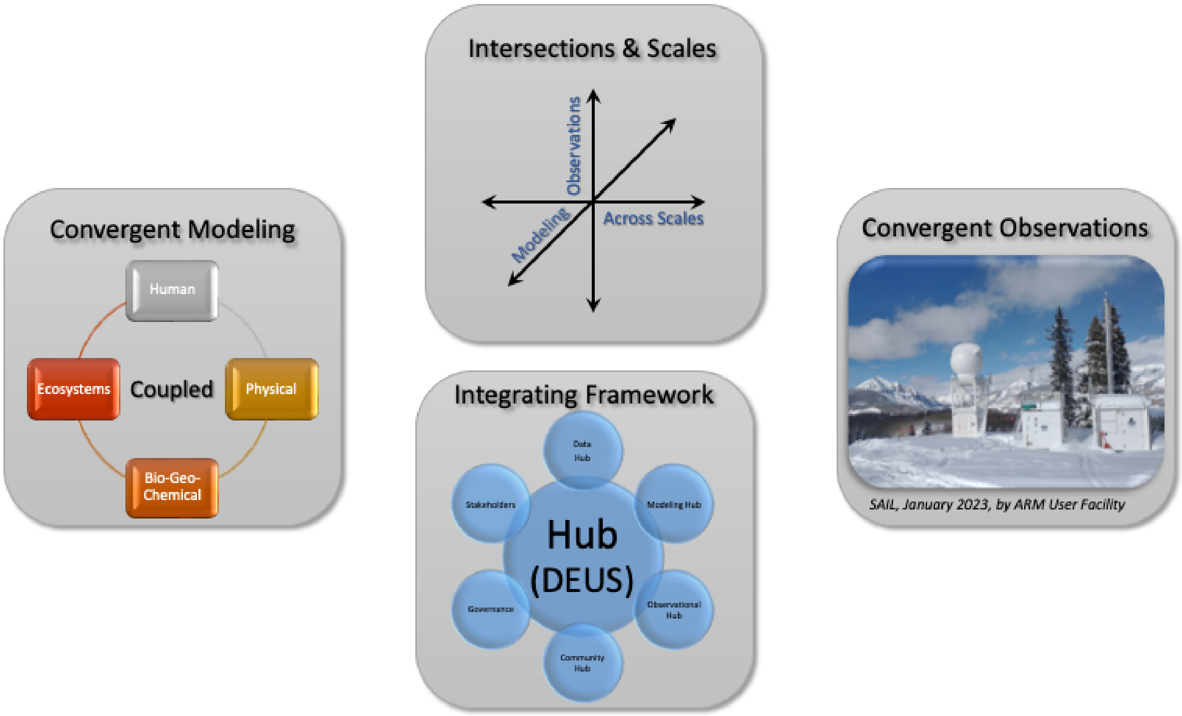
- Western US for Drought-Fire nexus
- Mountains (Especially Western US)
- Northern Great Plains for Land Atmosphere coupling and organized convection
- Regional focus on the regional water scale for human systems

Some Existing Projects for Examples

- European Centre for Medium-Range Weather Forecasts (ECMWF)/Copernicus: https://digital-strategy.ec.europa.eu/en/policies/destination-earth#ecl-inpage-l1d9i86r
- WCRP Digital Earths Lighthouse Activities: https://www.wcrp-climate.org/digital-earths
- Especially the 2022 report of the high resolution modeling workshop: https://www.wcrp-climate.org/WCRP-publications/2022/WCRP_Report_08-2022_k-scale-report-final.pdf
- The Digital Earths Lighthouse Science plan: https://www.wcrp-climate.org/JSC42/documents/WCRP_Digital_Earths_Science_Plan_Final.pdf
- National Academies - Digital Twins in Atmospheric, Climate, and Sustainability Science - A Workshop: https://www.nationalacademies.org/event/02-01-2023/digital-twins-in-atmospheric-climate-and-sustainability-science-a-workshop

III. A Synthesis Across Themes

Given the highly interconnected nature of the thematic research areas (WGs), a number of high-level cross-working group themes emerged. These overarching themes are depicted graphically here:



Convergent modeling: Models are one of our primary tools to predict or project what will happen in future. They are also important tools to test our understanding of a system; you cannot build an accurate model if you do not understand the system you are modeling. In this case, the US-RHP seeks to model the water, energy and carbon cycles over the CONUS. Recognizing that all of the elements are interacting and evolving, our models need to to represent the human, the physical, the biogeochemical, and the ecological systems. We also need approaches to estimate and reduce the uncertainty of our model output.

The implications of the changes we are seeing in these systems, due to anthropogenic factors, lead to cascading/compounding events, and are potentially an existential threat to many forms of life. To develop models to represent these processes and understand how the natural and human systems are changing, will require a deep integration across the disciplines represented by the WGs. This is convergent modeling.

Convergent observations: Matching the complexity and challenges of convergent modeling, a comprehensive integrated strategy is required to measure and monitor a rapidly changing system that is impacted immensely by human activity, and for which the physical, biogeochemical, and eco-systems are responding and evolving.

Intersections and scales: Model development cannot be done without observations to inform their development and evaluate them against ‘truth.’ As such the observational approach informs model development. The converse is also true, the development and application of models should inform the observational strategy. They intersect in an interdependent and interdisciplinary way.

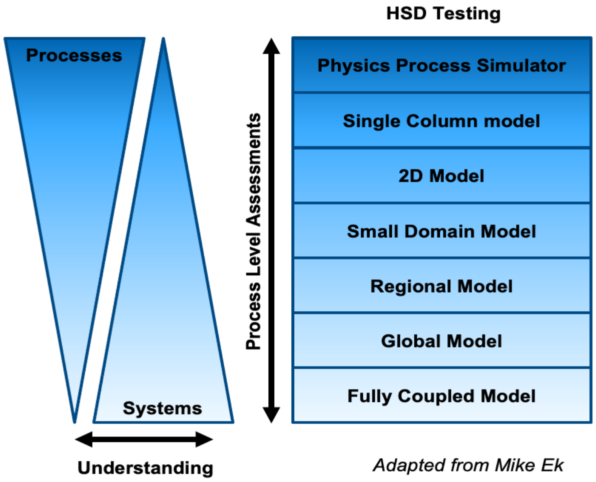
Another dimension of is the intersection of spatial and temporal scales. A common theme amongst the WGs, is the feedback of processes up and down scales. How does a local event affect the regional? How does the regional affect the global? What are the implications for cascading/compounding extreme events? How do changes in the global state (say global warming) manifest at finer scales? There are also many similar questions across the WGs about predictions, predictability, and uncertainty across temporal scales; from analyses, through decadal and centennial timeframes, though S2S comes up quite frequently.

An integrating framework: A construct is needed to share and synthesize data and information, to enable the intersection of convergent modeling and observations and analyses; from which knowledge can be generated, and then shared openly in a way that (hopefully) the knowledge garnered is applied wisely to solve the great challenges of the day. This is the function of DEUS

3.1 Hierarchical System Development

Implicit in the plans described by the working groups is the concept of Hierarchical System Development (HSD), which is an efficient and scalable way to conduct systems development. It provides a structural framework to enable the complex undertaking inherent in the intersection of convergent modeling and observations.

Taking Earth System Model (ESM) development as an example: to effectively integrate the model development process, with the ability to test small elements (e.g. physics schemes) in an ESM first in isolation, then progressively connecting elements with increased coupling between ESM components as you progress through the HSD steps. The system in HSD is end-to-end: it includes data ingest/quality control, data assimilation, modeling, post-processing, and verification. HSD includes Single Column Models (SCMs; including individual physics elements), small-domain and regional models, all the way to complex fully-coupled global ESMs with atmosphere/chemistry/aerosol, ocean/wave/sea-ice, land-hydrology/snow/land-ice, and biogeochemical cycle/ecosystem

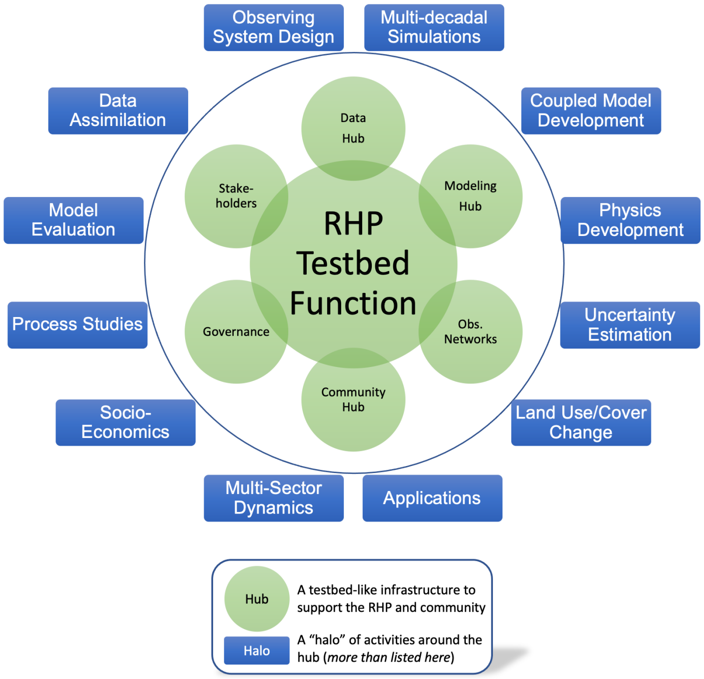


Adapted from Mike Ek

components. Datasets used for the different HSD steps are from observational networks and field programs, ESM output, or idealized conditions (e.g. used to “stress-test” ESM elements and components). To advance from one HSD step to the next requires appropriate verification metrics of ESM performance, many at the process level. It’s important to note that this process is concurrent and iterative such that more complex HSD steps can provide information to be used at simpler HSD steps, and vice versa. The HSD approach can also help understand spatial and temporal dependencies in model solutions, where consistency for different models and resolutions across HSD steps is required.

IV. Strategic Considerations

This section describes the foundations of how our project will function. It will grow and evolve as the project progresses from conceptual (today), to Initiating RHP (detailed planning and support), to funding and execution.

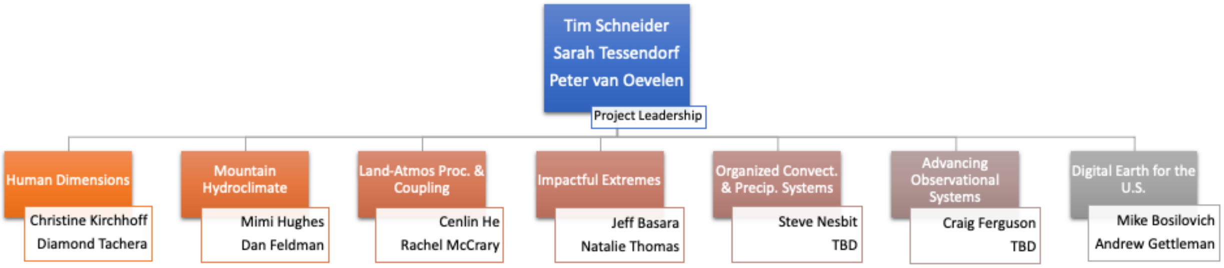


4.1 Governance

A "Hub and Halo" concept has been conceived to support and enable the US-RHP. Collectively this could be thought of as a Hydroclimate Testbed. The basic idea is that a central Hub provides a basic construct upon which the US-RHP functions. It sustains the US-RHP community by providing coordination, facilitating collaboration and data and tool sharing and dissemination, and providing a framework for integration (DEUS) and stakeholder engagement. The Hub enables an associated Halo of activities, as described in Section II, "US-RHP Scientific Strategy."

4.1.1 Management Structure, Core Teams, and Projects

The project has established an initial basic governance structure which consists of a Project Lead and two Co-Leads. The leads are supported and advised by seven Scientific Working Groups, each of which nominally has two co-leads.



The organizational chart above, identifies the people currently in leadership positions. This governance structure will evolve with the project as the RHP evolves and grows.

4.1.2 Data and Information Management

A detailed data and information management plan will be developed upon attaining Initiating RHP status, as a part of an extensive implementation plan. The goal will be to adhere to current open science and open data best practices according to the US Federal website https://open.science.gov/: "*Open Science is the principle and practice of making research products and processes available to all, while respecting diverse cultures, maintaining security and privacy, and fostering collaborations, reproducibility, and equity.*"

Data Provenance and Sovereignty

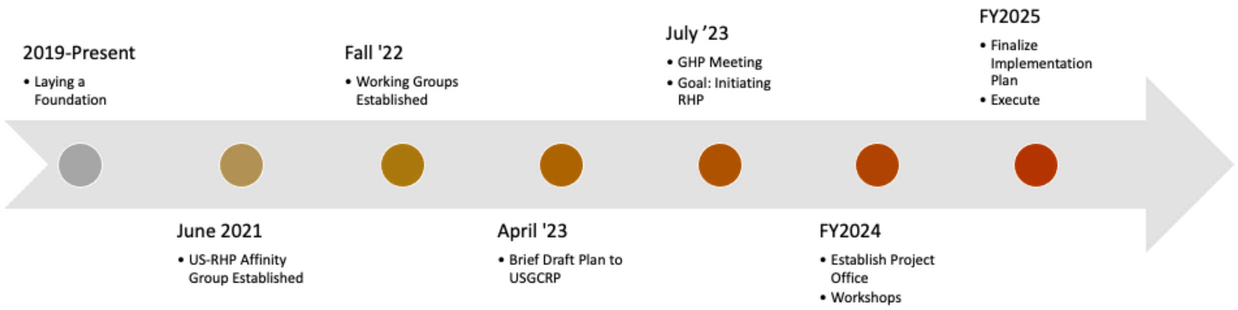
Best practices include ensuring complete and thorough documentation of data provenance; which is a documented trail that accounts for the origin of the data, and important information related to how data was created (model namelists, instrument settings, QA/QC applied, etc.), as well as its history after creation, including any and all changes (who, what, why, when, where).

Another important consideration is data sovereignty, which refers to a group or individual's right to control and maintain their own data, including the collection, storage, and interpretation of their data. This is especially important for Traditional Ecological Knowledge (TEK) and the autonomy of Indigenous peoples to participate, steward and control data that is created with or about themselves.

These aspects will be addressed explicitly in our data management element of our implementation plan and respected in our work.

4.2 Timeline

The goal of this plan is to become an Initiating RHP in July, 2023. Coordination with US Federal Agencies to align activities and objectives and identify possible means of support will continue in parallel on an ongoing basis. This timeline provides a snapshot of the evolution of this effort as well as next steps in the foreseeable future:



Getting a bit more specific, once Initiating RHP status is established, a workshop or series of workshops (TBD) will be organized and held. We will seek funding from the program agencies to establish a project office to execute and coordinate this and provide resources for the workshop. Using this plan as a starting point, and the outcomes from the workshop(s), the

US-RHP Affinity Group will develop a detailed implementation plan, and pursue sources of funding to execute and sustain our work.

4.3 Measuring Success

Metrics of success are an important consideration, and the US-RHP is committed to adhering to this best practice. Though simple at this time, our first metric will be to achieve formal standing in GEWEX. This science plan will continue to evolve and be enhanced and will lead to the next milestone, which will be to develop a detailed, executable implementation plan, which will include metrics, and a process to monitor progress and document our successes. Scientific publications are likely to be among our metrics as this is one way to achieve scientific credibility. But we must challenge ourselves to move beyond this measure, especially as we embrace and engage and coproduce with Indigenous and other knowledge systems.

4.4 Domestic & International Coordination

Coordination with domestic and international partners is one of the advantages of having a GEWEX RHP. The primary touchpoint for the US-RHP is the GEWEX Hydroclimatology Panel (GHP). Within GEWEX, the GHP is the body that oversees RHPs. This Plan, when complete, will be submitted to the GHP. The US-RHP has also engaged with the GEWEX Scientific Steering Group, providing regular briefings to them, and has received their endorsement to pursue this effort.

Other RHPs and Cross Cutting Projects

The GHP provides a venue to foster cross-RHP coordination within the GEWEX community. With an eye towards growing and developing coordination and collaboration, nascent US-RHP connections have been established with: ANDEX, a Regional Hydroclimate Initiative for the Andes; Baltic-Earth in Europe; and the Canadian Global Water Futures (GWF). We've also engaged in dialogue with GHP cross-cutting activities: the multi-scale Transport and Exchange processes in the Atmosphere over Mountains – programme and experiment (TEAMx); as well as the International Network for Alpine Research Catchment Hydrology (INARCH). The US-RHP is engaged in Phase II of the GEWEX/GASS initiative, Impact of Initialized Land Temperature and Snowpack on Sub-seasonal to Seasonal Prediction (LS4P), an initiative under the GEWEX Global Atmospheric System Studies (GASS) Panel.

WCRP Lighthouse Activities

The US-RHP is a natural touch point with the WCRP Lighthouse Activities; as noted below we are already engaging with two of them. As noted on the the WCRP webpage: *"Lighthouse Activities are designed to be ambitious and transdisciplinary (integrating across WCRP and collaborating with partners) so that they can rapidly advance some of the new science and technologies, and institutional frameworks, that are needed to manage climate risk and meet society's urgent need for robust and actionable climate information more effectively.*"

The two Lighthouse Activities that we have been engaged with are:

Digital Earth Lighthouse Activity: We have been in direct contact with the Digital Earth Lighthouse Activity and are coordinating with them as appropriate at this early juncture. Again referring to the WCRP webpages, *"the overall objective of this activity is to carry out research activities that support the establishment of integrated interactive digital information systems that provide information on the past, present, and future of our planet."* As described earlier in the DEUS section, there is a direct and obvious link between the US-RHP and this Lighthouse Activity, which we expect to continue and grow.

Global Precipitation Experiment Lighthouse Activity: GPEX is to be launched as a new WCRP Lighthouse Activity in October 2023. As its name suggests, GPEX will be about improving our skill in our precipitation predictions and projections. It will address major gaps in observing, understanding, and modeling precipitation, as well as to accelerate improvements in the provision of precipitation products. As such the US-RHP is planned to be part of the U.S. contributions and leadership in field campaigns, process understanding, and improvement of precipitation modeling and prediction to this effort.

Domestic

Domestic coordination is currently happening through two types of activities.

1. The US-RHP Affinity Group itself is extraordinarily diverse, in terms of subject matter expertise, in the human sense, geographically, and institutionally
2. We have been organizing technical sessions at both the American Geophysical Union (AGU) Fall Meeting and the American Meteorological Society (AMS) Annual Meeting for several years now

Since this effort was revived in 2019, project leadership has been engaging the U.S. Global Change Research Program (USGCRP), as well as independently with several individual U.S. Federal Agencies.

Another evolving domestic connection is the Integrated Hydro-Terrestrial Modeling (IHTM) effort. In an effort to create a "seamless national hydro-terrestrial modeling and data capability" within the U.S., the *Community Coordinating Group on Integrated Hydro-Terrestrial Modeling* organized an interagency workshop on "Integrated Hydro-Terrestrial Modeling: Development of a National Capability" in 2019 (Community Coordinating Group on Integrated Hydro-Terrestrial Modeling, 2020). Representatives from this group have approached the US-RHP to coordinate, with the goal to align and leverage our efforts. Additional dialogue is planned beginning in the Fall of 2023.

In short, the US-RHP will be a vehicle that will foment and enable coordination and collaboration within the U.S., as well as to enable appropriate international scientific engagement.

4.5 Resources Needed

Presently the US-RHP is presently an ‘all volunteer’ effort (with some very modest but much appreciated support from George Mason University/NASA to help the project leads coordinate and facilitate). This is not sustainable. To carry this project forward, in the very near future resources will need to be identified to

i. Establish a project office of 1-3 full time equivalent (FTE) staff to provide scientific leadership; project management and coordination; and administrative and technical support. The degree to which each of these functions can be met, obviously depends upon the level of support provided.
ii. Travel (domestic and international) for project leadership
iii. Support for one or more workshops, including travel for key participants (scientific advisory group; comprised nominally of the WG Leads) and facilitation
iv. A modest amount of support for each of the WGs to work on the development of the US-RHP Implementation Plan

Long-term sustained sources of funding will need to be identified and secured to execute thereafter. Two current GEWEX RHPs provide paradigms that bookend how the US-RHP can succeed:

(i.) Global Water Futures (GWF): On the “moon shot” end of the spectrum is the GWF RHP in Canada. The GWF has a budget of $77.84M+ (CAD). This demonstrates the ‘art of the possible’ and would be an ideal approach from our perspective. It would certainly require Congressional appropriations, but It is not beyond the realm of possibility, and strategies to achieve this are being considered.

(ii.) Baltic-Earth: A more “grassroots” approach, the Baltic-Earth RHP has a small supported program office based at Helmholtz-Zentrum Hereon in Geesthacht, Germany. Contributions to the project come from various investigators who secure their own resources to participate in Baltic-Earth.

Of course there are a range of possibilities between these two extremes. The US-RHP is committed to making this important work happen, and will be agile and creative in our approach. We will work with US Agencies and sponsors to identify what is possible and ensure that the US-RHP is helping to address their missions in the service of the public and the Earth. Realistically, we will begin with a grassroots effort and grow with moonshot aspirations.

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Appendix A. List of Acronyms

AGU	American Geophysical Union
AMS	American Meteorological Society
ANDEX	A Regional Hydroclimate Initiative for the Andes
AORC	Analysis of Record for Calibration (NOAA)
ARM	Atmospheric Radiation Measurement (DOE)
ASR	Atmospheric System Research (DOE)
CBT	Colorado-Big Thompson project
CCI	Climate Change Initiative (ESA)
CESM	Community Earth System Model
CONUS	Conterminous United States
CPM	Convection permitting models
CPO	Climate Program Office (NOAA)
CZNet	Critical Zone Collaborative Network
CZO	Critical Zone Observatories
DEUS	Digital Earth for the United States
DOE	Department of Energy
DOW	Doppler on Wheels
E3SM	Energy Exascale Earth System Model
EB	Energy balance
EC	Eddy covariance
ECMWF	European Centre for Medium-Range Weather Forecasts
ECOSTRESS	ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station
ESA	European Space Agency
ESM	Earth system model
ESS	Environmental System Science (DOE)
ET	Evapotranspiration
FTE	Full time equivalent (employee)
GAPP	GEWEX Americas Prediction Project
GCIP	GEWEX Continental-Scale International Project
GCM	General circulation model
GEWEX	Global Energy and Water Exchanges Program
GHP	GEWEX Hydroclimatology Panel
GLAFO	GEWEX Land Atmosphere Feedback Observatory
GPEX	Global Precipitation Experiment
GRACE	Gravity Recovery and Climate Experiment
GRACE-FO	GRACE Follow-On

GWF	Global Water Futures
HSD	Hierarchical system development
HI-SCALE	Holistic Interactions of Shallow Clouds, Aerosols, and Land-Ecosystems campaign
HRRR	High-Resolution Rapid Refresh
IDS	Interdisciplinary Research in Earth Science (NASA)
IHOP	International H2O Project
IHTM	Integrated Hydro-Terrestrial Modeling
IMS	Interactive Multisensor Snow and Ice Mapping System
INARCH	The International Network for Alpine Research Catchment Hydrology
L-A	Land-atmosphere
LES	Large eddy scale
LiDAR	Light detection and ranging
LS4P	Impact of Initialized Land Temperature and Snowpack on Sub-seasonal to Seasonal Prediction
LSM	Land surface model
LULC	Land use land cover
MBRFC	Missouri Basin River Forecast Center
MCS	Mesoscale convective system
MODIS	Moderate Resolution Imaging Spectroradiometer
MTBS	Monitoring Trends in Burn Severity
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NEON	National Ecological Observatory Network
NGWOS	Next Generation Water Observing System
NOAA	National Oceanic and Atmospheric Administration
Noah-MP	Noah-Multiparameterization Land Surface Model
NSF	National Science Foundation
PBL	Planetary boundary layer
PECAN	Plains Elevated Convection at Night
PGW	Pseudo-global warming
PRE-STORM	Preliminary Regional Experiment for STORM-Central
RAP	Rapid Refresh
RELAMPAGO	Remote Sensing of Electrification, Lightning, and Mesoscale/Microscale Processes with Adaptive Ground Observations
RHP	Regional Hydroclimate Project (GEWEX)

S2S	Subseasonal to seasonal
SAIL	Surface Atmosphere Integrated Field Laboratory
SCAN	Soil Climate Analysis Network
SCM	Single column model
SDFIR	Small double fence intercomparison reference
SFA	Scientific Focus Area
SGP	Southern Great Plains (DOE ARM site)
SMAP	Soil Moisture Active Passive satellite mission
SMOS	Soil Moisture and Ocean Salinity satellite mission
SNOTEL	Snow Telemetry
SNOWIE	Seeded and Natural Orographic Wintertime Clouds: The Idaho Experiment
SPLASH	Study of Precipitation, the Lower Atmosphere and Surface for Hydrometeorology
SWE	Snow water equivalent
SWOT	Surface Water and Ocean Topography satellite mission
TEAMx	Multi-scale **T**ransport and **E**xchange processes in the **A**tmosphere over **M**ountains – programme and e**x**periment
TEK	Traditional Ecological Knowledge
TEP	Terrestrial Ecology Program (NASA)
THP	Terrestrial Hydrology Program (NASA)
USDA	United States Department of Agriculture
USGCRP	US Global Climate Change Research Program
USGS	United States Geological Survey
VIIRS	Visible Infrared Imaging Radiometer Suite
WCRP	World Climate Research Programme
WG	Working group
WPO	Weather Program Office (NOAA)
WRF	Weather Research and Forecasting model
WRF-Hydro	Hydrological modeling system

Appendix B. US-RHP Affinity Group Membership

As of the writing of this document there are presently 161 members of the US-RHP Affinity Group. The Affinity Group meets on a biweekly basis, sharing our scientific findings with each other and developing this plan.

Ronnie Abolafia-Rosenzweig
Nachiketa Acharya
Amir AghaKouchak
Allison Aiken
Caspar Ammann
Kevin Ash
Bronson Azama
Adriana Bailey
Dan Barrie
Jeffrey Basara
David Bensob
Michael Bosilovich
Elizabeth Boyer
Michael Brody
Melissa Bukovsky
Christopher L. Castro
Fei Chen
Liang Chen
Sen Chiao
Matt Coleman
William Collins
Caitlin Crossett
Kate Cullen
Nicholas Dawson
Belay Demoz
Ankur Desai
Paul Dirmeyer
Diana Dombrowski
Francina Dominguez
Erin Dougherty
Stanley G. Edwin
Mike Ek
Kelsey Emard
Jared Entin
John Eylander
Daniel Feldman
Farshid Felfelani
Craig Ferguson
Kimberly Fewless
Anjuli Jain Figueroa
Kirsten Findell
Gael Jennie Fleurant
John Forsythe
Maria Frediani
Andrew Gettelman
Manuela Girotto
David Gochis
Mike Gremillion
Drew Gronewold
Yu Gu
Ethan Gutmann
Masahiko Haraguchi
Benjamin Hatchett
Cenlin He
Yi Hong
Leiqiu Hu
Jin Huang
Xingying Huang
Susan Hubbard
Mimi Hughes
Sara Hughes
Margaret Hurwitz
Charles Ichoku
Yi-Shin Jang
Jonghun Kam
Junkyung Kay
Aaron Kennedy
Christine Kirchhoff
Michée A. Lachaud
Timothy Lahmers
Laura Lautz
Richard (Rick) Lawford
David Lawrence
David Lesmes
L. Ruby Leung
Gabriel Lewis
Xiaolu Li
Yishen Li
Min-Hui Lo
Lorena Medina Luna
Hsi-Yen Ma
Kaveh Madani
Julie Malmberg
Jiafu Mao
Carlos Martinez
Maribel Martinez
Emilio Mateo
Talea Mayo
Rachel McCrary
Linda Opal Mearns
Tilden Meyers
Maria Molina
Annareli Morales
Monica Morrison
Ali Nazemi
Stephen Nesbitt
Michelle Newcomer
Andrew Newman
Guo-Yue Niu
Nicole Ngo
Mark Olsen
Nina Omani
Gigi Owen
Ming Pan
Shaun Parkinson
Tom Parris
Angie Pendergrass
Christa Peters-Lidard
Justin Pflug
Yadu Pokhrel

Andreas Prein
Yun Qian
Bob Rabin
Arezoo RafieeiNasab
Kabir Rasouli
Kristen Rasmussen
Roy Rasmussen
Nicholas Reynolds
Alan Rhoades
Joshua Roundy
Kyoungho Ryu
Vidya Samadi
Venkadesh Samykannu
Joseph A Santanello
Russ Scott
Tim Schneider
Andrew Schwartz
Stephen Sebestyen
Shima Shams
Erica Siirila-Woodburn
Aaryaman Singhal
Mohsen Soltani
Mukul Sonwalkar
Matthias Sprenger
Alyssa Stansfield
Diamond Tachera
Sarah Tessendorf
Natalie Thomas
Shabeh ul Hasson
Julie Vano
Peter van Oevelen
Arianna Varuolo-Clarke
Haruko Wainwright
Ryann Wakefield
Curtis Walker
Guiling Wang
Veronica Webster
Tammy Weckwerth
Olga Wilhelmi
Christopher Williams
Andy Wood
Marshall Worsham
Volker Wulfmeyer
Yangyang Xu
Lulin Xue
Yongkang Xue
David Yates
Jinwoong Yoo
Xubin Zeng
Yunyan Zhang
Zhe Zhang

A Caricature of our Affinity Group by Expertise