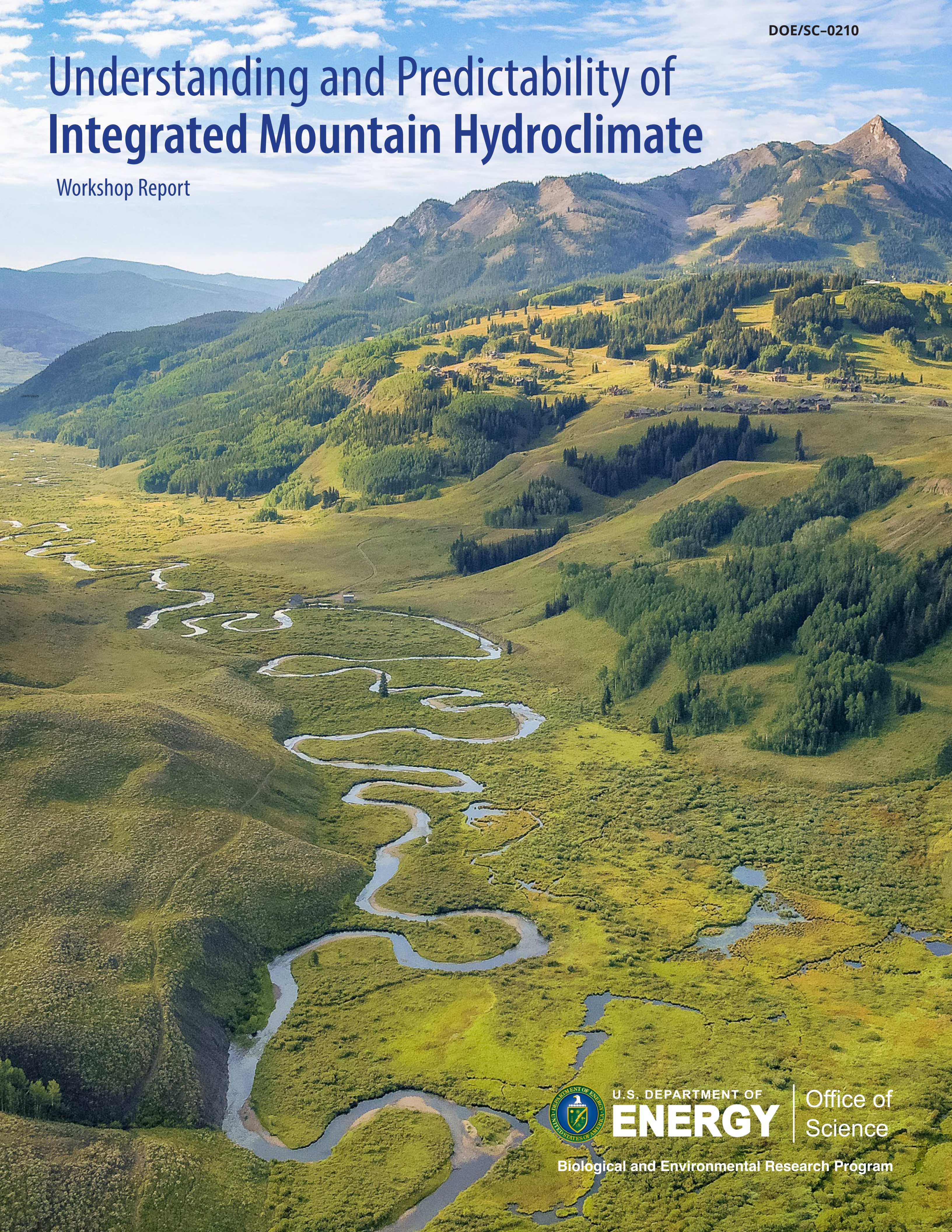
DOE/SC–0210

Understanding and Predictability of Integrated Mountain Hydroclimate

Workshop Report



U.S. DEPARTMENT OF ENERGY | Office of Science

Biological and Environmental Research Program

Understanding and Predictability of Integrated Mountain Hydroclimate Workshop

November 15–16, 2021, and January 19, 2022

Convened by
U.S. Department of Energy
Office of Science
Biological and Environmental Research (BER) Program

Co-Chairs

Michelle Newcomer
Lawrence Berkeley
National Laboratory

L. Ruby Leung
Pacific Northwest
National Laboratory

Kristen Rasmussen
Colorado State
University

Organizers

BER Earth and Environmental Systems Sciences Division

Jennifer Arrigo
Environmental
System Science

Paul Bayer
Environmental
System Science

Brian Benscoter
Environmental
System Science

Xujing Davis
Earth System
Model Development

Justin Hnilo
Data
Management

Renu Joseph
Regional and Global
Model Analysis

Sally McFarlane
Atmospheric Radiation
Measurement User Facility

Jeff Stehr
Atmospheric
System Research

Bob Vallario
MultiSector
Dynamics

Topical Co-Leads

Nathaniel Chaney
Duke
University

Naresh Devineni
The City College
of New York

Andrew Jones
Lawrence Berkeley
National Laboratory

Ian Kraucunas
Pacific Northwest
National Laboratory

Andreas Prein
National Center
for Atmospheric Research

Alan Rhoades
Lawrence Berkeley
National Laboratory

McKenzie Skiles
University
of Utah

Matthias Sprenger
Lawrence Berkeley
National Laboratory

Ning Sun
Pacific Northwest
National Laboratory

Peter Thornton
Oak Ridge
National Laboratory

Paul Ullrich
University of
California, Davis

Adam Varble
Pacific Northwest
National Laboratory

Nathalie Voisin
Pacific Northwest
National Laboratory

Simon S. Y. Wang
Utah State
University

Erica Siirila-Woodburn
Lawrence Berkeley
National Laboratory

About BER

The BER program advances fundamental research and scientific user facilities to support U.S. Department of Energy missions in scientific discovery and innovation, energy security, and environmental responsibility. BER seeks to understand biological, biogeochemical, and physical principles needed to predict a continuum of processes occurring across scales, from molecular and genomics-controlled mechanisms to environmental and Earth system change. BER advances understanding of how Earth's dynamic, physical, and biogeochemical systems (atmosphere, land, oceans, sea ice, and subsurface) interact and affect future Earth system and environmental change. This research improves Earth system model predictions and provides valuable information for energy and resource planning.

Cover Images: East River Watershed, Crested Butte, Colo.; Courtesy Jeremy Snyder, Lawrence Berkeley National Laboratory

Suggested Citation: U.S. DOE. 2023. *Understanding and Predictability of Integrated Mountain Hydroclimate Workshop Report*, DOE/SC-0210. U.S. Department of Energy Office of Science. https://doi.org/10.2172/1967878.

DOE/SC–0210

Understanding and Predictability of Integrated Mountain Hydroclimate

Workshop Report

April 2023

U.S. DEPARTMENT OF ENERGY | Office of Science

Biological and Environmental Research Program

Contents

Executive Summary

Mountainous systems cover approximately 23% of Earth's land and are distributed across all continents. They can capture and store atmospheric moisture that is then cycled through the terrestrial surface and subsurface system, released to downstream communities, and cycled back to the atmosphere. Mountain hydroclimate—characterized by steep gradients, geological, ecological, and biogeochemical diversity—is influenced by topographic forcing and elevated warming and susceptible to large subseasonal to multidecadal variability and rapid changes. Terrestrial hydrological and biogeochemical cycles also experience cascading effects from global warming impacts, such as multidecadal declines in mountain snowpack, longer growing seasons, and increased frequency and severity of extreme events like droughts and wildfires. However, little is known about the effects of these impacts and their feedbacks on climate systems and surface-subsurface compartments. Also unknown are the full implications of changing hydroclimate and extreme events on hydrobiogeochemical cycles across atmosphere, terrestrial, and human systems in mountain regions and beyond (see Fig. ES.1, p. iv). This knowledge gap is critical, given human reliance on mountain systems for stable water supply and quality. Mountain systems' increasing vulnerability to climate change and human perturbations motivates the need to improve understanding of integrated mountain hydroclimate (IMHC) systems and their feedbacks and impacts on humans across scales. However, due to large heterogeneity and strong gradients, coupled natural-human processes in mountain regions present significant challenges for observations, modeling, predictions, and projections.

Integrated Mountain Hydroclimate

The collection of system components and complex processes in mountainous regions—spanning the deep subsurface, surface, and atmosphere—that interact at multiple spatiotemporal scales in response to natural and human influences.

Motivated by gaps in mountain hydroclimate understanding, observations, and modeling and the need for credible projections of future changes, the U.S. Department of Energy's (DOE) Biological and Environmental Research (BER) program organized a virtual workshop on "Understanding and Predictability of Integrated Mountain Hydroclimate." Sponsored by BER's Earth and Environmental Systems Sciences Division (EESSD), the workshop aimed to inform and catalyze EESSD's growing interests in enhancing predictive understanding of IMHC. Organizers structured the workshop to identify (1) knowledge gaps, (2) observational and modeling challenges, (3) short-term (1 to 3 years) and long-term (10 years and beyond) research opportunities, and (4) strategies for fostering collaboration and coordination. To address the outstanding challenges of IMHC, the workshop included two sessions organized by disciplinary, cross-disciplinary, and crosscutting science topics. The disciplinary and cross-disciplinary topics focused on essential IMHC elements: atmosphere, terrestrial, and human systems and their interactions. Breakout sessions on disciplinary and cross-disciplinary topics facilitated identification of crosscutting topics and central emerging themes. Session 1 focused on connecting existing DOE investments to accelerate progress related to scientific challenges in understanding mountain hydroclimate. In Session 2, participants further explored key Session 1 takeaways through the lens of multiagency collaborations and coordination.

Figure ES.2 (see p. v) summarizes the workshop goals and structure. Key findings that emerged from the disciplinary and cross-disciplinary topics in Session 1 are summarized by thematic outcomes, and crosscutting topic discussions are summarized by integrated activities. This report also outlines the multiagency

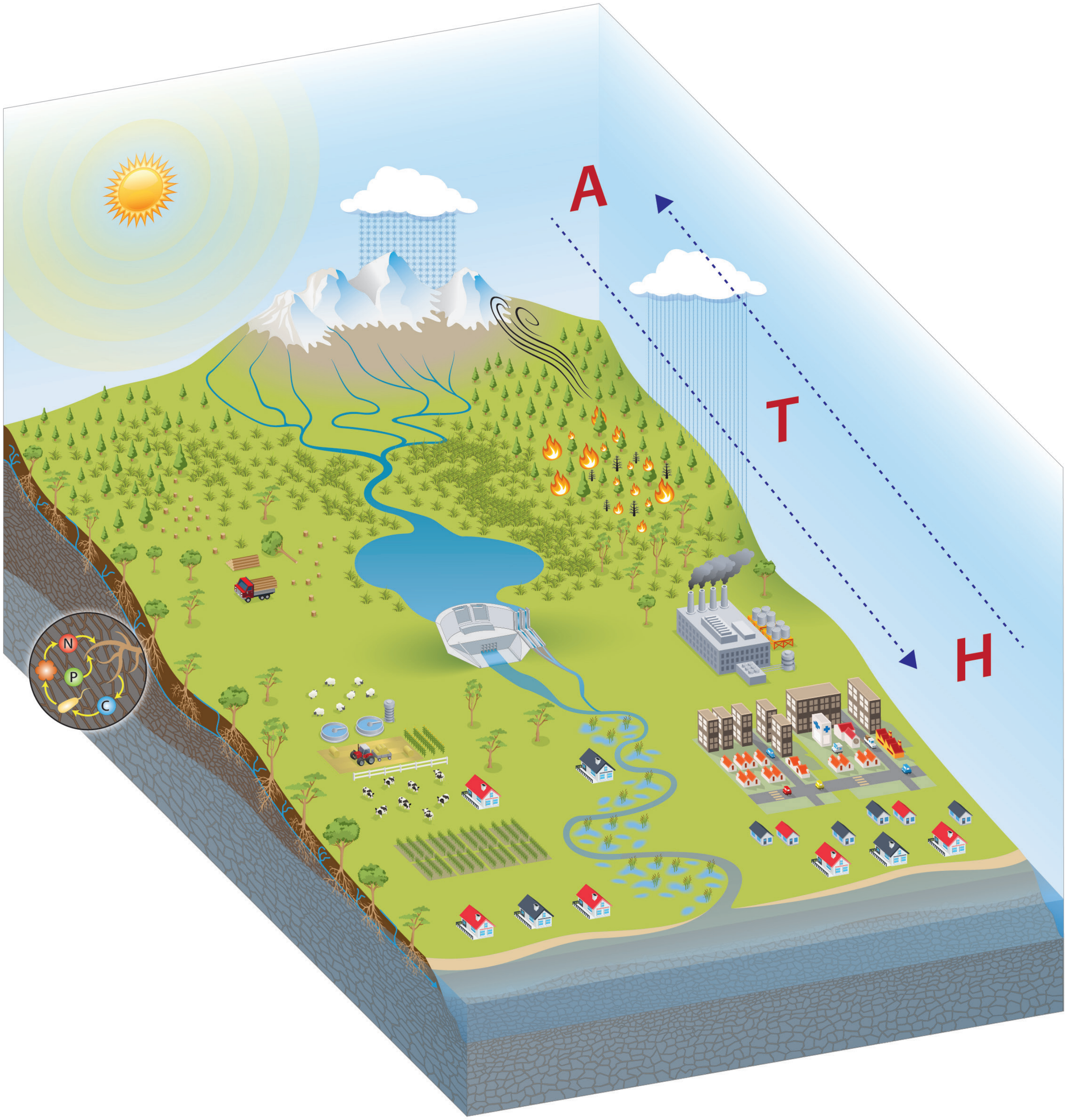


Fig. ES.1. Atmosphere, Terrestrial, and Human Systems (ATH): Integrated and Connected Components of Mountainous Regions. Atmospheric conditions in mountain regions regulate water partitioning through the terrestrial compartment (e.g., through infiltration and runoff partitioning to surface water and ground-water). Subsurface biogeochemical cycles from bedrock through vegetation regulate evapotranspiration fluxes back to the atmosphere; carbon dioxide fluxes from soils and streams; and watershed exports of carbon (C), nitrogen (N), and other elements. When water and elements reach downstream human systems, water regulation and decision-making become critical controls on water and elemental feedbacks to the atmosphere.

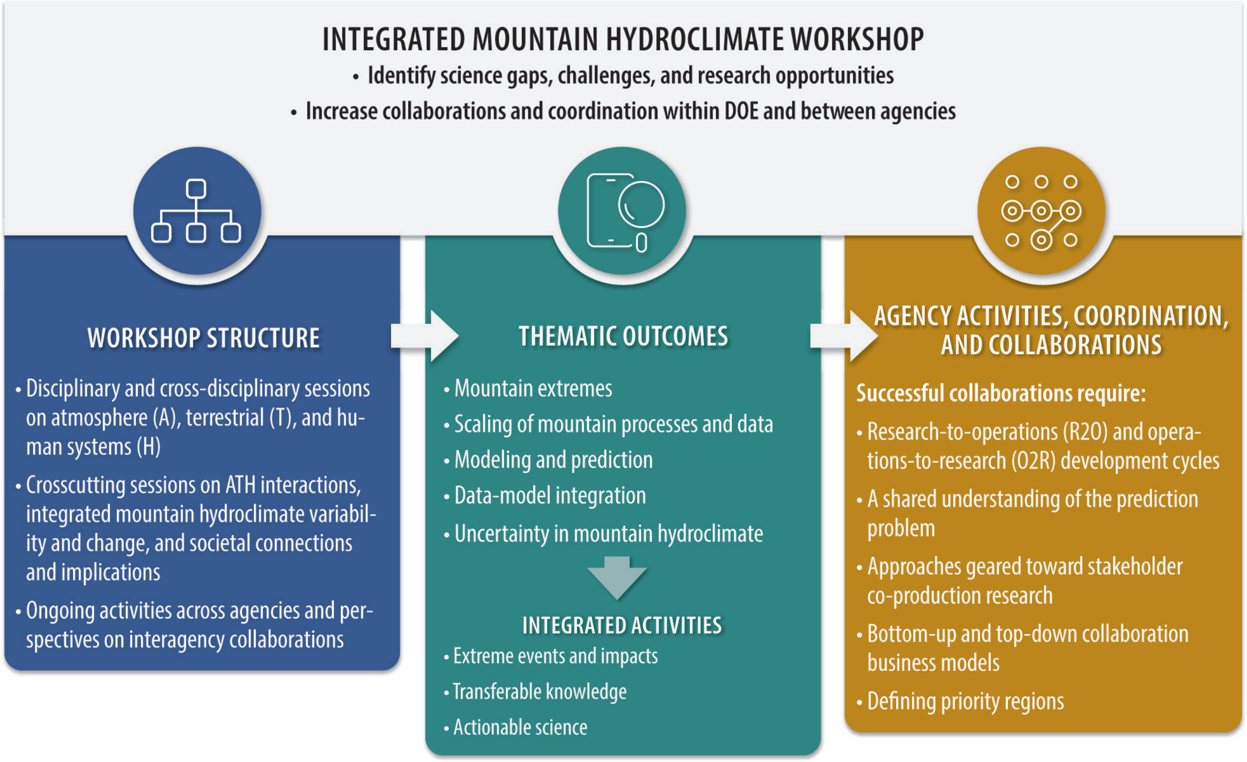


Fig. ES.2. Integrated Mountain Hydroclimate Workshop Goals and Structure. Participants identified science gaps, challenges, research opportunities, and ways to increase collaborations and coordination within DOE and with other agencies.

activities, coordination, and collaborations discussed in Session 2.

Science Gaps, Challenges, and Research Opportunities

Workshop participants identified science gaps, challenges, and research opportunities across five thematic topics: (1) mountain extremes, (2) scaling of mountain processes and data, (3) modeling and predicting mountain processes, (4) data-model integration in mountain regions, and (5) uncertainty in mountain hydroclimate. Each topic is discussed in detail below.

Topic 1: Mountain Extremes

Gaps and Challenges

Extreme events occurring in mountain regions include heavy orographic-driven precipitation; rain-on-snow events; rapid and early onset snowmelt; hot droughts driven by temperature and evaporation anomalies; snow and precipitation droughts caused by temperature and precipitation anomalies; and wildfires resulting from anomalies of temperature, humidity, soil moisture, fuel load, and fuel moisture. Extreme events present major threats to mountain ecosystems and play important roles in the global climate system and in broader energy, water, and food security. Threats and impacts to humans from extreme events in mountain regions include flooding, power outages, critically low water yields that affect hydroelectric power and agriculture, and nutrient loading. Considering these impacts, research on extremes in mountains and their future intensification is critical.

While much research has focused on the drivers of extreme events, major gaps persist in (1) quantifying thresholds and tipping points before and after extreme events; (2) determining the scales at which extreme events interact to cause downstream impacts;

(3) identifying feedbacks of extreme events on regional and global hydrological cycles; (4) understanding changes of extreme mountain phenomena in the coming decades; (5) assessing the threat of growing water demand; and (6) examining mitigations of extreme event risk to agriculture, water supply, and water demand and quality. Workshop participants also highlighted compounding extreme events (e.g., snow droughts and wildfire) as critical research gaps because of their interdependence on each other and on mountain hydroclimate regimes, their vulnerability to changing snow conditions, and the direct human influence on wildfire risk associated with expansion of wildland-urban interfaces along mountain foothills.

Research Opportunities

These knowledge gaps present the following research opportunities:

- Develop long-term, spatially comprehensive, and frequent snowpack observations to advance understanding and modeling of snowpack spatial distributions and regimes that drive extreme events—including rain-on-snow flooding and compound extremes related to snow drought and wildfires.
- Generate long-term datasets of mountain biomes to ascertain ecosystem steady states before extreme events and improve quantification of these events' downstream impacts, thresholds, and tipping points.
- Combine paleo- and synthetic data with *in situ* and remote-sensing data to understand a range of system outcomes of extreme events.
- Gather critical extreme event–scale data using rapidly deployable observational campaigns.
- Improve the entire model chain—encompassing weather, climate, hydrology, ecosystems, and risk—to understand feedbacks of extreme events on the hydrological cycle and develop novel and transformative mitigation strategies.
- Leverage the co-benefits of nontraditional experimental campaigns such as controlled forest management to better understand extreme event thresholds and disentangle anthropogenic land-use factors from atmospheric and terrestrial influences.

Topic 2: Scaling of Mountain Processes and Data

Gaps and Challenges

Understanding spatiotemporal scaling of processes and data is difficult in mountain regions at short and long timescales. The challenges arise from these regions' large topographic gradients, heterogeneous biomes, and varying land cover and use, which can amplify the spatiotemporal variability of hydroclimates and their response to anthropogenic activities. Undersampling the extreme spatiotemporal variability of mountain regions not only limits the ability to scale mountain processes (e.g., orographic precipitation, snowpack distribution, streamflow generation, and biogeochemical fluxes), it also limits use of this data as model inputs and benchmarking datasets. Additional observational and modeling challenges arise from the spatial connectivity within mountain regions through surface and subsurface hydrology and between mountains and their upstream and downstream regions through atmospheric processes and connected human systems.

Important gaps and challenges include (1) a wealth of existing data that has yet to be fully curated, quality controlled, and utilized; (2) observational networks that are not keeping pace with increasing modeling needs; (3) gridded products that have limited to no validation in mountain regions; (4) undersampling across elevation gradients with inadequate temporal coverage leading to simplified interpolation products that have limited value for analysis at timescales of climate variability and climate change; and (5) spatiotemporal scale mismatches among measurements, modeling, and decision-making that prevent researchers from realizing the full potential of EESSD's model-experiment (ModEx) approach (ess.science.energy.gov/modex/), especially at climate variability and change timescales.

Research Opportunities

These challenges may be addressed through the following opportunities:

- Identify and close short- and long-term spatiotemporal observational gaps and optimize experimental sampling design using systematic approaches.
- Improve spatiotemporal variability sampling to understand mountain process scaling using flexible, nimble, and networked mobile data collection platforms (e.g., artificial intelligence–guided, 5G, and autonomous frameworks).
- Bridge scales and leverage the wealth of temporal data at point scales by using (1) space-for-time approaches (i.e., substituting temporal sampling with spatial sampling across environmental and mountain gradients), (2) paired catchment studies, and (3) new upscaling approaches between point measurements and remote sensing.
- Improve gridded products by integrating multi-source, multiscale datasets from vast observational networks for value-added products and conducting data harmonization using artificial intelligence (AI) and machine learning (ML).
- Better leverage underutilized data by integrating and analyzing data from past field campaigns in a more comprehensive and systematic manner and developing new ways to incorporate these data into state-of-the-art models as a pre-ModEx activity (i.e., before designing and developing new operational and observational networks).
- Facilitate knowledge transfer and promote the use of observations for model development and evaluation by improving coordination of long-term collaborative research stations and networks across different global mountain regions and developing research networks that involve scientists and stakeholders as partners at the onset.
- Produce and combine multiple independent data streams (e.g., geophysics, hydrometrics, and tracers) into bedrock-to-atmosphere data collages to generate new theoretical and conceptual scaling constructs of mountain regions.
- Enhance decision-making (e.g., water and forest management) by collecting and analyzing data across systems and scales using citizen science, crowdsourced data, integrated social science, and community engagement.

Topic 3: Modeling and Predicting Mountain Processes

Gaps and Challenges

Many processes important to mountain hydroclimate are missing or poorly represented in coupled modeling frameworks. As a result, the ability to understand and predict bedrock-to-atmosphere processes in mountain systems is limited, particularly in the face of change. To address mountain hydroclimate challenges, coupled modeling frameworks should include novel process-based coupling (e.g., deep bedrock fracture flow coupled with vegetation) and microbial biogeochemical cycling from deep bedrock weathering as a response to and a driver of atmospheric feedbacks (e.g., carbon dioxide release). Notably, even small-scale storms can significantly affect flooding, and hillslope-scale hydrological processes can create hot spots and hot moments of biogeochemical activity with large signatures that feed back to the atmosphere, highlighting the need to model multiscale processes in mountain regions.

Major challenges in modeling and prediction include (1) determining the process representation and spatial resolution needed to credibly simulate mountain hydroclimate variability, change, and feedbacks in different regions; (2) advancing rudimentary observations, understanding, and modeling of system feedbacks, tipping points, and steady states in mountain systems; (3) developing benchmark observational datasets needed for model evaluation; and (4) improving the limited representations of human systems in IMHC models.

Research Opportunities

These challenges highlight the following opportunities for advancing modeling and prediction of mountain hydroclimate:

- Inform model development and experimental design by systematically evaluating the impact of model complexity, resolution, coupling, and ensemble size.

- Address cross-disciplinary scaling challenges by developing benchmarking datasets and novel metrics where science gaps exist, including (1) orographic precipitation, (2) concentration-discharge relationships, (3) evapotranspiration and atmospheric carbon fluxes, (4) wildfires, (5) human system components (e.g., related to infrastructure operations, wildland-urban interfaces, cloud seeding, or water management activities), and (6) spatiotemporally dense precipitation.
- Improve bedrock-to-atmosphere process coupling for models across a range of resolutions, including representation of process interactions at the subgrid scale.
- Overcome limited understanding of mountain system feedbacks and tipping points through enhanced modeling of bedrock-to-atmosphere coupling.
- Advance the design of novel numerical experiments to understand system feedbacks and tipping points in mountain hydroclimate changes through hierarchical modeling of atmospheric, terrestrial, and human systems and their interactions for mountain regions, including models of different complexities and configurations.
- Enhance human systems representation in models by creating a typology of human systems and their interactions with other mountain processes and developing new testbeds that leverage historical observational datasets and stakeholder community input.
- Develop benchmarking datasets and design modeling experiments and intercomparisons that integrate model transferability throughout the entire modeling process, from developing models to developing diagnostics and metrics for model evaluation.

Topic 4: Data-Model Integration in Mountain Regions

Gaps and Challenges

Although many past and ongoing studies include aspects of both modeling and observations, critical gaps in data-model integration are exacerbated for mountain regions and limit advances in mountain hydroclimate understanding and modeling. One challenge is the limited ability to use data in models because the data do not adhere to model spatiotemporal and quality assessment and quality control requirements (e.g., data from rugged terrain, limited spatiotemporal footprints, and absence of wireless networks to transfer data in real time). Another gap involves breaks in the ModEx cycle due to limited observational and numerical experimental designs preceding model development.

Research Opportunities

In addition to the research opportunities discussed in the previous two sections, the following opportunities emphasize data-model integration to jointly advance data and modeling capabilities:

- Close spatiotemporal gaps and improve availability of mountain modeling datasets by expanding collaborations with research and nonresearch partners (e.g., local agencies and technology firms).
- Integrate measurements, multiscale models, and ML to inform observational needs and model development for improved understanding and modeling of mountain systems.
- Advance and expand model-data integration approaches for mountain processes by using instrument simulators to more directly compare what instruments observe and what models simulate.
- Employ real-time data assimilation to integrate data with models and conduct observing-system simulation experiments to evaluate the value of a new observing system before its deployment.
- Better represent critical mountain processes, including hydrological, ecological, and human systems, in current Earth system models by developing AI emulators based on data and model simulations.
- Improve modeling of atmosphere-terrestrial-human interactions and feedbacks using hierarchical modeling capabilities that represent cross-scale

interactions of atmospheric and terrestrial processes to enable ModEx-based explorations.

- Harmonize and integrate terrestrial and human data to the same spatiotemporal resolution to generalize human-Earth interactions (e.g., use AI/ML models to integrate field experiments and other data).

Topic 5: Uncertainty in Mountain Hydroclimate

Gaps and Challenges

Understanding and quantifying uncertainty in IMHC remain outstanding challenges. Key unanswered science questions for mountain systems are: What are the scales and spatiotemporal distributions of model, data, and predictive uncertainty? How is decision-making impacted by the uncertainty in these distributions that propagates through the chain of model outcomes for atmosphere, terrestrial, and human systems? Correspondingly, major science gaps include (1) quantifying and attributing uncertainty due to downscaling approaches, model resolution, and model representation; (2) understanding the roles of system feedbacks in uncertainty propagation; (3) evaluating the impact of inadequate or missing representation of human multisector dynamics on uncertainty; and (4) communicating uncertainty to stakeholders and decision-makers.

Research Opportunities

Workshop participants identified several research opportunities to address uncertainty:

- Quantify and attribute model uncertainty by developing multimodel and large ensembles featuring (1) different modeling approaches, (2) simulations with and without model couplings, (3) simulations at different modeling resolutions, and (4) perturbations of initial conditions.
- Inform the changing risk landscape and trade-offs to support decision-making by developing and using probabilistic modeling frameworks to address uncertainties.
- Understand the limit of predictability from subseasonal to multidecadal timescales through novel numerical experiments specifically designed to study IMHC predictability and inform decision-making.
- Improve uncertainty quantification for extreme and compounding events (i.e., drought followed by heatwaves and wildfires) by mining "Big Data" and improving simulations coupled with measurements.
- Co-produce knowledge and data between scientists and stakeholders to improve communication of uncertainty, actionability, and decision relevance of modeling and prediction research.

Integrated Activities

A synthesis of the thematic gaps, challenges, and opportunities summarized above highlights the needs and opportunities for further advancing IMHC research through integrated activities on three crosscutting topics: extreme events and impacts, transferable knowledge, and actionable science.

- **Extreme Events and Impacts**. Extreme events and disturbances are typically defined relative to an historical baseline, but such definitions do not necessarily translate into the impacts of these events. There is broad agreement on the need to redefine extreme events in terms of their impacts, as determined by stakeholders, based on the unique characteristics of each mountain system. Using extreme-producing phenomena and their impacts as a central focus may accelerate progress in addressing gaps and challenges discussed in the "Topic 1: Mountain Extremes" section (see p. v).
- **Transferable Knowledge**. Mountain hydroclimates share many similarities, but they also differ due to variations in physical conditions, spatiotemporal scales of phenomena, and human systems management at upstream and downstream locations. Opportunities to enable knowledge transfer include (1) taking advantage of existing "network-of-network" groups to explore existing datasets across global observatories and identify process drivers, (2) designing model simulations to inform new measurements needed for different

communities, and (3) performing model intercomparison studies across spatiotemporal scales and locations to inform drivers and responses to change.

- **Actionable Science**. Providing actionable science insights and predictions to support decision-making requires minimizing biases, since dynamical simulations are subject to uncertainties and errors. To advance actionable science, leveraging existing stakeholder engagements may provide important opportunities for defining the requirements and needs for simulations and observation data. Other approaches include co-producing knowledge and data, developing regional themes related to extreme events that disproportionately impact society, and quantifying risk tolerance in decision-making.

Agency Activities, Coordination, and Collaborations

A need for long-term observational platforms and research to improve models motivates further intentional efforts to facilitate cross-divisional and interagency collaboration and coordination. Multiple EESSD-supported field campaigns and coordinated projects already feature cross-divisional collaboration on IMHC research. Some grassroots efforts also exist among scientists and agencies to foster networking and idea generation for future collaboration. Other modes of interaction to facilitate collaboration include: (1) "give-to-get" approaches in which a project supported by one agency provides data, modeling, and observational resources to a second project supported by another agency for an effort that fits within the other agency's missions but contributes to a shared program or goal; (2) "build it and they will come" scenarios in which field-based user facilities and community watersheds are developed with the goal of stimulating new funding by other agencies to support research in the same location and contribute to a shared vision; and (3) new shared funding opportunities whereby interagency teams develop and support research from the outset.

An interagency roundtable with program managers during the workshop highlighted that successful collaborations across federal, state, and local decision-making entities will require (1) Research-2-Operations (R2O) and Operations-2-Research (O2R) development cycles, (2) a shared understanding of the prediction problem, (3) approaches geared toward stakeholder co-production of research, (4) bottom-up and top-down collaboration business models, and (5) defining priority regions. Because of the need for long-term observational platforms and modeling research for mountain systems, several opportunities were highlighted:

- Improve knowledge transfer and shared understanding by fostering more collaborations and comparisons across sites in mountain catchments instrumented around the globe.
- Connect with stakeholders by envisioning and executing storyline approaches focusing on how specific extreme events observed in the past may unfold in the future under climate change (e.g., "Miracle March," "Monsoon Rescue," and "Santa Slammers").
- Accelerate model development and improve testbeds by expanding coordination across regions and programs that more optimally leverage observational datasets, stakeholders, and science communities.
- Leverage "community watersheds" that support and attract a community of researchers with common interests to facilitate increased collaborations through shared resources and goals.
- Enable knowledge transfer by guiding decision-making for new mitigation strategies to address impacts of mountain hydroclimate extreme events.
- Facilitate grassroots and agency-driven mountain research collaboration by developing experimental watersheds to host long-term observational and modeling platforms.

Wasatch Mountain Range, Utah
Courtesy Dual Usage: Unsplashed License & Public Domain

Chapter 1

Introduction

1 Introduction

Mountainous systems cover approximately 23% of the global land surface and are distributed across all continents of the globe (Fattorini et al. 2021). Mountain systems can capture and store atmospheric moisture, which is then cycled through the subsurface and terrestrial system, released to downstream communities, and cycled back to the atmosphere. Over 40% of global mountains maintain a seasonal snowpack (Wrzesien et al. 2019) that plays a critical role in providing water during dry seasons (Viviroli et al. 2007). As such, mountain regions function as "water towers" for major population centers. In addition to supporting human activities, mountain water resources are vital to diverse ecosystems and biogeochemical cycles in mountain environments.

1.1 Significance of Changing Mountain Hydroclimate

Mountainous systems are undergoing rapid climate change (Hock et al. 2019). Amplified warming with elevation (Mountain Research Initiative EDW Working Group 2015), multidecadal declines in April snowpack (Mote et al. 2016), and increased growing season lengths are having cascading effects through terrestrial and aquatic ecosystems (Huss et al. 2017) and on hydrological partitioning and water delivery (Rumsey et al. 2017). As extreme events become more severe due to warmer temperatures and associated increases in atmospheric moisture (Song et al. 2022), mountain hydroclimate may change nonlinearly and drive historically assumed system behavior into conditions with no historical analogs. Humans and ecosystems rely on mountain systems for stable water sources, but these systems are increasingly vulnerable to climate change–induced disturbances and extreme events. This vulnerability highlights the need to address challenges for predicting and understanding integrated mountain hydroclimate (IMHC) systems and their feedbacks and impacts on humans across scales.

Changing mountain hydroclimate is projected to profoundly impact mountain water supply. Along with changes in the water cycle, future mountain snowpacks are expected to decline and even disappear in some climate-sensitive mountain regions (Siirila-Woodburn et al. 2021). While complete loss of snow is the worst-case scenario, even a shift from rare or short-term occurrences of low-to-no snow to more persistent occurrences could significantly affect mountain resource management. Given projected declines and potential disappearance of mountain snowpacks and the importance of spring snowmelt in water management decisions, additional research is needed to understand the drivers and processes underlying observed mountain hydroclimate changes. This research would enable scientists to assess current and future snow conditions in mountains across the globe and understand how these changes will impact downstream water delivery.

Atmospheric impacts on water partitioning have cascading effects on mountain watershed hydrobiogeochemistry. Bedrock-to-atmosphere interactions can be a feedback of major greenhouse gas emissions to the atmosphere. However, a fundamental research gap exists regarding how these interactions and the biogeochemical cycles critical for regulating nutrient storage and release mechanisms will respond to changing water cycles. For example, in the Upper Colorado river basin, decadal declines in river exports of nitrate have been identified and associated with important vegetation, biogeochemical, microbial, and hydrological exchange patterns that are controlling this downward decadal trend (Newcomer et al. 2021a). Determining how watersheds retain and release essential elements—in the face of changing climate in general and changing snow conditions in particular—is important for understanding past and future changes in biogeochemical cycles not only in mountain areas but also in downstream regions through sediment, element, and nutrient (e.g., carbon and nitrogen) transport by rivers.

Future snowpack and other mountain-wide changes may have implications not only for water supply and hydro-biogeochemistry but also for local-to-regional circulation and teleconnections from mountain to lowland areas. For example, large perturbations of atmospheric flow by the Rockies can propagate downwind and influence cloud formation and precipitation in the U.S. Great Plains (Carbone and Tuttle 2008). Research is needed to examine how changes in hydrological processes in mountain regions may have long-range implications for atmospheric circulation and hydroclimate. Conversely, aerosol deposition on snowpack from long-range atmospheric transport could affect mountain snowpack, with subsequent local and remote influences through perturbations of surface energy and water balance (Qian et al. 2009; Kassianov et al. 2017; Sarangi et al. 2020).

1.2 Workshop to Identify Research Needs and Opportunities

Motivated by gaps in understanding and modeling mountain hydroclimate and the need for credible projections of future changes, the Earth and Environmental Systems Sciences Division (EESSD) within the U.S. Department of Energy (DOE) Biological and Environmental Research (BER) program sponsored a virtual workshop titled "Understanding and Predictability of Integrated Mountain Hydroclimate" to inform and catalyze EESSD's interests and approaches to addressing the scientific and societal challenge of enhancing predictive understanding of IMHC. In the context of the workshop, IMHC is defined as a collection of mountain subsystems, from the deep subsurface through vegetation to the atmosphere, that interact as a result of water and elemental movement and nature-societal interactions. Key natural processes controlling how energy, water, and biogeochemistry interact from bedrock to the atmosphere include (1) water, energy, and elemental transport in the soil-plant-atmosphere continuum; (2) vegetation and groundwater table dynamics; (3) boundary layer turbulence; (4) clouds and convection; and (5) radiative transfer in the atmosphere and vegetative canopy. Key human-related processes that critically influence mountain systems include water infrastructure, forest management, land use, and agriculture. Important to the definition of IMHC are the dynamic interactions and feedbacks among various system components and influences that give rise to complex system behaviors, including compound extreme events and potential system thresholds and tipping points.

The workshop aimed to provide insight on priority challenges and regions and to identify future research needs and opportunities for increased collaborations among federal agencies. Participants addressed the following charge questions:

1. What are the key science gaps, questions, and highest-priority research challenges in IMHC? Are there domain-specific science gaps that must be addressed to facilitate progress on integrated research challenges?
2. Are there highest-priority regions (within North America and globally) for focused research in mountain hydroclimate systems to address these science questions? Are there strategic regions to develop transferable knowledge and extensible approaches that can be applied at global scales?
3. What are some of the short-term (1 to 3 year) and medium-term (3 to 6 year) integrated research opportunities to advance understanding and prediction of hydroclimate processes and interactions in mountainous regions?
4. What are the short-term (1 to 3 year) and medium-term (3 to 6 year) opportunities within and across existing projects and BER Science Focus Areas to build more integrated frameworks that are extensible across multiple regions and employ leading-edge science approaches (e.g., integrated observatories; data-model integration; high-resolution, hierarchical, and hybrid modeling; multiscale modeling; edge computing; and artificial intelligence and machine learning)?
5. What is the long-term (10 year) DOE vision for addressing IMHC challenges? What are the future opportunities and research needs, and how can the

short- and medium-term opportunities and goals related to research challenges and existing DOE projects come together to meet this vision?

1.3 Workshop Structure

IMHC research identified in this report will accelerate progress on four of the five grand challenges identified in the 2018 Earth and Environmental Systems Sciences Division Strategic Plan: integrated water cycle, biogeochemistry, drivers and responses in the Earth system, and data-model integration (U.S. DOE 2018). Additionally, IMHC research incorporates many disciplines and applications aligned with these grand challenges, including climate and atmospheric sciences, hydrology, biogeochemistry, ecology, and human multisector dynamics, all of which are connected by the integrated water cycle.

To address IMHC's outstanding challenges, the workshop included two sessions—one focused on connecting existing DOE investments and the other on creating interagency collaborations—organized by disciplinary, cross-disciplinary, and crosscutting science topics (see Appendix A: Agenda, p. 63). The disciplinary and cross-disciplinary topics focused on essential IMHC elements: atmosphere, terrestrial, and human systems and their interactions. Breakout sessions on disciplinary and cross-disciplinary topics facilitated identification of crosscutting topics and central emerging themes. Workshop co-chairs worked closely with co-leads of the disciplinary and crosscutting topics to further identify and invite plenary speakers, panelists, and workshop participants. The workshop was conducted in a virtual format, with 104 participants from U.S. and international universities, national laboratories, industry, and government agencies. To address the interdisciplinary challenges of mountain hydroclimate systems and to provide a broad range of perspectives, workshop participants represented diverse expertise in atmospheric, ecosystem, and watershed sciences; Earth system variability and change; and observational, experimental, and Earth and environmental systems modeling of both natural and human components (see Appendix B: Participants, p. 69).

1.3.1 Session 1: Connecting Current DOE Investments

This two-day session (November 15–16, 2021) focused on connecting existing DOE investments to accelerate progress on scientific challenges to understand the mountain hydroclimate system and associated processes. It provided a forum for scientists across a variety of academic, nonacademic, and federally funded research programs to present mountain hydroclimate–relevant projects and resources, including field campaigns and research projects, long-term field sites and investments, and modeling activities.

Day 1 focused on disciplinary and cross-disciplinary science needs associated with three key topics: atmospheric, terrestrial, and human (ATH) system processes. Workshop participants discussed current status, gaps, and opportunities in understanding, observing, and modeling local processes, remote connections, and hydrological connectivity across multiple spatial and temporal scales from subseasonal to seasonal, and on to multidecadal variability and changes.

Day 2 focused on three integrated, crosscutting topics and challenges: ATH, IMHC variability and change, and societal connections and implications. Workshop participants discussed the status, gaps, and opportunities in understanding, observing, and modeling ATH interactions in the context of:

- Diurnal and seasonal variability.
- Extreme events.
- Coupled water-carbon-nutrient cycles.
- IMHC variability and change, including contrasting different climate and hydrological regimes and responses to large-scale forcing.
- Climate change impacts and processes in mountain systems.
- Challenges in connecting mountainous hydroclimate research to meet societal needs.

Based on common themes that emerged from the disciplinary, cross-disciplinary, and crosscutting topical discussions, workshop participants also examined three integrated activities: extreme events, transferable knowledge, and actionable science.

1.3.2 Session 2: Creating Interagency Collaborations

In this one-day session (January 19, 2022), Session 1 participants were joined by program managers and project representatives from other federal agencies in addition to DOE. Workshop co-chairs presented a set of key outcomes from Session 1 at the opening of the session. Short presentations from multiple agencies followed, along with a roundtable discussion on ongoing activities across different agencies. Panel discussions were held on both disciplinary topics (atmosphere, terrestrial, and human systems) and crosscutting topics (ATH interactions, IMHC variability and change, and societal connections and implications). Lastly, a panel of program managers provided perspectives on interagency collaborations on IMHC research and led an open discussion. During the short presentations and discussions, key takeaways from Session 1 were further explored through the lens of multiagency collaborations and coordination.

Through plenary presentations, breakout groups, panel presentations, and roundtable discussions, workshop participants shared research goals and progress, identified gaps in understanding and modeling mountain hydroclimate, and discussed short-term (1 to 3 years), medium-term (3 to 6 years), and long-term (10 years) opportunities to address data, measurement, and modeling gaps.

The chapters that follow summarize the workshop's key outcomes and provide insights into priority challenges and future research needs for advancing understanding of IMHC in disciplinary science (Ch. 2), cross-disciplinary science (Ch. 3), crosscutting science (Ch. 4), and integrated activities (Ch. 5). Chapter 6 identifies opportunities to increase collaborations among existing EESSD programs, projects, and high-value synergies and to leverage EESSD investments and other federal agency efforts.

Sierra Mountains, Calif.
Courtesy Adobe Stock

Chapter 2

Disciplinary Science

2 Disciplinary Science

2.1 Atmospheric Processes

Atmospheric processes across various scales play major roles in shaping the integrated mountain hydrological cycle (see Fig. 2.1, this page). Small-scale processes (e.g., aerosol-cloud-radiation interactions) intersect with both medium-scale processes (e.g., orographic circulations, clouds, and precipitation) and large-scale processes (e.g., atmospheric rivers and teleconnections). Ultimately, these complex multiscale interactions influence atmospheric vertical gradients and spatiotemporal variability in temperature and precipitation timing, amount, and phase, which, in turn, shape the rate of water storage and transport from headwaters to downstream communities. The multiscale aspects of atmospheric processes that shape mountain environments require a variety of approaches to better understand the interactions of mountain processes across scales and the unique effects of climate change in different global mountain regions. These approaches include long-term observational networks and shorter-term intensive field campaigns, paleoclimate proxies, regional high-resolution modeling, and long-range climate model projections.

2.1.1 Atmospheric Knowledge Gaps and Challenges

Understanding of atmospheric processes in mountain terrain has steadily improved over the last 50 years, leading to significant advances in mountain hydroclimate predictions. However, many science gaps remain related to cloud processes, feedbacks, and scale interactions, all of which lead to challenges for modeling and predictive understanding. This section outlines the following four knowledge gaps and challenges: cloud processes in mountain terrain, atmosphere-surface

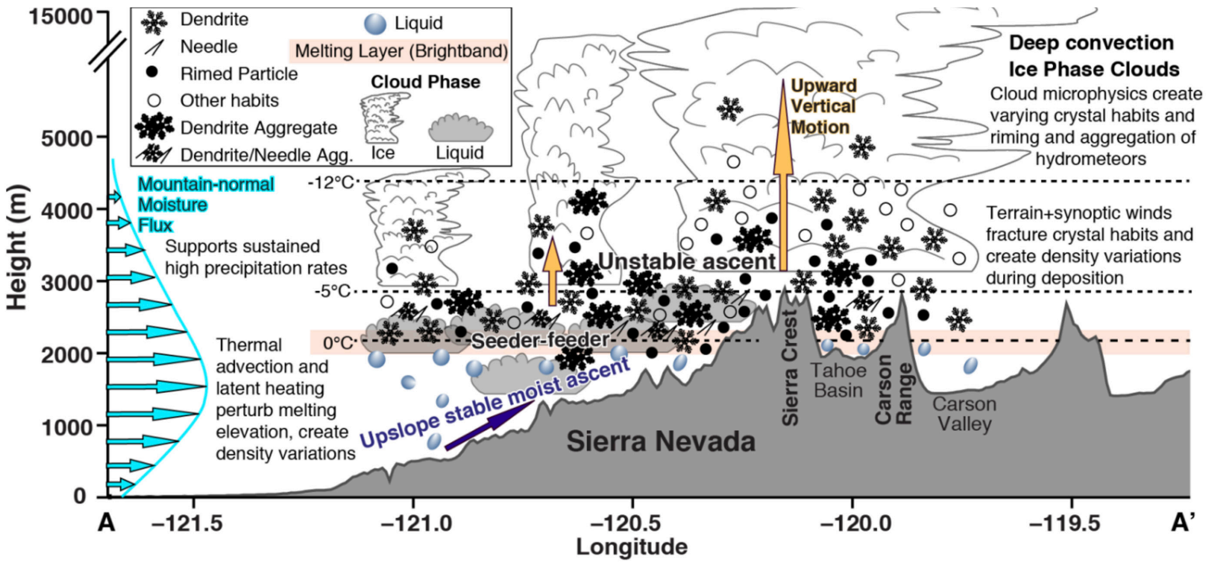


Fig. 2.1. Atmospheric Processes Relevant to Mountain Regions from Lowlands to Mountaintops. Mountain regions play a critical role in shaping precipitation phase, distribution, magnitude, and intensity. [Reprinted from Hatchett, B. J., et al. 2016. "Some Characteristics of Upside-Down Storms in the Northern Sierra Nevada, California-Nevada, USA," *Proceedings from the 2016 International Snow Science Workshop*, Breckenridge, Colorado. © Montana State University Library 2022.]

interactions, cross-scale interactions within and downstream of mountains, and modeling limitations and trade-offs in complex terrain.

Cloud Processes in Mountain Terrain

Mountain terrain influences atmospheric conditions that determine cloud radiative effects and precipitation phase, intensity, and spatiotemporal distribution. When critical cloud processes operate at scales that are too small to be resolved by modern weather and climate prediction models, the processes need to be parameterized. However, subgrid process representation introduces uncertainties and biases in cloud and precipitation properties. Though difficult to represent in models, the complex cloud systems that form when mountain terrain forces multiscale circulations are important for surface radiation balance, which can impact snowmelt and temperature as well as subsequent clouds and precipitation.

One challenge in predicting mountain precipitation is understanding hydrometeor phase partitioning and its effects on riming and vapor growth, which control precipitation type, efficiency, and location. For example, greater riming contributes to more windward slope precipitation, and vapor growth pushes precipitation toward the lee of mountains (Hobbs et al. 1973). These processes depend on small-scale updrafts and are influenced by similar scale topographic features; neither are sufficiently resolved in even high-resolution regional models (e.g., Kirshbaum 2020).

Most precipitation in many mountain regions is produced through convection initiated by topographically induced ascent (Kirshbaum et al. 2018). Numerous aircraft radar measurements show that convective circulations are common even in larger-scale stratiform precipitation with clear local precipitation enhancement (e.g., Geerts et al. 2015), which is difficult to predict (Fuhrer and Schär. 2005). Moreover, deep convection preferentially forms over and near mountain terrain due to orographic circulations. At times, this formation produces extreme precipitation events that are difficult to predict given the relatively small-scale nature of some storms. Combined with runoff channeling, mountain terrain is particularly susceptible to flash floods (Smith et al. 2018), which can be destructive when produced by slow-moving, relatively small-scale storms (Maddox et al. 1978).

Extreme precipitation and flooding over mountain terrain can also occur through sustained upslope flow, where collision-coalescence contributes significantly to precipitation amount (e.g., Gochis et al. 2015). However, these processes are difficult to predict due to their dependence on aerosol concentrations (Choudhury et al. 2019), which are modulated by (1) poorly quantified precipitation scavenging of aerosols and complex orographic flow interactions (e.g., Muhlbauer and Lohmann 2008) and (2) anthropogenic and wildfire emissions that are often absent in models. Additionally, deep tropospheric lift and cool, moist air trapped in mountain valleys or blocked flow often produce multilayer clouds in mountainous terrain. These clouds can lead to seeder-feeder interactions that can double daily rainfall in mountain valleys and may be a major source of model bias because of the difficulty in resolving such complex cloud layers (e.g., Duan and Barros 2017). All these processes require further observational constraints and improved representation in weather and climate models.

Atmosphere-Surface Interactions

Clouds, precipitation, and surface state interact to affect integrated mountain hydroclimate (IMHC). The impacts of multiscale land-atmosphere coupling on mountain meteorology and surface conditions such as snowpack require inquiry across feedback pathways and scales. For example, rain-snow partitioning is largely assumed to be solely temperature dependent in most atmosphere and land-surface models. However, new research shows that surface humidity and winds can appreciably augment snowfall presence at above-freezing conditions (Jennings et al. 2018). Insufficient snowpack or surface moisture can warm and dry the boundary layer, feeding back to clouds and precipitation. Other feedback loops involving atmosphere and land surface processes are also likely to occur and impact predictions of mountain hydroclimate across scales (Siirila-Woodburn et al. 2021). Cloud and precipitation prediction errors consequently increase through their impacts on surface conditions and surrounding atmospheric circulation patterns that feed back to influence subsequent evolution of cloud and precipitation. These feedbacks are not well characterized and may also affect much larger-scale circulations and remote regions through teleconnections (e.g., Letcher and Minder 2018), but such interactions remain poorly understood.

Cross-Scale and Downstream Interactions

Cross-scale processes in mountain terrain and their downstream atmospheric circulation responses are not well-represented in models. Higher-resolution models have led to substantially improved precipitation prediction over mountain terrain (e.g., Wang, Y., et al. 2018), such that they are now thought to outperform gridded observational retrievals that rely on statistical relationships to spatially interpolate in some data-sparse regions like mountains (e.g., Lundquist et al. 2019). However, the improved predictive capability of higher-resolution models is not true everywhere, and a scarcity of robust observational data limits the ability to quantify model bias and truly assess the added value of resolution in many mountain regions such as the South American Andes (Condom et al. 2020; Thornton et al. 2022). Such models are also computationally expensive and are thus limited in domain size, simulation length, and ensemble possibilities.

Systematic analyses of coordinated regional climate modeling ensembles like the World Climate Research Programme's (WCRP) Coordinated Regional Climate Downscaling Experiment (CORDEX) have been invaluable in deciphering multiscale and intermodel differences in simulating mountain precipitation character (i.e., intensity, frequency, and duration). A key finding from these coordinated modeling efforts is the clear, systematic improvement in modeled diurnal and seasonal precipitation when models are run at 3-km versus 12-km resolution across the European Alps (Ban et al. 2021). Furthermore, a long-standing, systemic bias in representing atmospheric general circulation (Baldwin et al. 2021)—namely the double-Intertropical Convergence Zone (ITCZ) bias, which has profound implications for downstream mountain hydroclimates (Dong et al. 2021)—might be partly mitigated by better resolving mountain terrain (e.g., Sierra Madres of Mexico) at higher resolution.

Another long-standing modeling issue has been how to best represent boundary layer mixing in complex terrain with limited resolution. Many climate models lack the necessary vertical resolution—particularly in the boundary layer—to properly represent surface fluxes and mixing into the upper atmosphere that can, in turn, influence local microclimates and downstream atmospheric circulations. Further, boundary layer mixing parameterizations have largely been designed for flat, homogeneous terrain (Finnigan et al. 2020), which may generate too much stability in complex terrain—especially over snow covered areas (Slater et al. 2001)—and lead to erroneous surface temperature lapse rates at higher resolutions (Rhoades et al. 2018). To assess the added value of resolution, cross-scale interactions, and scale-aware physical representations, more emphasis must be placed on mountains as important natural testbeds during model development.

Modeling Limitations and Trade-Offs in Complex Terrain

The model setup required to assess mountain hydrological cycle processes is still unknown, particularly when factoring in the regional importance of internal variability and scenario uncertainty. Mountain landscape heterogeneity emphasizes the need for systematically evaluating the necessary model setup in terms of resolution (both horizontal and vertical) and model complexity, both of which are required for climate models to sufficiently represent the mountain hydrological cycle.

Model setup also needs to be juxtaposed in terms of its relative importance to both internal variability and scenario uncertainty in driving regional hydroclimates, and setups may differ from one mountain region to the next. Enabling this advance requires more internationally coordinated, high-resolution, multimodel ensembles assessed across a matrix of horizontal and vertical resolutions (structural uncertainty), ensemble members (internal variability), and socioeconomic development scenarios (scenario uncertainty; Gutowski et al. 2020; Schär et al. 2020). This effort would be better enabled—particularly at sub-3-km resolutions—if model code were adapted to new supercomputing architectures (e.g., graphics processing units) and support staff were available to handle and curate exascale data volumes to expedite scientists' analysis workflows.

Given limited computational resources, a balance needs to be achieved between model resolution, initial condition and perturbed parameter ensembles, and physics parameterization complexity. However, the optimal balance for various weather and climate applications remains unclear, particularly in complex terrain. Furthermore, models are not equitably evaluated across global mountain ranges, hindering their utility in advancing hydrometeorological process understanding and climate impact assessments. At the same time, continued development of observational and modeling capabilities is required, which presents further challenges.

Depending on the problem being tackled, differing scales, uncertainties, and complexities are required, but it is unclear which should receive priority and how resources would be best balanced across a range of problems and methods. Similarly, models are often built to effectively predict mean states, but more than ever they also need to predict extremes for which they may not be well-suited (e.g., La Follette et al. 2021). Extreme events could act as potential opportunities to pinpoint process understanding and model representation deficiencies (e.g., orographic precipitation and freezing levels during atmospheric rivers) and model "blind spots" (e.g., downslope winds and wildfire-related impacts). Such events could also enhance usability of model hindcasts, forecasts, and projections for decision-relevant outcomes (e.g., Hatchett et al. 2020).

2.1.2 Atmospheric Research Opportunities

Progress on mountain regions' atmospheric science gaps and challenges can be pursued by using existing data better, harmonizing data, expanding coordination among modeling activities, mining large benchmark simulations, improving observational sampling and model integration, and transferring knowledge across communities. The sections that follow describe these research opportunities.

Using Existing Data Better

Fostering interconnections between resources could provide an opportunity to enable more effective use and synthesis of the wealth of existing atmospheric data from operational surface networks, research stations, and targeted field campaigns. Substantial data often remain unexplored, and some campaign objectives that depend on connecting several findings may not be fulfilled. Underutilized data accumulation and unfulfilled potential from past field campaigns coupled with operational networks and state-of-the-art modeling present a major research opportunity. For example, datasets shared among collaborators recently studying subtropical mountain terrain amplified the potential impact of this research by enabling multiple independent scientists to simultaneously analyze and compare the data. The collaboration involved the DOE-supported Clouds, Aerosols, and Complex Terrain Interactions (CACTI) field campaign and the Remote sensing of Electrification, Lightning, And Mesoscale/microscale Processes with Adaptive Ground Observations (RELAMPAGO) campaign supported by the National Science Foundation (NSF)—along with additional contributions from Argentinean and Brazilian colleagues and NASA.

Similarly, a data collection covering multiple mountain processes emerged from the coordination and collaboration of the DOE-supported Surface Atmosphere Integrated Field Laboratory (SAIL) campaign with the Study of Precipitation, the Lower Atmosphere, and Surface for Hydrometeorology (SPLASH) campaign supported by the National Oceanic and Atmospheric Administration (NOAA). The SAIL and SPLASH collaboration represents an opportunity to use an unprecedented level of mountainous meteorological coverage to explore research questions related to (1) scaling (upscaling and downscaling), (2) novel inclusion of spatially and temporally complete datasets into process-based models (i.e., bedrock-to-canopy hydro-biogeochemical models), and (3) exploration of mechanism transferability to other highly (and nonhighly) instrumented sites (see box, this page). Although these large, multi-agency campaigns require tremendous time and effort to organize, they hold immense potential for interdisciplinary scientific breakthroughs due to their comprehensiveness relative to smaller campaigns.

Harmonizing Data

The lack of standardized data formatting and quality control presents a major hurdle for researchers aiming to realize the full potential of so many underutilized datasets. In addition, datasets tend to be spread across a patchwork network of different data archives. Expanding data harmonization and building data repositories would greatly amplify research efficiency and impact. Many programs have large, organized repositories with readily accessible datasets in common, easy-to-use formats. A good example is the data center for the Atmospheric Radiation Measurement (ARM) user facility within the Earth and Environmental Systems Sciences Division (EESSD) of DOE's Biological and Environmental Research program. However, not all atmospheric observation and modeling programs have invested in creating such user-friendly repositories or adopting standard data and metadata formats. Such widely variable designs impede efficient research.

Efforts have increased to build repositories with graphical user interfaces that facilitate actionable science by stakeholders focused on specific topics such as California's Cal-Adapt, which allows users to search peer-reviewed data about the effects of climate change at state and local levels. Recent projects have also started to harmonize extensive global datasets of specific properties (Reddington et al. 2017). For example, the Global Aerosol Synthesis and Science Project (GASSP) created a sizeable global dataset of aerosol measurements to better understand global aerosol effects on climate. While this trend is promising, these tasks represent a small portion of what is possible.

Large data-harmonizing projects requiring significant time and effort are not sufficiently recognized, funded, or rewarded outside of modeling programs such as the WCRP's Coupled Model Intercomparison Project (CMIP). Agreement on common variables (e.g., Thornton et al. 2021) and standardized naming and unit conventions for variables are of first-order importance, as these classifications would enable easier combinations of datasets from different observational and modeling programs over long periods. Given the number of datasets and variability among them, this standardization effort, though challenging, would yield impactful statistical power that circumvents the application of a primary observational weakness (i.e., unrepresentative, limited sampling) to model evaluation and improvement. The wide range of measurement facilities across multiple agencies must adopt a common framework to successfully build the largest, most

Scaling

Methods to represent heterogeneity of states, mechanisms, processes, and parameters at different distinguishable scales.

Scalability

The ability of observations and mechanistic parameters to be representative of systems at different scales.

Transferability

The applicability and transfer of states, mechanisms, processes, parameters, and knowledge to new locations.

Storylines

A physical climate storyline is a physically self-consistent unfolding of past events or of plausible future events or pathways. Storylines provide an alternative approach to representing uncertainty in physical aspects of climate change. They are inherently public-facing approaches to describing climate and meteorological phenomena.

representative, and easiest-to-use datasets possible for model evaluation, improvement, and machine-learning (ML) applications.

Expanding Coordination Among Modeling Activities

Within the modeling community, a number of recently developed projects include both mountain hydroclimate and atmospheric process components. Several DOE-supported projects[1] have objectives that align with projects supported by other programs.[2] Projects are often organized by region or storyline with multiscale foci ranging from regional mean climate to smaller-scale high-impact events. Some collaboration already occurs between project and model development teams, but more integration is possible, as are more interactions with stakeholders who can use the most relevant predictive information to make appropriate societal decisions. These projects need to be maintained, but opportunities exist to expand coordination across regions and programs that enable various stakeholders and science communities to more optimally leverage observational datasets in developing testbeds for model evaluation and improvement.

Mining Large Benchmark Simulations

Recent computational advances have led to projects implementing regionally focused historical and future climate runs (e.g., CORDEX) down to kilometer-scale grid spacing [e.g., Liu et al. 2017; Musselman et al. 2018; the EXtreme scale Computing and data platform for cLoud-resolving weAther and clImate Modeling (EXCLAIM)]. These advances significantly reduce precipitation and temperature biases in mountain terrain. Considerable resources are being spent to expand these projects further into global- and regionally refined kilometer-scale simulations using the DOE Energy Exascale Earth System Model (E3SM; Caldwell et al. 2021; Liu et al., in review). Although kilometer-scale simulations do not fully resolve mountain processes (e.g., orographic precipitation and its hydrologic impacts), they demonstrate obvious improvements compared to climate simulations typically run at grid spacing between 25 to 100 km. Seasonal-to-decadal kilometer-scale simulations are also feasible using regional models and global models with regionally refined meshes. However, kilometer-scale simulations are far from fully utilized, with ample opportunities to mine well-curated output from such simulations to target critical, uncertain processes. Large-eddy simulations can be used to probe more detailed processes over complex terrain. Further opportunities exist to better link model components from different communities (e.g., implementing snow models into mesoscale models or developing integrated bedrock-to-atmosphere modeling capabilities that capture the entire mountain hydrological cycle, including subsurface processes).

Improving Observational Sampling and Integration with Models

More than ever, opportunities exist to better integrate measurements, multiscale models, and ML for scientific advances, model development, and improved guidance of observational needs. While observations are a critical check on models, which often contain errors due to simplifications relative to the real world, the limits of observational sampling produce representativeness errors. Observations also measure a state rather than a process and often employ imperfect models to retrieve variables. Thus, models are also critical for informing and gapfilling observations. Advances in computing are creating opportunities to connect observable atmospheric-state properties to unobservable processes in novel ways using high-resolution modeling with complex physics parameterizations, observational simulators, and ML. Such methods could also revolutionize data assimilation

---

[1] Examples include DOE's HyperFACETS, a merger of DOE's Hyperion Project and the Framework For Analysis Of Climate-Energy-Technology Systems (FACETS) project; the Water Cycle and Climate Extremes Modeling (WACCEM) Science Focus Area; the Calibrated and Systematic Characterization, Attribution, and Detection of Extremes (CASCADE) project; and the Coupling of Land and Atmospheric Subgrid Parameterizations (CLASP) project.

[2] Examples that align with HyperFACETS, WACCEM, CASCADE, and CLASP objectives include the High Mountain Asia Team (HiMAT), NASA's collaborative research study of cryospheric changes; TEAMX, a multiscale exploration of transport and exchange processes in mountain atmosphere hosted at Austria's University of Innsbruck; and ANDEX, a regional hydroclimate program in the Andes mountain range established as part of WCRP's Global Energy and Water Exchanges (GEWEX) project.

by overcoming linear operator limitations, observational networks, and targeted field campaigns through optimized designs for specific targets and through large, low-cost ensembles to improve prediction uncertainties.

Model ensembles also could be used to objectively determine which observations are most valuable and where they should be obtained. Models and observations have tended to focus on geographical regions such as the Rockies and the European Alps, which share some characteristics with other mountain ranges of the world (e.g., glacier retreat in a warming climate) but are also meteorologically unique. Even within relatively well-observed ranges, some microclimates remain poorly characterized. Remote, high ridgelines and peaks are poorly sampled by surface measurements (Thornton et al. 2022), while valleys are poorly observed by remote sensing. Yet, characteristics and processes within these undersampled regions each play critical roles in modulating atmospheric circulations that control precipitation intensity, duration, and location. These sampling biases may have skewed scientific understanding and model designs that would potentially benefit from studying poorly observed ranges. However, cases can also be made for targeting mountain ranges that are expected to experience emerging climate shifts sooner or those that are most vulnerable or relevant to societal needs (e.g., water yields).

Research that embraces DOE's coupled Model-Experimentation (ModEx) approach (see box, this page) can be used to better inform observational strategies and guide these important decisions related to selecting locations and scales of priority regions. The strategy and success of the ModEx approach rely on early model application efforts to regions before any *new* observational campaigns are deployed. These early efforts can be achieved by adequately synthesizing and testing pre-existing available and historical datasets as a pre-ModEx activity. Model development in new regions is also needed to broaden the use of observational data that span multiple regions and components of the mountain hydrological cycle as a way of testing model transferability. This development requires incentive structures that break down traditional scientific silos and the development of multi-disciplinary teams to evaluate bedrock-to-atmosphere processes.

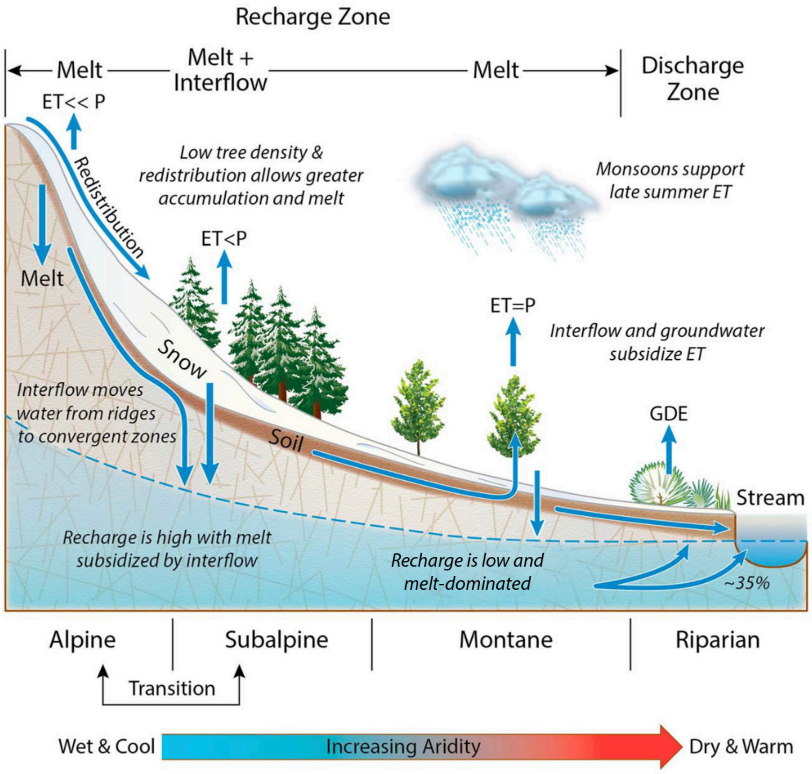
The ModEx Approach

The ModEx approach integrates process research, which involves observations, experiments, and measurements performed in the field or laboratory, with modeling research, which simulates these processes. This integrated loop ensures that models incorporate state-of-the-science knowledge about critical systems, and the resulting improved models can be used to guide field and laboratory research to inform future decisions.

Transferring Knowledge Across Communities

To achieve better predictive understanding of and project future changes to mountain systems, a coordinated effort is needed to diagnose essential underlying mountain processes that will be impacted by climate change (e.g., snow albedo feedback and dynamical and thermodynamical controls on orographic precipitation). A model hierarchy also needs to be leveraged to inform best practices in observational constraints and downscaling methods. However, insufficient communication and knowledge transfer between different communities with common goals have limited scientific progress. For example, while studies of weather events within the context of climate have become widespread, only limited collaboration exists among top scientists and programs in these different communities.

While efforts have been made to include more scientists from relatively data-sparse and study-limited regions into major modeling and observational initiatives, significant improvements are still needed. Many such efforts to date have focused primarily on North America and Europe. More inclusive and broader-scoped research studies spanning multiple data- and model-poor mountain regions around the globe (e.g., Africa and South America) are needed to understand fundamental mountain processes, how they



Recharge and Landscape Position

Alpine
Recharges groundwater and generates interflow.

Transition (Upper Sub-alpine)
Convergent zone with melt and interflow producing recharge.

Montane
Melt occurs early in spring to generate recharge. ET supplemented by interflow and monsoon rains.

Riparian
A discharge zone with ET largely supported by monsoon rains and groundwater.

Fig. 2.2. Conceptual Model of Water Fluxes Across Large Mountain Gradients in Topography, Aridity, and Vegetation. Dominant mechanisms of the terrestrial water cycle in mountains are highlighted (GDE = groundwater dependent ecosystem; ET = evapotranspiration; P = precipitation). [Reprinted under a Creative Commons license (CC-BY-NC-ND) from Carroll, R. W. H., et al. 2019. "The Importance of Interflow to Groundwater Recharge in a Snowmelt-Dominated Headwater Basin," *Geophysical Research Letters* **46**, 5899–5908.]

are modeled, and how they might be affected under climate change to ensure that they are extensible, transferable, and useful for planning and adaptation efforts. Knowledge and capability transfer between different countries requires better frameworks that more easily facilitate collaborations and communications among scientists and relevant stakeholders (e.g., Rhoades et al. 2022).

2.2 Terrestrial Processes

Through snowpack accumulation and melting, mountain regions are "water towers" for major population centers and agricultural regions. The role of mountains as water towers is reflected mostly on the regional scale—the scale at which mountains define the hydraulic gradient—with higher elevation regions contributing to lower elevation regions through lateral groundwater flow and surface water exchange. The associated processes on the catchment scale[3]—the area of land from which water flows into a river, lake, or reservoir—are largely driven by local topography, which defines the water and energy balance due to aspect, solar angle, and shading. The resulting water and energy gradients in mountain catchments can lead to highly localized spatial variability that can exceed the impact of regional climate dynamics (see Fig. 2.2, this page).

This multiscale spatial organization leads to a complex pattern of precipitation partitioning into evapotranspiration and drainage to groundwater and streams, which is often expressed in the natural vegetation pattern. As

---

[3] Observing and representing processes at the catchment scale allow scientists to study interactions between slopes, channels, and individual vegetation stands.

an example, different plant communities are observed on water-limited slopes versus energy-limited slopes. While the water-energy coupling leads to a complex spatial structure of generalizable traits (e.g., heterogeneous vegetation and water-energy storages and fluxes) in mountain catchments, generalizable processes such as water and material transport from the ridge to the valley may lead to similar, common characteristics within different components of mountain systems. An example is wetter valleys with thicker soils, which are again reflected in the vegetation present.

Disturbances (e.g., wildfire, drought, insects, and changes in snow regime) present additional challenges to predicting IMHC fluxes and storage regimes of water and elements due to the incomplete understanding and representation of how terrestrial ecosystems evolve and feed back on other processes after disturbances. For wildfire, hydrological partitioning between runoff and infiltration will be coupled strongly to the post-fire evolution of soil, deep roots, and vegetation (Balocchi et al. 2020; Keeley and Fotheringham 1998; Lloret and Zedler 2009; Zedler et al. 1983), including the development of wildfire ash and burned soils as new layers in the soil profile (Cardenas and Kanarek 2014; Ebel and Martin 2017; Moody et al. 2016). Changes in hydrological water partitioning will control an array of subsequent watershed processes, including erosion and geomorphology, subsurface water flow paths and residence times, biogeochemical reactions, and reactive and nonreactive elemental fluxes to the river.

2.2.1 Terrestrial Knowledge Gaps and Challenges

The large topographic relief and high elevation of mountain catchments amplify many challenges that are generally identified in terrestrial science. Therefore, the key research gaps identified below are not necessarily exclusive to mountain hydrology but are instead more pronounced for mountain systems due to environmental conditions, complex bedrock terrain, and pronounced topographical gradients. The following challenges are highlighted: surface energy balance; surface and subsurface hydrology; soil-plant-root interactions; ecohydrological interfaces and biogeochemical cycling; data integration with models limited by spatial and temporal resolution; and terrestrial-climate feedbacks.

Surface Energy Balance

The complexity of mountain regions makes observing and modeling surface energy balance enormously challenging. For example, the intense spatial variability in aspect, slope, and canopy characteristics can lead to highly variable incoming solar radiation in mountain areas. This variability, in turn, has consequential impacts on the rest of the surface energy balance, including latent and sensible heat fluxes. Quantifying surface energy input is further exacerbated by the high temporal variability of snow albedo, which can be impacted not only by snow metamorphism and snowmelt but also by the deposition of atmospheric tracers, such as dust and black carbon (e.g., Skiles and Painter 2017) and ash from wildfires that exacerbates snowmelt (Pu et al. 2021). Hence, key challenges remain in robustly characterizing and quantifying the different components of surface energy balance at multiple spatial and temporal scales over large mountain regions. As a result, significant research challenges persist in measuring, modeling, and benchmarking evapotranspiration, which is a function of the complex surface energy balance in mountains. For example, evapotranspiration fluxes highly depend on water availability in the terrestrial part of the water cycle, but they also are strongly influenced by atmospheric interactions of air temperature, wind speed, and relative humidity.

Other challenges for obtaining surface energy balances over mountain regions are (1) identifying the degree of heterogeneity of surface states (e.g., snow cover density and snow water equivalent) and (2) understanding the key role of spatial connectivity among landscapes. To be more specific, processes such as snow drifting, secondary circulations, overland flow, and subsurface flows lead to highly interconnected hydrological systems that, in turn, have a large impact on surface energy partitioning. As a result, observing the states and fluxes over these regions is especially challenging. For example, the use of eddy covariance towers to estimate surface fluxes in the presence of secondary circulations (e.g., upslope or downslope flows) can be critically misleading.

For mountain regions, identifying spatial and temporal snow cover distribution and persistence poses a specific challenge because snowmelt properties are difficult to track in real time at the level of spatial resolution needed to honor the inherent heterogeneity. *In situ* observations with innovative instrumentations range from cameras (e.g., Pohl et al. 2014) to temperature profiling systems (Dafflon et al. 2022), remote-sensing approaches like the Airborne Laser Scanning applied on individual trees (Russell et al. 2021), and entire catchments through the Airborne Snow Observatory (Painter et al. 2016). Despite these innovative approaches, problems with snow cover observations are further exacerbated when attempting ModEx approaches with local and Earth system modeling because of the need to more explicitly resolve these fine spatial scales and interconnectivities to enable appropriate process representation. Scientists generally agree that modeling surface fluxes over mountain regions is deficient due to over-reliance on theories and parameterizations solely based on flat terrain.

Surface and Subsurface Hydrology

Subsurface water storage and its connectivity to streams play crucial roles in the partitioning of precipitation into groundwater recharge, stream discharge, and evapotranspiration. While subsurface processes are generally difficult to observe, data collection and model development for mountain environments pose additional challenges related to study site access, relatively shallow soil depths, and high rock content with unknown fracture density distributions. These challenges result in a pronounced lack of process understanding of mountain subsurface hydrology. Moreover, most mountain systems display significant first principle unknowns in terms of the amount of water stored in mountain catchments (e.g., groundwater depth variation in space), the variability of this storage in space and time, and the drivers of storage changes (e.g., snow drought versus increases in evapotranspiration).

Wildfires also represent a critical perturbation to mountain regions through their impacts on surface and subsurface hydrological partitioning (Williams et al. 2022; Maina and Siirila-Woodburn 2019; Havel et al. 2018). Although wildfires are fundamental to the disturbance regime in many terrestrial ecosystems (McLauchlan et al. 2020), the record-breaking severity, duration, and frequency of recent “megafires” represent a regime shift that may lead to different hydro-biogeochemical responses across the surface-subsurface continuum (Stavros et al. 2014). Hydrological partitioning can include many nonlinear responses such as (1) increased runoff and decreased canopy interception, (2) increased base flow through decreased evapotranspiration, and (3) in some cases decreased runoff and increased infiltration through new macropore formation. These alterations can lead to cascading effects down mountain valleys. Ultimately, these unknowns lead to an inability to close even basic water budgets at subwatershed-to-basin scales under current and future hydroclimatic conditions and in response to disturbances.

Spatially complex snow patterns, large topographic gradients, fractured bedrock geology, and vegetation distribution give rise to highly heterogeneous and dynamic infiltration patterns and subsurface flow paths in mountain systems. As a feedback mechanism, subsurface hydrological flow paths can also impact spatial patterns in snow redistribution, sublimation, snowmelt rate and timing, and responses to variable hydroclimatology through controls on vegetation distribution that affect shading (Maina et al. 2020a; see also Chapter 3: Cross-Disciplinary Science, p. 29). These uncertainties in the understanding of stream water generation and groundwater recharge hinder a mechanistic implementation of subsurface hydrology in regional- to large-scale land-atmosphere models.

An important research challenge is the representation of lateral hydrological processes (i.e., connectivity) in Earth system models (ESMs). For example, research has shown that lateral groundwater flow impacts evapotranspiration rates on continental scales (Maxwell and Condon 2016). Due to large topographic and hydraulic gradients, this effect will be very pronounced in mountain regions. However, challenges exist with the characterization of subsurface geological structure and the parameterization necessary to describe subsurface flow volume and its variability in time.

Another challenge is the scale-appropriate parameter representation of bedrock fracture flow paths and densities in both local reactive transport models and global ESMs. Currently, subsurface models represent bedrock fractures with effective van Genuchten parameters [i.e., required parameters for running subsurface hydrological models, including parameters for developing soil water retention curves, and hydraulic conductivity curves (van Genuchten 1980)] that do not reflect or accurately represent the physical fracture subsurface flow process. Recent DOE-funded work in Colorado's East River Community Watershed using large airborne electromagnetic measurements allowed derivation of shallow bedrock electrical resistivities across large areas of the watershed (Uhlemann et al. 2022). Such novel information can be included in subsurface characterization of spatially distributed hydrological and biogeochemical models at an unprecedented level of detail required for process-based predictions.

For ESMs, approaches like the representative hillslope concept allow some degree of accounting for subgrid heterogeneity (Swenson et al. 2019); but relating observations on the plot or hillslope scale to simulations on catchment to basin scales remains a grand challenge (Fan et al. 2019). Unresolved scalability challenges include (1) appropriate parameter representation (e.g., hydrological, biogeochemical, ecological) on model grids of various coarseness and (2) upscaling and downscaling approaches to refine and gapfill input grid-based datasets and parameters (e.g., snow water equivalent, precipitation, and van Genuchten parameters). While novel high-resolution datasets provide the necessary inputs for next-generation, process-level hydrological prediction and understanding, obtaining these datasets everywhere is not feasible. Thus, based on the desired outcome, a balance must be struck between "black box" predictions, which rely on models that are not straightforwardly interpretable, and true process-level understanding.

Soil-Plant-Root Interactions

Due to the spatial complexity in available energy and water distribution in mountain regions, the diversity of mountain plant communities, root distributions, and soil structures poses a challenge to understanding ecohydrological and biogeochemical processes. Dynamic feedbacks between soil and plants within the Critical Zone—spanning from bedrock groundwater to the plant canopy (Grant and Dietrich 2017)—are difficult to observe and predict. This challenge occurs because most feedbacks take place at short temporal scales (Dubbert and Werner 2019) and small spatial scales in the subsurface root zone (York et al. 2016) that are not observable without complex *in situ* equipment. Moreover, roots' access to moisture at soil and bedrock depths is chronically understudied (Dawson et al. 2020). Soil-plant-root interactions are a highly interdisciplinary challenge because of the interplay of water and nutrient cycles that occurs at these interfaces. However, a proper understanding of soil-plant-root feedback loops is crucial to enable model predictions of fluxes along the continuum from soils, plants, and roots through the atmosphere, since these interactions are so sensitive to climate change (see Section 3.1, p. 30, in Chapter 3: Cross-Disciplinary Science and Section 4.1, p. 41, in Chapter 4: Crosscutting Science).

Projections of ecohydrological interactions into a nonsteady future with hydro-meteorological drivers ranging from earlier snowmelt to longer drought periods or wildfires will require accurately representing how plants will respond to such extreme events. Wildfires can induce changes to nutrient and soil biogeochemical cycles, soil and rhizosphere microbiomes, vegetation structures, and feedback mechanisms across these compartments (Bouskill et al. 2022; Dove et al. 2021; Graham et al. 2016; Lloret and Zedler 2009). Therefore, important challenges to address include field observations and model implementation of (1) plant root depth, distribution, and potential for water uptake; (2) biogeochemical

Hot Spots

Patches that show disproportionately high reaction rates (or other relevant mechanisms and parameters) relative to the surrounding matrix.

Hot Moments

Short periods of time that exhibit disproportionately high reaction rates (or other relevant mechanisms and parameters) relative to longer intervening time periods.

cycling; (3) hydraulic redistribution; and (4) root feedbacks on bedrock fracture distribution and element liberation.

Ecohydrological Interfaces and Biogeochemical Cycling

Ecohydrological interfaces, including river and riparian corridors, are unique components in mountain areas because their relevance and control on river chemistry highly depends on the scales at which their features function (Gomez-Velez and Harvey 2014). The confluence of river channels, hillslopes, and floodplains is a distinct feature in mountain ecosystems, especially in headwaters where presses and pulses of water delivery from snowmelt, rainfall, and dry periods facilitate emergence of hot spots and hot moments of activity that have outsized influence at the small scales found in headwater systems (McClain et al. 2003; see box, this page). Confluences in these areas show signatures in their water, energy, microbiology, and biogeochemical cycles that can be noticeably different from surrounding watersheds and potentially reflect unique landscape characteristics and mechanisms (Newcomer et al. 2021a; Matheus Carnevali et al. 2021). While these river and riparian regions occupy only a relatively small fraction of headwater area, they can play a key role in ecosystem functioning in headwaters as revealed by their aggregated downstream signatures (Arora et al. 2020). Features of riparian corridors include meadows, hyporheic zones, and floodplains that are fundamentally smaller regions of the larger mountain area. These features can also impose a very large signature on stream chemistry and larger-scale biogeochemical cycles (Newcomer et al. 2018; Rogers et al. 2021).

Despite the importance of these interfaces in mountainous regions, many knowledge gaps and model-data integration approaches currently fail to represent the role of small-scale features, which leads to fundamental inaccuracies and misguidance in process attribution. While river corridor features and emergences of hot spots and hot moments are well represented in local, scale-appropriate models, their aggregated role (and the potential to predict this aggregated role) is fundamentally ignored in ESMs. This inattention is partly because observations of riparian corridors have mostly been dominated by local and catchment-level studies without a comprehensive evaluation of riparian corridors and their role on ecosystem functioning. The move of ESMs to include hillslopes processes (Fan et al. 2019) provides a promising path forward. However, this work is only now being coupled with modeled stream networks (Chaney et al. 2021).

A need persists outside of computationally intensive, physics-based models to bridge the scale gap between lab-to-field work and field-to-modeling work in hot spot and hot moment research and to re-imagine how modeling parameterization is conducted at each appropriate scale. For example, since hot spots and hot moments play such an outsized role in biogeochemical cycling, how do scientists adequately parameterize their mechanisms and level of influence without having to resort to millimeter-size mesh grids at all locations where they occur? More generally, hillslopes, floodplains, and stream systems need to be thought of as interconnected functional systems instead of independent units, highlighting the need to develop research that considers novel functional zonation and characterization approaches (e.g., Wainwright et al. 2022; Chaney et al. 2018; Enguehard et al. 2022).

Data Integration with Models Limited by Spatial and Temporal Resolution

While field observations have never been as extensive as those currently being performed, coupling gathered data with simulations remains challenging (Hubbard et al. 2020). The discrepancy between the temporal and spatial scales of observations and simulations limits the integration of field data into models (Clark et al. 2015). Subsurface data especially is commonly restricted to point-scale information, but the hydrological and biogeochemical response of catchments or basins is usually the scale of interest. Remote sensing of the land surface has been considered as a way to help scale up local observations; however, the extent to which remotely sensed surface and shallow soil (e.g., the Soil Moisture and Ocean Salinity and Soil Moisture Active Passive missions) data allow for inferring subsurface structures has yet to be explored.

Although there is consensus that tracer data and widely available hydrometric data (e.g., discharge and soil moisture) will provide valuable insights into the flow and transport of water and its constituents (Sprenger et al. 2022), remote sensing cannot provide such information on transport processes. Therefore, intensive labor and extensive instrumentation are needed to gather hydrological and biogeochemical tracer data, such as stable isotopes (e.g., of water isotopes for ^{2}H and ^{18}O or nitrate isotopes for ^{18}O and ^{15}N), ions, and dissolved organic carbon. Such information is orthogonal to the more common hydrometric data and adds opportunities to investigate velocities (e.g., how fast water and its constituents flow) in addition to celerities (e.g., response in hydrograph or soil water content; McDonnell and Beven 2014).

The DOE-funded Watershed Function Science Focus Area (SFA) has gathered extensive tracer and solutes datasets from Colorado's East River that have revealed new insights on groundwater recharge processes (Carroll et al. 2018), nitrogen export (Newcomer et al. 2021a), and river gains and losses along stream reaches (Arora et al. 2020). Implementation of the tracer transport and the associated isotopic and/or biogeochemical processes into models will provide opportunities for multi-objective calibration approaches or benchmark simulation tests. A recent example is the use of over 1,600 nitrogen concentration measurements from streams, groundwater, and vadose zone samples from the East River to calibrate a newly developed High-Altitude Nitrogen Suite of Models (HAN-SoMo; Maavara et al. 2021).

Terrestrial-Climate Feedbacks

The strong interconnectivity between climate and mountain terrain is readily apparent in the high spatial complexity of water, energy, and biogeochemical cycles that emerge due to elevation, aspect, parent material (and soil), and microclimate differences. Questions remain regarding how the role of these spatial pattern drivers will evolve under a changing climate. Wildfire critically impacts hydrological processes because of resulting vegetation loss, reduced evapotranspiration, increased hydrophobicity, and altered hydrological connectivity. A key challenge for models at various scales is simulating process-level interactions between atmosphere, vegetation, and the subsurface and how they feed back and respond to regional hydroclimatic conditions and wildfire events. Also unclear is how resilient the strong biodiversity across mountain regions is to sudden long-term shifts in local microclimates.

In principle, ESMs offer the tools to answer these questions. However, the poor representation of spatial complexity over mountain regions in ESMs strongly limits their ability to inform terrestrial-climate feedbacks (Fan et al. 2019). This challenge arises not only from inadequate representation of the land surface and its interconnections but also from fairly *ad hoc* approaches to downscale coarse-grid meteorological variables to finer resolutions (e.g., radiation differences due to aspect) and upscale fine-scale parameters to more coarse resolutions. Ongoing DOE-, NASA-, and NOAA-funded terrestrial climate process teams (3D Land Energy and Moisture Exchanges and CLASP) are seeking to address these weaknesses (Hao et al. 2021; Huang et al. 2022). Overall, combining recent process-oriented observations and long-term climatological studies is still a major challenge in understanding hydrological dynamics and process variability. As a result, both quantifying and parameterizing these processes are especially difficult. Consequently, increasing the availability and quality of remote-sensing data could potentially close the gaps by integrating ground-based and remote-sensing observations over existing and new mountain experimental watersheds. Links between water and carbon cycles (e.g., greenhouse gas emissions) within the interplay of forests, soils, and water across mountain regions are especially not well understood.

2.2.2 Terrestrial Research Opportunities

Overcoming terrestrial science gaps and challenges can be achieved through the following three research opportunities: characterizing the terrestrial water balance in mountain catchments with multidisciplinary research; improving predictability of the terrestrial water balance in a changing mountain climate through model-data integration; and integrating hydrological and biogeochemical process understanding of mountain environments.

Characterizing the Terrestrial Water Balance in Mountain Catchments with Multidisciplinary Research

Promising new multidisciplinary research opportunities are emerging with the potential to provide insights into subsurface hydrological processes. Using concurrent methods from geophysics, hydrometrics, and tracer hydrology to generate independent data streams of the terrestrial water cycle of mountain systems will result in new insights that would otherwise not be possible in a single-discipline approach. For example, geophysical measurements combined with tracer data allow for a novel scaling-up approach. This combined approach goes beyond the point-scale measurements of water storage and volume changes (e.g., Nielson et al. 2021; Angermann et al. 2017) to provide an innovative method for studying water transport and turnover rates in unsaturated (Sprenger et al. 2016) and saturated zones (Jasechko 2019). As combined methodological techniques from different Earth science disciplines become more available, their application should be extended and intensified in the near term. In the longer term, these datasets will provide a great opportunity to constrain or parameterize hydrological and biogeochemical models in multi-objective calibration approaches from plot (Sprenger et al. 2015) to basin scales (Stadnyk and Holmes 2020).

In response to an altered climate and disturbances, mountain vegetative patterns may shift and exhibit a feedback effect on the atmosphere as vegetation changes through cascading hydro-biogeochemical cycles (see Fig. 2.3, p. 21). These shifts provide new opportunities to investigate ecohydrological linkages to determine how plants impact water and nutrient dynamics and vice versa. In summary, an ongoing challenge is to understand the changes in water partitioning into evapotranspiration, groundwater recharge, and catchment runoff depending on catchment characteristics and interannual variation of the in- and outflows.

Improving Predictability of the Terrestrial Water Balance in a Changing Mountain Climate through Model-Data Integration

Efforts are underway to represent hillslope-scale subsurface hydrological processes in ESMs and to include catchment- to hillslope-scale observations for model testing and benchmarking (Fan et al. 2019). Such developments in the near term can provide, for example, further opportunities to test the impact of lateral subsurface flow on the water cycle at large scales (Maxwell and Condon 2016). However, because consideration of subsurface hydrological processes in physically based mechanistic models is computationally expensive, ML approaches such as emulators provide an opportunity in the longer term to introduce complex subsurface flow pattern simulations at large scales (Tran et al. 2021). In this context, integrating surface-subsurface exchange in hydrological models is an opportunity to include the impact of gaining and losing stream reaches along the large relief in mountain basins on the total water cycle (Dwivedi et al. 2018).

Novel experimental work that allows for controlled boundary conditions—such as the DOE-funded Sensors at Mesoscale with Autonomous Remote Telemetry (SMART) soil testbed at Lawrence Berkeley National Laboratory (LBNL) or the NSF-funded Landscape Evolution Observatory (LEO) at Biosphere 2—provide research opportunities to investigate complex soil-plant interactions on small scales that need to be tested and transferred into field applications. Such controllable conditions make it possible to test innovative technology, such as the Tomographic Electrical Rhizosphere Imager (TERI) developed in the DOE-funded Ecosense effort or isotope tracer applications (Werner et al. 2021).

In the long term, improved connection between subsurface observations and remote sensing (e.g., NASA's Gravity Recovery and Climate Experiment and Sentinel-6 Michael Freilich mission) will help bridge the scales and include catchment-scale process understanding and observational data in large-scale modeling. To observe environmental change (e.g., vegetation shifts due to climate change, wildfires, or land-use

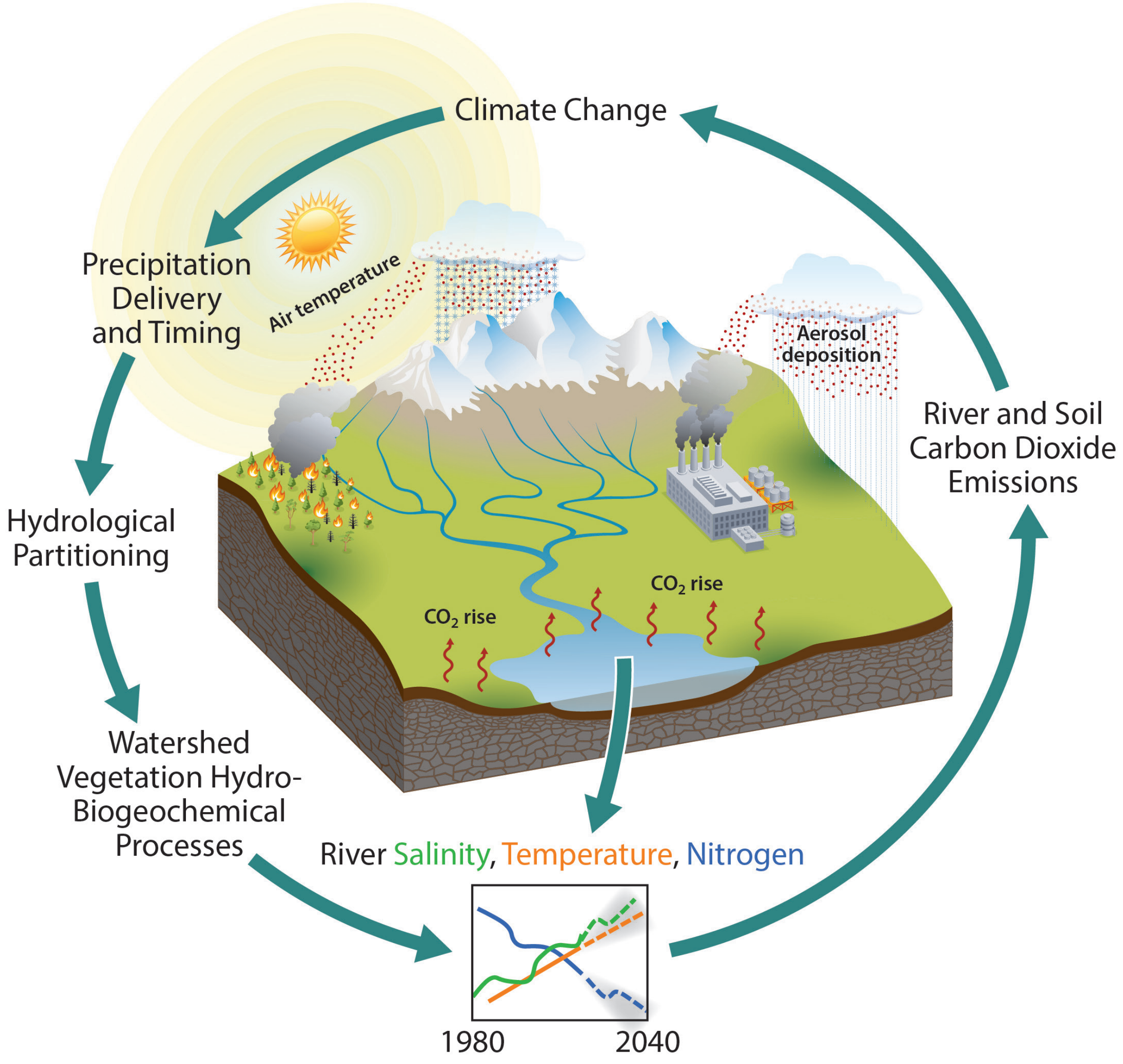


Fig. 2.3. Examples of Feedback Processes Across the Atmosphere-To-Bedrock Interface in Mountain Regions. Mountain hydroclimates deliver precipitation and aerosols at intervals that are influenced by climate change, including air temperature fluctuations and carbon dioxide (CO_2) rise. Variations in precipitation timing, magnitude, and frequency will alter subsequent hydrological partitioning and watershed vegetation–hydro-biogeochemical processes. River corridor networks will exhibit these changes through unique stream signals of salinity, temperature, nitrogen, and other elemental trends, which reflect the aggregated nature of landscape changes. Because streams are amalgamations of these interacting and bidirectional processes, rivers will be critical indicators of landscape change. Additionally, in response to biogeochemical change, river corridors and landscape soils will release CO_2 emissions back into the atmosphere, which is a direct feedback effect to climate change.

changes), initiation of long-time-series observations need to be funded in the near term with a long-term perspective. Resulting large datasets will enable application of ML and artificial intelligence (AI) to improve the predictive power of environmental models. The overarching research question for the terrestrial water cycle in mountain catchments is how the water balance will change in a warming climate. More specifically, scientists need to understand the uncertainties related to precipitation (e.g., relative share of snow versus rain and drought frequency) and evapotranspiration (e.g., vegetation changes and plant physiological response to climate change).

Integrating Hydrological and Biogeochemical Process Understanding of Mountain Environments

DOE supports research within the Watershed Function SFA and the Floodplain Hydro-Biogeochemistry SFA to improve understanding of spatiotemporal coupling of biogeochemical and hydrological processes in soil, capillary fringe, and the upper portion of the saturated zone. Building off these large-scale, field-based community watershed facilities, a long-term research opportunity is to study intensified connections between hydrological and biogeochemical processes. Doing so will provide opportunities to relate water cycle changes with consequences for nutrient and contaminant transport. Additionally, model development that accounts for appropriate representations of water flows and input, transformation, and solute export will enable assessments of how changes in precipitation pattern and evapotranspiration dynamics in a warming climate affect water quality downstream of mountain headwater catchments. In summary, an important research question would be to understand how water balance impacts the storage and release of carbon, nitrogen, and other constituents transported with water.

2.3 Human Systems Interactions

Predictability of the integrated human-Earth system requires detailed process understanding of the interactions among human and environmental systems across a wide range of scales. Indeed, human and Earth systems span a similar range of spatial and temporal scales, yet human systems science is still in its infancy in integrating with predictive ESMs (Reed et al. 2022). At the global scale, human activities aggregate to fundamentally influence Earth system processes through greenhouse gas emissions, aerosol emissions, and land-use and land-cover change (Riahi et al. 2017). At regional scales, human systems rely on and are vulnerable to changes within environmental systems that support critical infrastructure and the provision of resources such as energy, water, and food (Hoekstra and Mekonnen 2012).

Mountain systems provide an important context for examining human-Earth system interactions because of (1) the critical services that mountains provide to human societies and (2) the cross-scale interactions that take place between local and distal human and environmental processes in a mountain context. For instance, mountains are often conceptualized as the water towers of the planet, providing storage of cool-season precipitation in the form of snow and slow release of water supply during the warmer spring and summer months. Mountain processes thus drive downstream human systems through water availability (e.g., magnitude and timing) and water quality that are critical for infrastructure resilience, urban systems, and agriculture (Siirila-Woodburn et al. 2021). Mountains also provide important resources and services through biodiversity, minerals, forest products, tourism, and complex wind patterns that can be harnessed for wind energy.

Despite their significance to human societies, mountain regions remain sparsely inhabited compared to coastal zones and river confluences. Nonetheless, humans substantially impact mountain climate, hydrology, and biogeochemical cycles. These impacts include the direct effects of human activities within mountains, such as (1) operation of water infrastructure that alters streamflow, (2) forest management practices that remove carbon and influence wildfire and hydrological regimes, and (3) mining practices that affect water quality and biogeochemical processes (see Fig. 2.4, p. 23). Mountains are also influenced indirectly by distal human activities, including greenhouse gases

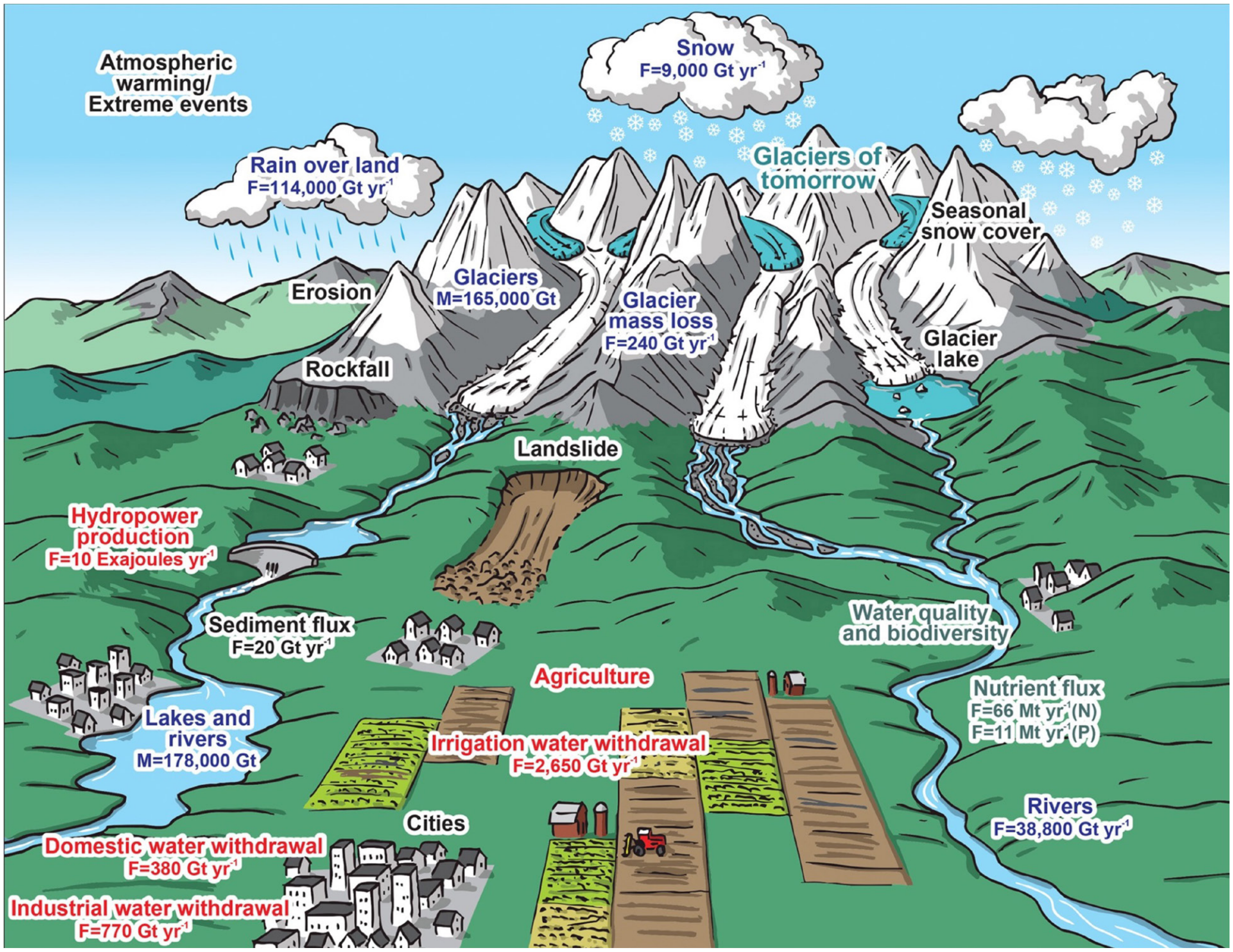


Fig. 2.4. Human-Mountain System Interactions. Human settlement is largely concentrated outside mountain regions, yet societies rely on mountains for numerous critical resources and services. In turn, mountain climate, hydrology, and biogeochemical processes are influenced by human activities, both directly through resource management activities and indirectly through global and regional environmental change. [Reprinted under a Creative Commons license (CC-BY-NC-ND) from Huss, M., et al. 2017. “Toward Mountains Without Permanent Snow and Ice,” *Earth’s Future* **5**(5), 418-435.]

that drive global climate change and aerosol emissions that deposit in mountains and influence snow hydrology. These bi-directional and cross-scale interactions among human and mountain systems create complex feedbacks with consequential implications for society.

2.3.1 Human Systems in the Context of Mountain Hydroclimate Dynamics

Understanding human systems as part of mountain hydroclimate requires investigating multiple spatial and temporal scales. Because current models are unable to fully capture the diversity of human systems, it is most often modeled in isolation. As a result, interactions between human systems and mountain hydroclimate are insufficiently understood. While case studies from this workshop allow navigation of some data challenges, overall uncertainties remain and the transferability of local interactions to larger scales must be addressed. This section discusses how three types of human systems—local, downstream, and distal—influence mountain system processes and outlines several recent advancements in human systems representation in ESMs.

Local Mountain Human Systems

At the local level, forest harvest is known to affect mean annual flow and peak flows (Storck et al. 1998). The compound impact of forest roads and tree removal has been shown to affect mean annual flow, while the impact on peak flow is influenced by the type of harvest (La Marche and Lettenmaier 2001; Beschta et al. 2000; Wemple and Jones 2003). Forest harvest also affects sediment yields (Safeeq et al. 2020), which, in turn, influence a river's water quality to support biodiversity as well as man-made reservoir management. The implications propagate to water-dependent human systems, including the energy sector (Hauer et al. 2018). From a human-systems perspective, local land-management models are available, but they lack connection with wood-sector models, which were developed to evaluate climate change and greenhouse gas emissions (Werner et al. 2010) instead of local interactions and adaptation strategies.

Human-made headwater reservoirs are another type of local human system. These reservoirs in mountain areas affect local land cover, with associated changes in albedo, wind, water table, and terrestrial-atmosphere interactions (Hossain et al. 2012). Through river and human systems connections, headwater reservoirs in mountain areas provide several "river services." These services include flood control, water supply, navigation, recreation, hydropower, environmental conservation, and water quality for downstream uses. Because of the large topographical gradient, reservoirs in mountain areas provide the largest hydropower generation capacity by volume of water. Pumped storage hydropower systems rely on smaller lakes in contrast to conventional hydropower and are particularly efficient in mountain areas due to the high topographical gradient and low losses through evaporation. This water-energy technology could play an important role in U.S. decarbonization strategies, given the value of energy storage for smoothing intermittent generation from renewables (Dimanchev et al. 2021). While hydropower provides valuable services to the power grid, it is connected through costly transmission lines in mountain regions due to complex terrain and landslide risks.

Downstream and Distal-Connected Human Systems

Many downstream human systems, such as water and energy infrastructure and the sectors that rely on those resources, depend on mountain systems. For instance, downstream human systems are not only connected to mountain systems through rivers that supply water but are also often supported by local mountain human systems such as reservoirs, which provide storage, regulate water flow, and generate hydroelectricity. Downstream human systems connected through the river system include the energy, agricultural, transportation, and industrial sectors. Some services are general across sectors (e.g., water supply security, flood control, and electricity), while other services (e.g., navigation, recreation, and environmental conservation) are more sector specific. Most of these services and connections are described in Section 2.3: Human Systems Interactions (see p. 22), although a more general definition of human systems interactions has also been described in other scientific literature (Yoon et al. 2022).

Physically distal human systems also influence mountain systems in various ways through infrastructural connections, environmental connections, and governance of human systems embedded directly within mountains. For example, governance and policy in the wood sector of the U.S. economy regulates wood harvest in mountain areas; the power grid drives short-term water releases from headwater reservoirs in coordination with the infrastructure protection and environmental conservation sectors; and the demands from the agricultural, industry, and urban water sectors drive weekly, seasonal, and even annual water storage and releases. Further interactions of governance and policy factors influence headwater reservoir operations across different services. For example, these factors can be combined to guide forest adaptation scenarios that manage wildfires, water resources, biomass, and economic recovery, all of which impact local- and distal-connected human systems (Povak et al. 2022). Notably, human systems in non-mountain areas also influence mountain hydroclimate and dynamics through policy and governance as well as dust and aerosol emissions transported to mountains (see Section 2.2: Terrestrial Processes, p. 14).

Recent Advancements in Human Systems Representation in ESMs

Coupling human systems models in ESMs allows inclusion of the intricate dynamics and feedbacks between Earth systems and human systems, which are essential for ESMs to address climate change vulnerability (Leung et al. 2020). During the past few years, Earth-human system modeling efforts have led to improved capabilities in representing human systems and complex interactions, with a focus on new couplings and endogenous processes.

E3SM (Leung et al. 2020; Golaz et al. 2022) has integrated dynamic land-use and land-cover change (Di Vittorio et al. 2020) consistent with integrated climate and human system scenarios (O'Neill et al. 2016) and as provided by the Global Change Analysis Model (GCAM; Calvin and Bond-Lamberty 2018). E3SM also implemented the Model for Scale Adaptive River Transport-Water Management (MOSART-WM), a spatially distributed water management model that represents reservoir operations, water allocation, and spatial distribution (Voisin et al. 2013a, 2017) based on the original MOSART framework's advances in representing river routing (Li et al. 2013, 2015). Finally, E3SM also includes two-way coupling of irrigation and river-routing water management (Zhou et al. 2020) to further propagate the impact of dynamic land-use and land-cover change onto the hydrological cycle. Together, these human systems enable a better representation of stream temperature, surface water–groundwater interactions, and overall distribution of water and energy fluxes. Building on the subgrid topographic representations in E3SMv2, coupling GCAM with E3SM may be improved to better represent human-Earth interactions in mountain regions.

2.3.2 Human Systems Knowledge Gaps and Challenges

Fundamental gaps existing in model representations of human-mountain system interactions ultimately give rise to three grand challenges for understanding and modeling integrated human-Earth systems: transferability and scalability, extreme events, and uncertainties.

Insufficiencies in Model Representations of Human-Mountain System Interactions

A gap exists in the representation of land-use and land-cover change in mountain areas associated with different scientific foci (e.g., logging, prescribed burns, urbanization, agriculture, and wildfires) and process representation across a range of models. Most often, land-use and land-cover change in governance-scale human system models is associated with greenhouse gas emissions (Calvin et al. 2019) and is disconnected from process-scale human system models, such as those for forest management (Povak et al. 2022). E3SM, which operates at an intermediate scale, currently lacks information from both the governance scale and process resolution to represent mountain land-use and land-cover change and interactions with hydroclimate processes. Lack of data that are scalable and transferable further exacerbates this gap. For example, most forest practice models and studies are local and in response to local human systems and science questions and thus are not transferable to other locations.

Overall, representation of water management is reasonable but particularly challenging in mountain areas because of complex mountain topography. For instance, small biases in inflow, such as after wildfires, prescribed burns, land-use and land-cover change, or out-of-sample precipitation conditions, will drive unrealistic and potentially catastrophic model representations of uncertainty to guide decision-making on reservoir operations (e.g., Oroville dam; Hollins et al. 2018; Michaelis et al. 2022). While generic operating rules can adapt to both inflow and changing reservoir characteristics to achieve overall reservoir operating objectives (Voisin et al. 2013b), the accuracy and structure of ESM simulations currently challenge the use of data-driven reservoir operations (Turner et al. 2020; Turner and Voisin 2022). In addition, human systems that are fully integrated into ESMs tend to be passive, with generic and static operating rules. However, the nature of human systems is typically forward-looking and highly responsive, as represented by optimization schemes in river-routing reservoir models, where science questions are human-systems oriented (Turner and Voisin 2022).

As spatial resolution increases to represent mountain and adjacent nonmountain regions, the largest gaps include human system diversity at appropriate scales and resolutions that can guide decision-making. For instance, only human systems connected to mountain regions by river systems are represented in ESMs (i.e., river services, see Section 2.3: Human Systems Interactions, p. 22; Voisin et al. 2017). Gaps in modeling dataset confidence persist between connected human systems and river systems connecting human systems and also in observations of the mountain and downstream-connected Earth systems. Finally, human systems are highly diverse, and the modeling fidelity of this diversity is already nonrepresentative in human systems, and even less so when integrated with ESMs.

Resulting Grand Challenges for Understanding and Modeling Integrated Human-Earth Systems

Transferability and Scalability

Local case studies, observations, and models are not necessarily representative of all mountain-human systems and associated interactions, given the diversity in regional human-mountain climate drivers and cross-scale contributions (see box, p. 11, "Transferability"). No systems currently represent the range of scales in interactions between human systems and Earth system mechanisms. Moreover, observations and mechanistic parameters are not representative of systems at different scales (see box, p. 11, "Scalability"). Fundamental research questions include determining the phenomena and scales that matter for human systems and how mountain systems are changing at those scales and for those phenomena.

Extreme Events and Human Systems

High-resolution interactions between human and Earth systems in mountain regions limit scientists' ability to understand the decomposition of extreme event drivers and how human systems specifically alleviate or worsen impacts. Current ESM representation of mountain-human systems supports the analysis of average processes and interactions, with perhaps better representations of droughts compared to floods. One fundamental research question involves understanding how human activities alter environmental processes and the probability of extremes, at the local level and through teleconnections. Another involves determining suitable mitigation strategies for decreasing the impact on human systems and controlling the frequency, intensity, and extent of mountain hydroclimate extreme events.

Uncertainty and Decision-Making

Predictability enables decision-makers to undertake complex choices about the future. Human systems rely on forward-looking knowledge (e.g., water management and agriculture), and large uncertainties surround the ways in which foresight informs human systems across scales and sectors. Many fundamental research questions exist that currently preclude an accurate assessment of tradeoffs and scenarios. These questions involve (1) determining the trade-offs among different scenarios and infrastructure choices, particularly in the context of limited water resources and cross-sectoral interactions; (2) identifying fundamental science needed to credibly evaluate those trade-offs; and (3) assessing the scales and spatiotemporal distributions of uncertainty and determining how they propagate through different models.

2.3.3 Human Systems Research Opportunities

The overall infancy of human systems science and its integration into ESMs coupled with the grand challenges described herein present numerous research opportunities. Long-term observational platforms and models that include multisector dynamics are needed to adequately capture the diversity of human systems. Also important is developing a bridge between fundamental science and decision-making agencies responsible for management actions and to provide forecasts and information useful for operational decision-making. This section outlines the following opportunities in human systems research to address major challenges:

- Operationalizing transferability and scalability methods.
- Using novel observations, theory, and increased interactivity among human and ESMs to understand fundamental interactions between human systems, environmental systems, and extreme events.
- Using basic science capabilities to understand and relay uncertainty and risk to end users, inform decision-making under such uncertainty, and evaluate trade-offs among alternative options.

Transferability and Scalability

Near-term priorities would include addressing transferability and scalability gaps. For example, investigating the range of interactions among human systems and between human and Earth systems across scales could involve storylines and hypothesis-based and exploratory ML approaches. DOE already supports existing initiatives with diverse experimental setups. Examples include physical climate storylines (see box, p. 11; Shepherd et al. 2018), such as California's "Miracle March" in 1991 when the state experienced its worst drought since the Dust Bowl before a record-breaking March snowfall, which tripled mountain snowpack. Similar storylines include (1) the Colorado River Basin's "Miracle May" in 2015 that brought an end to an unprecedented drought (Pokharel et al. 2022), (2) North America's "Monsoon Rescue" that happens when warm season monsoon moisture can rescue plants from droughts during winter months (Peltier and Ogle 2019), and (3) Crested Butte's "Santa Slammer" when almost 100 inches of precipitation fell in Colorado over the course of two weeks in December 2022 (Reaman 2022; ARM 2022). Regional climate modeling focused on storyline development is the first step in making outcomes for decision-making transferable.

Transferability could also be enhanced through a typology approach in which phenomena with similar characteristics are grouped to develop theoretical insights into the phenomena, explain their drivers and consequences, and transfer insights from one context to similar contexts (Biagini et al. 2014). A typology of human systems in mountain regions, and their interactions with other human systems—directly and through Earth system processes—might also be worth considering. Developing this typology may require generating a framework for understanding complex interactions among systems and scales—including uncertainty propagation, feedbacks, interactions, co-evolutionary processes, and other aspects—for existing DOE projects and activities as well as those supported by other government agencies. The exploratory framework would need to be versatile, given that human systems function differently than Earth systems.

Another way to address the scalability and transferability challenge would be to design a new knowledge and data co-production framework. Such a framework would enable practitioners and scientists to work collaboratively toward defining critical science questions and identifying the usability and salience of new knowledge for decision-making (Bremer and Meisch 2017). This framework would require observations and modeling of the phenomena and scales that matter for human systems. Additional opportunities to approach this challenge involve (1) leveraging observational datasets and stakeholder communities to develop model evaluation and improvement testbeds; (2) implementing regional climate modeling focused on storyline development relevant to local communities; and (3) conducting use-inspired, basic discovery science that is motivated by stakeholders (i.e., co-production) to link science to basic operational work.

Extreme Events and Human Systems

As transferability and scalability are better understood, new frameworks and theories for understanding human-Earth interactions and regional drivers of mountain-human systems would still be needed for the scientific community to further address extreme events. Promising research opportunities exist to develop field observations across human and Earth systems and across relevant system scales and sectors. For example, observational campaigns focusing on forest management activities (e.g., controlled burns and thinning) are opportunities to use controlled experiments to disentangle anthropogenic factors from atmospheric, ecosystem, and hydrological processes and to guide decision-making. This activity would require partnering with local agencies, holding workshops, and utilizing local resources and staff to aid in monitoring activities. Moreover, engaging scientists in workforce development and training would ensure successful knowledge transfer and communication in a co-production framework. Furthermore, leveraging the activities and capabilities of multiple agencies could prevent attempts to duplicate existing methods for experiments and model development that have already been proven effective.

Uncertainty and Decision-Making

In the long term, opportunities are available to advance an uncertainty propagation framework with a probabilistic predictive understanding that can inform a changing risk landscape and identify trade-offs among alternative pathways. New AI/ML approaches will likely be needed that not only extend complex datasets and help support coupling approaches while maintaining ESM scales but also recognize that the value of AI/ML applied to science is different than when applied to human systems. Examples include developing and applying AI/ML approaches to predict downstream water yield or quality under no-analog climate scenarios or to inform user-guided scenarios and storyline wish lists. Integration of human processes into ESMs is another example that would require both scientists and end users to better leverage observational networks and review process representation. These new modeling platforms would be key for examining which processes dominate critical outcomes of interest in different contexts. An important question to examine would be the warming level and context whereby climate change would overwhelm local effects of land-use change on hydrology.

Waldo Canyon Fire, Colo.
Courtesy Getty Images

Chapter 3

Cross–Disciplinary Science

3 Cross–Disciplinary Science

3.1 Atmosphere-Terrestrial Processes and Interactions

Processes occurring at the atmosphere-terrestrial interface are particularly complex in mountain environments due to the heterogeneous spatiotemporal patterns and feedbacks of ecosystems on environmental drivers such as warmer temperature. Fully understanding the integrated mountain hydrological cycle requires deeper insight into important feedback loops between terrestrial and atmospheric processes.

Climate change likely will increase the variability of mountain atmospheric conditions and intensify their trends. Such trends might include punctuated precipitation patterns, altered temperature increases with elevation, decreased snowfall fractions, diminished and earlier snowmelt, and increased evaporative demand. All these alterations will interact and modify how terrestrial processes respond through vegetation shifts, altered runoff efficiency, subsurface recharge, and evapotranspiration changes that, in turn, can result in nonlinear feedbacks to the atmosphere (e.g., wildfire). Better understanding how these processes interact and how they might respond to various climate change scenarios will be crucial in making more societally relevant predictions of the future.

3.1.1 Atmosphere-Terrestrial Knowledge Gaps and Challenges

Workshop participants identified five major atmosphere-terrestrial knowledge gaps: (1) vegetation dynamics and resolved evapotranspiration, (2) disturbances and the ability to measure and model systems, (3) wind redistribution, (4) elevation gradients in precipitation and temperature, and (5) snow-dominated hydrology.

Vegetation Dynamics and Resolved Evapotranspiration

Vegetation plays a key role in atmosphere-terrestrial interactions by actively transforming terrestrial water to atmospheric water through evapotranspiration. Vegetation further affects precipitation infiltration patterns into the terrestrial subsurface. Both processes are spatiotemporally heterogeneous in mountain regions, which makes their assessment challenging. For example, evapotranspiration fluxes highly depend on terrestrial water availability but also are strongly influenced by atmospheric interactions of air temperature, wind speed, and relative humidity. Small-scale heterogeneity in available water storage (see Section 2.2, p. 14) and hydro-meteorological drivers (see Section 2.1, p. 7) also makes measuring evapotranspiration (e.g., using flux towers) in mountain catchments challenging. For similar reasons, simulating actual evapotranspiration across mountain regions is difficult. Additionally, discrepancies between the scale of observations and the scale of simulations further challenges accurate representations of evapotranspiration fluxes in land-atmosphere modeling. However, an increase in evapotranspiration flux is identified as a major driver for observed mountain runoff reduction (Goulden and Bales 2014; Milly and Dunne 2020).

Disturbances and the Ability to Measure and Model Systems

Linkages between vegetation patterns and the spatial variability of snow accumulation and melt represent another important aspect of atmospheric-terrestrial interactions in mountain systems. Examples of these linkages include the impacts of canopy interception, long wave radiation from stems, and distribution of winds on snow (Varhola et al. 2010). Large gradients in vegetation cover (altitudinal zonation) and precipitation volumes as well as dynamic snow-to-rain transitions result in a complex interplay between land cover and precipitation inputs into mountain systems. The consequences of these interactions for an individual plant's resilience to environmental stressors (e.g., drought, beetle infestations, and windfall) remain a grand challenge in mountain ecohydrology. Of particular interest is the interplay of atmospheric dynamics, vegetation, and the potential for increased forest wildfires. These dependencies are neither well understood nor widely implemented in Earth system models (ESMs). However, wildfires have important impacts on hydrological processes, such as post-wildfire vegetation loss, increased hydrophobicity, and altered hydrological connectivity. In addition, wildfires may affect soil erosion and dust emissions by reducing vegetation cover and soil moisture, with impacts on radiation, clouds, precipitation, and terrestrial biogeochemistry (Yu and Ginoux 2022).

Wind Redistribution

Although not well understood, wind acts as a crucial forcing on mountain hydrological processes and is thought to significantly influence the spatiotemporal variability of available mountain water. Wind patterns help determine snowfall elevational gradients, snowpack redistribution, and the magnitude of snowpack sublimation. Research has estimated some general relationships between topography, wind, and snowdrift, but the impacts of these processes on catchment-scale runoff dynamics and the snow volumes lost to sublimation remain elusive.

Elevation Gradients in Precipitation and Temperature

Precipitation and temperature gradients in mountains are considerable but undersampled by observational networks. Stations are often limited to accessible areas, and thus sufficient observations are lacking for high elevations where precipitation, especially snowfall, is highest and lapse-rates are maximized. As a result, scientists have developed different interpolation procedures through the years to provide spatiotemporally complete estimates of these data gaps in mountains. Interpolation assumptions have resulted in a diverse set of gridded hydro-meteorological products that show considerable differences in even climatological statistical quantities, such as annual average precipitation and mean daily air temperature. Discrepancies in these gridded estimates have direct implications for estimating the magnitude and flux of terrestrial processes, such as surface runoff and subsurface recharge (Schreiner-McGraw and Ajami 2020), and for rain-snow partitioning, which shapes seasonal snow dynamics. Consequently, land-atmosphere models, which account for many of the physical interactions across the atmosphere-terrestrial interface, are now posited to outpace the coverage of observational networks (Lundquist et al. 2019). Additionally, interpolation procedures built on empirical, geospatial, and climactic relationships might not hold in a rapidly changing climate.

Snow-Dominated Hydrology

Snowpack depends on myriad atmospheric processes (e.g., precipitation, temperature, humidity, and winds) and terrestrial processes (e.g., vegetation cover and geomorphology) and is an emergent property of the mountain water cycle as well as a key driver of seasonal runoff. The emergent nature of snowpack makes it particularly difficult to estimate and predict at landscape-resolving scales, especially in a changing climate. Although disagreement exists on how climate change will alter mountain precipitation patterns, continued temperature increases are more certain and will necessarily diminish the fraction of precipitation that falls as snow and accumulates as snowpack. Therefore, a greater understanding is needed of important mountain-specific differences, particularly in the time horizons of persistent and widespread snow loss across mountains. Critical mountain-specific changes might arise in the coming decades as precipitation increases while higher elevations continue to experience below freezing temperatures despite changes in the freezing levels. Changes in freezing levels may result in important regional differences in snowpack accumulation and supply at mid-century versus end-century. Regardless of the regional context of snowpack change, reduced snowpacks in mountain environments will have several trickle-down impacts on water budgets and ecosystems. For example, diminishing snowpacks will affect not only headwater-to-valley hydrology but also nutrient cycling, another poorly constrained process not yet widely represented in ESMs.

3.1.2 Atmosphere-Terrestrial Research Opportunities

Space-for-Time and Paired Catchment Approaches

Intersite comparisons using space-for-time approaches offer great potential for inferring hydrological response to altered atmospheric drivers. For example, extending observed gradients by combining mid-altitude to high-altitude and maritime to continental catchments can enable researchers to represent different snow dynamics in models. These approaches also could shed light on hydrological responses to a rapidly changing climate (and potential tipping points), particularly in rain-to-snow transition zones. Further, new interest in the concept of interseasonal repeatability of mountain environmental patterns might further support space-for-time analysis across global mountain regions. Since several mountain catchments around the world are already instrumented, a concerted effort to foster more collaborations across sites would be feasible in the short term. These international collaborations would provide new scientific insights that could be vetted across different mountain regions (e.g., Early Career Network of Networks). In the long term, coordinated efforts with optimized instrumentation and sampling design would increase comparability across different mountain areas. Rapidly deployable observational campaigns (e.g., after disturbances such as wildfire) would be instrumental in providing "out of sample" estimates of mountain environmental conditions and identifying priority environmental variables that require continual monitoring or enhanced detail in rapidly changing mountain environments (Newcomer et al. 2021b).

Hierarchical Modeling of Atmosphere-Terrestrial Interactions Across Scales

Hierarchical modeling capabilities represent a readily available approach for improving model representation of cross-scale interactions of atmospheric and terrestrial processes, enabling simulations and predictions that cross environmental components. A hierarchical approach also allows researchers to systematically evaluate the relative contribution of each process in shaping the integrated mountain hydrological cycle and, in turn, examine how the processes individually (and collectively) impact decision-relevant outcomes. To date, such modeling approaches have not focused on mountain environments or considered atmosphere-to-bedrock processes.

In the short term, researchers could conduct hierarchical experiments with individual model components to test fidelity with and without model coupling. This near-term effort could entail model testing and improvements in atmosphere-terrestrial feedbacks underpinned by new insights from the DOE Atmospheric Radiation Measurement (ARM) user facility's sites and campaigns, such as the Surface Atmosphere Integrated Field Laboratory (SAIL) campaign. In the long-term, all model components would need to be fully coupled and vetted. A fully coupled bedrock-to-atmosphere modeling capability would enable researchers to evaluate the best available understanding of mountain processes and their interactions and to identify systemic biases that must be addressed. Examples of such research directions are DOE-funded efforts to:

- Couple Community Land Model version 4.5 (CLM4.5) and the multiphysics Parallel Reactive Flow and Transport Model (PFLOTRAN) to simulate stream-aquifer-land interactions (Bisht et al. 2017).
- Couple CLM to the ParFlow hydrologic model forced with the Weather Research and Forecasting (WRF) model (Maina et al. 2020b) to land-atmosphere interactions at hillslope scale.
- Couple ParFlow to ELM-FATES (the Energy Exascale Earth System Model's Land Model–Functionally Assembled Terrestrial Ecosystem Simulator) to represent vegetation-hydrology interactions at the hillslope scale (Fang et al. 2022).

Such modeling capabilities will also advance understanding of the integrated mountain hydrological cycle and ultimately yield insights on how climate change will drive a cascade of responses that affect decision-relevant outcomes. Given major recent computational advances, atmosphere-to-bedrock simulations with landscape-resolving capabilities are potentially achievable in the near term.

Fostering Interdisciplinary Exchange

Activities to improve observations and modeling will enable researchers to use a model-experimentation (ModEx)-based approach to explore opportunities to establish the long-term datasets necessary for model advancements. Specifically, increased measurement frequencies, coordinated measurements across different atmosphere-terrestrial components, and continued improvements in measurement technology should lead to massive increases in data availability. These advances will enable more machine learning (ML) and artificial intelligence (AI) applications.

Due to the complex linkages among climate, meteorology, hydrology, and ecology in the atmosphere-terrestrial interface, connections need to be established across atmospheric and terrestrial science disciplines. Interdisciplinary exchange can be strengthened in the near term through workshops and targeted conferences. However, since interdisciplinary research must be a sustained effort, long-term support for such science is crucial. The foundation for multidisciplinary understanding should begin during an individual's education, and funding calls need to provide resources to sustain interdisciplinary research across various career stages.

3.2 Human-Atmosphere Processes and Interactions

Mountain hydroclimate atmospheric processes directly impact human systems in three primary ways: precipitation that affects water, energy, and agricultural resources; wind damage to human infrastructure; and wildfires. Across spatial and temporal scales, accurate predictions of atmospheric processes and human-atmosphere interactions are required for stakeholders to make well-informed decisions. Atmospheric rivers, in which strong water vapor transport occurs in narrow corridors, produce heavy orographic precipitation in many mid- and high-latitude mountain ranges, including the U.S. Sierra Nevada and Cascades. Strong atmospheric rivers are critical water sources in many mountain regions, but they also are responsible for infrastructural damage due to winds, flooding, mudslides, and rockslides (Payne et al. 2020).

Water in other mountain ranges often depends more on precipitation from deep convection and winter storms. Downstream regions tend to be major agricultural areas susceptible to severe weather, such as flash flooding and hail facilitated by thermodynamic setups reliant on airflow over and into the lee of major mountain ranges (Houze 2012). These regions, such as the U.S. Great Plains, also rely on major rivers fed by precipitation over mountains such as the Rockies. Similarly, in tropical and subtropical regions, infrastructure needs to withstand and capture heavy orographic precipitation during the monsoon season when nearly all annual precipitation falls. Many islands additionally depend on orographic precipitation in what otherwise would be very dry climates. Planning resilient societal water resource infrastructure critically relies on accurately predicting climate change effects on a wide variety of multiscale precipitation properties over mountains and the downstream regions affected by mountains.

Internal climate variability contributes significantly to uncertainty in precipitation predictions. Decadal variability is large over mountain regions, such as those in the western United States, and currently is difficult to predict when considered with greenhouse gas warming that influences variability (e.g., Stuivenvolt-Allen et al. 2021). This challenge is problematic for water management planning, which requires 20- to 30-year timescale predictions. Another key contributor to uncertain decadal predictions is future anthropogenic emissions that affect not only greenhouse warming but also aerosols such as black carbon. Black carbon and dust generated by human-caused land degradation are deposited on snow where they absorb solar radiation and increase the rate of snowmelt and runoff. This effect can generate snowmelt quantities that meet or exceed those caused by greenhouse warming, leading to runoff earlier in the season as particles accumulate on the snow surface as snowpack melts over time (Qian et al. 2015).

3.2.1 Human-Atmosphere Knowledge Gaps and Challenges

Primary human-atmosphere research gaps fall into two categories pertaining to either (1) the influence of mountain atmospheric processes on human systems or (2) the influence of human systems on atmospheric processes that impact mountain systems. Key gaps in the first category focus on understanding how climate variability and change in mountain regions impact hydroclimate extremes. These extremes include high precipitation events, drought, snow drought, and high-volume runoff associated with precipitation occurring as rain rather than snow or with rain falling on existing snowpack. For the second category of knowledge gaps, workshop participants highlighted the role of anthropogenic aerosol deposition on snowpack, which can influence the timing and speed of snowmelt processes.

Precipitation Observations and Predictions Require Improvement

Fundamental understanding is incomplete in terms of how thermodynamic and dynamic changes in the atmosphere interact with one another to influence the characteristics of precipitation events. Warmer air will hold more moisture, though precipitation will increase more slowly (Trenberth et al. 2003). However, researchers are uncertain about how circulations that advect and condense moisture will change across different regions, and yet understanding this process is critical to understanding regional precipitation changes (Swain et al. 2018).

Research suggests that as the global climate warms, many wet regions will get wetter while dry regions will become drier as large-scale circulations shift, though this effect may not occur over land (Greve et al. 2014). Warmer temperatures will also increase evaporation; as a result, increasing precipitation will not necessarily decrease the probability of drought (Sherwood and Fu 2014). Increases in overall precipitation are likely to take the form of:

- More numerous extreme precipitation periods (Allan and Soden 2008).
- Changes in precipitation systems' organization (Tan et al. 2015; Feng et al. 2016; Prein et al. 2017).
- Changes in the intensity of atmospheric river events (Huang et al. 2020).
- Potential super Clausius-Clapeyron scaling (i.e., extreme precipitation increasing at a higher rate than the Clausius-Clapeyron scaling of water vapor with temperature; Lenderink et al. 2017).

A warming climate also shifts snowfall to rainfall in mountain regimes where temperatures are commonly near freezing, but predicting precipitation phase, melt, or accumulation remains difficult because of subtle but important changes in temperature and precipitation intensity.

The impact of these combined possible changes on any single mountain region remains mostly unknown due to limited and short-term observational records and insufficiently detailed models. Outcomes will likely vary by region, highlighting the importance of feedback between cross-disciplinary scientists and stakeholders as decisions are made on how to design future infrastructure. In addition, researchers have an incomplete understanding of how large-scale atmospheric changes interact with local-scale feedbacks involving (1) complex terrain features, (2) turbulent flows, (3) planetary boundary layer evolution, and (4) couplings with land-surface moisture and energy fluxes that dynamically change with vegetation and snow cover.

Internal Climate Variability Is Poorly Predicted

Given limited availability of decadal and subseasonal-to-seasonal (S2S) data, it is unclear whether climate models can accurately capture S2S and short-range internal climate variability, which is significant in many mountain regions including those in the western United States. These models clearly have room for improvement.

An additional complication is the role of temperature and land-surface changes in contributing to shifts in aridity and feedbacks to precipitation (Berg et al. 2016; Pendergrass et al. 2020). These processes not only impact drought and water availability but also affect the probability of wildfires (Holden et al. 2018).

Anthropogenic Aerosol Emissions Are Unresolved Hydrological and Ecosystem Perturbations

Both local and remote emissions arising from human activities impact cloud, precipitation, and snowmelt processes in mountain regions. Agricultural soil disturbance generates dust, and fossil fuel usage produces black carbon in often distant upstream industrialized and urbanized regions. Such emissions of aerosols can also occur locally in mountain regions because of forest management practices that influence wildfire regimes and related emissions. Key research gaps include characterizing the source of aerosol emissions; measuring and modeling their transport and deposition through the atmosphere; and understanding how aerosol emissions influence snow albedo, melt dynamics, and cascading effects on aquatic systems and greenhouse gas emissions.

In addition, wildfire-related emissions are influenced by the complex interactions among anthropogenic climate change with larger-scale climatic variability as well as ecosystem dynamics. Understanding how these drivers interact with one another to influence wildfire risk, burn dynamics, and emissions is a grand challenge requiring a careful combination of observations and modeling.

Finally, aerosol concentrations influenced by human and plant emissions may affect precipitation via direct radiative effects that alter lower atmospheric temperature structure. Indirect effects can suppress warm rain (Ramanathan et al. 2001) and intensify heavy precipitation and flooding (Fan et al. 2015). All these processes remain poorly quantified.

3.2.2 Human-Atmosphere Research Opportunities

Science gaps and challenges limit the current predictability of interactions between atmospheric and human systems but also provide opportunities for advances. Greater integration between observations, model development, and model testing is one strategy for improvement, along with expanded understanding of internal climate variability across scales.

Integrating Observational and Modeling Projects

Given that numerous human and atmospheric processes interact across scales within geographically specific contexts, a key strategy to address many mountain hydroclimate science challenges involves further combining multipronged observational campaigns with model development and testing in case-study regions. Existing field laboratories that focus on relatively natural regions within mountains may lack a component that examines managed forests within these regions. This gap creates the possibility of conducting new studies or leveraging existing experiments with controlled management trials to disentangle anthropogenic land-use factors from atmospheric, ecosystem, and hydrological processes. For example, investigating which levels of forest management and defensible space (i.e., distance between a building and surrounding wildland area) are required to meaningfully impact structure burning during wildfires requires interagency collaboration, studies focused on the wildland-urban interface and on structures, and planned research that leverages management activities. Identifying which mitigation strategies are suitable in the context of mountain hydroclimate extreme events is a critical opportunity in this area.

Expanding Cross-Scale Interdisciplinary Understanding and Modeling

It is well known that internal climate variability spanning timescales of up to decades dominates over forced variability from anthropogenic emissions at local-to-regional scale. However, decadal and S2S predictability remain extremely limited. Even modest improvements could significantly impact efforts to guide societal investments. More understanding of internal climate variability will improve models, but substantial advances also might be gained by applying new statistical techniques, such as ML approaches for bias correction, ensemble-based uncertainty quantification, and extreme event predictability. Coupling longer-range predictive models that have simplified process representations and limited spatiotemporal resolution with detailed aerosol, cloud, surface, and human system models also could advance understanding, improve predictions, and guide better decisions.

3.3 Terrestrial-Human Processes and Interactions

As the world's water towers, mountains are critical for both *in situ* and downstream human activity (Viviroli et al. 2007), resulting in a strong interdependence between terrestrial and human processes for many of the world's mountain chains (Immerzeel et al. 2020). For example, human settlements, agricultural practices, and water use have developed over centuries and millennia around historically reliable upstream discharge flows (e.g., Himalayas). Furthermore, man-made water storage in mountains (e.g., reservoirs) strongly depend on snowmelt and glacial melt to ensure higher agricultural yields and hydroelectric production. In contrast, anthropogenic impacts on mountain systems are leading to changes not only in mountain hydroclimate but also in land use, land cover, and groundwater processes (Biemans et al. 2019).

In mountain systems, many terrestrial-human processes and connections span multiple spatial scales. For example, groundwater reserves in valleys can be driven by both local river recharge and groundwater recharge in high mountains (e.g., San Joaquin Valley; Wada et al. 2016). These local to regional groundwater systems, along with riparian corridors that form downstream, can supply water for agricultural and human use. Furthermore, upstream agricultural and livestock practices can directly impact downstream water quality and quantity. Figure 3.1, p. 37, shows a satellite image of the Boise, Idaho, region where agriculture and water use are intricately connected to mountain hydroclimate.

Interactions between human and terrestrial processes over mountain regions lead to a complex interconnectivity between hydroclimate, agriculture, urbanization, environment, and energy needs that cannot be disentangled in regions where human populations strongly depend on mountain hydroclimate systems. These interactions are tested under extreme events such as floods, droughts, and wildfires.

3.3.1 Terrestrial-Human Knowledge Gaps and Challenges

Terrestrial-human grand challenges include improving observational data and modeling capabilities for human-terrestrial interactions, wildfires, and extreme events and developing new scientific methods and approaches for understanding their complex connections.

Human-Terrestrial Interactions

Human-terrestrial interactions span multiple spatial and temporal scales among water, energy, carbon, and biogeochemical cycles. These interactions and complex feedback loops in mountain regions remain poorly understood, both qualitatively and quantitatively. One challenge is a lack of data from physical and human interactions in mountain regions. Complex mountain topography makes observational efforts difficult, resulting in insufficient data across terrestrial processes (e.g., land use, land cover, snowpack, rivers, land-surface interactions, soil biogeochemistry, and river biogeochemistry). Additionally, even though riparian corridors are critical components of the mountain hydroclimate system, data on their terrestrial-human interactions is poor and their representation in ESMs is practically nonexistent. Finally, human systems are most often represented as individual and local assets, but models largely ignore regional organization of human systems and cross-scale interactions. Human behavior needs to be generalized, and the science of human systems must be advanced as these systems are integrated with terrestrial processes for interpretation (Scanlon et al. 2017).

Fig. 3.1. Multiscale Terrestrial-Human Interactions in the Boise, Idaho, Region. The area, shown here by satellite, uses mountain river discharge for regional water supply and for agriculture along riparian corridors. [Imagery ©2022 TerraMetrics, Map data ©2022 Google]

Wildfires

Wildfires are changing the predictability of both terrestrial and human systems. With human systems, changes can be punctuated and temporary, such as loss of electricity transmission and substations. Other impacts include changes in electricity and water demands associated with the loss of infrastructure and changes to ecosystem hydrology and biogeochemistry that can last years. Conceptual research of complex interactions between wildfires and fuels is currently ongoing as are studies of wildland-urban interfaces. However, observation and modeling capabilities remain deficient overall (AghaKouchak et al. 2020).

Extreme Events

Extreme human-terrestrial events are difficult to quantify and identify. Human systems are operated to minimize terrestrial extreme events, but tipping points are poorly understood or recognized. Similarly, the sequences of multiple events ultimately leading to extreme events are largely unexplored (Zscheischler et al. 2018). For example, a rain-on-snow event for an average snowpack can lead to an extreme event in human systems. Also, drought severity has often been measured by its local impact on human systems, but studies are emerging that define drought severity in terms of how it is impacted by governance systems

(Hadjimichael et al. 2020). Understanding these complex interactions between terrestrial and human systems requires developing new scientific methods (Reed et al. 2022).

3.3.2 Terrestrial-Human Research Opportunities

Although the study of terrestrial-human interactions within mountain systems remains in its infancy, many research opportunities exist within this area.

Human-Terrestrial Interactions

As topologies of human systems emerge (Yoon et al. 2022; Brelsford and Abbott 2021), a specific topology of human-terrestrial system interactions would motivate future hypothesis-based research. To advance human system sciences in the context of Earth systems, this topology should integrate social scientists and stakeholder communities who are excellent resources for data collection across systems and scales. A first step within this topology could involve cataloging existing datasets to understand observational benchmarks and evaluate modeling approaches. Small-scale terrestrial-human field and laboratory experiments can help provide observations in the short term while the evolving topology further defines the observations needed across scales. For example, field greenhouses can test how different emission scenarios or prescribed fires impact hydro-biogeochemical feedbacks. Such experiments could aid the development of management strategies for carbon sequestration and water crises across drought-prone mountain regions. This activity specifically helps address pressing research questions to determine which mitigation strategies are suitable in the context of extreme events that influence mountain hydroclimate.

Near-term research opportunities include modeling exercises complemented by dataset extensions. Although scientists have advanced model representations of human-terrestrial interactions in Earth-human systems (Voisin et al. 2013a; Yassin et al. 2019), human systems in models typically lack coordination (Rougé et al. 2019), and interactions between terrestrial and human systems tend to be driven by climate variability. Efforts in ESM parameterizations and representation of human-terrestrial interactions (e.g., riparian corridors and reservoir management) are expected to help incorporate these new interactions in models. Efforts are also needed to build and organize datasets, including AI/ML-based dataset extensions that integrate terrestrial-human data harmonized to the same spatial and temporal resolutions. These capabilities should improve the definition of extreme events associated with terrestrial-human systems interactions.

In the long-term, an array of modeling approaches is envisioned to study integrated human-terrestrial interactions across a range of scales for robust to nonstationary conditions. Experiments using fully integrated models, hybrid coupling, and storyline formats will enable researchers to generalize model structures and parameterizations describing human behavior. As part of this vision, efforts to collect data and capture governance of local human system interactions will benefit from citizen science and crowdsourcing as well as close collaboration with other agency efforts, such as those led by the U.S. Bureau of Reclamation, U.S. Army Corps of Engineers, and nongovernmental agencies including the National Hydropower Association.

Wildfires

Wildfire research is challenged by fast changes in hydrological and human system responses and the current inability to predict their occurrences. Many observations encompass post-wildfire efforts that examine restoration advances with assumed indirect benchmarks such as streamflow. Human system responses to wildfires need to be better understood, and human-terrestrial interactions need to be explored before and after wildfires using analog basins. AI/ML dataset extensions might help in these endeavors.

Since data are critical to such research, scientists need to push boundaries by better integrating social scientists and engaging with stakeholder communities to collect and analyze data across systems and scales and to catalog existing datasets to understand benchmarks in observing and evaluating modeling approaches. Data and modeling capabilities are needed not only for mountain climates with complex topography but also for those within the U.S. high plateaus where urbanization is changing mountain foothills and wildland-urban interfaces. In the long term, enhanced predictability of the source and evolution of mountain forest wildfires could be achieved by better understanding and modeling triggers—both natural (e.g., lightning) and man-made (e.g., transmission lines and campfires)—and associated mountain soil and vegetation conditions including forest practices and roads.

Extreme and Consecutive Events

In addition to wildfires, enhanced predictability of extreme event sources and evolution can be achieved by better understanding and modeling (1) natural and man-made triggers, (2) initial conditions, and (3) interactions between co-evolving terrestrial and human systems and associated consecutive events such as drought followed by wildfires. Defining extreme events—including floods, landslides, avalanches, drought, snow droughts, sediment loads and associated erosion, and stream thermal events—across terrestrial-human system interactions must go beyond typical engineering definitions, such as percentiles and return periods. The research community needs to work with human system operators to qualitatively understand the definition of extreme events in the context of impacts to human systems. Consecutive events, which themselves might represent an extreme event, could be considered in a similar way. Even from a biogeochemistry perspective, an extreme event is most often monitored through human systems interest (e.g., river chemistry) and biodiversity. An additional need is further investment in developing longer records to capture extreme events and define benchmarks.

A challenge of terrestrial-human system interactions is their very fast co-evolution. A hybrid of paleo data and synthetic data is needed to understand a range of system outcomes. In the long term, leveraging extreme event remote sensing (e.g., through satellite and airborne capabilities) over mountain regions is envisioned. This approach would help generalize and extrapolate local information and address transferability of understanding and observation of extreme events to different mountain regions for robust analytics in environments with few observations. Such an effort would also include exploration of synthetic datasets.

Flooding Rain Over California
Courtesy Getty Images

Chapter 4

Crosscutting Science

4 Crosscutting Science

4.1 Integrated Mountain Hydroclimate Variability and Change

Hydroclimate in mountain regions is among the most sensitive to climate change and human system impacts. A changing climate will result in warmer mountain conditions, precipitation that includes more extremes, and shifts in precipitation phase (e.g., from snow to rain) that will affect snow and seasonal water supply and water resource predictions (see Fig. 4.1, p. 42). These changes will impart complex and unknown consequences on water partitioning because of bedrock-through-atmosphere interactions and processes ranging from continental to watershed spatial scales and subannual to decadal timescales. Improved process understanding within and across mountain ranges is needed to ensure that knowledge is transferred to decision-makers and that proactive adaptation strategies to these changes are considered now. Advances in observations and Earth system models (ESMs) require a balance of improved process fidelity representation and an ability to perform uncertainty quantification. An overarching objective is to determine the minimum process representation sufficient to advance integrated mountain hydroclimate (IMHC) variability and change.

4.1.1 IMHC Variability and Change Knowledge Gaps and Challenges

Research on IMHC variability and change centers around six grand challenges: (1) modeling orographic precipitation, (2) understanding vegetation feedbacks, (3) predicting snow drought, (4) expanding spatial observations and cataloging existing datasets, (5) addressing uncertainties in modeling mountain hydroclimate, and (6) predicting future changes in mountain hydroclimate.

Modeling Orographic Precipitation

Precipitation seasonality, spatial patterns, and structure can vary substantially across and within mountain regions. However, climate models often are too coarse in resolution to resolve complexity associated with orographic precipitation, land surface heterogeneity, and feedbacks between atmospheric and terrestrial processes. As a result, modeling orographic precipitation, particularly projecting future changes in precipitation pattern and structure, is a key challenge. For future climates, better insight is needed on the implications of changing precipitation for other hydroclimatic variables (e.g., snowpack, runoff, and terrestrial water storage), their trend and seasonality, and hydroclimatic extremes (e.g., flooding, drought, and wildfire).

Understanding Vegetation Feedbacks

Key challenges for models at various scales are simulating process-level interactions between the atmosphere and vegetation and determining how they feed back into regional hydroclimatic conditions and extremes. For example, researchers do not fully understand how extreme events such as drought and wildfire impact structural vegetation (e.g., vegetation patterns, distributions, and composition) and physiological vegetation feedbacks (e.g., soil moisture extraction and evapotranspiration). Also unclear is how multiscale vegetation–soil moisture feedbacks might influence hydroclimatic variability across scales. For example, Maina and Siirila-Woodburn (2019) showed that post-wildfire landscape changes affect water surface and surface flow pathways through shifts in infiltration patterns and increases in snowpack accumulation, which nonlinearly affect water partitioning.

Many studies confirm the dominant influence of fine-scale forest canopy characteristics (e.g., canopy density, structure, and spatial arrangement) on snowpack dynamics and snow cover distribution. However,

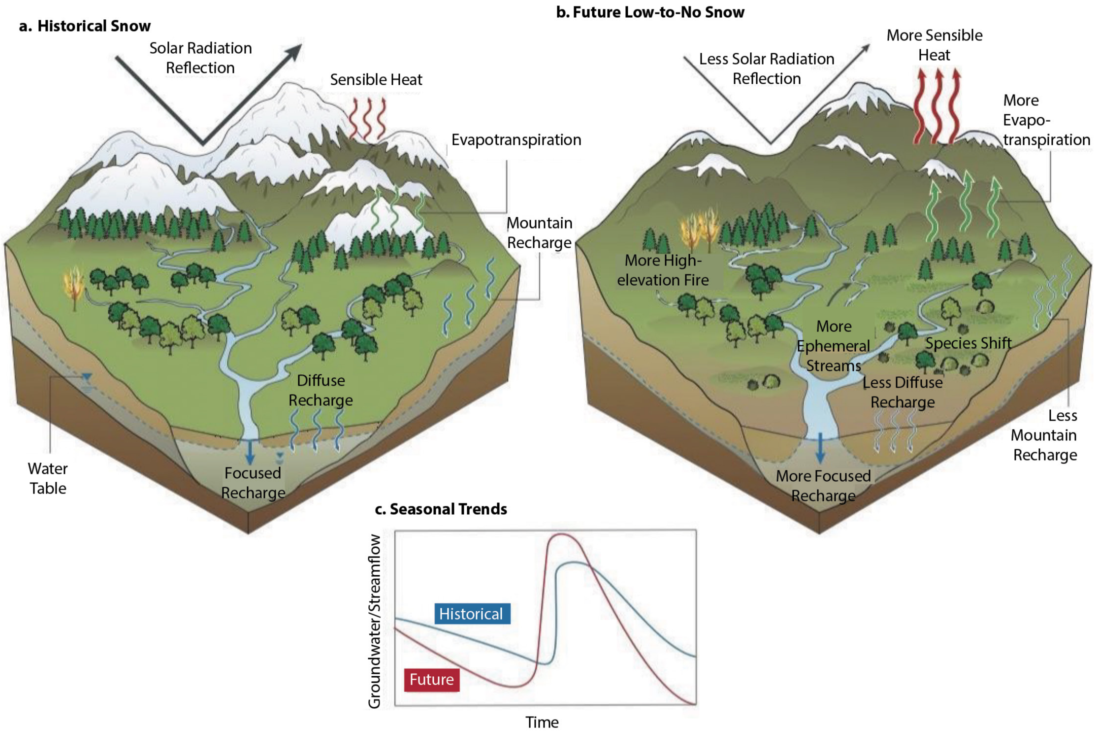


Fig. 4.1. Expected Mountain Hydroclimate Variability and Change with Shifts in Climate, Precipitation Phase, and Snowpack Conditions. These changes will have subsequent ecohydrological impacts within and down-gradient from mountain environments. [Reprinted with permission from Springer Nature from Siirila-Woodburn, E. R., et al. 2021. "A Low-to-No Snow Future and Its Impacts on Water Resources in the Western United States," *Nature Reviews Earth & Environment* **2**, 800–819.]

subpixel-scale canopy representations are lacking in ESMs and regional hydroclimate models (Mazzotti et al. 2020; Sun et al. 2022). Also unknown are potential thresholds or tipping points for extreme events (e.g., drought duration and post-drought wetness) that might cause irreversible changes or hysteresis in vegetation dynamics and related hydroclimatic processes. For example, a recent study by Peterson et al. (2021) found that the prolonged Millennium Drought occurring in southeast Australia induced changes in vegetation phenology. These vegetation changes resulted in irreversible shifts in watershed hydrological regimes that are characterized by a persistently higher evapotranspiration rate and a reduced runoff-to-precipitation ratio, even after the drought and despite wet and dry years.

Predicting Snow Drought

In western U.S. mountain regions where seasonal snowpack provides much of the downstream freshwater resources, snow droughts can significantly impact regional water availability and ecological and socioeconomic systems. Global warming is expected to exacerbate snow droughts, which are largely affected by storm tracks on seasonal to decadal timescales. Modeling and thus understanding how snow drought may change in future climates are current challenges. Also lacking is understanding of how the climate system's internal variability might influence future snow droughts. Depending on the meteorological driver, snow droughts can be classified into warm snow drought (caused by above-normal warm winter temperatures), dry snow drought (caused by winter precipitation deficits), and combined warm and dry snow drought (Harpold et al. 2017; Hatchett et al. 2022). Recent studies suggest more frequent warm snow droughts in future climates as warming is expected to shift the precipitation phase from snow to rain (Rhoades et al. 2018; Musselman et al. 2018).

Still unclear is how snow droughts caused by different climate drivers may change in the future and how they may impact downstream water availability regimes. The cascading impacts of multiyear diminished snowpack conditions are also poorly constrained (Siirila-Woodburn et al. 2021). With reduced snowpack in future warmer climates, predicting seasonal water supply for mountain regions is an immediate challenge. A recent study shows that by late century (2070–2099), the ability to use snow information to predict seasonal drought and streamflow will diminish for 83% of historically snow-dominated areas in the western United States, with warming impacting lower-elevation coastal areas the most (Livneh and Badger 2020).

Expanding Spatial Observations and Cataloging Existing Datasets

Given the importance of snow processes for mountain hydroclimate and the fine-scale heterogeneity of snow cover and snow regimes, high-resolution, spatially comprehensive snow observations are crucial for better understanding and modeling snowpack spatial distributions and regimes. Such observations include snow depth, snow water equivalent, snow density, and snow surface temperature and are particularly important for understanding forested environments where snow processes are strongly influenced by forest canopy.

Despite increasing availability of high-resolution spatial data, such as NASA Airborne Snow Observatory and lidar measurements, spatial snow and canopy observations spanning multiple years are still lacking for much of the world's mountain regions, particularly at high elevations and in snow-rain transitional zones (Musselman et al. 2018; Sun et al. 2019). Also lacking are co-located measurements of climate, canopy, and snow variables as well as catchment discharge, limiting understanding of the control processes of snowpack dynamics. This lack of data also prevents parameterizations of snow processes, including in the canopy, and subsequent impacts on surface and subsurface hydrology at the subgrid level in ESMs or hydro-terrestrial models. Additionally, the ability to rapidly collect data during extreme events is limited, highlighting a major gap in process representation and understanding.

Although a wealth of data already exists, it has yet to be fully curated, stored, quality assessed, and controlled, which contributes to current data needs and requirements for models. Existing data is underutilized because of a lack of data standardization formats and integration across similar datasets. Accumulation of underutilized data from past field campaigns underscores the need for prioritizing comprehensive data interpretation and analysis.

Addressing Uncertainties in Modeling Mountain Hydroclimate

Characterizing and quantifying model uncertainties require a framework that respects spatial heterogeneity and interactions between systems in ESMs like the Energy Exascale Earth System Model (E3SM). This framework is particularly important for modeling and understanding mountain hydroclimate with large gradients in topography, temperature, precipitation, and vegetation cover. Substantial uncertainties can be attributed to:

- Choices and downscaling approaches used for global or regional climate models.
- Model resolution and representation of land-use and land-cover spatial variability and their interplay with terrestrial processes involving, for example, snow and soil-water interactions.
- Model representation of feedbacks between atmospheric and terrestrial processes.

Additional uncertainties exist for human system feedbacks (see Sections 2.3, p. 22; 3.2, p. 33; and 3.3, p. 36), including scientific and modeling gaps between anthropogenic activities associated with adaptation and mitigation strategies. Examples include reservoir dynamics, operations, and dead pools; hysteresis effects; and human response to system perturbations like the "miracle spring," a prolonged drought unexpectedly mitigated by a significantly large amount of spring precipitation.

In modeling, the choice of certain processes and scales often comes at the expense of other critical processes, with unknown and unquantified uncertainty resulting from such exclusions. With multimodel ensembles, advanced model couplings, and multiscale model intercomparisons, new opportunities exist to understand the resolution required to simulate different types of key processes or extremes and inform ESM subgrid parameterization or process refinement. Furthermore, this high-resolution information should be used in coupled human-ESMs to understand feedbacks and tipping points in these systems. For example, coupling variable-resolution ESMs with integrated hydrological models enables researchers to jointly consider thermodynamic and dynamic shifts in a projected climate while explicitly modeling hydrogeological responses in above- and belowground water energy balance at decision-relevant scales. Bedrock-to-atmosphere coupling of process representations and feedbacks, while still in its infancy, represents the type of "hierarchy of systems" that potentially can be aided by work in new artificial intelligence (AI) and machine-learning (ML) techniques. For instance, AI emulators provide an opportunity to introduce simulations of complex subsurface flow, biogeochemistry, or wind patterns at various scales.

Predicting Future Changes in Mountain Hydroclimate

Complexities in the spatial and temporal patterns of shifting mountain hydroclimate challenge efforts to predict ongoing and future change. Studies are needed to quantify the characteristics of these changes. For example, signatures of extremes (e.g., very dry versus very hot years) can be used as indicators of potential change. However, given nonlinearity and a lack of natural analogs of expected changes, reliance on physically based models will be important to make accurate and informed projections. Considerations of regionally specific characteristics (e.g., the response of land use and land cover) will be important to quantify how one region will respond to different levels of change. These challenges point to a need for comprehensively sampling extremes, utilizing large ensembles, and developing baselines of observed and simulated historical data for comparison.

4.1.2 IMHC Variability and Change Research Opportunities

Research needs and opportunities associated with the grand challenges of IMHC variability and change include (1) regionally refined modeling and dynamical downscaling, (2) comprehensive AI/ML representation of mountain systems, (3) data cataloging and metrics for model evaluations and cross-region comparisons, (4) bedrock-to-atmosphere process understanding and modeling, and (5) region-specific mitigation and adaptation strategies for future extremes.

Regionally Refined Modeling and Dynamical Downscaling

Mountain regions' large interannual variability makes disentangling signal from noise difficult and underscores a need for large ensembles of climate model simulations. Several large, publicly available ensembles have contributed significantly to understanding the climate system and its response to climate change (Deser et al. 2020), but the grid spacing used in these simulations (typically about 110 km) is insufficient for resolving mountain topographic and meteorological features. Addressing this gap requires high-resolution climate simulations (Roberts et al. 2018) to enable more accurate representations of topography, extreme weather features, and atmosphere-land surface interactions. For example, Rhoades et al. (2018) showed that mountain snowpack is generally convergent in atmospheric models when grid spacing is around 14 km, but higher resolution is needed to capture mountain valleys and other features of mountain meteorology. However, the high computational cost of such simulations currently precludes their development. To overcome this problem, targeted ensembles using technologies such as regional refinement or dynamical downscaling should be developed and made available to the scientific community for analysis (Gutowski et al. 2020; McCrary et al. 2022).

Comprehensive AI/ML Representation of Mountain Systems

AI and ML have proved immensely useful in identifying relationships in systems where processes are not well constrained. Researchers could use AI emulators of mountain hydrological, ecological, or biogeochemical processes to improve their representations in regional or global ESMs. For instance, recent developments in using AI/ML have refined representations of the IMHC system, including streamflow (Duan et al. 2020), snow water equivalent (Meyal et al. 2020), groundwater (Sahoo et al. 2017), and wildfires (Wang et al. 2021).

Some studies have shown that AI/ML systems can outperform process-based models (Kratzert et al. 2019). AI-based systems also are being used for downscaling of climate information from coupled climate models (Vandal et al. 2019). Simultaneously, explainable AI–related efforts are helping clarify which relationships AI-based models identify, thus making the "black box" of these models more transparent (McGovern et al. 2019). Nonetheless, researchers are continuously exploring new methods and model designs and applying them to problems in mountain regions. When combined with adequate datasets, AI/ML representation can advance the full potential of model-experimental (ModEx) approaches.

Data Cataloging and Metrics for Model Evaluations and Cross-Region Comparisons

The research community continues to expand observational datasets, perform deeper analyses with existing data products, and conduct more simulations at resolutions needed to resolve mountain processes. These advances, combined with improved dataset cataloging (e.g., through efforts such as the Observations for Model Intercomparison Project; Waliser et al. 2020) can potentially accelerate scientific discovery and enable more comprehensive model evaluation.

Accumulation of data from past field campaigns presents a major research opportunity to curate spatially and temporally complete datasets in existing catalogs across the globe. Fully utilizing all existing datasets and simulations (both past and present) provides further opportunity to develop and deploy new metrics and diagnostics for comprehensively evaluating the climate modeling systems and terrestrial processes key to understanding regional hydroclimate. Research efficiency and impact could be greatly amplified by expanding data harmonization and data repositories to include data processing and analysis tools.

Metrics that address cross-region similarities and differences at multiple scales should also be developed. These include efforts to quantify the dominant mechanisms of regional hydroclimate or measure the sensitivity of hydroclimatic regime to changing climate. These metrics potentially should be used as references for evaluating model or knowledge transferability across regions. One example is the snow model intercomparison project (ESM-SnowMIP; Krinner et al. 2018), which recently explored metrics for evaluating the performance of various mountain snowpack models.

Comprehensive model evaluation using multiple metrics and all available observational datasets can enable the identification of correlations between model biases and upstream drivers of those biases (Xu et al. 2019). Initiatives such as Coordinated Model Evaluation Capabilities or the Model Diagnostics Task Force (Maloney et al. 2019) also should be used to improve interoperability between model evaluation software tools. Advancements in capabilities for analyzing extreme events could be achieved by revisiting underutilized data from past field campaigns, coupling those data with novel state-of-the-art modeling, and developing rapidly deployable observational campaigns.

Bedrock-to-Atmosphere Process Understanding and Modeling

Mountain processes extend from the deepest aquifers through the land surface and troposphere and into the stratosphere. Comprehensive bedrock-to-atmosphere modeling of the system would enable disentangling the relationships among processes at all levels while conserving invariants such as water mass. A hierarchy of modeling systems should be developed further to incorporate observations at all scales. Such observations include those from the Atmospheric Radiation Measurement (ARM) user facility's Surface Atmosphere Integrated Field Laboratory (SAIL) campaign (Feldman et al. 2021), the Airborne Snow

Observatory (Painter et al. 2016), and other ongoing or planned observational campaigns. This hierarchy of systems could be aided by work in AI/ML systems.

Novel AI/ML, hybrid, and lumped modeling approaches that combine bedrock-to-atmosphere remote sensing and field-based data layers offer incredible potential to improve conceptual model development and reveal insights beyond those provided by current mechanistic models (Wainwright et al. 2022; Chaney et al. 2018). For example, in the Upper Colorado River Basin, researchers have observed decadal declines in river nitrate (Newcomer et al. 2021a); model limitations currently preclude a predictive understanding of the causal factors contributing to these declines because river chemistry is a complex function of highly nonlinear interacting hydrological, biogeochemical, and ecological factors across bedrock-vegetation-atmosphere interfaces. Using AI/ML, hybrid, and lumped models to examine these interactions could prove useful, since these approaches have successfully identified causal relationships in systems where process representation is nonexistent or poorly constrained (Maavara et al. 2021).

Region-Specific Mitigation and Adaptation Strategies for Future Extremes

Planning for extreme events, such as prolonged drought or flooding, is difficult because of large interannual and intra-annual hydroclimatic variability in mountain regions. In conjunction with local stakeholders and policy-makers, efforts are underway to identify optimal mitigation or adaptation strategies. However, many questions remain about how mountain regions can best adapt to a changing climate, particularly when considering complex intersectoral dynamics and future uncertainty. For example, the impacts of prolonged drought and reservoir operations on the capacity of hydroelectric dams to generate electricity are not fully understood (Szinai et al. 2020). Also unclear is the best strategy for managing montane forests amid increased wildfire risk and climatic shifts (Keenan 2015) and whether legal frameworks related to water rights can be managed when water supplies are insufficient (Schwarz 2015). Because of the substantial spatial heterogeneity in hydroclimatic extremes and land surfaces, management strategies for future extremes need to be made at decision-relevant scales that are much finer than ESM grid resolution (>4 km). Multimodel ensembles and multiscale model intercomparisons provide opportunities to understand the resolution required to simulate key processes for different types of extremes and inform ESM subgrid parameterization or process refinement. This high-resolution information also should be used in coupled human-ESMs to understand feedbacks and tipping points in these systems.

4.2 Atmosphere-Terrestrial-Human Interactions

Identifying and minimizing biases in model simulations are major science objectives in atmosphere-terrestrial-human (ATH) interactions research. The key science question is how can the biases, real means, variability, and extremes in mountain hydroclimate be best understood and used to improve simulations of means and extremes spanning days to centuries? The large spatial extent of model simulations in mountain regions also poses significant challenges to existing observational systems and reduces the availability of actionable information at fine scales.

Extreme precipitation and associated landslides and debris flows are important processes at the intersection of ATH systems. Improved operational forecasts and gridded precipitation estimates are needed to help resolve current model variability for event prediction with short lead times. Research priorities include the development of parameterizations that account for subgrid-scale processes, such as turbulent flows, flow interaction with topography, and snow redistribution and evaporation. Also urgently needed are efforts to simulate mountain environments beyond their natural state by including the effects of human activities on the hydroclimate.

4.2.1 ATH Knowledge Gaps and Challenges

Knowledge gaps driving ATH research include (1) determining priority landscapes,

(2) understanding shifting extremes, and (3) modeling ATH interactions.

Determining Priority Landscapes

Mountain regions are characterized by strong temperature and precipitation gradients; high variability and extremes; and heterogeneous human settlement, with populations concentrated in hospitable zones. Because of these factors, the impacts of climate change and shifting extremes on coupled ATH systems are stronger and less predictable in mountain regions than on flatlands.

Mountains are challenging regions for decision-making and risk management because of the combination of species distributions and steep, shifting climate gradients in landscapes with diverse past and current management practices and natural disturbances such as wildfire and insect damage. The biogeography of mountain forest distributions, growth rates, and susceptibility to disturbance is complex and only partially understood, and human intervention amid ongoing shifts in climate means and extremes is an uncertain endeavor. To the extent that society prioritizes natural ecosystems as potential resources for mitigating ongoing climate change, mountain watersheds in the western United States will be important for managing long-term carbon storage.

Understanding Shifting Extremes

Flooding along the Yellowstone River in Montana in June 2022 provides an example of the amplification of climate change impacts on coupled systems in mountain watersheds. Extremes in snowpack, temperature excursions, and precipitation, combined with economically vital development patterns that follow the main river channel, produced flooding that halted transportation, commerce, and tourism. The damage to critical infrastructure will take years and millions of dollars to repair.

In mountain hydroclimates, extreme climate gradients and high variability across timescales from days to decades complicate efforts to adequately measure and characterize these regions. An important challenge for ATH interactions research is knowing how many measurement capabilities to deploy and where to place them. Many important locales are simply inaccessible to instruments or data collection (e.g., steep ridges, remote high-elevation plateaus, and wind-swept divides). Remote detection instrumentation (e.g., radar) is often obstructed by terrain, and airborne and spaceborne remote-sensing platforms are hampered by frequent cloud cover and the challenges that variable snow cover presents for image interpretation.

Compounding extreme events, such as snow droughts and wildfire, are critical mountain research gaps because of their direct relationships and vulnerability to climate change. Both wildfire conditions and snow drought are largely affected by storm tracks on seasonal to decadal timescales. Research across the coupled groundwater-soil-vegetation continuum is needed to understand the mechanisms by which wildfire is exacerbated by snow drought and antecedent soil moisture conditions and how wildfire can then tip soil hydro-biogeochemistry toward new steady states and biomes. Along mountain foothills, the expansion of wildland-urban interfaces is a direct anthropogenic influence on wildfire risk, burn dynamics, and emissions, all of which require a combination of observations and modeling to strategically address.

Modeling ATH Interactions

Integrated research is required to support future IMHC activities and address the significant challenge of modeling ATH interactions. Highlighting the need for this research is a use case exemplifying interrelated ATH interactions involving wildfire in response to evapotranspiration, precipitation, and human systems. Modeling these coupled conditions in mountain systems motivates the need for new advancements in modeling and observational platforms.

Wildfire

Mountain wildfire is the perfect use case for illustrating the necessary integration of ATH interactions across scales. Wildfire plays a key role in landscape hydrological and biogeochemical processes because of interactions and changes across the soil-vegetation continuum. These impacts include vegetation loss and evapotranspiration shifts, changes in soil hydraulic parameters, and introduction of new solutes and nutrients from combustion byproducts. Important drivers of potential wildfire impacts on hydrological partitioning include post-wildfire precipitation frequency, magnitude, and duration (Maina et al. 2020a; Murphy et al. 2015, 2018).

A key challenge for models is simulating process-level interactions and feedbacks between wildfire, the atmosphere, vegetation, and subsurface biogeochemistry. Additionally, more efforts are necessary to include wildfire-related impacts on critical parameters, such as porosity and hydraulic conductivity, and to incorporate these new parameters into the model. Given that wildfires increasingly occur at the wildland-urban interface, models must account for human-induced wildfire ignitions and spread as well as anthropogenic chemicals (e.g., phosphates and nitrates) that greatly impact terrestrial biogeochemical cycles. Observational campaigns and models are not yet equipped to respond to the rapid onset of wildfires. As such, new ModEx-style network-of-network groups and rapid-response activities will be necessary to quickly leverage capabilities across communities to achieve measurable progress in observing and predicting mountain hydroclimate response to wildfire.

Evapotranspiration

Measuring, modeling, and benchmarking evapotranspiration remain significant research challenges. Because evapotranspiration fluxes highly depend on ATH interactions, a coupled bedrock-vegetation-atmospheric model is needed to benchmark observational datasets and conduct modeling experiments under land (e.g., forest) management activities or wildfire.

Precipitation

Orographic precipitation directly controls evapotranspiration and wildfire. Consequently, modeling and measuring this precipitation (including pattern and structure across mountain topography) are critical. The discrepancy between the scale of precipitation observations and the scale of simulations further complicates accurate representations of evapotranspiration fluxes in land-atmosphere modeling. Additional challenges for current ATH modeling and observational capabilities are the role of wildland-urban interface expansion in mountain systems and the feedbacks of this expansion on both vegetation-driven evapotranspiration and local atmospheric forcings (e.g., changes to surface energy balance and water use).

Human Systems

ESM representation of human system responses to mountain evapotranspiration, wildfire, and precipitation changes is still in its infancy. To enable actionable science and inform decision-making, models that properly represent human processes as forcing mechanisms are needed. Also critical for successful model predictions of pre- and post-wildfire conditions are long-term observational platforms and models that include human and multisector dynamics that adequately capture human system diversity.

Data, Observation, and Risk Estimate Needs

The assumptions used for models are becoming less valid due to changing aerosol emissions (e.g., from increasing wildfires) and warming conditions that alter melt processes in mountains. Consequently, new observations for calibrating and updating model process representations are immediately needed, along with improved multiscale predictions and risk estimates of compound extreme events. Examples include prediction of simultaneous droughts, heatwaves, or wildfires followed by intense precipitation. Insufficient integration of climate and weather services is a limiting factor in engaging stakeholders in risk estimates and predictions of these events. This lack of data integration can impact critical decisions, communications, and responses by members of the public.

4.2.2 ATH Research Opportunities

New research opportunities emerge in the context of ATH interactions, including:

- Learning from heterogeneity studies in low-relief terrain as physical and thermal forcing interactions are considered in mountain terrain.
- Combining existing and new model subgrid capabilities, such as those used in E3SM's Land Model (with a topography-defined subgrid), with an approach that recognizes the natural organization

of watersheds (including nested watershed analysis).

- Integrating a dynamical, high-resolution approach[1] with a statistical approach[2] to produce a more reliable historical hydroclimate database, which is useful for quantifying impacts and extremes and for forcing of hydrology and impact models.
- Acquiring and curating data to improve forecasts and uncertainty quantification.
- Including bedrock-to-atmosphere process representations of ATH interactions across local and global models.
- Using wildfire as a use-case scenario to benchmark models and observations.

Data integration should be prioritized. Using and acquiring new aerosol, precipitation, and snowpack measurements will be important for updating and improving remote-sensing retrievals and predictive models. High-resolution, spatially comprehensive, and long-term snow observations are crucial for better understanding and modeling snowpack spatial distribution and regime, which drive extreme phenomena. Also essential to these efforts are long-term datasets that establish ecosystem steady states before extreme events. Gathering critical extreme event–scale data will require rapidly deployable observational campaigns that respond to extreme phenomena at times and places where they occur.

Big Data mining and improved simulations coupled with measurements present opportunities to advance uncertainty quantification of compound extreme events. Guiding decision-making through more accurate simulations of such events will require improving the entire forecast chain, beginning with current and future weather inputs to hydrological models that then provide the basis for risk dissemination and mitigation strategies. Much work is needed to examine mitigation strategies in the context of climate change and extreme events using models as forecasting tools. Also needed are observational and co-beneficial experimental approaches that underpin development of novel and potentially transformative mitigation strategies. For example, mountain forest management activities could also address science questions related to extreme event thresholds for hydro-biogeochemistry as part of research with co-benefits for improving the ability to mitigate extreme event impacts on the hydrological cycle.

Nontraditional observational campaigns create the possibility of conducting new experiments or using ongoing studies with controlled management trials to disentangle anthropogenic land-use factors from atmospheric and terrestrial influences. Making code more transferable between modeling systems is a necessary next step. For instance, many high-resolution models that can simulate mesoscale processes in mountain regions have simple land-surface schemes while coarse-resolution ESMs typically have much more advanced land-surface models but struggle to simulate fine-scale processes.

4.3 Societal Connections and Implications

Risk and uncertainty are two major concerns related to the societal connections and implications of IMHC variability and change. Of utmost importance is the perception of risk and risk tolerance, including quantifying risk in the decision-making process. Current challenges involve relaying uncertainty to end users and making decisions under untold or unquantified uncertainty. Since uncertainty will persist in current modeling tools, a central objective and opportunity for DOE in the next 5 to 10 years involves determining how uncertainty is best communicated and adapted to stakeholders and how it varies with different sectors.

Societal sectors affected by current challenges in addressing and communicating uncertainty are:

---

[1] An example includes the Hydro-Terrestrial Earth Systems Testbed (HyTEST) project, a community modeling testbed between the National Center for Atmospheric Research and the U.S. Geological Survey Division of Water Resources.

[2] An example includes Oak Ridge National Laboratory's Daymet, which provides daily weather and climatological summaries by interpolating and extrapolating ground-based observations through statistical modeling techniques.

- Water management, including irrigation and groundwater pumping.
- Landscape and forest management, including prescribed burns and thinning.
- Tourism, which is affected by snowpack change and extreme floods and droughts.
- Anthropogenic local aerosols, including sulfate, black carbon, dust, and biological particles.

These sectors and their associated issues affect all mountain regions in the world, particularly in developing countries where water-related conflicts and hazards are acute and legal mechanisms for resolving resource-related conflicts are not well developed. For the developed world, collaboration is equally needed to ensure that knowledge and models are transferable to different regions and water economies. In the United States, suggested priority regions include the Colorado River Basin; California and Sierra Nevada; and the Great Salt Lake, all of which could be threatened due to rapid drying. Another challenge is that current U.S.-developed hydrological models are biased toward U.S. conditions, thereby limiting their application to other continents.

In 2013, the much-cited Colorado River Water Supply and Demand study was released, which outlined what future water imbalance might look like through 2050. In hindsight, the simulated water supply missed the low-frequency variability and associated prolonged drought in the historical record. Moreover, the most recent drought (from 2020 to 2021) was worse than anything projected by those climate-hydrological models. Contributing to current water supply uncertainty is the ongoing drought impacting the Colorado River system's ability to reliably meet water allocation agreements and hydroelectric power generation targets. In addition, future rising temperatures and shifting precipitation from snow to rain could make streamflow harder to predict and water resources less reliable. Any precipitation increases that might occur would likely be offset by the impacts of warming temperatures. The key to addressing these uncertainties is developing decadal prediction as a middle ground between end-of-the-21st-century projection and seasonal prediction.

4.3.1 Societal Connections and Implications Knowledge Gaps and Challenges

Two knowledge gaps help drive societal connections and implications efforts: (1) uncertainty in water supply projection and (2) risks that shift with a forecast's initial condition.

Uncertainty in Water Supply Projection

Under a projected future climate in which the atmosphere's evaporative demand will increase and mountain precipitation consequently will shift from snow to rain, the relationship between water supply and hydroelectric power production must be understood. This key connection stems from the uncertainty in climate model simulations of processes driving low-flow conditions and their likelihood of future occurrence. For example, the U.S. Bureau of Reclamation's Colorado River (CR) operations use three types of forecasts for a 2- to 5-year time frame: CR Midterm Modeling System, CR Streamflow Forecast Testbed with the University of Colorado–Boulder, and Temperature-Informed Streamflow Projections with the National Center for Atmospheric Research (NCAR). All these forecasts produce a weighted projection of Lake Powell inflows to decrease by another 10% in the next 5 years, but the uncertainty in this projection is still large.

Another example is an experimental system developed by Utah State University that projects decadal CR water supply. This system incorporates the recent downturn but projects an overall increase, as shown in the 2013 Colorado River Water Supply and Demand study. Stakeholders have raised concerns, though, over the system's unquantified reliability and functionality (U.S. Bureau of Reclamation 2012). At the state level (e.g., Utah), the uncertainty in water supply projections for rapidly developing metropolitan areas highlights the challenge in trying to predict Utah's water supply without the ability to fully account for water allocation of the Great Salt Lake's tributaries. Consequently, scientists, decision-makers, and stakeholders

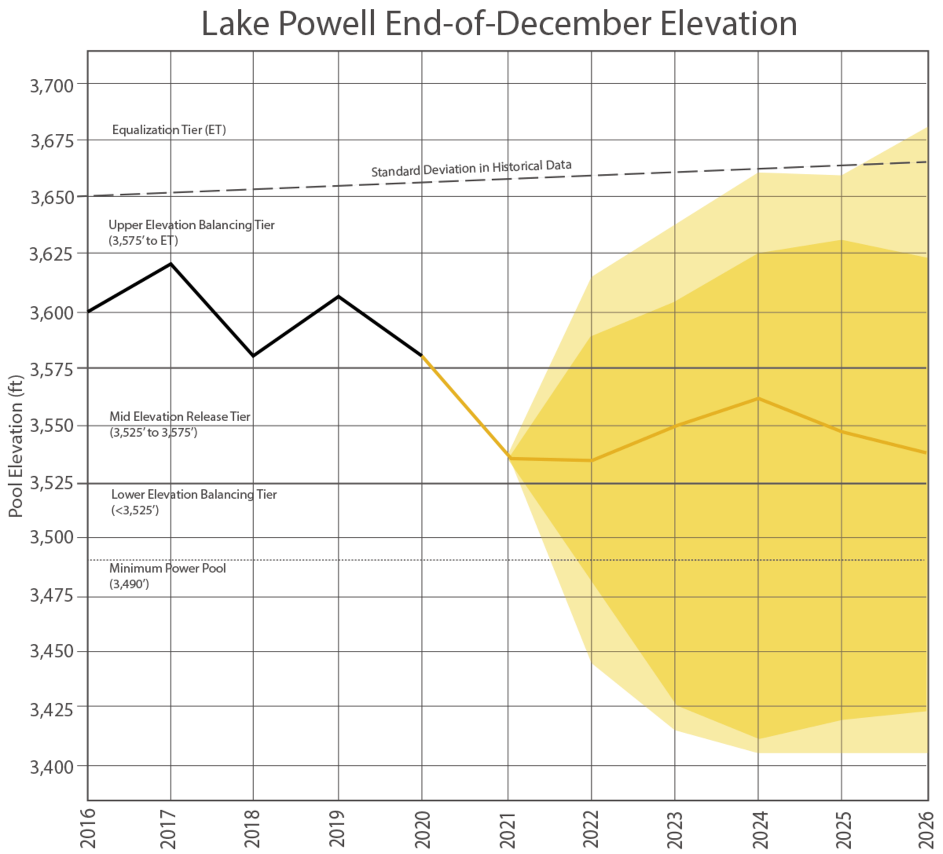


Fig. 4.2. Projections of Lake Powell Water Levels Through 2026. The colored region, or cloud, for the scenario represents the minimum and maximum of the projected reservoir elevations. Solid lines represent historical elevations (black), and median projected elevations for the scenario (yellow). The range shown in this figure may not be representative of the full range of possible conditions that could occur with different modeling assumptions. [Courtesy U.S. Bureau of Reclamation, www.usbr.gov/lc/region/g4000/riverops/crss-5year-projections.html]

face difficulties determining how to respond to a recent New York Times article that states, "As the Great Salt Lake Dries Up, Utah Faces An 'Environmental Nuclear Bomb'" (Flavell 2022).

Dealing with Risks that Shift with Initial Conditions of Forecast

The risk from uncertainty in everyday hydrological operations can be illustrated in Fig. 4.2 (this page), which shows Lake Powell's water level projection, as initialized in December 2021. An enormous spread quickly emerges from the Year 2 (2023) forecast and expands to exceed the full range of standard deviation in the historical data in Year 5 (2026). Lake Mead's projected water level also exhibits a similarly large spread (figure not shown), albeit with a more gradual error growth than the Lake Powell forecast. The challenge of large forecast variability is attributed to the initial condition of inputs fed into the forecast model. Streamflow models account for considerable details, including fine-scale and rapidly changing surface and atmospheric conditions. Utilizing too much detail to predict too far into the future ruins a forecast. Meteorologists learned this lesson in the 1950s while developing numerical weather predictions. A change in the initial conditions alters the forecast, and so having flawed initial conditions produces an impractical range of variability and errors, including the huge variability and errors for Lake Powell.

To remedy uncertainties in projections of long-range water supplies, a “get-by” solution might involve reducing the hydroclimatic factors that affect changes to large mountain river systems in the near future (i.e., 5 to 10 years). Examples of this approach include (1) the Colorado River decadal prediction system (Chikamoto et al. 2020) and (2) statistical modeling (Plucinski et al. 2019) resulting from DOE’s Hyper-FACETS—a merger of DOE’s Hyperion Project and the Framework for Analysis of Climate-Energy-Technology Systems (FACETS) project—and from Pacific Northwest National Laboratory’s Metric-Guided Model Development (U.S. Bureau of Reclamation 2021). These models’ numerical prediction framework identifies the most important factors from coupled ocean-atmosphere-land systems that affect the time-mean streamflow (e.g., annual) and then uses only these factors to predict the averaged streamflow. This approach is fundamentally different from simulating and forecasting the daily or weekly streamflow using all possible factors and then averaging the forecast streamflow for the next 5 years; the latter approach would accumulate errors rapidly, making the uncertainty too large to be useful.

Important questions associated with risk, decision-making, and adaptation are embedded in understanding how decision-making lead-time (e.g., decision is needed 10 to 20 years in the future) determines the tools used and their variability across timescales.

- **Risk**—One challenge is knowing how well the risk of a hydrological system’s future states can be estimated after the system to be forecasted shifts strongly in one direction (e.g., with reservoirs at new extremely low values). In addition, there is a need to understand whether current risk estimates adequately account for the system’s new state. Issues associated with communicating risk to stakeholders from different sectors also need to be considered.
- **Decision-Making**—Clarity is needed on how and where dam operators and water managers place confidence in climate services that include long-range climate forecasts. Also needed is an understanding of the optimal spatial variability in observations (desired versus reality) and how well landscape processes should be represented in models.
- **Adaptation**—The ideal timescales and tools needed for decision-making across scales are unclear. Stakeholders routinely face these questions and seek answers from the scientific community.

Expanding Instrumentation: Adding Surface Measurements

Reducing forecast errors requires quality model input data. For stakeholders, the installation of more observations across the western United States is vitally important, along with accurate snowpack monitoring. High-elevation automatic weather station (AWS) installations remain rare because of the combined challenges of difficult access and harsh conditions. Existing AWS data, however sparse, improves understanding of critical atmospheric processes, climatic processes, and ground-atmosphere interactions in the context of local catchments, regional hydrology, and the high-mountain cryosphere.

Most stakeholders make decisions based on existing conditions derived from *in situ* observations plus their institutional knowledge. Recent efforts to increase observations include forest managers’ expansion of weather station coverage to monitor and mitigate wildfire danger (National Wildfire Coordinating Group 2019). Stakeholders also urged the expansion of rugged, low-power measurement systems for timely monitoring in snowy climates. Preferable observation systems will measure snow depth, snow-water equivalence, air temperature, relative humidity, and wind speed and direction. Such data are useful for displaying current weather, identifying snow-making conditions, forecasting spring runoff and summer water availability, and modeling avalanche conditions. To observe environmental variables unique to a particular state, stakeholders could promote the installation of regional or state-operating weather monitoring networks, as reported by National Public Radio on March 15, 2022 (Eggers 2022).

4.3.2 Societal Connections and Implications Research Opportunities

Extended and potentially skillful projections of water supply can be developed by combining the effects of ocean precursors and long-term climate projections. The major task lies in identifying observed long-term climate change components because the current generation of climate models still exhibits large biases and deficient physics schemes. Model development requires stakeholder engagement. To strengthen stakeholder involvement in interpreting, evaluating, and applying model forecasts, scientists need to engage effectively in knowledge and data co-production, whereby researchers and stakeholders advance science together to meet real needs.

To motivate co-production between stakeholders and scientists and improve understanding of the coupled human-hydrology system, efforts should focus on identifying how climate data are used and where outstanding data needs exist. Co-production discussions subsequently inform which fields and processes are needed to address gaps, and they allow scientists to formulate metrics that enable stakeholders to understand model and dataset performance. Co-production can seek to identify which processes are most critical to model performance and investigate the relative importance of other external forces (e.g., greenhouse gas emissions, water use, or land-cover change). Past research has indicated that such added understanding frequently motivates further questions related to model credibility and facilitates a continuous cycle of engagement (Jagannathan et al. 2021).

Over the next decade, DOE could benefit from its investment in hydroclimatic research and analysis and be recognized among stakeholders and scientists as a pioneer in knowledge co-production. Use of co-production processes would improve the actionability and decision relevance of hydrological prediction research by iteratively refining research questions, objectives, methods, and deliverables. These refinements could be achieved by flexibly deploying teams of stakeholders and scientists in working groups that would iteratively collaborate on specific research challenges and deliverables. Examples of such co-produced research include addressing risk and uncertainty surrounding Colorado River water supply forecasts and drought-induced depletion of the Great Salt Lake's water supply.

When Can the Colorado River Be Relied on Again?

A co-production research project focused on the Upper Colorado River Basin is addressing the risk and uncertainty issues that plague long-range water supply forecasts. The project is identifying long-term climate change signals and model biases in simulations of hydroclimate processes using an approach that isolates the internally generated climate variability from the radiatively forced component and then adjusts model biases in future climate projections (Morgan et al. 2020). From a similar analysis, researchers can then estimate ocean-induced multiyear drought components in current and future climate conditions and apply the outcomes to develop multiyear and long-term water supply forecasts (Chikamoto et al. 2020). Another example involves a team of climate scientists and a group of Colorado River water managers who worked together to explore the "miracle spring," a high-precipitation event that unexpectedly saved a water-deficit year (Pokharel et al. 2021a). Their efforts included determining how to define and predict the elusive miracle.

Within these forecasts, scientists and stakeholders could work together and assess plausible warmer climate projections to understand what might happen to seasonal or multiyear streamflow (and subsequently hydropower production) under different conditions. Scenarios might examine, for instance, the timings of decreased snowpack accumulation, peak snowmelt shifts earlier in the water year, or low-to-no snow conditions that persist for decades at a time. By working routinely with water management personnel (through DOE sponsorship), scientists could assess reservoir storage (i.e., surplus and deficit) behavior as a function of inflows and demand, both current and projected.

The minimum active storage pool could then be used as an operations guide to estimate supply and demand imbalances and subsequent climate risks.

When Will the Great Salt Lake Go Dry?

Another example of co-production research involves collaborations between researchers and local water managers to address the Great Salt Lake's depleting water supply amid the recent drought, which has spurred media coverage since 2021. For example, the New York Times reported that "climate change and rapid population growth are shrinking the lake, creating a bowl of toxic dust that could poison the air around Salt Lake City" (Flavell 2022). Additionally, the Weather Channel stated that the "Great Salt Lake in Utah is projected to drop to a new record low this year after hitting a record low last year" (Bonaccorso 2022), and CNN announced the "Great Salt Lake is shrinking fast. Scientists demand action before it becomes a toxic dustbin" (Kafanov et al. 2021). Recently, a local politician made national headlines with his drastic solution to save the lake—"Desperate Lawmakers Discuss Piping Ocean Water to Fill Great Salt Lake" (Taft 2022).

While the lake itself has significant ecological and environmental impacts, it also serves as a gauge for underground water storage. Agriculture accounts for about 80% of Utah's water use, and 80% of agriculture irrigation uses groundwater. At the decadal timescale, the Great Salt Lake's elevation changes commensurately with northern Utah's groundwater fluctuation (Hakala 2014; Masbruch et al. 2016) and the Colorado River's water supply (Wang, S.-Y. et al. 2018), making the lake a vital indicator of the intermountain region's subsurface water resource. Researchers have used statistical methods to try to predict the Great Salt Lake's future (Gillies et al. 2015), but projections using an integrated hydroclimatic modeling approach are lacking, highlighting this topic as a priority for future DOE research.

The only way for humans to modify natural water sources and shift initial conditions is through weather modification techniques, such as cloud seeding (i.e., wintertime orographic glaciogenic precipitation enhancement). Various western states have conducted cloud seeding operations for decades in hopes of gaining more water during droughts (Williams 2022). While seeding orographic clouds can lead to quantifiable precipitation increases, recent research suggests that high-resolution weather models and complex statistical techniques can help evaluate the effectiveness of cloud seeding programs. Thus, the future could be very prosperous for seeding operations (Tessendorf et al. 2015). Scientific investigation involving stakeholder participation and engagement has occurred in Wyoming and Utah (Pokharel et al. 2020) through collaborations with local water conservation districts.

Cloud seeding continues to be popular and is sponsored by most electric companies (e.g., Idaho Power Company and PacifiCorp). Despite this sustained popularity, insights into its effect on increasing winter precipitation remain elusive and scientifically uncertain. DOE support for research to quantify the effects and uncertainty of western U.S. cloud seeding is therefore important. Another research opportunity involves assessing the performance of ground-based cloud seeding programs. These programs use generators that release microscopic particles into clouds to act as nuclei for ice crystal formation. Because this process works best once the clouds reach a mountain barrier, where rapidly lifting and cooling winds help turn clouds into snow, the precise location of these generators is critically important. Without a scientific baseline, there is no way to know whether the program's performance might be improved by moving the generators to more suitable locations.

Finally, in a warming climate, some mountains have gained seeding suitability and others have lost it. In Lower Basin states, the U.S. Bureau of Reclamation and the Utah Division of Water Resources are working together to support scientific research into cloud seeding (Pokharel et al. 2021b). However, regional and integrated research is needed to assess the degree of future water gains through cloud seeding.

Death Valley, Calif.
Courtesy Adobe Stock

Chapter 5

Integrated Activities

5 Integrated Activities

Extreme events across spatial and temporal scales are fundamental characteristics of integrated mountain hydroclimate (IMHC) systems. Addressing the scientific challenges within these systems requires integrated research efforts essential for predicting and understanding the role of IMHC systems and their feedbacks and impacts on humans across scales. Integrated activities are key factors in three crosscutting topics that emerged from the disciplinary, cross-disciplinary, and crosscutting workshop discussions: extreme events, transferable knowledge, and actionable science. These topics further emphasize the cross-disciplinary nature of IMHC challenges and represent example science questions that the community can address together.

5.1 Extreme Events

Science Questions

How are extreme events defined, and what integrated activities may help advance observation and modeling of these events in mountain regions, including their upstream influence and downstream impacts?

Extreme events and disturbances are typically defined relative to an historical baseline, but this definition does not necessarily translate into their impacts. The research community broadly agrees on the need to redefine extreme events in terms of their impacts, as determined by stakeholders based on the unique characteristics of each mountain system. Stakeholder perspectives include topics on miracle springs, large dust storms and wildfires, extreme runoff, and megadroughts and provide input on research to consider the full realm of impacts spanning vegetation to water quality. Also significant are the sequencing of extreme events and compounding disturbances. Using extreme-producing phenomena as a central focus for investigating processes and impacts presents several opportunities: (1) designing experiments and field sites with extreme events as the central motivating research factor, (2) developing flexible and rapidly deployable mobile platforms and field campaigns, (3) investing in long-term collaborative research stations and networks across different global mountain regions, and (4) developing venues for improving interactions between scientists and stakeholders.

5.2 Transferable Knowledge

Science Question

How can knowledge transfer be enabled through integrated activities across mountain regions with different geographies, topographic features, climate and hydrological regimes, human systems, and socioeconomics?

Mountains exert dominant influences on atmospheric and terrestrial processes through their impacts on atmospheric circulation, clouds and precipitation, and surface fluxes. As a result, mountain hydroclimates share many similarities, but they also differ in their local-to-large-scale environments as well as surface and subsurface properties. Human systems and their management also vary depending on communities and geopolitical context. To enable knowledge transfer, three short-term opportunities exist with current data and modeling tools: (1) leveraging "network-of-network" groups to explore existing datasets across global observatories and identify process drivers, especially for regions that can be compared based on similarities and uniqueness; (2) designing model simulations to inform new measurements needed for different communities; and (3) conducting model intercomparison studies across scales and locations to inform drivers and responses to change.

5.3 Actionable Science

Science Questions

What integrated activities may help advance use-inspired research and actionable science for mountain regions? Do stakeholders have concerns that are more unique to mountain regions, and if so, what are these concerns?

Providing predictions and projections to support actionable science requires identifying and minimizing biases in two areas: (1) dynamical simulations are subject to uncertainties and errors due to physics parameterizations, model resolutions, and simulation design and (2) observations are subject to sampling errors, uncertainties in retrieval algorithms, and instrument inaccuracies. Stakeholder engagements provide important opportunities to advance actionable science by defining the requirements and needs for simulations and observation data, co-producing knowledge and data, and developing regional themes around extreme events that have disproportionate societal impacts. A research opportunity also exists to leverage current stakeholder engagements to improve understanding of the means, variabilities, and extremes of mountain hydroclimate and to quantify risk tolerance in the decision-making process.

East River Watershed, Crested Butte, Colo.
Courtesy Jeremy Snyder, Lawrence Berkeley National Laboratory

Chapter 6

Interagency Collaboration Opportunities

6 Interagency Collaboration Opportunities

During Session 2 of the workshop (January 19, 2022)—which focused on interagency collaborations—federal and federally funded scientists shared information on projects and research relevant to integrated mountain hydroclimate (IMHC) across various agencies (see Appendix A: Agenda, p. 63). The workshop's morning session focused on three disciplinary areas, with panels on atmosphere-terrestrial-human (ATH) system interactions. The afternoon session featured panels on three crosscutting topics that were discussed during the November 2021 workshop: ATH system interactions; climate variability and change in mountain systems; and societal implications of IMHC.

Panelists shared project and research information and commented on potential interagency opportunities, such as how other agencies and projects could assist with IMHC challenges and provide ways to leverage or synergize current DOE-supported research.

6.1 Interagency Opportunities in Disciplinary Science

6.1.1 Atmosphere Panel

Panelists highlighted a broad range of ongoing activities to develop understanding of key physical quantities connecting atmosphere and surface;[1] advance understanding and modeling of water cycle processes and extreme events;[2] parameterize heterogeneous subgrid exchange between land and atmosphere;[3] and understand the 4D evolution of processes controlling convective life cycle and impacts near complex terrain.[4]

Panelists also discussed DOE's Energy Exascale Earth System Model (E3SM)—a modeling, simulation, and prediction project that focuses on the water cycle, biogeochemical cycle, and cryosphere processes. Ultimately, they noted that both observations and modeling are key elements of these projects and identified several opportunities for future collaborations. Prospects included developing datasets for model evaluation, conducting model intercomparisons, integrating data across multiple measurement platforms, modeling across scales (e.g., large eddy simulations to Earth system models), implementing model-data fusion, developing analysis and diagnostic tools, and enhancing observation networks.

6.1.2 Terrestrial Panel

Panelists from many local, state, federal, and research network groups presented their ongoing projects and work, discussed a wide range of activities,[5] and highlighted current collaborations across all groups. The panel's focus was to highlight potential requirements for successful collaboration, and many synergistic ideas emerged. Examples included ensuring that lines of communication, trust, and sharing are clear and central to the collaborative vision; coordinating activities around common field sites and models with a goal of co-creating joint outputs (e.g., symposia and publications); and developing a shared vision for core

---

[1] NOAA's Study of Precipitation, the Lower Atmosphere, and Surface for Hydrometeorology (SPLASH) program.

[2] DOE's Water Cycle and Climate Extremes Modeling (WACCEM) Science Focus Area (SFA) and Energy Exascale Earth System Model (E3SM).

[3] Coupling of Land and Atmospheric Subgrid Parameterizations (CLASP), a collaborative project funded by NASA, NOAA, and DOE.

[4] Multi-agency collaboration between NSF, DOE, NASA, and NOAA involving DOE's Clouds, Aerosols, and Complex Terrain Interactions (CACTI) field campaign and NSF's Remote sensing of Electrification, Lightning, And Mesoscale/microscale Processes with Adaptive Ground Observations (RELAMPAGO) campaign.

[5] DOE's Watershed Function SFA and Floodplain Hydro-biogeochemistry SFA; NSF's Long-Term Ecological Research (LTER) program at the H. J. Andrews Experimental Forest and the Critical Zone Collaborative Network's (CZNet) Dynamic Water cluster; the U.S. Geological Survey's Integrated Water Prediction (IWP) program; and NASA's SnowEx program.

integrated critical zone and water experiments (field and modeling) across multiple scales.

6.1.3 Human Systems Panel

Panelists introduced three DOE-funded projects[6] featuring development and use of integrated modeling tools and analysis methods to advance understanding of coupled human-physical systems; their complex interactions; their risk and response behaviors; and their evolution, vulnerability, and resilience. Understanding and quantifying uncertainty are common challenges in these projects.

Panelists also discussed the Integrated Climate and Land-Use Scenarios (ICLUS) project, an effort funded by the U.S. Environmental Protection Agency that produces population and land-use projections to inform national global change assessments. Ultimately, broad collaborations are critical for bridging disciplinary methods, tools, and concepts to address complex interactions. Moreover, sharing data, tools, and models facilitates collaborations within teams and with the broader research community. Also key to successful collaborations are open-source models; the principles of findability, accessibility, interoperability, and reusability (FAIR); diverse modes of communications; and building communities of practice.

6.2 Interagency Opportunities in Crosscutting Topics

6.2.1 ATH Interactions Panel

Panelists were representatives from many different federal programs with projects focusing, in some form, on various aspects of mountain systems.[7] Topics included developing advanced hydroclimate modeling tools, evaluating the interdependence of natural and human systems and the implications to decision-making capabilities, and advancing efforts to fill in broad data gaps. Panelists also discussed opportunities for collaborative research across ATH systems. Such prospects included sharing data compilations, choosing watersheds as "model basins," developing co-investments in data and model intercomparison projects and network-of-networks grassroots groups, and recognizing lack of subsurface observations as one of the largest data gaps for modeling. Many teams noted that several projects are already poised to facilitate successful collaborations and that these collaborations that could operate as funded and nonfunded endeavors. For example, the U.S. Geological Survey's (USGS) Integrated Water Prediction (IWP) program uses a "teams-of-teams" approach to collaborate across agencies, while other programs collaborate through co-investments and directed funding.

Finally, panelists considered the critical work still needed to facilitate collaborative research. Such activities included building and expanding linkages to state and local agencies, deciding collectively on next-generation observatories and modeling tools (e.g., artificial intelligence and machine learning approaches), and navigating the collaborative process with expert project coordinators.

6.2.2 IMHC Variability and Change Panel

Panelists introduced a diverse set of projects funded by multiple agencies. These projects aim to improve modeling of subgrid land-atmosphere coupling;[8] understand how warming affects ecohydroclimatology of mountain systems;[9] co-define climate change refugia to inform management of mountain headwater systems[10]; improve understanding of fundamental hydrological and ecological processes and interactions;[11] advance understanding of natural and anthropogenic influences on climate extremes;[12] enhance

---

[6] The Program on Coupled Human and Earth Systems (PCHES); the Integrated Multisector, Multiscale Modeling (IM3) SFA; and the Global Change Intersectoral Modeling System (GCIMS). All are funded under DOE's MultiSector Dynamics (MSD) program.

[7] U.S. Geological Survey's Integrated Water Prediction and Predictive Understanding of Multiscale Processes (IWP–PUMP) project; Established Program to Stimulate Competitive Research (EPSCoR), and DOE BER activities, such as the Surface Atmosphere Integrated field Laboratory (SAIL) and the Watershed Function and IM3 SFAs.

[8] The Coupling of Land and Atmospheric Subgrid Parameterizations (CLASP), a collaborative project funded by NASA, NOAA, and DOE.

[9] NSF's Niwot Ridge Long-Term Ecological Research program (NWT LTER).

[10] An NSF-funded collaborative research effort.

[11] The U.S. Forest Service's Coweeta Hydrologic Laboratory.

[12] DOE's Calibrated and Systematic Characterization, Attribution, and Detection of Extremes (CASCADE) project.

actionable climate science;[13] and understand and characterize the water, energy, and carbon cycles in the Anthropocene.[14]

Within the project teams, research needs are driving broad collaborations. These needs include integrating observations from multiple platforms and sampling strategies, modeling across scales, and developing and using new diagnostics and analysis tools. Several projects strongly engage stakeholders for knowledge co-production. Additional opportunities include different forms and topics of collaborations (e.g., observation, model, and forecast intercomparisons; use of field campaign data; and cross-site syntheses).

6.2.3 Societal Connections Panel

Panelists highlighted the need for Research-2-Operations (R2O) and Operations-2-Research (O2R) development cycles. Speakers from the DOE HyperFACETS project, U.S. Bureau of Reclamation, National Oceanic and Atmospheric Administration (NOAA), National Integrated Drought Information System (NIDIS), USGS, and the National Science Foundation (NSF) presented program and project updates and opportunities for collaborations. Topics included using new cloud seeding approaches to enhance precipitation in the western United States, managing drought risks and impacts, and understanding water storage in mountain catchments. All speakers highlighted the need to improve observational datasets, enhance numerical tools, pilot operational products, and assess model deficiencies that limit the skill of water prediction—specifically using an iterative R2O/O2R development life cycle.

The success of these efforts depends on access to new funding opportunities that concentrate on collaboration. Success also requires all collaborators work together to understand the prediction problem from end to end, deliver enhanced capabilities to specific stakeholders, work closely with end users and local partners, learn the environment of stakeholders and end users, and adopt a systems-engineering focus to research. Furthermore, an approach geared toward stakeholder co-production of research will require guiding research activities through iterative discussions and decision-relevant metrics that are established before the research begins. When stakeholder needs move in different directions, maintaining a flexible approach that supports scientific adaptations will also be critical.

6.3 Opportunities for Interagency Collaboration

Program managers from NSF, NASA, NOAA, and USGS shared agency or programmatic interests in IMHC and discussed opportunities or synergies for partnerships with IMHC research projects. In reflecting on key takeaways for collaborations, panelists remarked that many forms of collaborations across smaller and larger projects have grown organically within and across agencies. The discussion also highlighted specific needs underpinning productive collaborations.

For example, more multidisciplinary experts are needed to integrate research spanning the diverse processes and interactions characteristic of mountain hydroclimates. Increased stakeholder engagement will require appropriate expertise and funding support. Also needed are innovative techniques, designs, and strategies for data collection (including concurrent and co-located measurements), data sharing, storage, and management. Additionally, diverse and inclusive approaches for innovative research should be adequately supported, and research collaborations should prioritize open science, interoperable models, and the FAIR principles.

Evaluating the business models of successful collaborations—including both bottom-up and top-down approaches—could benefit the planning and development efforts of new partnerships. Future collaborations also will require adequate research support and infrastructure, access to sustained funding, and robust long-term visions to provide continuity. New partnerships will need to define priority regions on which to focus resources and address any operational challenges that emerge with cross-program and cross-agency collaboration.

---

[13] DOE's E3SM and the HyperFACETS project, a merger of DOE's Hyperion Project and Framework for Analysis of Climate-Energy-Technology Systems (FACETS) effort.

[14] The Global Energy and Water Exchanges (GEWEX) project's Regional Hydroclimate Project (RHP).

Shasta Dam, Calif.
Courtesy Adobe Stock

Appendices

Appendix A: Agenda

Session 1: DOE Focus

Day 1 (November 15, 2021)

**All times Eastern Standard Time*

11:00 a.m. **Introduction, Meeting Expectations, Workshop Charge**
Michelle Newcomer (Lawrence Berkeley National Laboratory), Kristen Rasmussen (Colorado State University), L. Ruby Leung (Pacific Northwest National Laboratory)

11:15 a.m. **Welcome and Context from DOE**
Gerald Geernaert and Jennifer Arrigo (U.S. Department of Energy)

11:30 a.m. **Day 1 Plenary: Systems Perspectives and Stage-Setting Talks**

- **Terrestrial Systems**
  Ying Fan Reinfelder (Rutgers University)
- **Human Systems**
  James Eklund (Eklund Hanlon, LLC)
- **Atmospheric Systems**
  Roy Rasmussen (National Center for Atmospheric Research)

12:30 p.m. **Break and Charge to Breakouts**

12:55 p.m. **Breakout #1: Disciplinary Groups**

- **Atmospheric Systems**
  Co-Leads: Adam Varble (Pacific Northwest National Laboratory), Alan Rhoades (Lawrence Berkeley National Laboratory)
  Panelists: Ana Barros (University of Illinois, Urbana-Champaign), Nikolina Ban (University of Innsbruck, Austria), Benjamin Hatchett (Desert Research Institute), Justin Minder (University at Albany)
- **Terrestrial Systems**
  Co-Leads: Matthias Sprenger (Lawrence Berkeley National Laboratory), Nathaniel Chaney (Duke University)
  Panelists: Hoori Ajami (University of California, Riverside), Teklu Tesfa (Pacific Northwest National Laboratory), Daniella Rempe (University of Texas, Austin), Noah Molotch (University of Colorado, Boulder)
- **Human Systems**
  Co-Leads: Nathalie Voisin (Pacific Northwest National Laboratory), Andrew Jones (Lawrence Berkeley National Laboratory)
  Panelists: Jeffrey Arnold (U.S. Army Corps of Engineers), Alejandro Flores (Boise State University), Nathalie Voisin, Mark Wigmosta (Pacific Northwest National Laboratory)

2:30 p.m. **Break**

2:45 p.m. **Breakout #2: Cross-Disciplinary Groups**

- **Atmosphere–Terrestrial Systems**
  Susan Hubbard (Lawrence Berkeley National Laboratory), Alex Hall (University of California, Los Angeles), Gautam Bisht (Pacific Northwest National Laboratory), Jessica Lundquist (University of Washington), James McNamara (Boise State University)
- **Terrestrial–Human Systems**
  Peter Nico, Charuleka Varadharajan (Lawrence Berkeley National Laboratory), Charles Luce (U.S. Forest Service), Jon Herman (University of California, Davis)
- **Human–Atmosphere Systems**
  Christine Shields (National Center for Atmospheric Research), Yun Qian (Pacific Northwest National Laboratory), Simon S.Y. Wang (Utah State University), Kristen Rasmussen (Colorado State University)

4:00 p.m. **Break**

4:15 p.m. **Report-Out from Breakout Sessions #1 and #2; Identify Integrated Research Topics (For Day 2, Breakout #4)**

Day 2 (November 16, 2021)

**All times Eastern Standard Time*

11:30 a.m. **Day 2 Plenary: Crosscutting Themes**

- **Atmosphere-Terrestrial-Human System Interactions**
  Ian Kraucunas (Pacific Northwest National Laboratory)
- **IMHC Climate Variability and Change**
  Ben Livneh (University of Colorado, Boulder)
- **Societal Connections**
  Andrew Jones (Lawrence Berkeley National Laboratory)

12:30 p.m. **Breakout #3: Crosscutting Themes**

- **Atmosphere–Terrestrial-Human System Interactions**
  Co-Leads: Peter Thornton (Oak Ridge National Laboratory), Naresh Devineni (The City College of New York), Andreas Prein (National Center for Atmospheric Research)
  Panelist: Nina Oakley (University of California, San Diego)
- **IMHC Climate Variability and Change**
  Co-Leads: Erica Siirila-Woodburn (Lawrence Berkeley National Laboratory), Paul Ullrich (University of California, Davis), Ning Sun (Pacific Northwest National Laboratory)
  Panelists: Adrienne Marshall (Colorado School of Mines), Daniel Feldman (Lawrence Berkeley National Laboratory), L. Ruby Leung, Xiaodong Chen (Pacific Northwest National Laboratory)

- **Societal Connections**
  Co-Leads: McKenzie Skiles (University of Utah), Simon S.Y. Wang (Utah State University), Ian Kraucunas (Pacific Northwest National Laboratory)
  Panelists: Jim Prairie (U.S. Bureau of Reclamation), Daniella Hirschfeld (Utah State University), Jake Serago (Utah Division of Water Resources), Michelle Newcomer (Lawrence Berkeley National Laboratory), Ning Sun (Pacific Northwest National Laboratory)

2:00 p.m. **Break**

2:30 p.m. **Breakout #4: Integrated Research Activities**

- **Group A**
  Breakout Leads: Peter Thornton (Oak Ridge National Laboratory), Erica Siirila-Woodburn (Lawrence Berkeley National Laboratory), Simon S.Y. Wang (Utah State University)
- **Group B**
  Breakout Leads: Naresh Devineni (The City College of New York), Paul Ullrich (University of California, Davis), McKenzie Skiles (University of Utah)
- **Group C**
  Breakout Leads: Andreas Prein (National Center for Atmospheric Research); Ning Sun, Ian Kraucunas (Pacific Northwest National Laboratory)

4:00 p.m. **Break**

4:15 p.m. **Report-Out from Breakout Sessions #3 and #4**

5:00 p.m. **Open Discussion and Closing Remarks**

Session 2: Interagency Collaborations

(January 19, 2022)

**All times Eastern Standard Time*

11:00 a.m. **Opening Session**

- **Welcome from Workshop Co-Chairs**
  L. Ruby Leung (Pacific Northwest National Laboratory), Michelle Newcomer (Lawrence Berkeley National Laboratory), Kristen Rasmussen (Colorado State University)
- **Welcome and Perspectives on IMHC from DOE**
  Gerald Geernaert (U.S. Department of Energy)
- **IMHC in the DOE EESSD Portfolio**
  Jennifer Arrigo (U.S. Department of Energy)
- **IMHC Workshop Session 1 Summary**
  L. Ruby Leung, Michelle Newcomer, Kristen Rasmussen

11:55 a.m. **Break and Transition to Panels**

IMHC Disciplinary Sessions

Federal and federally funded scientists share information on IMHC-relevant projects and research across various federal agencies in three disciplinary areas. Each panelist shared project or research information and commented on potential interagency opportunities (e.g., challenges that other agencies and projects could help with as well as leveraging or synergy opportunities).

12:00 p.m. **Atmosphere Panel**

- **SPLASH**, *funded by NOAA*
  Gijs de Boer (National Oceanic and Atmospheric Administration)
- **E3SM, HyperFACETS, ICOM, WACCEM**, *funded by DOE*
  L. Ruby Leung (Pacific Northwest National Laboratory)
- **Climate Process Teams,** *funded by NSF, NOAA, and DOE*
  Po-Lun Ma (Pacific Northwest National Laboratory)
- **RELEMPAGO/CACTI**, *funded by NSF and DOE*
  Steve Nesbitt (University of Illinois, Urbana-Champaign)
- **Wildfire Smoke, Missoula Fire Sciences Laboratory**, *funded by U.S. Forest Service*
  Shawn Urbanski (U.S. Forest Service)

12:40 p.m. **Terrestrial Panel**

- **Floodplain Hydro-Biogeochemistry Science Focus Area**, *funded by DOE*
  John Bargar (SLAC National Accelerator Laboratory)
- **CZNet Dynamic Water**, *funded by NSF*
  Holly Barnard, University of Colorado, Boulder
- **Integrated Water Science Basins**, *funded by U.S. Geological Survey*
  Katherine Skalak (U.S. Geological Survey)
- **H.J. Andrews Experimental Forest,** *funded by U.S. Forest Service*
  Brooke Penaluna (U.S. Forest Service)
- **Modeling Mountain Land Surface Processes**, *funded by DOE*
  Peter Thornton (Oak Ridge National Laboratory)
- **SnowEx**, *funded by NASA*
  Carrie Vuyovich (NASA)

1:20 p.m. **Human Systems Panel**

- **PCHES**, *funded by DOE*
  Danielle Grogan (University of New Hampshire)
- **Terrestrial Ecology Program**, *funded by NASA*
  Kathy Hibbard (NASA)
- **HyperFACETS**, *funded by DOE*
  Andrew Jones (Lawrence Berkeley National Laboratory)

- **ICLUS**, *funded by the U.S. Environmental Protection Agency*
  Philip Morefield (U.S. Environmental Protection Agency)
- **IM3**, *funded by DOE*
  Patrick Reed, Cornell University
- **GCIMS**, *funded by DOE*
  Thomas Wild (Pacific Northwest National Laboratory)

2:00 p.m. **Break**

IMHC Crosscutting Sessions
Federal and federally funded scientists share information on IMHC-relevant projects and research across various federal agencies in three crosscutting topics. Each panelist shared project or research information and commented on potential interagency opportunities (e.g., challenges that other agencies and projects could help with as well as leveraging or synergy opportunities).

2:15 p.m. **Atmosphere-Terrestrial-Human (ATH) System Interactions**

- **Integrated Water Prediction (IWS)–PUMP**, *funded by U.S. Geological Survey*
  Hedeff Essaid (U.S. Geological Survey)
- **SAIL**, *funded by DOE*
  Daniel Feldman (Lawrence Berkeley National Laboratory)
- **Investigating Subsurface Flow in Mountainous Catchments**, *funded by DOE EPSCoR*
  Payton Gardner (University of Montana)
- **Watershed Function SFA, East River Community Watershed**, *funded by DOE*
  Kenneth Hurst Williams (Lawrence Berkeley National Laboratory)
- **Modeling ATH Interactions,** *funded by DOE*
  Nathalie Voisin (Pacific Northwest National Laboratory)

2:55 p.m. **Climate Variability and Change in Mountain Systems**

- **Interagency Climate Process Teams**, *funded by DOE, NOAA, and NSF*
  Nathaniel Chaney (Duke University), Po-Lun Ma (Pacific Northwest National Laboratory)
- **Niwot Ridge LTER**, *funded by NSF*
  Noah Molotch (University of Colorado, Boulder)
- **Co-Defining Climate Refugia to Inform the Management of Mountain Headwater Systems**, *funded by NSF*
  Keith Musselman (University of Colorado, Boulder)
- **Coweeta Hydrologic Laboratory**, *funded by U.S. Forest Service*
  Andrew Christopher Oishi (U.S. Forest Service)
- **CASCADE,** *funded by DOE*
  Alan Rhoades (Lawrence Berkeley National Laboratory)

- **U.S. Regional Hydroclimate Project Affinity Group**, *funded by GEWEX*
  Tim Schneider (National Center for Atmospheric Research)

3:35 p.m. **Societal Implications of IMHC**

- **Upper Gunnison (CO) Research on Weather Modification**, *funded by U.S. Bureau of Reclamation*
  Lindsay Bearup (U.S. Bureau of Reclamation)
- **ASO and Forecasting,** *funded by NSF*
  David Gochis (National Center for Atmospheric Research)
- **HyperFACETS,** *funded by DOE*
  Andrew Jones (Lawrence Berkeley National Laboratory)
- **Drought/NIDIS**, *funded by NOAA*
  Joel Lisonbee (National Oceanic and Atmospheric Administration)
- **New Science, Tools, and Observations to Couple Geodesy with Hydrology for Modeling, Water Storage Change, and Streamflow Forecasting in Mountain Watersheds**, *funded by NSF*
  Hilary Martens (University of Montana)

4:15 p.m. **Break**

4:30 p.m. **Program Manager Panel**
Each agency panelist is asked to provide 3 to 5 minutes of opening remarks to share agency/programmatic interests in IMHC and to discuss opportunities or synergies they identified for their agency/program from the IMHC science presented during the earlier part of the day.

Moderator: Jennifer Arrigo (U.S. Department of Energy)
Panelists: Nicholas Anderson, Laura Lautz (National Science Foundation); Jared Entin (NASA), Jin Huang (National Oceanic and Atmospheric Administration), David Lesmes (U.S. Geological Survey)

5:15 p.m. **Final Remarks/Discussion**

5:30 p.m. **Adjourn**

Appendix B: Participants

Session 1: DOE Focus
(November 15–16, 2021)

Hoori Ajami
University of California, Riverside

Jeffrey Arnold
U.S. Army Corps of Engineers

Bhavna Arora
Lawrence Berkeley National Laboratory

Nikolina Ban
University of Innsbruck, Austria

Ana Barros
University of Illinois, Urbana-Champaign

Katrina Bennett
Los Alamos National Laboratory

Brian Benscoter
U.S. Department of Energy

Gautam Bisht
Pacific Northwest National Laboratory

Peter Blanken
University of Colorado, Boulder

Paul Brooks
University of Utah

Kate Calvin
Pacific Northwest National Laboratory

Nathaniel Chaney
Duke University

Xiaodong Chen
Pacific Northwest National Laboratory

William Collins
Lawrence Berkeley National Laboratory

Nicoleta Cristea
University of Washington

Xujing Davis
U.S. Department of Energy

P. James Dennedy-Frank
Lawrence Berkeley National Laboratory

Naresh Devineni
The City College of New York

James Eklund
Eklund Hanlon, LLC

Daniel Feldman
Lawrence Berkeley National Laboratory

Alejandro Flores
Boise State University

Efi Foufoula-Georgiou
University of California, Irvine

Gerald Geernaert
U.S. Department of Energy

Bart Geerts
University of Wyoming

David Gochis
National Center for Atmospheric Research

Ethan Gutmann
National Center for Atmospheric Research

Alex Hall
University of California, Los Angeles

Benjamin Hatchett
Desert Research Institute

Jon Herman
University of California, Davis

Daniella Hirschfeld
Utah State University

Justin Hnilo
U.S. Department of Energy

Susan Hubbard
Lawrence Berkeley National Laboratory

Kripa Jagannathan
Lawrence Berkeley National Laboratory

Andrew Jones
Lawrence Berkeley National Laboratory

Renu Joseph
U.S. Department of Energy

Daniel Kirshbaum
McGill University

Ian Kraucunas
Pacific Northwest National Laboratory

L. Ruby Leung
Pacific Northwest National Laboratory

Ben Livneh
University of Colorado, Boulder

Charles Luce
U.S. Forest Service

Jessica Lundquist
University of Washington

Po-Lun Ma
Pacific Northwest National Laboratory

Andrew Manning
U.S. Geological Survey

Adrienne Marshall
Colorado School of Mines

Melanie Mayes
Oak Ridge National Laboratory

Rachel McCrary
National Center for Atmospheric Research

Sally McFarlane
U.S. Department of Energy

James McNamara
Boise State University

Justin Minder
University at Albany

Noah Molotch
University of Colorado, Boulder

Michelle Newcomer
Lawrence Berkeley National Laboratory

Peter Nico
Lawrence Berkeley National Laboratory

Nina Oakley
University of California, San Diego

Jim Prairie
U.S. Bureau of Reclamation

Andreas Prein
National Center for Atmospheric Research

Yun Qian
Pacific Northwest National Laboratory

Mark Raleigh
Oregon State University

Kristen Rasmussen
Colorado State University

Roy Rasmussen
National Center for Atmospheric Research

Patrick Reed
Cornell University

Ying Fan Reinfelder
Rutgers University

Daniella Rempe
University of Texas, Austin

Alan Rhoades
Lawrence Berkeley National Laboratory

Angela Rowe
University of Wisconsin, Madison

Koichi Sakaguchi
Pacific Northwest National Laboratory

Tim Scheibe
Pacific Northwest National Laboratory

Adam Schneider
University of California, Irvine

Jake Serago
Utah Division of Water Resources

Christine Shields
National Center for Atmospheric Research

Erica Siirila-Woodburn
Lawrence Berkeley National Laboratory

McKenzie Skiles
University of Utah

Lauren Somers
Dalhousie University, Canada

Matthias Sprenger
Lawrence Berkeley National Laboratory

Daniel Stover
U.S. Department of Energy

Ning Sun
Pacific Northwest National Laboratory

Teklu Tesfa
Pacific Northwest National Laboratory

James Thornton
Mountain Research Initiative, Switzerland

Peter Thornton
Oak Ridge National Laboratory

Hoang Tran
Princeton University

Olga Tweedy
U.S. Department of Energy

Paul Ullrich
University of California, Davis

Bob Vallario
U.S. Department of Energy

Charuleka Varadharajan
Lawrence Berkeley National Laboratory

Adam Varble
Pacific Northwest National Laboratory

Nathalie Voisin
Pacific Northwest National Laboratory

Simon S.Y. Wang
Utah State University

Mark Wigmosta
Pacific Northwest National Laboratory

Kenneth Hurst Williams
Lawrence Berkeley National Laboratory

Charles Zender
University of California, Irvine

Yunyan Zhang
Lawrence Livermore National Laboratory

Session 2: Interagency Collaborations

(January 19, 2022)

Deb Agarwal
Lawrence Berkeley National Laboratory

Allison Aiken
Los Alamos National Laboratory

Hoori Ajami
University of California, Riverside

Nicholas Anderson
National Science Foundation

Bhavna Arora
Lawrence Berkeley National Laboratory

Jennifer Arrigo
U.S. Department of Energy

Nikolina Ban
University of Innsbruck, Austria

John Bargar
SLAC National Accelerator Laboratory

Holly Barnard
University of Colorado, Boulder

Paul Bayer
U.S. Department of Energy

Lindsay Bearup
U.S. Bureau of Reclamation

Katrina Bennett
Los Alamos National Laboratory

Brian Benscoter
U.S. Department of Energy

Gautam Bisht
Pacific Northwest National Laboratory

Gabrielle Boisrame
Desert Research Institute

Kristin Boye
SLAC National Accelerator Laboratory

Elizabeth Boyer
The Pennsylvania State University

Eoin Brodie
Lawrence Berkeley National Laboratory

Casey Burleyson
Pacific Northwest National Laboratory

Rosemary Carroll
Desert Research Institute

Nathaniel Chaney
Duke University

Xiaodong Chen
Pacific Northwest National Laboratory

Rob Cifelli
National Oceanic and Atmospheric Administration

Brian Colle
Stony Brook University

William Collins
Lawrence Berkeley National Laboratory

Nicoleta Cristea
University of Washington

Xujing Davis
U.S. Department of Energy

Gijs de Boer
National Oceanic and Atmospheric Administration

Jeffrey Deems
National Snow and Ice Data Center

P. James Dennedy-Frank
Lawrence Berkeley National Laboratory

Naresh Devineni
The City College of New York

Dipankar Dwivedi
Lawrence Berkeley National Laboratory

Ardeshir Ebtehaj
University of Minnesota, Twin Cities

Jared Entin
National Aeronautics and Space Administration

Hedeff Essaid
U.S. Geological Survey

Daniel Feldman
Lawrence Berkeley National Laboratory

Karen Fisher-Vanden
The Pennsylvania State University

Alejandro Flores
Boise State University

Efi Foufoula-Georgiou
University of California, Irvine

Payton Gardner
University of Montana

Gerald Geernaert
U.S. Department of Energy

David Gochis
National Center for Atmospheric Research

Aaron Grade
U.S. Department of Energy

Danielle Grogan
University of New Hampshire

Yu Gu
National Science Foundation

Abhinav Gupta
Desert Research Institute

Ethan Gutmann
National Center for Atmospheric Research

Samson Hagos
Pacific Northwest National Laboratory

Alex Hall
University of California, Los Angeles

Benjamin Hatchett
Desert Research Institute

Kathy Hibbard
National Aeronautics and Space Administration

Justin Hnilo
U.S. Department of Energy

Forrest Hoffman
Oak Ridge National Laboratory

Huanping Huang
Lawrence Berkeley National Laboratory

Jin Huang
National Oceanic and Atmospheric Administration

Susan Hubbard
Lawrence Berkeley National Laboratory

Mimi Hughes
National Oceanic and Atmospheric Administration

Andrew Jones
Lawrence Berkeley National Laboratory

Renu Joseph
U.S. Department of Energy

Aaron Kennedy
University of North Dakota

Charles Koven
Lawrence Berkeley National Laboratory

Ian Kraucunas
Pacific Northwest National Laboratory

Richard Lammers
University of New Hampshire

Neil Lareau
University of Nevada, Reno

Laura Lautz
National Science Foundation

Flavio Lehner
Cornell University

David Lesmes
U.S. Geological Survey

L. Ruby Leung
Pacific Northwest National Laboratory

Var Limpasuvan
National Science Foundation

Joel Lisonbee
National Oceanic and Atmospheric Administration

Ben Livneh
University of Colorado, Boulder

Sandy Lucas
National Oceanic and Atmospheric Administration

Charles Luce
U.S. Forest Service

Jessica Lundquist
University of Washington

Po-Lun Ma
Pacific Northwest National Laboratory

Andrew Manning
U.S. Geological Survey

Adrienne Marshall
Colorado School of Mines

Hilary Martens
University of Montana

Melanie Mayes
Oak Ridge National Laboratory

Sally McFarlane
U.S. Department of Energy

Marketa McGuire
U.S. Bureau of Reclamation

Pablo Mendoza
Universidad de Chile, Chile

Paul Miller
National Oceanic and Atmospheric Administration

Noah Molotch
University of Colorado, Boulder

Philip Morefield
U.S. Environmental Protection Agency

David Moulton
Los Alamos National Laboratory

Keith Musselman
University of Colorado, Boulder

Steve Nesbitt
University of Illinois, Urbana-Champaign

Michelle Newcomer
Lawrence Berkeley National Laboratory

Anne Nolin
University of Nevada, Reno

Ken Nowak
U.S. Bureau of Reclamation

Nina Oakley
University of California, San Diego

Andrew Christopher Oishi
U.S. Forest Service

Holly Oldroyd
University of California, Davis

Brooke Penaluna
U.S. Forest Service

Andreas Prein
National Center for Atmospheric Research

Yun Qian
Pacific Northwest National Laboratory

Mark Raleigh
Oregon State University

Kristen Rasmussen
Colorado State University

Patrick Reed
Cornell University

Alan Rhoades
Lawrence Berkeley National Laboratory

Koichi Sakaguchi
Pacific Northwest National Laboratory

Tim Scheibe
Pacific Northwest National Laboratory

Adam Schneider
University of California, Irvine

Tim Schneider
National Center for Atmospheric Research

Joseph Sedlar
National Oceanic and Atmospheric Administration

Christine Shields
National Center for Atmospheric Research

Katherine Skalak
U.S. Geological Survey

McKenzie Skiles
U.S. Geological Survey

Ronald Smith
Yale University

Matthias Sprenger
Lawrence Berkeley National Laboratory

Jim Steenburgh
University of Utah

Jeff Stehr
U.S. Department of Energy

Drew Story
U.S. Global Change Research Program

Daniel Stover
U.S. Department of Energy

Ning Sun
Pacific Northwest National Laboratory

Teklu Tesfa
Pacific Northwest National Laboratory

Julie Thériault
University of Quebec at Montreal, Canada

James Thornton
Mountain Research Initiative, Switzerland

Peter Thornton
Oak Ridge National Laboratory

Olga Tweedy
U.S. Department of Energy

Paul Ullrich
University of California, Davis

Shawn Urbanski
U.S. Forest Service

Bob Vallario
U.S. Department of Energy

Petrus Van Oevelen
George Mason University

Charuleka Varadharajan
Lawrence Berkeley National Laboratory

Adam Varble
Pacific Northwest National Laboratory

Nathalie Voisin
Pacific Northwest National Laboratory

Carrie Vuyovich
National Aeronautics and Space Administration

Dié Wang
Brookhaven National Laboratory

Mark Wigmosta
Pacific Northwest National Laboratory

Thomas Wild
Pacific Northwest National Laboratory

Kenneth Hurst Williams
Lawrence Berkeley National Laboratory

Taylor Winchell
Denver Water

Erica Siirila-Woodburn
Lawrence Berkeley National Laboratory

David Yates
National Center for Atmospheric Research

Charles Zender
University of California, Irvine

Xubin Zeng
University of Arizona

Yunyan Zhang
Lawrence Livermore National Laboratory

Appendix C: References

AghaKouchak, A., et al. 2020. "Climate Extremes and Compound Hazards in a Warming World," *Annual Review of Earth and Planetary Sciences* **48**, 519–48. DOI:10.1146/annurev-earth-071719-055228.

Allan, R. P., and B. J. Soden. 2008. "Atmospheric Warming and the Amplification of Precipitation Extremes," *Science* **321**(5895), 1481–84. DOI:10.1126/science.1160787.

Angermann, L., et al. 2017. "Form and Function in Hillslope Hydrology: Characterization of Subsurface Flow Based on Response Observations," *Hydrology and Earth System Sciences* **21**, 3727–48. DOI:10.5194/hess-21-3727-2017.

ARM. 2022. "SAIL at 1 Year: A Mountain Hydrology Campaign Sweeps Up Rich Data," Atmospheric Radiation Measurement (ARM) User Facility, U.S. Department of Energy Office of Science. (arm.gov/news/features/post/81524)

Arora, B., et al. 2020. "Differential C-Q Analysis: A New Approach to Inferring Lateral Transport and Hydrologic Transients Within Multiple Reaches of a Mountain Headwater Catchment," *Frontiers in Water* **2**(24). DOI:10.3389/frwa.2020.00024.

Baldwin, J. W., et al. 2021. "Outsize Influence of Central American Orography on Global Climate," *AGU Advances*, **2**(2), e2020AV000343. DOI:10.1029/2020AV000343.

Balocchi, F., et al. 2020. "The Effect of the 'Las Maquinas' Wildfire of 2017 on the Hydrologic Balance of a High Conservation Value Hualo (*Nothofagus glauca* [Phil.] Krasser) Forest in Central Chile," *Forest Ecology and Management* **477**, 118482. DOI:10.1016/j.foreco.2020.118482.

Ban, N., et al. 2021. "The First Multi-Model Ensemble of Regional Climate Simulations at Kilometer-Scale Resolution, Part I: Evaluation of Precipitation," *Climate Dynamics* **57**, 275–302. DOI:10.1007/s00382-021-05708-w.

Berg, A., et al. 2016. "Land-Atmosphere Feedbacks Amplify Aridity Increase Over Land Under Global Warming," *Nature Climate Change* **6**, 869–74. DOI:10.1038/nclimate3029.

Beschta, R., et al. 2000. "Peakflow Responses to Forest Practices in the Western Cascades of Oregon, USA," *Journal of Hydrology* **233**(1-4), 102–20. DOI:10.1016/S0022-1694(00)00231-6.

Biagini, B., et al. 2014. "A Typology of Adaptation Actions: A Global Look at Climate Adaptation Actions Financed Through the Global Environment Facility," *Global Environmental Change* **25**, 97–108. DOI:10.1016/j.gloenvcha.2014.01.00.

Biemans, H., et al. 2019. "Importance of Snow and Glacier Meltwater for Agriculture on the Indo-Gangetic Plain," *Nature Sustainability* **2**(7), 594–601. DOI:10.1038/s41893-019-0305-3.

Bisht, G., et al. 2017. "Coupling a Three-Dimensional Subsurface Flow and Transport Model with a Land Surface Model to Simulate Stream–Aquifer–Land Interactions (CP v1.0)," *Geoscientific Model Development* **10**(12), 4539–62. DOI:10.5194/gmd-10-4539-2017.

Bonaccorso, N. 2022. "Utah's Great Salt Lake Expected to Hit Record Low Levels Again This Year," *The Weather Channel*, 6 May 2022. (weather.com/photos/news/2022-05-06-great-salt-lake-shrinking)

Bouskill, N. J., et al. 2022. "Microbial Contribution to Post-Fire Tundra Ecosystem Recovery Over the 21st Century," *Communications Earth and Environment* **3**(1), 26. DOI:10.1038/s43247-022-00356-2.

Brelsford, C., and J. K. Abbott. 2021. "How Smart are 'Water Smart Landscapes'?" *Journal of Environmental Economics and Management* **106**, 102402. DOI:10.1016/j.jeem.2020.102402.

Bremer, S., and S. Meisch. 2017. "Co-Production in Climate Change Research: Reviewing Different Perspectives," *WIREs Climate Change* **8**(6). DOI:10.1002/wcc.482.

Caldwell, P. M., et al. 2021. "Convection-Permitting Simulations with the E3SM Global Atmosphere Model," *Journal of Advances in Modeling Earth Systems* **13**(11), e2021MS002544. DOI:10.1029/2021MS002544.

Calvin, K., and B. Bond-Lamberty. 2018. "Integrated Human-Earth System Modeling—State of the Science and Future Directions," *Environmental Research Letters* **13**(6), 063006. DOI:10.1088/1748-9326/aac642.

Calvin, K., et al. 2019. "GCAM v5. 1: Representing the Linkages Between Energy, Water, land, Climate, and Economic Systems," *Geoscientific Model Development* **12**(2), 677–98. DOI:10.5194/gmd-12-677-2019.

Carbone, R. E., and J. D. Tuttle. 2008. "Rainfall Occurrence in the U.S. Warm Season: The Diurnal Cycle," *Journal of Climate* **21**(16), 4132–46. DOI:10.1175/2008JCLI2275.1.

Cardenas, M. B., and M. R. Kanarek. 2014. "Soil Moisture Variation and Dynamics Across a Wildfire Burn Boundary in a Loblolly Pine (*Pinus taeda*) Forest," *Journal of Hydrology* **519**, 490–502. DOI:0.1016/j.jhydrol.2014.07.016.

Carroll, R. W. H., et al. 2018. "Factors Controlling Seasonal Groundwater and Solute Flux from Snow-Dominated Basins," *Hydrological Processes* **32**(14), 2187–202. DOI:10.1002/hyp.13151.

Carroll, R. W. H., et al. 2019. "The Importance of Interflow to Groundwater Recharge in a Snowmelt-Dominated Headwater Basin," *Geophysical Research Letters* **46**(11), 5899–908. DOI:10.1029/2019GL082447.

Chaney, N. W., et al. 2018. “Harnessing Big Data to Rethink Land Heterogeneity in Earth System Models,” *Hydrology and Earth System Sciences* **22**(6), 331130. DOI:10.5194/hess-22-3311-2018.

Chaney, N. W., et al. 2021. “HydroBlocks v0.2: Enabling a Field-Scale Two-Way Coupling Between the Land Surface and River Networks in Earth System Models,” *Geoscientific Model Development* **14**, 6813–32. DOI:10.5194/gmd-14-6813-2021.

Chikamoto, Y., et al. 2020. “Colorado River Water Supply is Predictable on Multi-Year Timescales Owing to Long-Term Ocean Memory,” *Communications Earth and Environment* **1**(26). DOI:10.1038/s43247-020-00027-0.

Choudhury, G., et al. 2019. “Aerosol-Orography-Precipitation – A Critical Assessment,” *Atmospheric Environment* **214**, 116831. DOI:10.1016/j.atmosenv.2019.116831.

Clark, M. P., et al. 2015. “Improving the Representation of Hydrologic Processes in Earth System Models,” *Water Resources Research* **51**(8), 5929–56. DOI:10.1002/2015WR017096.

Condom T., et al. 2020. “Climatological and Hydrological Observations for the South American Andes: *In situ* Stations, Satellite, and Reanalysis Data Sets,” *Frontiers in Earth Science* **8**(92). DOI:10.3389/feart.2020.00092.

Dafflon, B., et al. 2022. “A Distributed Temperature Profiling System for Vertically and Laterally Dense Acquisition of Soil and Snow Temperature,” *The Cryosphere* **16**, 719–36. DOI:10.5194/tc-16-719-2022.

Dawson, T.E., W. J. Hahm, and K. Crutchfield-Peters. 2020. “Digging Deeper: What the Critical Zone Perspective Adds to the Study of Plant Ecophysiology,” *New Phytologist* **226**(3), 666–71. DOI:10.1111/nph.16410.

Deser, C., et al. 2020. “Insights From Earth System Model Initial-Condition Large Ensembles and Future Prospects.” *Nature Climate Change* **10**, 277–86. DOI:10.1038/s41558-020-0731-2.

Dimanchev, E. G., J. L. Hodge, and J. E. Parsons. 2021. “The Role of Hydropower Reservoirs in Deep Decarbonization Policy,” *Energy Policy* **155**, 112369. DOI:10.1016/j.enpol.2021.112369.

Di Vittorio, A., et al. 2020. “Initial Land Use/Cover Distribution Substantially Affects Global Carbon and Local Temperature Projections in the Integrated Earth System Model,” *Global Biogeochemical Cycles* **34**(5), e2019GB006383. DOI:10.1029/2019gb006383.

Dong, L., et al. 2021. “Double-ITCZ as an Emergent Constraint for Future Precipitation Over Mediterranean Climate Regions in the North Hemisphere,” *Geophysical Research Letters* **48**(3), e2020GL091569. DOI:10.1029/2020GL091569.

Dove, N. C., et al. 2021. “Fire Alters Plant Microbiome Assembly Patterns: Integrating the Plant and Soil Microbial Response to Disturbance,” *New Phytologist* **230**(6), 2433–446. DOI:10.1111/nph.17248.

Duan, S., et al. 2020. “Using Convolutional Neural Networks for Streamflow Projection in California,” *Frontiers in Water* **2**, 28. DOI:10.3389/frwa.2020.00028.

Duan, Y., and A. P. Barros. 2017. “Understanding How Low-Level Clouds and Fog Modify the Diurnal Cycle of Orographic Precipitation Using *In Situ* and Satellite Observations,” *Remote Sensing* **9**(9), 920. DOI:10.3390/rs9090920.

Dubbert, M., and C. Werner. 2019. “Water Fluxes Mediated by Vegetation: Emerging Isotopic Insights at the Soil and Atmosphere Interfaces,” *New Phytologist* **221**(4), 1754–63. DOI:10.1111/nph.15547.

Dwivedi, D., et al. 2018. “Geochemical Exports to River from the Intrameander Hyporheic Zone Under Transient Hydrologic Conditions: East River Mountainous Watershed, Colorado,” *Water Resources Research* **54**(10), 8456–77. DOI:10.1029/2018WR023377.

Ebel, B. A., and D. A. Martin. 2017. “Meta-Analysis of Field-Saturated Hydraulic Conductivity Recovery Following Wildland Fire: Applications for Hydrologic Model Parameterization and Resilience Assessment,” *Hydrological Processes* **31**(21), 3682–96. DOI:10.1002/hyp.11288.

Eggers, C. 2022. “Many States are Setting Up Their Own Extensive Weather Monitoring Networks,” *National Public Radio*, 15 March 2022. (npr.org/2022/03/15/1086605663/many-states-are-setting-up-their-own-extensive-weather-monitoring-networks)

Enguehard, L., et al. 2022. “Machine-Learning Functional Zonation Approach for Characterizing Terrestrial–Aquatic Interfaces: Application to Lake Erie,” *Remote Sensing* **14**, 3285. DOI:10.3390/rs14143285.

Fan, J., et al. 2015. “Substantial Contribution of Anthropogenic Air Pollution to Catastrophic Floods in Southwest China,” *Geophysical Research Letters* **42**(14), 6066–75. DOI:10.1002/2015GL064479.

Fan, Y., et al. 2019. “Hillslope Hydrology in Global Change Research and Earth System Modeling,” *Water Resources Research* **55**(2), 1737–72. DOI:10.1029/2018WR023903.

Fang, Y., et al. 2022. “Modeling the Topographic Influence on Aboveground Biomass Using a Coupled Model of Hillslope Hydrology and Ecosystem Dynamics,” *Geoscientific Model Development* **15**(20), 7879–7901. DOI:10.5194/gmd-15-7879-2022.

Fattorini, S., et al. 2021. “Mountain Biodiversity and Sustainable Development” In *Life on Land. Encyclopedia of the UN Sustainable Development Goals*. Eds. Leal Filho, W.; A. M. Azul; L. Brandli; A. Lange Salvia; and T. Wall. pp. 640–60. ISBN:978-3-319-71065-5.

Feldman, D., et al. 2021. “Reliable Modeling and Prediction of Precipitation and Radiation for Mountainous Hydrology,” *Artificial Intelligence for Earth System Predictability (AI4ESP): SAIL White Paper.* U.S. Department of Energy Office of Science. DOI:10.2172/1769771.

Feng, Z., et al. 2016. “More Frequent Intense and Long-Lived Storms Dominate the Springtime Trend in Central U.S. Rainfall,” *Nature Communications* **7**, 13429. DOI:10.1038/ncomms13429.

Finnigan, J., et al. 2020. "Boundary-Layer Flow Over Complex Topography," *Boundary-Layer Meteorology* **177**, 247–313. DOI:10.1007/s10546-020-00564-3.

Flavell, C. 2022. "As the Great Salt Lake Dries Up, Utah Faces an 'Environmental Nuclear Bomb,'" *The New York Times*, 7 June 2022. Updated 22 September 2022. (nytimes.com/2022/06/07/climate/salt-lake-city-climate-disaster.html)

Fuhrer, O., and C. Schär. 2005. "Embedded Cellular Convection in Moist Flow Past Topography," *Journal of the Atmospheric Sciences* **62**(8), 2810–828. DOI:10.1175/JAS3512.1.

Geerts, B., et al. 2015. "Snow Growth and Transport Patterns in Orographic Storms as Estimated from Airborne Vertical-Plane Dual-Doppler Radar Data," *Monthly Weather Review* **143**(2), 644–65. DOI:10.1175/MWR-D-14-00199.1.

Gillies, R. R., et al. 2015. "Added Value from 576 Years of Tree-Ring Records in the Prediction of the Great Salt Lake Level," *Journal of Hydrology* **529**, 962–68. DOI:10.1016/j.jhydrol.2015.08.058.

Gochis, D., et al. 2015. "The Great Colorado Flood of September 2013," *Bulletin of the American Meteorological Society* **96**(9), 1461–87. DOI:10.1175/BAMS-D-13-00241.1.

Golaz, J.-C., et al. 2022. "The DOE E3SM Model Version 2: Overview of the Physical Model and Initial Model Evaluation," *Journal of Advances in Modeling Earth Systems* **14**(12), e2022MS003156. DOI:10.1029/2022MS003156.

Gomez-Velez, J. D., and J. W. Harvey. 2014. "A Hydrogeomorphic River Network Model Predicts Where and Why Hyporheic Exchange is Important in Large Basins," *Geophysical Research Letters* **41**(18), 6403–12. DOI:10.1002/2014GL061099.

Goulden, M. L., and R. C. Bales. 2014. "Mountain Runoff Vulnerability to Increased Evapotranspiration with Vegetation Expansion," *Proceedings of the National Academy of Sciences of the United States of America* **111**, 14071–75. DOI:10.1073/pnas.1319316111.

Graham, R. C., et al. 2016. "Wildfire Effects on Soils of a 55-Year-Old Chaparral and Pine Biosequence," *Soil Science Society of America Journal* **80**(2), 376–94. DOI:10.2136/sssaj2015.09.0317.

Grant, G. E., and W. E. Dietrich. 2017. "The Frontier Beneath Our Feet," *Water Resources Research* **53**(4), 2605–09. DOI:10.1002/2017WR020835.

Greve, P., et al. 2014. "Global Assessment of Trends in Wetting and Drying Over Land," *Nature Geoscience* **7**, 716–21. DOI:10.1038/ngeo2247.

Gutowski, W. J., et al. 2020. "The Ongoing Need for High-Resolution Regional Climate Models: Process Understanding and Stakeholder Information," *Bulletin of the American Meteorological Society* **101**(5), E664–83. DOI:10.1175/BAMS-D-19-0113.1.

Hadjimichael, A., et al. 2020. "Rhodium: Python Library for Many-Objective Robust Decision Making and Exploratory Modeling," *Journal of Open Research Software* **8**(1), 12. DOI:10.5334/jors.293.

Hakala, K. A. "Climate Forcings on Groundwater Variations in Utah and the Great Basin" (2014). *All Graduate Theses and Dissertations*. 3867. (digitalcommons.usu.edu/etd/3867)

Hao, D., et al. 2021. "A Parameterization of Sub-Grid Topographical Effects on Solar Radiation in the E3SM Land Model (Version 1.0): Implementation and Evaluation Over the Tibetan Plateau," *Geoscientific Model Development* **14**(10), 6273–89. DOI:10.5194/gmd-14-6273-2021.

Harpold, A., et al. 2017. "Defining Snow Drought and Why It Matters," *Eos* **98**. DOI:10.1029/2017EO068775.

Hatchett, B. J., et al. 2016. "Some Characteristics of Upside-Down Storms in the Northern Sierra Nevada, California-Nevada, USA," *International Snow Science Workshop 2016 Proceedings*. 1165–72. (arc.lib.montana.edu/snow-science/objects/ISSW16_P4.03.pdf)

Hatchett, B. J., et al. 2020. "Observations of an Extreme Atmospheric River Storm with a Diverse Sensor Network," *Earth and Space Science* **7**(8), e2020EA001129. DOI:10.1029/2020EA001129.

Hatchett, B. J., et al. 2022. "Monitoring the Daily Evolution and Extent of Snow Drought," *Natural Hazards and Earth System Sciences* **22**(3), 869–890. DOI:10.5194/nhess-22-869-2022.

Hauer, C., et al. 2018. "State of the Art, Shortcomings and Future Challenges for a Sustainable Sediment Management in Hydropower: A Review," *Renewable and Sustainable Energy Reviews* **98**, 40–55. DOI:10.1016/j.rser.2018.08.031.

Havel, A., A. Tasdighi, and M. Arabi. 2018. "Assessing the Hydrologic Response to Wildfires in Mountainous Regions," *Hydrology and Earth System Sciences* **22**, 2527–50. DOI:10.5194/hess-22-2527-2018.

Hobbs, P. V., R. C. Easter, and A. B. Fraser. 1973. "A Theoretical Study of the Flow of Air and Fallout of Solid Precipitation Over Mountainous Terrain: Part II. Microphysics," *Journal of the Atmospheric Sciences* **30**, 813–23. DOI:10.1175/1520-0469(1973)030<0813:ATSOTF>2.0.CO;2.

Hock, R., et al. 2019. "High Mountain Areas." In: *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate.* Eds. Pörtner, H.-O.; D.C. Roberts; V. Masson-Delmotte; P. Zhai; M. Tignor; E. Poloczanska; K. Mintenbeck; A. Alegría; M. Nicolai; A. Okem; J. Petzold; B. Rama; and N. M. Weyer. Cambridge University Press, Cambridge, U.K. and New York, N.Y. pp. 131–202. DOI:10.1017/9781009157964.004.

Hoekstra, A. Y. and M. M. Mekonnen. 2012. "The Water Footprint of Humanity," *Proceedings of the National Academy of Sciences of the United States of America* **109**(9), 3232–37. DOI:10.1073/pnas.1109936109.

Holden, Z. A., et al. 2018. "Decreasing Fire Season Precipitation Increased Recent Western U.S. Forest Wildfire Activity," *Proceedings of the National Academy of Sciences of the United States of America* **115** (36), E8349–57. DOI:10.1073/pnas.1802316115.

Hollins, L., D. Eisenberg, and T. Seager. 2018. "Risk and Resilience at the Oroville Dam. Infrastructures," *Infrastructures* **3**(4), 49. DOI:10.3390/infrastructures3040049.

Hossain, F., et al. 2012. "Climate Feedback–Based Provisions for Dam Design, Operations, and Water Management in the 21st Century," *Journal of Hydrologic Engineering* **17**(8), 837–50. DOI:10.1061/(ASCE)HE.1943-5584.0000541.

Houze, R. A. 2012. "Orographic Effects on Precipitating Clouds," *Reviews of Geophysics* **50**(1), RG1001. DOI:10.1029/2011RG000365.

Huang, M., et al. 2022. "Representing Surface Heterogeneity in Land-Atmosphere Coupling in E3SMv1 Single-Column Model Over ARM SGP During Summertime," *Geoscientific Model Development Discussions*. In review. DOI:10.5194/gmd-2021-421.

Huang, X., D. L. Swain, and A. D. Hall. 2020. "Future Precipitation Increase from Very High Resolution Ensemble Downscaling of Extreme Atmospheric River Storms in California," *Science Advances* **6**(29). DOI:10.1126/sciadv.aba1323.

Hubbard, S. S., et al. 2020. "Emerging Technologies and Radical Collaboration to Advance Predictive Understanding of Watershed Hydrobiogeochemistry," *Hydrological Processes* **34**(15), 3175–82. DOI:10.1002/hyp.13807.

Huss, M., et al. 2017. "Toward Mountains Without Permanent Snow and Ice," *Earth's Future* **5**(5), 418–35. DOI:10.1002/2016EF000514.

Immerzeel, W. W., et al. 2020. "Importance and Vulnerability of the World's Water Towers," *Nature* **577**, 364–69. DOI:10.1038/s41586-019-1822-y.

Jagannathan, K., A. D. Jones, and I. Ray. 2021. "The Making of a Metric: Co-Producing Decision-Relevant Climate Science," *Bulletin of the American Meteorological Society* **102**(8), E1579–90. DOI:10.1175/BAMS-D-19-0296.1.

Jasechko, S. 2019. "Global Isotope Hydrogeology Review," *Reviews of Geophysics* **57**(3), 835–965. DOI:10.1029/2018RG000627.

Jennings, K. S., et al. 2018. "Spatial Variation of the Rain–Snow Temperature Threshold Across the Northern Hemisphere," *Nature Communications* **9**, 1148. DOI:10.1038/s41467-018-03629-7.

Kafanov, L., L. Perrot, and E. C. McLaughlin. 2021. "Great Salt Lake is Shrinking Fast. Scientists Demand Action Before It Becomes a Toxic Dustbin," *CNN*, 17 July 2022. (cnn.com/2021/07/17/us/great-salt-lake-drought-dying/)

Kassianov, E., et al. 2017. "Large Contribution of Coarse Mode to Aerosol Microphysical and Optical Properties: Evidence from Ground-Based Observations of a Transpacific Dust Outbreak at a High-Elevation North American Site," *Journal of the Atmospheric Sciences* **74**(5), 1431–43. DOI:10.1175/JAS-D-16-0256.1.

Keeley, J. E., and C. J. Fotheringham. 1998. "Smoke-Induced Seed Germination in California Chaparral," *Ecology* **79**(7), 2320–36. DOI:10.1890/0012-9658(1998)079[2320:SISGIC]2.0.CO;2.

Keenan, R. J. 2015. "Climate Change Impacts and Adaptation in Forest Management: A Review," *Annals of Forest Science* **72**, 145–67. DOI:10.1007/s13595-014-0446-5.

Kirshbaum D. J., et al. 2018. "Moist Orographic Convection: Physical Mechanisms and Links to Surface-Exchange Processes," *Atmosphere* **9**(3), 80. DOI:10.3390/atmos9030080.

Kirshbaum, D. J. 2020. "Numerical Simulations of Orographic Convection Across Multiple Gray Zones," *Journal of the Atmospheric Sciences* **77**(10) 3301–20. DOI:10.1175/JAS-D-20-0035.1.

Kratzert, F., et al. 2019. "Towards Learning Universal, Regional, and Local Hydrological Behaviors via Machine Learning Applied to Large-Sample Datasets," *Hydrology and Earth System Sciences* **23**(12), 5089–5110. DOI:10.5194/hess-23-5089-2019.

Krinner, G., et al. 2018. "ESM-SnowMIP: Assessing Snow Models and Quantifying Snow-Related Climate Feedbacks," *Geoscientific Model Development* **11**(12), 5027–49. DOI:10.5194/gmd-11-5027-2018.

La Follette, P. T., et al. 2021. "Numerical Daemons of Hydrological Models are Summoned by Extreme Precipitation," *Hydrology and Earth System Sciences* **25**(10), 5425–46. DOI:10.5194/hess-25-5425-2021.

La Marche, J. L., and D. P. Lettenmaier. 2001. "Effects of Forest Roads on Flood Flows in the Deschutes River, Washington," *Earth Surface Processes and Landforms: The Journal of the British Geomorphological Research Group* **26**(2), 115–34. DOI:10.1002/1096-9837(200102)26:2<115::AID-ESP166>3.0.CO;2-O.

Lenderink, G., et al. 2017. "Super-Clausius–Clapeyron Scaling of Extreme Hourly Convective Precipitation and Its Relation to Large-Scale Atmospheric Conditions," *Journal of Climate* **30**(15), 6037–52. DOI:10.1175/JCLI-D-16-0808.1.

Letcher, T. W., and J. R. Minder. 2018. "The Simulated Impact of the Snow Albedo Feedback on the Large-Scale Mountain–Plain Circulation East of the Colorado Rocky Mountains," *Journal of the Atmospheric Sciences* **75**(3), 755–74. DOI:10.1175/JAS-D-17-0166.1.

Leung, L. R., et al. 2020. "An Introduction to the Energy Exascale Earth System Model (E3SM) Special Collection: Goals, Science Drivers, Development, and Analysis," *Journal of Advances in Modeling Earth Systems* **12**(11), e2019MS001821. DOI:10.1029/2019MS001821.

Li, H., et al. 2013. "A Physically Based Runoff Routing Model for Land Surface and Earth System Models," *Journal of Hydrometeorology* **14**(3), 808–28. DOI:10.1175/JHM-D-12-015.1.

Li, H.-Y., et al. 2015. "Modeling Stream Temperature in the Anthropocene: An Earth System Modeling Approach," *Journal of Advances in Modeling Earth Systems* **7**(4), 1661–79. DOI:10.1002/2015MS000471.

Liu, C., et al. 2017. "Continental-Scale Convection-Permitting Modeling of the Current and Future Climate of North America," *Climate Dynamics* **49**, 71–95. DOI:10.1007/s00382-016-3327-9.

Liu, W., et al. 2022. “The June 2012 North American Derecho: A Testbed for Evaluating Regional and Global Climate Modeling Systems at Cloud-Resolving Scales,” *Journal of Advances in Modeling Earth Systems*. In review. DOI:10.1002/essoar.10511614.1.

Livneh, B., and A. M. Badger. 2020. “Drought Less Predictable Under Declining Future Snowpack,” *Nature Climate Change* **10**(5), 452–458. DOI:10.1038/s41558-020-0754-8.

Lloret, F., and P. H. Zedler. 2009. “The Effect of Forest Fire on Vegetation.” In *Fire Effects on Soils and Restoration Strategies*. CRC Press, Boca Raton, Fl., pp. 40. ISBN:780429063596.

Lundquist, J., et al. 2019. “Our Skill in Modeling Mountain Rain and Snow is Bypassing the Skill of Our Observational Networks,” *Bulletin of the American Meteorological Society* **100**(12), 2473–90. DOI:10.1175/BAMS-D-19-0001.1.

Maavara, T., et al. 2021. “Modeling Geogenic and Atmospheric Nitrogen through the East River Watershed, Colorado Rocky Mountains,” *PLOS ONE* **16**(3), e0247907. DOI:10.1371/journal.pone.0247907.

Maddox, R. A., et al. 1978. “Comparison of Meteorological Aspects of the Big Thompson and Rapid City Flash Floods,” *Monthly Weather Review* **106**(3), 375–89. DOI:10.1175/1520-0493(1978)106<0375:COMAOT>2.0.CO;2.

Maina, F. Z., and E. R. Siirila-Woodburn. 2019. “Watersheds Dynamics Following Wildfires: Nonlinear Feedbacks and Implications on Hydrologic Responses,” *Hydrological Processes* **34**(1), 33–50. DOI:10.1002/hyp.13568.

Maina, F. Z., et al. 2020a. “Determining the Impact of a Severe Dry to Wet Transition on Watershed Hydrodynamics in California, USA with an Integrated Hydrologic Model,” *Journal of Hydrology* **580**, 124358. DOI:10.1016/j.jhydrol.2019.124358.

Maina, F. Z., et al. 2020b. “Sensitivity of Meteorological-Forcing Resolution on Hydrologic Variables,” *Hydrology and Earth System Sciences* **24**(7), 3451–74. DOI:10.5194/hess-24-3451-2020.

Maloney, E. D., et al. 2019. “Process-Oriented Evaluation of Climate and Weather Forecasting Models,” *Bulletin of the American Meteorological Society* **100**(9), 1665–86. DOI:10.1175/BAMS-D-18-0042.1.

Masbruch, M. D., et al. 2016. “Analyses of Infrequent (Quasi-Decadal) Large Groundwater Recharge Events in the Northern Great Basin: Their Importance for Groundwater Availability, Use, and Management,” *Water Resources Research* **52**(10), 7819–36. DOI:10.1002/2016WR019060.

Matheus Carnevali, P. B., et al. 2021. “Meanders as a Scaling Motif for Understanding of Floodplain Soil Microbiome and Biogeochemical Potential at the Watershed Scale,” *Microbiome* **9**(1), 121. DOI:10.1186/s40168-020-00957-z.

Maxwell, R. M., and L. E. Condon. 2016. “Connections Between Groundwater Flow and Transpiration Partitioning,” *Science* **353**(6297), 377–80. DOI:10.1126/science.aaf7891.

Mazzotti, G., et al. 2020. “Resolving Small-Scale Forest Snow Patterns Using an Anergy Balance Snow Model with a One-Layer Canopy,” *Water Resources Research* **56**(1), e2019WR026129. DOI:10.1029/2019WR026129.

McClain, M., et al. 2003. “Biogeochemical Hot Spots and Hot Moments at the Interface of Terrestrial and Aquatic Ecosystems,” *Ecosystems* **6**, 301–12. DOI:10.1007/s10021-003-0161-9.

McCrary, R. R., et al. 2022. “Projections of North American Snow from NA-CORDEX and Their Uncertainties, with a Focus on Model Resolution,” *Climatic Change* **170**(3), 1–25. DOI:10.1007/s10584-021-03294-8.

McDonnell, J. J., and K. Beven. 2014. “Debates—The Future of Hydrological Sciences: A (Common) Path Forward? A Call to Action Aimed at Understanding Velocities, Celerities, and Residence Time Distributions of the Headwater Hydrograph,” *Water Resources Research* **50**(6), 5342–50. DOI:10.1002/2013WR015141.

McGovern, A., et al. 2019. “Making the Black Box More Transparent: Understanding the Physical Implications of Machine Learning,” *Bulletin of the American Meteorological Society* **100**(11), 2175–2199. DOI:10.1175/BAMS-D-18-0195.1.

McLauchlan, K. K., et al. 2020. “Fire as a Fundamental Ecological Process: Research Advances and Frontiers,” *Journal of Ecology* **108**(5), 2047–69. DOI:10.1111/1365-2745.13403.

Meyal, A. Y., et al. 2020. “Automated Cloud Based Long Short-Term Memory Neural Network Based SWE Prediction,” *Frontiers in Water* **2**, 574917. DOI:10.3389/frwa.2020.574917.

Michaelis, A. C., et al. 2022. “Atmospheric River Precipitation Enhanced by Climate Change: A Case Study of the Storm That Contributed to California's Oroville Dam Crisis,” *Earth’s Future* **10**(3), e2021EF002537. DOI:10.1029/2021EF002537.

Milly, P. C. D., and K. A. Dunne. 2020. “Colorado River Flow Dwindles as Warming-Driven Loss of Reflective Snow Energizes Evaporation,” *Science* **367**(6483), 1252–55. DOI:10.1126/science.aay9187.

Moody, J. A., et al. 2016. “Relations Between Soil Hydraulic Properties and Burn Severity,” *International Journal of Wildland Fire* **25**(3), 279–93. DOI:10.1071/WF14062.

Morgan, B., K. et al. 2020. “Water Availability for Cannabis in Northern California: Intersections of Climate, Policy, and Public Discourse,” *Water* **13**(1), 5. DOI:10.3390/w13010005.

Mountain Research Initiative EDW Working Group. 2015. “Elevation-Dependent Warming in Mountain Regions of the World,” *Nature Climate Change* **5**, 424–30. DOI:10.1038/nclimate2563.

Mote, P. W., et al. 2016. “Perspectives on the Causes of Exceptionally Low 2015 Snowpack in the Western United States,” *Geophysical Research Letters* **43**(20), 10980–988. DOI:10.1002/2016GL069965.

Muhlbauer, A., and U. Lohmann. 2008. “Sensitivity Studies of the Role of Aerosols in Warm-Phase Orographic Precipitation in Different Dynamical Flow Regimes,” *Journal of the Atmospheric Sciences* **65**(8), 2522–42. DOI:10.1175/2007JAS2492.1.

Murphy, S. F., et al. 2015. "The Role of Precipitation Type, Intensity, and Spatial Distribution in Source Water Quality After Wildfire," *Environmental Research Letters* **10**, 084007. DOI:10.1088/1748-9326/10/8/084007.

Murphy, S. F., et al. 2018. "Fire, Flood, and Drought: Extreme Climate Events Alter Flow Paths and Stream Chemistry," *Journal of Geophysical Research: Biogeosciences* **123**(8), 2513–26. DOI:10.1029/2017JG004349.

Musselman, K. N., et al. 2018. "Projected Increases and Shifts in Rain-on-Snow Flood Risk Over Western North America," *Nature Climate Change* **8**, 808–12. DOI:10.1038/s41558-018-0236-4.

National Wildfire Coordinating Group. 2019. *NWCG Standards for Fire Weather Stations.* (www.nwcg.gov/sites/default/files/publications/pms426-3.pdf)

Newcomer, M. E., et al. 2018. "Influence of Hydrological Perturbations and Riverbed Sediment Characteristics on Hyporheic Zone Respiration of CO_2 and N_2," *Journal of Geophysical Research: Biogeosciences* **123**(3), 902–22. DOI:10.1002/2017JG004090.

Newcomer, M. E., et al. 2021a. "Hysteresis Patterns of Watershed Nitrogen Retention and Loss Over the Past 50 Years in United States Hydrological Basins," *Global Biogeochemical Cycles* **35**(4), e2020GB006777. DOI:10.1029/2020GB006777.

Newcomer, M. E., et al. 2021b. "AI4ESP Fire Community Observatory Whitepaper: Interdisciplinary, AI-informed Post-Fire Rapid Response for Improved Water Cycle Science at Watershed Scale." DOI:10.2172/1769642.

Nielson, T. J., et al. 2021. "Soil Structure and Soil Moisture Dynamics Inferred from Time-Lapse Electrical Resistivity Tomography," *CATENA* **207**, 105553. DOI:10.1016/j.catena.2021.105553.

O'Neill, B. C., et al. 2016. "The Scenario Model Intercomparison Project (ScenarioMIP) for CMIP6," *Geoscientific Model Development* **9**(9), 3461–82. DOI:10.5194/gmd-9-3461-2016.

Painter, T. H., et al. 2016. "The Airborne Snow Observatory: Fusion of Scanning Lidar, Imaging Spectrometer, and Physically-Based Modeling for Mapping Snow Water Equivalent and Snow Albedo," *Remote Sensing of Environment* **184**, 139–52. DOI:10.1016/j.rse.2016.06.018.

Payne, A. E., et al. 2020. "Responses and Impacts of Atmospheric Rivers to Climate Change," *Nature Reviews Earth and Environment* **1,** 143–57. DOI:10.1038/s43017-020-0030-5.

Peltier, D. M. P., and K. Ogle. 2019. "Legacies of La Niña: North American Monsoon Can Rescue Trees from Winter Drought," *Global Change Biology* **25**(1), 121–133. DOI:10.1111/gcb.14487.

Pendergrass, A. G., et al. 2020. "Flash Droughts Present a New Challenge for Subseasonal-to-Seasonal Prediction," *Nature Climate Change* **10**, 191–99. DOI:10.1038/s41558-020-0709-0.

Peterson, T. J., et al. 2021. "Watersheds May Not Recover from Drought," *Science*, **372**(6543), 745–749. DOI:10.1126/science.abd5085.

Plucinski, B., et al. 2019. "Feasibility of Multi-Year Forecast for the Colorado River Water Supply: Time Series Modeling," *Water* **11**(12), 2433. DOI:10.3390/w11122433.

Pohl, S., et al. 2014. "Potential of a Low-Cost Sensor Network to Understand the Spatial and Temporal Dynamics of a Mountain Snow Cover," *Water Resources Research* **50**(3), 2533–50. DOI:10.1002/2013WR014594.

Pokharel, B., et al. 2020. "A Modeling Examination of Cloud Seeding Conditions Under the Warmer Climate in Utah, USA," *Atmospheric Research* 248, 105239. DOI:10.1016/j.atmosres.2020.105239.

Pokharel, B., et al. 2021a. "Miracle Spring Precipitation under the Warmer Climate in Colorado River Basin," NOAA's 46th Climate Diagnostics and Prediction Workshop, College Park, MD, 26–28 October 2021. (cpc.ncep.noaa.gov/products/outreach/CDPW/46/sessions/presentations/session1_talk10.pdf)

Pokharel, B., et al. 2021b. "Commentary: Utah Can Get More Water from Our Clouds — If We Invest in Real Science," *The Salt Lake City Tribune*, 6 January 2021. (sltrib.com/opinion/commentary/2021/04/09/commentary-utah-can-get/)

Pokharel, B., et al. 2022. "Drought-Busting 'Miracles' in the Colorado River Basin May Become Less Frequent and Less Powerful Under Climate Warming," *Authorea*. Preprint. DOI:10.1002/essoar.10511012.1.

Povak, N. A., et al. 2022. "Evaluating Basin-Scale Forest Adaptation Scenarios: Wildfire, Streamflow, Biomass, and Economic Recovery Synergies and Trade-Offs," *Frontiers in Forests and Global Change* **5**, 805179. DOI:10.3389/ffgc.2022.805179.

Prein, A. F., et al. 2017. "Increased Rainfall Volume from Future Convective Storms in the U.S.," *Nature Climate Change* **7,** 880–84. DOI:10.1038/s41558-017-0007-7.

Pu, W., et al. 2021. "Unprecedented Snow Darkening and Melting in New Zealand Due to 2019–2020 Australian Wildfires," *Fundamental Research* **1**(3), 224–31. DOI:10.1016/j.fmre.2021.04.001.

Qian, Y., et al. 2009. "Effects of Soot-Induced Snow Albedo Change on Snowpack and Hydrological Cycle in Western United States Based on Weather Research and Forecasting Chemistry and Regional Climate Simulations," *Journal of Geophysical Research: Atmospheres* **114**(D3). DOI:10.1029/2008JD011039.

Qian, Y., et al. 2015. "Light-Absorbing Particles in Snow and Ice: Measurement and Modeling of Climatic and Hydrological Impact," *Advances in Atmospheric Science* **32**, 64–91. DOI:10.1007/s00376-014-0010-0.

Ramanathan V., et al. 2001. "Aerosols, Climate, and the Hydrological Cycle," *Science* **294**(5549), 2119–24. DOI:10.1126/science.1064034.

Reaman, M. 2022. "Town Catching Up with Snow Storage After the Santa Slammer," *Crested Butte News*, 12 January 2022. (crestedbuttenews.com/2022/01/town-catching-up-with-snow-storage-after-the-santa-slammer/)

Reddington, C. L., et al. 2017. "The Global Aerosol Synthesis and Science Project (GASSP): Measurements and Modeling to Reduce Uncertainty," *Bulletin of the American Meteorological Society* **98**(9), 1857–77. DOI:10.1175/BAMS-D-15-00317.1.

Reed, P. M., et al. 2022. "Multisector Dynamics: Advancing the Science of Complex Adaptive Human-Earth Systems," *Earth's Future* **10**(3), e2021EF002621. DOI:10.1029/2021EF002621.

Rhoades, A. M., et al. 2018. "Sensitivity of Mountain Hydroclimate Simulations in Variable-Resolution CESM to Microphysics and Horizontal Resolution," *Journal of Advances in Modeling Earth Systems* **10**(6), 1357– 80. DOI:10.1029/2018MS001326.

Rhoades, A. M., et al. 2022. "Asymmetric Emergence of Low-to-No Snow in the Midlatitudes of the American Cordillera," *Nature Climate Change* **12**, 1151–59. DOI:10.1038/s41558-022-01518-y.

Riahi, K., et al. 2017. "The Shared Socioeconomic Pathways and Their Energy, Land Use, and Greenhouse Gas Emissions Implications: An Overview," *Global Environmental Change* **42**, 153–168. DOI:10.1016/j.gloenvcha.2016.05.009.

Roberts, C. D., et al. 2018. "Climate Model Configurations of the ECMWF Integrated Forecasting System (ECMWF-IFS cycle 43r1) for HighResMIP," *Geoscientific Model Development* **11**(9), 3681–712. DOI:10.5194/gmd-11-3681-2018.

Rogers, D. B., et al. 2021. "Modeling the Impact of Riparian Hollows on River Corridor Nitrogen Exports," *Frontiers in Water* **3**, 590314. DOI:10.3389/frwa.2021.590314.

Rougé, C., et al. 2019. "Coordination and Control: Limits in Standard Representations of Multi-Reservoir Operations in Hydrological Modeling," *Hydrology and Earth System Sciences* **25**, 1365–88. DOI:10.5194/hess-25-1365-2021.

Rumsey, C. A., et al. 2017. "The Role of Baseflow in Dissolved Solids Delivery to Streams in the Upper Colorado River Basin," *Hydrological Processes* **31**(26), 4705–18. DOI:10.1002/hyp.11390.

Russell, M., et al. 2021. "Important Airborne Lidar Metrics of Canopy Structure for Estimating Snow Interception," *Remote Sensing* **13**(20), 4188. DOI:10.3390/rs13204188.

Safeeq, M., et al. 2020. "Disentangling Effects of Forest Harvest on Long-Term Hydrologic and Sediment Dynamics, Western Cascades, Oregon," *Journal of Hydrology* **580**, 124259. DOI:10.1016/j.jhydrol.2019.124259.

Sahoo, M., et al. 2017. "Space–Time Forecasting of Groundwater Level Using a Hybrid Soft Computing Model," *Hydrological Sciences Journal* **62**(4), 561–574. DOI:10.1080/02626667.2016.1252986.

Sarangi, C., et al. 2020. "Dust Dominates High-Altitude Snow Darkening and Melt Over High-Mountain Asia," *Nature Climate Change* **10**, 1045–51. DOI:10.1038/s41558-020-00909-3.

Scanlon, B. R., et al. 2017. "The Food-Energy-Water Nexus: Transforming Science for Society," *Water Resources Research* **53**(5), 3550–56. DOI:10.1002/2017WR020889.

Schär, C., et al. 2020. "Kilometer-Scale Climate Models: Prospects and Challenges," *Bulletin of the American Meteorological Society* **101**(5), E567-E587. DOI:10.1175/BAMS-D-18-0167.1.

Schreiner-McGraw, A. P., and H. Ajami. 2020. "Impact of Uncertainty in Precipitation Forcing Data Sets on the Hydrologic Budget of an Integrated Hydrologic Model in Mountainous Terrain," *Water Resources Research* **56**(12), e2020WR027639. DOI:10.1029/2020WR027639.

Schwarz, A. M. 2015. "California Central Valley Water Rights in a Changing Climate." *San Francisco Estuary and Watershed Science* **13**(2). DOI:10.15447/sfews.2015v13iss2art1.

Shepherd, T. G., et al. 2018. "Storylines: An Alternative Approach to Representing Uncertainty in Physical Aspects of Climate Change," *Climatic Change* **151**(3), 555–71. DOI:/10.1007/s10584-018-2317-9.

Sherwood, S., and Q. Fu. 2014. "A Drier Future?" *Science* **343**(6172), 737–39. DOI:0.1126/science.1247620.

Siirila-Woodburn, E. R., et al. 2021. "A Low-to-No Snow Future and Its Impacts on Water Resources in the Western United States," *Nature Reviews Earth & Environment* **2**, 800–19. DOI:10.1038/s43017-021-00219-y.

Skiles, S., and T. Painter, T. 2017. "Daily Evolution in Dust and Black Carbon Content, Snow Grain Size, and Snow Albedo During Snowmelt, Rocky Mountains, Colorado," *Journal of Glaciology* **63**(237), 118–32. DOI:10.1017/jog.2016.125.

Slater, A. G., et al. 2001. "The Representation of Snow in Land Surface Schemes: Results from PILPS 2(d)," *Journal of Hydrometeorology* **2**(1), 7–25. DOI:10.1175/1525-7541(2001)002<0007:TROSIL>2.0.CO;2.

Smith, J. A., et al. 2018. "Strange Floods: The Upper Tail of Flood Peaks in the United States," *Water Resources Research* **54**(9), 6510– 42. DOI:10.1029/2018WR022539.

Song, F., et al. 2022. "Trends in Surface Equivalent Potential Temperature: A More Comprehensive Metric for Global Warming and Weather Extremes," *Proceedings of the National Academy of Sciences* **119**(6), e2117832119. DOI:10.1073/pnas.2117832119.

Sprenger, M., et al. 2015. "Estimating Flow and Transport Parameters in the Unsaturated Zone with Pore Water Stable Isotopes," *Hydrology and Earth System Sciences* **19**, 2617–35. DOI:10.5194/hess-19-2617-2015.

Sprenger, M., et al. 2016. "Illuminating Hydrological Processes at the Soil-Vegetation-Atmosphere Interface with Water Stable Isotopes," *Reviews of Geophysics* **54**(3), 674–704. DOI:10.1002/2015RG000515.

Sprenger, M., et al. 2022. "Variability of Snow and Rainfall Partitioning into Evapotranspiration and Summer Runoff Across Nine Mountainous Catchments," *Geophysical Research Letters* **49**(13), e2022GL099324. DOI:10.1029/2022GL099324.

Stadnyk, T. A., and T. L. Holmes. 2020. "On the Value of Isotope-Enabled Hydrological Model Calibration," *Hydrological Sciences Journal* **65**(9), 1525–38. DOI:10.1080/02626667.2020.1751847.

Stavros, E. N., et al. 2014. “Regional Projections of the Likelihood of Very Large Wildland Fires Under a Changing Climate in the Contiguous Western United States,” *Climatic Change* **126**(3–4), 455–68. DOI:10.1007/s10584-014-1229-6.

Storck, P., et al. 1998. “Application of a GIS-Based Distributed Hydrology Model for Prediction of Forest Harvest Effects on Peak Stream Flow in the Pacific Northwest,” *Hydrological Processes* **12**(6), 889–904. DOI:10.1002/(SICI)1099-1085(199805)12:6<889::AID-HYP661>3.0.CO;2-P.

Stuivenvolt-Allen, J., et al. 2021. “Atmospheric Rivers Impacting Northern California Exhibit a Quasi-Decadal Frequency,” *Journal of Geophysical Research: Atmospheres* **126**(15), e2020JD034196. DOI:10.1029/2020JD034196.

Sun, N., et al. 2019. “Regional Snow Parameters Estimation for Large-Domain Hydrological Applications in the Western United States,” *Journal of Geophysical Research: Atmospheres* **124**(10), 5296–5313. DOI:10.1029/2018JD030140.

Sun, N., et al. 2022. “Forest Canopy Density Effects on Snowpack Across the Climate Gradients of the Western United States Mountain Ranges,” *Water Resources Research* **58**(1), e2020WR029194. DOI:10.1029/2020WR029194.

Swain, D.L., et al. 2018. “Increasing Precipitation Volatility in Twenty-First-Century California,” *Nature Climate Change* **8**, 427–33. DOI:10.1038/s41558-018-0140-y.

Swenson, S. C., et al. 2019. “Representing Intra-Hillslope Lateral Subsurface Flow in the Community Land Model,” *Journal of Advances in Modeling Earth Systems* **11**(12), 4044–65. DOI:10.1029/2019MS001833.

Szinai, J. K., et al. 2020. “Evaluating Cross-Sectoral Impacts of Climate Change and Adaptations on the Energy-Water Nexus: A Framework and California Case Study,” *Environmental Research Letters* **15**(12), 124065. DOI:10.1088/1748-9326/abc378.

Taft, M. 2022. “Desperate Lawmakers Discuss Piping Ocean Water to Fill Great Salt Lake,” Gizmodo, 18 May 2022. (gizmodo.com/utah-great-salt-lake-pipeline-pacific-ocean-1848943455)

Tan, J., et al. 2015. “Increases in Tropical Rainfall Driven by Changes in Frequency of Organized Deep Convection,” *Nature* **519**, 451–54. DOI:10.1038/nature14339.

Tessendorf, S. A., et al. 2015. “The Future of Winter Orographic Cloud Seeding: A View from Scientists and Stakeholders,” *Bulletin of the American Meteorological Society* **96**(12), 2195–98. DOI:10.1175/BAMS-D-15-00146.1.

Thornton, J. M., et al. 2022. “Coverage of *In Situ* Climatological Observations in the World’s Mountains,” *Frontiers in Climate* **4**, 814181. DOI:10.3389/fclim.2022.814181.

Thornton, J. M., et al. 2021. “Toward a Definition of Essential Mountain Climate Variables,” *One Earth* **4**(6), 805–27. DOI:10.1016/j.oneear.2021.05.005.

Tran, H., et al. 2021. “Development of a Deep Learning Emulator for a Distributed Groundwater–Surface Water Model: ParFlow-ML,” *Water* **13**(23), 3393. DOI:10.3390/w13233393.

Trenberth, K. E., et al. 2003. “The Changing Character of Precipitation,” *Bulletin of the American Meteorological Society* **84**(9), 1205–18. DOI:10.1175/BAMS-84-9-1205.

Turner, S. W. D., W. Xu, and N. Voisin. 2020. “Inferred Inflow Forecast Horizons Guiding Reservoir Release Decisions Across the United States,” *Hydrology and Earth System Sciences* **24**(3), 1275–91. DOI:10.5194/hess-24-1275-2020.

Turner, S. W. D., and Voisin, N. 2022. “Simulation of Hydropower at Subcontinental to Global Scales: A State-of-the-Art Review,” *Environmental Research Letters* **17**(2), 023002. DOI:10.1088/1748-9326/ac4e38.

Uhlemann, S., et al. 2022. “Surface Parameters and Bedrock Properties Covary Across a Mountainous Watershed: Insights from Machine Learning and Geophysics,” *Science Advances* **8**(12), eabj2479. DOI:10.1126/sciadv.abj2479.

U.S. Bureau of Reclamation. 2012. *Colorado River Basin Water Supply and Demand Study.* U.S. Department of the Interior. (usbr.gov/lc/region/programs/crbstudy/finalreport/Study%20Report/CRBS_Study_Report_FINAL.pdf)

U.S. Bureau of Reclamation. 2021. 24-Month Projections of Lake Powell and Lake Mead. (usbr.gov/uc/water/crsp/studies/images/PowellElevations.pdf)

U.S. DOE. 2018. *Climate and Environmental Sciences Division Strategic Plan 2018–2023*, DOE/SC–0192. U.S. Department of Energy Office of Science. (science.osti.gov/-/media/ber/pdf/workshop-reports/2018_CESD_ Strategic_Plan.pdf)

van Genuchten, M. T. 1980. "A Closed-Form Equation for Predicting the Hydraulic Conductivity of Unsaturated Soils,” *Soil Science Society of America Journal* **44**(5), 892–898. DOI:10.2136/sssaj1980.03615995004400050002x.

Vandal, T., et al. 2019. “Intercomparison of Machine Learning Methods for Statistical Downscaling: The Case of Daily and Extreme Precipitation,” *Theoretical and Applied Climatology* **137**(1), 557–570. DOI:10.1007/s00704-018-2613-3.

Varhola, A., et al. 2010. “Forest Canopy Effects on Snow Accumulation and Ablation: An Integrative Review of Empirical Results,” *Journal of Hydrology* **392**(3–4), 219–33. DOI:10.1016/j.jhydrol.2010.08.009.

Viviroli D., et al. 2007. “Mountains of the World, Water Towers for Humanity: Typology, Mapping, and Global Significance,” *Water Resources Research* **43**(7), W07447. DOI:10.1029/2006WR005653.

Voisin, N., et al. 2013a. “On an Improved Sub-Regional Water Resources Management Representation for Integration into Earth System Models,” *Hydrology and Earth System Sciences* **17**(9), 3605–22. DOI:10.5194/hess-17-3605-2013.

Voisin, N., et al. 2013b. “One-Way Coupling of an Integrated Assessment Model and a Water Resources Model: Evaluation and Implications of Future Changes over the U.S. Midwest,” *Hydrology and Earth System Sciences* **17**(11), 4555–75. DOI:10.5194/hess-17-4555-2013.

Voisin, N., et al. 2017. "Effects of Spatially Distributed Sectoral Water Management on the Redistribution of Water Resources in an Integrated Water Model," *Water Resources Research* **53**(5), 4253–70. DOI:10.1002/2016WR019767.

Wada, Y., et al. 2016. "Modeling Global Water Use for the 21st Century: The Water Futures and Solutions (WFaS) Initiative and Its Approaches," *Geoscientific Model Development* **9**(1), 175–222. DOI:10.5194/gmd-9-175-2016.

Wainwright, H. M., et al. 2022. "Watershed Zonation Through Hillslope Clustering for Tractably Quantifying Above- and Below-Ground Watershed Heterogeneity and Functions," *Hydrology and Earth System Sciences* **26**(2), 429–44. DOI:10.5194/hess-26-429-2022.

Waliser, D., et al. 2020. "Observations for Model Intercomparison Project (Obs4MIPs): Status for CMIP6," *Geoscientific Model Development* **13**(7), 2945–58. DOI:10.5194/gmd-13-2945-2020.

Wang, S. S.-C., et al. 2021. "Identifying Key Drivers of Wildfires in the Contiguous U.S. Using Machine Learning and Game Theory Interpretation," *Earth's Future* **9**(6), e2020EF001910. DOI:10.1029/2020EF001910.

Wang, S.-Y., et al. 2018. "Cross-Basin Decadal Climate Regime connecting the Colorado River and the Great Salt Lake," *Journal of Hydrometeorology* **19**(4), 659–65. DOI:10.1175/JHM-D-17-0081.1.

Wang, Y., B. Geerts, and C. Liu. 2018. "A 30-Year Convection-Permitting Regional Climate Simulation Over the Interior Western United States. Part I: Validation," *International Journal of Climatology* **38**(9), 3684–704. DOI:10.1002/joc.5527.

Wemple, B. C., and J. A. Jones. 2003. "Runoff Production on Forest Roads in a Steep, Mountain Catchment," *Water Resources Research* **39**(8), 1220. DOI:10.1029/2002WR001744.

Werner, C., et al. 2021. "Ecosystem Fluxes During Drought and Recovery in an Experimental Forest," *Science* **374**(6574), 1514. DOI:10.1126/science.abj6789.

Werner, F., et al. 2010. "National and Global Greenhouse Gas Dynamics of Different Forest Management and Wood Use Scenarios: A Model-Based Assessment," *Environmental Science & Policy* **13**(1), 72–85. DOI:10.1016/j.envsci.2009.10.004.

Williams, A. P., et al. 2022. "Growing Impact of Wildfire on Western U.S. Water Supply," *Proceedings of the National Academy of Sciences of the United States of America* **119**(10), e2114069119. DOI:10.1073/pnas.2114069119.

Williams, C. 2022. "Experts Hope Cloud Seeding Will Help with Colorado's Drought," FOX5 New York, 6 June 2022. (fox5ny.com/news/cloud-seeding-could-help-with-colorados-drought)

Wrzesien, M. L., M. T. Durand, and T. M. Pavelsky. 2019. "A Reassessment of North American River Basin Cool-Season Precipitation: Developments from a New Mountain Climatology Data Set," *Water Resources Research* **55**(4), 3502–19. DOI:10.1029/2018WR024106.

Xu, Y., A. Jones, and A. Rhoades. 2019. "A Quantitative Method to Decompose SWE Differences Between Regional Climate Models and Reanalysis Datasets," *Scientific Reports* **9**(1), 1–11. DOI:10.1038/s41598-019-52880-5.

Yassin, F., et al. 2019. "Representation and Improved Parameterization of Reservoir Operation in Hydrological and Land-Surface Models," *Hydrology and Earth System Sciences* **23**(9), 3735–64. DOI:10.5194/hess-23-3735-2019.

Yoon, J., et al. 2022. "A Typology for Characterizing Human Action in MultiSector Dynamics Models," *Earth's Future* **10**(8), e2021EF002641. DOI:10.1029/2021EF002641.

York, L. M., et al. 2016. "The Holistic Rhizosphere: Integrating Zones, Processes, and Semantics in the Soil Influenced by Roots," *Journal of Experimental Botany* **67**(12), 3629–43. DOI:10.1093/jxb/erw108.

Yu, Y., and P. Ginoux. 2022. "Enhanced Dust Emission Following Large Wildfires Due to Vegetation Disturbance," *Nature Geoscience* **15**, 878–84. DOI:10.1038/s41561-022-01046-6.

Zedler, P. H., C. R. Gautier, and G. S. McMaster. 1983. "Vegetation Change in Response to Extreme Events: The Effect of a Short Interval between Fires in California Chaparral and Coastal Scrub," *Ecology* **64**(4), 809–18. DOI:10.2307/1937204.

Zhou, T., et al. 2020. "Global Irrigation Characteristics and Effects Simulated by Fully Coupled Land Surface, River, and Water Management Models in E3SM," *Journal of Advances in Modeling Earth Systems* **12**(10), e2020MS002069. DOI:10.1029/2020MS002069.

Zscheischler, J., et al. 2018. "Future Climate Risk from Compound Events," *Nature Climate Change* **8**(6), 469–77. DOI:10.1038/s41558-018-0156-3.

Appendix D: Participant Feedback

Participants who attended Session 1 of the "Understanding and Predictability of Integrated Mountain Hydroclimate" workshop (November 15–16, 2021) provided the following list of projects and research areas when asked for names and descriptions of IMHC-related projects and research. It is not intended to be a comprehensive list.

Project Name or Research Area	Description
U.S. Department of Energy (DOE)	
Calibrated and Systematic Characterization, Attribution, and Detection of Extremes (CASCADE)	The CASCADE project advances understanding of natural and anthropogenic influences on multiscale climate extremes in observations and models. For more information, see cascade.lbl.gov.
Cooperative Agreement To Analyze variabiLity, change and predictabilitY in the earth Sys-Tem (CATALYST)	CATALYST represents a sustained commitment between DOE and the University Corporation for Atmospheric Research to perform foundational research toward advancing a robust understanding of modes of variability (MOVs) and change using models, observations, and process studies. Topics include (1) understanding the limits of predictability of MOVs, (2) applying a hierarchy of models to address processes and feedbacks, (3) benchmarking MOVs in Earth system models (ESMs), and (4) investigating the relationship between MOVs and high-impact events. For more information, see cgd.ucar.edu/projects/catalyst.
Energy Exascale Earth System Model (E3SM)	E3SM is a state-of-the-art modeling, simulation, and prediction project to address the needs of the nation and DOE's energy mission. E3SM addresses three science drivers: water cycle, biogeochemistry, and cryospheric systems. For more information, see e3sm.org.
Environmental System Science Data Infrastructure for a Virtual Ecosystem (ESS-DIVE)	ESS-DIVE stores and publicly distributes data from observational, experimental, and modeling research funded by the DOE's Office of Science under its Environmental System Science program. For more information, see ess-dive.lbl.gov.
ExaSheds: Advancing Watershed System Science using Machine Learning for Data-Intensive Simulation	ExaSheds aims to fundamentally change how watershed function is understood by combining leadership-class computers, big data, and machine learning (ML) into learning-assisted physics-based simulation tools. For more information, see exasheds.org.
HyperFACETS: A Framework for Improving Analysis and Modeling of Earth System and Intersectoral Dynamics at Regional Scales	A joint continuation of DOE's Hyperion and Framework for Analysis of Climate-Energy-Technology Systems (FACETS) projects, HyperFACETS continues and extends these past projects by (1) further advancing understanding of processes at the climate-water-energy-land-decision interface and (2) fundamentally improving the ability to perform credible climate modeling of particular regions. The HyperFACETS project aims to address these questions: *How much can we trust given climate information for actionable climate science? How can we ensure its saliency?* For more information, see hyperfacets.ucdavis.edu.
Investigating the Impacts of Climate-Driven Disturbances on River Water Quality Using a Data-Driven Framework	This project examines how disturbances (i.e., floods, droughts, and heatwaves) affect river water quality through a novel data synthesis, analysis, and modeling framework that uses statistical and ML approaches.
Model-Data Fusion to Examine Multiscale Dynamical Controls on Snow Cover and Critical Zone Moisture Inputs	This project has developed a 34-year historical high-resolution (1-km spatial and 1-hr temporal) regional climate dataset in the Upper Colorado Basin and a 20-year historical 30m/1-day resolution snow cover dataset for Colorado's East River watershed.

Project Name or Research Area	Description
U.S. Department of Energy (DOE)	
Multiscale Modeling of Extremes and Impact Information	Part of DOE's Regional and Global Model Analysis program, this project will adopt a novel methodology for identifying the causality and predictability of hydrometeorological (i.e., the water cycle and the transfer of water and energy between the land surface and the lower atmosphere) extreme events. For more information, see climatemodeling.science.energy.gov/projects/multi-scale-modeling-extreme-events-and-impact-information.
Observations of Blowing Snow at DOE's Atmospheric Radiation Measurement (ARM) Sites	This project will process surface and remotely sensed data to detect blowing snow layers. Instrumentation (i.e., hydrometeor imager and blowing snow mass flux sensors) will be deployed during the second year of ARM's Surface Atmosphere Integrated Field Laboratory (SAIL) campaign.
Program on Coupled Human and Earth Systems (PCHES)	PCHES is a university-based consortium for multisector dynamics research aiming to create new, state-of-the-art, integrated modeling tools and methods to drive advances in the quantitative understanding of coupled systems, multisector dynamics, and risk and response behaviors. For more information, see aese.psu.edu/research/areas/environment-and-natural-resources/program-on-coupled-human-and-earth-systems-pches.
River Corridor Hydro-Biogeochemistry Science Focus Area (SFA)	The River Corridor Hydro-Biogeochemistry SFA is developing predictive understanding of the role of coupled hydrology and biogeochemistry in river corridors on watershed function. The project is based in the Yakima River basin, which extends from the crest of the Cascade Mountains to the mainstem Columbia River. Research emphasizes the role of hydrologic exchange and subsurface biogeochemistry on nutrient cycling and response to perturbations, including wildfires and extreme precipitation events. For more information, see pnnl.gov/projects/river-corridor.
SLAC Floodplain Hydro-Biogeochemistry SFA	Hydrology-driven biogeochemistry of floodplains (currently Slate River, Colo.). Focus on sediment interfaces, colloid formation and transport, microbiology responses, and reactive transport modeling. For more information, see sites.slac.stanford.edu/bargargroup.
Surface Atmosphere Integrated Field Laboratory (SAIL)	Mountains are the natural water towers of the world, but ESMs have persistently been unable to predict the timing and availability of water resources from mountains. The main science goal of the SAIL campaign is to develop a quantitative understanding of the atmosphere and land-atmosphere interaction processes, at their relevant scales, that impact mountain hydrology in the midlatitude continental interior of the United States. For more information, see sail.lbl.gov.
Water Cycle and Climate Extremes Modeling (WACCEM) SFA	WACCEM advances understanding and modeling of water cycle and extreme events and their response to warming. For more information, see climatemodeling.science.energy.gov/projects/water-cycle-and-climate-extremes-modeling.
Watershed Function SFA	The Watershed Function SFA uses a coupled data-model framework to understand how mountainous systems retain and release water, nutrients, and metals in the Anthropocene. The project is specifically interested in the impacts of shorter duration climate perturbations, such as drought and hot drought, on flows of water and nutrients over episodic to decadal timescales. For more information, see watershed.lbl.gov.
National Aeronautics and Space Administration (NASA)	
Evaluation of High-Resolution Snow-Covered Area Mapping in Mountain EcoSystems from PlanetScope Imagery	This research uses ML to map m-scale snow cover area with PlanetScope imagery in meadows and sparse forests.

Project Name or Research Area	Description
National Aeronautics and Space Administration (NASA)	
High Mountain Asia Team (HiMAT)	HiMAT is a collaborative research program studying cryospheric changes. Multiple research teams are investigating questions like: *What is driving changes in hydrology and cryosphere in the High Asia region? What range of possible impacts on local stakeholders can we expect in the future?* For more information, see himat.org.
Lifecycle of Snow in the Sierra Nevada USA: From Snowfall to Snowmelt and Effects on Endangered Bighorn Sheep	This interdisciplinary study models the lifecycle of snow from its formation in the atmosphere through its accumulation and ablation in current and future climates. Results will be used to examine snow effects on endangered Sierra Nevada bighorn sheep and understand how a future climate might modify habitat and behavior.
National Oceanic and Atmospheric Administration (NOAA)	
Advancing Probabilistic Prediction of High-Impact Winter Storms through Ensemble Numerical Weather Prediction Systems and Post-Processing	This research uses downscaling and snow-to-liquid ratio algorithms to improve high-resolution snowfall forecasts in complex terrain in the western continental U.S. For more information, see wpo.noaa.gov/advancing-probabilistic-prediction-of-high-impact-winter-storms-through-ensemble-nwp-and-post-processing.
National Science Foundation (NSF)	
Characterizing Mountain System Aquifer Recharge in the Sierra Nevada Mountains of California	This project investigates the most important drivers of groundwater recharge in the Kaweah River watershed in Sierra Nevada. Research combines groundwater and surface water chemistry and remotely sensed data with numerical models to understand recharge. This project was selected as an award recipient of the NSF Faculty Early Career Development (CAREER) Program.
Cyberinfrastructure for Intelligent High-Resolution Snow Cover Inference from Cubesat Imagery	This project will develop open-source, cloud-based cyberinfrastructure including an automated pipeline for processing, analyzing, and interpreting Planet Cubesat image data using an ML approach to infer snow cover at meter-scale resolution. This project was selected as an award recipient in the collaborative research category of the NSF CAREER Program.
Lake- and Sea-Effect Precipitation Systems in Complex Terrain	This NSF-funded project is conducting observational and numerical modeling studies of shallow convection (typically lake or sea effect) and its interaction with complex terrain.
Machine Learning Training and Curriculum Development for Earth Science Studies	This project is developing ML curriculum and training events for geoscientists. It was selected as an award recipient of the NSF Training-Based Workforce Development for Advanced Cyberinfrastructure Program.
Navigating the Clouds on the Horizon: Research and Education for Cloud-Enabled Computational Hydrology in the Data Revolution	This project examines climate variability and change in the Snake River Basin by applying intermediate and full-complexity land-atmosphere models in cloud computing environments. It was selected as an award recipient of the NSF Mid-Career Advancement (MCA) Program.
New Science, Tools, and Observations to Couple Geodesy with Hydrology for Modeling, Water Storage Change, and Streamflow Forecasting in Mountain Watersheds	This project bridges traditional disciplinary boundaries in Earth (geodesy) and water (hydrology, meteorology) sciences to generate new knowledge about the storage and flow of water through mountain watersheds. This project was selected as an award recipient in the collaborative research category of the NSF CAREER Program.

Project Name or Research Area	Description
National Science Foundation (NSF)	
Universalizing Similarity Theories Coupling the Atmosphere and Sloping Terrain	This project conducts observations and subgrid-scale parameterization development for land-water-atmosphere interactions. The new field campaign will take place in the Northern Sierra-Nevada Range and will also use data over slopes in the Swiss Alps, Utah (the MATERHORN Campaign), and Portugal (the Perdigão Campaign). This project was selected as an award recipient of the NSF CAREER Program.
U.S. Bureau of Reclamation	
Investigating the Potential of Cloud Seeding to Enhance Precipitation in the East River Basin, Colorado	This research project uses a combination of high-resolution modeling and available observations to investigate the potential of cloud seeding to enhance precipitation in a test site in the East River Basin, Colorado. For more information, see usbr.gov/research/projects/detail.cfm?id=22068.
U.S. Department of Agriculture (USDA)	
Linking Forest Stand Age to Aquatic Biodiversity	This research is linking aquatic biodiversity to forest stand age using eDNA metabarcoding in the Pacific Northwest.
Managing Forest System Diversity to Enhance Resilience and Ecosystem Services	This project uses forest ecology and ecohydrology in southern Appalachian forests (southeastern U.S.) to study the effects of forest understory management (cutting and prescribed fire) on hydrologic processes. For more information, see nicholas.duke.edu/node/29037.
Missoula Fire Lab Emission Inventory (MFLEI)	The MFLEI is a retrospective, daily wildfire emission inventory for the continental U.S. For more information, see data.nal.usda.gov/dataset/missoula-fire-lab-emission-inventory-mflei-conus.
National Forest Service Climate Change Maps	Developed by the Rocky Mountain Research Station and the Office of Sustainability and Climate, this project generates maps of climate change projections for snow and water resources on U.S. National Forests. For more information, see fs.usda.gov/rm/boise/AWAE/projects/national-forest-climate-change-maps.html.
USDA Forest Service and U.S. Environmental Protection Agency (EPA)	
Mobile Ambient Smoke Investigation Capability (MASIC)	To better understand wildfire smoke, the MASIC study is collecting air measurements from both EPA-designated reference and nonregulatory instruments to determine their performance capabilities during wildfires.
U.S. Geological Survey (USGS)	
Predictive Understanding of Multiscale Processes (PUMP)	This project aims to advance hydroclimate modeling capabilities in support of improving water availability assessments and contribute to a National Water Census.
International Agencies	
Global Energy and Water Exchanges (GEWEX)	A core project of the World Climate Research Programme, GEWEX is a 10-year project dedicated to understanding Earth's water cycle and energy fluxes at and below the surface and in the atmosphere. The project is driven by a need for climate justice and for tools to address water, food, and energy security in a changing future. For more information, see gewex.org.
IntegrAlp	This Swiss NSF-funded project aims to fully integrate 2D-3D surface-subsurface hydrological modeling in a complex Swiss Alpine catchment.

Appendix E: Acronyms and Abbreviations

AI	artificial intelligence
ARM	DOE Atmospheric Radiation Measurement user facility
ATH	atmosphere-terrestrial-human
AWS	automatic weather station
BER	DOE Biological and Environmental Research program
CACTI	Clouds, Aerosols, and Complex Terrain Interactions field campaign
CASCADE	Calibrated and Systematic Characterization, Attribution, and Detection of Extremes project
CLASP	Coupling of Land and Atmospheric Subgrid Parameterizations project
CLM	Community Land Model
CO_2	carbon dioxide
CORDEX	Coordinated Regional Climate Downscaling Experiment
CR	Colorado River
CZNet	Critical Zone Collaborative Network
DOE	U.S. Department of Energy
E3SM	Energy Exascale Earth System Model
EESSD	Earth and Environmental Systems Sciences Division
ELM-FATES	Energy Exascale Earth System Model's Land Model–Functionally Assembled Terrestrial Ecosystem Simulator
EPA	U.S. Environmental Protection Agency
EPSCoR	Established Program to Stimulate Competitive Research
ESM	Earth system model
EXCLAIM	EXtreme scale Computing and data platform for cLoud-resolving weAther and clImate Modeling
FACETS	DOE Framework for Analysis of Climate-Energy-Technology Systems project
FAIR	findable, accessible, interoperable, and reusable
GASSP	Global Aerosol Synthesis and Science Project
GCAM	Global Change Analysis Model
GCIMS	Global Change Intersectoral Modeling System
GEWEX	Global Energy and Water Exchanges project
HAN-SoMo	High-Altitude Nitrogen Suite of Models
HiMAT	High Mountain Asia Team
HyTEST	Hydro-terrestrial Earth Systems Testbed project
ICLUS	Integrated Climate and Land-Use Scenarios project
IM3	Integrated Multisector Multiscale Modeling

IMHC	integrated mountain hydroclimate
ITCZ	Intertropical Convergence Zone
IWP	Integrated Water Prediction program
IWP-PUMP	Integrated Water Prediction and Predictive Understanding of Multiscale Processes project
LBNL	Lawrence Berkeley National Laboratory
LEO	Landscape Evolution Observatory
LTER	Long-Term Ecological Research network
ML	machine learning
ModEx	model-experiment
MOSART	Model for Scale Adaptive River Transport
MOSART-WM	Model for Scale Adaptive River Transport-Water Management
MSD	DOE MultiSector Dynamics program
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NIDIS	National Integrated Drought Information System
NOAA	National Oceanic and Atmospheric Administration
NSF	National Science Foundation
NWT LTER	Niwot Ridge Long-Term Ecological Research program
O2R	Operations-2-Research
PCHES	Program on Coupled Human and Earth Systems
PFLOTRAN	Parallel Reactive Flow and Transport Model
R2O	Research-2-Operations
RELAMPAGO	Remote sensing of Electrification, Lightning, And Mesoscale/microscale Processes with Adaptive Ground Observations campaign
RHP	Regional Hydroclimate Project
S2S	subseasonal-to-seasonal
SAIL	Surface Atmosphere Integrated Field Laboratory
SFA	Science Focus Area
SMART	Sensors at Mesoscale with Autonomous Remote Telemetry
SPLASH	Study of Precipitation, the Lower Atmosphere, and Surface for Hydrometeorology program
TERI	Tomographic Electrical Rhizosphere Imager
USDA	U.S. Department of Agriculture
USGS	U.S. Geological Survey
WACCEM	Water Cycle and Climate Extremes Modeling SFA
WCRP	World Climate Research Programme
WRF	Weather Research and Forecasting model

U.S. DEPARTMENT OF ENERGY | Office of Science

Biological and Environmental Research Program