Model Hierarchy for Mountainous Hydrological Observatories (MH^{2}O)

1 Authors/Affiliations

William D. Collins (LBNL and UC Berkeley) and the Integrated Mountainous Hydrology Study Group (LBNL)

2 Focal Area

Predictive modeling through the use of AI techniques and AI-derived model components; the use of AI and other tools to design a prediction system comprising of a hierarchy of models (e.g., AI driven model/component/parameterization selection)

3 Science Challenge

Water from snowpack constitutes a critical environmental input as well as a critical natural reservoir in the western US resource. The spring freshet contributes half of the total runoff in the region, yet has shown a net decline across 90% of reporting stations over the last century. This poses a significant challenge as water from the Colorado River system, largely fed by snowpack in the Rockies, supports thirty million people, and one third of the annual water supply to California is supplied by snow melt from the Sierra Nevadas. The snowpack from these two mountain systems further support critical ecosystem services, agricultural production, hydroelectric power, and a billion dollar ski industry. In the coming decades, this decline may accelerate and result in historically-unprecedented disturbance regimes.

Yet, the exact magnitude, timing, and location of changes to mountain snowpack remain uncertain due to complex multi-scale interactions with enormous "trickle down" implications (based on when shifts in snow to rain are realized). Therefore, the practical and scientific challenge to projecting the future of these mountainous hydrological systems arises from historically-unprecedented disturbance regimes introduced by the local effects of global environmental change.

4 Rationale

The first class of disturbances mentioned above is due to major alterations to the forests in mountainous watersheds including shifts upslope in forest habitability zones, increased wildfire frequency, and more frequent tree die-off due to invasive pests. The second class of disturbances are due to major anticipated alterations to the mountainous hydroclimate, including a near total shift in the phase of precipitation from snow to rain to snow, accelerated warming with elevation (snow-albedo feedback), much more intense atmospheric rivers and summer monsoons, and longer intervals (in some cases encompassing severe droughts) between these storms.

These no-analog conditions imply that empirical research and operational models calibrated against the historical record will lose projective skill, necessitating the adoption of a physics-based projection platform.

DOI: https://doi.org/10.2172/1769748
DOE BER, AI4ESP 2021 #AI4ESP1026 (https://www.ai4esp.org)

5 Narrative

We propose to integrate the extensive observational and computational capabilities of DOE to build an unprecedented system to help constrain and provide clarity to these for these projections, the Model Hierarchy for Mountainous Hydrological Observatories, or MH^2O. The timeliness and immediacy of MH^2O is based on three transformative opportunities: (1. The creation of a world-leading bedrock-to-free troposphere hydrological observatory in the Rockies in 2021; (2. The dawn of DOE's true Exascale Leadership Computing Facilities (LCFs) in 2021 and 2022; and (3. The accelerated development of subsurface hydrological models optimized for these LCFs.

MH^2O will unite our existing capabilities in three "rungs" of a simulation echelon consisting of process-based, projection, and translational model suites. This hierarchy is designed to combine the advantages of computationally-intensive models operating at the same native space and time scales as our observational networks with computationally-inexpensive and hence more parameterized models designed for projections at decision-relevant time horizons. The rungs are connected by two-way transferability of metrics and error characterization: the process-based models can be tested deterministically against our observational assets; then the errors in the projection vs. process-based models can be quantified over the same observing periods using our CASCADE ILIAD (InitiaLized-ensemble Identify, Analyze, Develop) framework; and finally the uncertainties in the translational models can be quantified by running these with altered-climatic inputs generated by the projection models (run with the Model for Scale Adaptive River Transport – MOSART) in scenarios for droughts, extreme AR seasons, etc. Likewise, we can use our proven techniques from HyperFACETS to convert user-inspired metrics on river hydrology to metrics applicable to the projection and ultimate process-based models. Comparing the various runs of the hierarchy will be greatly facilitated by the Interoperable Design of Extreme-scale Application Software (IDEAS) framework to create interchangeable test "harnesses".

The process-based suite would combine models of atmospheric inputs together with detailed models of subsurface hydrological, chemical, biogeochemical, and thermodynamic processes. The atmospheric inputs would be supplied by WRF-LES (large eddy simulation) at the 10s-of-meters scales required to capture interactions with hill slopes, narrow stream and river channels, and sharp gradients in the landscape such as tree lines and ridge crests separating watersheds. The subsurface modeling would be conducted using the ExaSheds code base centered on Amanzi-ATS, and parallel simulations would be conducted with ELM-PFLOTRAN, a publicly released capability for E3SM. The three-year vision of ExaSheds is to be capable of conducting years-to-decades simulations of the East River on DOE's GPU-based LCFs – simulations of this length are required to see if the process-based model can reproduce the detailed annual cycle as well as interannual variability in the Watershed Function SFA experimental domain. The projection suite would be comprised of VR-E3SM and potentially a GPU-ized version of WRF. The DOE HyperFACETS and CASCADE teams have extensive experience using VR-CESM, a sister model to VR-E3SM, to simulate the hydroclimate of the mountainous American West at resolutions down to resolutions of several kilometers. The translation suite would be populated with the hybrid machine-learning/operational models successfully demonstrated under the first period of performance for ExaSheds.

The projections from this hierarchy will require extensive observationally-grounded metrics in order to quantify the physical fidelity and remaining uncertainties in the component models. DOE has several unique observational assets to serve as the foundation for these metrics. These include DOE's Watershed Function SFA and the upcoming DOE-led Surface Atmosphere Integrated field

Laboratory (SAIL) deployment of the DOE ARM Mobile Facility that will be coincident and collocated with Watershed observing systems. The combination of Watershed and SAIL is effectively a bedrock-to-free troposphere hydrological observatory and will provide comprehensive field-data tests of the process-based model suite. This data will be combined with the measurements from the USGS Next Generation Water Observing System (NGWOS) that was just launched in the headwaters of the Colorado and Upper Gunnison Basins starting in October 2019. NGWOS is an advanced observing system that provides quantitative information on streamflow, evapotranspiration, snowpack, soil moisture, a broad suite of water quality constituents, connections between groundwater and surface water, and water use. We will use the combination of Watershed Function, SAIL, and NGWOS data to test the process-based model suite.

For the projection suite we propose to develop new metrics linking observables to future responses, otherwise known as emergent constraints. These have the advantage that calibrating a model to the pertinent observable implies that it will also now correctly mimic the future response. We also plan to develop analogues to well-established metrics for AGCMs that link systematic biases that emerge in inexpensive, short-duration, large-end-member ensembles to systematic biases that emerge in much more expensive, long duration simulations of the global change. This facilitates eliminating systematic errors in long-range projections using a fast duty-cycle of calibrations.

For the translational suite, the HyperFACETS project is ideally suited to provide stakeholder-vetted and relevant metrics of streamflow, water catchment characteristics, etc. to test these models We will explore unified tests of short-range predictions on daily to weekly timescales and longer-range projections on seasonal to decadal timescales to understand how successes in reducing errors at one range of timescales translates into error amelioration at another, very different range of timescales. This is analogous to the approach used by unified NWP and climate models.

A key component of the MH^2O concept is robust uncertainty quantification. The four types of uncertainty we need to track from (exogenous) uncertainty boundary and initial conditions and from (endogenous) structural and parametric errors in the model formulation.

For the projection suite there is an extensive, very well-vetted, and ready-to-use collection of methods and data sets to help quantify the errors in the projections. These include estimates of structural uncertainty, by comparing VR-E3SM against the multi-model ensemble (MME) assembled for the Coupled Model Intercomparison Project (CMIP6) version 6 High Resolution MIP (HighResMIP), the world's first comprehensive MME run at 25 kilometer resolution. Boundary condition uncertainty can be easily quantified using the Shared Socioeconomic Pathways (SSPs) and Representative Concentration Pathways (RCPs), i.e. scenarios for future greenhouse gas emissions and concentrations, developed for the CMIP process. Initial condition uncertainty can be readily quantified using large ensembles of perturbed-initial-condition simulations analogous to NCAR's Large Ensemble. Parametric uncertainty can be quantified using Perturbed Parameter Ensembles (PPEs), and CASCADE has extensive experience generating and interpreting PPEs.

For the process-model suite, we can exploit the proof-of-principle applications from ExaSheds of machine learning to bound errors from uncertain initial and boundary conditions. For PPE we explore running limited ensembles of Amanzi-ATS and using machine learning to interpolate between these samples in parametric phase space following methods developed by CASCADE. For structural uncertainty we propose to orchestrate and run DOE's first subsurface "hydro MIP" using codes comparable to Amanzi-ATS from sister laboratories. We propose to convert all the output from these codes to a common format analogous to that adopted by CMIP's Climate Model Output Rewriter (CMOR) and serve the results to the US hydrological communities via ESS-DIVE.

6 Suggested Partners/Experts

Partners could include team members of ExaSheds, IDEAS, Watershed Function SFA, E3SM, and SAIL.

7 Data access and FAIR standards

The underlying projects all operate under the DOE data policies and are or will make all code, data, and derived products publicly available.