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Propagating Meteorological Uncertainty in Physically Based Mountain Snow Simulations

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Abstract.

Snow estimation in mountainous regions is uncertain because meteorology varies with topography, in situ observations are sparse and biased, and snow models have structural and scale limitations. Probabilistic methods are increasingly recognized as essential for quantifying and propagating these uncertainties in hydrological assessment. This study generates meteorological forcing ensembles designed for mountainous terrain and applies them for probabilistic, physically based snow modeling. Precipitation from global station datasets is corrected for wind induced undercatch using standardized transfer functions. Using the Geospatial Probabilistic Estimation Package (GPEP), we generate station based meteorological ensembles that combine static topographic predictors with dynamic atmospheric predictors from reanalyses. Deterministic fields are estimated with locally weighted regression and random forests, and spatially correlated random fields are used to sample residuals and produce skillful, reliable ensembles. The resulting ensembles drive the SUMMA energy-balance snow model in three contrasting basins: the Chena (Interior Alaska), Bow (Canadian Rockies), and Tuolumne (Sierra Nevada). Undercatch correction improves cold-season precipitation, dynamic predictors enhance regression skill, and random forests outperform locally weighted regression. Ensemble verification yields positive Brier Skill Scores, and ensemble-forced SUMMA simulations reproduce observed snow water equivalent with credible magnitude, timing, and uncertainty estimates. This structured approach advances probabilistic estimation of mountain snow by explicitly representing forcing uncertainty in complex terrain, supporting modeling, data assimilation, and water resource management applications.

1 Introduction

Measurements and model estimates of mountain snow are essential for predicting runoff, managing flood risk, and planning for water scarcity in snow-dependent regions (Huning and AghaKouchak, 2020; Immerzeel et al., 2020; Sturm et al., 2017; Wood and Lettenmaier, 2008). However, despite the recognized benefits and concerted research efforts, quantifying mountain snow continues to be a persistent and multi-faceted challenge characterized by considerable uncertainty (Girotto et al., 2020; Largeron et al., 2020; Dozier et al., 2016). This challenge is driven by the influence of complex terrain on meteorology, snow distribution, and the inability to obtain observations that are spatially and temporally representative (Clark et al., 2011; Frei

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and Isotta, 2019). Snow models forced with meteorological data are also uncertain, as coarse-scale representations of both meteorology and snow dynamics fail to capture actual snowpack variability (Marsh et al., 2024). Observations used to evaluate and constrain models are typically limited in spatial density and temporal frequency relative to the processes governing snow accumulation and melt (Sturm et al., 2010; Miller et al., 2022; Blöschl and Sivapalan, 1995). The result is high uncertainty in mountain snow estimation that often remains unquantified.

Estimating meteorological variables in complex terrain has traditionally relied on interpolating sparse station observations into gridded fields while accounting for topographic effects. Early approaches focused on physiographic interpolation, using elevation and terrain descriptors to adjust station data for lapse rates and orographic gradients (Daly et al., 1994; Clark and Slater, 2006). Products such as the Parameter-elevation Regression on Independent Slopes Model (PRISM) follow this framework, combining station observations with expert-based weighting to represent climate fields in mountains (Daly et al., 2008, 2021). Complementary statistical approaches, including locally weighted regression, capture relationships between meteorological variables and static predictors such as elevation, slope, and aspect (Newman et al., 2020). Gridded meteorological datasets are widely used in snow modeling, but can exhibit substantial bias and lack explicit uncertainty characterization, particularly in mountainous regions (Daly et al., 2021; Henn et al., 2018a). These biases propagate through snowpack simulations, making meteorological forcing a dominant source of model uncertainty (Raleigh et al., 2015). Global reanalyses such as ERA5 combine observations with numerical weather prediction to produce spatially and temporally complete datasets (Hersbach et al., 2020). While they offer consistency and coverage, they often underperform in complex terrain and require bias correction and downscaling before hydrological use (Beck et al., 2017; Hong et al., 2022; Berg et al., 2024; Lussana et al., 2018). Deterministic gridded products can overly smooth spatial variability and underestimate extremes (Ensor and Robeson, 2008; Gervais et al., 2014). Machine learning (ML) methods such as Random Forests (RF) have also been successfully applied to resolve patterns of meteorological data in complex terrain (Wolfensberger et al., 2021; Baez-Villanueva et al., 2020). However, accurately resolving such variability requires far denser observational networks than currently exist (Frei and Isotta, 2019).

Snow measurement is essential for understanding snowpack evolution and constraining models, but remains limited in spatial and temporal coverage. In-situ networks, including snow pillows, automated sensors, and manual surveys, provide locally accurate estimates of snow depth and water equivalent, yet are too sparse to capture heterogeneity driven by topography, wind, and vegetation (Pomeroy et al., 2007; Brown et al., 2019; Mortimer and Vionnet, 2025; Clark et al., 2011). Airborne and terrestrial lidar, along with satellite remote sensing, have expanded the ability to map snow depth, cover, and albedo across larger domains (Deems et al., 2013; Painter et al., 2016; Gascoin et al., 2024). However, their use remains constrained by infrequent coverage, uncertainties in converting depth to water equivalent, and retrieval challenges in forested or complex terrain (Sturm et al., 2010; Margulis et al., 2019). Reanalysis and remote-sensing products complement ground-based observations by providing spatially continuous meteorological fields where in-situ measurements are sparse or unreliable (Lundquist et al., 2019).

Snow models are widely used to quantify snow mass, codify process understanding and support hydrologic prediction (Pomeroy et al., 2007; Vionnet et al., 2021a; Essery et al., 2013; Sun et al., 2019; Marsh et al., 2024). Modeling in complex terrain presents challenges, including steep energy-balance gradients, heterogeneous snow processes, and systematically bi-

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ased precipitation inputs (Zhao and Li, 2015; Clark et al., 2011). Approaches range from conceptual degree-day models to physically based, high-resolution systems that solve processes such as resolving energy balance, blowing snow, canopy interception, and avalanching (Hrachowitz and Clark, 2017; Magnusson et al., 2015). However, increased model complexity does not necessarily improve predictive performance, as meteorological forcing, structural and parameter uncertainties often dominate and compensate for unresolved processes (Menard et al., 2021). Model Intercomparison Projects (MIPs) demonstrate that inter-model variability arises not only from differing process representations but also from forcing data, calibration, and scale mismatches (Essery et al., 2013; Menard et al., 2021). Key processes such as refreezing, sublimation, wind redistribution, and rain-on-snow thermodynamics remain difficult to accurately simulate, yet strongly influence snow mass and energy budgets (Marks et al., 1998; Pomeroy et al., 2016; Barlage et al., 2010). As a result, snow model uncertainty reflects both incomplete process understanding and the difficulty in parameterizing subgrid variability in meteorological and terrain drivers (Günther et al., 2019). Increasingly, ensemble modeling, data assimilation, and high-resolution process studies are being used to constrain model states and improve predictive skill (Girotto et al., 2020; Largeron et al., 2020; Vionnet et al., 2021a; Sun and Margulis, 2025; Mott et al., 2023).

Ensemble approaches provide a means to represent and propagate uncertainty in both model inputs and model states. In meteorology and climate science, ensembles are used to characterize distributions of plausible outcomes (Collins, 2007), and hydrology has increasingly adopted ensemble methods to quantify predictive uncertainty and provide probabilistic streamflow forecasts (Cloke and Pappenberger, 2009; Wu et al., 2020). In mountain environments, where predictive skill depends critically on accurate representation of snowpack states, ensemble methods enable the integration of various observations through data assimilation to improve snow estimation (Clark et al., 2006; Wood et al., 2016; Vernay et al., 2015; Largeron et al., 2020; Girotto et al., 2020). Better characterization of precipitation and temperature uncertainty is particularly important, for example, given the increasing frequency of rain-on-snow events under a warming climate (Hotovy et al., 2025; Musselman et al., 2018). Recent developments in meteorological ensembles that incorporate both static topographic controls to observations and dynamic atmospheric predictors offer promising pathways to capture input uncertainty (Clark and Slater, 2006; Newman et al., 2020; Bunn et al., 2022; Tang et al., 2024). This evolution from deterministic interpolation to probabilistic ensemble generation reflects a growing recognition that uncertainty quantification is essential in mountainous terrain (Frei and Isotta, 2019; Bertoncini and Pomeroy, 2025; Kim et al., 2021; Mott et al., 2023).

A key gap remains in how probabilistic meteorological information is generated and evaluated for mountain snow modeling. Most existing studies in complex terrain focus on developing or validating probabilistic precipitation and temperature estimates (e.g., Frei and Isotta, 2019; Bertoncini and Pomeroy, 2025), yet few extend this uncertainty representation through to physically based snow modeling. Consequently, the influence of forcing uncertainty on simulated snowpack evolution, melt timing, and water availability remains poorly quantified (Dozier et al., 2016; Largeron et al., 2020; Girotto et al., 2020; Tang et al., 2025a). Mountain snow modeling studies using physically based or energy-balance approaches very often continue to rely on a single deterministic meteorological forcing, typically derived from gridded observation-based or downscaled reanalysis products (Essery et al., 2013; Vionnet et al., 2021a; Berg et al., 2024; Marsh et al., 2024). Many studies evaluating snow ensembles are using “ensembles of opportunity” assembled from independent reanalysis datasets, which capture the diversity of datasets but

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not the true uncertainty (Schreiner-McGraw and Ajami, 2022; Henn et al., 2018b; Kim et al., 2021; Tyson et al., 2023; Casson et al., 2018).

This study directly addresses that gap by linking station-based probabilistic meteorology with physically based snow modeling. The workflow explicitly corrects for precipitation undercatch, generates spatially and temporally coherent high resolution meteorological ensembles, and propagates these uncertainties through the SUMMA energy-balance snow model. By testing this approach across three contrasting mountain basins, the Chena (Interior Alaska), Bow (Canadian Rockies), and Tuolumne (Sierra Nevada), and using large domain datasets, this study demonstrates a transferable approach for representing and evaluating forcing uncertainty through to physically based snow modeling in complex terrain. The remainder of this paper is structured as follows. Section 2 describes the study areas and river basins. Section 3 describes the datasets used to construct and evaluate the ensembles and snow simulations. Section 4 describes the ensemble forcing methodology, including undercatch correction, predictor screening, and ensemble generation using the Geospatial Probabilistic Estimation Package (GPEP; (Tang et al., 2024)), followed by the process-based modeling approach. Section 5 presents the evaluation of the ensemble in the three basins, Section 6 discusses the implications of constructing mountain meteorological ensembles and snow modeling, and Section 7 summarizes key findings and future directions.

2 Study Area

Three river basins were selected to represent a broad range of hydroclimatic, physiographic, and monitoring contexts: the Chena above Two Rivers (Alaska), the Bow above Calgary (Alberta), and the Tuolumne above Hetch Hetchy (California) (hereafter Chena, Bow, and Tuolumne; Figure 1). Snow observation datasets in the basins have comparable station densities, however, they differ in meteorological observational networks, climate regime, and hydrological landscape. These contrasts encompass subarctic, continental mountain, and maritime influenced high-elevation environments. Together, these basins provide a set of testbeds that capture the diversity of conditions under which ensemble meteorological forcing systems for mountainous snow modeling must operate.

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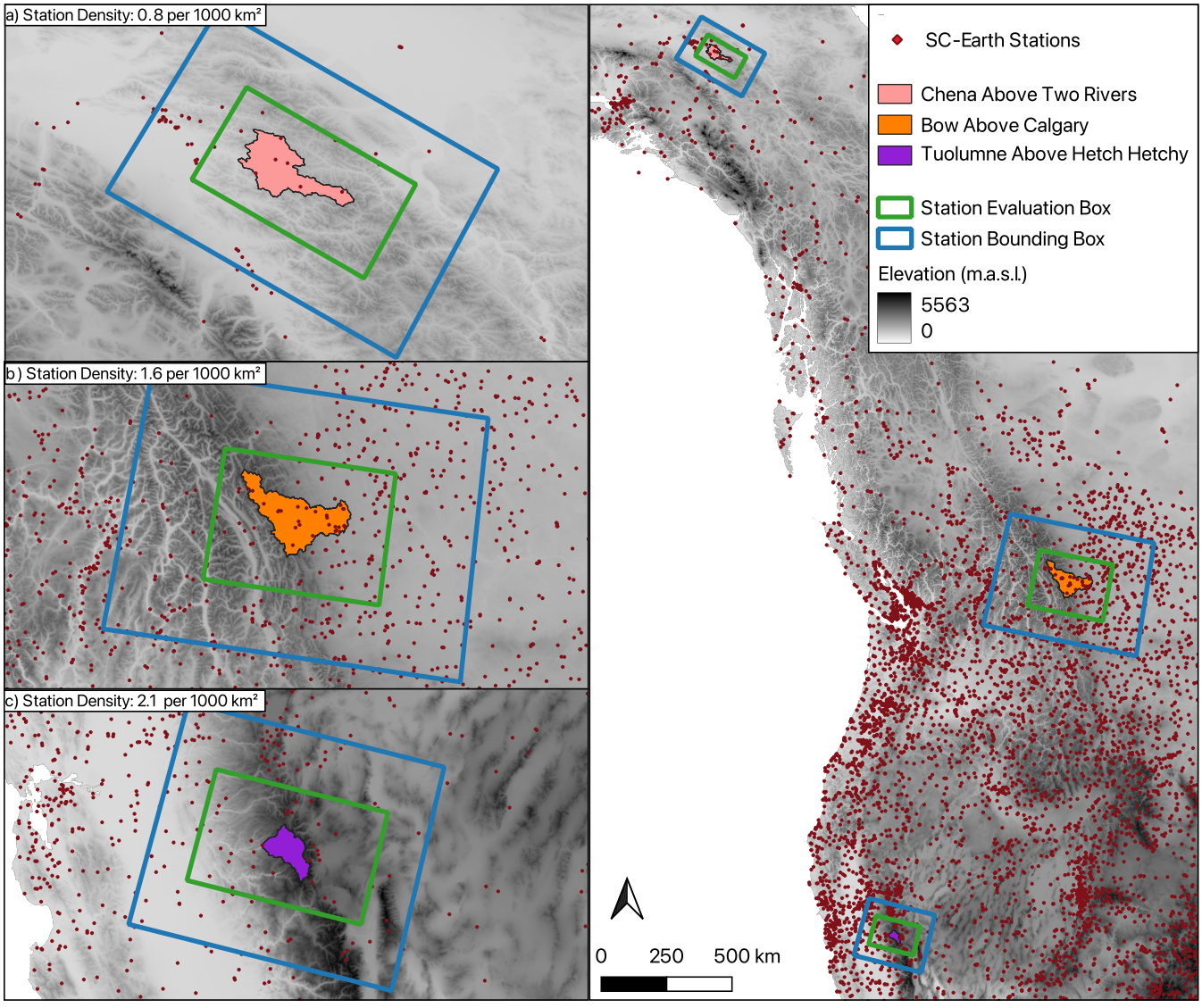


Figure 1. Chena, Bow, and Tuolumne river basins shown with SC-Earth meteorological stations. The larger station bounding box (blue) delineates the stations used to build ensembles and the area for grid generation. The smaller station evaluation box (green) delineates the stations used to evaluate meteorological ensemble performance. The elevation is shown as meters above sea level (m.a.s.l.) from MERIT Hydro.

The Chena is a tributary of the Tanana River in Interior Alaska, flowing westward towards Fairbanks. The Chena originates in the Yukon-Tanana Uplands, a region of rolling hills and mountains, with vegetation characterized by a mixture of boreal forest and permafrost (Frey et al., 1970; Anderson, 1970). The basin covers an area of approximately 5,500 km^2, with an elevation ranging from approximately 100 m.a.s.l. at the outlet to 1,600 m.a.s.l. at its highest point (Vuyovich and Daly, 2012). It contains discontinuous permafrost, with the highest concentrations occurring at higher elevations. The watershed experiences

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a subarctic climate, characterized by cold, dry winters and warm, relatively humid summers. Annual precipitation averages 380 to 510 mm per year with its hydrology that is dominated by snowmelt runoff, though the largest recorded floods have occurred in summer due to intense rainfall (Liao and Zhuang, 2017). Snow observations in the Chena region are challenging due to difficulties in accurately measuring solid precipitation and the sparse distribution of observation stations across a large terrain Bennett et al. (2019). Due to previous flood events, infrastructure developments and location above Fairbanks, there are dedicated snow monitoring stations and programs in the Chena. The majority of snow monitoring stations are part of the Natural Resources Conservation Service (NRCS) Snow Telemetry (SNOTEL) program (Fleming et al., 2023). The NRCS also conducts snow surveys twice per year at the start of April and May at several locations throughout the basin (Vuyovich and Daly, 2012).

The Bow is located in the Eastern Canadian Rocky Mountains in Southern Alberta. It flows south-east through Banff National Park and the foothills, then meanders eastward through the Prairies towards its confluence with the Oldman River (Tanzeeba and Gan, 2012). The Bow basin covers approximately 25,000 km^2 and begins at Bow Lake at 1,920 m.a.s.l., then drops to 1,180 m.a.s.l. at its confluence with the Oldman River (BRCB, 2010). The Bow has a semi-arid climate with precipitation of roughly 400-500 mm per year. Snowmelt runoff accounts for roughly 80 % of the Bow River inflow, the rest coming from rainfall, groundwater, and a small (3%) contribution from glacier melt (Bash and Marshall, 2014). The mountainous regions of the watershed are a dominant source of surface water, and exert control over flood-to-drought conditions (Vionnet et al., 2020). Snow monitoring in the Bow is a combination of automated sites and manual snow surveys focused on late winter, May, and April. The measurements have been consolidated in the Canadian historical SWE dataset (CanSWE) which provides a detailed QA/QC dataset across Canada (Vionnet et al., 2021b). Bow watershed meteorological stations in the Environment and Climate Change Canada (ECCC) surface network have undergone undercatch evaluation as part of a modernization and shift from manual to automatic stations (Smith et al., 2022).

The Tuolumne is located in the Sierra Nevada in California and flows from high-elevation headwaters in Yosemite National Park to its confluence with the San Joaquin River. The Tuolumne spans 700–3,900 m.a.s.l. in elevation, covering approximately 1,650 km^2. Tuolumne streamflow is primarily driven by seasonal snowmelt, supporting downstream ecosystems, agriculture, and urban water supplies. Approximately 80–90% of the annual precipitation (800–1000 mm per year) occurs as snow during winter months, though both precipitation amount and timing show considerable seasonal and year-to-year variability (Cristea et al., 2014). The Tuolumne Above Hetch Hetchy has low human intervention, such as dams or diversions, and land-use changes (Rice et al., 2011). The snow distribution in the Tuolumne River Basin is relatively similar year to year, mostly controlled by strong topography and similar storm tracks controlling snow deposition patterns (Pflug and Lundquist, 2020; Lundquist et al., 2015a). The Tuolumne has been extensively studied for snow distribution due to its importance for water supply and the availability of high-resolution snow-depth measurements from airborne lidar (Painter et al., 2016). The combination of scanning lidar, an imaging spectrometer, and physically based modeling has produced a unique dataset of high-resolution snow water equivalent and snow albedo maps. This spatially detailed data has led to numerous studies assessing snow quantity and distribution (Margulis et al., 2019; Currier and Lundquist, 2018; Pflug and Lundquist, 2020), as well as water balance and runoff estimation (Lundquist et al., 2015b; Henn et al., 2016, 2018c; Hedrick et al., 2020).

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3 Data

All datasets used in this study were selected and processed in accordance with FAIR data principles (Wilkinson et al., 2016). The analysis integrates publicly available meteorological, topographic, and snow observation datasets, each documented with open metadata and standardized formats to promote transparency and interoperability.

3.1 Meteorological Station Data

This study uses Serially Complete (SC) station dataset that includes daily precipitation, temperature mean, temperature range and wind speed with global spatial coverage from 1950-2019 (Tang et al., 2021). This SC-Earth station dataset is derived primarily from raw data from the Global Historical Climatology Network–Daily (GHCN-D; Durre et al., 2010) and the Global Surface Summary of the Day (GSOD; Menne et al., 2012). ERA5 reanalysis data are also used in SC-Earth production to correct a timeshift issue and assist with global gap filling. GHCN-D has been widely used for the production, evaluation, and correction of gridded meteorological datasets (Contractor et al., 2020; Beck et al., 2017; Hong et al., 2022; Tang et al., 2020). It includes precipitation and temperature data that undergo a comprehensive, automated quality assurance process (Durre et al., 2010). GSOD provides complementary wind speed observations used here to implement a precipitation undercatch correction strategy, though its quality control protocols are less rigorous, and caution is advised when using GSOD and SC-Earth wind estimates (Tang et al., 2021). GHCN-D, GSOD, and SC-Earth datasets do not include undercatch adjustments.

Station data compiled in SC-Earth originate from diverse networks employing various gauge configurations. In the Bow watershed, for instance, multiple monitoring networks use different gauge types even within the same region (Bertoncini and Pomeroy, 2025). Across the Chena, Bow, and Tuolumne basins, meteorological observations come from numerous providers lacking detailed gauge metadata. Although additional research datasets exist for these basins, they were not examined in this study due to limited temporal coverage, study specific assumptions and lack of serial completeness (Daly and Vuyovich, 2012; Fang et al., 2019; Lundquist et al., 2016; Henn et al., 2016; Bertoncini and Pomeroy, 2025).

3.2 Topographic and Land Surface Data

The MERIT Digital Elevation Model (DEM) is used for multiple applications in this study, including the derivation of topographic descriptors for geospatial estimation. MERIT DEM is available globally at 3 arcsecond (90-m at the equator) horizontal resolution (Yamazaki et al., 2017). In a previous study using the GPEP methodology, descriptors such as elevation, latitude, longitude, and west-east and south-north slopes (which proxy for terrain aspect) were utilized (Newman et al., 2015). This current study assesses these predictors, and also examines aspect, slope, and topographic position index (TPI). Smoothing of topographic predictors with a Gaussian 2D filter over different radii was also performed to evaluate the relative skill as a regression predictor.

TanDEM-X Hydro (TDX-Hydro), a catchment and vector stream network dataset, was used for the spatial discretization for snow modeling, as shown in Figure 2. This dataset was derived from a high-resolution (12m) TanDEM-X elevation data conditioned with vegetation bias removal, adaptive smoothing, river enforcement, and depression handling, resulting in a highly

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detailed representation of global hydrography (Carlson et al., 2024). The underlying TanDEM-x elevation data are not publicly available, however, TDX-Hydro discretizations are. The use of a high resolution catchment dataset helps capture topographic details such as elevation more accurately. Working with smaller catchments, the dataset can capture terrain variations that coarser datasets might miss; however, there is a trade off between spatial resolution and computational time in modeling (Chaney et al., 2018). For consistency between river basins, the discretization approach taken does not explicitly represent some topographic controls on snow, such as slope and aspect.

Multiple geospatial datasets are used to support hydrological model parameterization and calculation of catchment attributes for modeling such as land cover and aspect. Land cover characteristics are obtained from the MODIS MCD12Q1 dataset (Friedl and Sulla-Menashe, 2019), and the soil properties are sourced from the USDA NRCS database (Knoben, 2021) derived from the SoilGrids 250 m dataset (Hengl et al., 2017). Further details on these datasets applied for hydrological modeling are available in Knoben et al. (2022).

3.3 Snow Observation Data

The Northern Hemisphere Historical In Situ Snow Water Equivalent Dataset (NorSWE) provides a comprehensive record of snow water equivalent (SWE) observations spanning 1979–2021 (Mortimer and Vionnet, 2025). The NorSWE dataset integrates data from nine sources across North America, Russia, and Finland. It includes SWE measurements from manual snow surveys, snow pillows, airborne and ground-based passive gamma radiation sensors, with snow depth (SD) data included when available. Bulk snow density is derived where both SWE and SD are present. Quality control procedures, adapted from (Vionnet et al., 2021b), include variable-specific range checks and elevation verification using the USGS National Elevation Dataset where applicable. Although additional snow monitoring products, including airborne lidar, are available for the Tuolumne and to a lesser extent the Bow, the analysis is constrained to in-situ observations for consistency.

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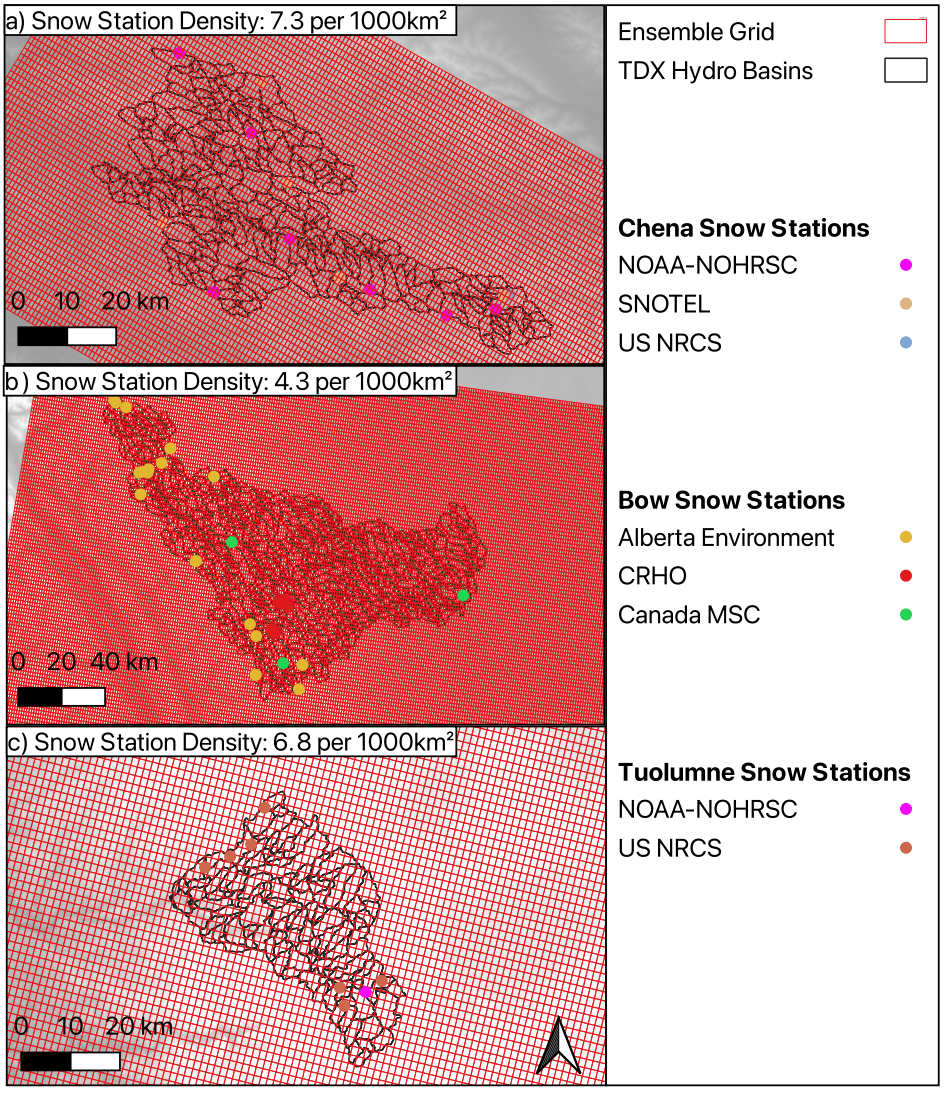


Figure 2. Chena, Bow, and Tuolumne River Basins showing the meteorological forcing grid (1/64°) in red, the TDX Hydro basin delineations in black, and the snow stations from the multi-source NorSWE dataset. Data sources include National Oceanic and Atmospheric Administration - National Operational Hydrologic Remote Sensing Center (NOAA-NOHRSC), SNOwpack TELemetry Network (SNOTEL), United States Natural Resources Conservation Service (US NRCS), Canadian Rockies Hydrological Observatory (CRHO) and Canada Meterological Services of Canada (Canada MSC).

For the calibration of snow parameters using a Large Sample Emulator (LSE) approach, station data from Mortimer and Vionnet (2025) and (Sun et al., 2019) are used. For analysis of the undercatch correction procedures, the quality controlled dataset of Smith et al. (2022) was used for comparative purposes.

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3.4 Meteorological Reanalyses

The European Centre for Medium-Range Weather Forecasts (ECMWF) Reanalysis v5 (ERA5) is a state-of-the-art global reanalysis dataset that provides consistent and high-quality estimates of atmospheric, land, and oceanic variables from 1950 to the present (Hersbach et al., 2020). ERA5 combines a vast array of historical observations with advanced numerical weather prediction models through data assimilation techniques to produce a spatial resolution of 0.25 degrees and hourly temporal resolution. In this study, we use wind and temperature from ERA5 for station precipitation undercatch correction when co-located measurement data is not available. Additionally, we use ERA5 as a benchmark forcing dataset for evaluating snow modeling performance within the Structure for Unifying Multiple Modeling Alternatives (SUMMA) hydrological modeling framework. (Clark et al., 2015a, c, b).

The Canadian Surface Reanalysis (CaSR) is a high-resolution, observation-constrained reanalysis dataset developed to provide detailed surface meteorological fields over North America (Gasset et al., 2021). The most recent version, CaSR v3.1, incorporates enhancements to the data assimilation system, expanded observational networks, and updated model physics to improve the representation of near-surface atmospheric conditions. CaSR provides meteorological variables at a 10 km spatial resolution and hourly temporal frequency, making it well-suited for regional hydrometeorological studies. In this study, CaSR is used as a source of dynamic predictor data for geospatial estimation and as a benchmark dataset for evaluating snow modeling performance within the SUMMA.

4 Methods

Reproducibility has historically been a challenge in hydrology and water resources research (Stagge et al., 2019). Recent efforts have emphasized open, transparent, and automated workflows in the Earth sciences (e.g., Gil et al., 2016; Knoben et al., 2022; Arnal et al., 2024). This study follows a structured workflow, which is illustrated at a high level in Figure 3.

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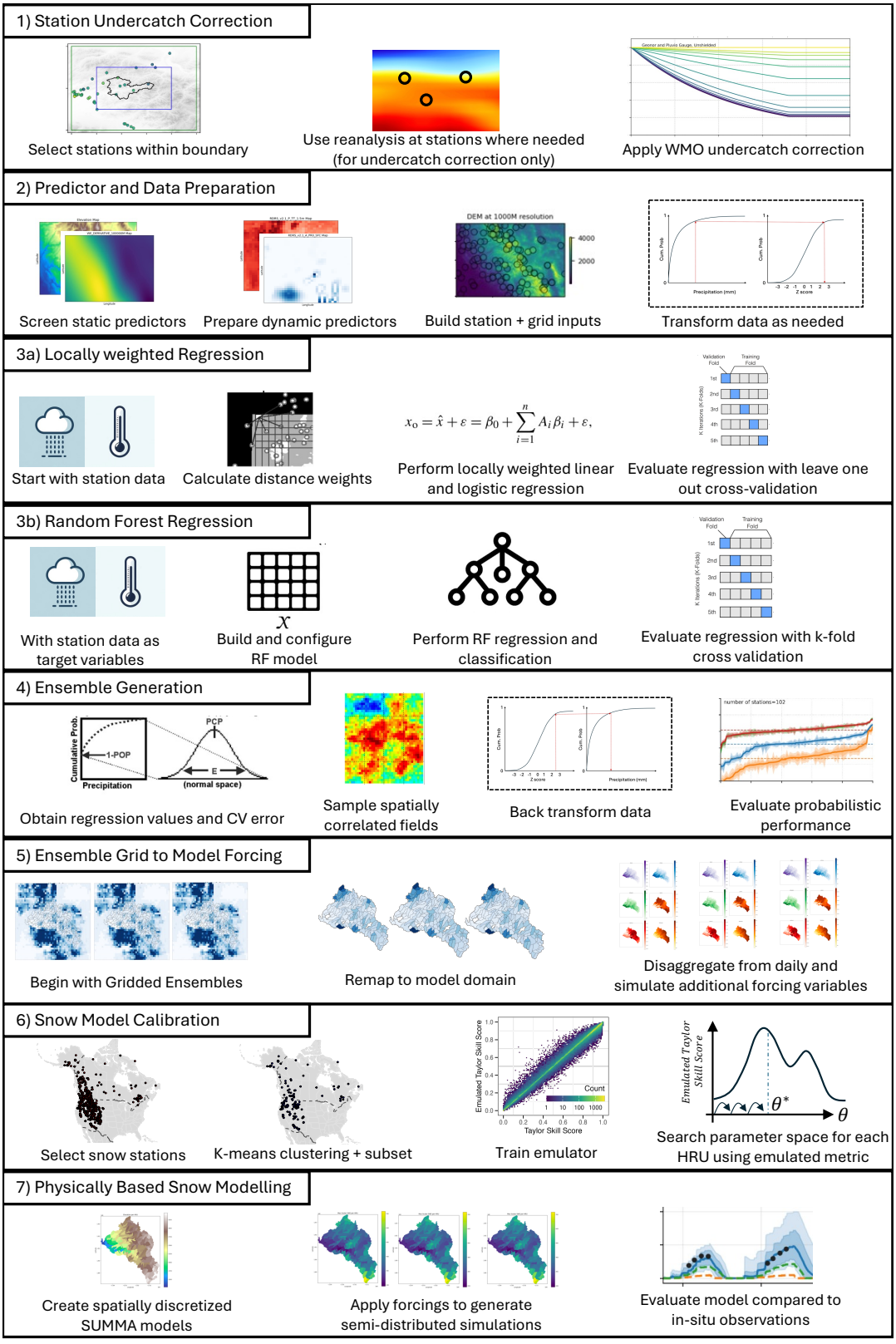


Figure 3. Overview of the Study Methodology. Methods 3-4 are components of the GPEP ensemble forcing generation approach.

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The study methodology from data processing to model simulation is implemented with Snakemake workflows (Köster and Rahmann, 2012). Snakemake is a rule based management system that utilizes a Directed Acyclic Graph (DAG) to represent and manage the dependencies within a workflow. This allows reproducibility, transparency, and scalability across computational environments. An example DAG illustrating the workflow structure is provided in the supplementary material.

4.1 Undercatch Correction

Undercatch refers to the systematic underestimation of precipitation caused by wind effects, gauge configuration, and precipitation phase, which reduce the fraction of precipitation captured by instruments (Kochendorfer et al., 2017a, b). The bias is most pronounced for solid precipitation in cold and windy environments (Smith et al., 2022; Mekis and Vincent, 2011; Mekis et al., 2018), making undercatch correction an important step when generating precipitation reanalyses and datasets (Newman et al., 2020; Behrangi et al., 2018). A range of approaches exists for correcting undercatch, including empirical wind-based transfer functions, water-balance closure, and computational fluid-dynamics modeling (Colli et al., 2018, 2020; Beck et al., 2019). In this study, we apply empirical, gauge-based correction functions derived in the World Meteorological Organization (WMO) Solid Precipitation Intercomparison studies (Goodison et al., 1998; Kochendorfer et al., 2017b, a). These functions relate collection efficiency (CE) to wind speed and air temperature and are derived specific to gauge types and shielding configuration.

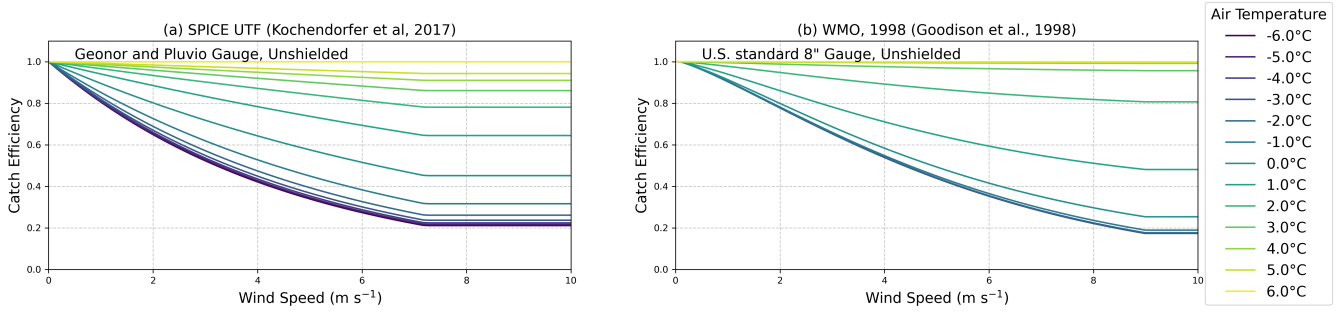


Figure 4. Catch efficiencies for the undercatch correction methods applied in this study based on temperature and wind speed. The updated SPICE UTF Kochendorfer et al. (2017a) to the Bow Basin is shown on the left side (a). On the right side (b) for the Chena and Tuolumne the approach from Goodison et al. (1998) and wind speed threshold behavior from Yang et al. (1998).

A regional approach that assumes consistent gauge type and configuration is taken. This follows a similar methodology to Newman et al. (2020) that derived large coverage station undercatch for Alaska, as well as undercatch corrections in Huidobro et al. (2023) that made similar assumptions due to lack of consistent gauge metadata across large domains of the United States. As recognized in Kochendorfer et al. (2017a) and Pierre et al. (2019), who, while recognizing the dominant effect of shielding, demonstrated climate exerts a strong influence on catch efficiency relative to specific instrument type and the robustness of generalized transfer functions. The primary objective is not to inter-compare methods directly, but to implement an appropriate correction for stations in each basin given available information. Due to a lack of station metadata in global datasets and with

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individual network providers, we assume a single gauge configuration per basin. Gridded reanalysis was used where data were co-located measurements were not available in an approach similar to Bertoncini and Pomeroy (2025). Wind observations at gauge height are used where available (e.g., GSOD), while ERA5 reanalysis winds translated to gauge height were used to supplement gaps for GHCN-D stations (Yang et al., 1998). ERA5 temperatures, lapsed to station elevation, are used to estimate precipitation phase and apply temperature-dependent correction factors. Full methodological details and equations are provided in Appendix A.

4.2 Topographic Descriptor Data

In complex terrain, such as mountainous environments, topography is an important consideration to determine variables such as precipitation and temperature (Clark and Slater, 2006; Böhner and Antonić, 2009). Elevation impacts temperature through the adiabatic lapse rate, where temperature decreases with altitude (Daly et al., 2008). Precipitation patterns shift at higher elevations due to orographic lifting, leading to increased rainfall on windward slopes and rain shadows on leeward sides (Napoli et al., 2019). Additionally, slope and aspect determine the amount of solar radiation received, affecting localized heating and cooling rates (Böhner and Antonić, 2009). West-East and South-North elevation derivatives (gradients or slopes) capture directional changes in terrain, which can influence wind flow and the distribution of moisture, further impacting weather patterns (Robert et al., 2013).

Topographic descriptors are terrain variables calculated from a DEM to quantify elevation, spatial gradients and patterns. In this study, topographic descriptors derived from MERIT DEM are evaluated and applied as static predictor variables for precipitation and temperature. We compare simple intuitive descriptors of elevation, latitude, and longitude to derived ones, such as directional derivatives, Topographic Position Index (TPI), and aspect. Smoothing of topographic descriptors is performed to reduce noise and emphasize broader trends across the landscape. This is explicitly examined by applying a 2D Gaussian filter with varying radii (200 m, 1,000 m, 10,000 m, 100,000 m, 150,000 m) to assess skill as a static predictor of precipitation and temperature. Most prior applications of GMET and GPEP have used elevation, latitude, longitude, and smoothed West-East and North-South elevation gradients as static predictors. Optimal radii selected from a single predictor are subsequently used in a forward screening approach to build predictor sets for regression.

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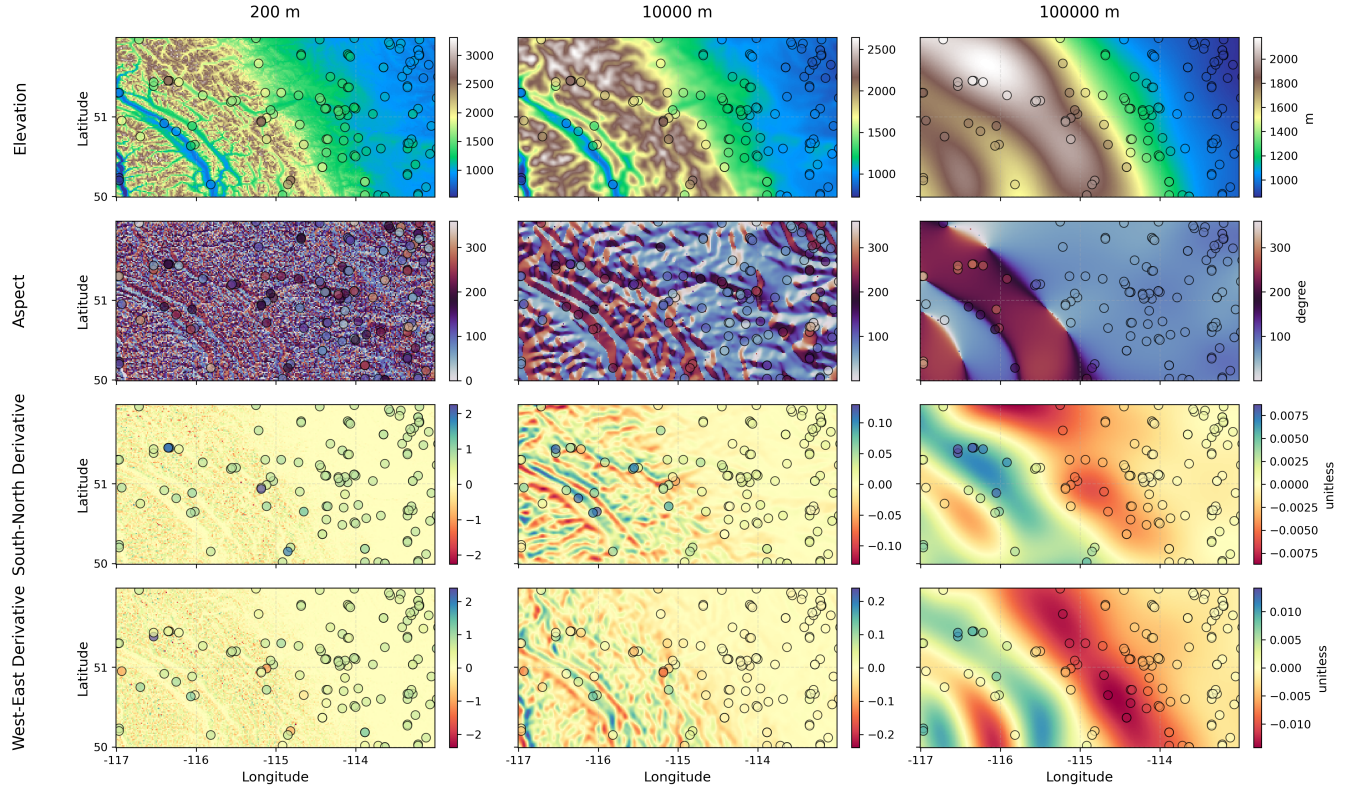


Figure 5. Visual comparison of topographic descriptors used as static predictors in deterministic regression. Calculated based on the MERIT-DEM, and applying a 2D Gaussian filter of varying radii (200 m, 10,000 m, and 100,000 m) examples for DEM, Aspect, South-North and West-East Derivatives are shown. Station location and values derived from the gridded products are indicated within the circles.

4.3 Ensemble Meteorological Forcing Generation Approach

Meteorological datasets that represent spatially distributed meteorological fields are fundamental to hydrology and land-surface modeling. The fidelity of these datasets depends on their ability to capture spatial variability and to characterize associated uncertainties in observation-based estimates. To address this challenge, a probabilistic interpolation framework was first developed by Clark and Slater (2006), who implemented a Locally Weighted Regression (LWR) approach for generating ensembles of daily precipitation and temperature from station observations along with Spatially Correlated Random Fields (SCRF) to produce ensembles from sampling regression residuals. This foundational approach provides a statistical means of estimating both the mean and uncertainty of meteorological fields through spatial regression and stochastic simulation. Newman et al. (2015) refactored this approach into a formal FORTRAN-based software (the Gridded Meteorological Ensemble Tool, GMET) and produced a 100-member ensemble of daily precipitation and temperature for the contiguous United States (CONUS), demonstrating a practical capability to generate uncertainty-aware large-domain gridded forcings. Newman et al. (2020) applied the framework for Alaska, including station based undercatch based on regional gauge type assumptions. Subsequent enhance-

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ments enabled integration with deterministic gridded fields and data assimilation applications, providing dynamic uncertainty estimates through ensemble dressing (Liu et al., 2022). Finally, Bunn et al. (2022) advanced GMET by enabling the inclusion of dynamical predictors (e.g., from numerical weather prediction models, reanalyses or radar analyses), implementing formal cross-validation methods, and demonstrating improved performance in event-based precipitation estimation.

GMET was then generalized and re-implemented in the open-source Geospatial Probabilistic Estimation Package (GPEP; (Tang et al., 2024)), a Python-based platform extending (and superseding) GMET capabilities to enable treatment of a wider range of variables, predictor types, and spatial domains. GPEP now provides a modular framework for generating ensemble geophysical datasets (not only meteorological) using a variety of methods (the original regression and/or ML techniques), followed by stochastic sampling from spatially correlated random fields to produce ensemble realizations. The tool incorporates advances such as flexible predictor selection and station-based cross-validation for predictive uncertainty estimation. For a more detailed description, the statistical formulation, parameter estimation, and ensemble generation processes are detailed in Appendix B, as well as the configuration choices specific to this implementation. Ensembles were generated at a $1/64°$ resolution, or approximately 1 km grid spacing.

In this study, we evaluate the Random Forest (RF) capability within GPEP and compare its performance with the original locally-weighted regression (LWR) approach. Both methods are systematically applied to assess how individual and combined topographic predictors improve geospatial estimation in mountainous terrain. We further examine the contribution of dynamic meteorological grids from reanalyses to better capture transient meteorological variability. By linking station observations with gridded topographic and reanalysis data, this approach enables an explicit evaluation of how terrain features and large-scale meteorological conditions jointly influence skill. Together, these experiments provide insight into the relative strengths of machine-learning and regression-based approaches for probabilistic meteorological estimation in complex terrain.

4.3.1 Regression Cross Validation

Cross validation results measure the regression error at station locations. In this study, leave-one-out cross-validation is used for locally weighted regression, and k-fold cross-validation (k=10) is used for Random Forest. Involving the division of the dataset into k subsets (k=10), with the model trained on k-1 subsets and validated on the remaining one. This process is repeated k times, each time with a different subset serving as the validation set.

GPEP offers 16 metrics for the regression cross-validation that can be used to evaluate regression approaches. As in Tang et al. (2024), an augmented Kling-Gupta Efficiency, KGE″, is used because it normalizes the bias term using the standard deviation instead of the mean, making it more appropriate for temperature variables. This formulation mitigates the influence of measurement units (e.g., Kelvin versus degrees Celsius) and reduces the exaggerated bias that can occur near zero degrees Celsius (Tang et al., 2021). Precipitation values are evaluated in transformed form (e.g. with Box-Cox). See also Santos et al. (2018) for a discussion regarding near zero values on transformed values of streamflow.

$$\mathrm{KGE}'' = 1 - \sqrt{(r-1)^2 + (\alpha-1)^2 + \beta^2}, \tag{1}$$

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where r is the Pearson correlation coefficient between observations (o) and estimates (e), $\alpha = \frac{\sigma_e}{\sigma_o}$ is the variability ratio, $\beta = \frac{\mu_e - \mu_o}{\sigma_o}$ is the bias term, μ is the mean value, and σ is the standard deviation.

4.3.2 Predictor Screening and Combination Building

Predictor selection for the regression models used cross-validation error in a sequential forward screening procedure. An initial evaluation of static predictors was conducted to identify an appropriate level of spatial smoothing, after which the static variables were combined through iterative screening. Starting from an empty model, the static predictor producing the highest cross-validated Kling–Gupta Efficiency (KGE″) was first selected. Then additional static predictors were added one at a time, each time retaining the variable that yielded the greatest improvement in cross-validated KGE″. This process continued until the model skill no longer increased appreciably (defined as a gain in KGE″ ≤ 0.01).

Dynamic predictors from gridded reanalysis were subsequently incorporated using the same forward screening procedure. The screening and regression fitting were performed independently for precipitation and temperature, allowing the most relevant static and dynamic predictors to be identified for each variable. The resulting predictor sets for precipitation and temperature were then combined to form the final predictor configuration used in the ensemble generation stage. The dynamic predictors consisted of the seven meteorological forcing variables required to drive the physically based hydrological model. Precipitation and temperature were the primary variables of interest, while shortwave and longwave radiation, humidity, and wind speed were included to represent spatial variability in energy balance and atmospheric conditions. Together, these variables form the standard meteorological forcing set used in land surface models, ensuring that precipitation and temperature remain physically consistent with broader climatic drivers while maintaining practicality for operational implementation. A complete list and description of the dynamic forcing variables used in this study are provided in Appendix C.

4.4 Probabilistic Skill Evaluation and Bootstrapping

To evaluate the probabilistic performance of the ensemble meteorological estimates against station observations, we use the Brier Skill Score (BSS). The BSS measures the relative skill of a probabilistic prediction compared to a reference prediction and is widely applied in ensemble meteorology and hydrology to quantify the reliability and resolution of probabilistic predictions (Wilks, 2011; Hallouin et al., 2024).

The BSS is defined as

$$\mathrm{BSS} = 1 - \frac{\mathrm{BS}_{\mathrm{ens}}}{\mathrm{BS}_{\mathrm{ref}}}, \tag{2}$$

where $\mathrm{BS}_{\mathrm{ens}}$ is the Brier Score (BS) of the ensemble prediction and $\mathrm{BS}_{\mathrm{ref}}$ is the Brier Score of a reference prediction, in this study the observed climatology. A BSS of 1 indicates perfect probabilistic prediction, a value of 0 indicates no improvement over the reference, and negative values indicate degraded skill.

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The underlying Brier Score (BS) represents the mean squared error between the predicted probability f_i of an event (e.g., precipitation occurrence or exceedance of a threshold) and the corresponding binary observation o_i (1 if the event occurred, 0 otherwise):

$$\mathrm{BS} = \frac{1}{N}\sum_{i=1}^{N}(f_i - o_i)^2, \tag{3}$$

where N is the number of predictions.

In this study, the ensemble probability of event occurrence (e.g., daily precipitation $> 0\ \mathrm{mm}$ is computed from the fraction of ensemble members predicting the event at each station location (Clark et al., 2006). The resulting probabilities are compared against observed station data to calculate the BSS, providing a quantitative measure of how well the ensemble captures the observed event frequency and variability at station locations.

To quantify the sampling uncertainty of the Brier Skill Score, we apply a nonparametric resampling bootstrap method, following the approach of Clark et al. (2021a) as implemented in Hallouin et al. (2024). Bootstrapping provides an intuitive and data-driven means to estimate the empirical probability distribution of performance statistics, enabling confidence or tolerance intervals to be derived without reliance on analytical assumptions. Specifically, we employ the non-overlapping block bootstrap (NBB) method which resamples data in one-year blocks (Carlstein, 1986). For each bootstrap replicate, the BSS is recomputed, producing an ensemble of estimates from which the tolerance intervals are determined.

4.5 Probabilistic Physically Based Snow Modeling

4.5.1 Model Description

The SUMMA hydrological modeling framework is used in this study for snow modeling. It provides physical representations of snow accumulation, interception, metamorphism, and ablation processes using an energy balance approach to calculate temperature and phase change (Clark et al., 2015b, c, 2021b). The snowpack is represented as a dynamic set of layers, each with specific physical properties, allowing detailed simulation of the snowpack, including compaction, sublimation, meltwater, and refreezing (Clark et al., 2015a).

SUMMA was selected because it offers a comprehensive, process-based framework that extends beyond snowpack modeling to hydrological simulation, enabling future translation of snow states and ensemble uncertainties into runoff predictions. Its modular design and explicit energy-balance formulation make it particularly suited to evaluate the effects of meteorological forcing uncertainty on snowpack evolution and hydrological response. While SUMMA does not explicitly represent wind redistribution or avalanching, which remain limitations for steep alpine terrain, it provides a physical basis and extensible framework for quantifying how forcing uncertainty propagates through snow accumulation and melt processes to influence basin runoff. SUMMA model decisions in this study, which control parameterization and physics descriptions in the model framework are consistent with Farahani et al. (2025).

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The Chena, Bow, and Tuolumne River Basins in this study are discretized to represent the watershed as a collection of Grouped Response Units (GRUs). While this study focused on snow, in fact the hydrological simulation extends to runoff generation. In this approach, a vertical column for each GRU is conceptualized to model the movement and transformation of water and energy through different layers, from the vegetation canopy down to the soil and underlying groundwater. This column-based representation allows for detailed simulation of processes such as interception, infiltration, soil moisture dynamics, evapotranspiration, and groundwater recharge. The semi-distributed nature of the model helps to represent essential spatial variability and dominant controls over land surface hydrology. TDX-Hydro is used directly for the spatial discretization of GRUs in this study. While Hydrologic Response Units (HRUs) can be derived from GRUs to capture finer spatial variability, this study focuses solely on GRUs. This is due to the high level of discretization in the TDX-Hydro dataset, and for clarity in evaluation. This approach captures elevation most directly in mountainous watersheds, without explicitly including aspect or slope. Precipitation and temperature ensemble gridded data are remapped to the GRUs defined by TDX-Hydro vector data using the EArth SYstem MOdeling REmapper (EASYMORE) package (Gharari et al., 2023). This remapping is a spatial average of gridded data calculated over the GRU units.

Each GRU is parameterized using globally consistent geospatial datasets following the standardized workflow of Knoben et al. (2022). Elevation is derived from the MERIT Hydro hydrologically adjusted DEM (Yamazaki et al., 2019), ensuring accurate flow connectivity and representation of topographic gradients. Soil properties are obtained from SoilGrids 250 m (Hengl et al., 2017), where sand, silt, and clay fractions are converted to USDA texture classes and the dominant soil type is assigned to each GRU. Land cover is taken from MODIS MCD12Q1 v6 (Friedl and Sulla-Menashe, 2019) using the IGBP classification to define vegetation type and surface characteristics. These layers are spatially intersected with the GRU geometries to extract mean elevation and modal soil and land-cover classes, forming the static physiographic attributes used by SUMMA to parameterize vegetation, surface roughness, and soil hydraulic and thermal properties.

4.5.2 Simulation of Meteorological Variables for Model Forcing

Physically based hydrological models require a wider range of meteorological inputs and finer temporal resolution than conceptual models because they explicitly represent both the energy and water balances. Sub-daily forcing is needed to resolve diurnal variations in key variables such as temperature and incoming solar radiation, which control melt and phase-change processes. These additional forcings enable a more detailed and physically consistent simulation of hydrological processes compared to conceptual approaches, where empirical relationships such as degree-day methods govern fluxes like snowmelt (Mosier et al., 2016). However, many of the required variables, including shortwave radiation, are not routinely observed at the spatial and temporal resolution needed to drive distributed hydrological models. In this study, such variables are therefore simulated using precipitation, temperature, location and topographic information.

MetSim (short for Meterology Simulator), is a Python package for the estimation of meteorological variables to support hydrological and land surface modeling (Bennett et al., 2020). The core algorithm for MetSim MTCLIM (v3.4) contains a mountain microclimate simulation model, three main computation modules for solar geometry, meteorological simulation, and temporal disaggregation (Hungerford et al., 1989). The MTCLIM meteorological downscaling scheme derives additional

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climate variables from daily minimum and maximum temperature and precipitation for use in hydrologic and land–surface models. Daylight mean temperature is estimated as a weighted average of extremes (Thornton et al., 1997), while cloud transmittance and cover are inferred from the relationship between diurnal temperature range, its smoothed climatology, and precipitation occurrence (Kimball et al., 1997). Dew point temperature and vapor pressure are obtained iteratively in conjunction with shortwave radiation and potential evapotranspiration, ensuring consistency among humidity, radiation, and evaporative demand. Shortwave radiation is calculated from potential clear-sky radiation, transmissivity, and humidity corrections (Bohn et al., 2013). More detailed algorithm description and implementation are provided in Bennett et al. (2020) and Bohn et al. (2013).

4.5.3 Snow Model Calibration

We calibrate eleven SUMMA parameters related to snow processes using the Large Sample Emulator (LSE) approach introduced in Tang et al. (2025b) for the Community Land Model and Farahani et al. (2025) for SUMMA. The LSE jointly leverages model simulations from a large sample of locations by using ML techniques to emulate a comprehensive model response surface, and uses the emulator as an inexpensive parameter set search tool in iterative sequential optimization. First, for each location (e.g., snow gauges), we run SUMMA using $N_{i=0}$ parameter sets. These parameter sets are obtained by using Latin Hypercube Sampling, and the parameter values vary across sites. For each parameter set, we compute performance metrics (e.g., Root Mean Square Error, Pearson correlation coefficient) by contrasting observed and simulated SWE values. Second, we train an emulator of the simulated surface response using parameter sets and climate attributes from each location as predictors (x), and the performance metric of interest as the predicted value (y). To this end, we use a matrix of $N_{sites} \cdot N_{i=0}$ rows and $N_\theta + N_{Atts}$ columns as x. Note that, for each site, the attributes remain constant among rows. y has $N_{sites} \cdot N_{i=0}$ rows and only one column. Then, the emulator relates $y = g(x) + \epsilon$, where g is the emulator (e.g., Random Forest) and ϵ represents the error. Third, we utilize the emulator to search for emulated surface responses and identify regions of the parameter space that may lead to improved performance metrics. The search is conducted at each site by using the Genetic Algorithm (GA) with a total budget of 10,000 runs (note that, in this step, the emulator is used in the GA search, not SUMMA). For each site, we select the parameter sets associated with the best 100 emulated responses and run the SUMMA model to obtain the actual performance metric. This leads to $N_i \cdot N_{site}$ new performance metric values, with $N_i = 100$. Finally, the new values are concatenated into the original matrix (now with $N_{sites} \cdot (N_{i=0} + N_i)$ rows), and a new emulator can be trained. This process is repeated until some criteria are met. In our case, we iterate until each site has 1,000 SUMMA runs (i.e., five iterations, starting with $N_{i=0} = 500$ parameter sets). We use the Taylor Skill Score (TSS) from Taylor (2001) as a target metric since it comprises temporal correlation and variance.

We consider snow gauges across Canada and the US, with four water years of measurements, each with at least 20 measurements per year taken from NorSWE dataset and quality-controlled SNOTEL stations (770 stations in total) (Sun et al., 2019; Mortimer and Vionnet, 2025). To reduce the computational burden, we conduct K-means clustering using climate attributes. For each resulting cluster, we randomly select 20 stations. If a cluster has fewer than 20 stations, all stations are considered to preserve equal representation from all clusters. Thus, to train the emulator, we reduce the number of snow gauges to 162.

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Hence, the final LSE comprises 162,000 SUMMA runs (162 stations · 1,000 parameter sets per station). This LSE is subsequently used to obtain parameter sets at each model GRU by searching the emulated surface response (which is conditional on the GRU's local geo-attributes) using the GA. Note that in this case, only one search is conducted (i.e., no iteration is carried out) and the parameter set associated with the best emulated performance metric is assigned to each GRU. Parameter ranges used in this calibration are provided in Appendix D.

4.6 Snow Model Evaluation Using In-situ Measurements

Evaluation of the snow simulations focuses on comparing modeled SWE from SUMMA against in-situ snow observations. SUMMA is run with each meteorological ensemble member, with input gridded data spatially averaged over each model GRU (Figure 2). Model simulations are compared to manual snow survey measurements from the NorSWE dataset, which provide estimates of SWE across representative terrain transects. These surveys are selected for model evaluation because they better capture local variability than automated snow pillows, which record conditions at a single point.

Model performance is assessed using skill target diagrams (Mudryk et al., 2025; Jolliff et al., 2009), which quantify model skill in terms of both temporal pattern similarity and bias. The total skill metric is expressed as the normalized two–component distance. The method uses a normalized spatial pattern (S_{pattern}) and bias (S_{bias}) to quantify model performance (S_{total}):

$$S_{\text{total}} = \sqrt{S_{\text{pattern}}^2 + S_{\text{bias}}^2} \tag{4}$$

$$S_{\text{pattern}} = f \cdot \left[1 - \frac{2(1+R)}{\left(\sigma_* + 1/\sigma_*\right)^2}\right] \tag{5}$$

$$S_{\text{bias}} = f \cdot \frac{|b|}{\text{uRMSE}_{\text{max}}} \left\|S_{\text{pattern}}\right\|_{\text{max}} \tag{6}$$

In these expressions, b is the mean bias, $\text{uRMSE}_{\text{max}}$ is the maximum unbiased RMSE among products (in absolute units), $\|S_{\text{pattern}}\|_{\text{max}}$ scales bias to the range of pattern errors, and f is a cross-test scaling factor set to 1 in this study. This standard relationship among uRMSE, R, and σ_* is also represented using Taylor diagrams to summarize multiple aspects of model performance for the snow simulations (Taylor, 2001). The standard-deviation ratio and its relationship to normalized unbiased RMSE are given by:

$$\sigma_* = \frac{\sigma_x}{\sigma_r} \tag{7}$$

$$\text{uRMSE}_*^2 = 1 + \sigma_*^2 - 2\sigma_* R \tag{8}$$

5 Results

5.1 Undercatch Correction

Catch Efficiency (CE) is the ratio of recorded to actual precipitation with lower CE values corresponding to greater undercatch correction. Figure 6 compares aggregated CE values calculated in this study for each basin throughout the year, as well as

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the net effect on accumulated precipitation over the water year. The seasonal and spatial patterns remain consistent with those reported in detailed field studies (Smith et al., 2022).

The use of reanalysis wind estimates to enable empirical correction of station undercatch was a key step, as indicated in Figure 6 wind gap filling stations. Reanalysis wind underestimated high wind speeds compared to observations resulting in conservative CE estimates. This biases can be improved by using daily maximum values from reanalysis, matching physical process understanding that snowfall events occur during storm periods. The use of ERA5 daily maximum wind speeds yields conservative CE estimates with other variables held constant reflects the tendency of reanalysis winds to underestimate site-level exposure (Kochendorfer et al., 2017b).

Further detail on the methodological choices and comparisons with reference datasets is provided in Appendix A. Although the approach requires several simplifying assumptions, it effectively captures and corrects wind-induced undercatch, an established and influential source of bias in mountainous snowfall and precipitation measurements.

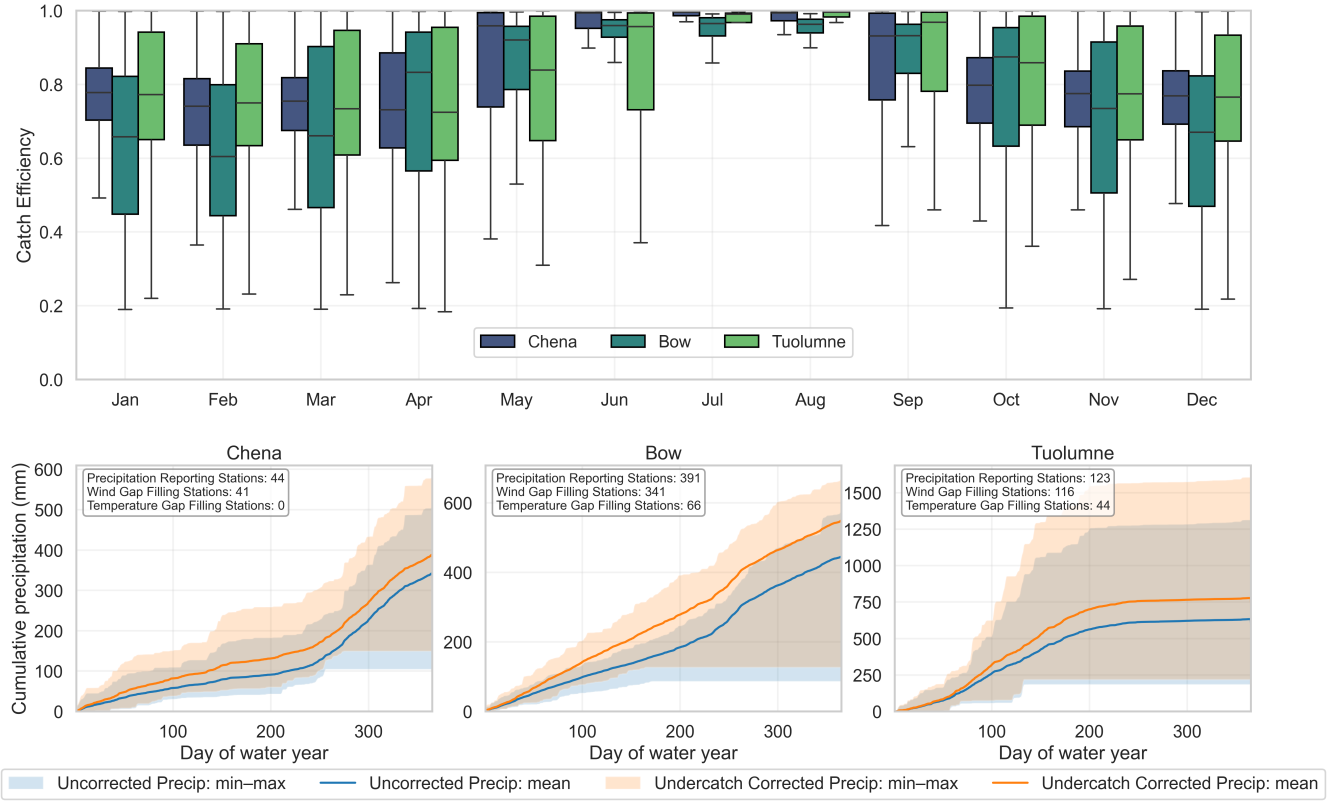


Figure 6. Gauge catch efficiency (CE) and Cumulative Precipitation. The top panel shows CE correction ranges per month across the Bow, Chena, and Tuolumne basins. The bottom panel shows effect of undercatch correction on precipitation accumulation over the water year (starting Oct 1st). Each water year and the mean of all years and stations is shown for each basin.

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5.2 Static Predictor Screening with Cross Validation

The initial screening of static topographic predictors used leave-one-out cross-validation (LWR) and 10-fold cross-validation (RF) at station locations. For each basin, single predictors were evaluated individually, with performance summarized using cross-validated KGE'' for daily precipitation (in transformed space) and daily mean temperature. Figure 7 shows the results for the Bow, with analogous figures for the Chena and Tuolumne provided in the Supplement. For single predictors, LWR typically yields slightly higher KGE'' than RF, reflecting the advantage of local weighting when only one static covariate is used.

For temperature, elevation and smoothed DEM fields are consistently skillful predictors for both LWR and RF, reflecting the dominant lapse-rate control on air temperature. Applying spatial smoothing with a larger Gaussian radius (more smoothing) to derived topographic descriptors (e.g., slope, aspect, terrain derivatives) improves cross-validation skill, as smoothing suppresses small-scale noise while retaining large-scale orographic gradients.

For precipitation, the relative performance of individual static predictors is more even. Smoothed variants of terrain descriptors (e.g., South-North and West-East) generally outperform their unsmoothed forms. Across all three basins, predictors smoothed with greater Gaussian radii perform better, indicating that large-scale physiographic structure is more informative than fine-scale terrain details for daily precipitation estimation at the available station density.

Based on the screening results, topographic descriptors smoothed with 100 km Gaussian radius were retained for subsequent predictor combination building, along with unsmoothed elevation, latitude, and longitude.

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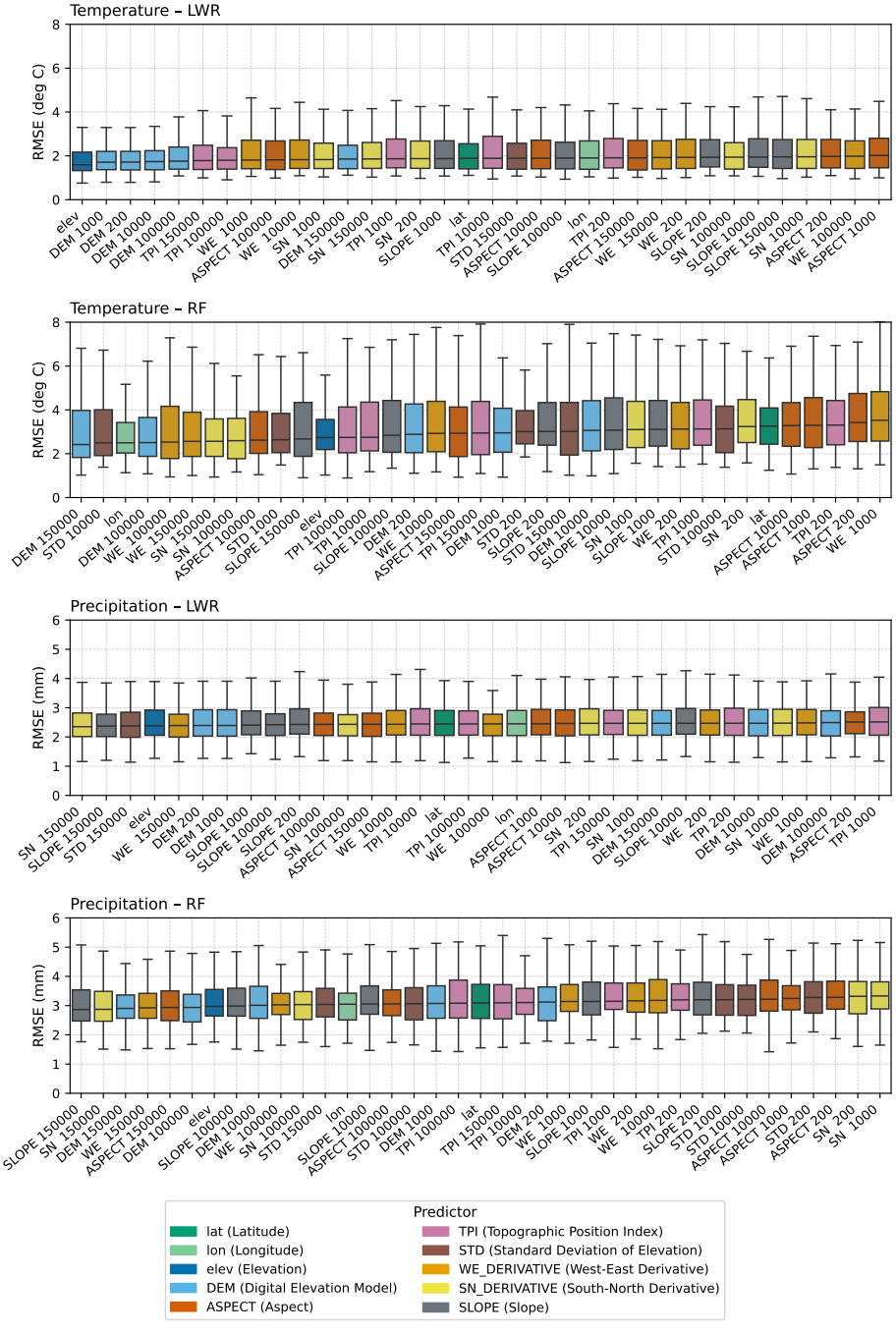


Figure 7. Static predictor screening showing single predictor cross validation results for the Bow. Topographic descriptors and their smoothed variants (200 m, 1,000 m, 10,000 m, 100,000 m, 150,000 m) are evaluated to assess cross-validation RMSE for Temperature and Precipitation for both Locally Weighted Regression (LWR) and Random Forecast (RF).

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5.3 Predictor Combination Selection and Regression Performance

Sequential forward screening was used to construct multivariate predictor sets separately for precipitation and temperature, and for each basin and regression method. Starting from an empty model, the static predictor that maximized cross-validated KGE″ was selected, after which additional predictors were added one at a time. Predictors were retained only if they increased KGE″ by more than 0.01, and the procedure was repeated after allowing dynamic reanalysis-based variables to enter the pool. The resulting optimal combinations are summarized in Table 1.

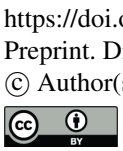
Table 1. Best static and static+dynamic predictor combinations by catchment, variable, and model (LWR - Locally Weighted Regression, RF - Random Forest).

Catchment	Variable	Model	Static predictors	+ Dynamic predictors
Chena	Precipitation	LWR	South–North Derivative	Surface pressure
		RF	Elevation, Longitude	Precipitation rate
	Temperature	LWR	Elevation	Air temperature
		RF	Latitude, Elevation, South–North Derivative	Humidity
Bow	Precipitation	LWR	Aspect, Latitude	Air temperature
		RF	Aspect, Latitude, Longitude	Surface pressure
	Temperature	LWR	Elevation	Shortwave radiation
		RF	Aspect, Elevation	Air temperature
Tuolumne	Precipitation	LWR	Elevation, West–East Derivative, Latitude	Air temperature
		RF	Aspect, Elevation, Latitude, Longitude	Precipitation rate
	Temperature	LWR	Elevation	Air temperature
		RF	Elevation, South–North Derivative	Air temperature

Across basins, elevation or its smoothed derivatives dominate temperature estimation, with only a small number of additional predictors needed. For LWR, elevation alone provides most of the skill, and adding a single dynamic predictor (air temperature or shortwave radiation from reanalysis) yields marginal but systematic improvements. RF models for temperature typically select combinations of elevation and one or two additional topographic descriptors (e.g., aspect, south–north derivative), then further improve performance when reanalysis air temperature or humidity is included. For precipitation, both static and dynamic predictors are important. In the Bow, LWR favors aspect and latitude, with air temperature as the dominant dynamic addition, whereas RF also selects longitude and surface pressure. In the Chena and Tuolumne, RF tends to use elevation and horizontal derivatives in combination with reanalysis precipitation rate and surface pressure, suggesting that non-linear interactions between orography and large-scale meteorology are important for daily precipitation.

Figure 8 shows the distribution of cross-validated KGE″ across all stations for the main predictor combinations. RF systematically outperforms LWR once multiple predictors are available, particularly for precipitation. Adding dynamic predictors

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further shifts the cumulative distributions to the right, indicating higher skill for the majority of stations. Temperature KGE'' is relatively high and similar across methods, whereas precipitation shows a clearer separation between LWR and RF, and between static-only and static+dynamic configurations. It is notable that inclusion of dynamic predictors can degrade the skill of LWR predictions, potentially due to overfitting or creating localized patterns that are not representative.

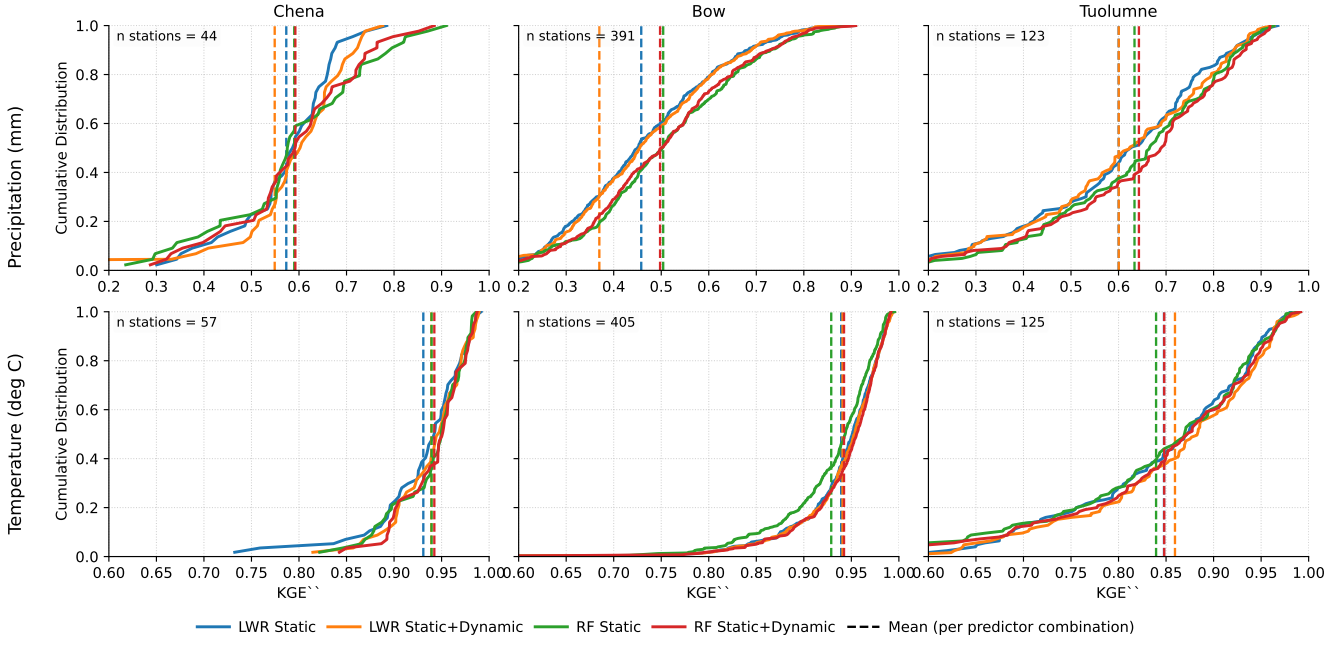


Figure 8. Cross validation KGE'' values for predictor combinations from forward screens. The KGE'' for all stations are shown as a Cumulative Distribution Function. Results further to the right of the x-axis are better. The number of stations available for each analysis is shown.

525 The spatial pattern of cross-validation performance for the RF static+dynamic combinations is shown in Figure 9. There is no strong dependence of KGE'' on elevation, station density, or location within each basin. Most stations achieve $\mathrm{KGE}'' > 0$ for precipitation and $\mathrm{KGE}'' > 0.4$ for temperature, with a small subset of outliers exhibiting lower skill, likely reflecting localized measurement issues or unresolved sub-grid variability.

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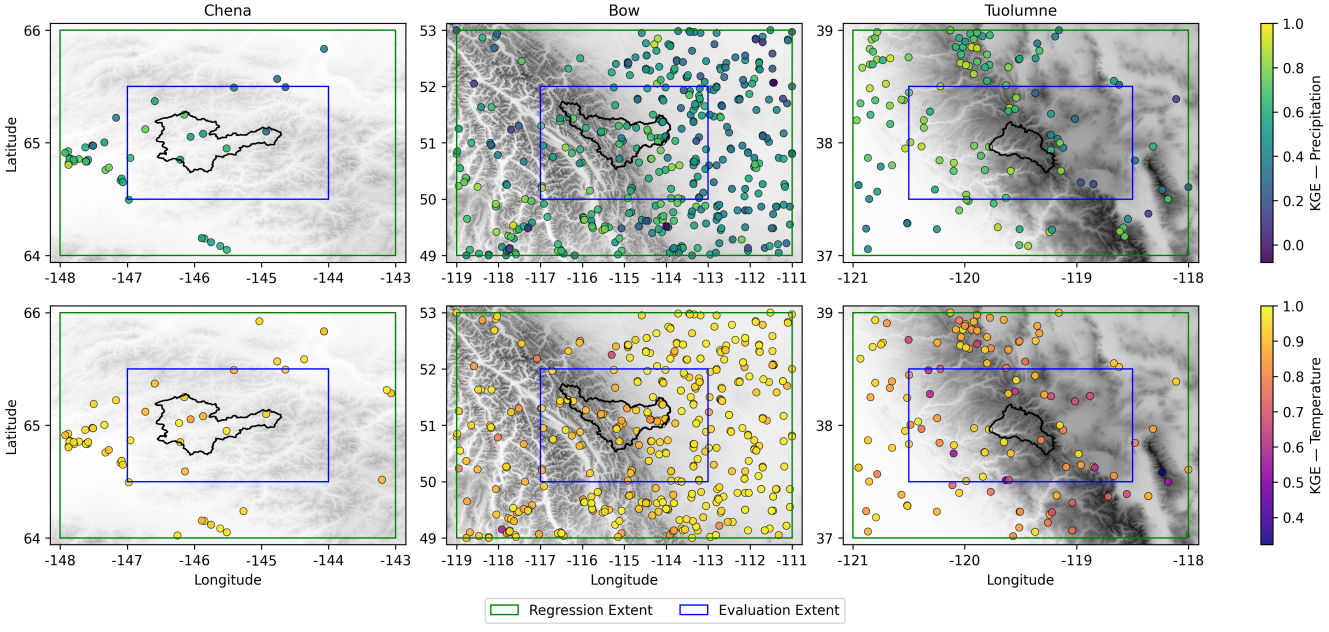


Figure 9. Cross-validation results for Chena, Bow, and Tuolumne River Basins shown as spatial plots for the RF (Random Forest) static and dynamic predictor combinations. Not all stations have both precipitation and temperature measurements.

5.4 Meteorological Ensembles

Using the selected predictor combinations (Table 1), 50-member daily precipitation and temperature ensembles were generated over each study area. To evaluate the probabilistic skill of these ensembles, we computed Brier Skill Scores (BSS) for station-based events, with climatological occurrence as the reference. For precipitation, the evaluated event was daily precipitation at three thresholds (≥ 0.1 mm,≥ 5 mm,≥ 10 mm). For temperature, exceedance events relevant to snow processes were considered (≥ -5 °C,$T > 0$ °C, $T > 5$ °C).

Figures 10 and 11 present the cumulative distribution of BSS across all stations for each basin and configuration, along with non-overlapping block bootstrap uncertainty intervals. Positive BSS values indicate that the ensembles provide more information than climatology, with $BSS = 1$ representing a perfect probabilistic forecast. For precipitation, all RF-based ensembles achieve predominantly positive BSS values, with distributions clearly shifted above zero compared to LWR. Incorporating dynamic predictors consistently increases BSS, demonstrating that reanalysis fields add useful information about event occurrence beyond static topography and climatology. LWR ensembles also show positive skill relative to climatology in most basins but with noticeably lower BSS, reflecting limitations of purely local, linear relationships for capturing event-scale variability. Temperature ensembles exhibit higher and more uniform BSS than precipitation across all methods (Figure 11). RF again outperforms LWR, and static+dynamic configurations yield the highest BSS. The bootstrap uncertainty bands confirm that these differences are statistically robust for the majority of stations. Overall, the ensemble verification indicates that the generated

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ensembles are skillful and reliable relative to the climatology. RF regression substantially enhance probabilistic performance, particularly for precipitation. The inclusion of dynamic predictors also provides some minor improvements in all cases.

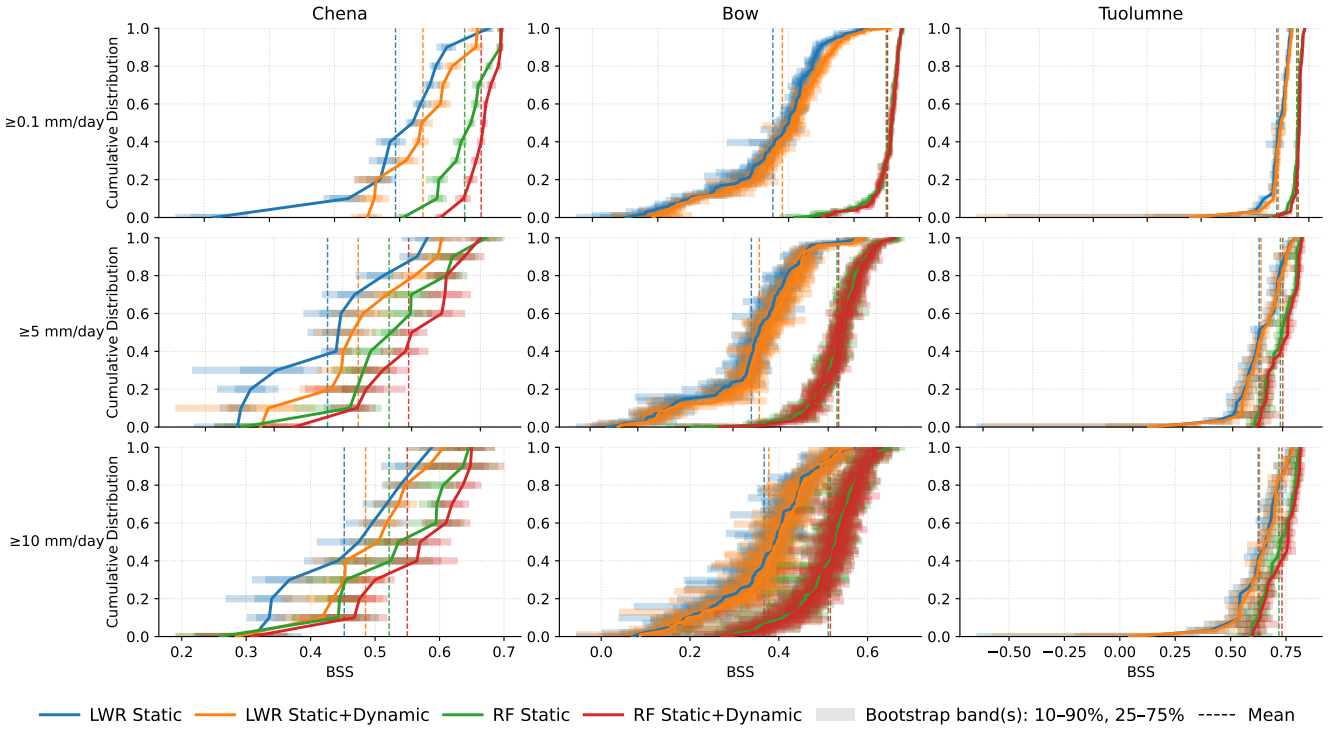


Figure 10. Brier Skill Scores (BSSs) for precipitation with bootstrapping. The CDFs of BSSs show the relative performance of each method compared to the climatology mean. $BSS = 1$ indicates a perfect probabilistic prediction, while all values above 0 are better than the climatology.

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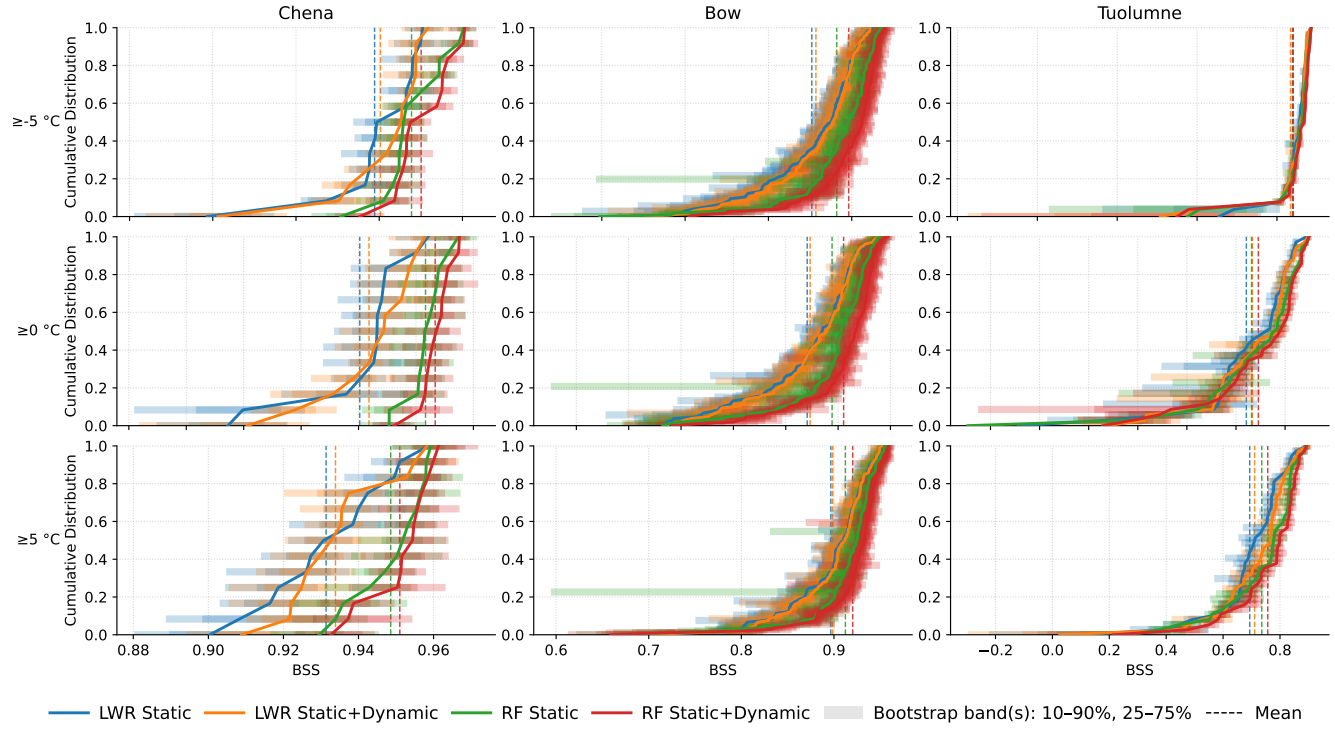


Figure 11. Brier Skill Scores (BSSs) with bootstrapping for select temperature thresholds. The CDFs of BSSs show the relative performance of each method compared to the climatology mean. Similar to Figure 10 but for select temperature thresholds.

5.5 Snow Modeling

The impact of ensemble meteorological forcing on snow simulations was assessed by driving SUMMA with the 50-member RF ensembles, and two deterministic benchmark forcings (CaSR and ERA5). Simulations were evaluated in GRUs containing NorSWE manual snow surveys (Figure 2), with modeled SWE compared to observed transect-based SWE. Figure 12 illustrates SWE time series at the three GRUs with the highest number of snow surveys in each basin. The RF-driven ensembles typically exhibit larger SWE magnitudes than the deterministic forcings, with observed values lying within the ensemble spread for most seasons. In the Bow, the ensemble mean SWE is similar in magnitude to CaSR and ERA5, but melt timing is generally better aligned with the observations. In the Chena and Tuolumne, ensemble members capture both low- and high-accumulation years, while revealing years where deterministic forcings substantially under- or over-estimate peak SWE.

Simulated timeseries evaluated at individual stations can have mixed results. For example, in the Bow station locations where reanalysis CASR and ERA5 simulation values appear to better match SWE observation magnitude than RF ensemble mean. This highlights challenges of constraining snow simulations with results that are not completely spatially or temporally representative. However, the overall magnitudes and timing of snow accumulation and melt processes do validate the study approach. Complete SWE timeseries results, including for snow pillows, are included in Appendix E.

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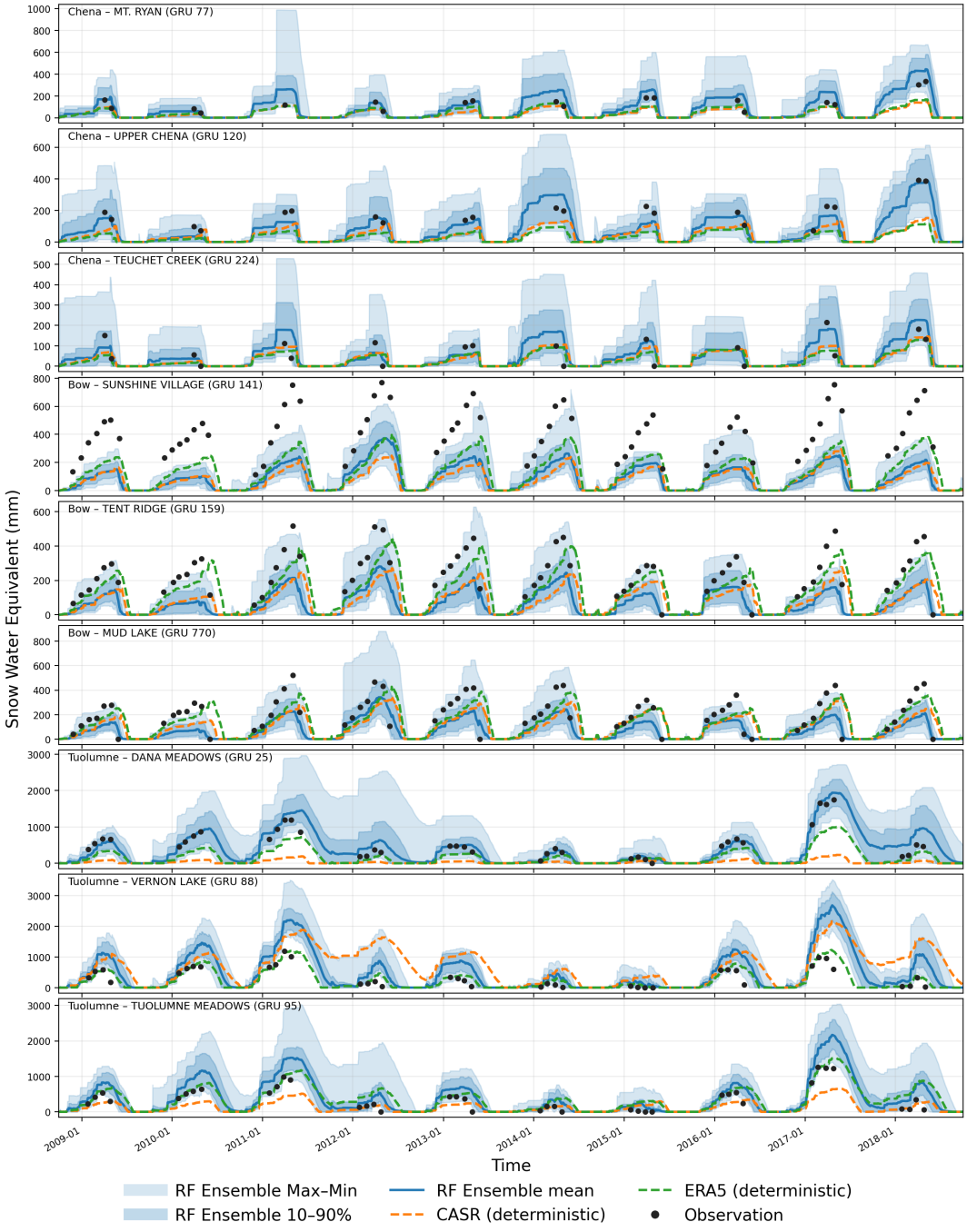


Figure 12. SUMMA snow simulations compared to snow surveys. Snow model simulations for the Chena, Bow and Tuolume Basins are plotted for RF ensembles, CASR, and ERA5 forcing. For each basin the 3 GRUs with the highest amount of snow survey data are shown.

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A summary of SWE performance for each basin is provided by the skill-target diagrams and Taylor diagrams in Figure 13. Each point represents a single GRU–forcing pairing (and ensemble member for the RF ensembles). In the skill-target diagrams, RF ensemble members cluster closer to the origin than ERA5 and CaSR, indicating lower combined pattern and bias error. The spread of RF points reflects the intended representation of forcing uncertainty, but the median skill distance is lower than for the deterministic products in all three basins. The Taylor diagrams show that the RF ensembles generally achieve correlations with observations comparable to ERA5 and CaSR, while generally having higher values than reference values of normalized standard deviation. There generally is a wider dispersion, which is absent in single-forcing simulations. Outlier GRUs with low skill highlight locations where scale mismatch, local wind redistribution, or other unresolved processes strongly influence SWE, regardless of forcing. Taken together, the snow simulation results demonstrate that the station-based meteorological ensembles translate into physically plausible SWE ensembles in SUMMA, the ensemble spread provides a meaningful envelope that contains the majority of observed SWE values; and the RF-based GPEP ensemble forcings yield equal or better pattern and bias skill than commonly used deterministic reanalyses, while additionally quantifying uncertainty in snow states.

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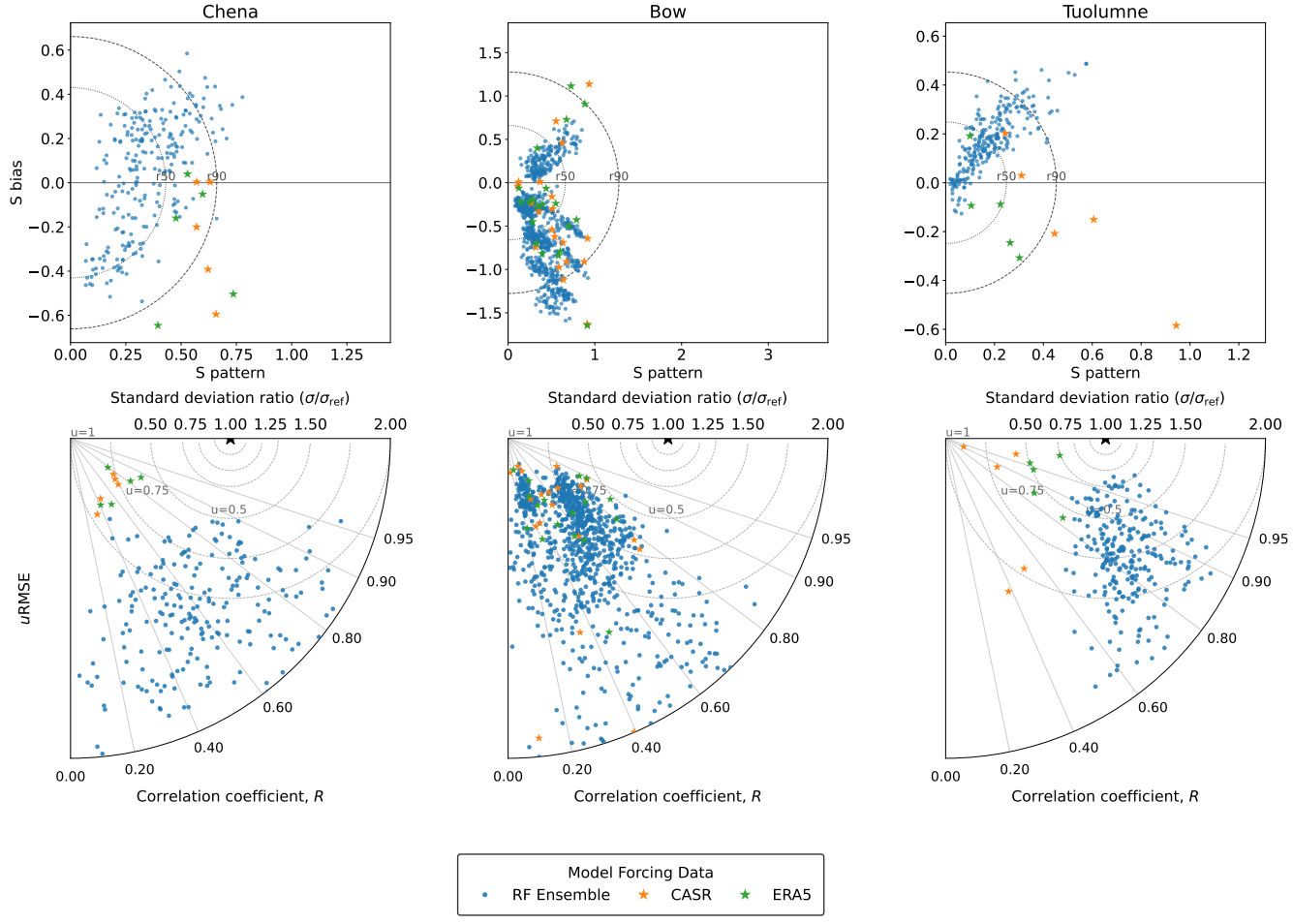


Figure 13. Evaluation of SWE simulations for forcing datasets (Ensemble produced with RF Static–Dynamic predictors (n=50), CASR, and ERA5) using the skill-target (top row) and Taylor diagram (bottom row). The skill-target diagrams (top) display normalized bias (S bias) versus normalized pattern amplitude (S pattern) relative to snow observations; the dashed circles denote 50th and 90th percentiles. Closer to the target origin at zero indicates better performance. The Taylor diagrams (bottom) summarize the same statistics in polar coordinates, with the azimuthal angle representing correlation (R), the radial distance showing normalized standard deviation (S pattern), and contours of equal centered RMSE (u) (Taylor, 2001). Together, the two panels quantify relative skill, bias and correlation consistency following the benchmarking protocol described in Mudryk et al. (2025)

6 Discussion

This study presents an end-to-end approach to representing meteorological forcing uncertainty in physically based mountain snow simulations. The structured approach integrates undercatch corrected station-based probabilistic meteorology through to an ensemble forcing and distributed energy-balance snow model simulation. Across three contrasting mountain basins,

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the approach improves deterministic estimation, yields probabilistic forecasts with positive Brier Skill Scores, and produces snow ensembles that capture the magnitude and timing of SWE with credible uncertainty bounds (Figs. 8, 10, 11, 13). The contribution lies not only in the individual components but in their coupling: bias corrected inputs and predictor design improve the estimation of meteorology in complex terrain, and these improvements are realized in physically based modeled snow states.

6.1 Ensemble Mountain Meteorology for Snow Modeling

The results advance a long line of efforts to map meteorology in complex terrain and quantify associated uncertainty. Physiographic approaches such as PRISM demonstrated the value of topographic predictors and expert weighting for gridded climatologies (Daly et al., 2008, 2021), while operational products such as seNorge and related systems have emphasized deterministic spatial continuity, but rarely provide event-scale uncertainty (Lussana et al., 2018). Probabilistic geostatistical frameworks, including GMET and subsequent extensions, established that regression against static predictors combined with stochastic sampling of spatially correlated residuals can generate calibrated ensembles (Clark and Slater, 2006; Newman et al., 2015). Our work builds directly on that foundation in two ways: it systematically incorporates dynamic predictors from reanalyses alongside static topography, and it evaluates machine-learning estimators against locally weighted regression within the same ensemble architecture. The finding that RF outperform LWR for precipitation and temperature in multiple mountain settings strengthens earlier indications that non-linear learners can better represent interactions between orography and time varying patterns (Wolfensberger et al., 2021; Baez-Villanueva et al., 2020).

A further contribution is the explicit propagation of this quantified forcing uncertainty into a physically based, energy-balance snow model and its evaluation against in-situ SWE observations. Mountain snow modeling studies, whether in multi-model intercomparisons or basin-specific analyses, most often rely on a single deterministic forcing or meteorologic "ensembles of opportunity" constructed from independent reanalyses (Essery et al., 2013; Henn et al., 2018b; Schreiner-McGraw and Ajami, 2022). While useful for assessing dataset spread, such ensembles do not reflect the underlying interpolation and representativeness uncertainties tied to the observing network. In contrast, the ensembles developed here are explicitly conditioned on stations and incorporate spatially structured residual variability, establishing a clearer link between observational density, predictor choice, and modeled uncertainty. The improved representation of SWE magnitude and melt timing relative to ERA5 and CaSR demonstrates the value of carrying realistic input uncertainty through an energy-balance model.

6.2 Methodological Implications

The behavior of the predictors and estimators is consistent with process understanding and with lessons from physiographic mapping. Elevation remains the dominant control on temperature, and moderate spatial smoothing of terrain derivatives improves estimation for both variables by emphasizing synoptic structure while retaining key orographic gradients. Dynamic predictors add physically relevant variability that static physiography cannot supply, aligning the estimation problem with the drivers used by land-surface models. The RF advantage over LWR suggests that non-linear interactions among static and dynamic fields are important in sparse mountain networks; at the same time, the LWR framework retains value where trans-

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parency and locality are priorities. Because ensemble reliability depends on the fidelity of both the mean and the residual fields, the deterministic gains translate directly into higher Brier Skill Scores once residuals are sampled with spatial correlation.

Workflows such as the one developed for this paper (which used a package called Snakemake) can also contribute to reproducibility and transferability. Implementing GPEP with rule-based automation can facilitate consistent application across regions, straightforward selection of predictor sets, and verification. In this study, the use of a standardized discretization (TDX-Hydro) and a consistent SUMMA configuration, coupled with emulator-assisted parameter selection, eased comparative inference across basins. Although such an end-to-end workflow adds an additional software wrapper, as well as dependencies and constraints in conducting such analyses, it also can provide efficiencies in generalizing the analysis, in contrast to methods used in local studies that may rely on tailored or manual data and preprocessing steps that are time-intensive to apply to new locations.

6.3 Potential Application and Limitations

The results indicate a practical route for operational agencies and research groups that require uncertainty-aware snow estimates. The approach can harness region specific station measurements and recent gridded analysis to produce skillful ensemble forcing. These data are available in real time, and the procedure can be automated. Driving an energy-balance snow model with these ensembles yields SWE state estimates with credible spread and timing that are directly usable in data assimilation, seasonal outlooks, and risk analyses. The demonstration across three distinct basins suggests that the approach is robust to differences in observing density and topographic complexity, which is essential for scaling to new regions.

Limitations remain across many stages of this approach. Undercatch correction relies on simplifying assumptions on gauge type that should be refined where suitable gauge metadata is available (Huidobro et al., 2023). While reanalysis winds provide a reasonable surrogate for undercatch correction, developing downscaled, gauge-height wind fields for mountains remains a clear priority (Mott et al., 2018; Berg et al., 2024; Marsh et al., 2023; Helbig et al., 2017). The absence of consistent gauge metadata in global archives continues to be a major source of uncertainty for undercatch corrections, reinforcing the need for curated, operator-specific metadata where available (Mekis et al., 2018; Smith et al., 2022; Sun et al., 2019). Daily ensembles subsequently disaggregated into sub-daily forcings limit the representation of diurnal energy fluxes and short-duration events; extending GPEP to hourly resolution could improve melt onset and rain-on-snow timing. The correlation structure and transformation chosen for precipitation influence extremes and dispersion and merit a targeted study. Also, the SUMMA configuration used here does not explicitly represent wind redistribution or avalanching, and GRU-scale evaluation against point or transect observations entails scale mismatch. This point is illustrated in Figure 14, where measurements collected in a well-instrumented research catchment with different localized settings within a single GRU yield highly different SWE magnitudes. Furthermore, a single model physics and parameter set is used in this study, so exploration of multi-physics and parameter ensembles could improve probabilistic representation. Finally, further benchmarking with spatial products, such as airborne lidar, could further disentangle and quantify forcing and structural uncertainties.

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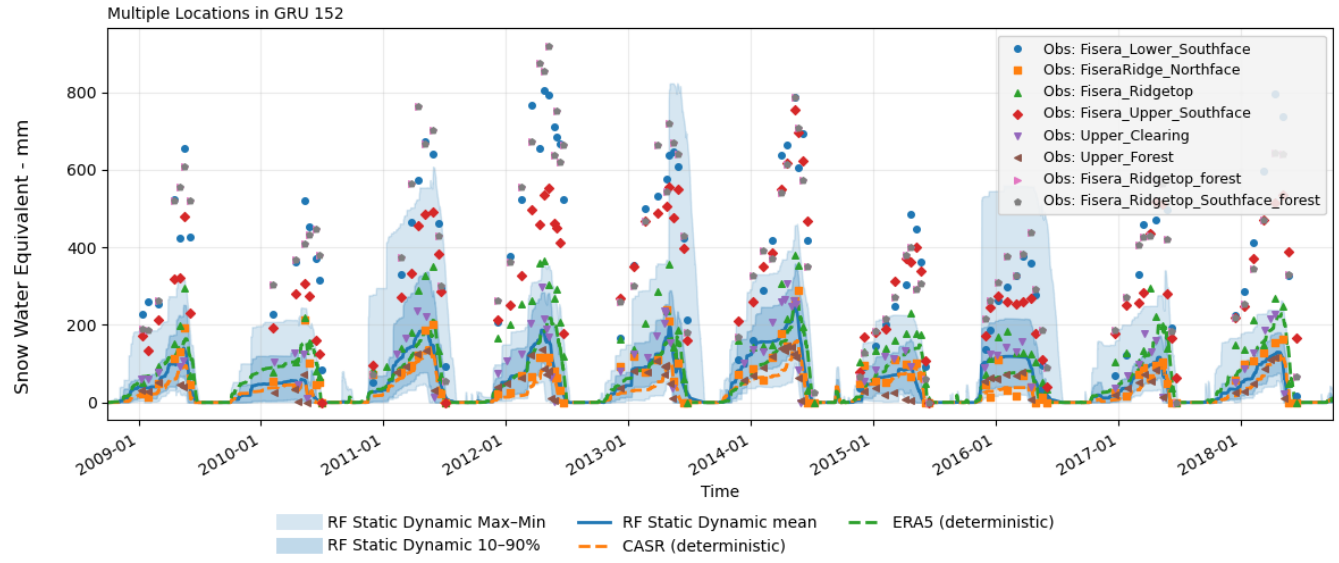


Figure 14. SUMMA SWE simulations of a single GRU with multiple observation sites. Measurement location has a large effect on the quantity of snow. This highlights the challenge of evaluation and interpretation of model simulations with in-situ data.

In summary, this work extends probabilistic geospatial estimation from the station network to physically based snow modeling and demonstrates that doing so improves both deterministic skill and probabilistic reliability in complex terrain. Relative to the existing literature, it integrates undercatch correction within ensemble construction across multiple catchments, leverages dynamic predictors with a non-linear estimator to enhance station-based ensembles, and shows that the resulting forcings translate into more credible SWE simulations than commonly used deterministic products. The combination of methodological transparency, open implementation, and multi-basin evaluation provides a clear pathway to improve probabilistic snow modeling and water prediction.

7 Conclusions

This study presents a structured approach for propagating meteorological uncertainty through physically based mountain snow modeling. The workflow begins with bias correction of precipitation observations, followed by geospatial estimation of meteorological variables and the generation of high-resolution ensemble meteorological fields. These ensembles capture the spatial and temporal variability of forcing data in complex terrain and are used to drive physically based snow simulations, which propagate input uncertainty into snow estimates. The approach is applied in three contrasting mountain basins: the Chena in Interior Alaska, the Bow in the Canadian Rockies, and the Tuolumne in the Sierra Nevada. These catchments represent a range of climatic conditions, monitoring contexts, and density of meteorological station observations. Applying this framework within the SUMMA modeling system enabled consistent and transparent representation of meteorological uncertainty in snow state predictions across these diverse settings.

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Addressing key deficiencies in mountainous meteorology estimation, namely the influence of complex topography and wind induced gauge undercatch, helps to improve meteorological estimates. Applying WMO-standard undercatch corrections improves the magnitude of cold-season precipitation estimates. Reanalysis wind data provide a practical supplement where in situ wind measurements are unavailable, enabling consistent correction across large domains. Topographic descriptors, particularly elevation and smoothed terrain derivatives, remain key predictors of both precipitation and temperature patterns. Incorporating dynamic atmospheric predictors from reanalysis further enhances model performance, particularly for precipitation, by capturing synoptic-scale variability that topography alone cannot explain.

Among the deterministic estimation methods, RF-based meteorological estimation models consistently outperformed locally weighted regression (the prior default method in studies applying GMET and GPEP), achieving higher cross-validation skill and greater probabilistic reliability once ensemble dressing with spatially correlated errors was applied. Ensemble meteorological forcing fields generated through this framework exhibited markedly higher Brier Skill Scores than climatological references, demonstrating that the ensembles are both reliable and informative. When used to drive physically based snow simulations, these ensembles improved the representation of uncertainty in snow water equivalent, providing a more credible basis for assessing snow-driven hydrologic variability.

Overall, this work highlights the importance and opportunity of explicitly representing meteorological uncertainty in mountain snow modeling. Probabilistic meteorological forcing estimation, when coupled with physically based modeling, provides an effective strategy to bridge the gap between sparse observations and complex terrain processes. Future developments should aim to extend this ensemble methodology to sub-daily timescales and integrate it with data assimilation systems to dynamically constrain snowpack states. As mountain hydrology faces growing challenges from climate variability and changing water demands, probabilistic, physically based approaches such as this offer a foundation for both scientific investigation and operational prediction that include uncertainty estimates.

Code and data availability.

All data and code used in this study are openly available. The primary station-based meteorological data are the Station-Based Serially Complete Earth Dataset (SCDNA; Tang et al., 2021), available through the US National Center for Atmospheric Research (NCAR) data repository. Topographic descriptors were derived from the MERIT Hydro digital elevation dataset (Yamazaki et al., 2017), which provides hydrologically conditioned elevation and drainage information at 3-arcsecond resolution. Atmospheric reanalysis predictors were obtained from the European Centre for Medium-Range Weather Forecasts (ERA5; Hersbach et al., 2020) and the Canadian Surface Reanalysis (CaSR v3.1; Gasset et al., 2021), both publicly accessible through their respective data portals.

All code for data processing and model coupling is open source and available via GitHub. The workflows for data preprocessing, undercatch correction, and geospatial probabilistic estimation are implemented in the repository `gpep_snakemake` (Casson, 2025b). The workflow used to couple ensemble meteorological forcings to the SUMMA model framework is available in `gpep_to_summa_snakemake` (Casson, 2025c). Both repositories include reproducible Snakemake pipelines, configu-

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ration files, and documentation for applying the Geospatial Probabilistic Estimation Package (GPEP; Tang et al., 2024) and the SUMMA hydrological model across diverse mountain basins.

The ensemble meteorological datasets and models generated for all three study basins, the Chena, Bow, and Tuolumne, along with the corresponding processed station and topographic data used in this study, are available via Zenodo and the Federated Research Data Repository (FRDR) (Casson, 2025d, a). These archives include ensemble forcing files, SUMMA model files, GPEP input files and basin-level metadata to support reproducibility and further research on probabilistic snow modeling in mountainous environments.

Appendix A: Undercatch Correction Methodology

Detailed equations, constants, and assumptions for the undercatch correction methods applied in this study are provided in Table A1. The WMO SPICE UTF (Kochendorfer et al., 2017a, b) is applied in the Bow Basin, while the WMO (1998) standard rain gauge correction (Goodison et al., 1998; Yang et al., 1998) is used for the Chena and Tuolumne basins. Wetting loss are not included in correction. Each approach assumes consistent gauge type and shielding within each basin, reflecting available metadata and historical network standards.

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Method	WMO SPICE Universal Transfer Function (2017)	WMO Solid Precipitation Measurement Intercomparison (1998)
General Information		
Key Reference	Kochendorfer et al. (2017a, b)	Goodison et al. (1998)
Study Areas	Bow (Canada)	Chena and Tuolumne (United States)
Assumed Gauge Type	Geonor and Pluvio	US standard 8" gauge
Shielding	No shield	No shield
Input Data		
SC-Earth Station Data	P: precipitation (uncorrected, mm/day); U: wind speed (m/s); T: air temperature (°C)	P: precipitation (uncorrected, mm/day); U: wind speed (m/s); T: air temperature (°C)
ERA5 Reanalysis	U: daily max wind speed (m/s), daily mean air temperature (°C)	U: daily max wind speed (m/s), daily mean air temperature (°C)
Correction Equations		
Catch Efficiency	$CE = e^{-aU}\left[1 - \tan^{-1}(bT) + c\right]$	$CE = \exp\left(d - eU^f\right)$
Precipitation Partitioning	Implicit in correction formula	$S = 1 - \frac{1}{1 + e^{a_0 + a_1 T}}$
Threshold Behaviour	$U < U_{\text{thres}}$; $T > T_{\text{thres}}$, $CE = 1$	$U < U_{\text{thres}}$
Wind Speed Correction	Transfer Function for 10m available	Logarithmic wind profile correction
Precipitation Correction		
Corrected Precipitation	$P_{\text{corr}} = \frac{P}{CE}$	$P_{\text{corr}} = (1 - S)P + \frac{S}{CE}P$
Additional Information		
Additional References	Smith et al. (2022)	Newman et al. (2020); Froidurot et al. (2014); Huidobro et al. (2023)

Table A1. WMO gauge undercatch methodologies used to correct precipitation measurements in Canadian and US catchments. A simplifying assumption of consistent gauge type within each study area is applied due to limited metadata on gauge configuration.

Undercatch correction implementation was compared to the benchmark dataset of Smith et al. (2022) who implemented SPICE UTF methods for stations across Canada. This was performed for overlapping stations (n=10) surrounding the Bow watershed. This comparison highlights differences between shielding assumption configurations, the use of ERA5 wind and correcting a comparison of 2 m compared to 10 m measurement heights. This comparison was performed for the Bow watershed as the assumption of consistent gauge assumptions in United States gauging networks is consistent with (Newman et al., 2020; Huidobro et al., 2023). As depicted in Figure A1, the methodology applied to SC-Earth data matches the seasonality and magnitude of the benchmark dataset. The use of ERA5 winds leads to conservative undercatch compared to in-situ data. The selection of shielding configuration is a key assumption, highlighting the need for station metadata across gauging networks.

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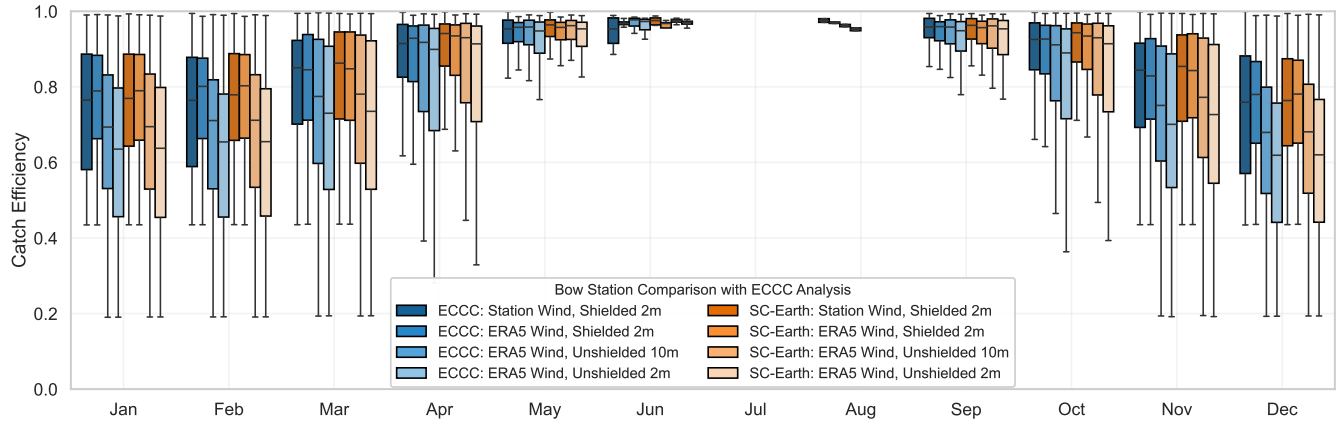


Figure A1. Comparison of methodological choices for undercatch correction using overlapping SC-Earth stations with that of Smith et al. (2022) in the Bow. The ECCC station dataset, shielded 2 m represents the reference dataset, while separate iterations compare supplementing SC-Earth station data, ERA5 wind and the change with wind height corrections.

Appendix B: GPEP Methodology

This appendix provides the statistical methods used in the Geospatial Probabilistic Estimation Package (GPEP) for this study. A more complete description of the software and computational considerations is available in Tang et al. (2024). A synthesis of the GMET method development prior to the Python GPEP implementation is available also available in Appendix B of Bunn et al. (2022).

B1 Deterministic Estimation

Deterministic estimation forms the first step of the probabilistic workflow. This step estimates the gridded mean of the target variable (e.g., precipitation or temperature measured at station locations) and for intermittent variables the probability of occurrence. These deterministic fields, calculated with Locally Weight Regression and Random Forest, form the basis for the ensemble generation process.

B1.1 Locally Weighted Regression

Locally weighted regression (LWR) is used to generate deterministic grid estimate. For each grid cell, the relationship between the observed or transformed variable x_o and a set of predictor variables A_i is described by

$$x_o = \hat{x} + \epsilon = \beta_0 + \sum_{i=1}^{n} A_i \beta_i + \epsilon, \tag{B1}$$

where A_i is the ith predictor, β_0 and β_i are regression coefficients, and ϵ is the residual error term. Spatial localization is achieved using distance-based weights that limit the influence of observations to those stations most relevant to the grid

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cell. This approach allows the regression to capture regional-scale variations while maintaining computational efficiency. As demonstrated by Bunn et al. (2022), the same formulation can incorporate temporally varying predictors such as NWP or reanalysis data.

For variables that are intermittent, such as precipitation, the probability of occurrence is estimated using a locally weighted logistic regression. This calculates the Probability of Precipitation (POP), defined as

$$\text{POP} = \frac{1}{1+\exp\left(-\left(\beta_0+\sum_{i=1}^{n} A_i\beta_i\right)\right)}. \tag{B2}$$

The resulting mean field and probability field are then used in the probabilistic estimation step to generate ensemble realizations that reflect both the expected value and its associated uncertainty.

B1.2 Random Forest Regression and Classification

Random Forest (RF) methods provide a non-parametric alternative to locally weighted regression for generating the deterministic estimate. RF models can be applied in both regression and classification modes, corresponding respectively to the estimation of continuous variables (e.g., precipitation amount, temperature) and the prediction of event probabilities (e.g., precipitation occurrence) (Wolfensberger et al., 2021). Within the geospatial probabilistic estimation framework, RF regression and classification serve analogous roles to the locally weighted linear and logistic regression, respectively.

An RF model consists of an ensemble of decision trees, each trained on a random subset of the available data and predictor variables (Breiman, 2001). This process introduces stochasticity in both the sampling of training observations (via bootstrapping) and the selection of predictors at each node, ensuring that the ensemble captures a diverse range of predictor–response relationships. The final prediction is obtained by aggregating the outputs of all trees, which improves generalization and reduces overfitting relative to a single decision tree (Cutler et al., 2007).

In regression applications, each tree produces an individual prediction $\hat{x}_j$ of the variable of interest x_o, based on a set of predictors $A_1, A_2, \ldots, A_n$. The ensemble mean prediction $\hat{x}$ is then computed as the arithmetic average across all T trees:

$$\hat{x} = \frac{1}{T}\sum_{j=1}^{T}\hat{x}_j, \tag{B3}$$

where T is the number of trees in the forest and $\hat{x}_j$ is the prediction from the jth tree. Each decision tree recursively partitions the predictor space by selecting split thresholds that minimize a specified cost function. The averaging of multiple decorrelated trees yields a stable estimate that reflects nonlinear relationships between predictors and responses without requiring an explicit parametric model (Tyralis et al., 2019).

In classification applications, each tree predicts a categorical outcome $\hat{y}_j$, such as the presence or absence of precipitation. The ensemble classification $\hat{y}$ is determined by majority voting across the T trees:

$$\hat{y} = \text{mode}(\hat{y}_1, \hat{y}_2, \ldots, \hat{y}_T), \tag{B4}$$

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where mode$(\cdot)$ denotes the most frequent class among the tree-level predictions. The result is a probability of occurrence derived from the fraction of trees that predict a given outcome, which can be used as the Probability of Precipitation (POP) in probabilistic estimation.

The RF models in GPEP are implemented using the scikit-learn library, enabling straightforward implementation (Pedregosa et al., 2011). Unlike locally weighted regression, RF models are inherently global: they are trained once using all available stations and predictor data, rather than fitting a separate model at each grid cell. This global structure allows the RF approach to exploit complex, nonlinear dependencies between predictors (e.g., topography, dynamic atmospheric predictors, and spatial coordinates), while maintaining computational scalability across large domains (Fox et al., 2020).

Random Forests, therefore, provide a robust and flexible alternative for deterministic gridded estimation of geospatial variables, particularly in regions where predictor–response relationships are highly nonlinear or where the spatial sampling of observations is sparse or irregular (Sekulić et al., 2020). The mean field and probability field outputs from RF regression and classification are subsequently used in the probabilistic estimation step, where uncertainty is represented through spatially correlated ensemble generation.

B2 Probabilistic Estimation and Ensemble Generation

The probabilistic estimation stage converts the deterministic fields into ensemble realizations that represent the spatial and temporal uncertainty of the estimated variables. This is achieved by combining the deterministic mean estimates, the associated uncertainty calculated from station error, and a stochastic component represented by spatially correlated random fields (SCRFs). The SCRFs ensure that the generated ensembles preserve realistic spatial coherence and correlation structures that are consistent with those observed in the station data and predictor fields.

In the general case, a variable X at a given grid cell and time step is represented as a random variable drawn from a Gaussian probability distribution, written in-text as $X \sim \mathcal{N}(\mu, \sigma^2)$, where μ corresponds to the deterministic mean estimate and σ quantifies local uncertainty. For variables such as temperature and temperature range, this normal approximation is appropriate. For intermittent and skewed variables such as precipitation, the distribution is decomposed into two components: the probability of occurrence (p_0) and the conditional distribution of nonzero values. The conditional precipitation field is transformed to normal space using a Box–Cox or power-law transformation to ensure approximate Gaussianity (Newman et al., 2015; Tang et al., 2024).

To represent spatial structure, ensemble perturbations are generated using SCRFs sampled from a standard normal distribution. The SCRFs impose correlation among neighboring grid cells using an exponential correlation model:

$$c_{i,j} = \exp\left(-\frac{d_{i,j}}{L_c}\right), \tag{B5}$$

where $c_{i,j}$ is the correlation between grid cells i and j, $d_{i,j}$ is the distance between them, and L_c is the spatial correlation length. The correlation length is estimated empirically from station data and varies by variable and domain. SCRFs are gen-

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erated using a conditional simulation approach (Clark and Slater, 2006), ensuring that each random field realization maintains both the specified correlation structure and the correct marginal statistics.

Temporal coherence is introduced by linking random fields across successive time steps using lag-1 autocorrelation coefficients derived from the observed data. Cross-variable correlations (for example, between precipitation and temperature range) can also be imposed to maintain realistic multivariate relationships (Tang et al., 2024).

For each ensemble member, the SCRFs are used to perturb the deterministic estimates according to their local uncertainty. For normally distributed variables such as temperature, the probabilistic estimate is computed as

$$x = \mu + R \cdot \sigma, \tag{B6}$$

where R is the corresponding value from the SCRF in that grid cell and time. For intermittent variables such as precipitation, ensemble generation proceeds in two steps. First, the probability of occurrence is evaluated: if the cumulative probability of R is less than the occurrence probability p_0, the grid cell is assigned zero precipitation. Otherwise, the nonzero precipitation amount is computed by scaling and back-transforming the random draw in normal space:

$$y = \begin{cases} 0, & \text{if } F_N(R) \le p_0, \\ \mu + F_N^{-1}\left(\frac{F_N(R)-p_0}{1-p_0}\right)\sigma, & \text{if } F_N(R) > p_0, \end{cases} \tag{B7}$$

where $F_N(\cdot)$ and $F_N^{-1}(\cdot)$ are the standard normal cumulative distribution and its inverse. The resulting y values are then inverse-transformed from normal space to yield precipitation in physical units. This process is repeated independently for each ensemble member, generating a suite of spatially and temporally coherent realizations.

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Appendix C: Surface Meteorology Inputs to SUMMA

Variable	Description	Units	CASR v3.1 variable	ERA5 variable
time	Time	s	time	time
precip	Precipitation rate	kg m^{-2} s^{-1}	A_PR0_SFC	pptrate
airtemp	Air temperature	K	P_TT_1.5m	airtemp
SWRadAtm	Downward shortwave radiation	W m^{-2}	P_FI_SFC	SWRadAtm
LWRadAtm	Downward longwave radiation	W m^{-2}	P_FB_SFC	LWRadArm
windspd	Wind speed	m s^{-1}	P_UVC_10m	windspd
airpres	Air pressure	Pa	P_P0_SFC	airpres
spechum	Specific humidity	kg kg^{-1}	P_HU_1.5m	spechum

Table C1. Summary of surface meteorology data input requirements for the SUMMA energy balance snow model, with corresponding CASR v3.1 and ERA5 variable names.

Appendix D: Model Calibration Parameter Ranges

Parameter name in SUMMA	Lower	Upper	Transformation	Units
tempCritRain	272.16	274.16		K
tempRangeTimestep	0.5	5		K
frozenPrecipMultip	0.95	1.05		
albedoMax	0.7	0.95		
albedoMinWinter	0.4	0.6		
albedoMinSpring	0.35	0.5		
albedoDecayRate	100000	5000000		
albedoRefresh	1	10		
Fcapil	0.01	0.1		
mw_exp	1	5		
z0Snow	0.0001	0.03	log10	m

Table D1. SUMMA snow parameters used in the Large Sample Emulator (LSE) calibration approach as well as the lower and upper bounds for parameter search.

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Appendix E: Complete SWE Timeseries Results

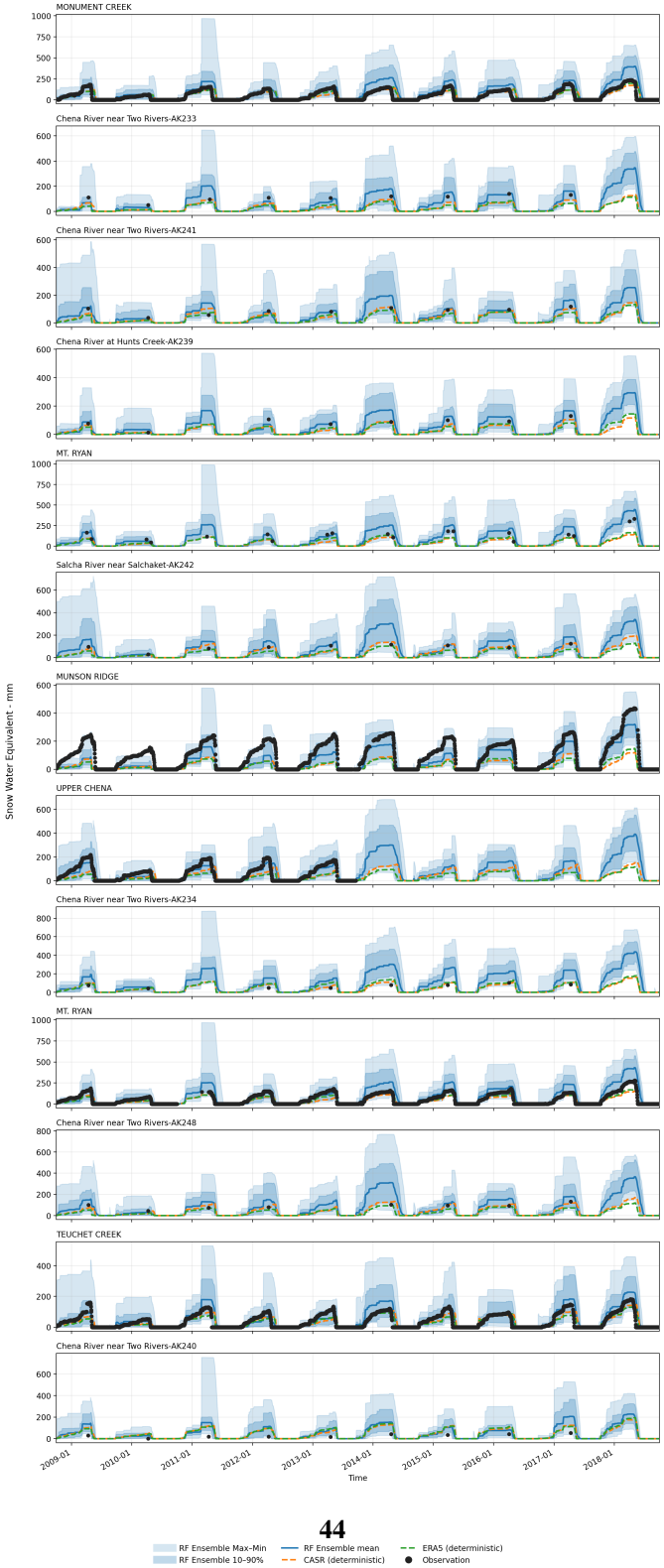


Figure E1. Chena SUMMA Snow Simulation Timeseries compared to NorSWE observations

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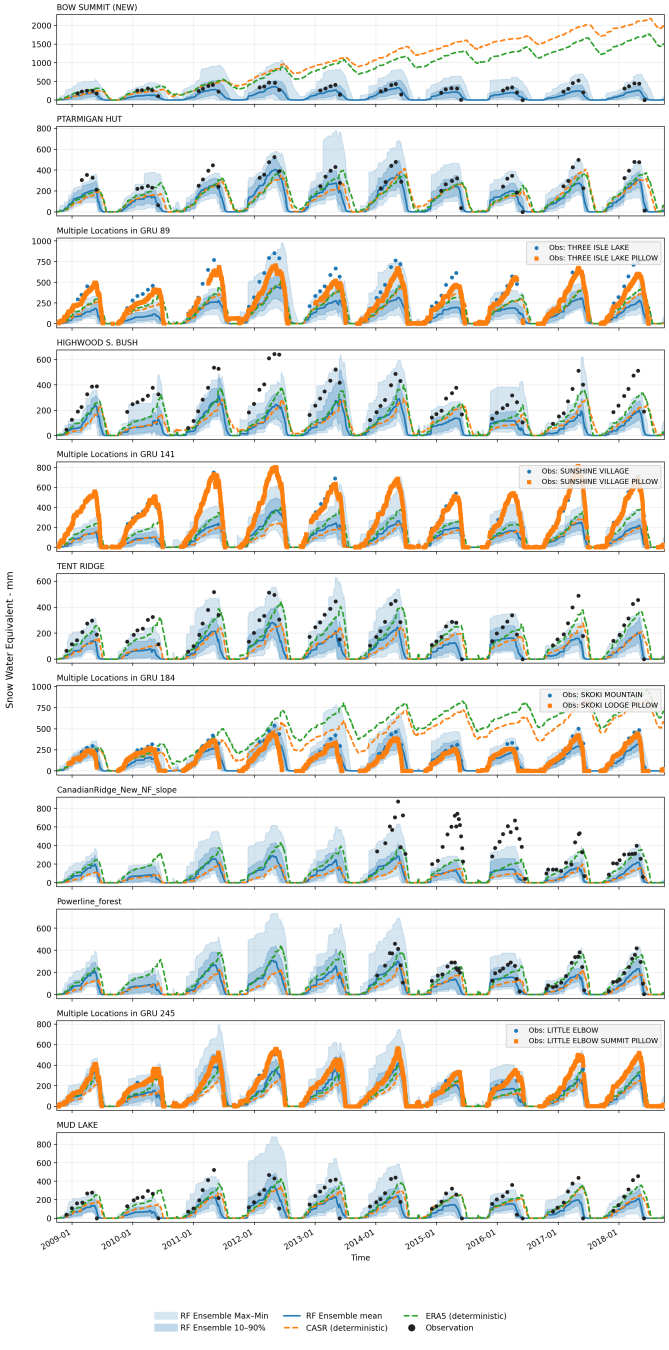


Figure E2. Bow SUMMA Snow Simulation Timeseries compared to NorSWE observations

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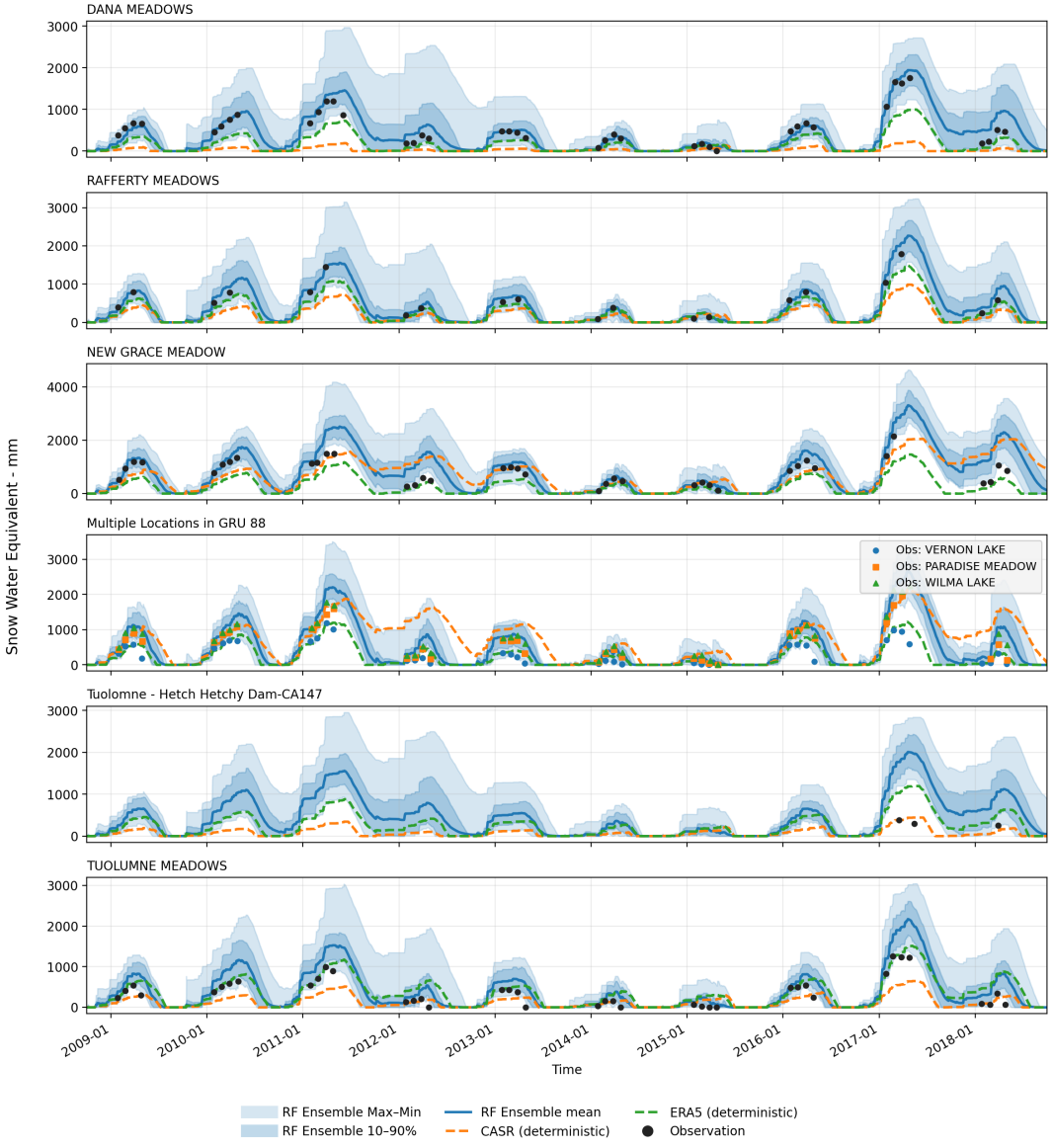


Figure E3. Tuolumne SUMMA Snow Simulation Timeseries compared to NorSWE observations

Author contributions. DC led the research, manuscript writing and performed the majority of technical tasks (Conceptualization; Methodology; Software; Data curation; Formal analysis; Investigation; Validation; Visualization; Writing, original draft). GT provided GPEP software guidance and helped shape the study approach (Software; Methodology; Conceptualization; Writing, review and editing). NV designed and executed SUMMA snow calibration, contributed to evaluation and figures, and reviewed the manuscript (Methodology; Software; Formal analysis; Investigation; Validation; Visualization; Writing, review and editing). AW contributed initial SUMMA model formulations,

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implementation code, and GPEP-prototype datasets (GMET) for the Tuolumne Basin, and to study design and manuscript revisions (Conceptualization; Software; Methodology; Writing, review and editing). MC supervised the research and secured funding (Supervision; Funding acquisition; Project administration; Conceptualization; Writing, review and editing). All authors reviewed and approved the final manuscript.

Competing interests. The authors declare that they have no conflict of interest.

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