Ensemble-Based Parameter Evaluation for Distributed Snow Modeling in the Western United States

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1. Introduction

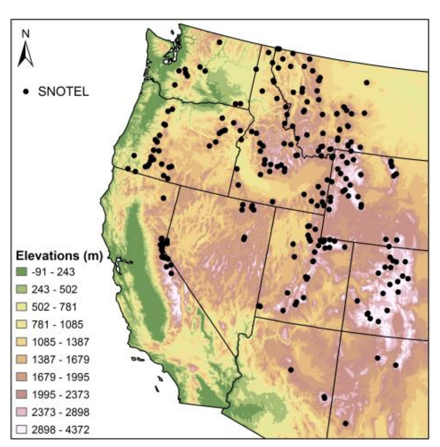
Due to limited availability of snow measurements at high-altitude mountainous sites, distributed hydrological models that represent the physical processes of snow accumulation and ablation have been extensively used to evaluate the potential changes in the snow and streamflow regime under altered conditions of climate and vegetation covers. While it is a common practice to calibrate and validate the snow modules with the observed snow data, the lack of regional studies on snow predictive uncertainties originating from parametric, observational and model intrinsic uncertainty remains a key challenge in snow-dominated hydrological modeling and predictions of extreme events in particular. This study highlights the significance of accounting for uncertainties in snow modeling for realistic estimates of the extreme hydrologic events that are often a result of snowmelt and rain-on-snow events in the Western United States.

2. Method & Data

We constructed 10,000 parameter ensemble using the Latin Hypercube Sampling (LHS) algorithm that samples from the prior uniform distribution of six control parameters of snow processes in DHSVM (Table 1).

Parameter	Prior Range	Description
T_R	[-4, 4]	minimum temperature that rain forms
T_S	[-4, 4]	maximum temperature that snow forms
λ_A	[0, 1]	albedo decay coefficients during snow accumulation
λ_M	[0, 1]	albedo decay coefficients during snow melt
A_{min}	[0.5, 1.0]	minimum allowable albedo during snow accumulation
M_{min}	[0, 0.5]	minimum allowable albedo during snow melt

Table 1. Prior distribution of DHSVM parameters that control snow processes.



For each member of the 10,000 parameter ensemble, we implemented the Distributed Hydrology-Soil-Vegetation Model (DHSVM) to simulate snow water equivalent (SWE) at the 3-hourly step at 246 Snowpack Telemetry (SNOTEL) stations across the Western United States, forced by high-quality SNOTEL meteorological measurements from WY 2007-2013.

We explored parameter sensitivity, evaluated the predictive performance of posterior parameters in SWE dynamics, and assessed the uncertainties in snow modeling associated with parameterization and model physics.

2.1 Evaluation Metrics

As the timing and magnitude of peak SWE events are critical to water resources mangers, we evaluated the performance of the ensemble parameters with three metrics that are sensitive to peaks:

- Nash–Sutcliffe Efficiency (*NSE*)
- Mean percentage error of annual peak SWE (*PEAK.ERR*)
- Mean differential days for the occurrence of annual peak SWE (*PDATE.ERR*) between SWE observations and predictions

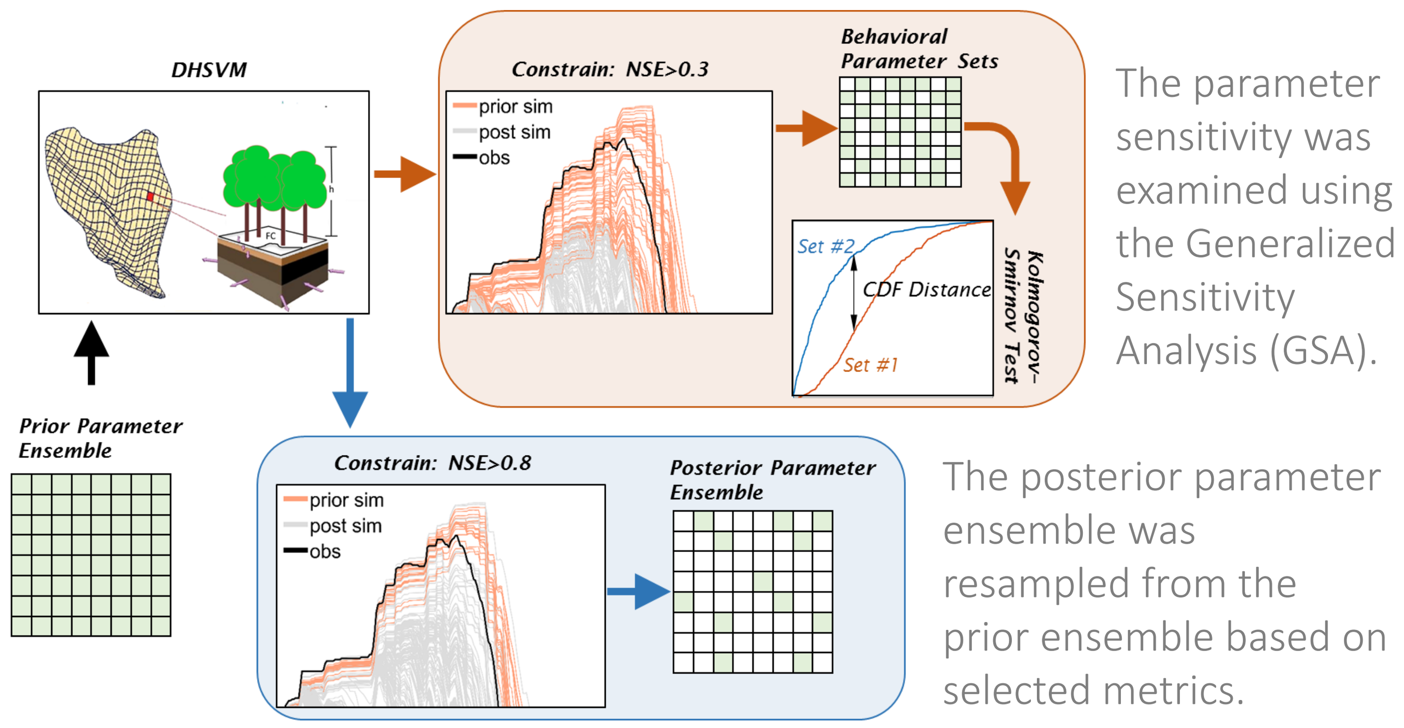


Figure 1. Workflow of parameter sensitivity analysis and posterior parameter construction.

3. Results

3.1 Best prediction

For each SNOTEL, the best prediction refers to the prediction set producing the highest *NSE* (Fig. 2).

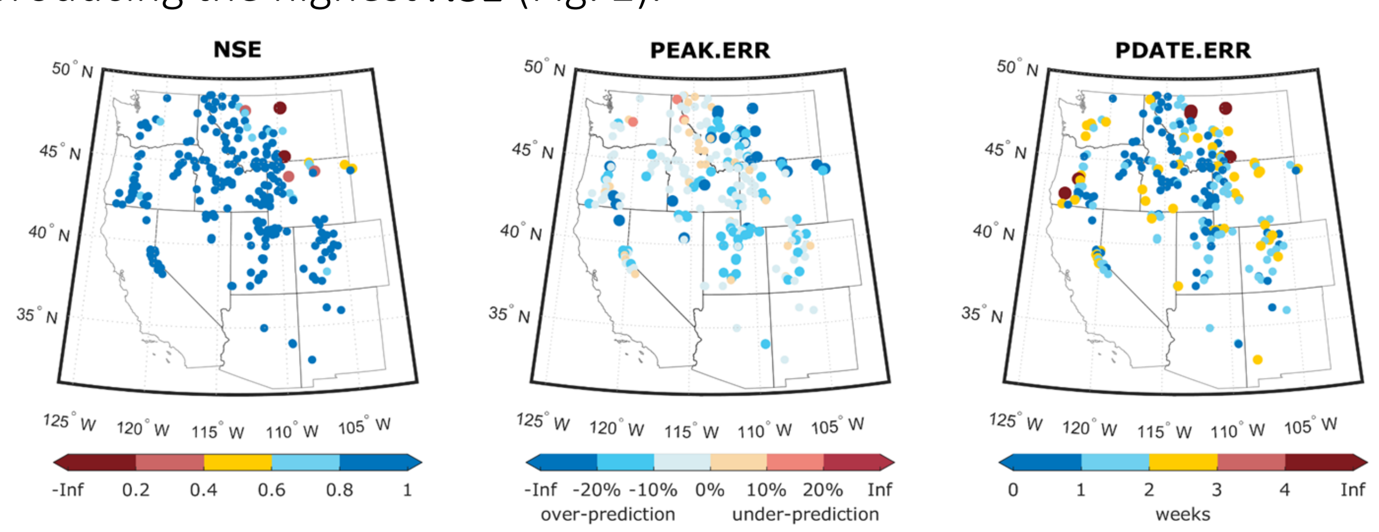


Figure 2. Evaluation of best prediction over 246 SNOTELs: *NSE*, *PEAK.ERR*, and *PDATE.ERR*.

With the best prediction:

- *NSE* > 0.8 at 90% of SNOTELs; *NSE* > 0.6 at 97% of SNOTELs
- *PDATE.ERR* < 1 week at 43% of SNOTELs; *PDATE.ERR* < 2 weeks at 80% of SNOTELs
- *PEAK.ERR* within ±10% at 65% of SNOTELs; *PEAK.ERR* within ±25% at 91% of SNOTELs
- At the majority of SNOTELs, DHSVM slightly overestimated peak SWE and predicted later melt. The SNOTELs where DHSVM underestimated peak SWE are mostly located in the Northern Rockies in western Montana and northeastern Idaho, as well as the Cascade-Sierra mountain ranges.
- Only eight SNOTELs have a poor NSE (< 0.6), all located in the Rocky Mountains in Montana and Wyoming.

3.2 Parameter Sensitivity

Predicted SWE at the majority of SNOTELs showed significant sensitivity to three parameters across all evaluation metrics: A_{min}, λ_M, and T_S (Fig. 3):

- During accumulation, snow albedo is more often fixed at A_{min} than the albedo decay function
- During melt, snow albedo is largely controlled by λ_M (i.e. the albedo decay function) at most SNOTELs.
- T_S is more important than T_R for determining the liquid/solid phase of precipitation. The majority of SNOTELs sensitive to T_S are located in the Pacific Northwest, Sierra Nevada areas and the Northern Rockies in western Montana and northeastern Idaho.

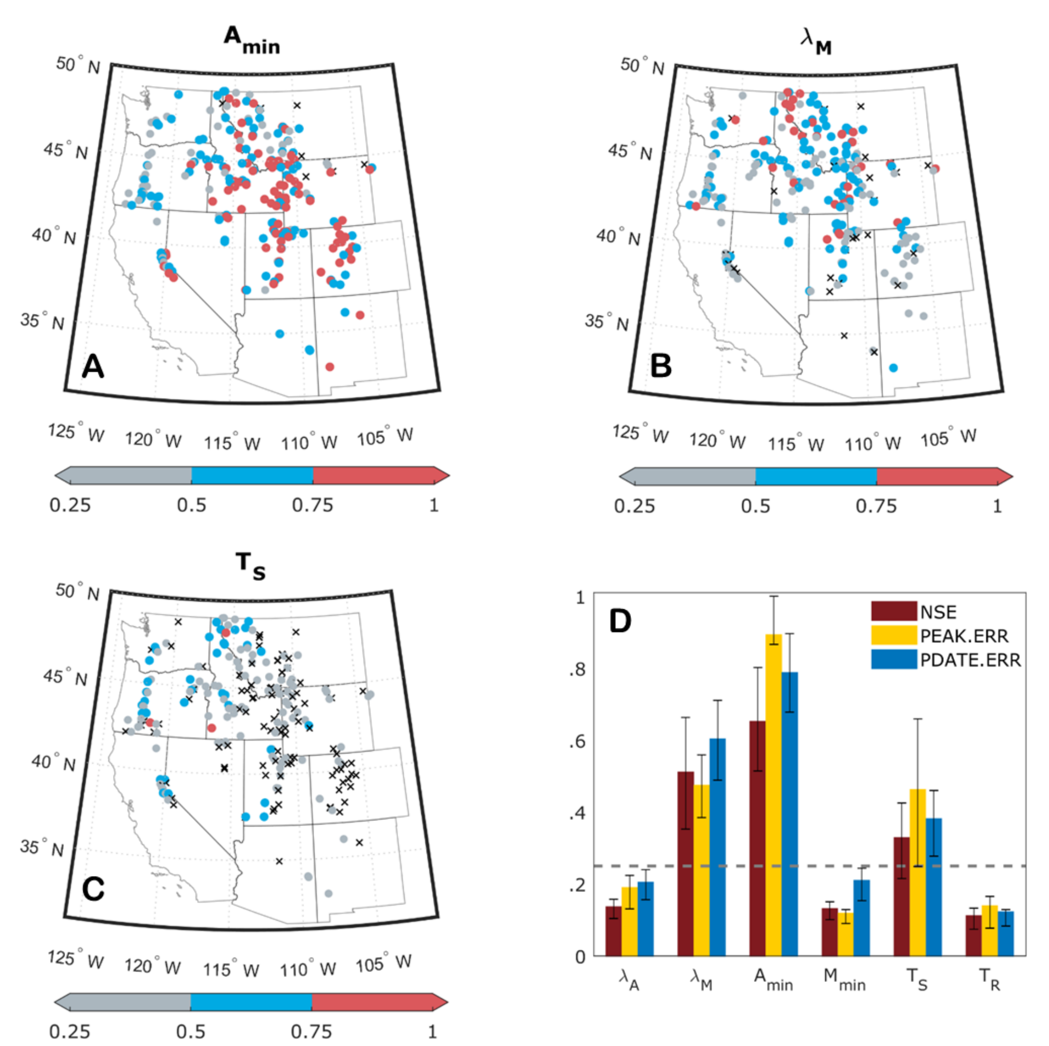


Figure 3. (A-C) Map showing KS statistic for three sensitive parameters: A_{min}, λ_M and T_S over SNOTELs. The symbol 'x' indicates non-sensitive parameter at the location. (D) The KS values for six parameters evaluated by *NSE*, *PEAK.ERR*, and *PDATE.ERR* over all 246 SNOTELs. The error bars quantify the variability over all SNOTELs (25th and 75th percentile). The dash line (*KS*=0.25) is the threshold that separates the sensitive (*KS*>0.25) and non-sensitive (*KS*≤0.25) parameters.

3.3 Posterior Parameter Ensemble

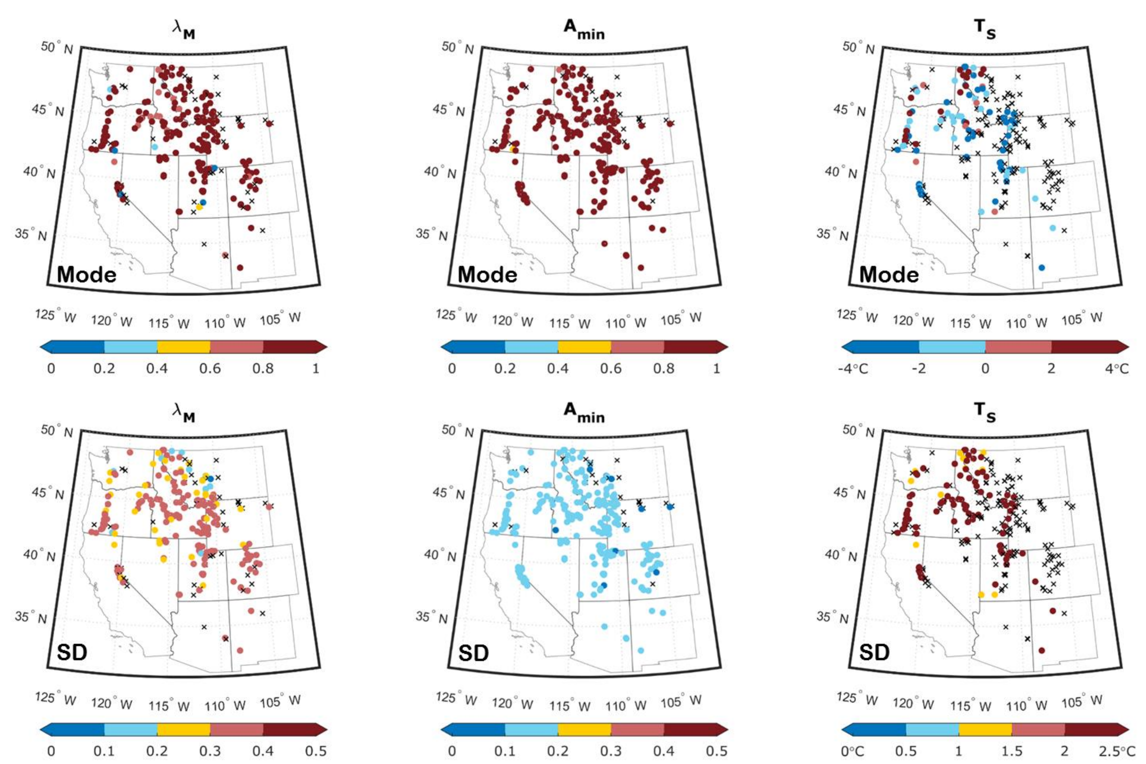
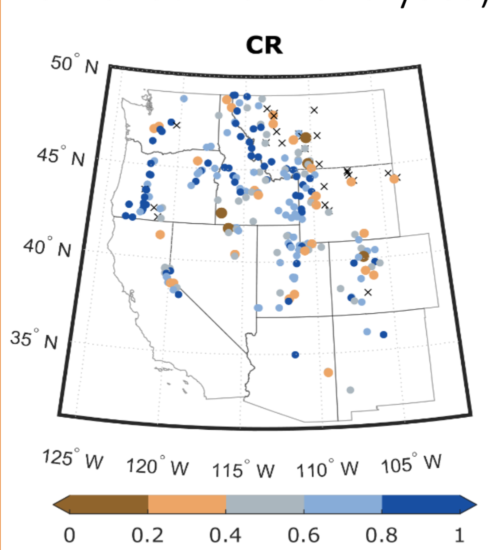


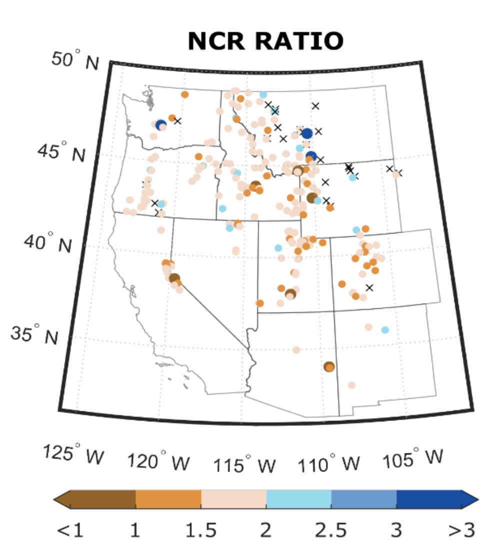
Figure 4. Posterior parameter ensemble expressed by the mode and standard deviation (*SD*) of posterior parameters. Non-sensitive parameters are not included (noted by the symbol 'x').

3.4 Prediction of Posterior Parameters

The performance of posterior parameters (*NSE* > 0.8) was evaluated by *CR* and *NCR RATIO* for 220 SNOTELs (26 stations with no qualified posterior parameters were removed from analyses).



CR: the containing ratio of SWE observations contained within the bounds of SWE time series simulated by the ensembles from WY 2007-2013. *CR* ranges from 0 to 1 with a higher value indicating better coverage. *CR* > 0.6 at 62% of SNOTELs.



NCR RATIO: the ratio of the posterior *NCR* to the prior *NCR*. *NCR* is normalized *CR* by the width of ensemble SWE prediction bounds. *NCR RATIO* > 1 indicates that the posterior predictions outperform the prior predictions. *NCR RATIO* > 1 at 97% of SNOTELs, and > 1.5 at 77% of SNOTELs.

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