



# Estimating the Water Stored as Snowpack Using Remote Sensing and Advanced Data Assimilation Techniques

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**Snowmelt represents a significant contribution to California's annual water budget. Remote sensing represents the most efficient method for estimating the snow water equivalent (SWE) of snowpack in mountainous regions. However, its usefulness has been compromised by difficulties in discerning deep and/or wet snow as well as excluding vegetative cover when using traditional snow retrieval algorithms. We have designed and field-tested an assimilation approach which is capable of providing estimated SWE in cases of deep snow, wet snow, and light to moderate vegetative cover.**

Like many semi-arid regions of the world, California depends on annual snowmelt for the majority of its water supply. However the primary method for estimating the amount of water stored in snow pack (snow water equivalent, SWE) still relies on field snow surveys. This approach is extremely limited since survey data are sparse point estimates which rely upon regression and comparison to historical measurements.

For the past several decades, researchers have been developing computer models which utilize remotely sensed snowpack data to estimate SWE. However these estimates can contain large uncertainty. For data retrieval methods, the uncertainty lies primarily in the relationship between the snow states and the remote sensing observations. For modeling, errors occur primarily as a result of the propagation of uncertainty in model inputs (e.g., precipitation) to the SWE estimates. It is this uncertainty that has motivated the development of the data assimilation approach used in this project.

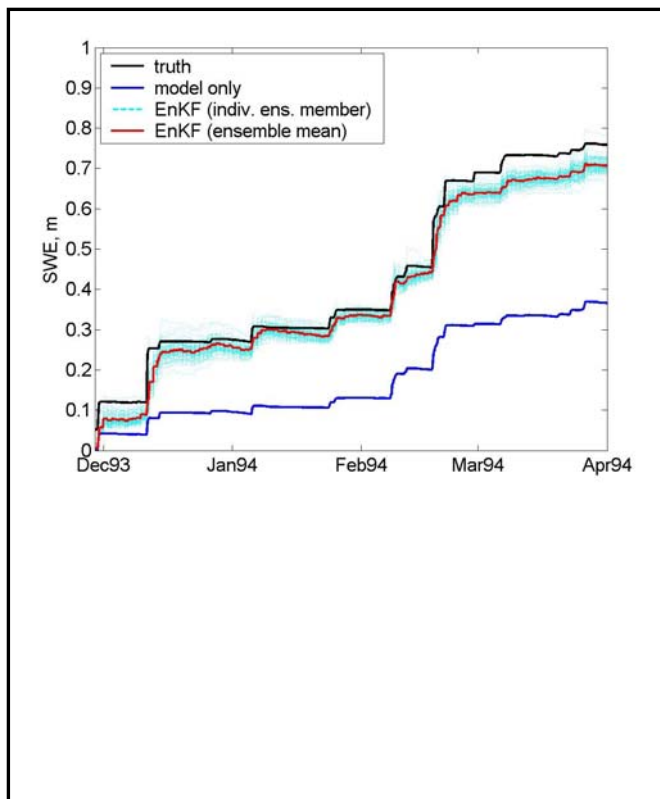
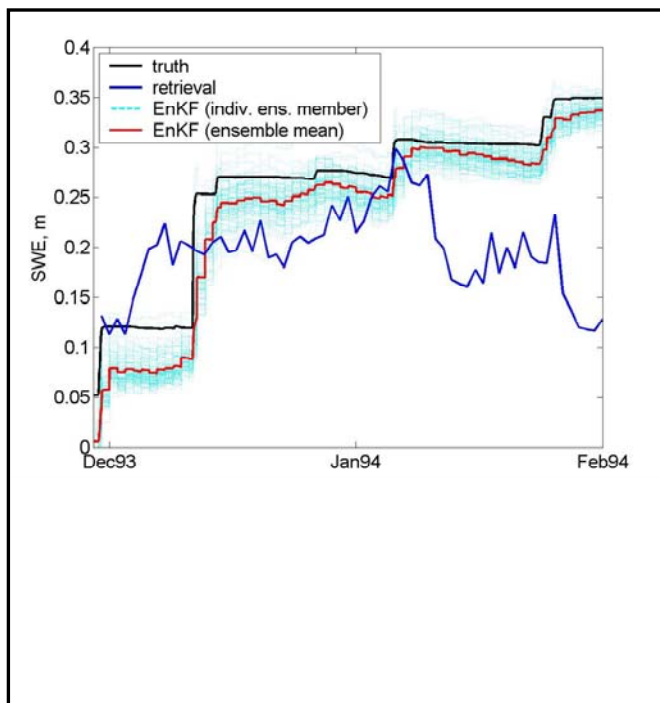
Data assimilation methods, such as the Ensemble Kalman Filter (EnKF) are used to merge remote sensing observations into a hydrologic model to produce estimates of SWE over the entire basin. The EnKF weighs the relative uncertainty of the model and of the observations and provides an estimate of the state variable as well as an estimate of its uncertainty. For this project, we have undertaken a feasibility study to estimate SWE through the incorporation of remote sensing observations in the microwave, visible, and thermal infrared parts of the spectrum into a physically-based snow model.

First, snow and remote sensing models were selected and developed that are appropriate for the data assimilation approach. We have chosen two widely

accepted models as the foundation of the data assimilation framework. During the preliminary testing phase we have incorporated more realistic models for the snow grain diameter evolution and snow albedo (reflectivity) which were found to be extremely important parameters in the radiative transfer (remote sensing) model. These model refinements should significantly improve SWE estimates. We have applied the model to data in the Mammoth Mountain region in the Sierra Nevada. These models have been embedded in a data assimilation framework (EnKF) to test their ability to estimate SWE from remotely sensed microwave radio-brightness observations.

Then, experiments at the point-scale were performed to test the feasibility of the approach. In these tests, synthetic realizations of the remotely sensed observations were used in the assimilation scheme to test whether the true snowpack characteristics could be recovered under conditions of uncertain initial conditions and precipitation. The methodology was shown to outperform commonly used retrieval methods and overcome significant biases often seen in precipitation.

The primary findings in this study are that the assimilation approach is capable of providing estimates of SWE in cases with i) deep snow, ii) wet snow, and iii) light to moderate vegetation cover. These are three of the primary confounding problems with traditional snow retrieval algorithms. Furthermore the method allows for improvements over traditional modeling approaches which are subject to large input errors due to sparsely collected data in remote mountainous regions. Our future work will extend the method to a spatially distributed basin-scale application.



### **Professional Presentations**

Durand, M., and S. Margulis, January 2005: Feasibility of snowpack characterization using multi-frequency remote sensing and advanced data assimilation techniques, American Meteorological Society Annual Meeting, San Diego, CA.

Durand, M., and S. Margulis, December 2004: Feasibility of snow water equivalent estimation using the Ensemble Kalman Filter, American Geophysical Union, Fall Annual Meeting, San Francisco, CA.

### **Publications**

Durand, M. and S.A. Margulis, Feasibility test of multi-frequency radiometric data assimilation to estimate snow water equivalent, *Journal of Hydrometeorology*, *accepted*.

Durand, M. and S.A. Margulis, 2005: Large-scale SWE Estimation: Optimal Use of Remote Sensing and Snow Modeling, *Southwest Hydrology*, 4(2), 20-21,32.

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