Project Progress Report for NWS Program Office (NWSPO)
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Title: Data Assimilation in Operational Watershed Models for Short and Long-term Hydrologic Forecasting
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Project Objectives

The goal of this proposal is to formulate a parsimonious data assimilation framework capable of integrating streamflow, soil moisture and snow products into the current National Weather Service River Forecasting System (NWSRFS) in order to improve ensemble streamflow forecasting. The project involves development and testing of an Ensemble Kalman Filter (EnKF) method to update NWS hydrologic model states for snow dominated basins using streamflow and SNOTEL observations. Ensemble streamflow prediction hindcasting techniques will then be used to assess the potential impact of the automatic updating scheme on current operational forecast skill. Initial testing is proposed for the American River basin and the plan is to extend the project to other operational forecast basins in the Western U.S. Guidance for development of the data assimilation framework is being solicited from NWS personnel at all agency levels. The proposed system design is intended to be modular and transferable to any NWS River Forecast Center. The system will also provide some degree of user control to meet the requirements of specific operational forecast settings.

Activities

Work during the first year of this project has consisted of extensive data collection (both ground and remotely-sensed observations), model formulation (coding SNOW17 and other necessary algorithms to Matlab and other languages), sensitivity analysis and calibration of the SNOW17 for western SNOTEL sites, and initial EnKF integration with the SNOW17 model. Each of these activities is briefly described below.

Data Collection

Initial SNOW17 modeling work has utilized 13 SNOTEL sites in the mountain zones of the western U.S. These sites include varying topographic and meteorological characteristics and are deemed representative of regional conditions. Daily precipitation, temperature, and pillow snow observations from gages were obtained from the NRCS. In the later stages of the study, the proposed framework will also be tested over two operational watersheds, the America River Basin and the Carson River Basin, which are both located in the northern Sierra Nevada Mountains. We are continuing to undertake extensive data collection (remote sensing products as well as ground-based observations in these two watersheds). We have also gathered data from both the Natural Resources Conservation Service (NRCS) Snow Telemetry (SNOTEL) database and the California Department of Water Resources (CDWR) California Cooperative Snow Surveys Program.

Model Calibration

Initial work has involved calibration of the SNOW17 to 13 SNOTEL sites throughout the western US with data records of at least five years. Only three primary parameters were calibrated (the snow correction factor, minimum melt factor and maximum melt factor) at all sites. The SNOW17 model simulations were highly accurate at 11 of these sites, indicating the potential for use of these SNOTEL sites (and others) for the data assimilation study (Figure 1). Calibration of additional SNOW17 parameters may improve results further. Six of these sites were selected for use in the sensitivity analysis and one site was further selected for initial testing of the EnKF.

Sensitivity Analysis

A sensitivity analysis was undertaken to assess parameter and model uncertainty across six of the SNOTEL sites in the western U.S. (Table 1; Figure 2). The ultimate goal of the sensitivity analysis is to guide uncertainty estimates and error structure for the EnKF (see below). Ground-based precipitation and temperature were used as forcing for the SNOW17 model. Snow pillow measurements were used for the observed SWE. A 10-year period, water years 1998 to 2007, was utilized as the analysis period. A modified regional sensitivity analysis (RSA) method (Hornberger and Spear, 1981) was used for the sensitivity analysis and to also evaluate parameter identifiability in the SNOW17 model. The RSA has two primary components: Monte Carlo sampling and "behavioral/non-behavioral" classification (according to a pre-set objective function or threshold). Monte Carlo sampling generates parameter sets in pre-specified reasonable ranges via a multivariate uniform distribution (Tang et al., 2007). According to model behavior (or performance) parameter sets are separated into two groups, behavioral sets (corresponding model performance is good) and non-behavioral sets (model performance is not satisfactory).

We utilized the Latin hypercube sampling (LHS) method to generate random realizations of parameters based on the recommendations of previous studies (McKay, 1988; Sieber and Uhlenbrook, 2005). The LHS is a stratified Monte Carlo sampling method in which parameter ranges are equally divided into N intervals (N is the number of samples) and one realization is sampled from each interval. The Nash-Sutcliffe efficiency (NSE) (Nash and Sutcliffe, 1970) is used as the metric in quantifying model performance and distinguishing behavioral from non-behavioral parameter sets.10,000 parameter sets are generated in their feasible ranges for each site and the SNOW17 model is run in parallel to obtain corresponding 10,000 SWE estimates for each site. Dotty plots, cumulative distribution curves (CDCs) (Figure 3), and Kolmogorov-Smirnov (K-S) values (Kottegoda and Rosso, 1997) (Figure 4) were evaluated for each of the six SNOTEL sites. In general, several parameters (e.g., MFMAX, PXTEMP) are sensitive for all sites, while some (e.g., NMF, TIMP) are generally insensitive for all sites. Sensitivities of some parameters (e.g., PLWHC) are site-dependent. In addition, the parameter SCF can dramatically impact the sensitivity of those sensitive parameters. Calibrated SCF values normally produces better results than default SCF (at one) or random SCF (10,000 samples) values. Analysis is ongoing and a paper is currently in preparation on sensitivity and parameter interactions within the SNOW17 model.

Ensemble Kalman Filter

An initial EnKF framework has been developed for the SNOW17 model. The feasibility of the framework was tested via synthetic experiments at one of the SNOTEL sites (site number 541) in the Sierra Mountains, CA. Synthetic feasibility tests were undertaken to address the following questions: 1) Is the EnKF framework applicable to extreme (wet/ dry) years in addition to normal years? 2) How sensitive are EnKF results to ensemble size, measurement uncertainties and frequencies (Figure 5)? 3) Precipitation error is deemed as a first-order source of SWE estimation uncertainty, especially during the accumulation season. Can incorporation SWE measurements into the framework overcome biases (e.g., 50% off) and uncertainties in precipitation? The tested EnKF framework is subsequently applied to merge the real SWE observation at the same site. The SNOW17 is used as the forward model. Inputs to the model include temperature and precipitation. The output is rain-plus-melt flux.

In our application of the EnKF, uncertain model inputs include time-variant forcing and time-invariant model parameters. Errors were accounted for in this study by assigning a physically reasonable distribution to the variables and specifying corresponding variation coefficients for them. Precipitation was assumed to follow multiplicative lognormal distribution. Air temperature was assumed to follow Gaussian distribution. It is further assumed that there is a temporal correlation between forcing at sequential time steps. A lag-1 auto-regressive model (AR (1)) model was applied to consider the temporal correlation. All states considered are assumed to follow lognormal distribution. The assumption is made on the basis that 1) states should not be negative, and 2) theoretically, there are no upper bounds for their values. All the parameters are assumed to follow β distributions. It is worth noting that for simplicity, no cross-correlation are specified between any states, forcing, and parameters in our initial EnKF testing; we are currently investigating inter-dependence and correlation between SNOW17 parameters. In addition, errors in initial conditions were also not integrated into the initial framework but will be tested in upcoming work.

The following three EnKF experiments were designed: 1) open-loop and EnKF simulations are conducted for a wet year (water year 1999), a normal year (water year 2000), and a dry year (water year 2001), respectively. 2) The normal year 2000 is used as the analysis period in order to evaluate the effect of ensemble size on EnKF estimates, parallel runs are performed using 5, 25, 50, 100, and 150 ensembles, respectively. To examine the effect of measurement errors on filter performance, parallel EnKF simulations were conducted using three different measurement variances. Similarly, to investigate the sensitivity of filter estimates to measurement frequencies, three scenarios were assigned with varying frequencies. This set of experiments also focuses on states WE and LIQW, as well as the flux RM. 3) Similar to the previous experiment, different correlation of variance (three sets) and correlation time (three sets) are specified for precipitation, parallel runs are conducted under each condition. The corresponding filter performance is assessed as well as the effects of correlation of variance and correlation time. Finally, the EnKF estimates were compared to the open-loop estimates. Initially, two metrics “Bias” and “Root-mean-squared-error (RMSE)” are being used to evaluate model performance throughout the synthetic experiments (based on the median ensemble).

In general, our initial testing shows that: 1) the open-loop approach underestimates all states; EnKF underestimates all states except for LIQW. EnKF overestimates LIQW significantly in the wet case (Table 2). The bias of ensemble mean LIQW estimate is even higher than the open-loop LIQW estimate in the wet case; 2) generally, EnKF outperforms open-loop in estimating states; 3) EnKF estimates of states in the wet case shows the highest biases and RMSE and in the dry case shows the lowest biases and RMSE; 4) both open-loop and EnKF approaches underestimate model flux (Figure 6). However, EnKF outperforms open-loop in estimating model flux in all years. Based on the above observations for the synthetic studies, the EnKF framework is applicable to extreme years in regards to providing improved state and flux estimates than the open-loop. Also, the performance of EnKF is slightly better in dryer years than which in the wetter years.

Dissemination of Results and Agency Collaboration

During this first year of the project the investigators have communicated with key NWS personnel and hydrologists, including Rob Hartmann from the CNRFC and D.J. Seo and Yuqiong Liu at the NWS Hydrologic Research Laboratory (HRL) in Silver Spring, MD. The SACSMA-SNOW17 modeling and assimilation framework is being developed in direct collaboration with HRL and RFC scientists in order to facilitate ultimate integration into the proposed RFC ensemble forecasting systems. Investigators Hogue and Franz visited the NWS HRL in February of 2008 to present ongoing related work and facilitate project collaboration with NWS researchers. In addition, the PIs have also presented various topics related to the objectives of this project at national meetings and invited seminars.

Presentations related to current project:

Improving Global Optimization of Hydrologic Models, Institute for Pure and Applied Mathematics (IPAM) Workshop on Transport Systems in Geography, Geosciences and Networks, UCLA, May 2008.

Hogue, T.S. and K. Franz, 2008: Hydrologic Tools and Products for Advancing Operational Forecast Systems, NOAA-NWS Hydrology Laboratory, March 2008.

Hogue, T.S., K. Franz and J. Barco, 2007: Performance and Probabilistic Verification of Regional Parameter Estimates for Operational Forecasting Models, AGU Fall National Meeting, December, 2007.

Peer-reviewed Journal Articles related to current project:

Franz, K.J., T.S. Hogue, and S. Sorooshian, 2008: Snow Model Verification Using Ensemble Streamflow Prediction and Operational Benchmarks, *in press*, *Journal of Hydrometeorology*

Kim, J. and T.S. Hogue, 2008: Evaluation of a MODIS-based Potential Evapotranspiration Product at the Point-scale, *Journal of Hydrometeorology,* 9, 444-460.

Franz, K.J., T.S. Hogue, and S. Sorooshian, 2008: Operational Snow Modeling: Addressing the challenges of an energy balance model for National Weather Service forecasts, *Journal of Hydrology*, 360, 48-66.

Hogue, T. S., L. A. Bastidas, H. V. Gupta, and S. Sorooshian, 2006: Evaluating model performance and parameter behavior for varying levels of land surface model complexity, *Water Resources Research*, 42, W08430, doi:10.1029/2005WR004440.

Hogue, T.S., H.V. Gupta, and S. Sorooshian, 2006: A “User-Friendly” Approach to Parameter Estimation in Hydrologic Models, Journal of Hydrology, 320, 202–217.

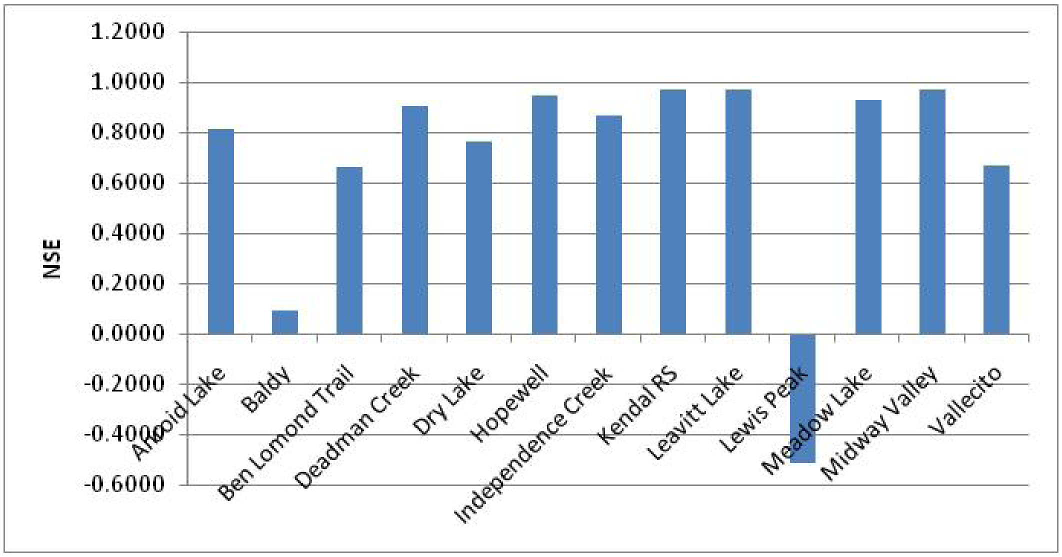

Figure 1. Nash Suttcliffe efficiency scores for SNOW17 simulated at 13 SNOTEL sites (point simulations) in the western United States. Perfect score = 1.

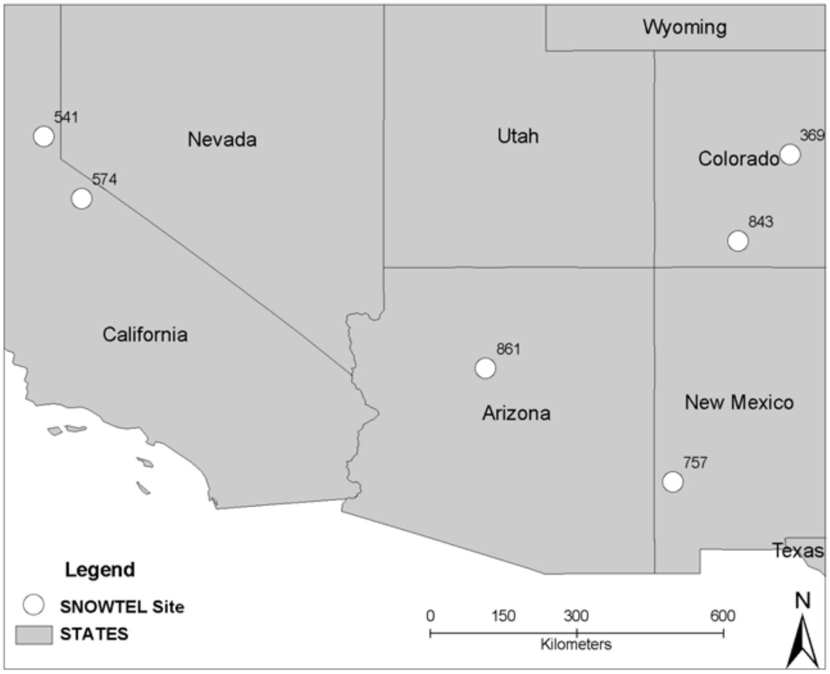

Figure 2. Spatial distribution of SNOTEL sites for sensitivity analysis.

Table 1. Summary of SNOTEL sites for sensitivity analysis

Basic information					Statistics of 10-year measurements			
Name	Number	State	Latitude	Longitude	Elevation (m)	Precipitation Mean (mm)	Temperature Mean (°C)	SWE Max. (mm)
Brumley	369	CO	39°05'	-106°32'	3231	592	0.04	351
Independence Lake	541	CA	39°25'	-120°18'	2546	1214	4.38	1720
Leavitt Lake	574	CA	38°16'	-119°36	2931	1395	2.91	2629
Silver Creek Divide	757	NM	33°22'	-108°42	2743	651	6.09	630
Vallecito	843	CO	37°29'	-107°30'	3316	812	3.24	777
White Horse Lake	861	AZ	35°08'	-112°09'	2188	536	8.71	254

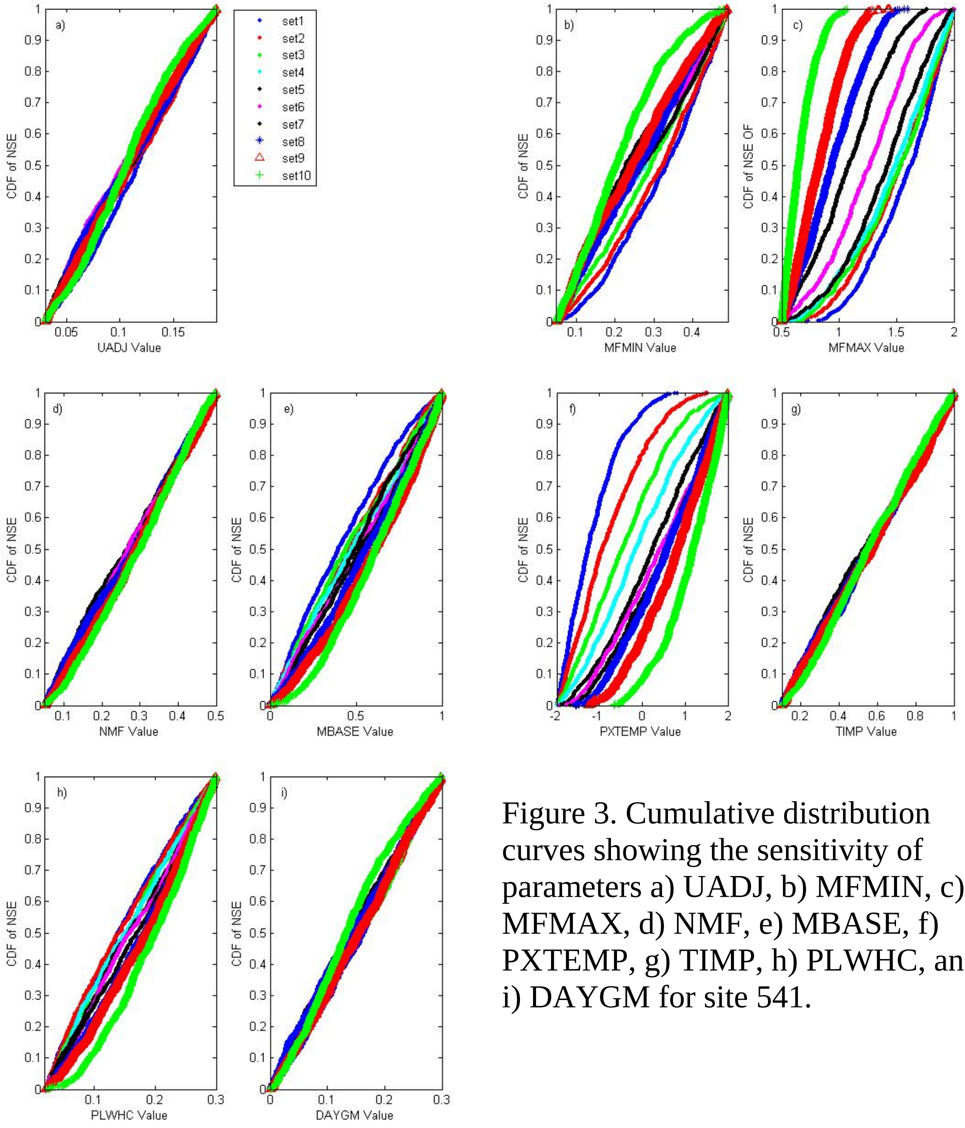

Figure 3. Cumulative distribution curves showing the sensitivity of parameters a) UADJ, b) MFMIN, c) MFMAX, d) NMF, e) MBASE, f) PXTEMP, g) TIMP, h) PLWHC, and i) DAYGM for site 541.

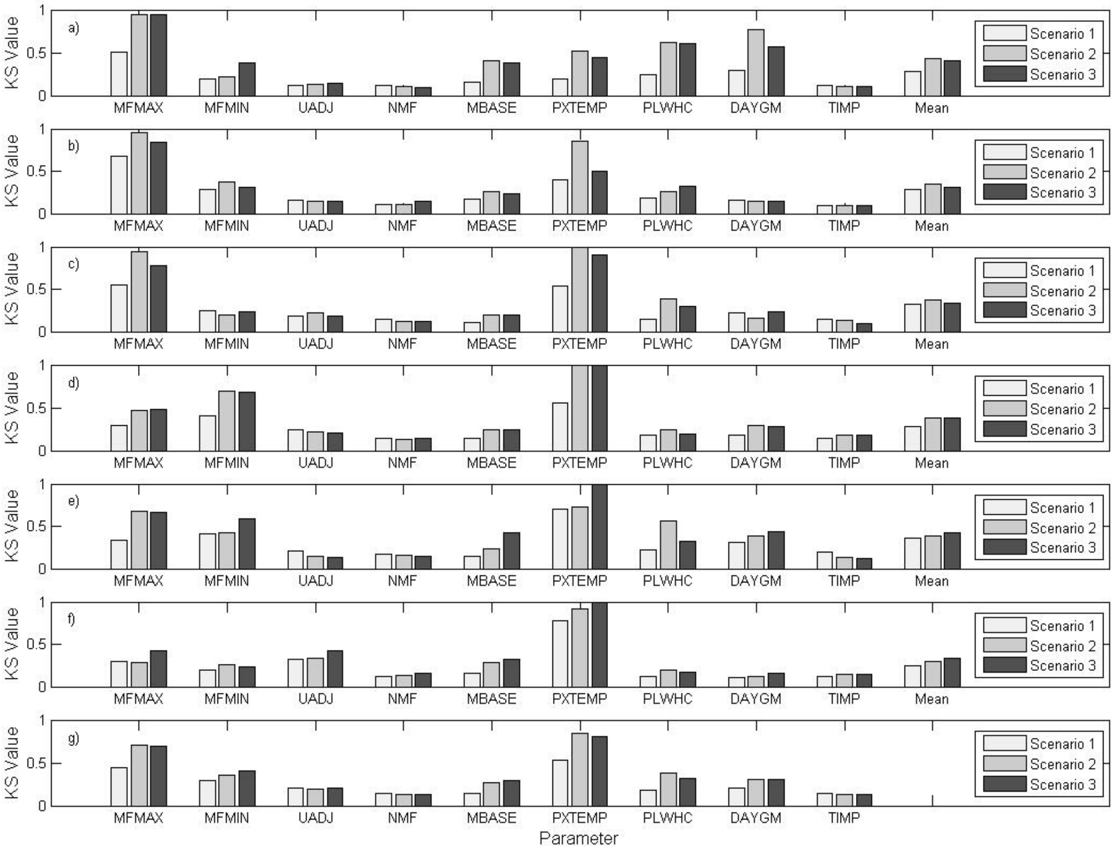

Figure 4. Plot of KS values calculated for three alternative parameter sensitivity scenarios at sites a) 369, b) 541, c) 574, d) 757, e) 843, f) 861, and g) mean KS values for all six sites. Light gray bars designate results from scenario one; medium-dark gray bars represent results from scenario two; dark gray shading bars designate results from scenario three. For each site, the mean sensitivity of all parameters is also plotted (termed "Mean" in plots a) to f)).

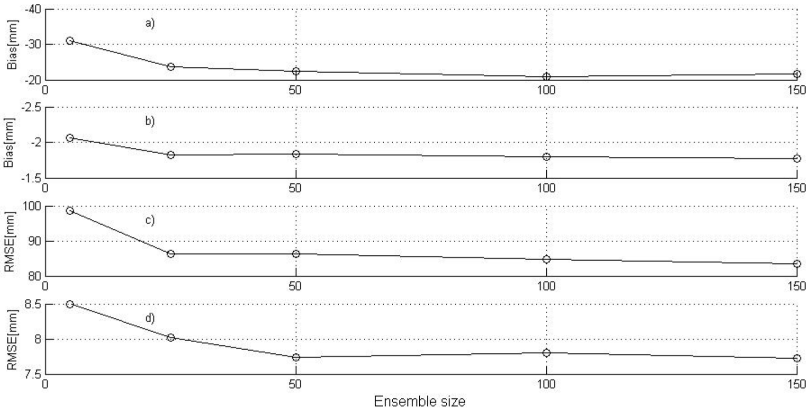

Figure 5. Bias and RMSE of WE and RM estimates from EnKF with various ensemble sizes: a) Bias of WE, b) Bias of RM, c) RMSE of WE, and d) RMSE of RM.

Table 2. The Bias and RMSE of the state and flux estimates for assimilating SWE observations and for the open loop simulation under in a wet year, a dry year, and a normal year. OL represents open-loop.

States and **Flux**	Wet case (WY1999)				Normal case (WY2000)				Dry case (WY2001)			
	Bias (mm)		RMSE (mm)		Bias (mm)		RMSE (mm)		Bias (mm)		RMSE (mm)	
	OL	EnKF	OL	EnKF	OL	EnKF	OL	EnKF	OL	EnKF	OL	EnKF
WE	-745.5	-81.9	949.8	160.0	-428.3	-21.5	612.0	85.8	-228.9	-18.8	345.6	61.2
NEGHS	-6.59	-5.52	13.5	12.0	-1.69	-1.09	4.23	2.73	-1.46	-0.81	3.77	2.34
LIQW	-52.2	67.4	163.8	105.7	-58.2	7.61	112.3	17.7	-37.9	3.23	68.2	14.3
TWE	-0.87	-0.48	3.32	1.52	-0.61	-0.28	2.66	1.50	-0.39	-0.08	1.93	0.96
STORGE	-0.65	-0.24	2.38	0.96	-0.43	-0.12	1.79	0.75	-0.26	0.00	1.15	0.44
SWE	-799.2	-15.2	1031	99.2	-487.5	-14.3	702.8	92.4	-267.4	-15.6	408.2	65.2
RM	**-3.93**	**-2.58**	**15.47**	**7.73**	**-3.07**	**-1.83**	**13.28**	**7.89**	**-1.96**	**-0.67**	**9.80**	**6.06**

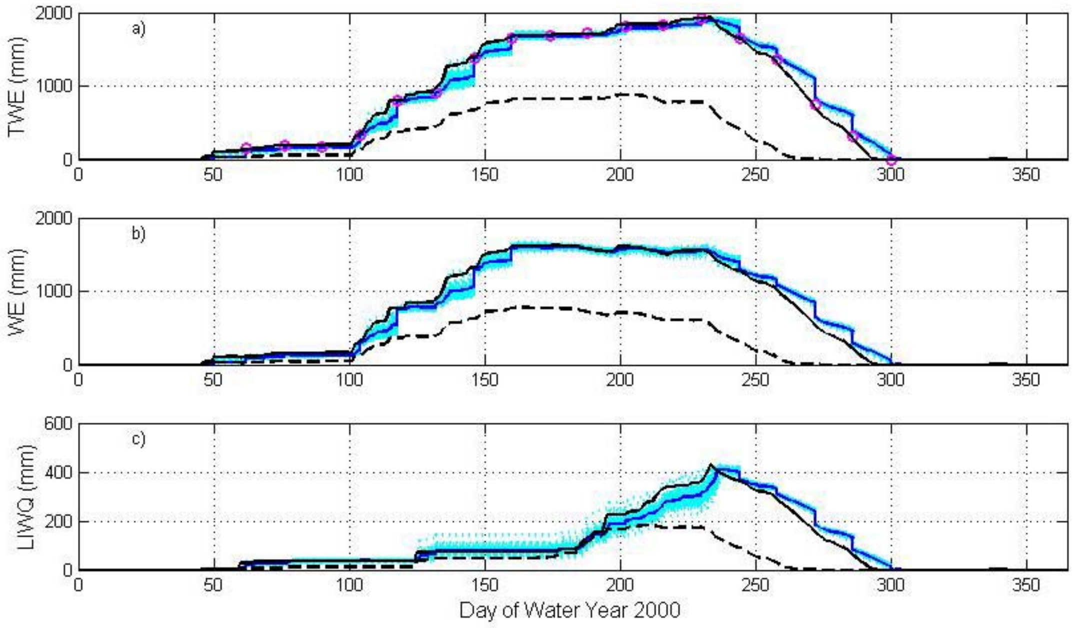

Figure 6. Snow water equivalent (WE) and liquid water content (LIQW) estimates obtained by assimilating snow water equivalent observations (SWE). The synthetic true is the dark solid line, the faint dotted lines are EnKF replicates, replicates mean is the light solid line, the open-loop simulation is the dashed line, and measurements are circles: a) SWE estimates, b) WE estimates, and c) LIQW estimates.