Title: **Multi-Scale Assimilation of AMSR-E Snow Water Equivalent and MODIS Snow Cover Fraction in Northern Colorado, *Water Resources Research*** (American Geophysical Union)

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Abstract:

Eight years (2002-2010) of remotely sensed AMSR-E snow water equivalent (SWE) retrievals and MODIS snow cover fraction (SCF) observations are assimilated separately or jointly into the Noah land surface model. A multi-scale ensemble Kalman filter (EnKF) is used, supplemented with a rule-based update. The satellite data are either left unscaled or scaled for anomaly assimilation. The SWE assimilation estimates (or their anomalies) are validated against in situ observations at 14 high-elevation SNOTEL sites and 4 lower-elevation COOP sites over a domain in Northern Colorado.

Both downscaling of coarse-scale AMSR-E SWE and assimilation of MODIS SCF data result in realistic spatial SWE patterns. However, AMSR-E retrievals are typically biased low, causing that assimilation without a priori scaling deteriorates the seasonal SWE variability for the deep and highly dynamic SNOTEL snowpacks. Furthermore, the AMSR-E retrievals lack a realistic interannual variability, which prevents anomaly SWE assimilation from improving the interannual SWE variations. Yet unscaled SWE assimilation brings the SWE estimates closer to the shallower COOP observations, because assimilation limits the snow accumulation and thus compensates for missing model processes like wind-driven snow redistribution.

SCF assimilation has only a marginal impact on the deep snowpack SNOTEL locations, because these sites experience extended periods of near-complete snow cover. At COOP sites with shallower snowpacks, SCF assimilation has more impact, and joint SWE and SCF assimilation further improves the results. Across all sites, SCF assimilation improves the timing of the onset of the snow season, but without a net improvement of SWE amounts.

Popular Summary:

Accurate estimates of snowpacks are of major importance to summer water supplies and prediction flood events. Remotely sensed snow observations from sensors like the Advanced Microwave Scanning Radiometer for the Earth Observing System (AMSR-E) provide an estimate of the water amount (snow water equivalent, SWE) in snowpacks, but with a very low accuracy and at a coarse resolution (25 km). Moderate Resolution Imaging Spectroradiometer (MODIS) provides more detailed and accurate estimates of snow cover fraction (SCF), but these measurements are often missing because of cloud cover and only provide a partial estimate of the snow state. Alternatively, land surface models simulate snow amounts and cover over land continuously and at a fine resolution.

In this paper we explore if merging of AMSR-E and MODIS observations with Noah land surface model integrations using an ensemble Kalman filter (EnKF) allows improving snow pack estimates over a region in Northern Colorado. The coarse-scale AMSR-E SWE retrievals are dynamically downscaled to the finer scale model resolution. The MODIS SCF assimilation involves a mapping from observed SCF to unobserved snowpack variables (SWE and snow depth), which is only possible under partial snow cover. Furthermore, both in the absence of snow and in times of full cover, it is not possible to assimilate SCF with an EnKF. For these situations, a rule-based update has been introduced. Because of differences in the climatology of the satellite observations and the model forecasts, both direct assimilation (using the satellite retrievals as they are) and anomaly assimilation (focusing on the departures from the seasonal mean snow pack) have been explored. These 2 approaches were tested for 3 different assimilation experiments: (1) assimilation of coarse-scale AMSR-E SWE, (2) assimilation of MODIS SCF and (3) joint AMSR-E SWE and MODIS SCF assimilation.

Snow cover assimilation can only add information in shallow snowpack periods and locations (partial cover), and mainly during accumulation, because snow cover (if observed) cannot be maintained once the model starts the snow melt. AMSR-E SWE is biased low and assimilation without scaling destroys the temporal variability for deep snowpacks. However, it is beneficial for shallow snowpacks, because it imposes the low variability and compensates for some model error. Assimilation of anomalies, however, does not help because the AMSR-E SWE retrievals appear to lack a realistic interannual variability. AMSR-E or MODIS snow observations alone come with a number of limitations and joint snow cover and snowpack data assimilation has not yet proven to overcome these limitations. However, there is still potential to improve the results pending further advances in assimilation methods, particularly improvements in the interpretation of the satellite microwave brightness temperatures over snow-covered land and the application of more sophisticated bias mitigation techniques.