Estimating North American Snow Water Equivalent by Assimilating GRACE and MODIS into CLM

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Introduction

Snow cover represents an important component in the Earth's climate system. Of all the large-scale surface features, snow cover exhibits the largest fluctuations in space and time, ranging from 7% to 40% in the Northern Hemisphere during the annual cycle. Accurate estimation of snow water equivalent at large scales is important for climate trend detection, regional hydrological prediction and land-atmosphere-ocean interaction, among others.

Although the importance of snowpack physical conditions to the hydroclimatology research is largely recognized by the scientific community, the spatial variability and dynamic evolution of large scale snow cover have yet been fully understood and described. The reasons for this deficiency are presumably three-fold: (1) observational data of snowpack have inherent limitations, including sparse and irregular distributions for in-situ snow survey data, also large uncertainty in the algorithms for snow data retrival from satellite. (2) macro-scale snow physics has not been well represented in current generation of snow models used in land surface models (LSMs) (3) the methodologies that merge observational data and model simulated results are less advanced, restricting the ability to optimally combine the complementary information within these sources. Data assimilation with ensemble approaches offered new opportunity to combine satellite datasets and model. This research (Su et al., 2008, 2009) included two topics: (1) use MODIS SCF data to constrain the snow simulation in Community Land Model (CLM); (2) use MODIS and GRACE data (multi-sensor) to further enhance the model estimation and account for the limitation of assimilating MODIS only.

Improve LSM SWE Estimation by Assimilating MODIS Global SCF Observation

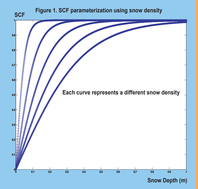
Parameterizing SCF and SWE relationship using snow density

The basic strategy in this work is to use snow cover fraction information to enhance model simulated snow water equivalent estimates based on the ensemble Kalman filter theory (EnKF). In order to accomplish this goal, a robust observation operator which parameterizes the relationship between snow cover fraction and water equivalent in the land surface model specified scale is important. Here a nonlinear observation operator is applied based on snow density.

The mathematical form of this parameterization is shown in equation (1). where SCF is the fractional snow cover; h_{sno} and z_0 are the snow depth and the ground roughness length, respectively. ρ_{new} is the fresh snow density with adjustable values from 100-150 kg/m^3 and a is an adjustable parameter depending on grid scale, which is estimated as 1.0-1.5 for local scales and 2.0-3.5 for GCM grid scales (Niu and Yang, 2007).

$$SCF = \tanh\left(\frac{h_{sno}}{2.5 z_0 (\rho_{sno}/\rho_{new})^a}\right) \quad (1)$$

Figure 1. SCF parameterization using snow density



The underlying mechanism of this operator can be interpreted from Figure 1. It plots a group of snow depletion curves (each representing a non-linear relationship between snow cover fraction and snow depth) given a land grid. Different curves stand for different accumulation or melting stages in the cold season. In particular the grid integrated snow density is used to represent this difference. This dynamical depletion curve approach is similar to the evolving total precipitation approach used in the statistical distribution method.Offline comparison demonstrated that the new snow density parameterization can produce an enhanced simulation of snow cover than the baseline method used in CLM at continental scale.

Assimilation Results

The MODIS data assimilation system run on the 1 degree by 1 degree model resolution, and from Jan, 2002 to Dec, 2004. The meteorological forcing data is from Global Land Data Assimilation System (GLDAS).

Compared to the open loop, the EnKF method more accurately simulates the seasonal variability of SWE and reduces the uncertainties in the ensemble spread in many middle latitude regions.

Different simulations are also compared with spatially distributed climatological statistics from a regridded dataset (Figure 2).

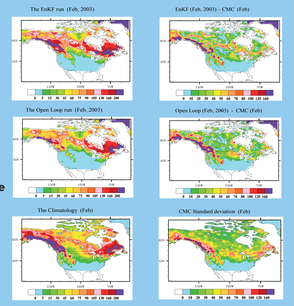


Figure 2. (Left column) Monthly averaged SWE (mm) in Feb from the EnKF and open loop simulations, and the CMC climatology. (Right column) SWE difference between the EnKF and CMC, SWE difference between Open loop and CMC, and SWE difference standard deviation for the CMC climatology.

It is found that integrating MODIS information significantly improved the quality of SWE data in many areas, especially in the Northern Great Plains, western mountainous regions, and costal regions in high latitudes. While it is also noted in some high latitude regions, e.g., boreal forest, the EnKF can degrade the SWE estimation compared with open loop.

Multi-Sensor Data Assimilation of MODIS and GRACE: the Incremental Value of GRACE Information

The second part of work continues to quantify the incremental value of multi-sensor assimilation in SWE estimation, i.e., the joint assimilation of MODIS SCF data and GRACE terrestrial water storage (TWS) anomaly data. This work is partly motivated by the limitation in MODIS only data assimilation approach, which includes (1) the SCF signal saturation (nearly 100%) in many high latitude regions in winter, especially in boreal forest and tundra regions, where the correlation between SCF and SWE is low; (2) the parameters uncertainty in the observation equation primarily due to the scaling of highly heterogeneous processes within the large model grid cell (1 degree by 1 degree); (3) the uncertain error magnitude of MODIS SCF data in the forest and mountainous regions, where the MODIS signal is complicated by vegetation and topography.

This multi-sensor data assimilation experiment is configured in the similar way as the MODIS experiment in terms of the EnKF analysis.GRACE TWS information (on 4 ° by 4 ° tiles) is optimally distributed into the archived daily state vector (on 1°×1° grids) consisting of the daily averaged SWE, snow depth, canopy snow, soil moisture, and aquifer storage with the Ensemble Kalman Smoother (EnKS). For the detail of the implementation of the EnKF and EnKS in MODIS-GRACE data assimilation, please refer to Su et al. (2009).

Figure 3 displays the difference of monthly SWE (mm) between the MODIS/GRACE data assimilation and MODIS data assimilation only in the cold season of 2003. The spatial pattern of this difference field reflects the ability of GRACE TWS information to correct the MODIS SWE estimation error in high latitude regions. Their differences have been evaluated by comparing the climatologic SWE in April of each simulation with CMC data, and the result is shown in Figure 4. The MODIS/GRACE run performs significantly better in high latitude regions than MODIS. Also it is noted that in some high latitude areas Open Loop has a comparable or even better performance than MODIS/GRACE.

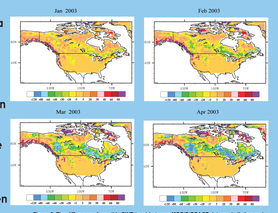
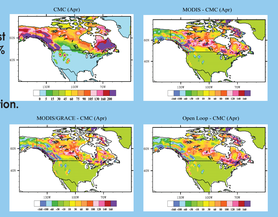


Figure 3. The difference of monthly SWE (mm) between MODIS/GRACE data assimilation and MODIS data assimilation in the cold season of 2003.

Figure 5 presents the monthly averaged correlation between SWE and soil moisture and between SWE and groundwater. In most of the domain they are not significant (at 5% level), which implies the importance of auto-correlation of SWE in controlling the magnitude of useful information in the original GRACE data regarding SWE estimation.



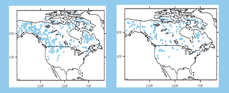


Figure 5. The grids (blue) in which the monthly average correlation in Mar, 2003 is significant at 5% level (p value < 0.05). Left (SWE and soil moisture); Right (SWE and groundwater).

Figure 4. The difference of climatologic April SWE (mm) between MODIS/GRACE MODIS, Open Loop and CMC. The CMC April SWE is given for reference.

Concluding Remarks

(1) We used a new SCF parameterization in the EnKF MODIS snow data assimilation experiment. It significantly improved the quality of SWE data in many areas, especially in the Northern Great Plains, western mountainous regions, and coastal regions in high latitudes.
(2) The MODIS only data assimilation experiment can degrade the SWE simulation in boreal forest.
(3) The multi-sensor experiment, which combines both MODIS and GRACE information in CLM, provides significant improvements over MODIS only approach, for example, in Saint Lawrence, Fraser, Mackenzie, Churchill & Nelson, and Yukon river basins, and the south-west rim of Hudson Bay; also it performs similarly with the MODIS run in middle-latitude where both are better than the Open loop. In some high latitude areas the Open loop run has a comparable or better performance than the MODIS/GRACE run.

Acknowledgments

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References

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