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# Multi-sensor land data assimilation: Toward a robust global soil moisture and snow estimation

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ABSTRACT

Global monitoring of soil moisture and snow is now available through various satellite observations from optical, microwave, and gravitational sensors. However, very few modeling frameworks exist that conjointly use the above sensors to produce mutually and physically consistent earth system records. To this goal, a prototype of multi-sensor land data assimilation system is developed by linking the Community Land Model version 4 (CLM4) and a series of forward models with the Data Assimilation Research Testbed (DART). The deterministic Ensemble Adjustment Kalman Filter (EAKF) within the DART is utilized to estimate global soil moisture and snow by assimilating brightness temperature, snow cover fraction, and daily total water storage observations from the Advanced Microwave Scanning Radiometer for Earth Observing System (AMSR-E), Moderate Resolution Imaging Spectroradiometer (MODIS), and Gravity Recovery and Climate Experiment (GRACE), respectively. A 40-member of Community Atmosphere Model version 4 (CAM4) reanalysis is adopted to introduce ensemble spread in CLM4 land states and some methods are used to reduce the computational load. Data assimilation with different combinations of sensors is implemented for 2003–2009 to investigate individual contributions from different satellite observations. Evaluation results and cross-comparison of open-loop and data assimilation cases suggest that 1) assimilation of MODIS snow cover fraction slightly improves snow estimation in mid and high latitudes; 2) lower and higher frequencies of AMSR-E brightness temperature play complementary roles in improving global soil moisture and snow estimation; 3) assimilation of GRACE tends to degrade soil moisture estimation but poses potential in improving snow depth estimation in most high-latitude regions. Generally, the combination of MODIS, GRACE, and AMSR-E observations with regard to spatial locations holds promise to provide a robust global soil moisture and snow estimation through the multi-sensor land data assimilation system.

## 1. Introduction

Soil moisture and snow have long been recognized as essential components in the land-atmosphere interactions, and play critical roles as initial conditions in weather forecast and seasonal predictions (Barnett et al., 1989; Dirmeyer et al., 2006; Drusch, 2007; Dutra et al., 2012; Lin et al., 2016). However, high quality global soil moisture and snow datasets are lacking, and limitations exist in conventional acquisition approaches like ground measurement, remote sensing (Che et al., 2016; Dai et al., 2012), and land surface simulation (Entin et al., 1999; Loew et al., 2013; Romano, 2014; Snauffer et al., 2016). Nevertheless, land data assimilation (DA) that constrains model simulations using satellite observations is expected to produce the most reliable estimates of soil moisture and snow with a wide range of spatiotemporal coverage and resolution. Indeed, the past decade has seen many such efforts (Che et al., 2014; Forman et al., 2012; Han et al., 2016; Qin et al., 2009; Reichle et al., 2002; Su et al., 2008).

Microwave remote sensing is commonly used in large scale soil moisture monitoring due to its advantage in penetration depth and small sensitivity to atmosphere vapor. Some widely used global soil moisture retrievals are from AMSR-E (Advanced Microwave Scanning Radiometer for Earth Observing System) (Koike et al., 2004; Njoku et al., 2003; Owe et al., 2008), ASCAT (METOP-A Advanced Scatterometer) (Bartalis et al., 2007), SMOS (Soil Moisture and Ocean salinity) (Kerr et al., 2016), and SMAP (Soil Moisture Active and Passive) (Entekhabi et al., 2014). In terms of snow, while passive and active microwave are also used to estimate snow mass (Chang et al., 1982; Che et al., 2012, 2016; Dai et al., 2012), visible and near-infrared signals are

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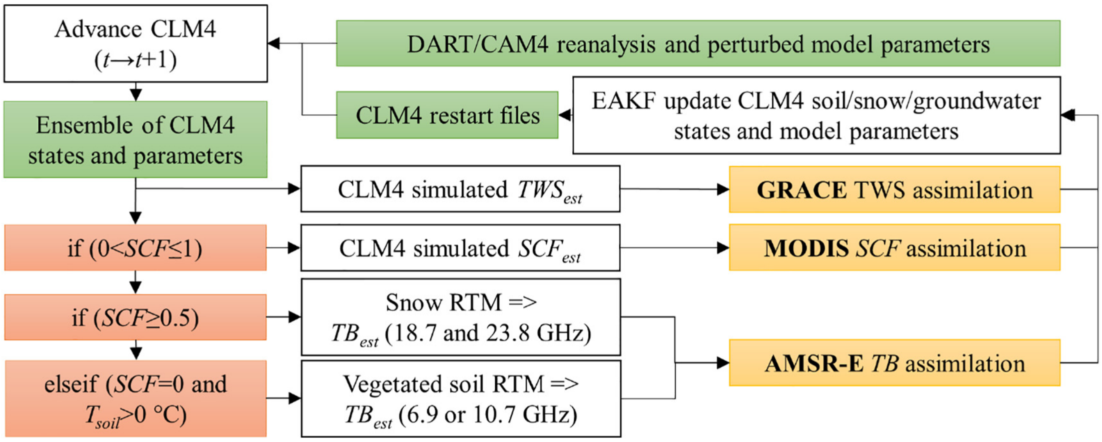

**Fig. 1.** Flowchart of the CLM4-DART multi-sensor land data assimilation system.

often used to detect snow extent over most of land surfaces (Hall et al., 2002). However, uncertainties and biases are commonly observed in satellite retrieved soil moisture (Al-Yaari et al., 2014; Jackson et al., 2010), snow cover fraction (SCF) or snow water equivalent under certain circumstances (Foster et al., 2005; Hall and Riggs, 2007). Therefore, some studies attempt to directly assimilate microwave brightness temperature (TB) observations using a radiative transfer model for soil moisture estimation, and key model parameters are either simultaneously updated with land states (Han et al., 2016; Moradkhani et al., 2005; Qin et al., 2009) or pre-calibrated prior to data assimilation (De Lannoy and Reichle, 2016; De Lannoy et al., 2013; Yang et al., 2007; Zhao et al., 2016). There are also a series of data assimilation explorations trying to improve snow estimation by assimilating either MODIS SCF (De Lannoy et al., 2012; Su et al., 2008) or AMSR-E TB (Bateni et al., 2015; Che et al., 2014; Kwon et al., 2016). In addition to satellite products from optical and microwave sensors, the Gravity Recovery and Climate Experiment (GRACE) satellites provide observations on the total water storage (TWS) changes over lands, which includes canopy water, snow, soil moisture, surface water, and groundwater (Rodell and Famiglietti, 2001). The relative low spatial resolution and difficulty in discriminating different water components remain a major challenge in hydrological applications, and one way to make use of GRACE is through land data assimilation. In fact, the past years have seen many studies that assimilate GRACE TWS observations aiming to further improve soil moisture (Li et al., 2012) and snow (Forman et al., 2012; Houborg et al., 2012; Su et al., 2010) estimates. However, the GRACE assimilation tends to have a mixed performance with regard to spatial locations (Kumar et al., 2016).

Land surface models, e.g., the Community Land Model version 4 (CLM4; Oleson et al. (2010)), play a complementary role in providing spatiotemporally continuous estimates of land states. However, the pure model simulations are known to be biased (Cai et al., 2014; Du et al., 2014; Long et al., 2013; Toure et al., 2016), and the past years have seen many efforts in improving CLM soil moisture and snow estimation through land DA using the aforementioned AMSR-E and MODIS observations. Zhang et al. (2014) first linked CLM4 and the Data Assimilation Research Testbed (DART) to assimilate MODIS SCF and found the snow estimate is much improved along the snowline near lower–middle-latitudes while marginal over higher-latitudes where snow cover approaches 100%. Based on the same framework, Kwon et al. (2016) assimilated AMSR-E brightness temperature into CLM for snow depth estimation and found improvements are expected when model states and parameters are simultaneously updated following a so-called rule-based scheme, in which prior estimates are updated depending on their correlation with predicted TB within the ensemble. In terms of soil moisture, Zhao et al. (2016) assimilated AMSR-E brightness temperature through a radiative transfer model by using pre-calibrated model parameters and improvements are seen in multi-layer soil moisture over most of the selected sub-regions over the globe.

While a single satellite sensor is unable to guarantee consistent improvements in certain land state estimates through DA, the above studies do point to a potential of combining optical, microwave, and gravitational sensors in a land DA system to improve soil moisture and snow estimates under various conditions. There are recently some studies to assimilate multiple satellite observations at local scales (Huang et al., 2016), while few of them have extended this research to regional and global scales. To this goal, we have developed a prototype multi-sensor global land DA system based on the CLM4-DART framework. Specifically, this study intends to explore the joint assimilation of satellite observations from AMSR-E TB, MODIS SCF, and GRACE TWS, and aims to achieve a robust global soil moisture and snow estimation.

This paper is organized as follows. The CLM4-DART multi-sensor land DA system and the integration of satellite sensors are detailed in Section 2. Section 3 presents data assimilation experiments using different sensor-combinations, followed by global evaluation of surface/root zone soil moisture and snow depth. Section 4 discusses individual sensor's contributions, and finally, a summary is provided in Section 5.

## 2. Methodology and data

### 2.1. The CLM4-DART-based multi-sensor land data assimilation system

A prototype of multi-sensor land data assimilation system is developed by using CLM4-DART and complementary satellite observations. A general schematic flow of this DA framework is shown in Fig. 1. Model predictions and DART assimilations are implemented grid by grid in a parallel manner. For a certain grid-cell, following steps are taken in a typical assimilation cycle.

1) Given an ensemble of initial conditions and atmospheric forcing, CLM4 first simulates an ensemble of land states (including multi-layer snow thickness, snow temperature, soil temperature, soil moisture, and groundwater) and their characteristics (e.g. snow density, grain radius, and wetness), which are preserved in restart files at a daily basis. Soil and snow layering information is detailed in Section 2.2.
2) All the relevant variables, as shown in the second column of Table 1, will be transferred into the DART sequence.
3) Whenever a satellite observation is available, the related variables will then be fed into the corresponding forward model to produce an observational estimate.
4) The deterministic Ensemble Adjustment Kalman Filter (EAKF) (Anderson, 2001) in DART will then perform data assimilation and the calculated increments will be applied to both observed and