



Retrieving snow mass from GRACE terrestrial water storage change with a land surface model

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Received 18 April 2007; revised 6 June 2007; accepted 10 July 2007; published 4 August 2007.

[1] A reliable snow water equivalent (SWE) product is critical for climate and hydrology studies in Arctic regions. Passive microwave sensors aboard satellites provide a capability of observing global SWE and have produced many SWE datasets. However, these datasets have significant errors in boreal forest regions and where snowpack is deep or wet. The Gravity Recovery and Climate Experiment (GRACE) satellites are measuring changes in terrestrial water storage (TWS), of which snow mass is the primary component in winter Arctic river basins. This paper shows SWE can be derived from GRACE TWS change in regions where the ground is not covered by snow in a summer month if accurate changes in below-ground water storage (including soil water and groundwater) can be provided by a land surface model. Based on gravity change, the GRACE-derived SWE estimates are not affected by the boreal forest canopy and are more accurate in deep snow regions than microwave retrievals. The paper also discusses the uncertainties in the SWE retrievals. **Citation:** Niu, G.-Y., K.-W. Seo, Z.-L. Yang, C. Wilson, H. Su, J. Chen, and M. Rodell (2007), Retrieving snow mass from GRACE terrestrial water storage change with a land surface model, *Geophys. Res. Lett.*, *34*, L15704, doi:10.1029/2007GL030413.

1. Introduction

[2] Arctic warming has profound impacts on snow cover and, in turn, permafrost, river discharge, and organic carbon release. Snow cover extent in the northern hemisphere as monitored by the Advanced Very High Resolution Radiometer (AVHRR) is decreasing since middle 1980s in response to global warming trend [Robinson and Frei, 2000; Brown, 2000]. On the other hand, Arctic warming may be accelerated by decreases in snow cover due to the positive snow-albedo feedback. Chapin *et al.* [2005] recently reported that Arctic summer warming mainly results from an increase in snow-free days and the transition from tundra to forest.

[3] Snow cover controls Arctic climate and hydrology. Snow cover exhibits seasonal fluctuations ranging from 7% to 40% in the Northern Hemisphere [Hall, 1988]. Associated with these fluctuations are variations in surface albedo

and surface energy budgets, sensible heat and water vapor fluxes into the atmosphere through sublimation and evaporation. Snow mass accumulated in winter is critical for estimating springtime snowmelt and river flow, the freshwater input to the Arctic Ocean [Yang *et al.*, 2003]. Runoff from Arctic river systems constitutes about 50% of the net flux of freshwater into the Arctic Ocean [Barry and Serreze, 2000] and thus can affect ocean salinity, sea ice conditions, and hence the global thermohaline circulation. In addition, melting of snow mass cools the atmosphere in spring.

[4] Ground-observed snow water equivalent (SWE) datasets are useful for validating snowmelt models, hydrological models, and satellite-derived SWE products. However, SWE datasets are rare, confined to limited regions, and representative of small spatial scales. Passive microwave sensors aboard satellites, such as the Scanning Multi-channel Microwave Radiometer (SMMR) and the Advanced Microwave Scanning Radiometer (AMSR) provide a capability of observing global SWE and have produced many SWE datasets. However, these datasets have significant errors in boreal forest regions and where snowpack is deep or wet [Foster *et al.*, 2005]. The Gravity Recovery and Climate Experiment (GRACE) twin satellites measure changes in terrestrial water storage (TWS). Because snow mass is the primary component of TWS in winter Arctic river basins, SWE can be derived from GRACE TWS change by separating snow mass from other water storages. While Frappart *et al.* [2006] employed an iterative inverse approach to separating contributions of snow mass to total gravity field using hydrologic models' outputs as the "first guess", we pursue an alternative approach in this paper. We derive SWE from GRACE TWS change with the aid of the modeled below-ground water storage from an advanced land surface model (LSM). Because GRACE TWS change estimates are based on gravity change and thus are not affected by the boreal forest canopy, a GRACE-based SWE estimate may be more accurate in boreal forest regions than microwave retrievals.

[5] Various model intercomparison projects [e.g., Entin *et al.*, 1999; Guo and Dirmeyer, 2006] have indicated that LSMs are much better at simulating a "soil moisture" anomaly (i.e., deviation from the mean) than simulating the absolute value of soil moisture. However, changes in ΔS_{bg} can be affected by snowmelt, permeability of frozen soil, runoff parameterization, and vegetation dynamics in Arctic regions. Thus, a more physically-based LSM is critical for estimating ΔS_{bg} . In this paper, we show how SWE can be derived from GRACE TWS estimates with the

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aid of an advanced LSM and the uncertainties due to GRACE TWS estimates and the modeled ΔS_{bg} .

2. Method

2.1. Derivation of SWE From the GRACE TWS Change

[6] Given a river basin in Arctic regions, the GRACE-measured TWS change ΔS , has two major components:

$$\Delta S = \Delta SWE + \Delta S_{bg} \quad (1)$$

where ΔSWE and ΔS_{bg} are, respectively, changes in SWE and water storage below the ground, which can be provided by an LSM. Then,

$$\Delta SWE = \Delta S - \Delta S_{bg} \quad (2)$$

The actual SWE on the ground in a winter month can be determined as snow mass changes from its previous summer month when there is no snow on the ground. This no-snow condition can be easily satisfied in August for most of the areas in Arctic river basins. The accuracy of GRACE-derived SWE depends on the accuracy of the GRACE-derived ΔS and the modeled ΔS_{bg} .

2.2. Data

[7] We used $1^\circ \times 1^\circ$, 3-hourly, near-surface meteorological data processed by the Global Land Data Assimilation System (GLDAS) [Rodell *et al.*, 2004] to drive the model during the period 2002–2004. These included a spatially and temporally downscaled version of NOAA Climate Predictions Center's Merged Analysis of Precipitation (CMAP) [Xie and Arkin, 1997] and satellite based shortwave and longwave radiation. Other forcing fields were air temperature, air pressure, specific humidity, and wind speed. The vegetation and soil parameters at $1^\circ \times 1^\circ$ were interpolated from the high-resolution raw data of the standard CLM 2.0.

[8] The Earth's gravity field detected by the GRACE satellites can be used to infer TWS change [e.g., Wahr *et al.*, 2004; Tapley *et al.*, 2004; Chen *et al.*, 2006; Seo *et al.*, 2006; Swenson *et al.*, 2006] at a precision of approximately 15 mm (global mean) at about 1000 km spatial scale [Wahr *et al.*, 2004]. We used two GRACE TWS datasets that were derived from two different gravity field releases by the Center for Space Research (CSR, University of Texas at Austin), i.e., RL01 (covers up to degree and order 120) and RL04 (covers up to degree and order 60), through a dynamic filtering algorithm [Seo *et al.*, 2006].

2.3. NCAR Community Land Surface Model (CLM)

[9] We used the National Center for Atmospheric Research (NCAR) Community Land Model (CLM), version 2.0 [Oleson *et al.*, 2004] in this study. CLM has important features for accurately estimating ΔS_{bg} . These are: (1) a 10-layer soil model that solves Richards equation to compute soil moisture to a depth of 3.43 m; (2) a multi-layer snow submodel, which accounts for various internal processes, such as liquid water retention within the snowpack, diurnal cycles of thawing-freezing, and densification, and external processes, such as surface frost and sublimation; and (3) an explicit solution of freezing-thawing of soil water depending on soil-layer's energy budgets. In this study, we used an

4. Summary

[16] This paper proposes a methodology to retrieve snow mass from GRACE TWS changes for large river basins in Arctic regions. With the aid of an LSM, we derive SWE by subtracting below-ground water storage change from GRACE water storage changes. Although this GRACE-based SWE product has coarser spatiotemporal resolutions than AMSR-E SWE, it shows more reasonable spatial pattern than the AMSR-E SWE product especially in deep-snow regions (where SWE is greater than 50 mm). Uncertainties in the derived SWE due to model estimates of ΔS_{bg} are smaller than those due to GRACE ΔS estimates. This indicates that the accuracy of SWE estimates is more dependent on GRACE ΔS estimates. Nevertheless, uncertainties in SWE estimates (indicated by standard deviations) due to modeled ΔS_{bg} (4.45 mm) and GRACE-derived ΔS (6.10 mm) are relatively small compared to

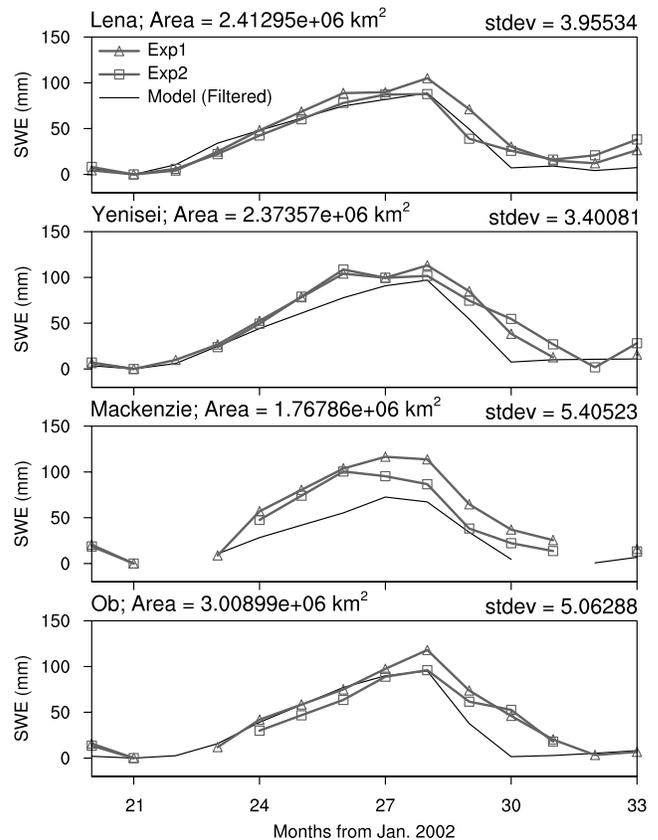


Figure 4. Uncertainties in the GRACE-derived SWE (RL04) due to different values of the decay parameter, f , of the groundwater discharge ($f=1.0$ in Exp1 and $f=2.5$ in Exp2). Also shown on the top-right corner of each panel are the standard deviations of SWE estimates from Exp1 and Exp2.

basin-averaged SWE in deep winter and early spring (above 100 mm). This indicates the proposed approach is promising for estimating SWE in large Arctic rivers in deep-snow seasons.