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

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[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:

$$\Delta S = \Delta SWE + \Delta S_{bg} \tag{1}$$

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

$$\Delta SWE = \Delta S - \Delta S_{bg} \tag{2}$$

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° × 1°, 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° × 1° 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 augmented version of the CLM 2.0, which includes the representations of the effects of frozen soil on snowmelt runoff and water storage [*Niu and Yang*, 2006] and groundwater dynamics, which describes variations in water storages within aquifers [*Niu et al.*, 2007]. The model with an observation-based scheme of snow cover fraction was demonstrated to have a capability of reproducing satellite-observed snow cover fraction and ground-based observations of SWE and snow depth in various North American river basins [*Niu and Yang*, 2007]. Model outputs of SWE and below-ground water storage are also filtered using the same filtering algorithm of *Seo et al.* [2006].

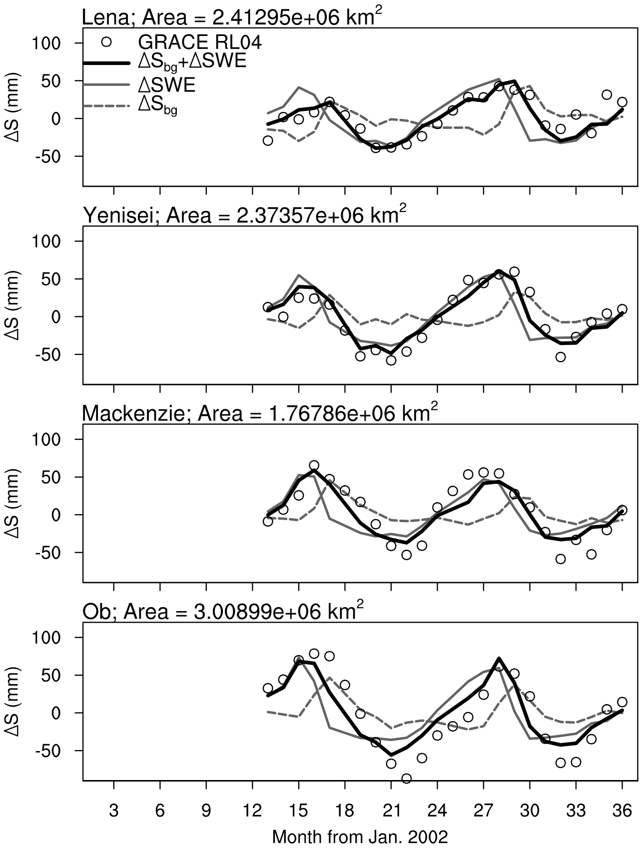

Figure 1. The anomalies (deviation from the mean) of various water storages (SWE and below-ground water storage) in four largest Arctic river basins in comparison with GRACE estimates from CSR RL04.

3. Results

3.1. Feasibility of the Method

[10] Seasonal variations of total water storage are greatly influenced by SWE in all the four largest Arctic river basins (Figure 1), showing positive anomalies in winter and negative anomalies in summer. Seasonal variations of below-ground water storage are opposite to those of SWE and the total water storage, showing negative anomalies in winter due to groundwater drainage and positive anomalies in spring due to infiltration of snowmelt water. Snow mass contributes 197% (averaged over two March months in the four river basins) to total water storage in March, while below-ground water storage contributes about −97%. The

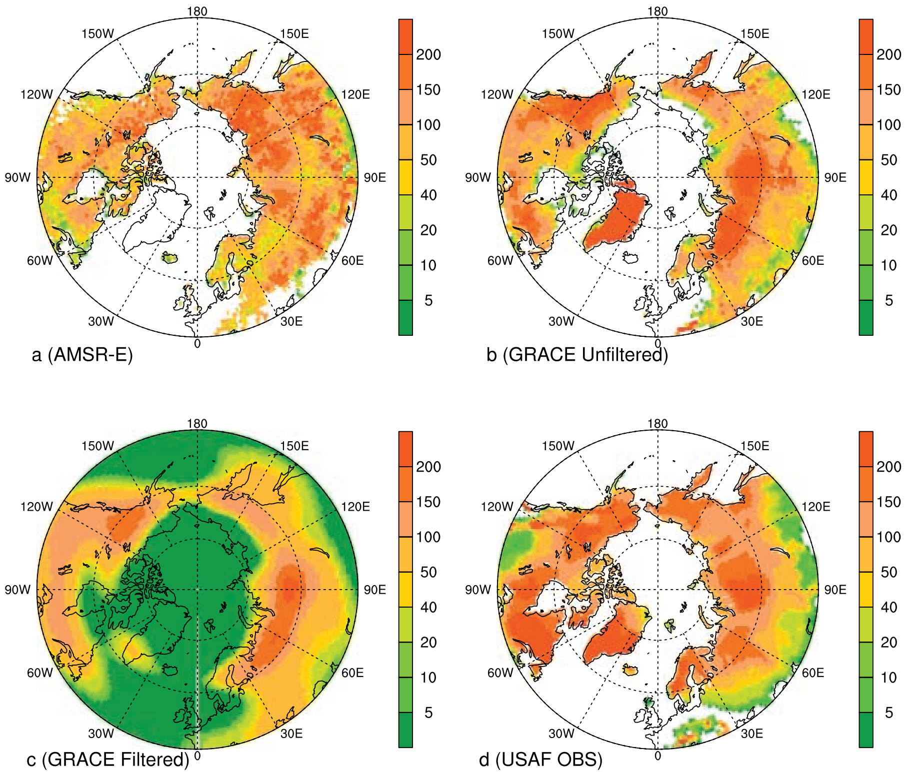
a (AMSR-E)
b (GRACE Unfiltered)
c (GRACE Filtered)
d (USAF OBS)

Figure 2. Snow water equivalent (in mm) in March of 2004. (a) AMSR-E, (b) GRACE RL04 TWS minus unfiltered model outputs of below-ground water storage change, (c) GRACE RL04 TWS minus filtered model outputs of below-ground water storage change, (d) USAF/ETAC ground-based climatology, which is converted from snow depth multiplying snow density (300 kg m^{-3}).

modeled water storage change agrees fairly well with GRACE estimates from RL04. Note that, to match GRACE estimates, we calibrated two model parameters that greatly affect snow cover and runoff. These results provide a basis for retrieving snow mass from GRACE estimates.

[11] To demonstrate feasibility of retrieving SWE from GRACE, we show the derived SWE in March of 2004 from RL04 using equations (1) and (2). The spatial pattern of GRACE-based SWE (Figures 2b and 2c) agrees better with that of ground-based U. S. Air Force (USAF) Environmental Technical Application Center (ETAC) SWE climatology (Figure 2d) than AMSR-E estimates (Figure 2a), especially in deep-snow regions (e.g., central Siberia and northern North America). However, in tundra regions surrounding the Arctic Ocean, GRACE estimates appear to be too small, most likely because of the leakage error induced by relatively smaller signals over ocean. In mid-latitudes (near the southern edge of the snow-covered regions), GRACE estimates appear to be lower than AMSR-E. However, ASMR-E may overestimate SWE in these regions, where snowpack is melting. An evaluation [*Dong et al.*, 2005] of SMMR SWE data corrected for vegetation and wet-snow effects [*Foster et al.*, 2005] indicates that corrected SMMR data overestimate SWE when the observed SWE is less than 50 mm. Note that, in this study, we used the USAF/ETAC SWE climatology that was converted from USAF/ETAC snow depth by multiplying snow density (300 kg m^{-3}) for only evaluating the spatial pattern of various SWE estimates, while we were aware that more accurate ground-based SWE climatology was available, but only for North America and a different time period (1979–1996) [*Brown et al.*, 2003].

3.2. Uncertainties Due to GRACE ΔS Estimates

[12] The accuracy of GRACE ΔS and related estimates has been assessed in part by *Seo et al.* [2006]. In Arctic regions, they estimated noise levels as rms signal error in monthly estimates. They consider three error sources, the GRACE measurement system, model errors in the GRACE processing system used to remove atmospheric and ocean signals, and spatial leakage error associated with a limited range of spherical harmonics. Errors were estimated to be below 5 mm for GRACE measurement, 10 to 50 mm for atmosphere and ocean model (AOD) errors, and about 10 mm for leakage errors. The final estimate obtained by *Seo et al.* [2006] indicated a two to one or better signal to noise ratio estimate for GRACE water storage estimates in Arctic regions.

[13] Considering temporal overlaps among GRACE RL01 (2002 Aug.–present), RL04 (2003 Jan.–present), and model outputs (2002 Jan.–2004 Dec), we derived GRACE ΔS for the time period of 2003 Jan–2004 Dec. Deriving SWE in a winter month needs GRACE ΔS in one of its previous summer month when there is no snow. For such a reason, we can derive only one entire snow season of 2003–2004. Together with model SWE outputs (filtered and unfiltered), the GRACE-derived SWE estimates for four largest Arctic river basins are shown in Figure 3. The basin-averaged GRACE-derived SWE is around filtered model outputs of SWE and lower than unfiltered model

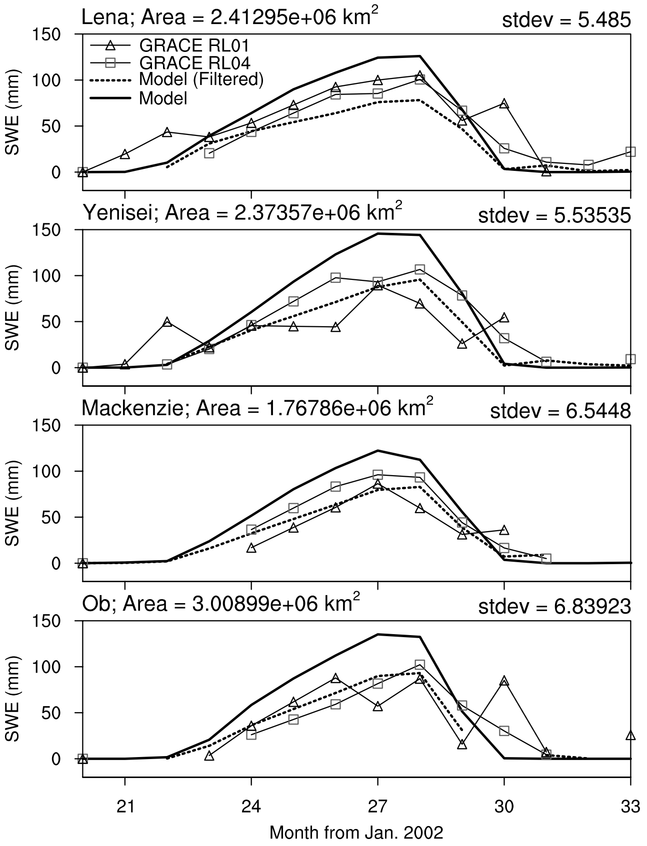

Figure 3. Basin-averaged SWE for the four largest Arctic river basins. GRACE RL01, SWE derived from CSR RL01; GRACE RL04, SWE derived from CSR RL04; Model (Filtered), modeled SWE filtered using the same filter; Model, modeled SWE without filtering. Also shown on the top-right corner of each panel are the standard deviations of SWE estimates from RL01 and RL04.

outputs of SWE. RL04 improves ΔS estimation over RL01 by updating models of ocean tide and ocean pole tide (leakage to land), AOD, and solid earth tide and by improving data processing (editing and weighting schemes). The difference between RL01 and R04 reflects uncertainties in GRACE ΔS estimates. The standard deviation (stdev) of RL01 and RL04 estimates varies from 5.49 mm in Lena to 6.84 mm in Ob river basins.

3.3. Uncertainty Due to Model

[14] The uncertainty of ΔS_{bg} depends on the realism of hydrologic processes represented by CLM and the accuracy of model inputs including snowfall. The below-ground water storage in winter and spring is greatly affected by infiltration of snowmelt water and groundwater discharge. Uncertainty induced by different values of the runoff decay factor, f, which determines wintertime groundwater discharge and thus below-ground water storage, represents one of the largest uncertainties in producing the below ground water storage by the augmented version of CLM.

[15] We conducted two experiments using different values of f to reflect uncertainties induced by model. In Experiments 1 (Exp1), f = 1.0 m^{-1} and f = 2.5 m^{-1} in Experiment 2 (Exp2). Because a smaller f value can produce greater groundwater discharge in winter given the same groundwater storage, Exp1 produces less below-ground water storage, resulting in more SWE (Figure 4). However, the uncertainty induced by different values of f (standard deviation averaged for the four river basins, stdev = 4.45 mm) is relatively less than that induced by different GRACE releases (stdev = 6.10 mm).

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

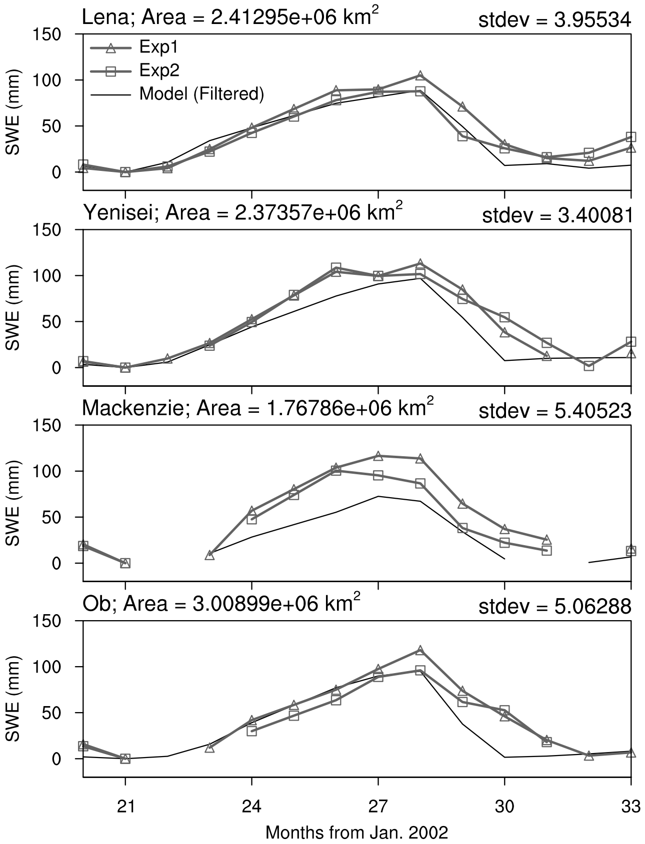

Figure 4. Uncertainties in the GRACE-derived SWE (RL04) due to different values of the decay parameter, f, of the groundwater discharge (f = 1.0 in Exp1 and f = 2.5 in Exp2). Also shown on the top-right corner of each panel are the standard deviations of SWE estimates from Exp1 and Exp2.

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.

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