Evolution of high-latitude snow mass derived from the GRACE gravimetry mission (2002–2004)

Frédéric Frappart, Guillaume Ramillien, Sylvain Biancamaria, Nelly M. Mognard, and Anny Cazenave

Laboratoire d'Etudes en Géophysique et Océanographie Spatiales, UMR 5566, CNES/CNRS/IRD/UPS, Toulouse, France

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[1] Since March 2002, the GRACE mission provides monthly global maps of geoid time-variations. These new data carry information on the continental water storage, including snow mass variations, with a ground resolution of ~600–700 km. We have computed monthly snow mass solutions from the inversion of the 22 GRACE geoids (04/2002–05/2004). The inverse approach developed here allows to separate the soil waters from snow signal. These snow mass solutions are further compared to predictions from three global land surface models and snow depths derived from satellite microwave data. We find that the GRACE solutions correlate well with the high-latitude zones of strong accumulation of snow. Regional means computed for four large boreal basins (Yenisey, Ob, Mac Kenzie and Yukon) show a good agreement at seasonal scale between the snow mass solutions and model predictions (global rms ~30–40 mm of equivalent-water height and ~10–20 mm regionally). **Citation:** Frappart, F., G. Ramillien, S. Biancamaria, N. M. Mognard, and A. Cazenave (2006), Evolution of high-latitude snow mass derived from the GRACE gravimetry mission (2002–2004), *Geophys. Res. Lett.*, *33*, L02501, doi:10.1029/2005GL024778.

1. Introduction

[2] The snow pack is an important component of the climate system. Over the boreal regions, the unprecedented global warming of the 1980s has been accompanied by a retreat of the mean annual snow cover that is particularly important in Eurasia [*Brown*, 2000; *Mognard et al.*, 2003]. Unfortunately, climate-related processes of the boreal and arctic regions are poorly observed, partly because of the enormous size and remoteness of the regions, the adverse environmental conditions and the sparse surface weather station network.

[3] In March 2002, a new generation of gravity missions was launched: the Gravity Recovery and Climate Experiment (GRACE) space mission [*Tapley et al.*, 2004a, 2004b]. The main application of GRACE is to quantify the terrestrial hydrological cycle through measurements of geoid (i.e., gravity field) variations, which represent over land the vertically-integrated water mass changes inside aquifers, soil, surface reservoirs and snow pack, with a precision of a few mm in terms of water height and a spatial resolution of ~500–700 km [*Wahr and Molenaar*, 1998; *Rodell and Famiglietti*, 1999; *Swenson et al.*, 2003].

[4] An iterative inverse approach for unraveling the contributions of the different continental water storage to the time-varying gravity field measured has been recently developed by *Ramillien et al.* [2004], and applied to the observed monthly GRACE geoids [*Ramillien et al.*, 2005], recently released by CSR and GFZ [*Tapley et al.*, 2004a]. This inverse method approach, described in details by *Ramillien et al.* [2004, 2005] produces separate series of monthly liquid water and snow solutions at maximum degrees of 25–30 (spatial resolution of ~660 km) for the period April 2002 to May 2004.

[5] Because of the scale of snow pack variability, *in-situ* snow measurements cannot be used to assess the snow mass anomalies derived from GRACE geoids while the resolution of global land surface models and satellite-derived snow depth estimates is adapted to the coarse resolution of GRACE. This paper presents the two-year time-series of 22 monthly snow mass solutions. For validation, we compared these GRACE-derived snow mass anomalies with the anomalies from outputs of three different global land surface models and satellite microwave data. Maps of rms differences between GRACE and models or microwave data are computed as well as regionally integrated time-series of snow volume for four large boreal basins (Ob, Yenisey, McKenzie, Yukon).

2. Available Snow Mass Data Sets

[6] For comparison with GRACE, two data sources are used: satellite microwave observations from the Special Sensor Microwave/Imager (SSM/I) and outputs from global land surface models. Several land surface models provide global snow mass expressed in mm of water equivalent thickness (in the followings, we use the abbreviation wet). Here, we use: the Water GAP Global Hydrology Model (WGHM) [*Döll et al.*, 2003], the Land Dynamics model (LaD) [*Milly and Shmakin*, 2002] and the Global Land Data Assimilation System (GLDAS) [*Rodell et al.*, 2004].

2.1. WGHM Model

[7] The WGHM model computes 0.5° × 0.5° gridded time series of monthly runoff and river discharge and is tuned against time series of annual river discharges measured at 724 globally distributed stations. It also provides monthly grids of snow and soil water. The effect of snow is simulated by a simple degree-day algorithm. Below 0°C, precipitations fall as snow and are added to snow storage. Above 0°C, snow melts with a rate of 2 mm/day per degree in forests and of 4 mm/day in case of other land cover types.

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These monthly data are available from January 2002 to June 2004.

2.2. LaD Model

[8] The LaD model provides monthly $1^\circ \times 1^\circ$ gridded time series of surface parameters estimated from January 1980 to April 2004. For each grid-cell of the model, the total water storage is composed of three stores: a snowpack, a root-zone and a groundwater store. We used the monthly $1^\circ \times 1^\circ$ maps of snow mass (mm of wet).

2.3. GLDAS

[9] GLDAS, which is an uncoupled land surface modelling system used for climate analysis, is forced by real time outputs of the National Centers for Environmental Prediction (NCEP) reanalysis, satellite data and radar precipitation measurements. Parameters are deduced from high-resolution vegetation, soil coverage and ground elevation data. The data assimilation process is performed by one-dimensional Kalman filtering strategy to produce optimal fields of surface parameters. Nominal spatial and temporal resolutions of the grids are 0.25 degree and 3 hours respectively, and all fields are defined for all land north of −60 deg. Monthly $1^\circ \times 1^\circ$ means of snow mass (mm of wet), from the NOAH land surface model [*Koren et al.*, 1999] driven by GLDAS, were interpolated from these nominal 3-hour outputs from 01/2002 to 05/2004.

2.4. SSM/I Microwave Measurements

[10] Passive microwave sensors provide information on both snow extent and depth independently of solar illumination and cloud cover. The *Chang et al.* [1987] static algorithm was used to derive snow depth fields from radiances measured by SSM/I. The National Snow and Ice Data Centre (NSIDC) provided the SSM/I data mapped to the Equal Area SSM/I Earth Grid (EASE-Grid [*Armstrong et al.*, 1994]), with a 25×25 km^2 resolution from January 2002 to November 2003. These daily fields of snow depth were averaged over a month and $1^\circ \times 1^\circ$ and converted to mass (mm of wet) using the ratio of density between snow and water with a large-scale averaged snow density of 300 kg/m^2.

2.5. GRACE-Derived Snow Mass Solution

[11] Monthly snow mass solutions derived from the 22 CSR (Center for Space Research, Austin, Texas) GRACE geoids were computed by *Ramillien et al.* [2005] for the period April 2002–May 2004. These solutions were truncated at degrees 25–30 (i.e., spatial resolution of ~660 km) to minimize the effect of noise in the GRACE data at short wavelengths [*Tapley et al.*, 2004a]. According to the method presented earlier by *Ramillien et al.* [2004], the computation of these snow mass solutions consists of improving iteratively the input coefficients ("first guess") of a global land surface model (e.g., WGHM), using the GRACE observations as constraints. These estimated snow mass solutions were then converted into water mass coefficients (expressed in mm of wet) by a simple isotropic filtering [*Wahr and Molenaar*, 1998; *Ramillien*, 2002] that takes the elastic compensation of the Earth's surface into account. Associated *a posteriori* uncertainties on these estimated coefficients were also computed during the inversion.

3. Deriving Time-Series of the Snow Mass From GRACE/Model S/SSMI Data

[12] For comparison, we selected the GRACE period from May 2002 to May 2004 for the models outputs and the SSM/I data (when the data were available). We developed these data in spherical harmonics and used the same cut-off degree (25–30) as for GRACE. The GRACE data were linearly interpolated for the same monthly period.

3.1. Data Representation on the Terrestrial Sphere

[13] A surface load variation $\delta q(\theta, \lambda, t)$ that represents the global map of snow mass anomaly and depends upon co-latitude θ, longitude λ and time t can be expanded in surface spherical harmonic coefficients to a maximum degree N:

$$\delta q(\theta, \lambda, t) = \sum_{n=1}^{N} \sum_{m=0}^{n} [\delta C_{nm}(t)\cos(m\lambda) + \delta S_{nm}\sin(m\lambda)] P_{nm}(\cos\theta) \tag{1}$$

where n and m are the degree and order respectively, P_{nm} is the associated Legendre function, and $\delta C_{nm}(t)$ and $\delta S_{nm}(t)$ are the normalized coefficients of the harmonic decomposition (units: mm of equivalent-water thickness).

[14] Each monthly map provided by the WGHM, LaD and GLDAS models or by SSM/I observations was expanded in spherical harmonic coefficients that are defined in (equation (1)), up to the maximum degree $N = 100$. Over oceans and snow-free land, data are set to zero before the spherical harmonic analysis.

3.2. Filtering of the Model Coefficients and SSM/I Data

[15] Monthly harmonic coefficients of the model outputs and SSM/I data were then low-pass filtered at the cutting degree of 25–30 (i.e., spatial resolution of ~660 km) to remain consistent with the spatial resolution of the starting snow mass GRACE solutions by multiplying $\delta C_{nm}(t)$ and $\delta S_{nm}(t)$ by this filter [*Ramillien*, 2002]:

$$W_n = \frac{2\pi G R_e \rho_W}{(2n+1)\overline{\gamma}}(1 + z_n) \tag{2}$$

where z_n represents the Love numbers used to take into account the elastic compensation of the Earth to the surface load. $\overline{\gamma}$ is the normal gravity on the reference ellipsoid (~9.81 m/s^2), G (~6,67.10^{-11} m^{3}kg^{-1}s^{-2}) is the gravitational constant, R_e (~6378 km) is the mean Earth's radius and ρ_W (~1000 kgm^{-3}) is the mean water density. For each type of data, we computed a mean snow map for 2002–2003. This mean was further removed to the monthly maps to compute anomalies.

3.3. Computation of the Snow Volume Time-Series

[16] The spherical harmonic analysis of snow mass anomaly grid δq from δC_{nm} and δS_{nm} coefficients was

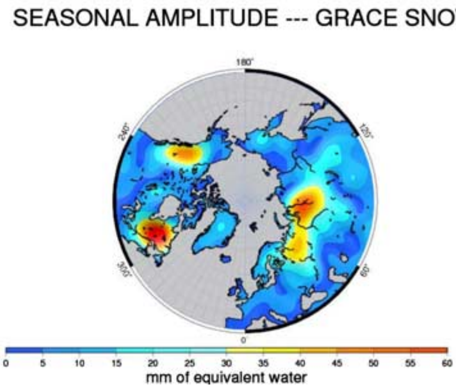

Figure 1. Map of the fitted seasonal amplitudes of snow mass anomaly according to the inversion of the GRACE geoids.

produced for each month using equation (1). For a given monthly period t, the mean geographical value of snow mass volume $\delta V(t)$ over a given river basin A is simply computed from the snow load δq_j, with $j = 1, 2, \ldots$ (expressed in terms of equivalent-water height) representing the index of the considered points inside basin A, and the elementary surface $R_e^2\ \delta\lambda\ \delta\theta\ \sin\theta_j$:

$$\delta V(t) = R_e^2 \sum_{j \in A} \delta q_j(\theta, \lambda, t) \sin\theta_j \delta\lambda\delta\theta \quad (3)$$

where $\delta\lambda$ and $\delta\theta$ are the grid steps in longitude and latitude respectively (generally $\delta\lambda = \delta\theta$). In practice, all points of A used in equation (3) are extracted over the four drainage basins. The geographical contour of each basin is based on masks of 0.5° resolution from *Oki and Sud* [1998].

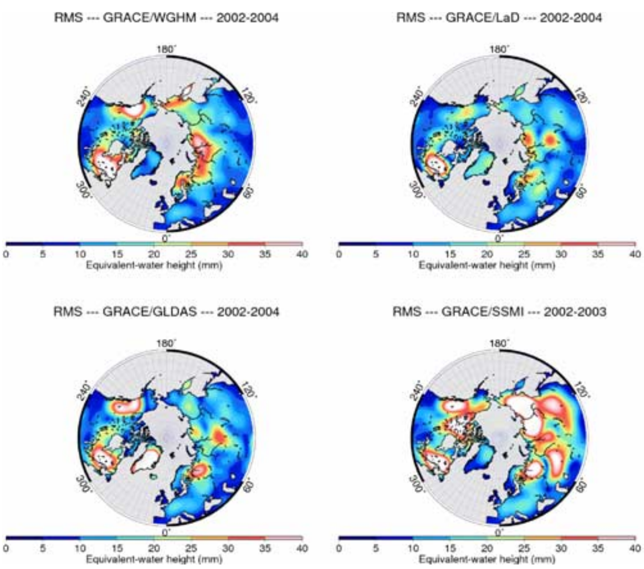

Figure 2. Maps of the root-mean square (rms) differences between the GRACE-derived snow mass anomaly and the outputs of WGHM, LaD and GLDAS models and SSM/I data.

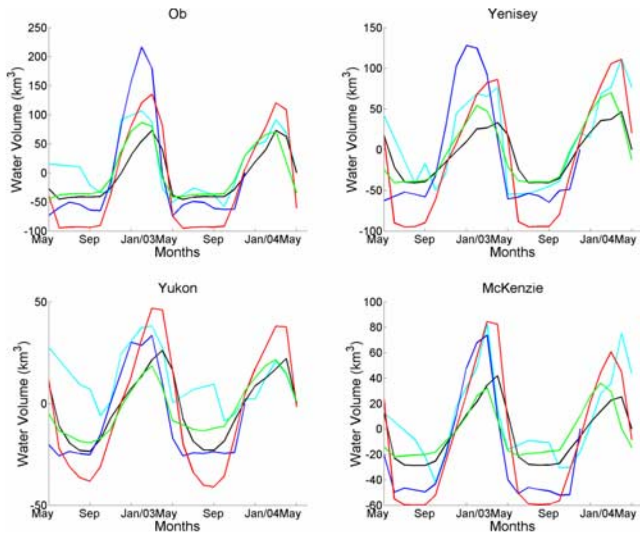

Figure 3. Time series of snow volume changes for four arctic drainage basins: Ob, Yenisey, MacKenzie, Yukon: GRACE-derived snow volume variations (light blue), LaD (black), SSM/I (blue), WGHM (red), GLDAS (green). The mean error on GRACE derived snow mass anomalies is 0.9, 0.8, 0.4 and 1.1 km^3 for the Ob, Yenisey, Yukon and McKenzie basins respectively.

4. Results and Discussion

[17] To analyse the series of snow mass anomaly maps (expressed in water equivalent thickness), the temporal trend and the seasonal amplitude were successively fitted by least-square adjustment at each grid point. Figure 1 presents the seasonal amplitude of the snow anomaly derived from GRACE over the boreal regions. In agreement with the USAF Environmental Technical Applications Center (USAF/ETAC) snow depth climatology [*Foster and Davy*, 1988] and with large scale snow accumulation patterns, the GRACE maximum amplitude features are located in the Quebec and the northern part of the Rocky Mountains for North America, and in the Svernaya Dvina and Ob river basins, reaching ~60 mm of equivalent water height. Important interannual variations are observed on the snow anomaly maps, and the spatial patterns of snow cover and snow maxima location vary from year to year. To compare GRACE with the models outputs and the SSM/I estimates, we computed the maps of the root mean-square (RMS) differences between the GRACE-derived snow mass anomalies and the anomalies provided by the models (GLDAS, WGHM and LaD) and the SSM/I data (Figure 2). These differences were estimated for the northern hemisphere winter period of 2002–2004 (i.e., November–April). The maximum RMS values are lower than 35 mm, 41 mm, 33 mm, 50 mm with the GLDAS, WGHM and LaD models and SSM/I-derived snow mass signals respectively. These values have to be compared with snow annual variations of 300 mm (rms error <14%). Extreme errors are located in the regions of maximum snow accumulation for the three models, and in the regions of

Table 1. Root-Mean Square (rms) Differences Between GRACE Snow Mass Anomalies and Microwave Observations or Model Snow Mass Outputs (mm)

	GRACE-LaD	GRACE-WGHM	GRACE - GLDAS	GRACE-SSM/I
Ob	14	14	14	17
Yenisey	19	17	19	25
Mac Kenzie	13	15	17	24
Yukon	11	14	18	16

depth hoar formation for SSM/I. A better agreement is obtained with GLDAS and LaD models than with WGHM outputs and SSM/I observations. These large differences can be explained by the simplistic scheme for deriving snow accumulation in WGHM model [*Döll et al.*, 2003] and by the lack of reliability of the static algorithm used to retrieve the SSM/I snow depth [*Mognard and Josberger*, 2002].

[18] Time-series of the snow volume anomaly were obtained using equation (3) over four main Arctic drainage basins (Ob and Yenissey in Siberia, Yukon and Mac Kenzie in North America). Figure 3 presents the snow mass time-series from GRACE and from the WGHM, LaD and GLDAS models and SSM/I data. A good agreement is observed between GRACE snow mass estimation and the model outputs at seasonal scale, while for SSM/I important phase differences are found over the four basins as well as amplitude differences over the Eurasian basins. The errors on the snow mass anomaly include leakage errors (that we cannot evaluate) and uncertainties on GRACE processing. This latter error includes the measurements errors and the *a posteriori* uncertainties on the inverse method. For each period and basin, the error on snow mass anomalies are approximately 0.4 and 1 km^3. Results of the numerical comparison for the different basins are presented in Table 1. Regionally, the RMS differences between the GRACE snow mass anomalies and the model and SSM/I profiles ranges from 11 to 25 mm, suggesting that the GRACE snow anomalies amplitudes remain very comparable to model fields and SSM/I observations, especially at the seasonal time-scale for all the chosen basins.

5. Conclusion

[19] In this study, we present new solutions of time-variations in snow water equivalent storage from the inversion of the GRACE geoids (spatial resolution of ~660 km).

[20] The GRACE estimated seasonal amplitude of snow mass agrees with the USAF/ETAC snow climatology. This provides a high degree of confidence in the ability of GRACE to correctly retrieve snow parameters, which are not correctly estimated with the classical SSM/I satellite retrieval [*Grippa et al.*, 2004]. Comparisons with global land surface models and SSM/I data indicate that GRACE is currently able to provide an estimate of the spatio-temporal variability of snow mass in the boreal regions. The RMS differences are lower than 14% of the snow annual variation. From monthly snow anomaly time series, we also estimate the temporal variations of the snow volume anomaly over four Arctic drainage basins. RMS differences lower than 20 mm and 25 mm were respectively found with the models and SSM/I data. Better agreement is found with LaD and GLDAS models than with the WGHM model (although the WGHM model was used as first guess to retrieve the GRACE solutions) and SSM/I observations.

[21] The possibility that the GRACE snow solutions may be contaminated by the liquid land waters contribution cannot be completely excluded. This problem can contribute to the rms residuals of the differences with the model outputs. This point will be examined in a further study.

[22] **Acknowledgments.** We would like to thank Petra Döll (WGHM), Chris Milly (LaD) and Matthew Rodell (GLDAS) for having made the monthly outputs of their models available. This work was partly funded by the French Programme National de Télédétection Spatiale (PNTS). One of the authors (FF) is supported by a CNES/Alcatel Space grant.

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S. Biancamaria, A. Cazenave, F. Frappart, N. M. Mognard, and G. Ramillien, Laboratoire d'Etudes en Géophysique et Océanographie Spatiales, UMR 5566, CNES/CNRS/IRD/UPS, 14 Av. Edouard Belin, F-31400 Toulouse, France. (frederic.frappart@legos.cnes.fr)