GREENLAND MASS BALANCE ESTIMATION FROM SATELLITE GRAVITY MEASUREMENTS

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ABSTRACT

The Gravity Recovery and Climate Experiment (GRACE) data is used to estimate the secular trend and periodic variations of ice mass variability over Greenland. To do this, we use 92 monthly GRACE level 2 Release-04 (RL04) data from the Center for Space Research at the University of Texas (UTCSR) during the period April 2002 to February 2010. The high frequency noise of data has been filtered out with three smoothing cap radius as in [3]. For separation of leakage effects, the appropriate reduction model is used. Taking the average over all smoothing radius after the leakage effects correction, the annual ice-mass loss becomes -155±3 Gt/year. Note that these values are free of any GIA correction.

1. Introduction

The GRACE satellites have been providing the scientific community with valuable information regarding Earth's gravity field. Due to its global coverage, GRACE provides an excellent tool for mapping the gravity field over large areas. GRACE not only maps the Earth's static gravity field but it also provides temporal variations of Earth's gravity field to a scale of several hundred kilometers and with a period of around one month. Changes in the gravity field are caused by the redistribution of mass within the Earth and on or above the Earth's surface. The majority of the change is related to water mass transport [8]. The GRACE data have been used by numerous authors to study changes in land water storage, ocean mass and changes in land-locked ice, including glaciers, the Greenland and the Antarctic ice sheets. Several authors have used GRACE data to estimate the rate of mass loss over Greenland. There are also several estimates of the Greenland mass variability which have been obtained using a variety of other techniques than GRACE. A problem common to all these techniques is the difficulty of monitoring the entire ice body and they can provide estimates for only a portion of ice sheet or critical regions. This problem can be overcome using GRACE satellite time variable gravity measurements. The main advantages of satellite time variable gravity measurements are that they are sensitive to the entire ice body, and that they provide mass estimates with only minimal use of supporting physical assumptions or ancillary data. Due to the limited spatial resolution and the presence of non-random noise, obtaining ice-volume loss estimates from GRACE data is not straightforward and results vary widely between 111 km³/yr and 250 km³/yr ([1], [4], [5], [6], [7] and [9]). In this paper, we estimate the secular trend in Greenland mass based on almost all available monthly GRACE data until now (June 2002, July 2002 and June 2003 data are missing). We also use the latest release (UTCSR RL04) with improved geophysical signal models and data processing techniques resulting to smallest error among other releases. The issues of high frequency noise of GRACE data and the leakage effects of the mass loss signal of the Greenland ice sheet to adjacent regions as well as signals from other regions leaking into the domain of the Greenland ice sheet are also addressed.

2. Surface mass change from GRACE

The change in surface mass density can be computed as [8]:

$$\Delta\sigma(\varphi,\lambda) = \frac{a\rho_{\text{ave}}}{3}\sum_{l=0}^{\infty}\sum_{m=0}^{l}\frac{2l+1}{1+k_l}\bar{P}_{lm}(\sin\varphi) \times\left[\Delta C_{lm}\cos m\lambda + \Delta S_{lm}\sin m\lambda\right] \quad (1)$$

where ρ_{ave} is the average mass density of the Earth (=5517 kg/m³), $\bar{P}_{lm}$ is the normalized associated Legendre function, (φ, λ) denote latitude and longitude of point of the interest, k_l is the load Love number of degree l, a is the major semi axis of a reference ellipsoid and ΔC_{lm} and ΔS_{lm} are time-variable components of the GRACE observed Stokes coefficients for some month of degree and order (l, m) or the changes relative to the mean of the monthly solutions. Values of the Love numbers used in this study are given in [8]. Many applications require estimates of mass variability for specific regions; for example in this investigation, estimating total changes in mass of the Greenland ice sheet. For these sorts of problems, we can use specific averaging functions which are optimized

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for those regions. An exact regional average would take the form:

$$\Delta\sigma_{\text{region}} = \frac{1}{A_{\text{region}}} \int \Delta\sigma(\varphi,\lambda)\tau(\varphi,\lambda) \times \cos\varphi \mathrm{d}\varphi \mathrm{d}\lambda \quad (2)$$

where A_{region} is the area of the region of interest, and

$$\tau(\theta,\lambda) = \begin{cases} 0 & \text{outside the basin} \\ 1 & \text{inside the basin} \end{cases} \quad (3)$$

3. Numerical investigating

We estimate the secular trend and periodic variations of ice mass variability over Greenland using about 8 years of GRACE level 2 RL04 data from the Centre for Space Research at the University of Texas (UTSR) during the period April 2002 to February 2010. We have also used monthly Satellite Laser Ranging (SLR) estimates for C_{20} coefficient to be used to replace the estimates from GRACE (J. Ries, personal communication, 2010). In the first step, the high frequency noise in the GRACE observed Stokes coefficients has to be filtered out by appropriate smoothing techniques, as these errors manifest themselves in maps of surface mass variability as elongated, linear features, generally oriented north to south. Kusche et al (2007) developed a method in which they designed a regional spatial filter so as to minimize the satellite measurement error. Kusche et al (2009) revised the method with three smoothing cap radius of 240 km, 340 km and 530 km. In this study, we use these three decorrelation filters to account for the correlated noise contained in GRACE data (see also [3]). Because the regional filter is optimized by the trade-off between the satellite measurement error and the leakage error, it is impossible to reduce these errors simultaneously. The leakage errors were estimated as follows. We first calculated the Stokes coefficients associated with the leakage effects using Eq. 4 by integrating only outside the area concerned:

$$\begin{Bmatrix} \Delta C_{lm} \\ \Delta S_{lm} \end{Bmatrix} = \frac{3(k_l+1)}{4\pi a \rho_{\text{ave}}(2l+1)} \times \iint \Delta\sigma(\varphi,\lambda)\bar{P}_{lm}(\sin\varphi) \begin{Bmatrix} \cos m\lambda \\ \sin m\lambda \end{Bmatrix} \cos\varphi \mathrm{d}\varphi \mathrm{d}\lambda \quad (4)$$

The leakage effects were then estimated by using Eq. 1 in to the derived Stokes coefficients. Finally, the effects were subtracted from the GRACE gravity solutions. There may be two candidates for the input data of $\Delta\sigma(\varphi,\lambda)$ in Eq. 4: one is calculated from model values and the other from GRACE data. In this study, we chose to use the GRACE data. The next step is to form an approximate estimate of total mass change for each month, by taking Eq. 2 over grid elements. To calculate secular and periodic variations, a general expression of the form

$$f(\varphi,\lambda,t) = A + Bt + \sum C_i \cos(\omega_i t) + D_i \sin(\omega_i t) \quad (5)$$

is used. Here, the value of the considered functional f is the mass anomaly at a selected location (φ, λ) and time t is approximated by a static value A, and its secular (B) and periodic (amplitudes C_i and D_i of typical angular frequencies ω_i) variations. Fig. 1 shows monthly estimates of total Greenland mass change in Gigatonne. The results show a clear trend (long term variability), supper-imposed on short-period variability. Our objective is to estimate the long term trend in ice mass change. To recover the trend, using un-weighted least squares method, a four-parameter fit for bias, secular trends and yearly seasonal variations is used. It is evident from Fig. 1 that the procedure used in this study reduces the contamination by the seasonal variability. Fig. 1 shows a clear decrease in ice mass during the investigation (about 8 years) period. Interpreting the trend as due entirely to a change in ice, we obtain a mass decrease of 155±3 Gt/yr. This estimate is an average of the results derived from three smoothing cap radius.This value of mass decrease is equivalent to a global sea level rise of 0.43±0.01 mm/yr.

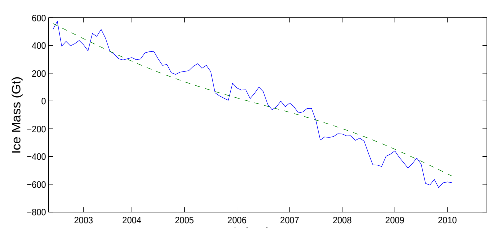

Figure1. Time series of ice mass changes for the Greenland estimated from UTCSR monthly mass solutions using non-isotropic decorrelation filter during the period April 2002 to February 2010 (continuous blue line) . The best-fitting four-parameter profile is shown in dashed green line.

In this estimation, the contaminating factors like the effects of variations in atmospheric mass and the solid Earth contribution from high-latitude Post Glacial Rebound (PGR) are not applied. The atmospheric effect is negligible for Greenland on the long term trend ([6], [7]). We also chose not to apply the correction for the

PGR signal in this study, considering the total uncertainty in the PGR estimations ([6], [7]).

4. Conclusions

Greenland is a major contributor to recent global sea level rise. Given the size and shape and complexity of the Greenland ice body, it makes it difficult to measure ice mass change in the Greenland. A variety of techniques are used to estimate Greenland ice mass balance each of which with limitations and uncertainties. The spherical harmonics coefficients of GRACE twin satellites allow regional estimation of Greenland ice mass balance. In contrast to most other techniques, GRACE measures Greenland mass variability over the entire ice sheet. Furthermore, to obtain this mass variability, the process is less ambiguous for GRACE as the relationship between gravity and mass variability follows directly from Newton's law. The main disadvantage of GRACE models for obtaining the Greenland mass change is errors caused from mismodeled postglacial rebound. GRACE is unable to separate gravitational effects of the Greenland ice sheet from those of the underlying solid Earth. Our GRACE estimate of the total Greenland mass loss using about 8 years of GRACE level 2 RL04 data from UTCSR during the period April 2002 to February 2010 is 155±3 Gt/yr. This result is in agreement with previous studies and shows an acceleration of the ice mass loss over Greenland. Time periods of higher losses and also longer periods are observed during April 2002 to February 2010. It should be stated here that mass balance estimates from GRACE measurements are not straightforward and results vary widely. This could be due to the different observation periods, and different methods used. Our GRACE estimate shows that the ice mass loss is not constant and trends are increasingly negative.

5. References

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