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Climate-driven interannual ice mass evolution in Greenland

I. Bergmann [a,*], G. Ramillien [b], F. Frappart [b]

[a] Helmholtz-Centre Potsdam, GFZ German Research Centre for Geosciences, Potsdam, Germany
[b] Université de Toulouse, UPS, OMP, GET, Toulouse, France

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ABSTRACT

We re-evaluate the Greenland mass balance for the recent period using low-pass Independent Component Analysis (ICA) post-processing of the Level-2 GRACE data (2002–2010) from different official providers (UTCSR, JPL, GFZ) and confirm the present important ice mass loss in the range of −70 and −90 Gt/y of this ice sheet, due to negative contributions of the glaciers on the east coast. We highlight the high interannual variability of mass variations of the Greenland Ice Sheet (GrIS), especially the recent deceleration of ice loss in 2009–2010, once seasonal cycles are robustly removed by Seasonal Trend Loess (STL) decomposition. Interannual variability leads to varying trend estimates depending on the considered time span. Correction of post-glacial rebound effects on ice mass trend estimates represents no more than 8 Gt/y over the whole ice sheet. We also investigate possible climatic causes that can explain these ice mass interannual variations, as strong correlations between GRACE-based mass balance and atmosphere/ocean parallels are established: (1) changes in snow accumulation, and (2) the influence of inputs of warm ocean water that periodically accelerate the calving of glaciers in coastal regions and, feed-back effects of coastal water cooling by fresh currents from glaciers melting. These results suggest that the Greenland mass balance is driven by coastal sea surface temperature at time scales shorter than accumulation.

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1. Introduction

The mass balance of the Greenland Ice Sheet (GrIS), and its contribution to sea level rise, are of high interest in the context of global warming. According to the latest IPCC report (2007), melting of the

* Corresponding author.
E-mail addresses: Inga.Bergmann@gfz-potsdam.de (I. Bergmann), guillaume.ramillien@get.obs-mip.fr (G. Ramillien), frederic.frappart@get.obs-mip.fr (F. Frappart).

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whole GrIS would contribute nearly 7 m to sea level rise. Even a less substantial mass loss would have a strong impact on sea level rise. Over the last 20 years, observations of the GrIS show an acceleration of ice mass loss caused by rapid glacier flow on the southeast and northwest coasts (see Allison et al. (2009) and Zwally et al. (2011) for reviews), in response to the recent warming affecting both the atmosphere (Box and Cohen, 2006) and sea water (Hanna et al., 2009). Nevertheless, analysis of changes in the glaciers reveals a succession of periods of mass loss acceleration and deceleration.

Since its launch in March 2002, the GRACE mission has demonstrated great potential for studying the ice sheet mass changes. The GRACE data have been increasingly used for assessing mass balance of Greenland and Antarctica. First studies revealed a significant mass loss of Greenland with an acceleration of melting starting in 2004 (Velicogna and Wahr, 2005, 2006; Chen et al., 2006; Luthcke et al., 2006; Ramillien et al., 2006). Mass loss occurred mainly on the east coast of Greenland whereas the interior of the continent exhibited a small mass increase (Luthcke et al., 2006; Wouters et al., 2008). Recent studies showed acceleration of the mass loss during 2006–2008 (Velicogna, 2009) and a deceleration during 2008–2009 (Chen et al., 2011). Nevertheless, the results obtained so far are highly dependent on the length of the GRACE time series, the chosen data set, the nature of the post-processing, and the method for computing linear trends (i.e., with or without adjusting the seasonal components). Results can vary by a factor ~3 depending on the data set (e.g. CSR, GFZ or JPL; Baur et al., 2009). From these previous GrIS mass balance estimates, linear trends were simply computed over the complete (or parts of the) period of availability of the GRACE data, assuming the ice melting to be constant in time. Only Velicogna (2009) and Rignot et al. (2011) estimated accelerations for 2004 and 2008–2009.

In this study, we re-evaluate the Greenland mass balance over a longer time span (October 2002–July 2010), using Level-2 GRACE data from the Science Data Centre (UTCSR, GFZ and JPL) and different post-processing techniques (Gaussian and Independent Component Analysis-based approaches) at continental and ice field scales. We also analyze the interannual variability of the mass balance using the robust Seasonal Trend Decomposition by Loess (LOcally wEighted Scatterplot Smoothing) (STL) approach. The non-stationarity of the mass balance is then related to climate forcings from the atmosphere and the ocean through comparisons with snow depths (SD) and sea surface temperatures (SST).

2. Data sets

2.1. GRACE-based water mass variations

Since its launch in March 2002, the Gravity Recovery And Climate Experiment (GRACE) mission, consisting of a pair of co-orbiting satellites at an altitude of 400–450 km, provides a systematic mapping of the spatio-temporal variations of the Earth's gravity field. These are estimated with an unprecedented precision of ~1 cm in terms of geoid height (Tapley et al., 2004), or equivalently ~15–20 cm in equivalent-water thickness when averaged in regions of 300×300 of square kilometers (Ramillien et al., 2008; Schmidt et al., 2008). The Level-2 GRACE solutions consist of monthly Stokes coefficients (i.e., normalized spherical harmonics of the geo-potential) estimated by a least-squares adjustment of GRACE orbit measurements – especially very accurate inter-satellite K-Band Range (KBR) variations – made by different official providers [GeoForschungsZentrum (GFZ) in Potsdam Germany, Center of Space Research at University of Texas (UTCSR) in Austin, TX, Jet Propulsion Laboratory (JPL) in Pasadena, CA]. In this process, the Stokes coefficients are corrected for known atmospheric and oceanic gravitational contributions (Bettadpur, 2007), so that the residuals represent non-modeled phenomena, mainly variations in land water storage, glaciers, and ice sheet mass. These Level-2 GRACE solutions are available at: ftp://podaac.jpl.nasa.gov/grace/ up to harmonic degree of 50–60 (i.e., spatial resolution of 333–400 km), and the corresponding global 1°x1° grids of equivalent-water heights are also downloadable. In our study, we use monthly GFZ, UTCSR and JPL solutions from 04/2002 to 07/2010.

The GRACE solutions suffer from the presence of an unrealistic high-frequency noise appearing as north–south striping, caused by orbit resonance during the Stokes coefficient determination and aliasing with short-term oceanic and atmospheric phenomena that are not well modeled. Several post-processing methods, such as low-pass Gaussian filtering, have been proposed to solve this problem (Jekeli, 1981; Swenson and Wahr, 2002). However most of them suffer from the risk of losing signal energy in the spectrum truncation (i.e., drastic loss of spatial resolution). This also needs arbitrary tuning of required parameters (e.g., a priori level of noise, cutting spatial frequencies,…) in absence of criteria. To get rid of the noise in the L-2 GRACE solutions, we preferred to use the global ICA estimates obtained by combination of GFZ/UTCSR/JPL solutions, to isolate statistically independent components of the observed gravity field, in particular the continental water storage contribution that we compared with continental water storage estimated from classical Gaussian-filtered solutions.

2.2. ICA solutions

A post-processing method based on ICA (Comon, 1994; De Lathauwer et al., 2000) was applied to the Level-2 GRACE solutions prefiltered with Gaussian filters of 400 km and 500 km of radius. This so-called blind source separation (BSS) approach does not require a priori information, except the assumption of statistical independence of the elementary sources that compose the total measured signals. Taking into account the consideration that the GRACE Level-2 products from CSR, GFZ and JPL are different observations of the same monthly gravity anomaly, and that the land hydrology and the north–south stripes are the independent sources.

Assuming that the observations y collected from N sensors are the combination of P $(N \geq P)$ independent sources represented by the source vector x, they can be written as a linear statistical model:

$$y = Mx, \quad (1)$$

where M is the mixing matrix whose elements m_{ij} $(1 \leq i \leq N,\ 1 \leq j \leq P)$ are the coefficients of linear combinations of the unknown sources. The columns $\{m_j\}$ are the mixing vectors. ICA aims at estimating the mixing matrix M and/or the corresponding realizations of the source vector x, only knowing the realizations of the observation vector y, under the following assumptions: i) the mixing vectors are linearly independent, and ii) the sources are statistically independent. The contributors to the observed gravity field are forced to be uncorrelated, numerically only considering completely objective constraints. The efficiency of ICA to separate gravity signals and noise from combined GRACE solutions has previously been demonstrated on Level-2 solutions over land (Frappart et al., 2010, 2011). Series of ICA-estimated global maps of continental and ice caps mass changes, computed over 08/2002–07/2010, are used in this study to estimate the mass balance of Greenland.

2.3. ECMWF Snow depth data

We used the daily snow depth grids from the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA-interim reanalysis with a horizontal resolution of 1.5°×1.5° (http://data-portal.ecmwf.int/data/d/interim_daily/; Dee et al., 2011). These grids were estimated from the improved snow scheme of the Hydrology Tiled ECMWF Scheme of Surface Exchanges over Land (HTESSEL) land surface