The Short-term Mass Change of Greenland Ice Sheet and the Atmospheric Forcing

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Abstract. In recent decades, the global warming drives the huge ice sheet melting in northern hemisphere. Previous studies on long-term melting rates of Greenland have basically reached agreement, but there is still a lack of the knowledge of the pattern the short-term ice mass change, makes it difficult to fulfill the understanding of the mechanism of the ice sheet. In this study, we used Gravity Recovery and Climate Experiment (GRACE) RL06 data to derive the time series of mass variation of Greenland Ice Sheet (GrIS), from January 2003 to December 2015. We derived the short-term mass change rate during 2003-2015 and found that the GrIS has experienced four melting stages, i.e., a steady melting (-204.4 Gt/yr) phase form 2003 to 2009, an abrupt accelerating (-384.6 Gt/yr) phase form 2010 to 2012, an abnormal pause (+24.8 Gt/yr) year in 2013 and a recovering (-207.3 Gt/yr) phase from 2014 to 2015. In addition, using ensemble empirical mode decomposition (EEMD), the high frequency signal has been removed and the annual mass change has been studied, which shows inter-annual variability. Meanwhile, we correlated the annual mass change with the Greenland Blocking Index (GBI) and North Atlantic Oscillation (NAO) during summertime and the correlation for 2003-2015 was found at $r=0.63$ between the summer GBI and the annual mass change, while $r=0.57$ between summer NAO and the annual mass change. Our results indicate that the short-term mass change of GrIS mainly forced by atmospheric variability.

1. Introduction
The global sea level rise has been accelerating due to the melting of ice sheets, glaciers and ice caps, in consequence of the global warming. Estimation of the global ice balance has been obviously improved in recent years based on available satellite observations, model simulations and the development of data processing technologies, e.g., using the Gravity Recovery and Climate Experiment (GRACE) [2,3] and the Ice, Cloud, and land Elevation Satellite (ICESat) [1,2]. In the last decade, most studies based on satellite observations have confirmed that the significant mass loss takes place in the Greenland ice sheet (GrIS), but we still need to focus on the continental ice or surface mass balance (SMB) caused by abnormal climate fluctuations in a short-term period, e.g. the accelerating period 2010-2012 and the pause year 2013. Meanwhile, the mechanism behind the ice sheet melting should be studied and figured out.

It is well known that the northern hemisphere is an amplifier of the global temperature and GrIS, as a delicate system, plays an indicator of the global sea level rise. Here, we present detailed mass balance results for the GrIS during 2003-2015 by estimating the anomalous acceleration of the mass loss. We use GRACE monthly gravity fields data to estimate the spatiotemporal variation of the ice mass balance. We also analyze the correlation between large scale atmospheric variability (such as
Greenland Blocking Index, i.e., GBI and North Atlantic Oscillation, i.e., NAO) and the annual mass change of GrIS.

2. Algorithm

2.1. Mass change from GRACE

The GRACE mission is particularly designed to detect the time-variable gravity fields. Launched jointly by NASA and the German Space Agency (DLR) in March, 2002, GRACE has been providing harmonic solutions especially in the form of Level-2 gravity products. The most important thing is to derive the time-variable components of the gravity and mass fields from these Level-2 products. It should be noted that the methods described here are described in more detail in Section 2.1 of Wahr et al., (1998) [4]. The surface water mass change can be expressed as equivalent water height (EWH):

\[ \Delta \text{EWH} = \frac{a}{3 \rho_{\text{ave}}} \sum_{l=0}^{\infty} \sum_{m=0}^{l} \frac{1+2}{1+k_l} P_{lm}(\cos \theta)(\Delta C_{lm} \cos(m \varphi) + \Delta S_{lm} \sin(m \varphi)) \]  

(1)

Where, the \( a \) is the average radius of the earth; \( \rho_{\text{ave}} \) is the average density of earth ( = 5517 kg/m\(^3\)); \( \rho_{\text{wat}} \) is the average water density ( = 1000 kg/m\(^3\)); \( k_l \) is the load love number at degree \( l \); \( P_{lm} \) are the normalized associated Legendre functions; \( \Delta C_{lm} \) and \( \Delta S_{lm} \) are the change in the spherical harmonic (Stokes) coefficients (to the mean of long-term field or the static field). Generally, we need to derive the total mass change of a specific region, this could be achieved by:

\[ \Delta M_{\text{region}} = \frac{a}{3 \rho_{\text{ave}}} \sum_{l=0}^{\infty} \sum_{m=0}^{l} \frac{1+2}{1+k_l} \nu_{lm}^C \Delta C_{lm} + \nu_{lm}^S \Delta S_{lm} \]  

(2)

Where the \( \nu_{lm}^C \) and \( \nu_{lm}^S \) are the Stokes coefficients from the regional kernel function \( \nu(\theta, \varphi) \), which is defined by:

\[ \nu(\theta, \varphi) = \begin{cases} 0, & \text{outside the region} \\ 1, & \text{inside the region} \end{cases} \]  

(3)

Mostly, we should take into account the noise in the raw data, the usual way is to apply a simple Gaussian smoothing filter to the raw model. The smoothed result can be expressed as:

\[ \Delta M_{\text{region}} = \frac{a}{3 \rho_{\text{ave}}} \sum_{l=0}^{\infty} \sum_{m=0}^{l} \frac{1+2}{1+k_l} W_l \left( \nu_{lm}^C \Delta C_{lm} + \nu_{lm}^S \Delta S_{lm} \right) \]  

(4)

Where the \( W_l \) are the Gaussian values developed by Jekeli (1981), and can be calculated using the recursion relations:

\[ W_0 = 1 \]

\[ W_l = \frac{1 + e^{-2b}}{1 - e^{-2b}} \frac{1}{b} W_l \]

\[ W_{l+1} = \frac{2l+1}{b} W_l + W_{l-1} \]  

(5)

Where

\[ b = \frac{\ln(2)}{(1 - \cos(r/a))} \]  

(6)

and \( r \) is the smoothing radius of the filter.

Due to the limited resolution of GRACE and the processing of smoothing, the signal of the specific region would leak out and the signal outside the region would leak in as well. To reduce the signal alias and attenuation, we introduce the scaling factor method [5] in this study. To better understand the effect of different leakage recovering schemes, we have chosen different smoothing level (no filtered, 250 km filtered and 350 km filtered), different masks of different area (exact mask and extended mask) and different kinds of prediction models [6]. We have found that, based on high resolution model, the
leakage recovering could perform well without a choose of extending the mask. In addition, we have compared our result to publishing from NASA Jet Propulsion Laboratory (JPL, https://grace.jpl.nasa.gov/). Our result shows that the correlation between the scaled mass change from GRACE in this study and the result from JPL is at $r^2=0.995$, indicating a high quality and reliability of our result.

Figure 1. The short-term trend of mass change: 2003-2010 (red), 2010-2013 (yellow), 2013-2014 (dark green), 2014-2016 (purple). The light green shallow circles represent the mass change time-series. The black double head arrow indicates the long-term trend for 2003-2012.

2.2. Long-term and short-term mass change

To derive the linear trend or the quadratic trend (acceleration) of the ice mass change in Greenland, the most useful way is to employ the fitting method. Usually the fitting function consist of polynomial functions and trigonometric functions:

$$y=\sum_{i=0}^{P}a_i x_i^P + \sum_{j=1}^{N}b_j \cos \omega_j x + c_j \sin \omega_j x$$

(7)

Where the $P$ is usually $\leq 2$ (when $P=1$ the linear trend could be determined, $P=2$ corresponds the acceleration), and for mass change of GrIS $N=2$, corresponding to a half year circle term and an annual circle term. In this study, the linear trend of GrIS mass change is $-266.6\pm8.2$ Gt/yr during 2003-2012 with an accelerating trend of $-29.2\pm3.6$ Gt/yr$^2$, which is in common with the results in Bevis [7]. Besides, we have identified 4 stages of the mass change of GrIS through fitting method. As shown in Fig.1, there is a mass change rate of $-204.4$ Gt/yr for 2003-2009, compared to the prominent acceleration of 2010-2012, when the linear trend is averaged at $-384.6$ Gt/yr. Following the peak at 2012, an abrupt pause occurred in 2013, accounting for the positive rate of $+24.8$ Gt/yr. The pause last 1 year till the early 2014, followed by a recover period of 2014-2015. The linear rate of 2014-2015 is $-207.3$ Gt/yr which is closed to the trend of 2003-2009. We’ve also checked the total acceleration for 2003-2015, which is about $-1$ Gt/yr$^2$. Apparently, the acceleration of melting in GrIS is significantly regulated by the abnormal melting events, and the pause of 2013 has compensated for the abnormally melting of 2010-2012.

We have also checked the spatial variability of the mass change, especially the annual mass change for the abnormal period: 2010 to 2013. It is apparently shown in Fig.2 that the spatial pattern of the mass change presents significant variability at annual scale: mass loss occurs in south and southwest Greenland in 2010; southwest and west Greenland in 2011; the most significant mass loss occurs in south and east Greenland in 2012; while mass gain shows in large area in north Greenland.
and surpasses the mass loss in south Greenland. We could see that the southern part of Greenland plays an important role in the mass imbalance of GrIS.

![Figure 2](image)

**Figure 2.** Spatial variability of annual mass change trend: (a) 2010, (b) 2011, (c) 2012, (d) 2013.

2.3. Large scale atmospheric variability

Previous studies have discovered a negative correlation between the North Atlantic Oscillation (NAO) phase and Greenland summer temperatures, and Greenland Blocking Index (GBI) generally correlates more highly than the NAO with Greenland summer temperatures[8]. Therefore, in this study, we used these two indexes to present the large-scale atmospheric variability over Greenland. Monthly NAO data is available from [https://www.cpc.ncep.noaa.gov/products/precip/CWlink/pna/nao.shtml](https://www.cpc.ncep.noaa.gov/products/precip/CWlink/pna/nao.shtml). The GBI dataset is obtained from the NOAA Earth System Research Laboratory (ESRL) at [https://www.esrl.noaa.gov/psd/gcos_wgsp/Timeseries/GBI_UL/](https://www.esrl.noaa.gov/psd/gcos_wgsp/Timeseries/GBI_UL/) and based on Hanna [9]. According to previous studies, we calculated the summer (JJAS) NAO (red line in Fig.3a) and GBI (red line in Fig.3b) and then correlated these indexes with the annual mass change of GrIS.

![Graph](image)
It should be noted that the mass change of GrIS consists of different components. In this study, our aim is to derive the annual mass change. Following Luthcke\cite{10}, we employed Ensemble Empirical Mode Decomposition \cite{3} to the mass change time-series (run at iteration of 50 and select the white noise with standard derivation of 0.2). The annual mass change is calculated from the reconstruction of intrinsic mode functions (IMFs): IMF2-6 and the residual, which means the high frequency (period shorter than 1 year) component is removed. The result shows that JJAS-NAO correlates with annual mass change of GrIS at r=0.57, while JJAS-GBI correlates with annual mass change of GrIS at r=-0.63 (both have passed the t-test at 95% confidence level). Generally, the JJAS-GBI correlates more highly with the annual mass change of GrIS, this difference mainly comes from the trend of NAO and GBI for 2006-2009, when the NAO goes oppositely against the trend of annual mass change. Despite of the abrupt increase in GBI in 2007, the trend of GBI reflects most of the change in annual mass change. Both indexes have presented the abrupt change in 2012 to 2013, when the mass change peaked at 2012 and paused at 2013.

3. Conclusions
Using GRACE RL06 Level-2 data and SMB data from RACMO 2.3, we have retrieved the mass change of GrIS for 2003-2015. With the fitting method, we have derived the short-term mass change rate of GrIS: -204.4 Gt/yr for 2003-2009, -384.6 Gt/yr for 2010-2012, an abrupt pause occurred in 2013 with a positive rate of +24.8 Gt/yr. The pause last 1 year and the linear rate recovered to -207.3 Gt/yr during 2014-2015, which is closed to the trend of 2003-2009. This four stages pattern has confirmed the short-term variability of mass change of GrIS. In addition, we have also found the evidence that the spatial variability of annual mass change due to the fact that the significant mass change is concentrated mostly in south Greenland. According to this, we further checked the annual mass change of GrIS, by applying the EEMD to scaled mass change time-series and removing the IMF1. The result shows that there is annual variability in mass change of GrIS, and this variability correlates with JJAS-NAO at r=0.57 and JJAS-GBI at r=-0.63, respectively. Based on this, our study has proved the correlation between large-scale atmospheric variability and the short-term mass change of GrIS.

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