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Geodetic measurements reveal short-term changes of glacial mass near Jakobshavn Isbræ (Greenland) from 2007 to 2017

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A B S T R A C T

The Global Positioning System (GPS) and Gravity Recovery and Climate Experiment (GRACE) provide important geodetic datasets to study glacial mass change. Applying the multichannel singular spectral analysis to the GPS-measured vertical and horizonal crustal displacement and GRACE-derived vertical displacement near Jakobshavn Isbræ (JI) in western Greenland from 2007 to 2017, we reconstruct the short-term loading displacements due to ice mass changes. Both the vertical and east displacements show strong seasonal variability. They also reveal three episodes of transient displacements: downward and eastward motion from late 2007 to around 2010, sustained upward and westward motion from 2010 to early 2013, and downward and eastward motion till late 2016. We also forward model the seasonal and transient displacements caused by surface mass balance (SMB) and glacier dynamics. Our model agrees well with the geodetic observations and provides quantitative insights into the contribution from SMB and ice dynamics to the ice mass changes. We find that SMB is the dominant contributor to the seasonal and transient displacements at three out of four GPS sites (AASI, ILUL, and QEQE). While, at the fourth GPS site (KAGA) that is closest to the glacier, the contributions to the transient displacements from SMB and glacier dynamics are comparable. The forward modeling also suggests that the dynamic mass change in the JI catchment underwent strong seasonal variations and these variations correlated more with the seasonal retreat and advance of the calving front than with the changes of glacial velocities. Our altimetry results reveal that the frontal portion of JI catchment lost 34 Gt in 2012 and this loss of ice declined to only 11 Gt in 2016 due to widespread thickening along the main flowline.

1. Introduction

Jakobshavn Isbræ is the largest and fastest outlet glacier on the west coast of Greenland, draining ∼6.5% of the ice sheet before 2000 (Krabill et al., 2000). JI changed dramatically from 1998 to 2003, during when it doubled the moving speed as its ∼15 km long floating ice tongue disintegrated (Thomas et al., 2003; Joughin et al., 2004). The ice mass loss rate in the JI catchment reached near 25 $\mathrm{Gt\,a^{-1}}$ by the end of 2002 and then stabilized and declined back under 20 $\mathrm{Gt\,a^{-1}}$ until 2006. It increased to 34 $\mathrm{Gt\,a^{-1}}$ by the end of 2007, and afterwards the ice mass loss rate fluctuated between 25 and 33 $\mathrm{Gt\,a^{-1}}$ (Howat et al., 2011).

JI showed a sudden acceleration in thinning and velocity in 1997, which was triggered by warm subsurface ocean water (Holland et al., 2008). At almost the same time, the JI catchment turned from slow thickening to sustained thinning (Thomas et al., 2003; Holland et al., 2008). Joughin et al. (2014) found that the mean annual speed of a point on JI for 2012 was about three times as that in the mid-1990s. Two severe melting events occurred in 2010 and 2012 (Tedesco et al., 2011; Nghiem et al., 2012), which temporally accelerated the ice mass loss in JI.

Ice discharge and calving front retreat are the two main contributors to JI's dynamic mass loss. Cassotto et al. (2015) pointed

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out that seasonal variations in calving influence a glacier's long-term rate of retreat through nonlinear processes (Amundson and Truffer, 2010; Joughin et al., 2012). Simulations carried out by Muresan et al. (2016) also showed that the changes of JI horizontal velocities are a response to variations in terminus position. Bondzio et al. (2017) investigated the mechanisms causing widespread flow acceleration of JI using a three-dimensional model and found that the calving front position is the dominant control.

These studies indicate that the glacial mass loss is far from a steady process and variations in surface mass balance (SMB), ice discharge, and calving front positions can significantly influence the short-term variation of JI's ice mass balance. However, there is still a lack of detailed and quantitative analysis on the seasonal and transient (inter-annual) mass changes caused by SMB, ice discharge, and calving font positions at or near JI.

Currently, more than 50 continuously-operating Global Positioning System (GPS) receivers are deployed around the edge of the Greenland Ice Sheet, most of which are part of the Greenland network (GNET). These GPS sites provide important geodetic data that records the crust's response to historical/present ice mass changes. Previous studies have used GPS measurements of vertical crustal movements to study the present-day glacial mass change (Khan et al., 2010a; Bevis et al., 2012; Nielsen et al., 2013; Adhikari et al., 2017; Kjeldsen et al., 2017) or to constrain the glacial isostatic adjustment (GIA) signal (King et al., 2010; Khan et al., 2016). However, most of these studies focused on the long-term changes of glacial mass and few of them have addressed the transient and seasonal variations and the interaction between them. Zhang et al. (2017) combined the GPS- and GRACE-derived vertical displacements to mitigate the negative impacts of colored noise in GPS data and the low sensitivity of GRACE data to outlet glaciers and successfully detected and identified the transient ice mass changes in Upernavik Isstrøm, another Greenland outlet glacier located 450 km north of JI.

In this study, we aim to (1) characterize the seasonal and transient variations of the ice mass changes in the JI catchment, and to (2) partition individual contributions from SMB, ice discharge, calving front positions, and their sum. We use both GPS vertical and horizontal displacements and GRACE-derived vertical displacements to reconstruct the seasonal and transient signals using the multichannel singular spectral analysis (M-SSA) (Sections 2 and 3). We forward model the seasonal and transient displacements due to SMB, ice discharge, and calving front position changes (Section 4). We compare the seasonal and transient displacements from observations and models and present the ice thickness change using altimetry data (Section 5). The forward model offers quantitative insights into the seasonal and transient mass variations caused by SMB, ice discharge, and calving front retreat (Section 6). Compared with Zhang et al. (2017), this work is new in three aspects. First, the east component of GPS position time series is successfully used to detect the seasonal and transient signals. Second, the seasonal and transient mass loss caused by ice discharge and calving front changes are quantified separately. Third, we use the altimetry data and find the widespread thickening near the glacier's frontal portion from April 2016 to April 2017, which never happened in the previous decade. In addition to the above innovations, this study uses multi-source geodetic data (GPS, GRACE, altimetry, and Synthetic Aperture Radar) to reveal the ice mass changes from different perspectives, providing us a comprehensive knowledge of the highly-dynamic mass variations of JI.

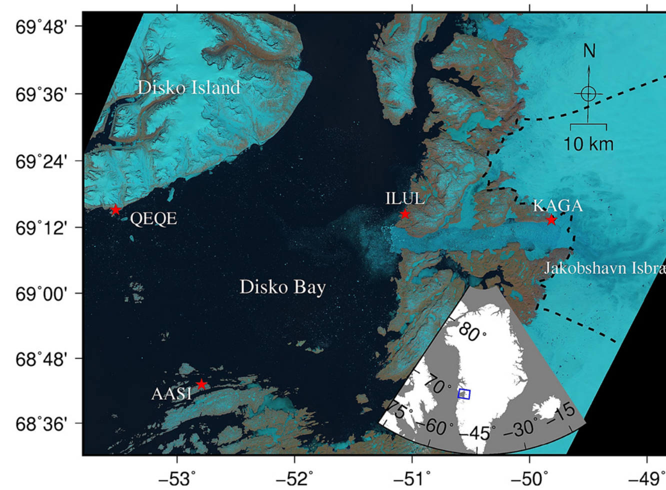

Fig. 1. Map of the study area. The background is a Landsat-8 image taken on May 31st, 2017. The red stars show the locations of the four GPS sites. The black dashed lines mark the JI catchment.

2. Geodetic data analysis

2.1. GPS data

As part of the GNET, four GPS sites were deployed near JI and on Disko Island in 2005 and 2006 (Fig. 1). Among them, KAGA is the closest to the glacier, which is only ∼6 km downstream from the calving front of JI on May 31, 2017; while ILUL, AASI, and QEQE are ∼56 km, ∼136 km, and ∼150 km from the calving front, respectively. The different sensitivities of the 4 sites to JI's mass change help to infer the approximate location of the mass change (Khan et al., 2010a; Wahr et al., 2013) and will also be beneficial for signal extracting.

The GPS data from April 2007 to April 2017 are processed by the same software and strategies as detailed in Khan et al. (2010a) and Liu et al. (2017). Data before 2007.4 at KAGA were bad in quality and thus are not used. At each site, we obtain time series of daily position solutions and their uncertainties in the local north, east, and up directions in the International Global Navigation Satellite System Service 2008 (IGS08) frame. Since we focus on the short-term displacements caused by ice loading changes, we first remove the trend and non-ice loadings from both the vertical and horizontal displacements. The technical details and the detrended time series can be found in Section S1 of the Supplementary Material (SM).

2.2. Vertical displacements derived from GRACE

We calculate the bedrock vertical displacements due to surface mass loading using the GRACE gravity data. The idea is to convert the time-varying gravitation fields to the vertical displacements using the load Love numbers (van Dam et al., 2007). We use the most recent release (RL06) of the GRACE GSM products (Level-2) from the Center for Space Research (CSR), University of Texas Austin. The CSR GSM products contain spherical harmonic coefficients up to degree 60 for each monthly gravity field. We include the degree-1 coefficients from Swenson et al. (2008) and use the monthly degree-2 order-0 coefficients from satellite laser ranging products provided by Cheng et al. (2013). These products have already removed the mass contributions from ocean and atmosphere. We further remove the continental water storage changes from the GSM products using the Noah land hydrology model in the Global Land Data Assimilation System (Rodell et al., 2004). The remain gravity changes are due to ice mass changes and GIA.