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Hybrid glacier Inventory, Gravimetry and Altimetry (HIGA) mass balance product for Greenland and the Canadian Arctic

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ABSTRACT

We present a novel inversion algorithm that generates a mass balance field that is simultaneously consistent with independent observations of glacier inventory derived from optical imagery, cryosphere-attributed mass trends derived from satellite gravimetry, and ice surface elevation trends derived from airborne and satellite altimetry. We use this algorithm to assess mass balance across Greenland and the Canadian Arctic over the Sep-2003 to Oct-2009 period at 26 km resolution. We evaluate local algorithm-inferred mass balance against forty in situ point observations. This evaluation yields an RMSE of 0.15 mWE/a, and highlights a paucity of in situ observations from regions of high dynamic mass loss and peripheral glaciers. We assess mass losses of 212 ± 67 Gt/a to the Greenland ice sheet proper, 38 ± 11 Gt/a to peripheral glaciers in Greenland, and 42 ± 11 Gt/a to glaciers in the Canadian Arctic. These magnitudes of mass loss are dependent on the gravimetry-derived spherical harmonic mass trend we invert. We spatially partition the transient glacier continuity equation by differencing algorithm-inferred mass balance from modeled surface mass balance, in order to solve the horizontal divergence of ice flux as a residual. This residual ice dynamic field infers flux divergence (or submergent flow) in the ice sheet accumulation area and at tidewater margins, and flux convergence (or emergent flow) in land-terminating ablation areas, which is consistent with continuum mechanics theory.

1. Introduction

Greenland is presently the single largest cryospheric source of sea level rise, contributing 0.73 ± 0.08 mm/a of sea level rise during the 2005 to 2010 period (Shepherd et al., 2012). Greenland's contribution to sea level rise was approximately equally divided between anomalies in meltwater runoff and iceberg calving during the 2000 to 2008 period (van den Broeke et al., 2009). Since 2009, however, meltwater runoff has been responsible for the majority of Greenland mass loss (Enderlin et al., 2014). Pursuing a process-level understanding of the contemporary partition of mass loss requires characterizing the spatial pattern of mass balance at a sub-basin or glacier scale, which allows mass balance to be differenced from modeled surface mass balance in order to solve for the ice dynamic component of mass change through iceberg calving. Accurate knowledge of the contemporary partitioning of mass loss between meltwater runoff and iceberg calving can serve as a key diagnostic modeling target, in order to improve confidence in prognostic model simulations.

Three methods are available for assessing mass balance at the ice sheet scale: (i) input–output, (ii) altimetry, and (iii) gravimetry. The first approach, also known as the mass budget approach, differences ice discharge estimated near the grounding line of outlet glaciers from surface mass balance modeled over the ice sheet (e.g. Rignot, Box, Burgess, & Hanna, 2008; van den Broeke et al., 2009). The second approach converts ice surface elevation trends observed by repeat airborne or satellite altimetry into mass trends using an effective density of change estimated through firn modeling (e.g. Sørensen et al. 2011; Zwally et al., 2011). The third approach uses repeat satellite gravimetry observations and numerous geophysical forward models to assess cryospheric mass trends (e.g. Velicogna & Wahr, 2005; Wu et al., 2010). Each method has unique advantages and disadvantages relative

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to the other methods (Alley, Spencer, & Anandakrishnan, 2007). While satellite altimetry characterizes the spatial variability of surface elevation trends at relatively high resolution, it relies on forward modeling of complex firn processes to estimate mass trends. Conversely, the cryospheric mass trends observed by satellite gravimetry and isolated by forward models, while accurate in absolute terms, have relatively poor spatial resolution.

Here, we combine the two strengths of gravimetry and altimetry in order to refine absolute measurements of cryosphere-attributed mass trends to higher spatial resolution. In this process, we overcome two complementary weaknesses: dependence on modeling complex firn processes as well as the fundamental spatial resolution of satellite gravimetry. The 26 km spatial resolution mass balance field we derive through an iterative inversion approach is simultaneously consistent with: (i) ice-sheet and glacier inventory derived from optical imagery, (ii) gravimetry-derived cryospheric mass trends, and (iii) altimetry-derived ice surface elevation trends. We refer to this as a Hybrid glacier Inventory, Gravimetry and Altimetry (HIGA) product. This data product is available in the supplementary material associated with this paper.

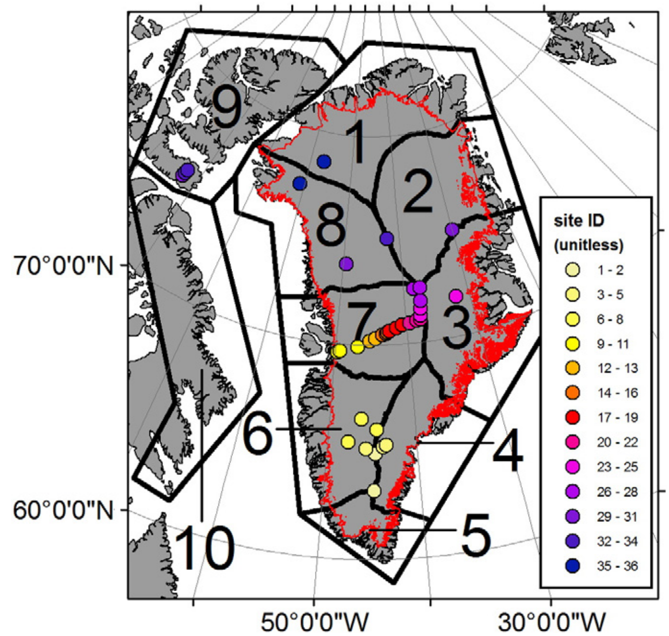

Fig. 2. The ten sectors in which mass balance is assessed. The eight Greenland sectors correspond to the major ice sheet drainage systems delineated by Zwally et al. (2012). Red line denotes the ice sheet margin. Points denote locations of in situ mass balance observations (Table 1).

2. Data

Our inversion algorithm requires three distinct pieces of input data: (i) fractional ice coverage derived from optical imagery, (ii) cryosphere-attributed mass trends derived from satellite gravimetry, and (iii) ice surface elevation trends derived from satellite and airborne altimetry. We compile each of these datasets over a common region of interest focused on Greenland and the Canadian Arctic (Fig. 1). Our time interval of interest is the Sep-2003 to Oct-2009 Ice, Cloud and land Elevation Satellite (ICESat) operational period. We assess mass balance in ten geographic sectors, eight in Greenland and two in the Canadian Arctic (Fig. 2). The eight Greenland sectors are equivalent to the eight major ice sheet drainage systems delineated by Zwally, Giovinetto, Beckley, and Saba (2012), but have been extended beyond the ice sheet margin to also encompass peripheral glaciers and ice caps. The two Canadian Arctic sectors are equivalent to those employed by Gardner et al. (2011). Shapefiles of these ten sector boundaries are available in the supplementary online material associated with this paper.

2.1. Glacier inventory

We calculate fractional ice coverage within our study region by clipping glacier inventory polygons with a polygon fishnet matching the inversion grid. We then sum the glacierized area within each grid cell, and scale areas to correct for projection-related distortion. In Greenland, we sum peripheral glacier and ice sheet coverage separately. The Greenland glacier inventory data are derived from aerophotogrammetry with a polygon accuracy of 10 m (Citterio & Ahlstrøm, 2013). This inventory has previously classified glaciers and ice caps demonstrating "no" (class zero or CL0) or "weak" (class one or CL1) connectivity with the

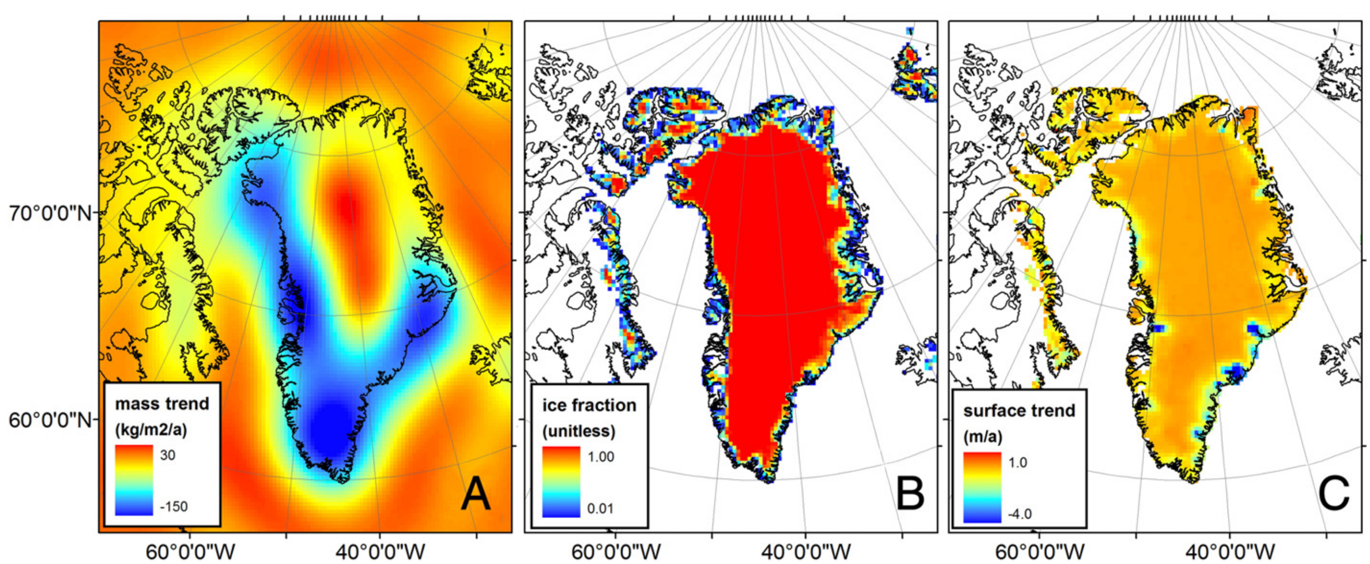

Fig. 1. A: Spherical harmonic representation of cryosphere-attributed mass trends derived from gravimetry (Luthcke et al., 2013). B: Fractional ice coverage, derived from glacier inventories generated by optical imagery (Citterio & Ahlstrøm, 2013; Pfeffer et al., 2014). C: Ice surface elevation trends derived from altimetry (Gardner et al., 2011; Schenk & Csatho, 2012). Map extent corresponds to inversion domain extent. Color scales saturate at minimum and maximum values.