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Accelerated West Antarctic ice mass loss continues to outpace East Antarctic gains

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A R T I C L E I N F O

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A B S T R A C T

While multiple data sources have confirmed that Antarctica is losing ice at an accelerating rate, different measurement techniques estimate the details of its geographically highly variable mass balance with different levels of accuracy, spatio-temporal resolution, and coverage. Some scope remains for methodological improvements using a single data type. In this study we report our progress in increasing the accuracy and spatial resolution of time-variable gravimetry from the Gravity Recovery and Climate Experiment (GRACE). We determine the geographic pattern of ice mass change in Antarctica between January 2003 and June 2014, accounting for glacio-isostatic adjustment (GIA) using the IJ05_R2 model. Expressing the unknown signal in a sparse Slepian basis constructed by optimization to prevent leakage out of the regions of interest, we use robust signal processing and statistical estimation methods. Applying those to the latest time series of monthly GRACE solutions we map Antarctica's mass loss in space and time as well as can be recovered from satellite gravity alone. Ignoring GIA model uncertainty, over the period 2003–2014, West Antarctica has been losing ice mass at a rate of -121 ± 8 Gt/yr and has experienced large acceleration of ice mass losses along the Amundsen Sea coast of -18 ± 5 Gt/yr^2, doubling the mass loss rate in the past six years. The Antarctic Peninsula shows slightly accelerating ice mass loss, with larger accelerated losses in the southern half of the Peninsula. Ice mass gains due to snowfall in Dronning Maud Land have continued to add about half the amount of West Antarctica's loss back onto the continent over the last decade. We estimate the overall mass losses from Antarctica since January 2003 at -92 ± 10 Gt/yr.

1. Introduction

Knowing where and how mass currently changes in polar ice sheets is of great importance (Oppenheimer, 1998; Mitrovica et al., 2011; Stocker et al., 2013). Observations indicate that the Antarctic Ice Sheet is very sensitive to climate change (Raymo and Mitrovica, 2012; Bromwich et al., 2013; Cook et al., 2013; Kopp et al., 2013), and knowledge of individual glaciers and ice streams is important to understand the process. Ultimately, the continental ice sheet response to global change is the sum of the behaviors within individual drainage basins, which are subject to the combined effects of surface mass balance, calving and basal melting, and influenced by their geographic location and topography. The contemporary record of ice sheet mass balance has solidified significantly partly owing to the data gathered since 2002 by GRACE, the Gravity Recovery and Climate Experiment (Chen et al., 2006, 2009; Velicogna and Wahr, 2006). The continent-wide, decadally averaged mass balances of Antarctica, estimated by a variety of techniques, all show that Antarctica is losing mass (Shepherd et al., 2012; Hanna et al., 2013) at an accelerated rate (Luthcke et al., 2013; Williams et al., 2014).

While the large-scale spatial and long-term temporal signal trends during the 1990s and 2000s have been well determined, we focus here on the smaller scales recoverable by satellite gravity, and quantify their uncertainty. In Antarctica, improvements in modeling the ongoing glacio-isostatic adjustment from the Last Glacial Maximum deglaciation (for an accessible review, see King, 2013) have increased the precision of gravimetric mass balance estimates. As a result, the detailed pattern of mass change has been the focus of recent GRACE studies (Sasgen et al., 2010, 2013; Harig and Simons, 2012; Horwath et al., 2012; King et al., 2012; Lee et al., 2012; Luthcke et al., 2013; Velicogna and Wahr, 2013; Bouman et al., 2014). To inform our estimates of sea level change for the coming century it is imperative that we continue to build and improve the detailed record of changes in ice mass (Overpeck et al., 2006; Little et al., 2013a, 2013b). In this paper we show

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when and where Antarctica has been losing mass over the last decade, using a method of spherical Slepian functions.

2. Motivation

As GRACE processing of intersatellite range-rates (Rowlands et al., 2005; Luthcke et al., 2006; Bettadpur and the CSR Level-2 Team, 2012) and global statistical estimation techniques (Schmidt et al., 2006; Han et al., 2008; Baur et al., 2009; Rowlands et al., 2010) have improved in recent years, the opportunity for contemporary gravimetric studies is to produce a better-resolved ice mass history and to understand its error structure at the same time. Knowledge of ice mass balance at a fine level of spatial detail is ultimately required to enable comparisons of gravity-based estimates with other data sets and models that discretely sample the surface. Data sets and models from point estimates (e.g., laser and radar altimetric observations, GPS time series, or surface mass balance studies) show that Antarctica's mass flux is highly spatially variable (Rignot et al., 2008a; Lenaerts et al., 2012; Pritchard et al., 2012). Fast-moving glaciers along the Amundsen Sea coast contribute the greatest amount of mass loss (Rignot, 2008; Rignot et al., 2011; Pritchard et al., 2009), while areas of the Antarctic Peninsula (Rignot et al., 2004) and Wilkes Land (Rignot et al., 2008a) are estimated to have experienced more modest losses. These high-resolution non-gravimetric observations are substantiated by our own new gravity-based results, which are aggregate, not point-based, measurements. The subtle differences between our regional solutions and those of other authors suggest that refining analysis approaches, increasing spatial resolution, and noise mitigation will all remain important research topics in the near future.

Rather than building a consensus model from different data types, each mismatched in their footprint and individual sensitivities to ice mass changes, here we use a uniquely sensitive Slepian-function based gravimetric processing method to localize global GRACE data to several Antarctic regions that display distinct geographic variability, and subsequently focus on the map changes over time within each region. In the main body of this paper we focus our attention on results obtained for the regions of greatest mass change in West Antarctica, and discuss ice mass loss trends in the Peninsula and Dronning Maud Land. Additional details are examined in the *Supplementary Material.*

3. Methods

In this study we use time-variable gravimetry to determine the mass change in Antarctica since 2003. We closely follow the methods of Harig and Simons (2012) and analyze GRACE Level 2 data using scalar spherical Slepian functions (Simons et al., 2006). GRACE data are released as coefficients to spherical harmonic functions, which spread their energy over the entire globe. In order to examine geophysical signals in specific regions, most authors (ourselves included) project global gravity data into alternate regionally sensitive bases, such as wavelets or radial basis functions (Schmidt et al., 2007; Eicker et al., 2014), pixel grids (Chen et al., 2009), point masses or mascons expressed as sensitivity functions in spherical harmonics (Baur and Sneeuw, 2011; Jacob et al., 2012; Luthcke et al., 2013; Schrama et al., 2014). Many of these approaches suffer the same limitations as spherical harmonics when used for regional analysis, namely a lack of orthogonality over arbitrary regions of interest. As a result, these approaches often use regularized inversion procedures which can sometimes negatively impact results (e.g., Bonin and Chambers, 2013). Spherical Slepian functions, by construction, are orthogonal both over the globe and over individual regions, thus simplifying data analysis.

3.1. Construction of the Slepian basis

The Slepian basis is a spatiospectrally localized linear combination of spherical harmonics optimized to study specific regions on the sphere (for a review, see Simons, 2010). The simplicity of the Slepian basis method is that its construction is tuned by only three variables: the spherical-harmonic bandwidth of the basis, the coordinates of the spatial region under study, and any buffer around the outlines of the region proper, to account for possible mass changes near the edges. The triplet of parameters is picked after a sequence of simulations using synthetic input data.

Our initial coordinate outlines for the Antarctic regions include grounded ice (except for the Peninsula, where all floating ice was used, as noted below and in the *Supplementary Material*) determined from ICESat altimetry (Zwally et al., 2012). Those regions were then enlarged with a buffer of 0.5° extending outward from land–ocean borders. The size of the buffer zone was determined by simulating and recovering a uniform mass change over grounded ice, to render the overall mass estimate unbiased. The buffer accounts for the fact that smoothly varying bandlimited functions are ill-suited for recovering a field near to a region boundary. The bandwidth of the Slepian bases covers spherical-harmonic degrees up to $L = 60$, which matches the bandwidth of GRACE data supplied by most data centers. Thus there is no loss of spatial resolution by projecting the Level 2 data onto the Slepian bases.

We use the outline of the region R to integrate the products of spherical harmonics Y_{lm} as

$$\int_R Y_{lm} Y_{l'm'}\, d\Omega = D_{lm,l'm'}. \tag{1}$$

The spherical-harmonic expansion coefficients of the Slepian functions, g_{lm}, are the eigensolutions of the equation

$$\sum_{l'=0}^{L} \sum_{m'=-l'}^{l'} D_{lm,l'm'}\, g_{l'm'} = \lambda g_{lm}. \tag{2}$$

The functions maximize their energy within the specified region; the corresponding eigenvalue λ is a measure of that concentration (Simons et al., 2006). Using only the most concentrated eigenfunctions ($\lambda \gtrsim 0.5$) leaves a low-dimensional scalar Slepian basis for the inverse problem, similar to a singular-value decomposition, which we can use to represent the potential field localized to our region without undue influence from other parts of the globe. In this manner, we explicitly seek to minimize the leakage in and out of our region. Truncated expansions of Slepian functions have many advantages over damped spherical-harmonic expressions for these kinds of estimation problems (Simons and Dahlen, 2006).

3.2. Solution of the inverse problem

With a sparse representation of the signal (which is perhaps the greatest advantage of the Slepian-function approach, and one that is successfully exported to inverse problems in other areas of geophysics and planetary studies; Simons et al., 2009) and empirical knowledge of the noise distribution (as derived from the correlation structure of the misfit of the expansion coefficients with respect to the modeled temporal behavior) our procedure extracts the time-variable geographic mass distribution with a unique spatio-temporal resolution. By increasing the local signal-to-noise ratio, the Slepian basis remains sensitive to spatial features within the region at the full resolution of the Level 2 GRACE data (up to a spherical-harmonic degree $L = 60$; higher-bandwidth solutions, up to $L = 90$, exist, but suffer from decreased signal-to-noise ratios), and we become less reliant on the spatial averaging