Spatial Localization of Greenland Mass Wasting Using a 2-D Wavelet Decomposition of GRACE Data and Comparison to Physical Drivers of Ice Loss

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This paper represents my own work in accordance with University regulations,

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Abstract

Melting ice from the Greenland Ice-Sheet has accounted for an increasing percentage — now estimated at over 25% — of rising global mean sea-level since the early 1990s. As recently as 2016, gravimetric and altimetric studies of Greenland melting rates found increasing rates of ice loss, which have not been borne out in GRACE gravimetric observations over the last few years (2015–2017). We hypothesize that the true trend of Greenland ice loss between 2003–2017 is linear, and that deviations from the linear trend may be explained by inter-annual variability in climate. We demonstrate a novel application of 2-dimensional discrete wavelet analysis to the GRACE dataset to recover spatial structure of inter-annual variability in ice loss, focusing on the unusual melt and accumulation seasons of 2012–2014. Finally, we compare our interpretation of the 2012–2014 anomaly in spatial scale and location to the results of others using independent atmospheric, altimetric, and meteorologic data sources.

Key Points:

1. We focus on inter-annual variability of the Greenland ice loss trend.
2. We analyze subregional signals using discrete wavelet transforms.
3. We define the 2012–2014 anomaly in spatial structure.

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Introduction

Average global surface temperature is rising at an increasing rate — approximately 0.09° C per decade since 1880, and approximately 0.26° C per decade since 1979 (Hartmann et al., 2013) — and has contributed to significant melting of the Greenland ice sheet, with recent ice loss approximated at -244 Gt per year (Harig & Simons, 2015, 2016). The Greenland Ice Sheet covers just over 1% of Earth's surface, and, if completely melted, would raise sea level by over 7 m (Vaughan et al., 2013). Massive loss of ice has significant repercussions for human civilization, bringing with it a rising sea level at about 1–2 mm per year at the end of 2010 (Church et al., 2013). Our broad goal is to understand deviations from modeled rates of Greenland ice melt in order to better understand, predict, and communicate the changing conditions of the planet.

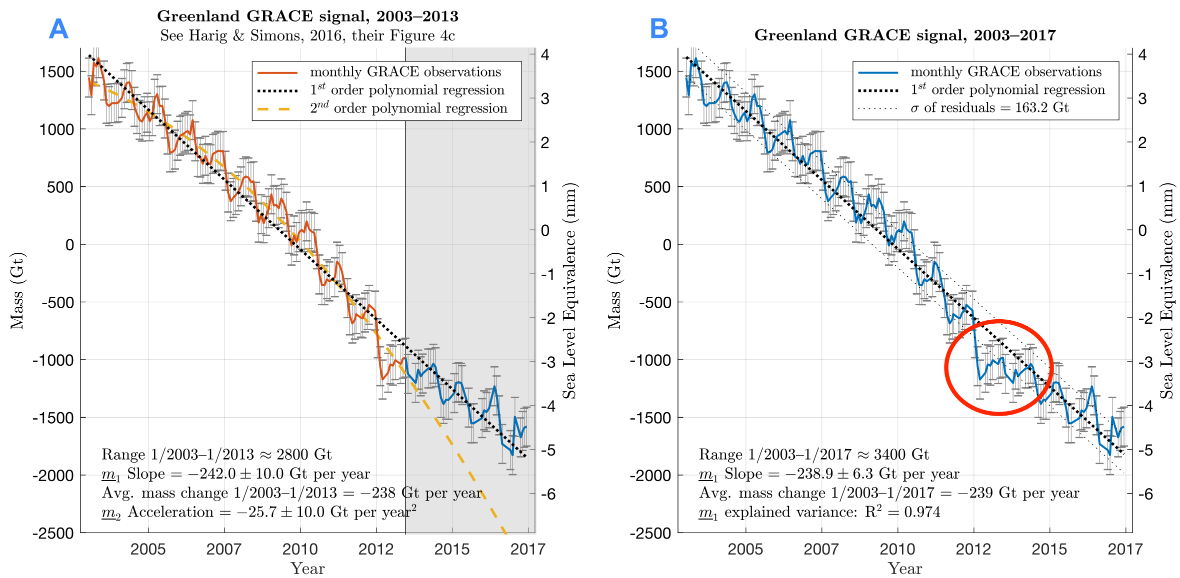

Figure 1: Total mass changes for Greenland over the complete GRACE record using equivalent methods to Harig & Simons (2016). Shown in **A** are the $\underline{m}_1$ (linear) and $\underline{m}_2$ (quadratic) models for 01/2003–06/2013, comparable to previous estimates of the mass trend (Harig & Simons, 2016). Note the significant departure of the extrapolated $\underline{m}_2$ model from the continuing signal. Shown in **B** is the $\underline{m}_1$ linear model for 01/2003–06/2017 with the standard of deviation of its residuals. Note that the $\underline{m}_1$ model does not significantly change after including the entire GRACE record. Error bars represent 2σ based on the combined variance of modeled Slepian coefficients f_α (see Harig & Simons (2016), as well as Getraer (2017, 2018)). This figure appeared in Getraer (2017, 2018), here with minor updates.

Ice loss on the Greenland Ice Sheet has been observed in gravitational measurements from NASA's Gravity Recovery and Climate Experiment (GRACE), satellite and airplane based altimetry, and energy balance models, finding acceleration of melt in the ice mass signal over most of the last two decades (Harig & Simons, 2016; Khan et al., 2015). Rates of ice loss increase by a combination of greater discharge from calving glacier termini at the edges of the ice-sheet and decreased surface mass-balance, the difference between seasonal snow accumulation and melting (Enderlin et al., 2014; Khan et al., 2015). Significant inter-annual variability and asynchronicity has been observed in the discharge rates of the Greenland Ice Sheet's major drainage basins, while surface mass-balance is comparatively more predictable (Enderlin et al., 2014; McMillan et al., 2016). Both contributions to ice loss accelerated between 2000–2012, combining for a total acceleration of ice mass estimated around -30 Gt per year^2 over all of Greenland (Enderlin et al., 2014; Velicogna, 2009).

A study by Harig & Simons (2016) modeling the mass of the Greenland Ice Sheet using GRACE data products showed deviations from the long-term accelerating trend, starting with a high level of melt in the summer of 2012, and followed by two summers of little melting in 2013 and 2014 (see Figure 1 A, comparable to Harig & Simons, 2016, their Figure 4). Our analysis of the complete GRACE data set (2002–2017) using identical methods showed a linear, not accelerating, trend of ice loss for the Greenland Ice Sheet, constraining the observed unexpected deviations to an unusually large melt summer of 2012 followed by a summer of unusually little melt in 2013 (see Figure 1 B).

The anomalous seasons of 2012–2013 have received attention in recent literature by studies attempting to understand how surface mass balance processes produce such inter-annual variability. Correlations have been found with climate indices such as the phase of the North Atlantic Oscillation (NAO) (Bevis et al., 2018; Getraer, 2017; McMillan et al., 2016), transient atmospheric transport of warm air and water vapor in so-called "atmospheric rivers" (Mattingly et al., 2018), and non-radiative energy flux enhanced by short-term cloud cover (Solomon et al., 2017).

The atmospheric circulation affecting the Greenland Ice Sheet is broadly controlled by the position of the polar jet

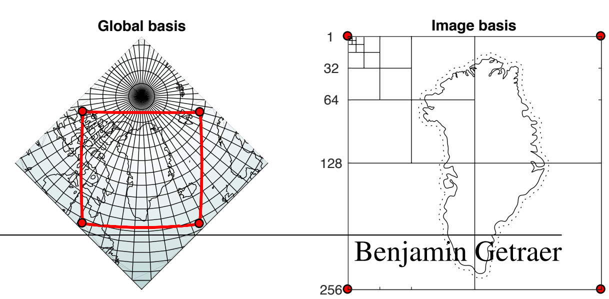

Figure 3: A grid is defined in the global basis on a face of the Cubed Sphere centered on Greenland, upon which the gravita-

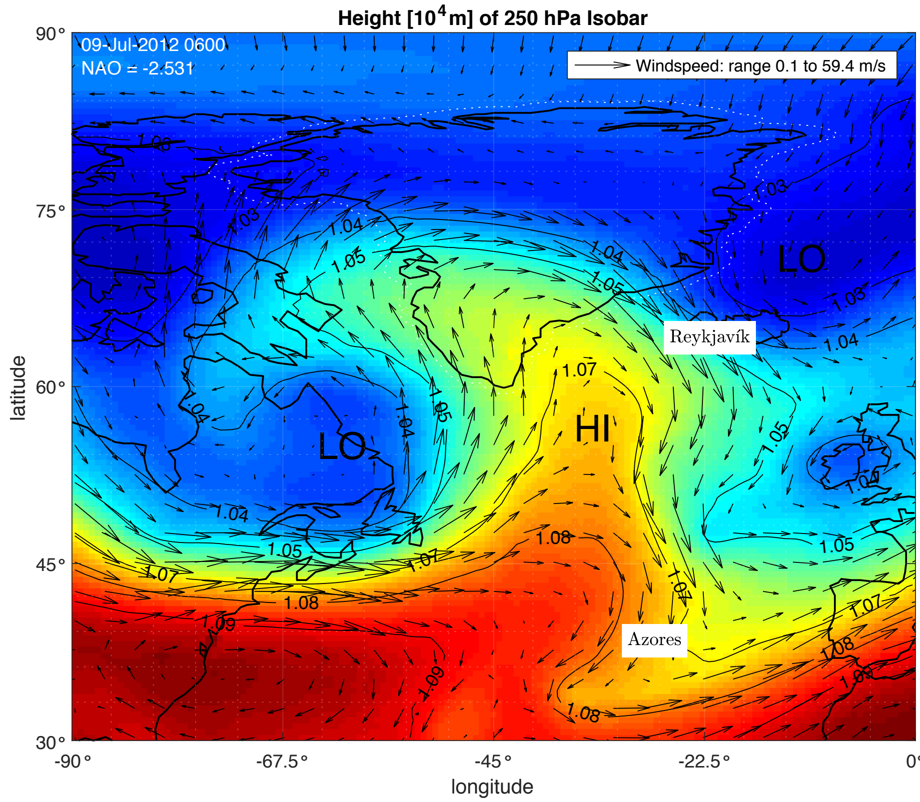

Figure 2: Example of atmospheric conditions at the 250 hPa isobar over the North Atlantic preceding record Greenland Ice Sheet surface melt, 07/09/2012 (from MERRA-2 reanalyzed data). Isobar height contours are labeled in 10^4 m, and wind vectors are shown by arrows. Note the location of the northern polar jet stream, dividing the low and high isobar heights around the 1.05×10^4 m contour. The temporary North Atlantic Rossby wave is labeled as the "HI" pressure anti-cyclone moving north towards southern Greenland, with a complementary "LO" pressure cyclone centered over Labrador. Note that the jet stream is deflected through the Labrador Sea and Baffin Bay, along the West Coast of Greenland. As a result of these conditions, the "LO" pressure over Reykjavík is pushed north, and the pressure difference between Reykjavík and Azores is lowered, resulting in an negative NAO index (top left).

stream in the northern hemisphere (Hanna et al., 2013; Mattingly et al., 2018). Specifically, strong summer melt events often occur with a negative NAO index and high pressure "blocking" over southern Greenland, advecting warm moist air into the Arctic along the west coast of Greenland (Bevis et al., 2018; Getraer, 2017; Hanna et al., 2013; Mattingly et al., 2018; McMillan et al., 2016). The NAO index broadly represents the difference in atmospheric pressure between the typically cold, low-pressure Arctic air near Reykjavík, Iceland, and the typically warm, high-pressure air near Azores, Portugal, divided by the location of the polar jet stream (see Figure 2). When the Azores high-pressure system pushes the jet stream northward, the pressure difference across the North Atlantic is weaker, producing a negative NAO index (Figure 2). This temporary high-pressure excursion into the arctic is known as a Rossby wave and is accompanied by complementary low-pressure cyclones which develop on either side of the high-pressure block, the combined flow from which advects warm air into the Arctic until the Rossby wave "breaks" and the jet stream return to its typical location. These atmospheric conditions are illustrated in Figure 2, illustrating the Greenland blocking event in July 2012, immediately preceding record surface melting on the Greenland Ice Sheet on 07/11/2012 (Hanna et al., 2013; Mattingly et al., 2018).

The general conclusions drawn by these studies point to common atmospheric processes of uncommon duration or intensity.

Previous Results

In my Spring 2018 JP, I explored the use of a 2-D wavelet basis to represent the GRACE gravimetric data over Greenland such that meaningfully contributing basis functions also contained information about spatial structure (see Figure 3).

I developed a procedure for choosing the most important wavelet basis functions in order to extract the true fluctuation of the signal from the over-determined image calculated from the typical GRACE spherical

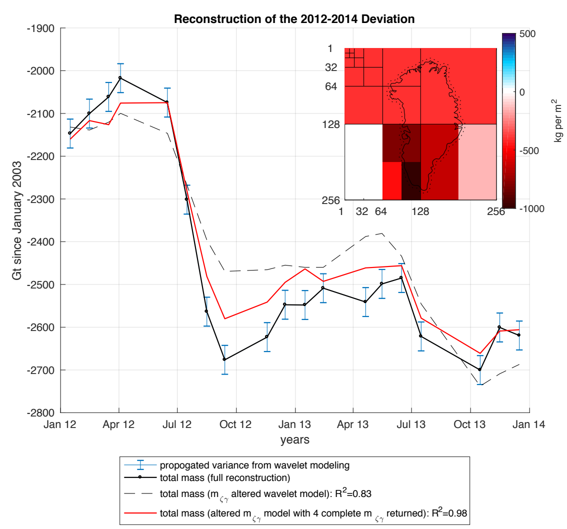

Figure 4: The 2012–2014 deviation in Greenland mass and the total from the reconstructed modeled wavelet coefficients. By adding in the real values of only four wavelet coefficients back into the modeled wavelet reconstruction we improve the variance explanation by 15%. These wavelets are shown inset, weighted by their values in September 2012, the extreme of the deviation, and are concentrated in southwestern Greenland. "$m_{\zeta\gamma}$" refers to a wavelet basis function "m" of index γ in level ζ. This Figure appeared in my Spring JP.

harmonic basis. I then tested which wavelet
basis function best captured the 2012–2013
deviation from the expected signal, finding the deviations to be concentrated in southwestern Greenland (see Figure 4).

Next steps

1. quantitative image to image comparison of moisture transport and mass loss
2. calculate mass loss on a sub basin spatial level across Greenland and compare to other estimates
3. pressure relationship

The NAO index is unitless, and represents the relative magnitude of the 500mb pressure difference between Azores and Reykjavík compared to the 1950–2000 monthly mean.

Appendix A: Data and code sources

RL05 spherical harmonic coefficients for the time-variant geopotential field from the GFZ, JPL, and CSR data processing centers are available at:

`ftp://podaac.jpl.nasa.gov/allData/grace/L2/`

Coefficients describing Earth's center of mass (spherical harmonic degree 1, from Swenson et al., 2008) are available at:

`ftp://podaac-ftp.jpl.nasa.gov/GeodeticsGravity/tellus/L2/degree_1/`

Coefficients describing Earth's oblateness (spherical harmonic degree 2, order 0, from Cheng et al., 2013) are available at:

`ftp://ftp.csr.utexas.edu/pub/slr/degree_2/`

Monthly values for the North Atlantic Oscillation Index are calculated by the Climate Prediction Center, with normalized monthly average values since January 1950 available at:

`ftp://ftp.cpc.ncep.noaa.gov/wd52dg/data/indices/nao_index.tim`

Reanalyzed MERRA-2 atmospheric data (3 dimensional, 6-hourly, instantaneous pressure-level analysis, V5.12.4) are calculated by NASA and made available by the Goddard Earth Sciences Data and Information Services Center at:

`https://goldsmr5.gesdisc.eosdis.nasa.gov/opendap/MERRA2/M2I6NPANA.5.12.4/`

Global Modeling and Assimilation Office (GMAO) (2015), MERRA-2 inst6$_3d_ana_Np : 3d, 6 - Hourly, Instantaneous, Pressure-Level, Analysis, AnalyzedMeteorologicalFieldsV5.12.4, Greenbelt, MD, USA,$
$[DataAccessDate], 10.5067/A7S6XP56VZWS$

MATLAB code for the expansion and manipulation of spherical harmonic eigenfunctions into Slepian bases and manipulation of GRACE files is borrowed and adapted from:

`https://github.com/csdms-contrib/`

MATLAB code developed for this project, including functions for executing the wavelet analysis and scripts for generating figures, can be accessed at:

`https://github.com/bgetraer/slepian_bgetraer/`

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