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

Benjamin Getraer

Senior Thesis Draft

Presented to the Faculty

of Princeton University

in Candidacy for the Degree

of Bachelor of Arts

Recommended for Acceptance

by the Department of

Geosciences

Adviser: Laure Resplandy

Second Reader: Frederik J. Simons

December 13, 2018

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

Benjamin Getraer

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.

Acknowledgements

Thank you to my thesis adviser Prof. Laure Resplandy who has helped me understand and think through atmospheric processes and the direction this project has taken this year. Thank you to my Junior Paper adviser Prof. Frederik J. Simons who helped me with the conceptualization, direction, and revision of earlier portions of this project. Thank you to the second reader of my Fall Junior Paper, Prof. Jessica Irving for feedback, suggestions, and encouragement. Thanks to Dr. Amanda Irwin Wilkins and "The Hare" writing workshop group for discussing and editing various figures and drafts of my Junior Papers. Thank you to Prof. Adam C. Maloof who taught me LaTeX, and to Dr. Chris Harig for providing some of the data files. Thank you to Prof. Gabriel Vecchi for insight into atmospheric and oceanic processes. Thank you to Jean Getraer, Andrew Getraer, Jonathan Feld, Rae Perez, and Zach Smart for proof-reading various Junior Paper drafts. Lastly, thank you to the numerous professors and graduate and undergraduate students in the Princeton Department of Geosciences for feedback, encouragement, and constructive criticism on various presentations of preliminary results. A big thanks especially to all of the people who asked me, "What is your independent work about?" and then patiently listened while I struggled to articulate this project in a way that made any sense.

Contents

Abstract **iii**

Acknowledgements **iv**

List of Figures **vi**

List of Tables **vii**

Main Text **1**

Introduction 1

Previous Results 3

References **4**

List of Figures

1 Greenland Mass Trend: 2003–2017 1

2 The Discrete Grid Around Greenland 2

3 Location of the 2012–2014 Deviation 3

List of Tables

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.

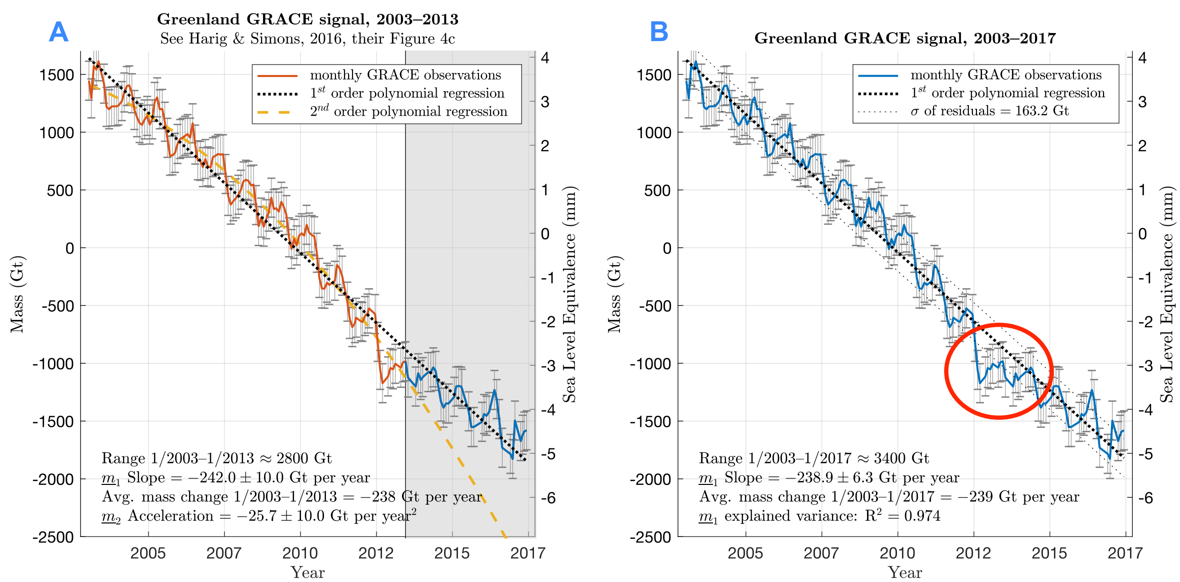

Figure 1: Total mass changes for Greenland over the complete GRACE record using equivalent methods to Harig & Simons (2016). Shown in **A** are the $\underline{m}_1$ (linear) and $\underline{m}_2$ (quadratic) models for 01/2003–06/2013, comparable to previous estimates of the mass trend (Harig & Simons, 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 mass of the Greenland Ice Sheet has been calculated using gravimetric data from NASA's Gravity Recovery and Climate Experiment (GRACE), as well as satellite and airplane based altimetry, finding decreasing rates in the ice mass signal over the last decade (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 quadratic 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).

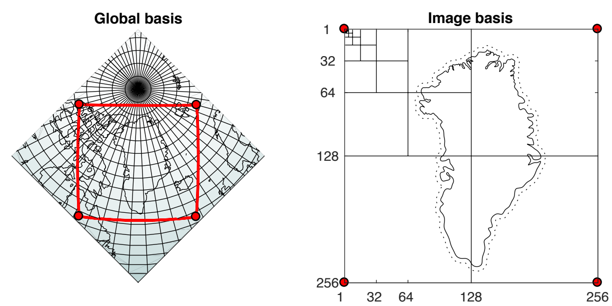

Figure 2: A grid around Greenland is defined in the global basis on a face of the Cubed Sphere centered on Greenland on which the GRACE spherical harmonic data are solved. In the image basis the grid is cartesian with length 256. Grid lines in the image basis represent the diminishing spatial support of wavelets of different levels, from $\zeta = 8$ (the entire image) to $\zeta = 1$ (a unit grid cell). Note that in reality, each wavelet level has coverage over the entire image. The dotted line around Greenland is a coastal buffer of 0.5° as in Harig & Simons (2016). This Figure appeared in my Spring JP.

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

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 2).

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 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 3).

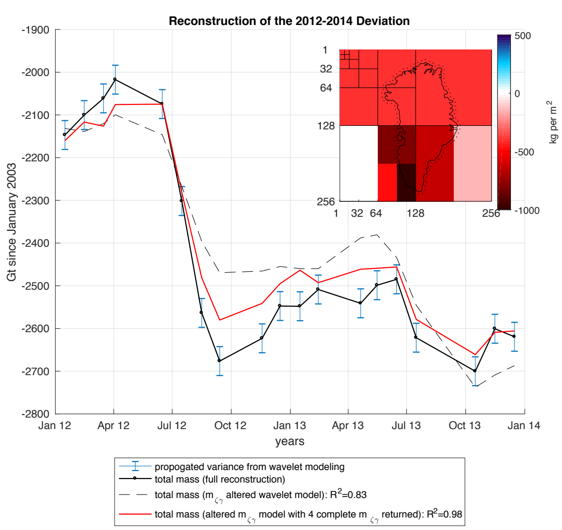

Figure 3: The 2012–2014 deviation in Greenland mass and the total from the reconstructed modeled wavelet coefficients. By adding in the real values of only four wavelet coefficients back into the modeled wavelet reconstruction we improve the variance explanation by 15%. These wavelets are shown inset, 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.

References

Bevis, M., Harig, C., Khan, S. A., Brown, A., Simons, F. J., Willis, M., Fettweis, X., van den Broeke, M. R., Madsen, F. B., Kendrick, E., Caccamise II, D. J., van Dam, T., Knudsen, P., & Nylen, T., 2018. Accelerating changes in ice mass within Greenland, and the ice sheet's sensitivity to atmospheric forcing, *in submission to Proc. Natl. Acad. Sc.*.

Church, J., Clark, P., Cazenave, A., Gregory, J., Jevrejeva, S., Levermann, A., Merrifield, M., Milne, G., Nerem, R., Nunn, P., Payne, A., Pfeffer, W., Stammer, D., & Unnikrishnan, A., 2013. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, chap. Sea Level Change, p. doi: 10.1017/CBO9781107415324, Cambridge Univ. Press.

Enderlin, E. M., Howat, I. M., Jeong, S., Noh, M.-J., van Angelen, J. H., & van den Broeke, M. R., 2014. An improved mass budget for the Greenland ice sheet, *Geophysical Research Letters*, **41**(3), 866–872 doi 10.1002/2013GL059010.

Getraer, B., 2017. Resolving and Contextualizing the Signal of Greenland Ice Loss 2014–2017, *Princeton Department of Geosciences*, **Fall Junior Paper, unpublished**.

Getraer, B., 2018. Regional Forcing of Greenland Ice Loss 2002–2017, *Princeton Department of Geosciences*, **Spring Junior Paper, unpublished**.

Harig, C. & Simons, F. J., 2015. Accelerated West Antarctic ice mass loss continues to outpace East Antarctic gains, *Earth Planet. Sci. Lett.*, **415**, 134–141, doi: 10.1016/j.epsl.2015.01.029.

Harig, C. & Simons, F. J., 2016. Ice mass loss in Greenland, the Gulf of Alaska, and the Canadian Archipelago: Seasonal cycles and decadal trends, *Geophysical Research Letters*, **43**(7), 3150–3159, doi: 10.1002/2016GL067759.

Hartmann, D., Tank, A. K., Rusticucci, M., Alexander, L., Brönnimann, S., Charabi, Y., Dentener, F., Dlugokencky, E., Easterling, D., Kaplan, A., Soden, B., Thorne, P., Wild, M., & Zhai, P., 2013. *Cli-*

mate Change 2013: The Physical Science Basis. Contribution of Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, chap. Observations: Atmosphere and Surface, p. doi: 10.1017/CBO9781107415324, Cambridge Univ. Press.

Khan, S. A., Aschwanden, A., Bjørk, A. A., Wahr, J., Kjeldsen, K. K., & Kjær, K. H., 2015. Greenland ice sheet mass balance: a review, *Reports on Progress in Physics*, **78**(4), 046801.

Mattingly, K., Mote, T., & Fettweis, X., 2018. Atmospheric River Impacts on Greenland Ice Sheet Surface Mass Balance, *Journal of Geophysical Research: Atmospheres*, **123**, 8538–8560, doi: 10.1029/2018JD028714.

McMillan, M., Leeson, A., Shepherd, A., Briggs, K., Armitage, T. W., Hogg, A., Munneke, P. K., van den Broeke, M., Noël, B., van de Berg, W. J., Ligtenberg, S., Horwath, M., Groh, A., Muir, A., & Gilbert, L., 2016. A high-resolution record of Greenland mass balance, *Geophysical Research Letters*, **43**(13), 7002–7010, doi: 10.1002/2016GL069666.

Solomon, A., Shupe, M. D., & Miller, N. B., 2017. Cloud-Atmospheric Boundary Layer-Surface Interactions on the Greenland Ice Sheet during the July 2012 Extreme Melt Event, *Journal of Climate*, **30**(9), 3237–3252.

Vaughan, D., Comiso, J., Allison, I., Carrasco, J., Kaser, G., Kwok, R., Mote, P., Murray, T., Paul, F., Ren, J., Rignot, E., Solomina, O., Steffen, K., & Zhang, T., 2013. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I Contribution to the Fifth Assessment Report*, chap. Observations: Cryosphere, p. doi: 10.1017/CBO9781107415324, Cambridge Univ. Press.

Velicogna, I., 2009. Increasing rates of ice mass loss from the Greenland and Antarctic ice sheets revealed by GRACE, *Geophysical Research Letters*, **36**(19), doi 10.1029/2009GL040222, L19503.