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

April 1, 2019

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 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

List of Figures

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) — with the past five years (2014–2018) being approximately 0.84° C warmer than the 1880–2018 average (NOAA, 2019). Earth's warming climate has contributed to significant melting of the Greenland ice sheet, and recent ice loss is estimated 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). Global melting of ice sheets and glaciers accounts for almost half of recently observed rising sea levels, with Greenland alone contributing almost 25% of the 3 mm per year of sea level rise observed since 1993 (Nerem et al., 2018). Our broad goal is to understand the nature and cause of deviations from modeled rates of Greenland ice melt in order to better understand, predict, and communicate the changing conditions of the planet.

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 at nearly -30 Gt per year^2 over all of Greenland (Bevis et al., 2019; 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 **??** 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 **??** 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., 2019; 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).

Atmospheric Circulation Over the Greenland Ice Sheet

The atmospheric circulation affecting the Greenland Ice Sheet is broadly controlled by the position of the polar jet stream in the northern hemisphere (Hanna et al., 2013; Mattingly et al., 2018). The northern polar jet stream is a strong current of air moving generally eastward, dividing the warm, high pressure air of the temperate mid-latitudes and the cold, low pressure air of the Arctic. In the North Atlantic, the average position of the polar jet results in a low pressure Arctic system centered near Iceland, and a high pressure temperate system centered near the Azores. The strength of the polar jet stream moving air zonally across the North Atlantic is determined by the relative meridional pressure difference across the North Atlantic, and varies irregularly in what is called the North Atlantic Oscillation (NAO).

The NAO is often indexed for use in climate analyses by differencing the atmospheric pressure over the North Atlantic and a "loading pattern" of pressure determined by principal component analysis to capture the average meridional pattern (CPC, 2012; NCAR, 2019). A positive phase NAO index reflects a stronger meridional difference in pressure than usual, while negative values reflect a weaker meridional difference than usual (NCAR, 2019). The index is a unitless ratio normalized by the variance of atmospheric pressure from the loading pattern.

In studying melt events on the Greenland Ice Sheet, many studies have used an NAO index to relate melting conditions to atmospheric pressure patterns. Strong summer melt events often occur with a negative NAO index, suggesting that mechanisms which drive the NAO may have some kind of predictable implications for melting on Greenland (Bevis et al., 2019; Getraer, 2017; Hahn et al., 2018; Hanna et al., 2013; Mattingly et al., 2018; McMillan et al., 2016). More precisely, the use of the NAO index suggests that meridional pressure differences which drive westerly winds across the North Atlantic are a physical mechanism for strengthening melt conditions over Greenland — warm, moist air, and increased cloud cover (Bevis et al., 2019; Getraer, 2017; Hahn et al., 2018; Hanna et al., 2013; Mattingly et al., 2018; McMillan et al., 2016). This assumption, however, obscures the fact that melt events are often caused by southerly winds advecting atmospheric rivers of warm, moist air north, which is driven by a zonal difference in pressure (Hanna et al., 2013; Mattingly et al., 2018).

The polar jet does not maintain stable zonal flow, and regularly develops wiggles in which flow is diverted meridionally in large waves. During these events, known as a Rossby waves, temporary high-pressure systems push northward into the arctic accompanied by complementary low-pressure cyclones which develop on either side of the high-pressure block. The combined flow from these pressure systems advects warm air from the temperate mid-latitudes into the Arctic until the Rossby wave "breaks" and the jet stream return to its typical location.

Melt events on Greenland are generally driven by zonal differences in pressure resulting from Rossby wave systems with high pressure "blocking" over southern Greenland, which create atmospheric rivers advecting warm moist air over the ice sheet (Mattingly et al., 2018). In contrast, the NAO index measures against a meridional patterns of pressure, with the result that although melt events often correspond with a weaker NAO, a lower the NAO index does not necessarily imply a greater melt event.

High pressure blocking over southern Greenland is often correlated with a negative NAO index, because the northern excursion of high pressure systems influences meridional pressure balance. However, despite their correlation, the two are fundamentally different atmospheric patterns which drive advection of air in different directions. In some recent studies, the Greenland Blocking Index (GBI) has been used, which is essentially the average pressure over Greenland. While this is more specific and more relevant than the NAO index, it still does not directly reflect the meridional advection which drives melt.

In this paper, I explore simple indices which directly compare zonal pressure differences which flow of warm air into the arctic over the Greenland Ice Sheet, and compare those results to the NAO and GBI indices.

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 **??**).

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 **??**).

Data

Ice Data

Observations of ice loss are measured remotely by weighing the mass by gravitational anomaly, photographing the surface area, and by measuring relative height of the ice with passive and active altimetry.

In addition to data sets which directly measure aspects of ice change, we have complimentary measurements which capture some of the processes which control melting, such as air temperature, humidity, and atmospheric pressure. Atmospheric data are measured directly at weather station all over the world, and are synthesized into large continuous data sets referred to as "reanalysis" data. "Reanalysis" data sets are the outputs of climate models, which use assumptions about the laws which govern atmospheric processes to compute simulations of the atmosphere constrained by directly observed weather data.

Atmospheric Data

Discussion

Often times monthly means are reported when comparing an NAO index to a melt event (Mattingly et al., 2018), even though daily or sub-daily solutions are readily available, and despite the fact that the physical atmospheric drivers of melting (such as temperature, cloud cover, etc.) are changing on a daily, not monthly, basis.

Greenland is melting, is it warming?

The melting of the Greenland Ice Sheet is strongly connected to warming temperatures in much of the literature, and the significant repercussions of various short-term warming scenarios on the evolution of ice sheet melting are of great importance to predicting sea-level rise over the next century (Hahn et al., 2018; Pattyn et al., 2018; Rückamp et al., 2018). To best understand the relationship between warming temperatures and Greenland melt, some caution must be used in drawing a direct line between increasing mean global surface temperatures and increases of melt on the Greenland ice sheet.

Between the late 1990's and 2012, an apparent pause in the rise of mean global temperatures coincided with the strongest acceleration in Greenland ice sheet mass loss of the last century (roughly 2000–2012) (Kosaka & Xie, 2013; **?**; **?**). The "hiatus" observed in global warming over the first decade of the 21st century has been correlated with natural climate variability such as the El Niño/Southern Oscillation (ENSO), with heat being stored in cooler La Niña ocean waters (Kosaka & Xie, 2013). Between 2012 and 2017, mean global temperatures resumed a strong upwards trend driven by a negative to positive shift in ENSO phase.

Over the same period, mean Greenland Ice Sheet near-surface temperature did not rise significantly, and in fact was decreasing slightly across almost the entire ice sheet between 2003 and 2017 (see Figs. 1 & 2, and Hearty et al., 2018; Reeves Eyre & Zeng, 2017; Westergaard-Nielsen et al., 2018). Temperatures over Greenland are expected to continue to rise with global temperatures into the future, but have not done so significantly since the 1990's (Reeves Eyre & Zeng, 2017)

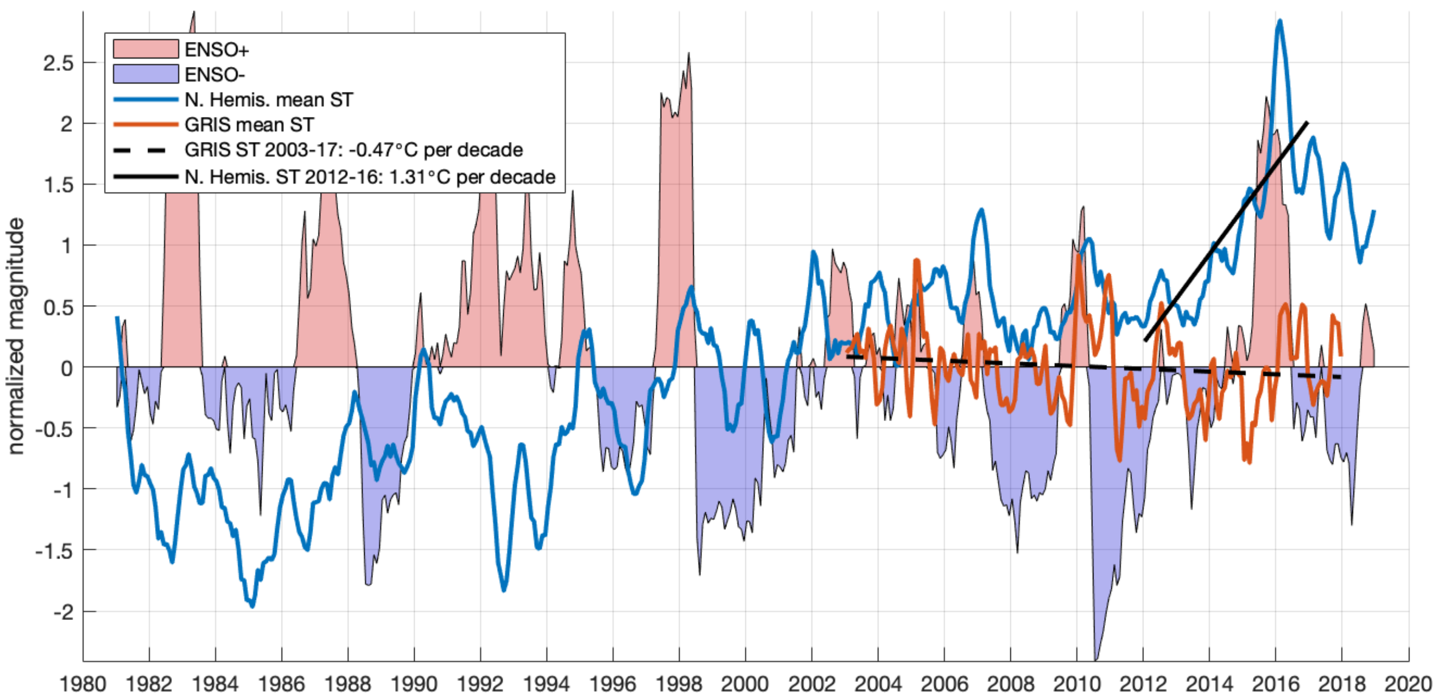

Figure 1

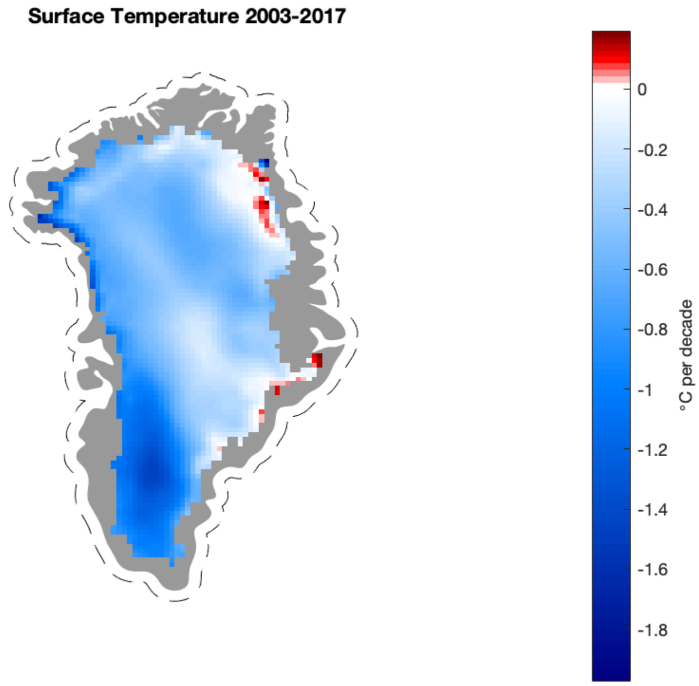

Figure 2

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,Analyzed Meteorological Fields V5.12.4, Greenbelt, MD, USA, Goddard Earth Sciences Data and Information Services Center (GES DISC), Accessed: [Data Access Date], 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/

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.*.

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, D. J., van Dam, T., Knudsen, P., & Nylen, T., 2019. Accelerating changes in ice mass within Greenland, and the ice sheet's sensitivity to atmospheric forcing, *Proceedings of the National Academy of Sciences*, **116**(6), 1934–1939, doi: 10.1073/pnas.1806562116.

Cheng, M., Tapley, B. D., & Ries, J. C., 2013. Deceleration in the Earth's oblateness, *Journal of Geophysical Research: Solid Earth*, **118**(2), 740–747, doi: 10.1002/jgrb.50058.

CPC, 2012. Northern Hemisphere Teleconnection Patterns, *National Weather Service Climate Prediction Center (Eds)*, **published online, last modified January 2012 at `https://www.cpc.ncep.noaa.gov/data/teledoc/telecontents.shtml`**.

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**.

Hahn, L., Ummenhofer, C. C., & Kwon, Y.-O., 2018. North Atlantic Natural Variability Modulates Emergence of Widespread Greenland Melt in a Warming Climate, *Geophysical Research Letters*, **45**(17), 9171–9178.

Hanna, E., Fettweis, X., Mernild, S. H., Cappelen, J., Ribergaard, M. H., Shuman, C. A., Steffen, K., Wood, L., & Mote, T. L., 2013. Atmospheric and oceanic climate forcing of the exceptional Greenland ice sheet surface melt in summer 2012, *International Journal of Climatology*, **34**(4), 1022–1037.

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. *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. Observations: Atmosphere and Surface, p. doi: 10.1017/CBO9781107415324, Cambridge Univ. Press.

Hearty, T. J., Lee, J. N., Wu, D. L., Cullather, R., Blaisdell, J. M., Susskind, J., & Nowicki, S. M. J., 2018. Intercomparison of Surface Temperatures from AIRS, MERRA, and MERRA-2 with NOAA and GC-Net Weather Stations at Summit, Greenland, *Journal of Applied Meteorology and Climatology*, **57**(5), 1231–1245.

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.

Kosaka, Y. & Xie, S.-P., 2013. Recent global-warming hiatus tied to equatorial Pacific surface cooling, *Nature*, **501**(7467), 403.

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.

NCAR, 2019. The Climate Data Guide: Hurrell North Atlantic Oscillation (NAO) Index (PC-based), *National Center for Atmospheric Research Staff (Eds)*, **published online, last modified January 2019 at `https://climatedataguide.ucar.edu/climate-data/hurrell-north-atlantic-oscillation-nao-index-pc-based`**.

Nerem, R. S., Beckley, B. D., Fasullo, J. T., Hamlington, B. D., Masters, D., & Mitchum, G. T., 2018. Climate-change–driven accelerated sea-level rise detected in the altimeter era, *Proceedings of the National Academy of Sciences*, **115**(9), 2022–2025, doi: 10.1073/pnas.1717312115.

NOAA, 2019. State of the Climate: Global Climate Report for Annual 2018, *National Centers for Environmental Information*, **published online, January 2019 at `https://www.ncdc.noaa.gov/sotc/global/201813`**.

Pattyn, F., Ritz, C., Hanna, E., Asay-Davis, X., DeConto, R., Durand, G., Favier, L., Fettweis, X., Goelzer, H., Golledge, N. R., et al., 2018. The Greenland and Antarctic Ice Sheets Under 1.5Â° C Global Warming, *Nature Climate Change*, p. 1.

Reeves Eyre, J. & Zeng, X., 2017. Evaluation of Greenland near surface air temperature datasets, *The Cryosphere*, **11**(4), 1591–1605.

Rückamp, M., Greve, R., & Humbert, A., 2018. Comparative Simulations of the Evolution of the Greenland Ice Sheet Under Simplified Paris Agreement Scenarios with the Models SICOPOLIS and ISSM, *Polar Science*.

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.

Swenson, S., Chambers, D., & Wahr, J., 2008. Estimating geocenter variations from a combination of GRACE and ocean model output, *Journal of Geophysical Research: Solid Earth*, **113**(B8), doi: 10.1029/2007JB005338.

Van Angelen, J., Van den Broeke, M., Wouters, B., & Lenaerts, J., 2014. Contemporary (1960–2012) evolution of the climate and surface mass balance of the Greenland ice sheet, *Surveys in geophysics*, **35**(5), 1155–1174.

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.

Westergaard-Nielsen, A., Karami, M., Hansen, B. U., Westermann, S., & Elberling, B., 2018. Contrasting temperature trends across the ice-free part of Greenland, *Scientific reports*, **8**(1), 1586.