Comparison of GRACE Derived Greenland Mass Wasting to Physical Drivers of Ice Loss From MERRA-2 Reanalysis

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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). I investigate the correlations of atmospheric variables from MERRA-2 climate model reanalysis to show the ways in which temperature over the Greenland Ice Sheet has changed over the MERRA-2 (1980–) and GRACE (2003–2017) records. Our results not only confirm that temporal and spatial changes in GRACE derived mass loss are coincident with changes in near surface temperature, but demonstrate some of the limitations in GRACE spatial resolution, and contextualize recent variability in ice loss within the variability and long term trend of Greenland temperature. As Greenland Ice Sheet melting continues to be more unpredictable than early GRACE studies predicted, context is extremely important in both interpreting and communicating trends in ice loss.

Key Points:

1. I focus on inter-annual variability of the Greenland ice loss trend.
2. I contextualize recent variation in melt and temperature through analysis of 1980–2017 MERRA-2 climate reanalysis data.

Acknowledgements

Thank you to my thesis adviser Prof. Laure Resplandy who has helped me think through my research questions, understand atmospheric processes, and for her support and patience in helping me with the direction this project has taken. Thank you to my Junior Paper adviser and second reader Prof. Frederik J. Simons who helped me with the conceptualization, direction, and revision of earlier portions of this project. Frederik's excitement about research and support of undergrads trying to wrap their heads around complex ideas has been a major reason why I chose to concentrate in Geosciences. 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 and for being a wonderful group of creative, curious, and competent people who give excellent feedback and support and fed me dinner. Thank you to Prof. Adam C. Maloof who taught me LaTeXand for the past three years has provided an omnipresent voice in my head asking me if I was "changing the world" which has been both a source of inspiration and stress. Thanks to Dr. Chris Harig at the University of Arizona for providing some of the data files for my Fall Junior Paper. Thank you to Prof. Gabriel Vecchi for helpful insights into atmospheric and oceanic processes. 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. Thank you to all of my friends and family who read drafts of various independent work and provided helpful feedback. Lastly, an especially big thanks to all of the people who asked me, "What is your independent work about?" and then patiently listened while I struggled to articulate my project in a way that made any sense.

My Mom and Dad have always encouraged me to pursue my interests, and their support has opened up so many life-changing opportunities for me. Finally, thank you to Drew Brazer for making sure that I never missed room draw or course registration these past three years.

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Introduction

Precipitous melting of the Greenland Ice Sheet forms a key part of the picture of climate change and global warming, especially in sensationalized news headlines in which subtlety and complexity of scientific conclusions may be waved in favor of drama (e.g. *"Greenland's Ice Melt Is in 'Overdrive,' With No Sign of Slowing"* (Berwyn, 2018); *"Greenland's ice is melting four times faster than thought"* (Leahy, 2019); *"'The only thing we can do is adapt': Greenland ice melt reaching 'tipping point,' study finds"* (Berlinger, 2019)). While generalized connections between climate warming and increased ice melting are both broadly true, and simple to communicate, there is a more complex picture behind the increased rates and tipping points referenced in popular media.

Physical drivers of the recent changes in ice melt have a significant amount of temporal and spatial variability, which complicate the picture one might get from merely extrapolating total losses over the past two decades into the future (Bevis et al., 2019; Enderlin et al., 2014; Hahn et al., 2018; Mattingly et al., 2018; McMillan et al., 2016). Previous work has shown that the total mass loss trend of the Greenland Ice Sheet between 2003–2017 is best modeled by a constant, not increasing, rate of ice melt (Getraer, 2017), and outside of the news headlines, the more extreme melt seasons of the past decade are increasingly being contextualized as natural variability occurring superimposed on underlying trends of global warming (Bevis et al., 2019; Hahn et al., 2018).

In this study, I examine the relationship between mass loss and temperature on the Greenland Ice Sheet, contextualizing recent trends and variability within the 1980–2017 climate record of the MERRA-2 climate reanalysis and the 2003–2017 mass anomaly record of the Gravity Recovery and Climate Experiment (GRACE) (see Data). I find that since 1980, temperatures over the Greenland Ice Sheet have risen differently from the overall Northern Hemisphere average, and that warming on the ice sheet has seasonal differences in both magnitude and spatial distribution. Direct comparison with mass loss shows that short-term (< 10 year) increases in melt rates, such as those observed leading up to the anomalously high melt season of 2012, are directly correlated in time and space with increasing temperature anomaly. Finally, spatial comparisons between climate variables and mass loss are examined for insight into the accuracy of GRACE measurements at spatial scales nearing fundamental spatial resolution.

An important motivator of this study is to explore the physical drivers of melting ice in order to better interpret communication about global warming and ice loss. When headlines prefer dramatic crisis over scientific accuracy, they risk losing both: the good science behind it is buried, and the door is left open to skeptics who often find legitimate flaws in the way information is being popularly disseminated (e.g. *"Skeptics put the freeze on NASA 'hot air' about Greenland ice"* (Fox News, 2012, last updated 2015), *"Greenland Glacier Grows, Despite Al Gore's Claims of Melting Glaciers"* (Goldsmith, 2019)). When policy decisions must be made on a relatively short timescale compared to variability within climate signals, and have a limited record of data to draw from, the legitimacy of policy and of science depends on getting the story right. In this paper I hope to contribute a small amount to that goal.

Previous Results

With the launch of NASA's Gravity Recovery and Climate Experiment (GRACE) in 2003, a single source, big picture answer was provided to the question "How much is Greenland Melting?" As the dataset extended and analysis improved over the next decade, the GRACE satellites provided gravitational measurements of mass change over Greenland, showing clear losses every summer season, with regression models showing an apparent 10% yearly acceleration ice loss through 2012 (Bevis et al., 2019; Enderlin et al., 2014; Harig & Simons, 2016; Van Angelen et al., 2014; Velicogna, 2009).

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 Earth's cryosphere, including the Greenland ice sheet where recent ice loss is estimated at

−244 Gt per year (Harig & Simons, 2015, 2016; Vaughan et al., 2013). 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.

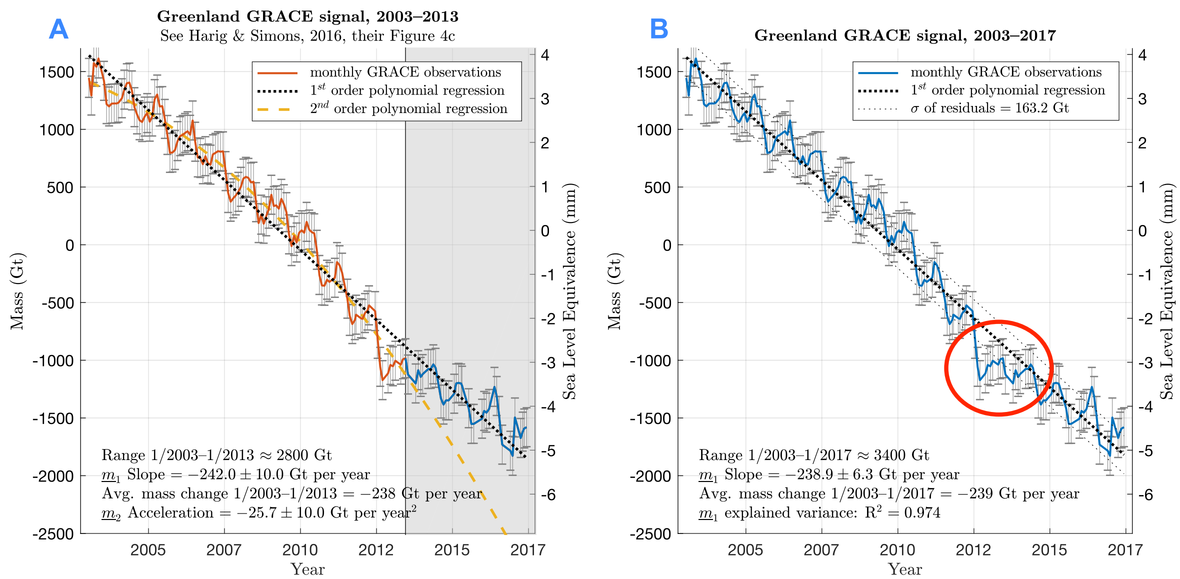

Figure 1: Total mass changes for Greenland over the complete GRACE record using equivalent methods to Harig & Simons (2016). Shown in **A** are the $\underline{m}_1$ (linear) and $\underline{m}_2$ (quadratic) models for 01/2003–06/2013, comparable to previous estimates of the mass trend (Harig & Simons, 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 at nearly -30 Gt per year^2 over all of Greenland (Bevis et al., 2019; Enderlin et al., 2014; Velicogna, 2009).

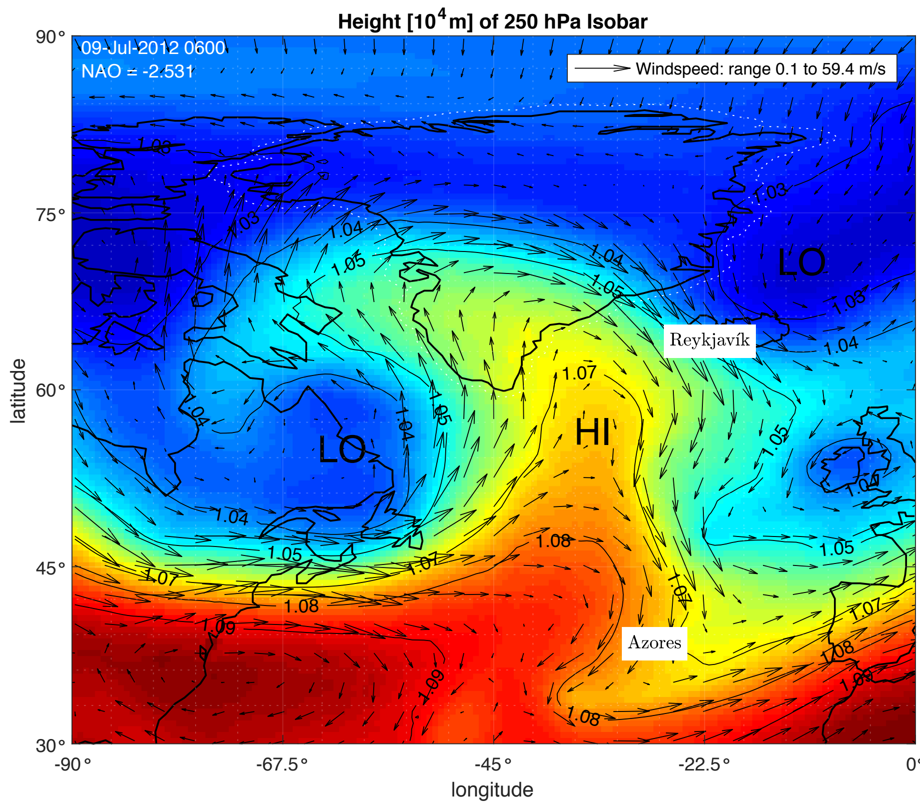

Figure 2: Example of atmospheric conditions at the 250 hPa isobar over the North Atlantic preceding record Greenland Ice Sheet surface melt, 07/09/2012 (from MERRA-2 reanalyzed data). Isobar height contours are labeled in 10^4 m, and wind vectors are shown by arrows. Note the location of the northern 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).

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., 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 strictly 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

Location of the 2012–2014

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 4).

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

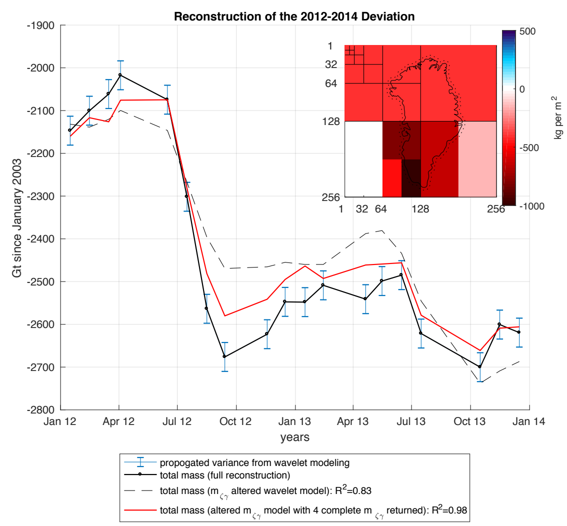

Figure 3: The 2012–2014 deviation in Greenland mass and the total from the reconstructed modeled wavelet coefficients. By adding in the real values of only four wavelet coefficients back into the modeled wavelet reconstruction we improve the variance explanation by 15%. These wavelets are shown inset,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

basis function best captured the 2012–2013 deviation from the expected signal, finding the deviations to be concentrated in southwestern Greenland (see Figure 3).

Data

Ice Mass Data

Observations of ice loss across large areas are measured remotely by satellites using several different methods, including weighing the mass by gravitational anomaly (such as NASA's GRACE and GRACE Follow-On missions), photographing surface area (such as NASA's Landsat and MODIS missions), and by measuring relative height of the ice with active laser altimetry (such as NASA's ICESat and ICESat-2 missions) (Khan et al., 2015).

Atmospheric Data

In addition to datasets which directly measure physical manifestations of ice sheet melting, there are complimentary datasets which capture some of the processes which control melting such as air temperature, humidity, and cloud cover. The primary atmospheric data used in this study are reanalysis products from the Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2) (see Table 1 and Appendix A: Data and code sources).

Variable	**Temporal Resolution**	**Dataset**
2 Meter Air Temperature	daily	tavg1_2d_slv_Nx
	monthly	statM_2d_slv_Nx
500 hPa Air Temperature	daily	tavg1_2d_slv_Nx
2 Meter Air Specific Humidity	daily	tavg1_2d_slv_Nx
500 hPa Air Specific Humidity	daily	tavg1_2d_slv_Nx
Skin Surface Temperature	daily	tavg1_2d_slv_Nx
Total Cloud Area Fraction	daily	tavg1_2d_rad_Nx
Surface Net Downward Shortwave Flux	daily	tavg1_2d_rad_Nx

Table 1: MERRA-2 data used in this study (see Appendix A: Data and code sources). Mean daily and monthly values were accessed on the default MERRA-2 0.625° lon$\times$0.5° lat grid with an original spatial resolution of approximately 50 km$\times$50 km(Bosilovich et al., 2016). Values are based on the GEOS climate models which combine direct observations into a globally continuous representation of the atmosphere, ocean, and surface interactions using a consistent set of of conservation assumptions (Bosilovich et al., 2016; Gelaro et al., 2017).

"Reanalysis" refers to a way of processing an ensemble of directly measured weather observations using a consistent set of rules that assume physical constraints on the ways in which different atmospheric variables interact temporally and spatially (Gelaro et al., 2017). These physical constraints are defined by a global climate model, which can both make forecasts of future developments of meteorological variables and output modeled solutions based on weather measurements directly observed at weather stations all over the world (Gelaro et al., 2017). Variable values for a given time and spatial location are calculated as a best fit of direct observations to the constraints of multiple different models which define processes such as radiation balances, physical movement, chemical interactions, precipitation, and so forth, or are inferred by the models' rules from variables which are directly measured (Bosilovich et al., 2016; Gelaro et al., 2017).

The data for this study come from NASA's Global Modeling and Assimilation Office's Goddard Earth Observing System (GEOS) climate models, and are publicly available in specific MERRA-2 data products through the NASA Goddard Earth Sciences Data Information Services Center (GES DISC) (see Appendix A: Data and code sources). MERRA-2 data are available in several different spatial and temporal formats for different variables. I use gridded daily averages for examining the connections between meteorological variables over the Greenland Ice Sheet, and gridded monthly averages for capturing the long-term development of Greenland's climate. Daily and monthly data are taken from collections of single-level, two-dimensional data which GES DISC provides in a few MERRA-2 datasets (see Table 1, Appendix A: Data and code sources).

Daily and monthly NAO climate index values are provided by the National Weather Service Climate Prediction Center, which calculates NAO index values from the 500 mb pressure level height over the spatial extent of 20–90° N (CPC, 2012). Pressure level heights are compared to a monthly loading pattern defined as the first principal component of a rotated principal component analysis on the 1950–2000 500 mb height time-series and values are normalized by monthly mean and standard of deviation for the 1950–2000 index time-series (see Appendix A: Data and code sources and CPC, 2012).

Lastly, Northern Hemisphere climate data are from the Goddard Institute for Space Studies Surface Temperature Analysis (GISTEMP v3) as a mean monthly Land-Ocean Temperature Index (LOTI), which takes into account dampening of atmospheric temperature changes due to the heat capacity of ocean water (Hansen et al., 2010). The data used here are a monthly index of temperature anomalies from 1951–1980 time-series, which are available from 1880–present (see Appendix A: Data and code sources and Hansen et al., 2010).

Methods

All analysis of MERRA-2 data over the Greenland Ice Sheet was masked using a widely-used shape-file of the ice sheet developed from the drainage subregions defined by Zwally et al. (2012), reorganized into quadrants similar to McMillan et al. (2016) (see Figure 5).

Results and Discussion

Near Surface Temperature Trends Since 1980

Over the 1980–2017 time period the Northern Hemisphere has been gradually warming, and averaging across the monthly LOTI anomaly with 10 year moving window reveals a quite linear trend of 0.24°C per decade (type 1 least-squares regression, with a variance reduction $R^2 = 0.987$), for a total increase of 0.89°C since 1980 (see Figure 6). Over the same time period, near surface temperature anomalies over the Greenland Ice Sheet had a significantly different pattern of increase, remaining static through the 1980's and more recently since the early 2000's, and increasing dramatically through the 1990's (Figure 6). Comparing the first 15 years (1980–1994) of the 1980–2017 time period to the last 15 years (2003–2017), the mean temperature rose 1.53 ± 0.42°C as illustrated in Figure 6 (two sample t-test found distributions of significantly

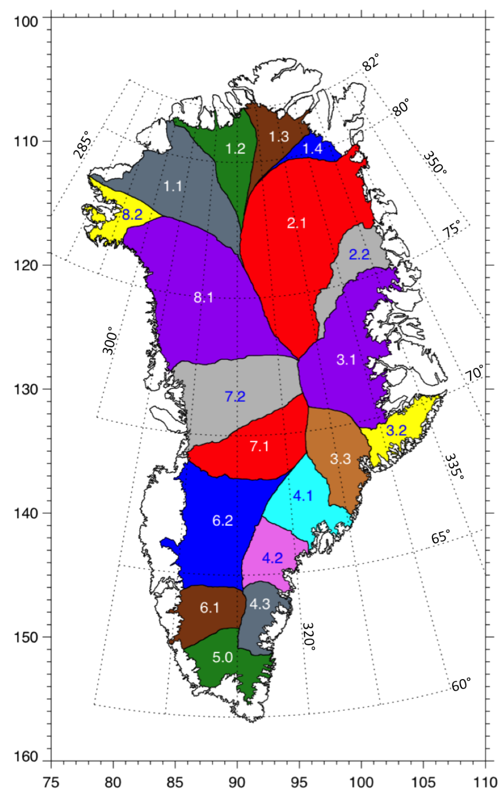

Figure 4: Drainage subregions of Greenland used to define ice sheet extent and quadrants in this paper (figure and data from Zwally et al., 2012). Quadrants used in this paper are unions of these subregions as follows: NW $= \cup(1.1, 1.2)$; NE $= \cup(1.3, 1.4, 2.1, 2.2)$; SE $= \cup(3.1, 3.2, 3.3, 4.1, 4.2, 4.3)$; SW $= \cup(5.0, 6.1, 6.2, 7.1, 7.2)$, similar to the divisions made in McMillan et al. (2016).

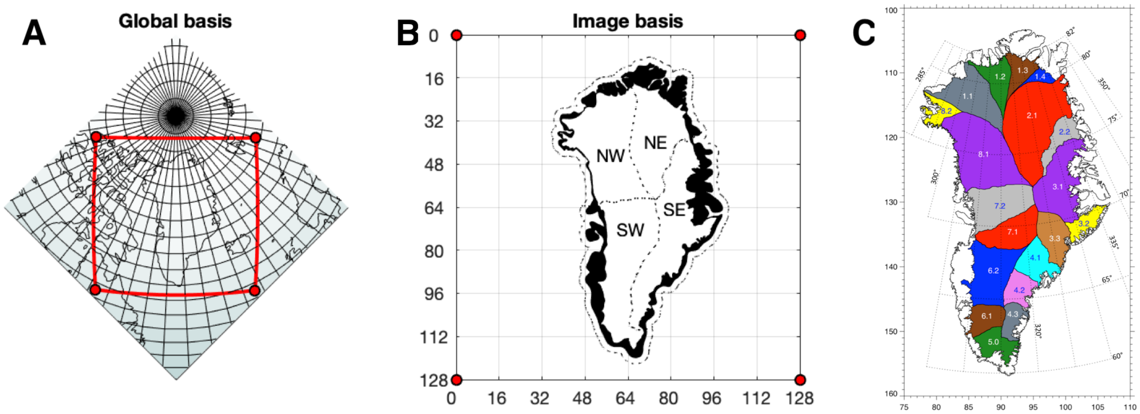

Figure 5: I defined a grid in the global basis on a face of the *Cubed Sphere* centered on Greenland (**A**), upon which the I evaluate gravitational anomaly from GRACE spherical harmonic solutions, and interpolate MERRA-2 data for comparison (see Ronchi et al., 1996). In the image basis (**B**) the grid is cartesian with length 128. The filled black area is the island of Greenland, with the extent of the ice sheet superimposed in white, and dotted lines delineating the regional four quadrants that we consider (see **C** & Zwally et al., 2012). Dotted around Greenland is a coastal buffer of 0.5°, within which the total Greenland mass budget from GRACE is integrated, as in Harig & Simons (2016). Points on the grid are approximately 20–25 km apart, finer than both GRACE and MERRA-2 spatial resolutions. Drainage subregions of Greenland used to define ice sheet extent and quadrants in this paper are derived from **C** (figure and data from Zwally et al., 2012). Quadrants shown in **B** are unions of these subregions as follows: NW $= \cup(1.1, 1.2)$; NE $= \cup(1.3, 1.4, 2.1, 2.2)$; SE $= \cup(3.1, 3.2, 3.3, 4.1, 4.2, 4.3)$; SW $= \cup(5.0, 6.1, 6.2, 7.1, 7.2)$, similar to the divisions made in McMillan et al. (2016)

different mean values, $p = 2.3\text{e}{-12}$; reported error represents the 95% confidence interval on the difference in mean values).

Rise in near surface air temperature across the Greenland Ice Sheet between 1980–2017 differed seasonally, with the greatest rise in temperature occurring in the Winter season (December, January, February) and the smallest rise in temperature occuring in the Summer season (June, July, August) (see Figure 7). The fitted linear trends were tested for significance against the hypothesis that a trend of the same magnitude could be generated from similar random data (normally distributed data of the same mean, standard of deviation, and number of points). p-values for the trends represent the percentage of trends of greater magnitude found in 10000 tests of similar random data (the trend slope of greatest absolute value would have $p(\max) = 0$, and a trend slope of 0 would have $p(0) = 1$). A similar method was used to calculate the confidence

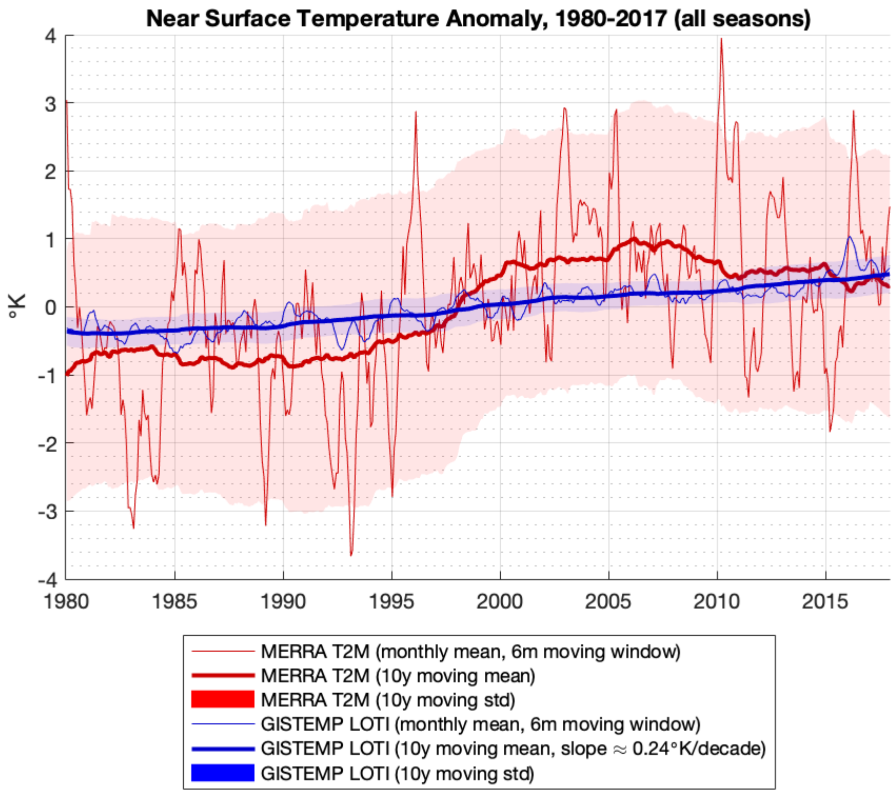

Figure 6: Mean monthly near surface temperature anomalies for the Northern Hemisphere (GISTEMP Land-Ocean Temperare Index, blue) and the Greenland Ice Sheet (MERRA-2 2m air temperature, red), 1980–2017. Data has been filtered using 6-month and 10-year moving windows for ease of interpretation, with the shaded area representing the spread of the data using the standard of deviation of the 10-year moving window. Note the more continuously linear increase in Northern Hemisphere temperature over the entire time-period compared to the non-linear jump in temperature over Greenland in the 1990's. Analyses of the unfiltered time-series show that: the Northern Hemisphere LOTI is increasing at 0.24°C per decade ($R^2 = 0.987$); near-surface air temperature increased 1.53 ± 0.42°C between the years 1980–1994 and 2003–2017.

interval of these trends, by subtracting the linear fit, generating 10000 tests of similar random data, and finding the 90th and 95th percentile of slope magnitude amongst the random test data.

For the seasonal near surface air temperature trends between 1980–2017, all were found to be significant at at least the $p < 0.05$ threshold compared to the 10000 tests of similar random data (see Table 2). The difference in trend between Winter and Summer months is significant in the random simulations, with the best fit trend for each falling outside of the 90% confidence interval of the other (see Table 2).

Despite the overall rise in temperature since the 1980's, near surface air temperature across the Greenland Ice Sheet was not increasing over the GRACE record (2003–2017) (Figure 7). In

Season	Trend [°C/decade]	95% conf. int.	90% conf. int.	p-value
1980–2017				
Winter (DJF)	$+0.80$	± 0.46	± 0.38	0.0015
Spring (MAM)	$+0.46$	± 0.36	± 0.30	0.0163
Summer (JJA)	$+0.35$	± 0.17	± 0.15	0.0002
Fall (SON)	$+0.48$	± 0.29	± 0.25	0.0021
2003–2017				
Winter (DJF)	-0.60	± 1.12	± 0.93	0.413
Spring (MAM)	-0.98	± 1.11	± 0.94	0.105
Summer (JJA)	-0.72	± 1.13	± 0.94	0.217
Fall (SON)	-0.02	± 1.13	± 0.94	0.971

Table 2: Seasonal trends in MERRA-2 2m air temperature calculated on mean monthly data across the Greenland Ice Sheet for the time period 1980–2017 and 2003–2017, shown in Figure 7. The trend is the type 1 least squares regression slope of the mean monthly data, and confidence intervals are the results of synthetic data tests analyzing the residuals of the data and the trend line. p-values represent the chances of finding a trend slope of equal or greater magnitude in a random sampling of a "similar" normal distribution. For 1980–2017, all seasons have trend magnitudes that are significantly different from a random sampling of a "similar" normal distribution at the $p < 0.05$ threshold; Winter and Summer seasonal trends are significantly different from each other at the 90% confidence interval; Fall and Spring trends are not significantly different from Summer, and are not well differentiated from Winter. For 2003–2017, Winter and Fall trends are well within expected fits for similar random data, and while the Spring and Summer trends are more unusual, those negative trends are also not significantly differentiable from similar random data in p-value or confidence interval.

fact, mean 2m air temperature anomaly over the ice sheet drifted cooler in every season, most markedly in Spring and Summer (see Figure 7 & Table 2). The cooling drift in temperature from 2003–2017 was analyzed for significance in the same manner as the trends over the entire 1980–2017 record (Table 2). The trends in Winter and Fall were indistinguishable from similar random data drawn from a normal distribution of the same mean and standard of deviation, and while the trends in Spring and Summer were more unusual for random variability, they too were poorly differentiated from similar random data in both p-value and confidence interval (Table 2).

Taking into consideration the probability of random simultaneous negative drift in 2m air temperature anomaly across all seasons ($\prod_{\text{season}=i} p_i = 0.0091$) it becomes apparent that within the larger, expected warming trend of 1980–present, Greenland experienced an unexpected cooling hiatus during the 2003–2017 GRACE record (see Figure 7 & Table 2). It is important to note that, regardless of fitted trends, the majority of the 10 warmest seasons of the 1980–2017 record have occurred during the GRACE record (6/10 Winters, 8/10 Springs, 8/10 Summers, 6/10

Falls), and for the first decade of GRACE data, all but one Summer season on the Greenland Ice Sheet had mean temperatures above the 1980–2017 average see (Figure 7 & Table 3).

In addition to differences in near surface temperature anomaly trends found in different seasons and decades, there is also significant spatial heterogeneity temperature anomaly trends across the Greenland Ice Sheet. I calculated a linear fit for temperature anomaly at each node of the grid across Greenland (see Figure 4) for years between 1980–2017, from the beginning of GRACE until the end of 2012 (2003–2012), and for the entire GRACE record (2003–2017), illustrated in Figure 11. The trends within those three time periods have very different features, characterized by widespread warming in all seasons (1980–2017), general cooling in non-summer seasons with strong Summer warming in the SW region (2003–2012), and general cooling across the vast majority of the ice sheet in all seasons (2003–2017) (Figure 11).

Strong warming in the SW during first decade of the GRACE record was followed by a very different pattern of warming in the north and cooling in the south from 2013–2017, resulting in a trend over the entire 2003–2017 period which obscures the temperature anomaly signal in the SW (Figure 11). Also of note is that Summer temperature trends differ significantly in both magnitude and spatial pattern from non-summer trends, which dominate the fitted trends seen when seasons are not considered separately (see Figures 7 & 11).

	Summer (JJA)		Winter (DJF)	
	Year	**T2M anom. °C**	**Year**	**T2M anom. °C**
1	2012 (1)	2.19 ± 0.51	2010	5.28 ± 0.70
2	2007 (7)	1.59 ± 0.56	1980	3.23 ± 2.19
3	2010 (3)	1.32 ± 0.77	2011	3.06 ± 2.67
4	2003 (8)	1.07 ± 1.02	2003	2.75 ± 1.59
5	2004 (13)	0.95 ± 0.55	2007	2.34 ± 1.84
6	2016 (2)	0.86 ± 0.50	2013	2.25 ± 0.34
7	2008 (9)	0.73 ± 0.25	1986	1.75 ± 2.92
8	1998	0.63 ± 0.59	2009	1.70 ± 0.48
9	2005 (5)	0.62 ± 1.22	1996	1.46 ± 0.48
10	2002	0.56 ± 1.60	1987	2.35 ± 3.79

Table 3: Top 5 years ranked by highest mean 2m air temperature for Summer and Winter seasons over the Greenland Ice Sheet (1980–2017). Adjacent to the year, in parentheses, is that year's rank by greatest mass loss (2003–2017). Mean temperature is the mean of the three monthly means in that season, and the reported error is the standard of deviation of the three monthly means in that season. Despite a downward drift in mean temperature between 2003–2017, a majority of the top ten warmest seasons on record occurred within that time frame. Note the separation of 2012 from the next closest years, making it the warmest summer on record. Worth noting is that 2013, the year of least mass loss on the GRACE record, ranks as the 5th coldest Summer season in the 1980–2017 record, and the coldest Summer season of the GRACE time period.

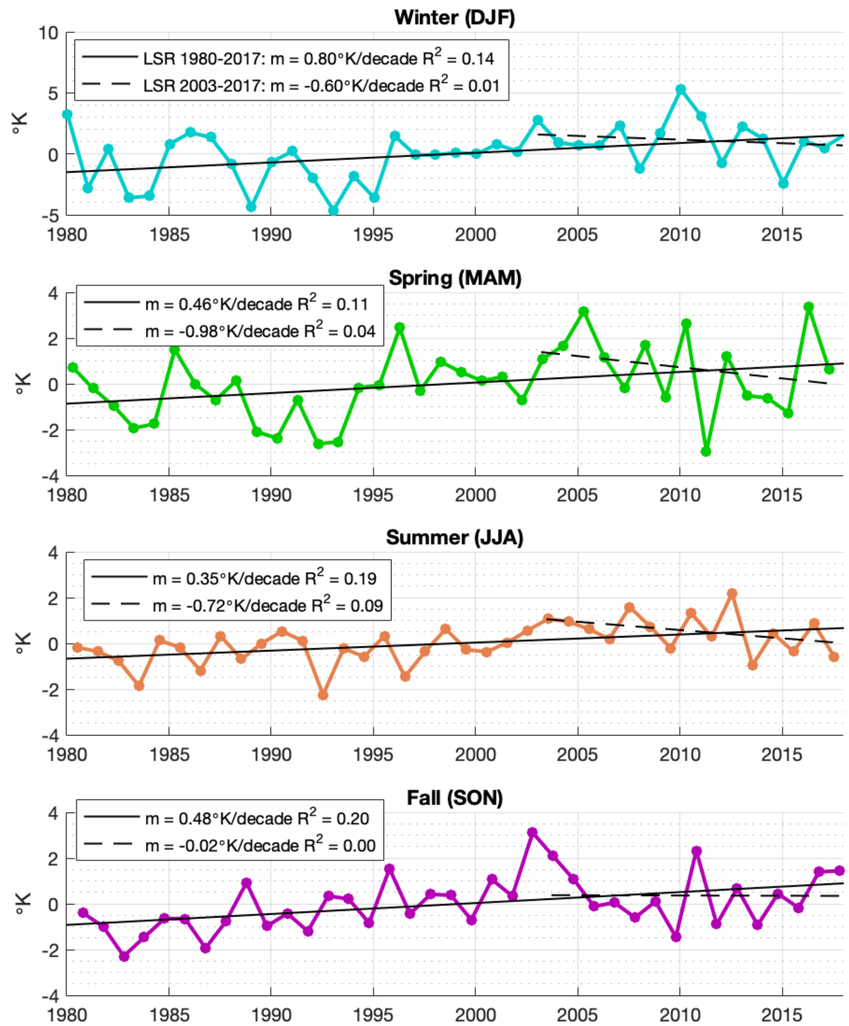

Figure 7: Seasonal trends in MERRA-2 2m air temperature across the Greenland Ice Sheet for 1980–2017. Plotted points are the seasonal mean for each year, and are fit with a type-1 least squares regression for the full time period (solid) and the GRACE time period (dashes). Note that between 1980–2017 Winter temperatures warmed more than summer temperatures, while during the GRACE time period (2003–2017) Summer temperatures dropped more than Winter temperatures. Table 2 contains an analysis of the significance of each trend and its confidence interval, showing that the seasonal trends in mean monthly temperature over the full time period are significant, while the seasonal trends over the GRACE period are not significantly differentiable (in both *p*-value and confidence interval) from trends in random data drawn randomly from a similar normal distribution.

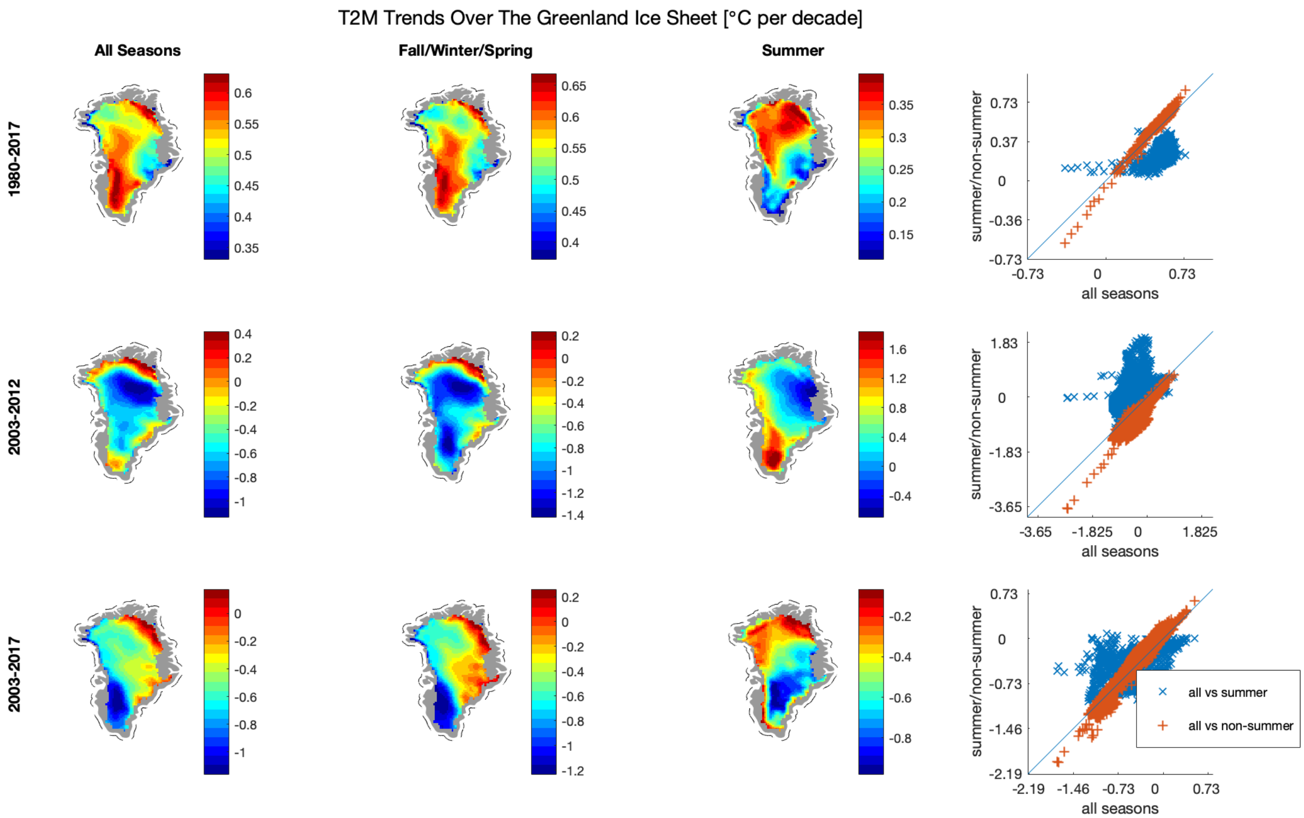

Figure 8: Linear trends in near surface temperature anomaly across the Greenland Ice Sheet. The trend maps show three different time periods in separate rows, and three different seasonal combinations in separate columns. Note that over the entire 1980–2017 record, Summer warming has occurred mostly in the N and NW regions. In contrast to that 37 year trend, the first decade of GRACE saw concentrated Summer warming in the SW. This SW warming did not continue through the last 5 years of the time period, which saw a counter balancing cooling in the S and warming in the N, resulting in an apparent overall Summer cooling over the entire 2003–2017 time period. The crossplots in the righthand column show the strong correlation of non-summer months to the trends seen when all seasons are considered, demonstrating that Summer trends are significantly different from the trends seen in other seasons, and are almost completely obscured unless Summer months are specifically isolated. Trend values are type-1 least square regressions after removing seasonal cycles.

Comparison of Mass Loss and MERRA-2 Variables

As a first order analysis of atmospheric drivers of ice loss, I compared the net change in Greenland mass over the entire GRACE period to mean the average Summer (JJA) surface skin temperature (ST), 2 meter air temperature (T2M), and 2 meter specific humidity (QV2M) over the entire period (Figure10). Point-to-point comparisons were binned every by mass loss, showing a positive correlation between temperature and humidity and ice loss, as generally expected (Figure10).

For areas with less than 750 kg/m^2 of ice loss over 2003–2017, higher amounts of ice loss correlated with quadratically higher temperatures and humidity (melting more ice requires a non-linear increase in temperature, Figure10)). In contrast, there was no difference in mean temperature between areas with 750 kg/m^2 of ice loss and those with 2000 kg/m^2, and it was only at losses over 2750 kg/m^2 at which mean temperature and humidity had to be significantly higher (Figure10).

The plateau in the relationship between mean temperature and humidity and mass loss of 750–2500 kg/m^2 (2003–2017) is the effect of GRACE detected mass loss within that range aligning with a large variance in mean temperature (Figure10). The average surface temperature (ST) within that range of mass loss hovers just above -8.15°C (265°K), corresponding generally with the mid-range of the ice sheet, below the upper accumulation zone where mass change was positive, but shy of the periphery (Figure10). Over the 2003–2017 record, mean ST was consistently about 2°C lower than T2M, and examining the best fit regressions between the two temperatures and the GRACE data, mass loss may to be subtly more sensitive to ST—melting more ice requires a smaller change in ST than T2M (Figure10).

Similar comparisons were conducted for each quadrant of Greenland comparing total mass loss to T2M (Figure**??**). The eastern half of the ice sheet showed strong quadratic correlation between mass loss and temperature for areas with less than 1000 kg/m^2, and the correlation in the NE never plateaus (Figure**??**). In contrast, the quadratic relationship for the western half of the ice sheet extends only to areas of less than 750 kg/m^2 in the NW, and barely exists in the SW where a subregion estimated by GRACE to have near 0 kg/m^2 of mass loss is located in one of the highest temperature coastal environments on the ice sheet (Figure**??**).

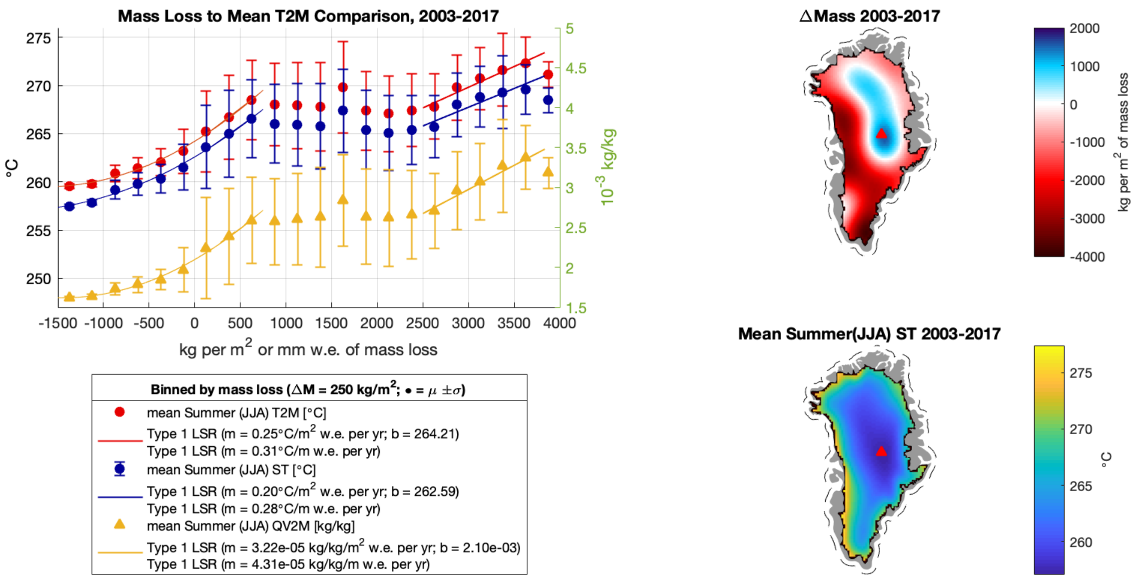

Figure 9: Total mass change over the Greenland Ice Sheet, compared to the average daily mean near-surface temperature (T2M, red), skin surface temperature (ST, blue), and near surface specific humidiy (QV2M, yellow) for the June/July/August Summer season. MERRA-2 data were smoothed using Matlab's gaussian smoothing filter and a smoothing kernel of $\sigma = 1$std before being bi-linearly interpolated on the grid (see Figure 4). Cross-plotted data were binned every 250 kg/m^2, with the mean and standard of deviation are represented here. Note that in zones of mass accumulation (negative mass loss on the *x*-axis) and loss of 750 kg/m^2 (or mm of water equivalence, mm w.e.) average temperatures and humidity over 2003–2017 scales quadratically with increasing mass loss, while regions with 750–2500 kg/m^2 of loss have similar ranges, and regions with > 2500 kg/m^2 of loss seem to scale linearly. The quadratic and linear relationships are shown in the legend in two lines, the first giving the acceleration and intercept of the modeled variable per 1000 kg/m^2 (m^2 w.e.) for mass loss < 750 kg/m^2, and the second giving the linear rate of the modeled variable per 1000 kg/m (m w.e.). As the mass losses are for the entire 14 year GRACE record, these rates were normalized to reflect the amount of ice loss per year that a given change in the modeled variable relates to.

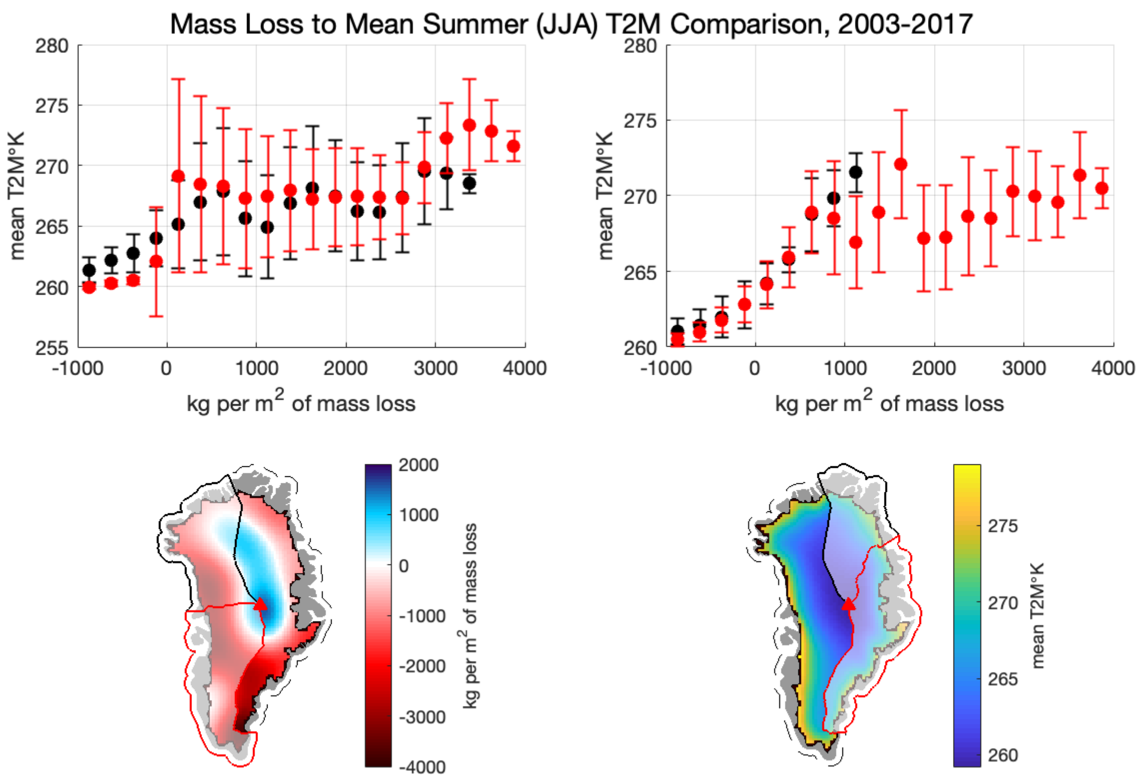

Figure 10

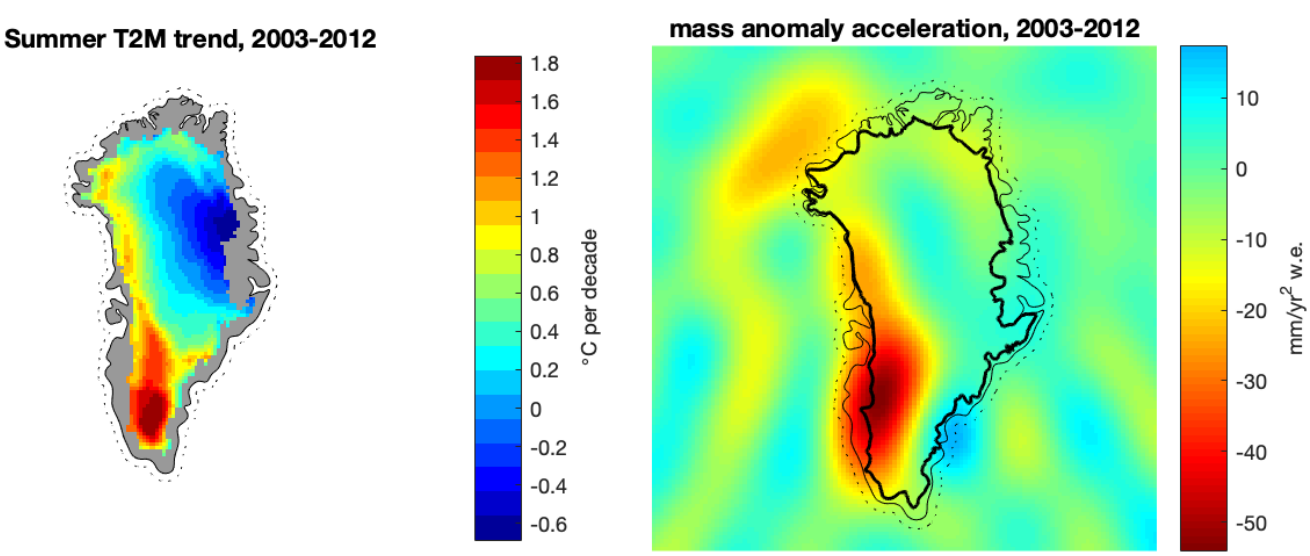

Figure 11

Discussion

Analysis of near surface temperature indicates that the warming of the 1990's brought average temperatures on the ice sheet to a level that remained significantly higher than previous decades, despite downward drift through the GRACE time period (see Figure 6). Leading into the first years of the GRACE record, average near surface Summer temperatures on ice sheet as a whole were $\sim 0.8°$C warmer than at the beginning of the 1980's (Figure 7), and through the first decade of GRACE (2003–2012), warming Summer temperature trends focused in the SW region estimate an additional increase in Summer temperatures of 0.8–1.8°C (Figure 11). These estimations of a temperature anomaly of almost 3°C in the SW in 2012 (compared to temperatures of the early 1980's) are similar to estimates which put the Summer of 2012 at 4°C warmer than the 1960–1990 average (Van Angelen et al., 2014).

Assuming that the physical relationship between temperature and melt is the same across the ice sheet, the underlying cause of the plateau in Figure10 may be related to measurement, interannual variability, or mass movement. Bias and spatial resolution in GRACE continues to be pushed (see Getraer, 2018; Harig & Simons, 2012; Save et al., 2016), but remains conservatively estimated at $\sim$ 300km $\times$ 300km (Scanlon et al., 2016, ; Greenland itself is approximately 2700km North–South $\times$ 1200km East–West).

Regions between the strong mass loss of the lower ice sheet and mass gain in the accumulation zone may be poorly resolved, and not accurately reflect local melt. This explanation is directly supported by the clear positive correlation between temperature, humidity, and mass loss seen at both the positive and negative extremes of mass anomaly, suggesting that the spherical harmonic basis of the GRACE data captures peaks of mass anomaly even when they are relatively close together (Figure10). Mass loss extremes on Greenland are located just over 400km away from each other, nearing the limit of GRACE resolution, and transitions between those areas may be biased by those extremes.

Complicating the spatial limitations of GRACE are the dimensions of the ice sheet itself. The steeper eastern slopes of the ice sheet have less melt for a given temperature anomaly, simply due to the distribution of the low altitude ablation zone in those regions (Bevis et al., 2019). As a result, the short-distance gradient in mass anomaly captured by GRACE is not as extreme on the eastern half of the ice sheet as it is on the western half, where a larger distribution of low altitude ice in the ablation zone is exposed temperature fluctuations. If GRACE may struggle to accurately resolve regions which fall in between very close extrema of mass anomaly (distances which approach the satellites' fundamental spatial resolution), we would expect the NE quadrant to have the clearest spatial correlation with temperature, which we do in fact observe (Figure**??**).

Another factor at play in the connection between total mass lost and mean temperature over a 14 year period is inter-annual variability. Taking a mean temperature over such a timescale obscures short periods of intense melting, which may have a significant contribution to total melt.

Additionally, while temperature and humidity contribute to melting ice, the redistribution of mass after ice is melted can differ depending on local conditions, and may flow relatively directly off of the ice sheet, or get stored within the snowpack or refrozen, conditions which themselves have changed dramatically over the GRACE observation period (de la Peña et al., 2015; Van Angelen et al., 2014).

"Greenland Ice Sheet Surface Melt and Its Relation to Daily Atmospheric Conditions"

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 (Bevis et al., 2019; Kosaka & Xie, 2013; Van Angelen et al., 2014). 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 (see Fig. 12).

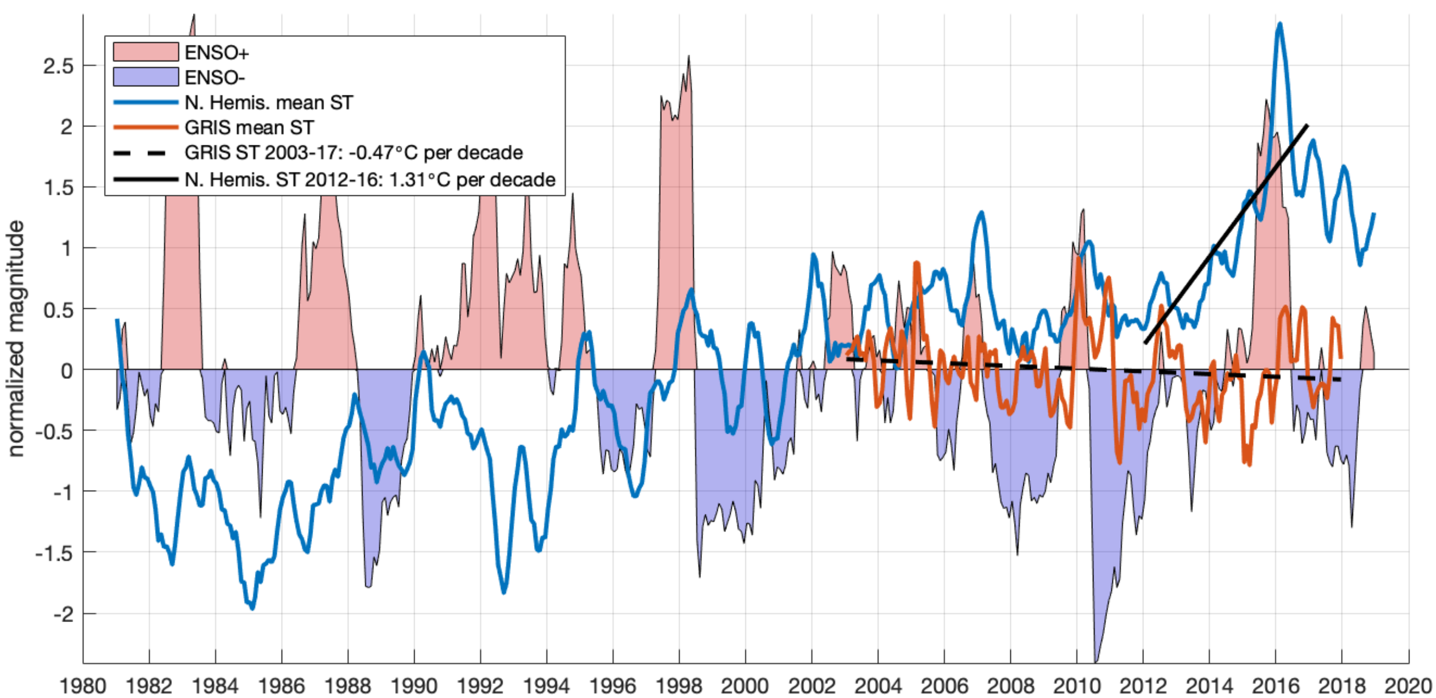

Figure 12

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. 12 & 13, and Hearty et al., 2018; Reeves Eyre & Zeng, 2017; Westergaard-Nielsen et al., 2018). Mean 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).

In interpreting the record of Greenland Ice Sheet mass wasting, it is important to note that the linear trend observed over the entire 2003–2017 GRACE record need not be driven by changing climate over that time period. Warming mean temperatures over Greenland in the 1990's drove the ice sheet into the linear decline we have seen in the GRACE record, with an approximately constant amount of summer loss each year (Getraer, 2017). Over that time period, anomalous years and accelerations in melt are likely due to variability in weather patterns across Greenland and the North Atlantic, and not regional or global warming (Bevis et al., 2019; Hahn et al., 2018).

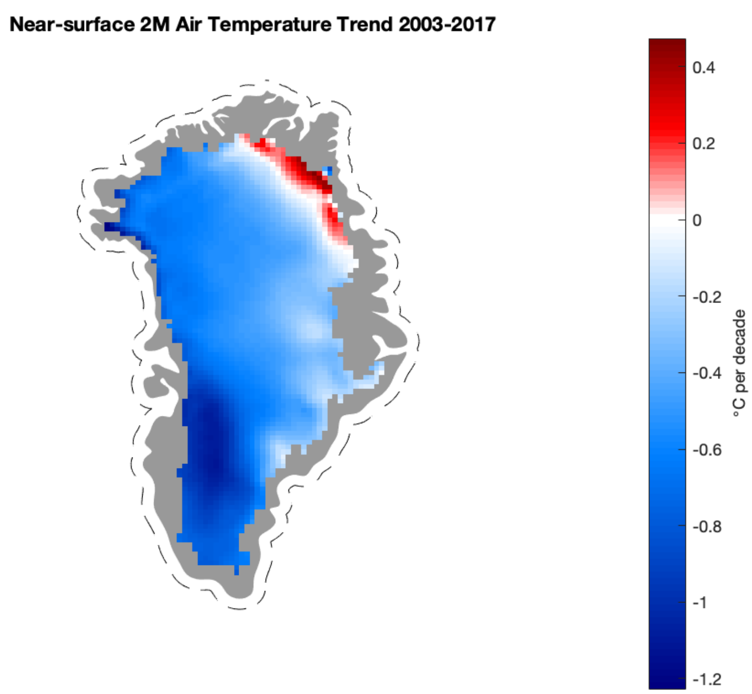

Figure 13

NAO Correlation with Melt

Often times when comparing the NAO to Greenland melt, monthly or seasonal means are used to correlate with melt events that occur over time scales of a few days (see, for example, Bevis et al., 2019; Mattingly et al., 2018; Van Angelen et al., 2014). These averaged NAO index values are used despite the fact that daily and sub-daily solutions are readily available for the NAO index, 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, and are interacting directly with atmospheric pressure (for example, Mattingly et al., 2018).

Appendix A: Data and code sources

RL05 spherical harmonic coefficients for the time-variant geopotential field from the Center for Space Research data processing center at The University of Texas at Austin are available at:

`ftp://podaac.jpl.nasa.gov/allData/grace/L2/CSR/RL05`

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/`

Index values for the North Atlantic Oscillation are calculated by the National Weather Service Climate Prediction Center (see CPC, 2012), with normalized monthly average values since January 1950 available at:

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

Normalized daily values since January 1950 are available at:

`ftp://ftp.cpc.ncep.noaa.gov/cwlinks/norm.daily.nao.index.b500101.current.ascii`

MERRA-2 atmospheric reanalysis data are calculated by the NASA Global Modeling and Assimilation Office (GMAO) as part of the activities of NASA's Science Mission Directorate, and are archived and distributed by the Goddard Earth Sciences Data and Information Services Center (GES-DISC). All data was accessed between September 2018 and April 2019.

A graphical user interface for generating data download links for specific subsets of variables, space, and time is available at: `https://disc.gsfc.nasa.gov`

Data used in this study can be directly accessed at the following addresses:

https://goldsmr4.gesdisc.eosdis.nasa.gov/data/MERRA2_MONTHLY/M2SMNXSLV.5.12.4/

https://goldsmr4.gesdisc.eosdis.nasa.gov/data/MERRA2/M2T1NXSLV.5.12.4/

https://goldsmr4.gesdisc.eosdis.nasa.gov/data/MERRA2/M2T1NXRAD.5.12.4/

Northern Hemisphere Land-Ocean Temperature Index anomalies from NASA's Goddard Institute for Space Studies Surface Temperature Analysis (GISTEMP v3, see Hansen et al., 2010) were accessed in March 2019 and are available at:

https://data.giss.nasa.gov/gistemp/tabledata_v3/NH.Ts+dSST.csv

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

Berlinger, J., 2019. 'The only thing we can do is adapt': Greenland ice melt reaching 'tipping point,' study finds, *CNN (online*.

Berwyn, B., 2018. Greenland's Ice Melt Is in 'Overdrive,' With No Sign of Slowing, *Inside Climate News*.

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.

Bosilovich, M. G., Lucchesi, R., & Suarez, M., 2016. MERRA-2: File Specification, *GMAO Office*, **Note No. 9 (Version 1.1), available from `http://gmao.gsfc.nasa.gov/pubs/office_notes`**.

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`**.

de la Peña, S., Howat, I. M., Nienow, P. W., van den Broeke, M. R., Mosley-Thompson, E., Price, S. F., Mair, D., Noël, B., & Sole, A. J., 2015. Changes in the firn structure of the western Greenland Ice Sheet caused by recent warming, *The Cryosphere (Online)*, **9**(3).

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.

Fox News, 2012, last updated 2015. Skeptics put the freeze on NASA 'hot air' about Greenland ice, *FOX News Network (online)*.

Gelaro, R., McCarty, W., Suárez, M. J., Todling, R., Molod, A., Takacs, L., Randles, C. A., Darmenov, A., Bosilovich, M. G., Reichle, R., Wargan, K., Coy, L., Cullather, R., Draper, C., Akella, S., Buchard, V., Conaty, A., da Silva, A. M., Gu, W., Kim, G.-K., Koster, R., Lucchesi, R., Merkova, D., Nielsen, J. E., Partyka, G., Pawson, S., Putman, W., Rienecker, M., Schubert, S. D., Sienkiewicz, M., & Zhao, B., 2017. The Modern-Era Retrospective Analysis for Research and Applications, Version 2 (MERRA-2), *Journal of Climate*, **30**(14), 5419–5454, doi: 10.1175/JCLI–D–16–0758.1.

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**.

Goldsmith, P. G., 2019. Greenland Glacier Grows, Despite Al Gore's Claims of Melting Glaciers, *Media Research Center TV (online*.

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.

Hansen, J., Ruedy, R., Sato, M., & Lo, K., 2010. Global Surface Temperature Change, *Reviews of Geophysics*, **48, RG4004**, 1–29, doi:10.1029/2010RG000345.

Harig, C. & Simons, F. J., 2012. Mapping Greenland's mass loss in space and time, *Proc. Natl. Acad. Sc.*, **109**(49), 19934–19937, doi: 10.1073/pnas.1206785109.

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., 2013. Recent global-warming hiatus tied to equatorial Pacific surface cooling, *Nature*, **501**(7467), 403.

Leahy, S., 2019. Greenland's ice is melting four times faster than thought—what it means, *National Geographic (Online)*, **Accessed online April 2019, at `https://www.nationalgeographic.com/environment/2019/01/greeland-ice-melting-four-times-faster-than-thought-raising-sea-level/`**.

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 1.5° 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.

Ronchi, C., Iacono, R., & Paolucci, P. S., 1996. The "Cubed Sphere": A New Method for the Solution of Partial Differential Equations in Spherical Geometry, *Journal of Computational Physics*, **124**(1), 93–114, doi: 10.1006/jcph.1996.0047.

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*.

Save, H., Bettadpur, S., & Tapley, B. D., 2016. High-resolution CSR GRACE RL05 Mascons, *Journal of Geophysical Research: Solid Earth*, **121**(10), 7547–7569, doi: 10.1002/2016JB013007.

Scanlon, B. R., Zhang, Z., Save, H., Wiese, D. N., Landerer, F. W., Long, D., Longuevergne, L., & Chen, J., 2016. Global Evaluation of New GRACE Mascon Products for Hydrologic Applications, *Water Resources Research*, **52**(12), 9412–9429, doi: 10.1002/2016WR019494.

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.

Zwally, H. J., Giovinetto, M. B., Beckley, M. A., & Saba, J. L., 2012. Antarctic and Greenland Drainage Systems, GSFC Cryospheric Sciences Laboratory, *Available at http://icesat4.gsfc.nasa.gov/cryo_data/ant_grn_drainage_systems.php. Accessed October 2018*, **1**, 2015.