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2015 Environ. Res. Lett. 10 114008

(http://iopscience.iop.org/1748-9326/10/11/114008)

Environmental Research Letters

OPEN ACCESS

RECEIVED
4 March 2015

REVISED
13 October 2015

ACCEPTED FOR PUBLICATION
13 October 2015

PUBLISHED
30 October 2015

LETTER

Coast-to-interior gradient in recent northwest Greenland precipitation trends (1952–2012)

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Keywords: Greenland, climate, precipitation, ice sheet, weather station, ice core, temperature

Abstract

The spatial and temporal variability of precipitation on the Greenland ice sheet is an essential component of surface mass balance, which has been declining in recent years with rising temperatures. We present an analysis of precipitation trends in northwest (NW) Greenland (1952–2012) using instrumental (coastal meteorological station) and proxy records (snow pits and ice cores) to characterize the precipitation gradient from the coast to the ice sheet interior. Snow-pit-derived precipitation near the coast (1950–2000) has increased (~7% decade^{-1}, $p < 0.01$) whereas there is no significant change observed in interior snow pits. This trend holds for 1981–2012, where calculated precipitation changes decrease in magnitude with increasing distance from the coast: 13% decade^{-1} (2.4 mm water equivalent (w.e.) decade^{-2}) at coastal Thule air base (AB), 8.6% decade^{-1} (4.7 mm w.e. decade^{-2}) at the 2Barrel ice core site 150 km from Thule AB, −5.2% decade^{-1} (1.7 mm w.e. decade^{-2}) at Camp Century located 205 km from Thule AB, and 4.4% decade^{-1} (1.0 mm w.e. decade^{-2}) at B26 located 500 km from Thule AB. In general, annually averaged precipitation and annually and seasonally averaged mean air temperatures observed at Thule AB follow trends observed in composite coastal Greenland time series, with both notably indicating winter as the fastest warming season in recent periods (1981–2012). Trends (1961–2012) in seasonal precipitation differ, specifically with NW Greenland summer precipitation increasing (~0.6 mm w.e. decade^{-2}) in contrast with decreasing summer precipitation in the coastal composite time series (3.8 mm w.e. decade^{-2}). Differences in precipitation trends between NW Greenland and coastal composite Greenland underscore the heterogeneity in climate influences affecting precipitation. In particular, recent (1981–2012) changes in NW Greenland annual precipitation are likely a response to a weakening North Atlantic oscillation.

1. Introduction

The fresh water stored within the Greenland ice sheet (GrIS) is equivalent to ~7.5 m of global mean sea level rise (Bamber *et al* 2013), and this frozen reservoir responds to changing climate by adjusting its mass balance. Since 2000 A.D., Greenland has experienced record high surface temperatures (Mote 2007, Tedesco *et al* 2014), record warm coastal air temperatures (Hanna *et al* 2012, Mernild *et al* 2013), and record ice sheet melt extents (Fettweis *et al* 2011, Nghiem *et al* 2012, Hanna *et al* 2014). GrIS mass balance over this period has become increasingly negative (e.g., Krabill 2004, Sasgen *et al* 2012), and evidence suggests this is in response to a warming climate (Hanna *et al* 2008). The GrIS is projected to continue losing mass with warming temperatures despite projected increases in snowfall (e.g., Hanna *et al* 2013). Mass changes of the GrIS are concentrated near the margins (Helm *et al* 2014), so changes in accumulation in this region are critical in the changing mass balance of the GrIS.

Data from long-term, reliable instrumental and proxy records have been used to characterize trends in coastal Greenland climatology (e.g., Putnins 1970, Box 2002, Hanna *et al* 2012, Mernild *et al* 2013, Mernild *et al* 2014). Over the period 1961–2012, these studies document that coastal Greenland annual precipitation increased on average ∼1.5% decade^{-1} (∼1.3 mm water equivalent (w.e.) decade^{-2}) despite a 3.8 mm w.e. decade^{-2} decrease in summer seasonal precipitation (Mernild *et al* 2014). This is coincident with a positive trend in mean air temperatures including very strong (locally >10 °C) recent winter warming (Hanna *et al* 2012). However, these current coastal composite studies do not include stations north of Upernavik on the west coast. Hawley *et al* (2014) found a ∼10% increase in northwest (NW) Greenland accumulation rates over the past 52 years based on isochronous layers imaged with ice penetrating radar along the Greenland Inland Traverse (GrIT) route. They observe the largest increases in accumulation near the coast in the Thule region, and hypothesize that warmer temperatures may be responsible for the increased accumulation.

Here, we investigate NW Greenland precipitation trends along a coast-to-interior transect using 23 snow pit and ice core glaciochemical records collected during the 2010 and 2011 GrIT. We present seasonal and annual temperature and precipitation time series from a near-coastal meteorological station in NW Greenland. We investigate annual and seasonal trends in temperature and precipitation at this site for 30-year 'normal' periods, as defined by the World Meteorological Organization (WMO), and shorter periods, to characterize changing climatology in NW Greenland.

2. Methods

2.1. Precipitation proxy records

We use annual layer thicknesses (in water equivalent) from 20 snow pits and three ice cores as proxies for precipitation for the NW GrIS (table 1, figure 1). Accumulation rates for Camp Century and B26 ice cores are inferred from δ^{18}O-based annual layer identification and density data (Clausen *et al* 1988, Buchardt *et al* 2012). The 2Barrel (57 km west of Camp Century) ice core was collected in July 2011 using a Kovacs Enterprise Mark III (7.25 cm diameter) coring system (Hawley *et al* 2014). The core was shipped frozen back to the laboratory (Hanover, New Hampshire) where it was processed and logged. Following methods outlined in Osterberg *et al* (2006), we collected and analyzed discrete, co-registered samples for major ion, trace element, and stable water isotope analyses. Seasonal peaks from these analyses were used to annually date the 2Barrel ice core from 2011–1990.

We sampled snow pits in 2010 and 2011 as part of the GrIT, an annual logistics traverse that follows a route nearly identical to that taken by Carl Benson and the US. Army Snow, Ice and Permafrost Research Establishment (SIPRE) between 1952 and 1955 (Benson 1962; figure 1). We sampled snow pits at 5–10 cm depth resolution for chemistry wearing non-particulating Tyvek suits and polyethylene gloves. Samples were collected in pre-cleaned polyethylene bottles and stored frozen until melting for chemical and isotopic analyses (see Osterberg *et al* 2006). We determined annual layer demarcations for the snow pits using the seasonal peaks of a suite of parameters, primarily Na, Al, δ^{18}O, methanesulfonic acid, and Ca data, and calculated accumulation rates using co-registered density data. We assume annual layer thickness uncertainty in our snow pits to be equivalent to half of the mean sample thickness (∼17 mm w.e.).

2.2. Coastal meteorological records

Coastal precipitation and temperature data were measured at synoptic weather stations located in NW Greenland and operated by the Danish Meteorological Institute (DMI) (Cappelen 2013; table 1) and Thule Air Base (AB). Station locations and observational periods are listed in table 1. All climate data have been quality controlled (via visual inspection) at the daily to monthly timescale.

We construct a composite climate record, Thule AB, using DMI stations Dundas (04 200) and Pituffik (04 202) and observations collected directly from the current weather center at Thule AB (BGTL, *pers. comm.*), producing composite precipitation and temperature records with no gaps from 1952 to 2012. The Thule AB composite record was assessed for homogeneity using the standard normal homogeneity test (Steffensen *et al* 1993) with the nearest available neighboring station data used as the reference station (Aasiaat; Cappelen 2013). Such a composite record, created from coastal points located within a few km of each other, may provide a more regionally representative value with diminished local effects (Bales *et al* 2009). Seasonal analyses are based on the standard 3-month meteorological seasons: winter (December through February), spring (March through May), summer (June through August), fall (September through November).

2.3. Correction factors

Precipitation datasets may be subject to systematic errors such as wind-induced undercatch and wetting losses (Goodison *et al* 1989, Rasmussen *et al* 2012). Yang *et al* (1999) found that solid precipitation is most affected by undercatch, and reported total annual precipitation correction factors of 1.50–1.75 for northern coastal Greenland sites. The correction factor magnitude is due to the inherently larger snow component in a northern stations' total reported precipitation, the observed higher wind-induced loss for snow than for rain, and the greater amount of absolute precipitation in the warm season than in the cold season. We correct for undercatch in the Thule AB monthly precipitation time series by first estimating the percentage of solid precipitation based on temperature (e.g., Bales *et al* 2009), and then applying the bias correction factor Bales *et al* (2009) reported for Thule (1956–1980; 1.72) to the calculated solid precipitation fraction. The bias correction for Thule AB, based on monthly values of meteorological variables, averaged ∼55%, which compares well with previously reported corrections of 50%–75% for northern Greenland locations (Yang *et al* 1999).

Similarly, we address the potential loss in surface mass balance due to sublimation and evaporation (Mernild *et al* 2008, Mernild and Liston 2012) by adding 8% to every proxy precipitation record (see Mernild *et al* 2014). This study cannot account for blowing snow and mass divergence (e.g., Bintanja 1998, Box *et al* 2004) due to incomplete wind data. We minimize noise (meter- to kilometer-scale spatial variability due to glaciological processes) from the climate signal in precipitation proxy records (e.g., Fisher *et al* 1985, Banta and McConnell 2007) by averaging over 10–20 year intervals (see Mosley-Thompson *et al* 2001). We minimize changes in snow pit-derived accumulation resulting from slight variations between the Benson and GrIT traverse routes by applying a spatial correction value to the Benson (1962) data (see Hawley *et al* 2014) calculated using Polar MM5 climate model accumulation rate output (Burgess *et al* 2010).

2.4. Statistical analysis

We apply standard statistical techniques (mean, standard deviation) and linear regression trend analysis to characterize and evaluate NW Greenland temperature and precipitation trends for various climatological periods, including as many WMO normal periods as our dataset allows. We evaluate shorter periods coincident with the recent period of warming, and consider trends in temperature and precipitation significant when $p < 0.10$.

3. Results

3.1. Accumulation trends in NW Greenland

Point calculations of mean precipitation (m w.e. a^{-1}) derived from GrIT snow pits, firn cores, and Benson (1962) snow pits are shown in figure 2. Calculated over the entire traverse route, mean annual precipitation in

Table 1. Details of the coastal Greenland meteorological stations, ice cores, and Greenland inland traverse (GrIT) snow pits used in this study.

Station/site	Data source	WMO[a] code or data type	Latitude (°N)	Longitude (°W)	Data period available
Dundas[b]	DMI[c]	04 200	76.57	68.80	January 1961–August 1983
Pituffik[b]	DMI[c]	04 202	76.53	68.75	January 1974–November 2006
BGTL[b]	USAF and DMI[c]	04 202	76.53	68.75	September 1951–December 2012
2Barrel	Hawley[d]	Ice core	76.93	63.15	1990–2010
2Barrel pit	This study	Snow pit	76.93	63.15	2010
Galen pit	Hawley[d]	Snow pit	74.42	39.29	2007–2010
Camp Century	Buchardt[e] and Clausen[f]	Ice core	77.17	61.10	1762–2008
B26	Buchardt[e]	Snow pit and ice core	77.25	49.22	1928–2010
GrIT (2010) 1	This study	Snow pit	77.46	49.89	2008–2009
GrIT (2010) 2	This study	Snow pit	77.30	46.50	2008–2009
GrIT (2010) 3	This study	Snow pit	76.79	44.24	2009
GrIT (2010) 4	This study	Snow pit	76.25	42.11	2008–2009
GrIT (2010) 5	This study	Snow pit	75.41	41.07	2008–2009
GrIT (2010) 6	This study	Snow pit	74.09	38.75	2009
GrIT (2010) 7	This study	Snow pit	73.52	38.64	2009
GrIT (2010) 8	This study	Snow pit	72.94	38.54	2009
GrIT (2010) 9	This study	Snow pit	72.70	38.65	2009
GrIT (2011) A	This study	Snow pit	76.80	64.89	2010
GrIT (2011) B	This study	Snow pit	77.13	61.04	2010
GrIT (2011) C	This study	Snow pit	77.36	47.15	2009–2010
GrIT (2011) D	This study	Snow pit	76.50	43.73	2009–2010
GrIT (2011) E	This study	Snow pit	75.13	40.54	2007–2010
GrIT (2011) F	This study	Snow pit	73.65	38.68	2008–2010
GrIT (2011) G	This study	Snow pit	74.51	41.34	2008–2010
GrIT (2011) H	This study	Snow pit	77.41	49.02	2009–2010
GrIT (2011) I	This study	Snow pit	77.13	61.04	2010
GrIT (2011) J	This study	Snow pit	76.93	63.15	2010

[a] World Meteorological Organization (WMO).
[b] Stations are used in our Thule AB series (1952–2012).
[c] Danish Meteorological Institute (DMI); United States Air Force (USAF).
[d] From Hawley *et al* (2014).
[e] From Buchardt *et al* (2012).
[f] From Clausen *et al* (1988).

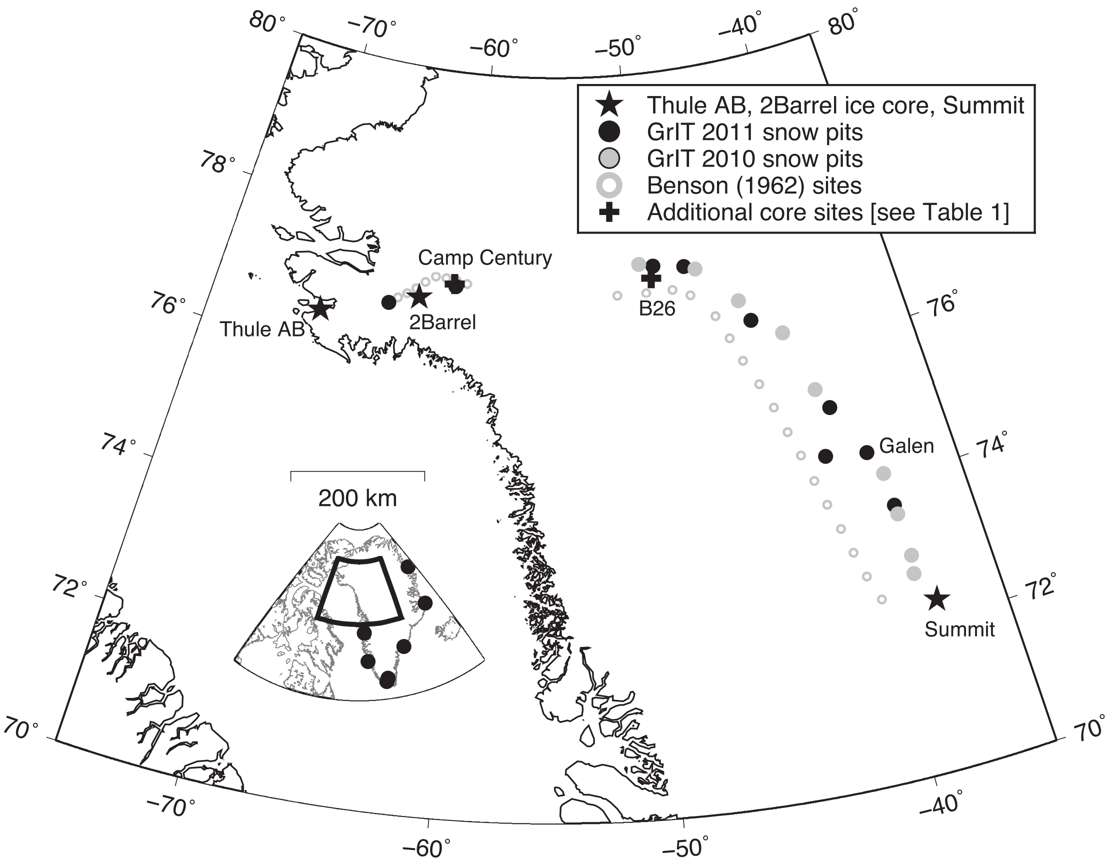

Figure 1. Map of northwest Greenland, Thule AB, Greenland inland traverse (GrIT) and Benson (1962) snow pits, and additional ice core sites. Black circles on inset map represent DMI meteorological stations used in coastal composite Greenland precipitation (CGP1) time series (Mernild *et al* 2014).

NW Greenland (1990–2010) using GrIT snow pits and firn cores is 259 ± 155 mm w.e. a^{-1}, which is not significantly different from 262 ± 95 mm w.e. a^{-1} calculated from snow pits sampled by Benson over the period 1945–1955 (Benson 1962). We perform a two-way ANOVA of annual precipitation to assess changes in precipitation over time (Benson (1962) snow pits compared with GrIT snow pits) and along the traverse route between lower-elevation, coastal sites (0–150 km from Thule AB) and higher-elevation, interior sites (300–1000 km from Thule AB). Our analysis shows a significant ($p < 0.05$) difference between the coastal sites and the interior sites, with coastal sites also being significantly different between the two time periods ($p < 0.05$). Mean precipitation at coastal sites increased on average 2.7 mm w.e. a^{-1} ($p < 0.05$), indicating a ~7% $decade^{-1}$ increase over the recent five decades. Interior sites were not significantly different over the two time periods. However, the GrIT snow pits are unsuitable for annual trend analysis because 16 of the 20 snow pits contain only one or two full annual layers, with only two snow pits containing four full annual layers.

Annual precipitation anomalies for the 2Barrel, Camp Century, and B26 ice cores are shown over the period 1952–2012 (figure 3). Mean annual precipitation totals and standard deviations for various time periods are shown in table 2, and trends are shown in table 3. Using the three ice core records to assess variability in NW Greenland precipitation, we find mean annual precipitation rates decreased with increasing distance from Thule AB towards the GrIS interior, ranging from 548 ± 138 mm w.e. a^{-1} at 2Barrel (most coastal site) to 204 ± 41 mm w.e. yr^{-1} at B26 (most interior site) from 1991–2010. Camp Century, situated between 2Barrel and B26, recorded a mean annual accumulation of 326 ± 62 mm w.e. a^{-1} for a similar period (1991–2008). Over the 1991–2008 period, neither 2Barrel (4.7 mm w.e. a^{-1}, 0.9% a^{-1}), Camp Century (1.5 mm w.e. a^{-1}, 0.5% a^{-1}) nor B26 (−0.5 mm w.e. a^{-1}, −0.2% a^{-1}), show statistically significant ($p < 0.1$) changes in annual precipitation.

3.2. Thule AB precipitation trends

Mean annual and seasonal precipitation trends from the Thule AB composite dataset are presented for various climatological periods in tables 2 and 3, respectively. Mean annual precipitation at Thule AB for the most recent 2001–2012 period is 202 ± 66 mm w.e. a^{-1}, which is the highest recorded mean annual precipitation total for any period in this study. Annual precipitation at Thule AB during the 1981–2012 period increased 2.4 mm w.e. a^{-2} (1.3% a^{-1}, $p < 0.05$), which continues the pattern observed in

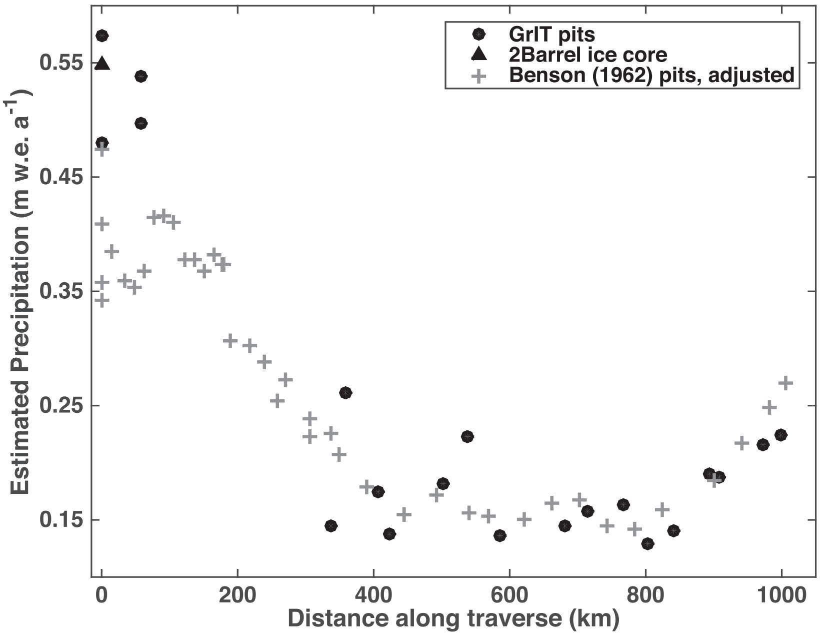

Figure 2. Estimated annual precipitation derived from GrIT snow pits, 2Barrel ice core, and Benson (1962) snow pits are plotted with respect to distance traveled along the GRIT traverse route, and their estimated precipitation totals have been adjusted to the GrIT route using an accumulation map from Burgess *et al* (2010) (see Hawley *et al* 2014). Between 1945–1955 (Benson 1962) and 1990–2010 (GrIT and 2Barrel, this study), mean precipitation for sites 0–150 km along the traverse are on average 2.7 mm w.e. a^{-1} greater (~7% $decade^{-1}$ increase), in agreement with Hawley *et al* (2014).

snow pit data where significant increases in precipitation are observed closer to the coast.

Thule AB receives 35% of its precipitation during the autumn, followed by 29% in summer, 20% in winter, and 16% in spring (table 2). Thus, most of Thule's annual precipitation falls in the summer and autumn, similar to coastal stations further south in west central Greenland (Porter and Mosley-Thompson 2014). The recent 2001–2012 period yields the highest mean summer precipitation (79 ± 50 mm w.e. a^{-1}) and third-highest mean spring precipitation (31 ± 22 mm w.e. a^{-1}) for Thule AB. The highest mean spring precipitation (35 ± 23 mm w.e. a^{-1}) occurs during the 1991–2012 period. The 1952–1980 period recorded the highest mean autumn (65 ± 28 mm w.e. a^{-1}) and winter (42 ± 30 mm w.e. a^{-1}) season precipitation for Thule AB.

Variability in the annual precipitation may follow summer precipitation trends. In the 1981–2012 period, when the annual precipitation trend is positive, summer precipitation increases 1.4 mm w.e. a^{-2} (2.4% a^{-1}, $p < 0.1$) and spring precipitation increases 0.8 mm a^{-2} (2.8% a^{-1}, $p < 0.05$), whereas autumn (−0.1 mm a^{-2}, −0.2% a^{-1}) and winter (0.4 mm a^{-2}, 1.2% a^{-1}) have no significant trends. Since 1952, Thule AB summer precipitation has increased 0.6 mm w.e. a^{-2} (1.0% a^{-1}, $p < 0.05$; figure 4). In contrast, changes in Thule AB spring (0.1 mm w.e. a^{-2}, 0.4% a^{-1}), autumn (−0.2 mm w.e. a^{-2}, −0.3% a^{-1}) and winter (−0.2 mm w.e. a^{-2}, −0.4% a^{-1}) precipitation are statistically insignificant over the same time period (figure 4).

3.3. Temperature trends at Thule AB

We present annual and seasonal mean air temperatures and trends from the Thule AB composite dataset for various climatological periods in tables 4 and 5, respectively. Annual mean air temperature at Thule AB for the recent 2001–2012 period is −9.7 ± 0.8 °C, which is the warmest calculated temperature observed for any period in this study. Mean annual temperatures have increased 1.5 °C ($p < 0.05$) since weather observations began in 1952, with a greater increase in recent periods: 2.7 °C ($p < 0.05$) over the 1981–2012 period, and 3.3 °C ($p < 0.05$) over the 1991–2012 period.

Seasonal temperature trends are also positive since 1952, with the most recent period (2001–2012) being the warmest seasonally on record for Thule AB. Over the 1952–2012 period, spring and autumn warmed the most (1.8 °C, $p < 0.05$) followed by summer (1.6 °C, $p < 0.05$), and winter (0.9 °C, insignificant) (figure 4). However, over the more recent 1991–2012 period, winter warmed the most at 5.4 °C ($p < 0.05$), followed by summer 3.4 °C ($p < 0.05$), autumn 2.5 °C ($p < 0.05$), and spring 2.2 °C ($p < 0.10$). Every season shows at least one climate period with a cooling trend within the 1952–2012 record, although no more than two seasons show cooling trends in any single climate period (table 5).

3.4. Correlations between precipitation and accumulation in NW Greenland

We examine how well correlated the coastal precipitation record is with inland ice core sites to assess the

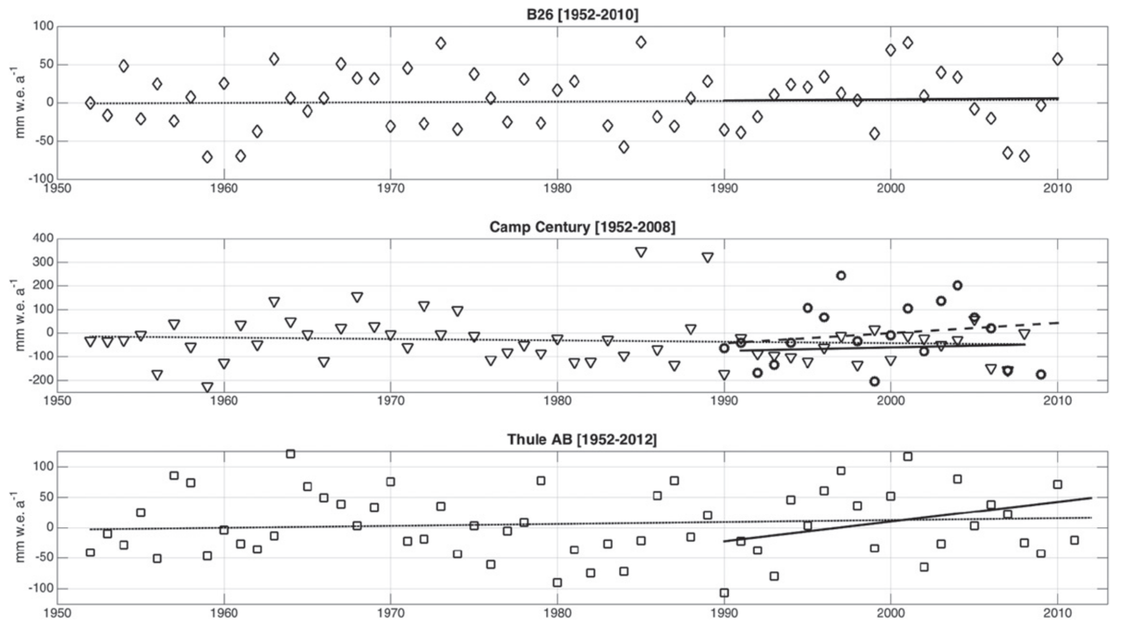

Figure 3. Time-series of Greenland mean annual precipitation anomalies, including trend lines, from Thule AB, 2Barrel, Camp Century, and B26 (see table 1 for data sources). The precipitation is relative to a 1961–1990 baseline (1990–2010 baseline used for 2Barrel). Symbols represent the annual precipitation and trends are shown for 1952–2012 and 1990–2012 periods, or to the extent a proxy record will allow. 2Barrel data (circles with dashed trend line; 1990–2010) are plotted with Camp Century data (triangles; 1991–2008). Note the different scales on the ordinate.

Table 2. Thule AB annual and seasonal mean precipitation totals and standard deviations (mm w.e. a^{-1}) for WMO 'standard', recent shorter, and instrumental periods, and calculated mean annual accumulations at 2Barrel, Camp Century (CpCent), and B26 for the same periods (see table 1 for data sources).

Period	Annual	Spring	Summer	Autumn	Winter	2Barrel	CpCent	B26
2001–12	202 ± 66	31 ± 22	79 ± 50	61 ± 31	34 ± 22	575 ± 116[a]	341 ± 73[b]	203 ± 49[a]
1991–12	196 ± 60	35 ± 23	65 ± 42	59 ± 26	36 ± 22	548 ± 138[a]	326 ± 62[b]	204 ± 41[a]
1981–12	184 ± 61	29 ± 22	59 ± 38	63 ± 28	33 ± 22	—	346 ± 122[b]	197 ± 46[a]
1971–00	170 ± 53	29 ± 20	48 ± 21	61 ± 26	35 ± 26	—	354 ± 120	199 ± 42
1961–90	177 ± 55	29 ± 16	48 ± 20	62 ± 25	38 ± 26	—	387 ± 123	197 ± 44
1952–80	184 ± 51	31 ± 16	46 ± 23	65 ± 28	42 ± 30	—	366 ± 91	200 ± 37
1952–12	184 ± 56	30 ± 19	53 ± 32	64 ± 28	37 ± 26	—	356 ± 105[b]	199 ± 41[a]
1961–12	185 ± 57	32 ± 20	55 ± 32	61 ± 25	37 ± 26	—	364 ± 108[b]	200 ± 43[a]

[a] Period ends at 2010.

[b] Period ends at 2008.

Table 3. Thule AB annual and seasonal mean precipitation trends (mm w.e. a^{-2}) for WMO 'standard', recent shorter, and instrumental periods, and calculated mean annual accumulation trends for 2Barrel, Camp Century (CpCent), and B26 for the same periods (see table 1 for data sources).

Period	Annual	Spring	Summer	Autumn	Winter	2Barrel	CpCent	B26
2001–12	2.5	<u>3.1</u>[c]	−4.6	4.0	−0.3	−8.2[a]	−9.6[b]	−6.9[a]
1991–12	2.1	0.1	1.5	0.9	−0.1	4.7[a]	1.5[b]	−0.5[a]
1981–12	**2.4**[c]	**0.8**[c]	<u>1.4</u>[c]	−0.1	0.4	—	−1.7[b]	0.9[a]
1971–00	1.5	0.5	0.1	0.3	−0.1	—	−2.2	0.1
1961–90	<u>−1.9</u>[c]	**−1.1**[c]	−0.3	0.6	<u>−1.0</u>[c]	—	−1.2	−0.6
1952–80	−0.2	0.5	0.3	<u>−1.0</u>[c]	0.2	—	1.2	0.8
1952–12	0.3	0.1	**0.6**[c]	−0.2	−0.2	—	−0.6[b]	0.1[a]
1961–12	0.3	0.0	<u>0.6</u>[c]	0.1	−0.3	—	<u>−2.0</u>[b,c]	0.0[a]

[a] Period ends at 2010.

[b] Period ends at 2008.

[c] Significant trends ($p < 0.05$ and $p < 0.10$) are in bold type and underlined, respectively.

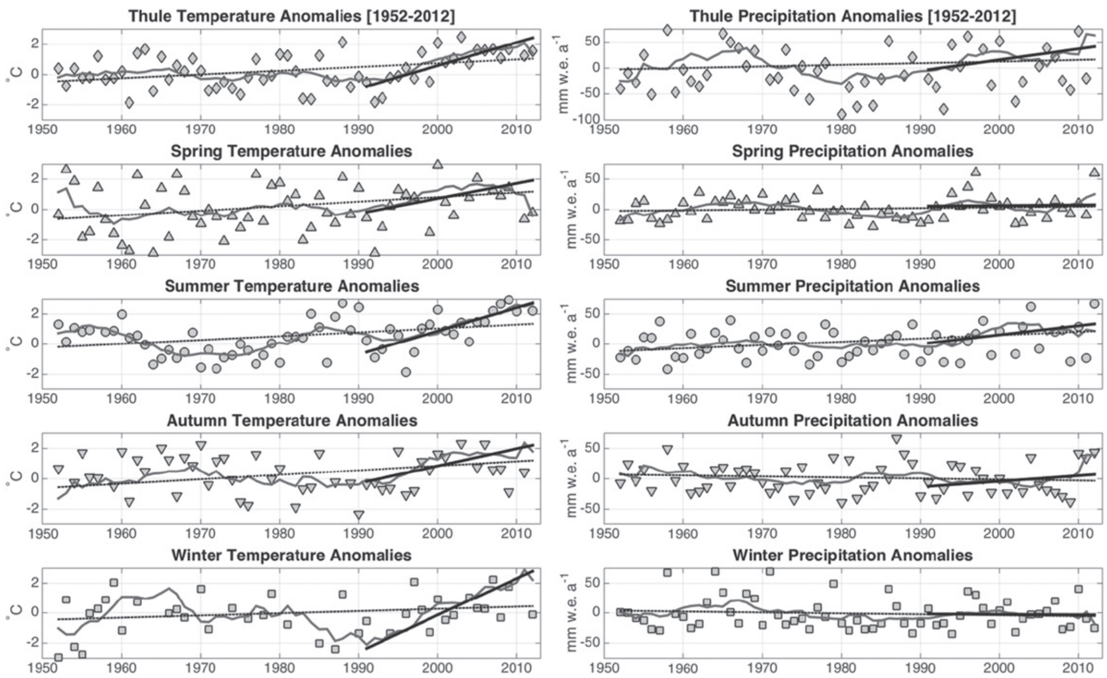

Figure 4. Time-series of Thule AB temperature and precipitation anomalies (1952–2012), where symbols represent either the annual mean temperature and precipitation or the seasonal mean temperature and precipitation for that calendar year, including 10-year running means and trend lines (1952–2012 (dashed) and 1991–2012 (solid)). The temperatures and precipitation are relative to a 1961–1990 baseline.

Table 4. Thule AB annual and seasonal mean air temperatures and standard deviations (°C) for WMO 'standard', recent shorter, and instrumental periods.

Period	Annual	Spring	Summer	Autumn	Winter
2001–12	−9.7 ± 0.8	−14.2 ± 1.5	5.0 ± 0.9	−7.8 ± 1.4	−21.8 ± 1.9
1991–12	−10.5 ± 1.3	−14.7 ± 1.8	4.3 ± 1.2	−8.6 ± 1.5	−23.1 ± 2.4
1981–12	−10.8 ± 1.3	−15.0 ± 1.7	4.3 ± 1.2	−8.9 ± 1.8	−23.5 ± 2.8
1971–00	−11.5 ± 1.1	−15.6 ± 1.6	3.5 ± 1.3	−9.7 ± 1.7	−24.2 ± 2.8
1961–90	−11.4 ± 1.1	−15.8 ± 1.5	3.2 ± 1.2	−9.6 ± 1.8	−23.3 ± 3.1
1952–80	−11.3 ± 0.9	−15.9 ± 1.7	3.2 ± 1.1	−9.7 ± 1.6	−23.1 ± 2.5
1952–12	−11.0 ± 1.2	−15.5 ± 1.7	3.8 ± 1.3	−9.3 ± 1.8	−23.3 ± 2.7
1961–12	−11.0 ± 1.3	−15.4 ± 1.7	3.7 ± 1.3	−9.2 ± 1.8	−23.2 ± 2.8

Table 5. Thule AB annual and seasonal mean air temperature trends (°C per time period) for WMO 'standard', recent shorter, and instrumental periods.

Period	Annual	Spring	Summer	Autumn	Winter
2001–12	0.8	−0.4	**2.5**[a]	−0.9	2.3
1991–12	**3.3**[a]	2.2[a]	**3.4**[a]	**2.5**[a]	**5.4**[a]
1981–12	**2.7**[a]	**2.1**[a]	**1.7**[a]	**2.6**[a]	**4.1**[a]
1971–00	0.8	1.3	**1.8**[a]	0.4	−0.3
1961–90	−0.1	0.9	**2.1**[a]	−0.8	−2.6
1952–80	−0.1	0.5	**−2.6**[a]	0.4	1.4
1952–12	**1.5**[a]	**1.8**[a]	**1.6**[a]	**1.8**[a]	0.9
1961–12	**1.8**[a]	**2.0**[a]	**2.9**[a]	**1.7**[a]	0.5

[a] Significant trends ($p < 0.05$ and $p < 0.10$) are in bold type and underlined, respectively.

homogeneity of precipitation in NW Greenland. Thule AB annual, autumn and winter precipitation correlate with annual precipitation derived from the coastal 2Barrel core at $p < 0.01$ (figure 5; 1990–2010), while summer ($R^2 = 0.12$) and spring ($R^2 = 0.07$) seasonal precipitation do not significantly correlate with 2Barrel annual precipitation ($p > 0.1$). We performed similar calculations over the same period for annual precipitation from the Camp Century and B26 cores, and found that Thule AB annual and seasonal precipitation are not significantly correlated with Camp Century ($R^2 = 0.0002$–0.048, $p > 0.1$). Thule AB annual and autumn precipitation correlate with annual precipitation derived from the inland B26 core at $p < 0.05$ ($R^2 = 0.30$ and $R^2 = 0.20$, respectively), and summer precipitation correlate with B26 annual precipitation at $p < 0.10$ ($R^2 = 0.15$). In summary, Thule AB precipitation is more strongly correlated with precipitation recorded at the more coastal ice core site (2Barrel) than with the more inland B26 and Camp Century sites. This may indicate that mechanisms forcing precipitation have important differences from the coast to the inland sites.

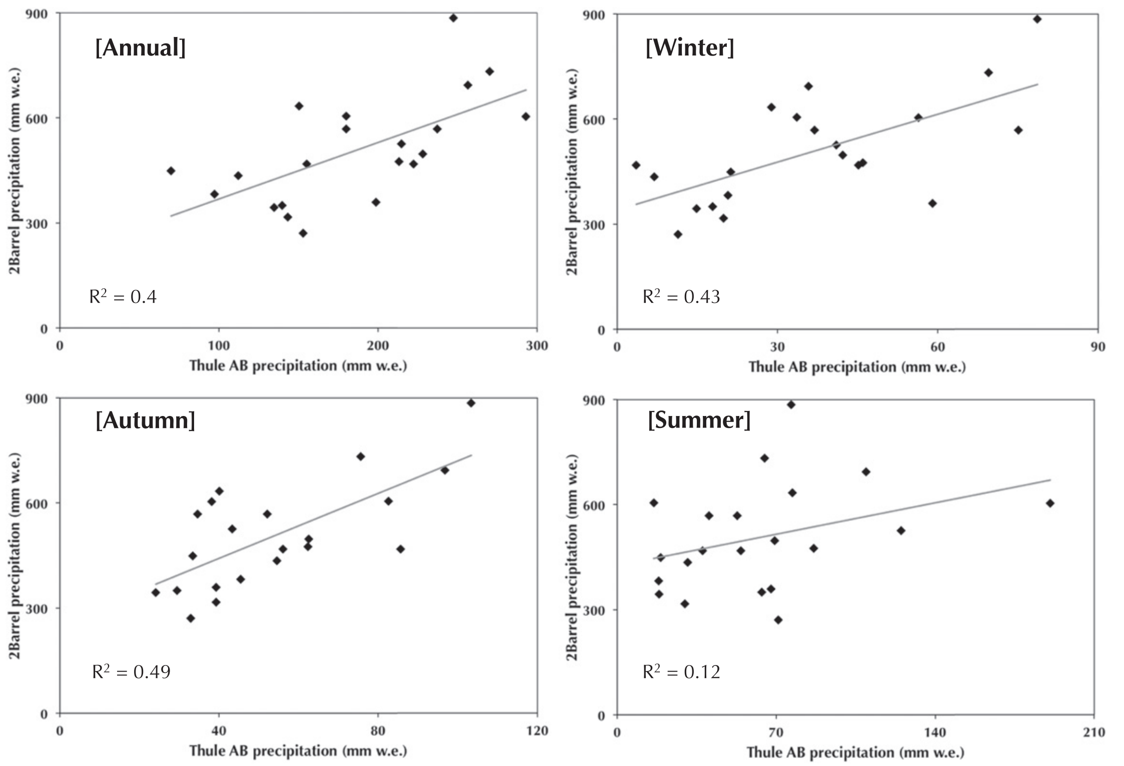

Figure 5. Scatter plots for 2Barrel annual precipitation and Thule AB composite precipitation for the period 1990–2010. Thule AB annual and seasonal (winter, autumn, summer) precipitation totals are shown. Spring, not shown, has an $R^2 = 0.07$.

4. Discussion

4.1. NW Greenland precipitation trends

We use the 1961–2012 climatological period to compare and contrast annual trends in Thule AB precipitation with a coastal composite Greenland precipitation (CGP1) time series from Mernild *et al* (2014). Mernild *et al* (2014) construct their CGP1 using mean annual precipitation from four west coast and three east coast DMI weather stations. Mean annual precipitation at Thule AB (1961–2012) is 185 ± 57 mm w.e. a^{-1}, which is much less than the mean annual precipitation calculated for CGP1 (858 ± 127 mm w.e. a^{-1}). This follows the gradient of coastal Greenland precipitation observed by Mernild *et al* (2014), where mean annual precipitation decreases with increasing latitude. The northernmost DMI weather station in the CGP1 time series is at Aasiaat (68.70 °N, 52.75 °W), located ∼1000 km south of Thule AB. Aasiaat had a mean annual precipitation of 474 ± 112 mm w.e. a^{-1} (1961–1990) compared to 177 ± 55 mm w.e. a^{-1} at Thule AB for the same time period. For the 1961–2012 period, there are no significant trends in mean annual precipitation at either Thule AB (∼2% decade^{-1}, 0.3 mm w.e. a^{-2}, $p > 0.1$), or in the CGP1 coastal Greenland composite record (∼1.5% decade^{-1}, 1.3 mm w.e. a^{-2}, $p > 0.1$). Mernild *et al* (2014) report positive precipitation trends of 2%–33% decade^{-1} (0.6–20.5 mm w.e. a^{-2}) in western Greenland over the 1991–2012 period, but they find negative precipitation trends (7%–18% decade^{-1}, 3.5–24.6 mm w.e. a^{-2}) in southern and eastern Greenland. We find significant positive precipitation trends at Thule AB from 1981–2012 (13% decade^{-1}, 2.4 mm w.e. decade^{-2}), with calculated positive mean annual precipitation (11% per decade, 2.1 mm w.e. a^{-2}, insignificant) over the more recent 1991–2012 period. Large inter-annual variability can explain the insignificant Thule AB precipitation 'trend' during the 1991–2012 period. Further, the positive precipitation trends along the western Greenland coast suggest that the Thule AB 1991–2012 period is part of the long-term, significant positive trend in Thule AB precipitation during the 1981–2012 period. Thus, in recent decades we generally observe opposing annually averaged precipitation trends in western (positive) and eastern (negative) Greenland.

On a seasonal timescale, Thule AB (1961–2012) precipitation increased in summer (10.9% decade^{-1}, 0.6 mm w.e. a^{-2}, $p < 0.1$), with insignificant precipitation changes in autumn (1.6% decade^{-1}, 0.1 mm w.e. a^{-2}), winter (−8.1% decade^{-1}, −0.3 mm w.e. a^{-2}) and spring (−0.3% decade^{-1}, −0.01 mm w.e. a^{-2}). In contrast, Mernild *et al* (2014) report increasing CGP1 seasonal precipitation for spring, autumn, and winter (1.8%–3.4% decade^{-1}, 0.4–0.6 mm w.e. a^{-2}, $p > 0.1$), and decreasing summer precipitation (1.8% decade^{-1}, 0.4 mm w.e. a^{-2}, $p > 0.1$). However, save for the summertime trend at Thule AB, long-term seasonal trends in coastal Greenland precipitation are insignificant due to large inter-annual variability. Furthermore, differences in seasonal trends for Thule compared to CGP1 can largely be explained by regionally variable precipitation responses to dominant atmospheric circulation patterns in each season. Seasonality of precipitation may be an important element to consider when interpreting trends in coastal Greenland precipitation (Porter and Mosley-Thompson 2014).

On a year-to-year basis, Thule wintertime precipitation is strongly correlated ($r = -0.51, p < 0.01$; 1952–2012) with the wintertime North Atlantic oscillation (NAO; Hurrell *et al* 2003), a seesaw of atmospheric condition that influences the North Atlantic storm track (e.g., Appenzeller *et al* 1998a, 1998b, Wanner *et al* 2001, Mosley-Thompson *et al* 2005, Schuenemann *et al* 2009, Merz *et al* 2013). A positive NAO index, associated with strong westerlies, occurs when the pressure gradient between the Azores high and the Icelandic low is greater than normal, and vice versa. The negative winter Thule precipitation trends from 1961–1990 and 1971–2000 are consistent with a positive winter NAO trend over those periods, and the rising winter precipitation trends from 1952–1980 and 1981–2012 are similarly consistent with weakening to declining winter NAO values over those intervals. Further, the fourth-highest wintertime precipitation total in the Thule record occurred in 2010, the same winter that recorded the lowest NAO value since 1950. Annual average precipitation at Thule is also significantly correlated with annually averaged NAO values ($r = -0.32$, $p < 0.01$), although winter is the only season with a significant correlation and thus appears to be largely responsible for the annual relationship. Mernild *et al* (2014) likewise note a significant influence of the NAO on the first empirical orthogonal function (EOF1) of their coastal precipitation compilation. However, the sign of the NAO correlation varies regionally around the Greenland coast, with reanalysis data generally showing positive NAO-precipitation correlations in eastern and southwestern Greenland, and negative correlations in western and southeastern Greenland (Rogers *et al* 2004, Hutterli *et al* 2005). Thus, the resulting wintertime trend in CGP1 depends on the relative balance of stations in regions with opposing responses to the NAO.

Examining the summertime precipitation trends of the DMI stations comprising CGP1 reveals consistent positive summer precipitation trends in one coastal station throughout the 1961–2012 period: Aasiaat, with an observed 2.0% decade^{-1} increase (0.3 mm w.e. a^{-2}, $p > 0.05$) over the 1981–2012 period. Thule AB experienced a ~24% decade^{-1} increase (1.4 mm w.e. a^{-2}, $p < 0.10$) in summer precipitation over this period. This positive trend in summer precipitation in west-central and coastal NW Greenland is also likely related to more frequent meridional airflow along the western flank of the GrIS (Hanna *et al* 2012) resulting from changes in the sign of the NAO. Further, earlier seasonal ice-out and later ice-in of Baffin Bay sea ice (Parkinson and Cavalieri 2008) may increase the potential for moist, oceanic near-surface air penetrating inland (Schuenemann *et al* 2009, Noël *et al* 2014, Kopec *et al* 2014).

4.2. NW Greenland temperature trends

Temperature trends observed at Thule AB and in the composite Greenland Temperature 2 (CGT2) time series indicate that changes in coastal Greenland temperatures are regionally consistent around coastal Greenland (Hanna *et al* 2012). Hanna *et al* (2012) construct CGT2 using temperature data from eight west coast and one east coast (Tasiilaq) DMI weather stations. The northernmost DMI weather station in the CGT2 time series is at Upernavik (72.78 °N, 56.13 °W), which is ~550 km south of Thule AB. In the 2001–2012 period, a time of negligible net change in northern hemisphere temperatures, Hanna *et al* (2012) observe coastal Greenland mean air temperatures increased significantly in winter (2.9 °C) and summer (0.8 °C), but decreased insignificantly in autumn (−1.1 °C) and spring (−0.2 °C). In the same period, we observe a significant ($p < 0.05$) increase in summer temperatures (2.5 °C). We also observe a slight warming in winter (2.3 °C) and cooling in autumn (0.9 °C) and spring (0.4 °C), but these changes are statistically insignificant. Thule AB seasonal mean air temperatures generally demonstrate very strong warming over the past few decades, especially during winter (locally >5 °C since 1991), which is similar to trends observed along the west coast of Greenland (Hanna *et al* 2012). This warming is attributed to recent negative trends in the NAO and positive trends in the Atlantic Multidecadal Oscillation (AMO) (Hanna *et al* 2008, 2012, Howat *et al* 2008).

4.3. Coast-to-interior gradient in NW Greenland precipitation trends

Hawley *et al* (2014) observe an average ~2% decade^{-1} increase (~0.4 mm w.e. a^{-2}) in NW Greenland accumulation rates calculated over the past five decades, where differences between snow pit-derived accumulation rates (Benson 1962) and ground-penetrating radar (GPR)-derived accumulation rates are more pronounced at the lower-elevation, coastal end of the GrIT. Over a similar time period investigated by Hawley *et al* (2014), we observe no statistically significant change ($p < 0.1$) in snow pit-derived precipitation rates from the interior of the GrIS, but a 7.2% decade^{-1} (0.05 mm w.e. a^{-2}, $p < 0.05$) increase in precipitation from snow pits located near the coast.

We used our suite of long-term precipitation records to examine the spatial variability of precipitation change along a coast-to-interior gradient in NW Greenland. In particular, we investigated the recent period (1981–2012), when regional warming is significant ($p < 0.05$) for every season. Similar to snow pit-derived precipitation rates, we observe no statistically significant change ($p > 0.1$) in precipitation rates recorded by the Camp Century (−5.2% decade^{-1}, 1.7 mm w.e. decade^{-2}), B26 (4.4% decade^{-1}, 1.0 mm w.e. decade^{-2}), or 2Barrel (8.6% decade^{-1}, 4.7 mm w.e. decade^{-2}, 1991–2012 period) ice cores. Conversely, Thule AB precipitation increased 13% decade^{-1} (2.4 mm w.e. decade^{-2}) in the 1981–2012 period. Increased precipitation due to orographic uplift occurs at the margin (Bales *et al* 2009), and the high mean annual precipitation at 2Barrel (table 2) may indicate a relative maximum with sites further inland (e.g., Camp Century, B26) reflecting the counterbalancing effect of drier conditions. In spite of positive changes at the coast near the ice sheet margin, negligible changes in precipitation observed over the interior of Greenland coupled with increasing surface melting, run-off and ice discharge will likely continue the trend of regional mass loss in NW Greenland (e.g., Sasgen *et al* 2012). Relative increases in precipitation at a particular site may also reflect increases in temperature, a result of the *Clausius–Clapeyron* relation. The large increase in coastal snow pit precipitation, consistent with the zone of GrIS thickening now extending to elevations above 1500 m (Thomas *et al* 2006), may signal significant increases in GrIS temperatures occurring at lower to midlevel elevations (e.g., 2Barrel, ∼1680 m) versus smaller temperature increases at higher elevations.

We examine how well Thule AB annual and seasonal precipitation correlate with NW Greenland proxy records to assess regional seasonal precipitation bias. In the recent period (1991–2012), Thule AB annual precipitation is strongly correlated with 2Barrel precipitation. Winter is warming the fastest during this period, and Thule AB winter precipitation is also strongly correlated with 2Barrel estimated precipitation. This implies the 2Barrel proxy precipitation record is well-suited for examining the influence of the NAO (e.g., Porter and Mosley-Thompson 2014), and characterizing the coast-to-ice sheet precipitation gradient for NW Greenland (e.g., Taurisano *et al* 2004). Future work with the 2Barrel record will investigate the influences of changing atmospheric circulation and Baffin Bay sea ice extent on NW Greenland climate.

5. Conclusions

We investigate the spatial variability of precipitation along a coast-to-interior gradient, and find more substantial increases in precipitation at sites more proximal to the coast. Snow pit-derived precipitation near the coast (1950–2000) has increased ∼7% decade^{-1} ($p < 0.01$), whereas we observe no significant change at interior snow pits. Hawley *et al* (2014) found a ∼2% decade^{-1} increase over this period across the NW GrIS, which is consistent with our result when one considers differences in precipitation are more pronounced at the lower-elevation, coastal sites. This regional gradient is also observed in our suite of long-term precipitation records, where changes in precipitation are significant near the coast (13% decade^{-1} at Thule AB) in contrast to negligible changes in precipitation in the GrIS interior (4.4% decade^{-1} at B26). The strong correlation between 2Barrel precipitation and Thule AB annual precipitation, likely representative of shared regional-scale climate features (Crüger *et al* 2004), coupled with significantly correlated Thule AB autumn and winter season precipitation, indicates that 2Barrel would be an excellent record to extend and study winter variability in the NAO.

Comparing temperature trends observed at Thule AB with CGT2 demonstrate that changes in coastal Greenland temperatures are regionally consistent. Mean annual and seasonal temperature trends in Thule AB are positive, similar to trends observed in CGT2 (1961–2012) with similar positive seasonal trends for most climate periods. In contrast, coastal Greenland precipitation trends show regional variability associated with dominant atmospheric circulation patterns. While increasing Thule AB annual precipitation since 1981 is consistent with rising western Greenland precipitation observed in CGP1 (Mernild *et al* 2014), seasonal Thule precipitation trends differ from those of CGP1. Specifically, Mernild *et al* (2014) do not observe increasing trends in summer CGP1 precipitation totals, whereas Thule AB summer precipitation trends are positive (∼0.6 mm w.e. decade^{-2}; 1961–2012).

Since 1981, Thule AB winter season mean air temperatures are warming the fastest and Thule AB summer and spring season precipitation totals have been increasing the fastest. These positive trends in NW Greenland temperature and precipitation are associated with a weakening NAO (wintertime), which enhances meridional flow and precipitation in western Greenland. A companion study of NW Greenland climate will systematically analyze the regional atmospheric circulation patterns as they relate to NW Greenland precipitation on a seasonal basis. The coastal climate records presented here contribute to the understanding of spatial variability in NW Greenland precipitation and provides useful boundary conditions for ice sheet mass balance studies interpolating between inland proxy records and coastal meteorological data (e.g., Bales *et al* 2009).

Acknowledgments

This project was supported by the National Science Foundation (NSF) under grants OPP-0909265 and ARC-1107411, with additional support from NSF grants DGE-0801490 and DGE-0947790. Special thanks are given to Susanne Buchardt at the Centre for Ice and Climate (U. Copenhagen) for providing Camp

Century and B26 δ^{18}O and density data and the Danish Meteorological Institute for providing observed meteorological station data. NAO Index Data (PC-based) provided by the Climate Analysis section, NCAR, Boulder, USA, Hurrell (2003). We thank Mike Handley at the Climate Change Institute (U. Maine), Sarah Caughey and Lauren Culler (Dartmouth College) for help with snow pit and ice core analyses. We acknowledge Ben Kopec and Xiahong Feng for thoughtful discussions, and thank the editor and three anonymous reviewers whose comments and suggestions helped improve the manuscript. The authors have no conflict of interest.

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