The SUMup dataset: Compiled measurements of surface mass balance components over ice sheets and sea ice with preliminary analysis over Greenland

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Abstract

Increasing atmospheric temperatures over ice cover affects surface processes including melt, snowfall and snow density. Here, we present the SUMup dataset, a standardized dataset of Arctic and Antarctic observations of surface mass balance components. The July 2017 SUMup dataset consists of three subdatasets, snow/firn density (doi:10.18739/A26D6F), snow accumulation on land ice (doi:10.18739/A2XX0V), and snow depth on sea ice (doi:10.18739/A22Q35), to monitor change and improve estimates of surface mass balance. The measurements in this dataset were compiled from field notes, papers, technical reports, and digital files. SUMup is a compiled, community-based dataset that can be and has been used to evaluate modeling efforts and remote sensing retrievals. Preliminary analysis of the dataset shows that Greenland ice sheet density measurements in the top 1 m do not show a strong relationship with annual temperature. At Summit Station, Greenland, accumulation and surface density measurements vary seasonally with lower values during summer months. The SUMup dataset is a dynamic, living dataset that will be updated and expanded for community use as new measurements are taken and new processes are discovered and quantified.

1. Introduction and Background

Earth's polar regions are warming at an accelerated rate. As increased air temperatures, and associated feedbacks with radiative heating, persist the ice cover is changing particularly at the ice/atmosphere interface (e.g. Vaughan and others, 2003; Serreze and Francis, 2006; Hall and others, 2013). This change is evident by declining sea ice extent (e.g Ritcher-Menge and others, 2016) and the recent acceleration of mass loss from the Greenland Ice Sheet (GrIS) and Antarctic ice sheets (AIS), (e.g. Velicogna and others, 2014; Shepherd and others, 2012), that contributed ~11 mm to global sea levels between 1992 and 2011 (Shepherd and others, 2012). Surface change is particularly evident over the GrIS where surface mass balance processes, dominated by melt, now account for more than half of mass loss through surface melting and decreasing surface albedo (e.g. van Angelen and others, 2013; van den Broeke and others, 2009; Enderlin and others, 2014). To understand this change, and the processes driving the change, it is vital to compile measurements from the past and present, and continue to collect them in the future.

In 2012, at the Surface Mass Balance and Snow on Sea Ice Working Group (SUMup) meeting, the modeling and remote sensing communities clearly stated to observationalists that the lack of easy to access, standardized, in-situ measurements hindered scientific achievement. A public, annual, decadal, standardized time-series of measurements was recommended (Koenig and others, 2013). Modelling and remote sensing studies require validation measurements (e.g. Fettweis and others, 2017; Arthern and others, 2006; Burgess and others, 2010; Kuipers Munneke and others 2015; Koenig and others, 2016), ideally at their same spatial and temporal resolutions and over large sections of ice sheets or sea ice, which are difficult for an individual researcher to compile. Today, most field measurements for validation are dispersed across multiple data centers/datasets in differing formats. Some previous Arctic and Antarctic studies have compiled large sets of measurements, generally accumulation measurements (e.g. Mock 1967a; Mock 1967b; Ohmura and Reeh, 1999; Vaughan and others, 1999; Arthern and others, 2006; Machguth, 2016) most cover only a small region of the ice sheet and/or are not annually resolved. For instance, Machguth, 2016 provides a database spanning from 1892-2015 including over 3000 surface mass balance measurements from 46 sites in the ablation zone a standardized, formatted database from the Programme for Monitering of the Greenland Ice Sheet (PROMICE).

Here, we present the July 2017 SUMup dataset and its three subdatasets: density, accumulation, and snow depth on sea ice. This data paper serves to fully describe the dataset and includes preliminary analysis of the data over the GrIS demonstrating how this dataset increases our knowledge of surface mass balance processes by compiling previously dispersed measurements into a standardized dataset. Uses of SUMup include model validation, remote sensing validation and algorithm development, and long-term monitoring efforts.

2. The SUMup Dataset

2.1 Overview

The SUMup dataset is an expandable, community-based dataset of field measurements of surface mass balance components that is consistent in format, properly described through metadata, and publically available. The July 2017 SUMup dataset contains three subdatasets that consist of measurements of snow/firn density (doi:10.18739/A26D6F), snow accumulation on land ice (doi:10.18739/A2XX0V), and snow depth on sea ice (doi:10.18739/A22Q35). The SUMup dataset is a living document, meant to be expanded as new measurements are taken or previous measurements discovered. The current release of the July 2017 SUMup dataset and replaces the previous two smaller releases of July 2013 and July 2015. The measurements compiled in SUMup are from the polar regions and most date from 1950 to present day. (~2% of the accumulation subdataset predates 1950 and these measurements are included to keep complete records from ice cores.)

Figure 1 shows the locations of measurements represented by the July 2017 SUMup dataset. ~40 snow depth on sea ice locations off the coast of Finland in the Baltic sea are not shown on this map. Density and accumulation measurements are often co-located over the ice sheets where ice cores were collected (Fig. 1).

Figure 1

2.2 Sources

SUMup measurements were collected, formatted and compiled primarily through two methods: 1) searching data archives that traditionally host cryospheric data which included Pangaea (https://www.pangaea.de/), the Arctic Data Center (https://arcticdata.io/), NOAA's National Climate Data Center (https://www.ncdc.noaa.gov/) and the National Snow and Ice Data Center (https://nsidc.org/) and 2) by asking members of the cryospheric community to contribute field measurements. Keyword searches for the first method includes searching for the words "density", "accumulation", and "snow depth on sea ice". Annually resolved accumulation measurements are accepted. .. Various data types are compiled into the SUMup dataset including hand-written notes, technical reports, and digital files. Each measurement in the SUMup dataset contains a citation to the original source of the data. Based on keyword searches, data for this release, July 2017, should include most relevant measurements available in the data archival centers listed above posted before April 2016 with a focus on Greenland. It is possible, however, that datasets can be missed by keyword searches and the community is encouraged to contact the authors directly about any missing datasets that should be included in future releases of SUMup.

New and unique data sources are included in the SUMup dataset. Notably, the snow density subdataset includes snow pit data from Carl Benson's Greenland traverses in the early 1950's that, to our knowledge, have never before been digitized into a dataset, and include data from 1955 that previously had not been digitally scanned (Benson, 2013; Benson, 2017). The 1955 notebooks are only archived in the National Snow and Ice Data Center paper archives. The SUMup dataset also includes snow accumulation measurements from Summit Station, Greenland's stake network called the Bamboo Forest (Dibb and others, 2004) and corresponding density measurements at monthly temporal resolution (Dibb and others, 2007). Additionally, more widely used data sources are included, such as, US International Trans-Antarctic Scientific Expedition (US ITASE, Mayewski et al, 2013) ice cores, the Program for Arctic Regional Climate Assessment (PARCA, Mosley-Thompson et al, 2001) ice cores and The Greenland Inland Traverse (GrIT, Hawley et al, 2014) snow pits and ice cores. Section 2.4 provides more details on the specific sources for each of the three subdatasets including the complete list of all citations.

2.3 Contributing to the Dataset

The SUMup dataset will continue to expand on an annual basis as new measurements are taken and/or old measurements are discovered. Beyond expanding the current subdatasets, we expect to add additional subdatasets on surface mass balance processes which may include, but are not limited to, snow/ice albedo, snow temperature, and short-wave/long-wave radiation measurements. The community is encouraged to contribute data or suggest missing data sources/types to add to SUMup by contacting the authors directly.

2.4 Structure and MetaData

Each measurement contains common variables including the date taken, latitude, longitude, surface elevation if on land, the measurement itself, error associated with the measurement, the method in which the measurement was taken, and a citation for which the measurement can be sourced back to. By convention, negative latitudes represent south and negative longitudes represent west. For data that did not specify a specific date, but provided only the year, the date was entered as 'yyyy0000'. A fill value of -9999 was used for unknown or unmeasured parameters. Measurements can be separated into direct measurements, when the instrument measures the desired parameter directly, and derived measurements, when the instrument measures a parameter related to the primary parameter and uses a known relationship equation to derive the desired measurement. In this paper we refer to both direct and derived measurements as measurements.. For clarity, in the density dataset, methods 1-4, 6-9, and 13 are direct measurements (e.g. density cutters, ice core sections, etc.) while methods 5 and 10-12 are derived measurements (e.g. neutron density probe, X-ray microfocus computer tomography, Gamma ray attenuation, etc.). In the accumulation dataset, methods 1 and 3 are direct measurements (e.g. ice core sections and stake measurements) while method 2 is derived (radar isochrones). All snow depth on sea ice measurements are direct measurements.

If any of the original measurements/metadata were unclear or non-existent, the original author of the data was contacted to clarify inconsistencies or questions so the SUMup metadata is complete. Snow density measurements that exceeded a physically plausible range from >0 kg m^3 and <1000 kg m^3 were rejected. Specific details on measurement methods and citations for each subdataset are included in the SUMup metadata files hosted at the Arctic Data Center and described below.

2.4.1 Snow Density

The snow/firn density subdataset of SUMup is the largest, containing over 830,000 unique measurements of density at different depths (Fig. 1). Table 1 describes the parameters for each density measurement. The measurement methods include density cutters of different sizes (generally from 100 - 1000 cm^3) used in snow pits, gravitational methods used on ice core sections, neutron-density methods performed in boreholes, X-ray microfocus computer tomography performed on snow samples, gamma-ray attenuation in boreholes and pycnometers used on snow samples. The majority of the observations (~94%) come from Greenland ice cores or snow pits (Ohmura, 1991; Ohmura, 1992; Alley, 1999; Bolzan and Strobel, 1999(a-g); Miller and Schwager, 2000(a,b); Wilhelms, 2000(a,b,c,d); Bolzan and Strobel, 2001(a,b); Mosley-Thompson and others, 2001; Bales and others, 2001; Conway, 2003; Dibb and Fahnestock, 2004; Dibb and others, 2007; Baker and others, 2009; Chellman and others, 2009; Benson, 2013; Miège and others, 2013; Hawley and others, 2014; Koenig and others, 2014; Mayewski and Whitlow, 2016; Schaller and others, 2016; Benson, 2017). Antarctic measurements comprise ~6% of the snow density subdataset and is predominantly from ice cores (Mayewski et al, 2013; Lewis et al, 2011; Brucker and Koenig, 2011; Medley et al, 2013; Albert, 2007; Kreutz et al, 2011). The depth of the density measurements were recorded using two different methods, either the top and bottom depth or a midpoint depth. While a midpoint can be determined uniquely from the top and bottom depths the top and bottom cannot always be determined from the midpoint and researchers need to determine how to standardize or interpolate the depths for their specific applications.

Table 1

2.3.2 Snow Accumulation on Land Ice

The snow accumulation on land ice subdataset of SUMup contains over 230,000 unique measurements (Fig. 1). Table 2 describes the parameters for each accumulation measurement. While most of the data are measurements of accumulation between 1950 and present (~98%), to coincide with the time span of many regional climate models and reanalysis products, some ice core records (~2%) are included dating back to 1800. The measurement methods include ice cores and/or boreholes, snow pits, radar isochrons, and stake measurements. Arctic measurements are predominantly from ice cores and stake measurements and include one radar transect in southeast Greenland (Bolzan and Strobel, 1999(a-g); Bolzan and Strobel, 2001(a,b); Mosley-Thompson and others, 2001; Dibb and Fahnestock, 2004; Miège and others, 2013). The Antarctic measurements are predominantly from ice cores and include two radar transects, one in West Antarctica and one in East Antarctica (Spikes and others, 2005; Banta and others, 2008; Ferris and others, 2011; Verfaillie and others, 2012; Burgener and others, 2013; Mayewski and others, 2013; Medley and others, 2013). In most instances accumulation was provided in the original measurement, however, the Summit Station, Greenland bamboo forest measurements consist of weekly surface height change at 100 stakes along with snow density (Dibb and Fahnestock, 2004). We multiplied the height change by the coincident snow density and averaged across all stakes to get accumulation measurements for SUMup. Similarly, the Bolzan and Strobel data (1999 a-g; 2001 a,b) provided a snow pit depth, year, and density that were converted to accumulation. Most of the accumulation measurements are annually resolved with the major exceptions being the radar measurements which are approximately decadal and bamboo forest data which is approximately monthly.

Table 2

2.3.3 Snow Depth on Sea Ice

The snow depth on sea ice subdataset is the sparsest within SUMup with ~14,000 unique measurements. Table 3 describes the parameters for each snow depth measurement. The measurement methods include rulers and magnaprobes. The Arctic measurements are from the Finnish Meteorological Institute Sea Ice Observers data from 1990-2012 (Eero Rinne, personal communication). The Antarctic observations are from the Sea Ice Mass Balance in the Antarctic (SIMBA) dataset which was conducted from the research vessel/ice breaker *N.B. Palmer* in September and October 2007 in the Bellingshausen Sea (Lewis et al, 2011). Although this subdataset is rather small, we note that a large, standardized dataset of radar-derived snow depth on sea ice is available through the IceBridge Sea Ice Freeboard, Snow Depth and Thickness product and similar products derived from the IceBridge radars (Krutz and others, 2017; Kwok and others, 2017) as well as other products based off of the IceBridge Snow Radar (Kwok and Others, 2017). Because the IceBridge radar-derived snow depths are too large and numerous they are no longer included in the SUMup dataset and were removed from the July 2015 SUMup dataset for the current July 2017 SUMup dataset release.

Table 3

3. Data Analysis

The goal of the SUMup dataset is that it can be broadly used by the scientific community for a variety of research studies. Tables 4 and 5 provide the basic descriptive statistics for each subdataset for the Arctic and Antarctic, respectively. These tables provide a coarse overview of the data, however, when using the SUMup datasets subsetting by location, time, depth, etc will likely be required for specific applications. The minimum value for accumulation in the Arctic is -0.004 m WE/a which represents an ablation value from monthly Bamboo Forest measurements at Summit Station, Greenland. In total, there are 4 months with small negative accumulation measurements from Summit Station. These negative accumulation measurements are likely due to ablation processes of sublimation or wind redistribution.

Figure 2

Field data collected over the vast polar regions have spatial and temporal sampling bias, as the time, cost and logistics to systematically sample these regions is unreasonable. We describe the SUMup dataset here to elucidate possible bias. All the measurements in SUMup, with the exception of one location, were collected during the spring/summer season for that polar region, roughly April through August for the Arctic and October through February for the Antarctic. Summit Station, Greenland, the only GrIS station with year-round operations, is the one exception in the dataset where temporally-consistent, year-round measurements are taken. Below, we summarize the spatial and temporal distributions of the SUMup dataset by subdatasets. For the two largest subdatasets, snow density and accumulation we present preliminary analysis over the GrIS (Sect. 3.4). This analysis is meant to be an introduction to the dataset and is not exhaustive. We encourage the community to continue to use and more fully exploit this dataset. Figure 2 provides a bar graph showing the measurements methods that make up each subdataset showing that measurements techniques with high spatial (e.g. Radar) and high depth (eg neutron probes) dominate the number of measurements in a subdataset, however, they often have low spatial coverage.

Table 4
Table 5

3.1 Snow Density

Over 830,000 measurements were compiled of snow/firn density that cover ~280 sites in the Arctic and ~50 sites across Antarctica (Fig. 1). The majority of these measurements come from snow pits and ice cores on the GrIS and AIS, however, there are 7 locations of snow density measurements on sea ice in the Bellinghausen Sea. Here, we include only on the ice sheet measurements.

The Arctic snow density measurements, all on the GrIS, contain 94% of the measurements with <1% coming from Summit Station. The remaining 6% of the measurements come from the Antarctic. The density subdataset is dominated (97% of data) by high vertical depth resolution measurements (mm-scale for ~100 meters) from, X-ray microfocus computer tomography, neutron density methods and gamma-ray attenuation measurements taken on cores or in boreholes at 22 locations in Northern Greenland and on one core from West Antarctica (Fig. 2). (Wilhelms, 2000a;b;c;d; Miller and Schwager, 2000a,b; Schaller and others, 2016; Kreutz et al, 2011). Because of the high-depth resolution of these measurements, compared to more typical density measurements at centimeter and meter scale, these data saturate histogram representations of this subdataset. For this reason, we do not use these measurements in the following analysis ,thus providing a more realistic overview of the fraction of the density measurements taken throughout time and space.

Figure 3

Figure 3 provides histograms showing the fraction of density measurements taken by year for Antarctica, Greenland excluding Summit Station and for Summit Station. (Summit Station was defined as a bounding box of 72N to 73N and 38W to 39W.) Summit Station measurements are plotted separately because this unique site provides the only location on the GrIS with year round measurements over multiple years. The histograms for the Antarctic and Greenland show sporadic spikes through time related to major collection campaigns. Antarctic density measurements peak in the early and late decade from 2000 to 2010 related to US ITASE traverses conducted in West and East, Antarctica, respectively (Mayewski and others, 2013). Greenland measurements peak in the early 1950’s with measurements from Benson’s traverses, are relatively stable through the 1990’s related to the activities surrounding GISP2 and PARCA ice cores (Alley, 1999; Mosley-Thompson and others, 2001), and peak in the early 2010's with the Greenland Inland Traverse and the Arctic Circle Traverse cores (Miège and others, 2013; Hawley and others, 2014). Measurements from Summit station steadily increase in time from 1987 to 2014 with a slight peak in the late 1990's and early 2000's related to additional measurements provided by Dibb and Fahnestock (2004) and Alley (1999) in that year.

Figure 4

Figure 4 provides an overview of the distributions of depths sampled by the density subdataset. Overall, the number of measurements decrease with depth. The Antarctic measurements decrease more uniformly with depth which is related to the larger number of 50-100 m ice cores. The Greenland measurements decrease at a constant rate to 5 meters but has very few measurements below 25 m demonstrating the large number of shallow cores (~20 m) collected across Greenland. At Summit Station, the majority of the measurements are taken above 1 meter as a result of systematic tasking to dig ~1 m snow pits at approximately monthly intervals since 2003. The deep 100 m plus measurements at Summit come from the GISP2 ice core (Alley, 1999).

3.2 Accumulation

The ~230,000 measurements of accumulation rate over land ice were taken at ~30 locations in Antarctica, and ~35 locations in Greenland. These include two radar traverses that span several hundreds of km in Antarctica, and a 75-km radar traverse in Southeast Greenland. (Fig. 1).

62% of the accumulation measurements are from the Arctic, all within Greenland, with <1% of the overall measurements coming from Summit Station. The Antarctic contributes the remaining 38% of the measurements. The accumulation subdataset is dominated (97% of data, Fig. 2) by high horizontal spatial resolution (10's of m) radar accumulation measurements taken from 3 ice sheet transects (Fig. 1). These data saturate histogram representations of this subdataset and are not used in the following analysis to provide a more realistic overview of the fraction of accumulation measurements taken throughout time and space.

Figure 5 provides histograms showing the fraction of accumulation measurements taken by year for Antarctica, Greenland excluding Summit Station, and for Summit Station. Year, in this case, is defined as the year in which the ice core, snow pit, etc was collected/dug. The histograms for the Antarctic and Greenland show sporadic spikes through time related to major collection campaigns, similar to, yet more exaggerated than, the density subdataset. Antarctic measurements peak in the early 2000's when US ITASE ice cores were collected in West Antarctica (Mayewski and others, 2013). Greenland accumulation measurements peak in the late 1980's with ice cores preparing for the GISP2 core and in the late 1990's when the PARCA ice cores (Mosley-Thompson and others, 2001) were collected. Summit Station has a constant monthly collection of accumulation measurements from August 2000 to August 2002 from the monthly Bamboo Forest measurements (Dibb and Fahnestock, 2004) and represents the only year-round collection of accumulation in the SUMup dataset.

Figure 5

While understanding the date when accumulation measurements are taken is important, it is also important to understand the date, corresponding to the depth, represented by a sample. Figure 6 provides the distribution of years when annual accumulation was measured from 1950 to present. Antarctica has a relatively even distribution of accumulation measurements until 2000 when the number of samples decreases. This decrease is due to the fact that many of the cores collected by US ITASE from 2006-2008 in East Antarctica could not be dated to determine accumulation and also shows that most of the ice cores collected date back to 1950 or later. The Greenland accumulation measurements peak between 1980 and 2000. The mostly shallow ice cores in Greenland, and relatively higher accumulation rates compared to Antarctica, cause there to be less data from 1950 to 1980 in the ice cores. The sharp decline in the 2000's is due to a lack of coring efforts that occurred during that decade in

Greenland. Summit Station has a consistent year round sampling of accumulation from the 2003 from the Bamboo Forest. These systematic measurements significantly outnumber the single measurements per year collected from ice cores at Summit Station that sample the decades previous to 2000.

Figure 6

3.3 Snow Depth on Sea Ice

The ~14,000 measurements of snow depth on sea ice are from 7 locations off of the Antarctic Peninsula in the Bellingshausen sea (Fig. 1) and ~40 locations directly off the coast of Finland in the Baltic sea. The Arctic represents 78% of the measurements and the Antarctica represents the remaining 22%. The Finnish Meteorological Institute Sea Ice Observers measurements (Eero Rinne, personal communication) span from 1990-2012 (Fig. 7) while all the Antarctic measurements are all from 2007.

Figure 7

3.4 Preliminary Analysis over the Greenland Ice Sheet

Recent warming over the GrIS, including a melt event in 2012 that covered nearly the entire surface (Nghiem and others, 2012), has increased both snow density and snow accumulation in recent decades (e.g. Morris and Wingham, 2014; Machguth and others, 2016; Overly and others, 2016). Improved measurements, or models, of density and its evolution with time are needed to reduce uncertainties when converting altimetry measurements into total ice sheet mass balance using altimetry (e.g. Zwally and Li, 2002; Shepherd and others, 2012) and for converting radar isochrones into measurements of accumulation (e.g. Koenig and others, 2016). Many models use mean annual temperature and accumulation to model the spatial and temporal evolution of density (e.g. Harron and Langway, 1982; Reeh and others, 2005; Kuipers Munneke and others 2015). Some studies, however, show that density models generally underestimate surface (<1 m depth) density measurements (Koenig et al., 2016) while other studies point to the importance of the surface boundary condition for density models when comparing to measurements (Kuipers Munneke and others, 2015; Bellaire and others, 2017). Fausto and others (accepted) find mean annual temperature is a poor predictor of snow density from 0-10 cm depth. Here, we look more closely at the density and accumulation measurements within the SUMup dataset over the GrIS and their sampling distributions with respect to temperature, elevation and latitude.

3.4.1 Density distributions with Elevation, Latitude and Temperatures

Figure 8

Figure 8 shows the distribution of density measurements with elevation and latitude compared to the total distribution of elevations and latitudes for the entire GrIS derived from the Bamber 5 km Greenland digital elevation model (DEM; Bamber, 2001). Though higher resolution DEMs are available for the GrIS (ie Howat and others, 2014; Howat and others, 2015), a coarse resolution DEM is reasonable for this binning 100,000's of measurements into 100 m elevation bins. Figure 8 uses similar graphing techniques to those of Fausto and others (in revision) to clearly show sampling bias in the observation dataset. If there were no sampling bias, the fraction of measurements would be similar to the fraction of values from the DEM. This is not the case. For elevation (Fig. 7A) we see that elevations below 3000 m are undersampled, with the exception of the 1750-2000 m bin, and elevations above 3000 m are largely oversampled. The measurements are therefore biased to higher, inland elevations which, if averaged, would likely cause a low bias in sampled densities. Figure 8b shows that our dataset is sampled best over central Greenland. More measurements are required from lower elevations and southern (< 70N) and northern (> 78N) latitudes to fill the gaps in the current dataset and reduce spatial bias.

Figure 9

Because mean annual temperature is a parameter often used to model density (e.g. Harron and Langway, 1982; Reeh and others; 2005), Figure 9 shows the distribution of density measurements in Greenland by the mean annual temperature estimated by the Modèle Atmosphérique Régional (MAR) model version 3.5 (Fettweis and others, 2013) with a horizontal resolution of 25 km. The density measurements at each location were matched to a National Centers for Environmental Prediction–National Center for Atmospheric Research Reanalysis version 1 (NCEP-NCARv1) forced MAR 3.5 simulation (run from 1948–2015) to find the mean annual 3 m air temperature for the year the measurement was taken. The NCEP-NCAR forcing was chosen because it is more reliable than ERA forcings (Fettweis et al, 2017). The red line in Fig. 9 shows the distribution of annual average temperatures (derived from 1990-2015) for the entire GrIS. Figure 9 clearly shows a preferential sampling of GrIS regions with lower temperatures. Cold temperatures (-20 deg C and below) are oversampled in the density dataset while temperatures above -14 deg C, which make up ~30% of the GrIS, make up less than 5% of the sampled densities. As with elevation, the density sampling distribution by mean annual temperatures likely results in a low density bias when trying to characterize the entire GrIS. In general, the density measurements in SUMup across the GrIS oversample cooler, inland regions and undersample coastal, warmer regions.

Figure 10

Figure 10 plots all sites in Greenland with density measurements coincidently sampled to depths of 10, 25, 50 and 100 cm compared to the mean annual temperature. No clear relationship (Pearson Correlation coefficient, R2 = 0 to 0.057) between mean annual temperature and density is seen in our data until ~1 m depth (R2=0.255) where higher temperatures correspond to higher density. This results suggests that in the top 1 m of snow/firn on the GrIS, in the colder, more inland areas, temperature may not be the primary process leading to densification. Solar radiation and wind processes (e.g. Liston and others, 2007) are likely important in these region and require snow density models that account for these processes. Due to the spatial sampling bias in this dataset, melt processes are likely not a primary processes in determining snow density for these measurements, however, melt processes will contribute more in the future (Nghiem and others, 2012; McGrath and others, 2015)

Figure 11

Figure 11 compares the observed snow densities to modelled densities from MAR 3.7 at 10, 20, 50 and 100 cm. In all cases the MAR model, on average, underestimates the near-surface snow density. The root mean-square error (RMSE) values are all between 0.07-0.08 indicating a small variance and generally good fit of the model. The mean biases are all negative values between -0.05 and -0.04 in agreement with the model underestimating the “true” value of the observations. Similar results were found by Koenig and others (2016) using a smaller subset of the SUMup data and holds with the newly added measurements. This suggests that snow on the ground is densifying at a faster rate in the colder, more inland locations of the GrIS, than the MAR model is predicting in the top meter.

3.4.2 Accumulation distributions with Elevation and Latitude

Snowfall over the GrIS can also be parameterized by elevation and latitude. Figure 12 shows the distributions of the accumulation measurements over the GrIS by elevation and latitude. As with the density measurements the accumulation measurements all come from high elevations on the GrIS (>1750 m) with the highest elevations (>3000 m) being largely oversampled. The sampling across latitudes is the most evenly distributed, however, latitudes above 78 N represent a gap in the dataset. We do not compare the accumulation subdataset with mean annual temperatures here. Because each year of accumulation has a different mean annual temperature associated with it, we deem it beyond the scope of this analysis and suggest this as a future study that could be researched with the SUMup dataset.

Figure 12

3.4.3 Year round density and accumulation measurements from Summit Station.

Summit Station is the only site in the dataset, and on the GrIS, that has been systematically sampled for density and accumulation on a nearly monthly basis. Hence, it is the only location on the GrIS to watch the long-term, decadal, seasonal evolution of snow surface density. Figure 13 shows the seasonal trends of the mean surface density to depths of 10 cm, 25 cm 50 cm and 100 cm. A seasonal cycle is evident in the 10 cm and 25 cm depth mean densities with a decrease (trough) in density in late summer (August/September) and an increase (peak) in April. The decrease in summer density is likely due to surface hoar, a low density snow crystal formation that is well known to form at Summit Station in the Summer when wind speeds are low and humidity relatively high (e.g. Alley and other, 1990; Albert and Schultz, 2002; Dibb and Fahnestock, 2004). As wind speed increase and water vapor decreases in the winter the surface snow increases in density. The seasonal signal in density is damped out by 1 m depth at Summit Station. Figure 13 also shows larger natural variability in average density measurements in the top 50 cm compared to the top 100 cm. This is expected as the deeper snow is more insulated from atmospheric and radiative processes in this dry-snow-zone location.

Figure 13

Figure 14 show the seasonal cycle of accumulation at Summit Station. Accumulation is highly variable with slightly lower values in the early Summer months (May/June/July). Dibb and Fahnestock (2004) also showed a similar trend in stake measurements and Summit Station from just 2 years of data and explained that the summer season may not actually be seeing a decrease in accumulation but that thinning layers, densification, may be causing the stake measurements to not rise as much in the summertime compared to the wintertime when a snowfall event occurs. Determining if there is a true decrease in summer accumulation or increase in snow/firn compaction rate at Summit Station requires additional research.

Figure 14

5. Data Availability

The SUMup dataset is currently available through the Arctic Data Center. It hosts our three subdatasets in both csv and netcdf formats along with metadata files to further explain the methods and citations. The dataset will be updated annually.

6. Discussion and Conclusion

We present and describe the SUMup dataset, an expandable, community-based dataset of field measurements of surface mass balance components that is consistent in format, has clearly defined metadata, and is publically available. The subdatasets include compiled measurements of snow/firn density, accumulation on land ice, and snow depth on sea ice from the Arctic and Antarctica.

As seen in SUMup, the measurements over the GrIS and AIS are sporadic in time and space, peaking during specific field campaigns and lapsing in between. This sampling strategy makes monitoring change with and understanding processes from field measurements difficult, especially for parameters like density and accumulation, that change with both seasonal and climatic atmospheric condition. Overall, there are gaps in density and accumulation data from ~2000 forward and from locations on the periphery of the ice sheets. While there currently is a temporal gap in the most recent decades we note that the GreenTRaCs traverses have collected cores across the GrIS in 2016 and 2017, including at previous PARCA sites. Once these cores are processed, they will be able to help fill some of the time gaps for the GrIS (R. Hawley, personal communication).

Density and accumulation measurements of the GrIS oversample cooler, inland regions and undersample coastal, warmer regions. Oversampling these regions may lead to an underestimation of the total average surface density, especially in the summer season, when the measurements are undersampling regions with significant melt processes that increase density. No clear relationship between mean annual temperature and density is seen in the data until a depth of 1 m where a relationship between higher temperatures and increased density is observed. This suggests that additional parameters, such as wind speed and radiative balance, should be considered when modeling density for the GrIS at SUMup density locations and depths above 50 cm. MAR estimated densities are lower than the SUMup measurements in the top 1 m. Possible causes for the underestimation include that the atmospheric snowfall is preferentially low, that the initial density of freshly fallen snow is underestimated, or that the surface snow on the ground densifies at a quicker rate than modelled by MAR, due to radiative or wind-driven processes in these mostly dry-snow zone locations. Summit Station, Greenland is the only location with year-round density and accumulation measurements in the dataset, and on the GrIS, and seasonal cycles are evident in accumulation rate and density for depths above 50 cm.

We encourage the cryospheric community to contribute additional field data to the SUMup dataset. We also encourage the cryospheric community, including modelers and scientists working in the field of remote sensing to use this dataset for model validation for surface mass balance and satellite- or airborne-sensor algorithm development. SUMup is a dynamic, living dataset and is expected to be expanded and released annually.

Author Contributions:

LM compiled the SUMup dataset into the July 2017 dataset, developed the metadata and reformatted the dataset. She made all figures for this paper and co-wrote the paper. LK co-wrote this paper and developed the first SUMup dataset 2013. PA helped with the development of the SUMup dataset, performed the initial comparison of the SUMup data to the MAR model and contributed to the writing of this paper.

Competing Interests:

The authors declare that they have no conflict of interest.

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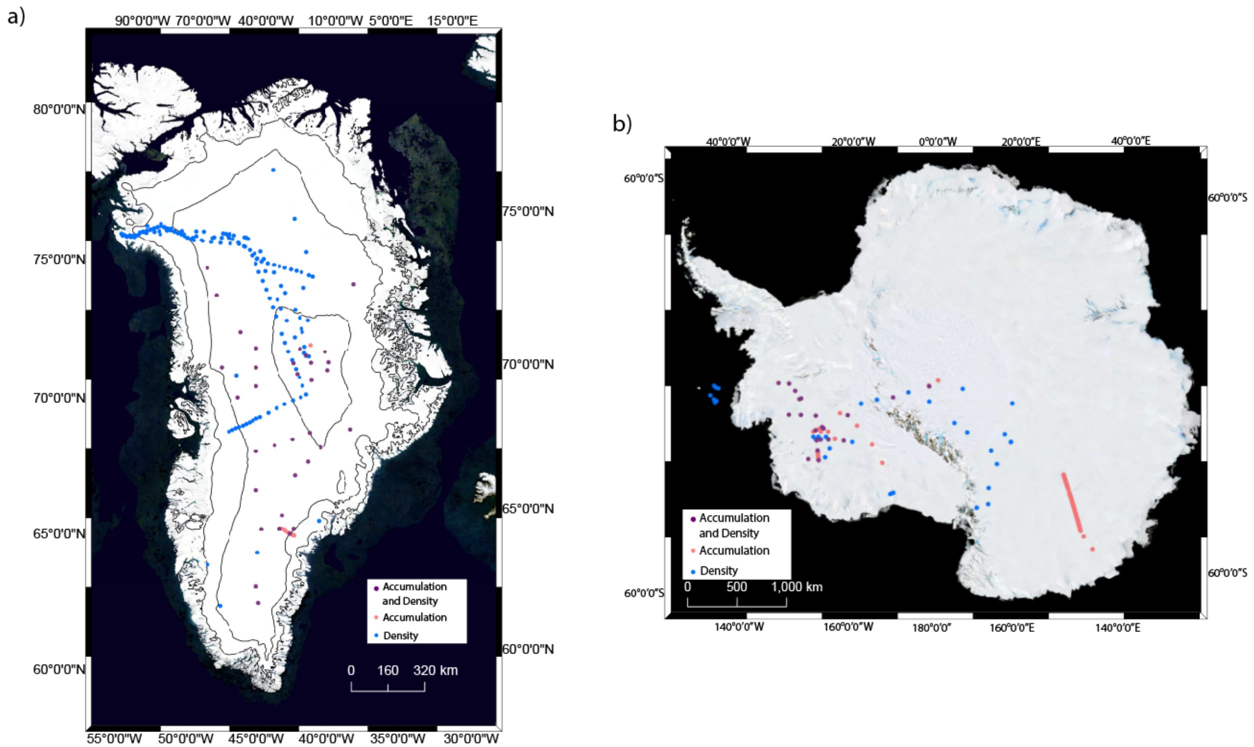

Figure 1 a) Measurement locations for accumulation (red), snow density (blue) or both (purple) for the SUMup dataset in the Arctic. Snow depth on sea ice data for the Arctic are not shown but include ~40 measurements taken off the coast of Finland in the Baltic Sea. b) Same as above but for the Antarctic. All locations not on the Antarctic ice sheet, those in the Bellingshausen Sea, include both snow density and snow depth on sea ice measurements.

Table 1: The parameters for each snow density measurement in the SUMup dataset with a brief description and the unit of measurement.

Column	Description	Unit
Date Taken	Date the data was taken	yyyymmdd
Latitude	Latitude of measurement	Decimal degree
Longitude	Longitude of measurement	Decimal degree
Start Depth	Top depth of the measurement in m from the snow/air interface (snow surface).	m
Stop Depth	Bottom depth of the measurement in m from the snow/air interface (snow surface).	m
Midpoint Depth	Midpoint depth of the measurement in m from the snow/air interface (snow surface).	m
Density	Snow density measurement	g/cm^3
Error	Uncertainty in density measurement	g/cm^3
Elevation	Elevation above sea level	m
Method	How the measurement was collected (see metadata for more details)	-
Citation	Cited source of data (see metadata for more details)	-

Table 2: The parameters for each snow accumulation measurement on land ice in the SUMup dataset with a brief description and the unit of measurement.

Column	Description	Unit
Date Taken	Date the data was taken	yyyymmdd
Latitude	Latitude of measurement	Decimal degree
Longitude	Longitude of measurement	Decimal degree
Start Year	First year of measurement if accumulation is not annual	year
End Year	Last year of measurement if accumulation is not annual	year
Year	Year of accumulation if accumulation is annual	year
Accumulation	Accumulation in m of water equivalent	m WE/a
Error	Uncertainty in measurement	m WE/a
Elevation	Elevation above sea level	m
Radar Horizontal Resolution	Horizontal resolution of radar data along track	m
Method	How the measurement was collected (see metadata for more details)	-
Name	Name of field campaign (see metadata for more details)	-
Citation	Cited source of data (see metadata for more details)	-

Table 3: The parameters for each snow depth on sea ice measurement in the SUMup dataset with a brief description and the unit of measurement

Column	Description	Unit
Date Taken	Date the data was taken	yyyymmdd
Latitude	Latitude of measurement	Decimal degree
Longitude	Longitude of measurement	Decimal degree
Distance Along Transect	Distance along a transect of in-situ snow depth measurements over sea ice from the initial Lat, Long. Used for snow-depth measurements where point by point Lat, Long was not recorded.	m
Snow Depth	Snow depth measurement	m
Snow Depth Error	Uncertainty in snow depth measurement	m
Density Taken	If density measurement was taken = 1, if no measurement =0.	-
Sea Ice Thickness	Sea ice thickness measurement	m
Sea Ice Thickness Error	Uncertainty in sea ice thickness measurement	m
Sea Ice Type	1=first year ice, 2=multilayer ice, -9999 = unknown	-
Sea Ice Freeboard	Sea Ice freeboard measurement	m
Sea Ice Freeboard Error	Uncertainty in sea ice freeboard	m
Snow Ice Thickness	Snow ice thickness measurement	m
Snow Ice Thickness Error	Uncertainty in snow ice thickness measurement	m
Radar Horizontal Resolution	Horizontal resolution of radar data along track	m
Method	How the measurement was collected (see metadata for more details)	-
Citation	Cited source of data (see metadata for more details)	-

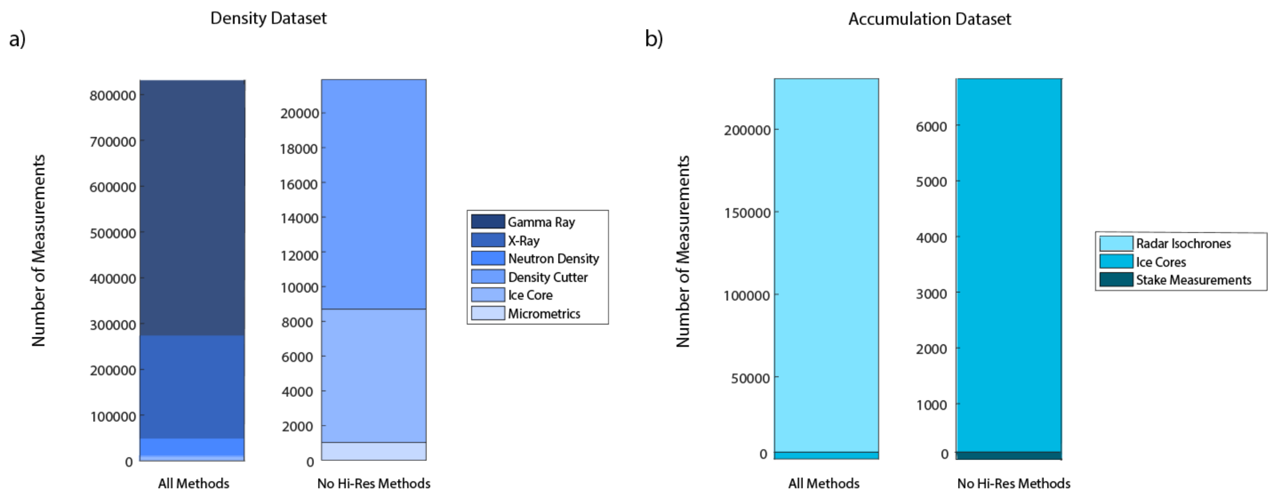

Figure 2: Bar charts showing the measurement methods in the a) density subdataset and b) accumulation subdataset. The left bar in each plot shows the distribution of all methods and the right bar shows the distribution of methods excluding the high-resolution spatial (accumulation) or depth (density) measurements.

Table 4: The descriptive statistics for the all of the Arctic measurements in SUMup including the minimum (min), maximum (max), mean, median, standard deviation (stdev) and number of measurements (N).

Statistic	Snow Density (g cm^{-3})	Accumulation on Land Ice (m WE/a)	Snow Depth on Sea Ice (m)
min	0.054	-0.004	0.000
max	0.970	2.257	0.500
mean	0.595	1.040	0.043
median	0.629	1.034	0.000
stdev	0.236	0.171	0.072
N	779439	144060	10979

Table 5: The descriptive statistics for the all of the Antarctic measurements in SUMup including the minimum (min), maximum (max), mean, median, standard deviation (stdev) and number of measurements (N).

Statistic	Snow Density(g cm^{-3})	Accumulation on Land Ice (m WE/a)	Snow Depth on Sea Ice (m)
min	0.208	0.019	0.000
max	0.938	0.790	1.900
mean	0.789	0.129	0.479
median	0.841	0.132	0.430
stdev	0.130	0.055	0.363
N	51664	86509	3176

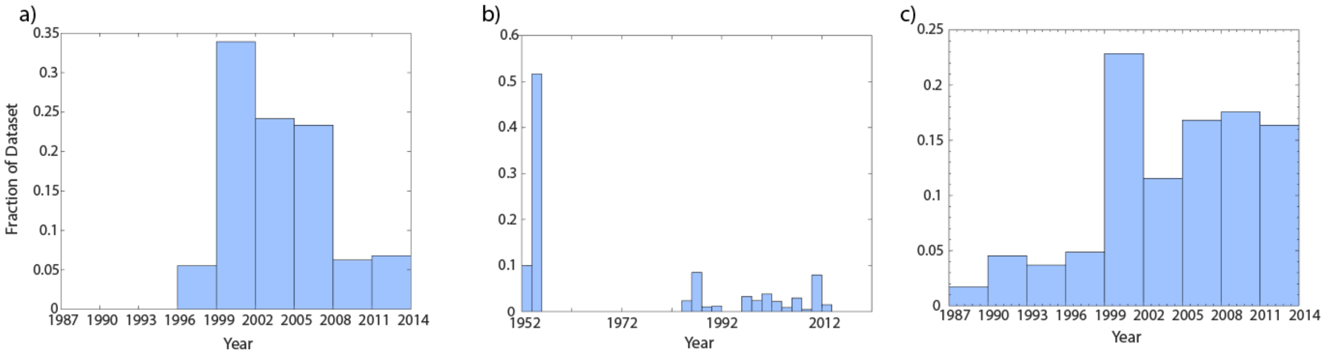

Figure 3. Histograms showing the date taken and associated fraction of the density dataset for A) Antarctica, B) Greenland excluding Summit Station, and C) Summit Station. Please note different time scales on x-axis.

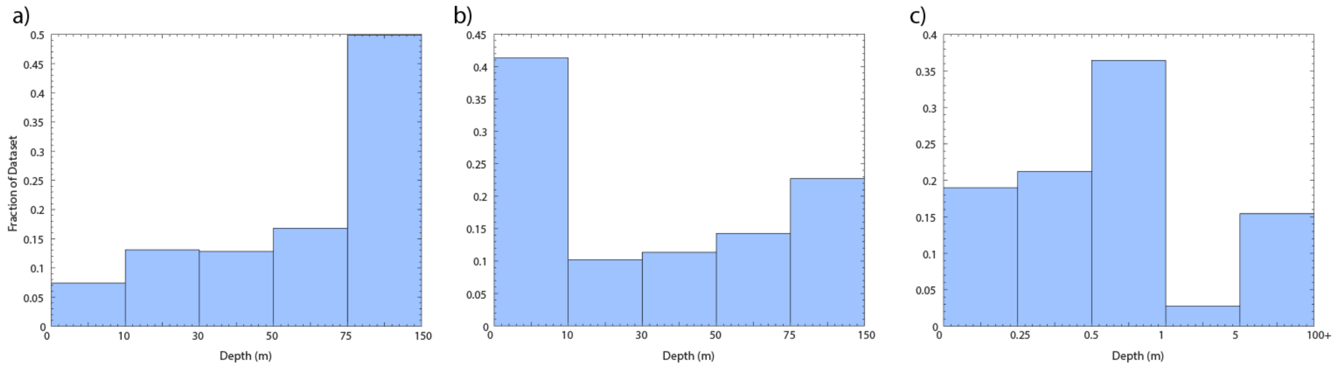

Figure 4. Histograms showing the fraction of the density dataset by mid-point sampling depths for A) Antarctica, B) Greenland excluding Summit Station and C) Summit Station.

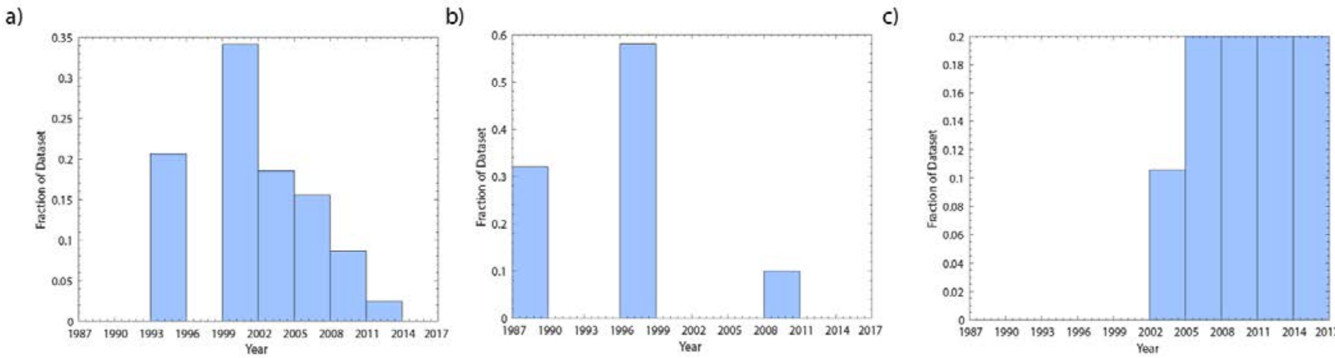

Figure 5. Histograms showing the date taken and associated fraction of the accumulation dataset for each area examined: A) Antarctica, B) Greenland excluding Summit Station, and C) Summit Station.

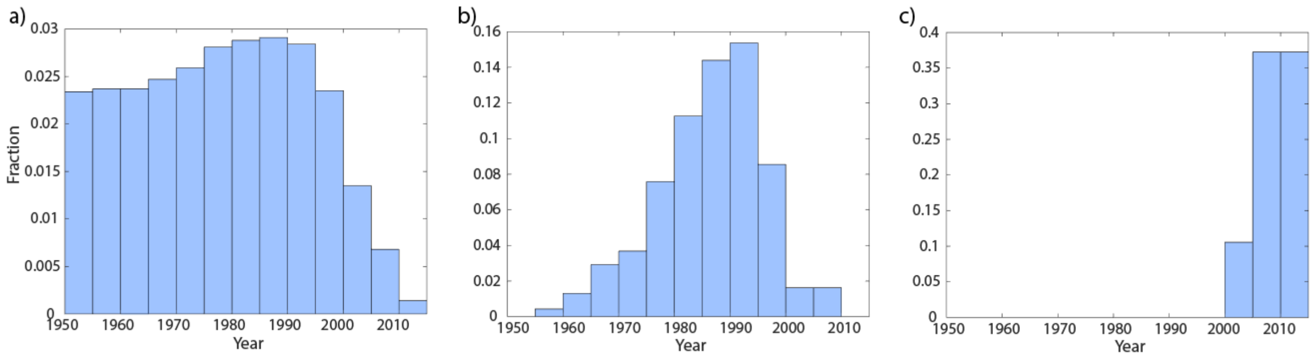

Figure 6: Histograms showing the fraction of accumulation measurements by year for A) Antarctica, B) Greenland excluding Summit Station and for C) Summit Station. Dates are only shown from 1950 forward.

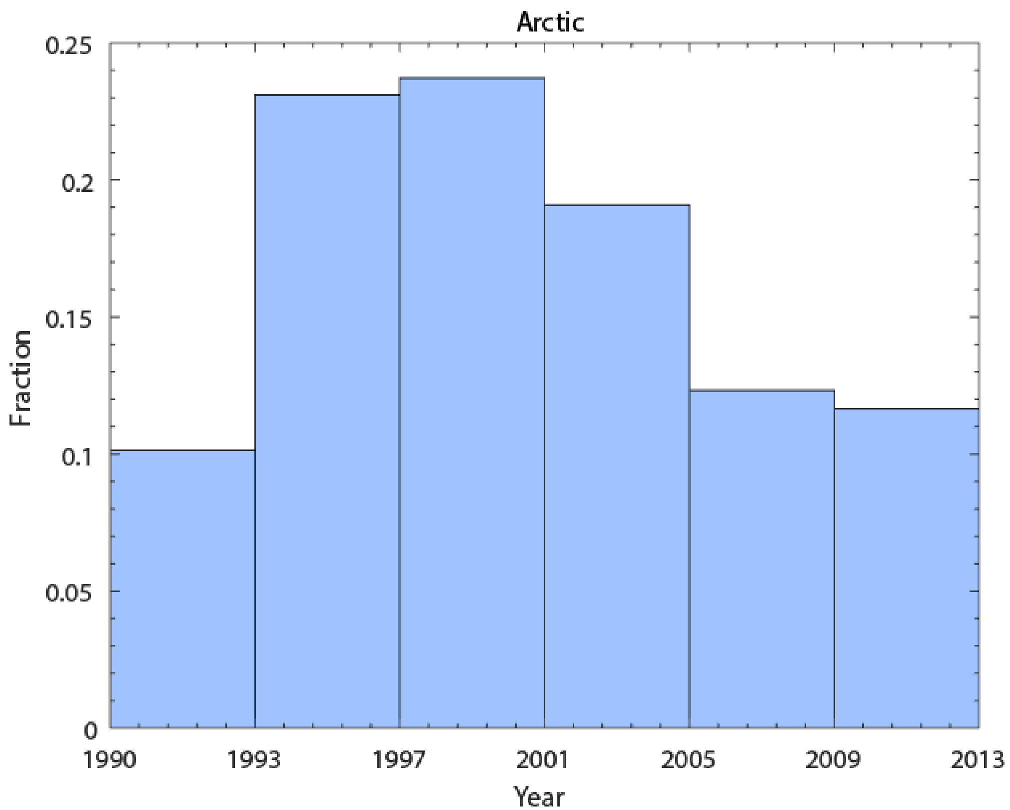

Figure 7: Histogram showing the fraction of snow depth on sea ice measurements by year.

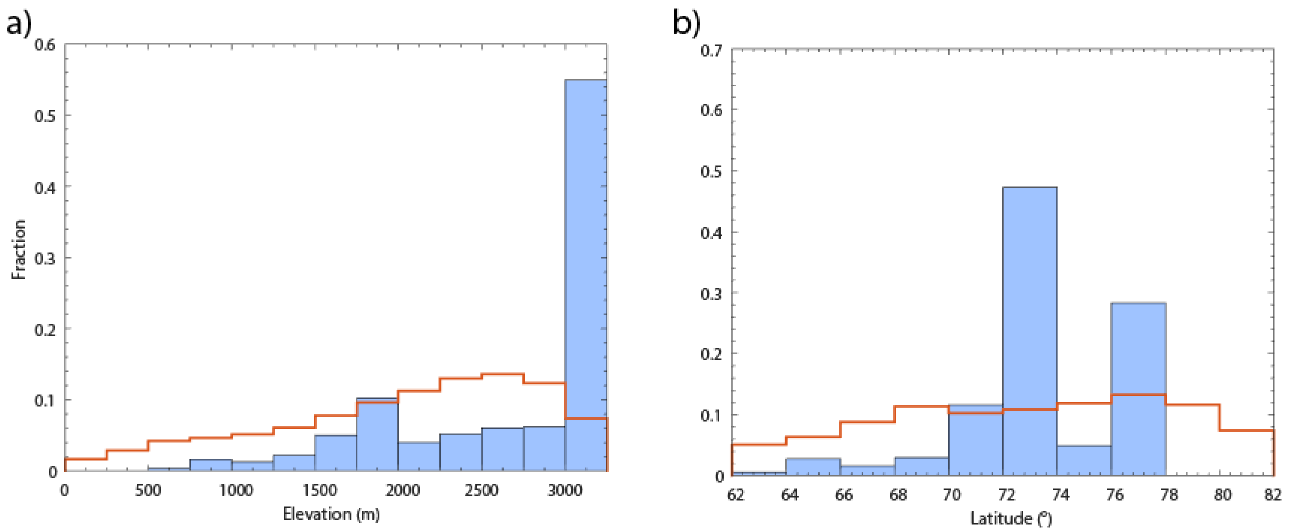

Figure 8: A) Histogram showing the fraction of density subdataset by elevation. Red line is the fraction of elevations for the entire GrIS from Bamber DEM. B) Histogram showing the fraction of density dataset by latitude. Red line is the fraction of latitudes for the entire GrIS using Bamber DEM.

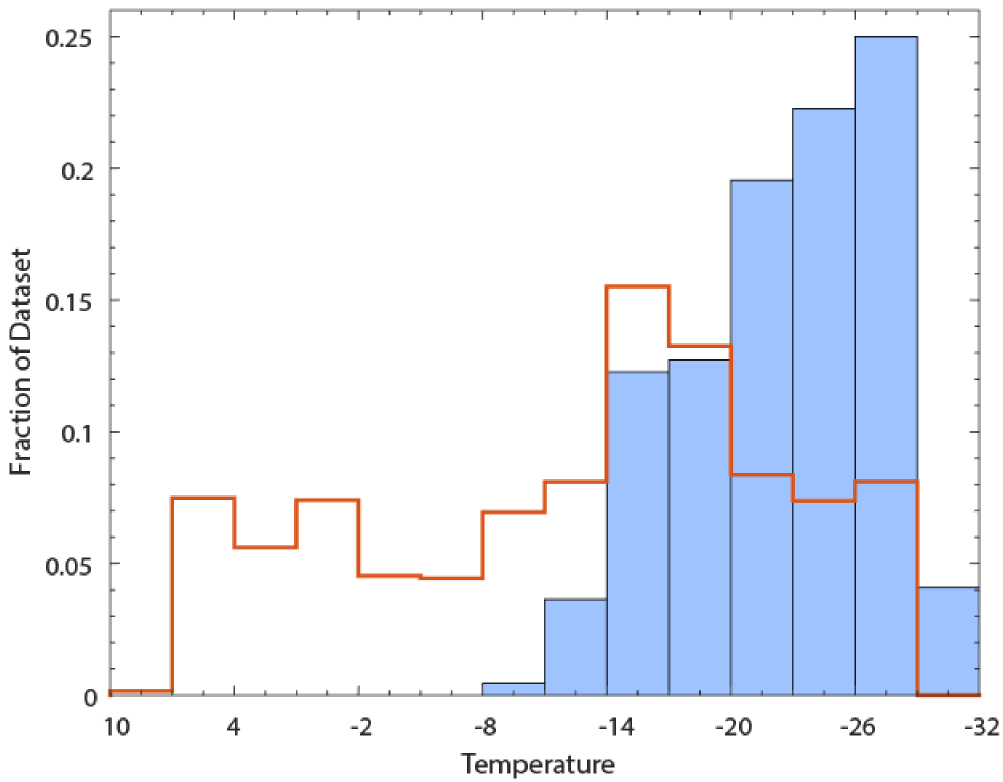

Figure 9: Histogram showing the fraction of the density subdataset by modeled 3m annual air temperature. Red line shows 1990-2015 annual average MAR3.5 model 3m air temperature distribution for each grid cell across the ice sheet.

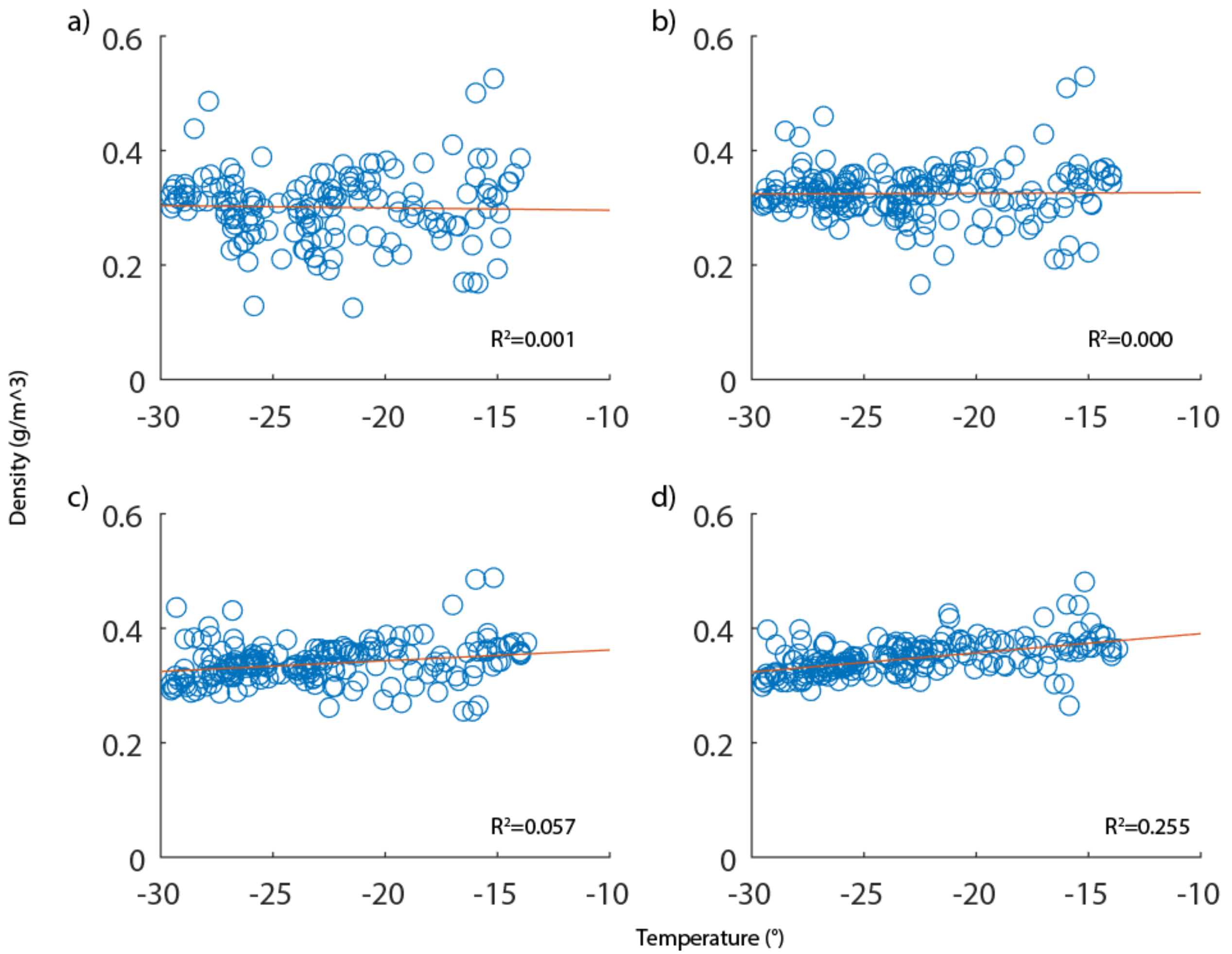

Figure 10. Scatterplot showing the MAR 3.5 modeled mean annual 3 m air temperature in the year the density was measured compared to the mean density in top A) 10 cm, B) 25 cm, C) 50 cm, and D) 100 cm.

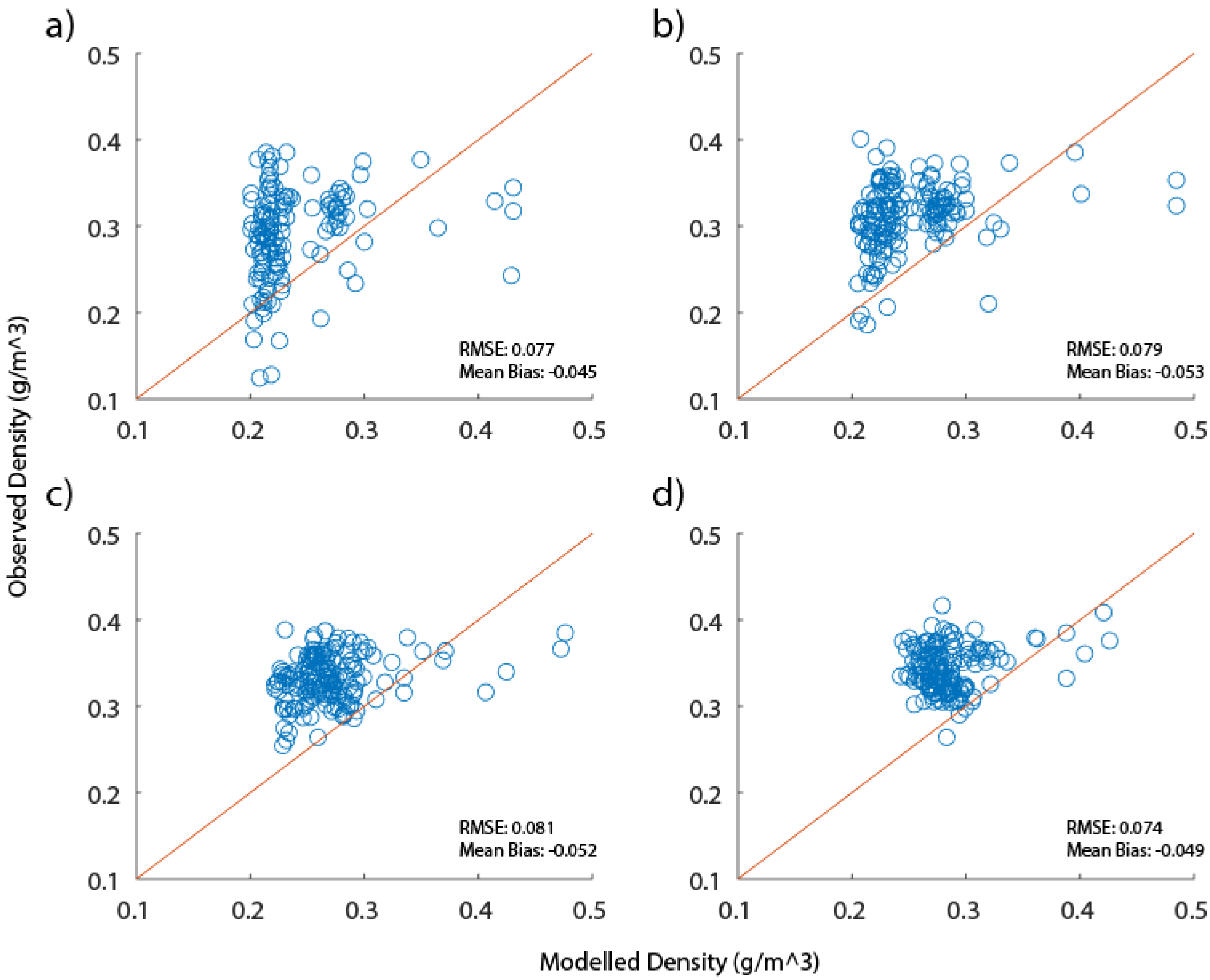

Figure 11: Scatterplot showing observed density (Y-axis) vs. MAR3.7 (x-axis) modelled density. One to one line in red. A) 10 cm B) 20 cm C) 50 cm D) 100 cm

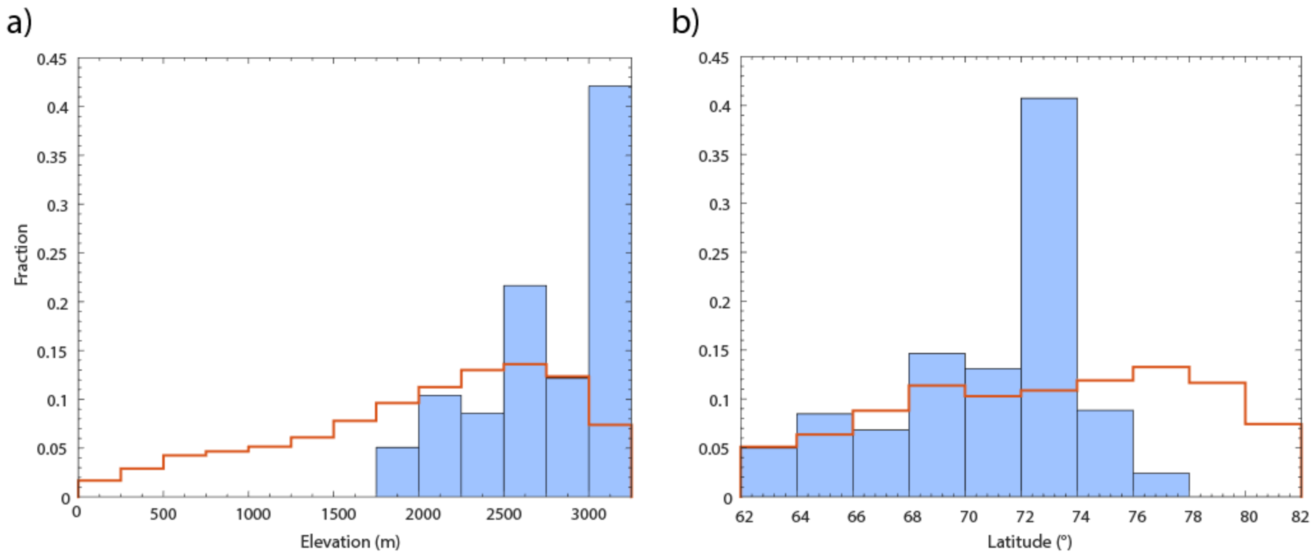

Figure 12: A) Histogram showing the fraction of accumulation subdataset by elevation. Red line is the fraction of elevations for the entire GrIS from Bamber DEM. B) Histogram showing the fraction of accumulation dataset by latitude. Red line is the fraction of latitudes for the entire GrIS using Bamber DEM.

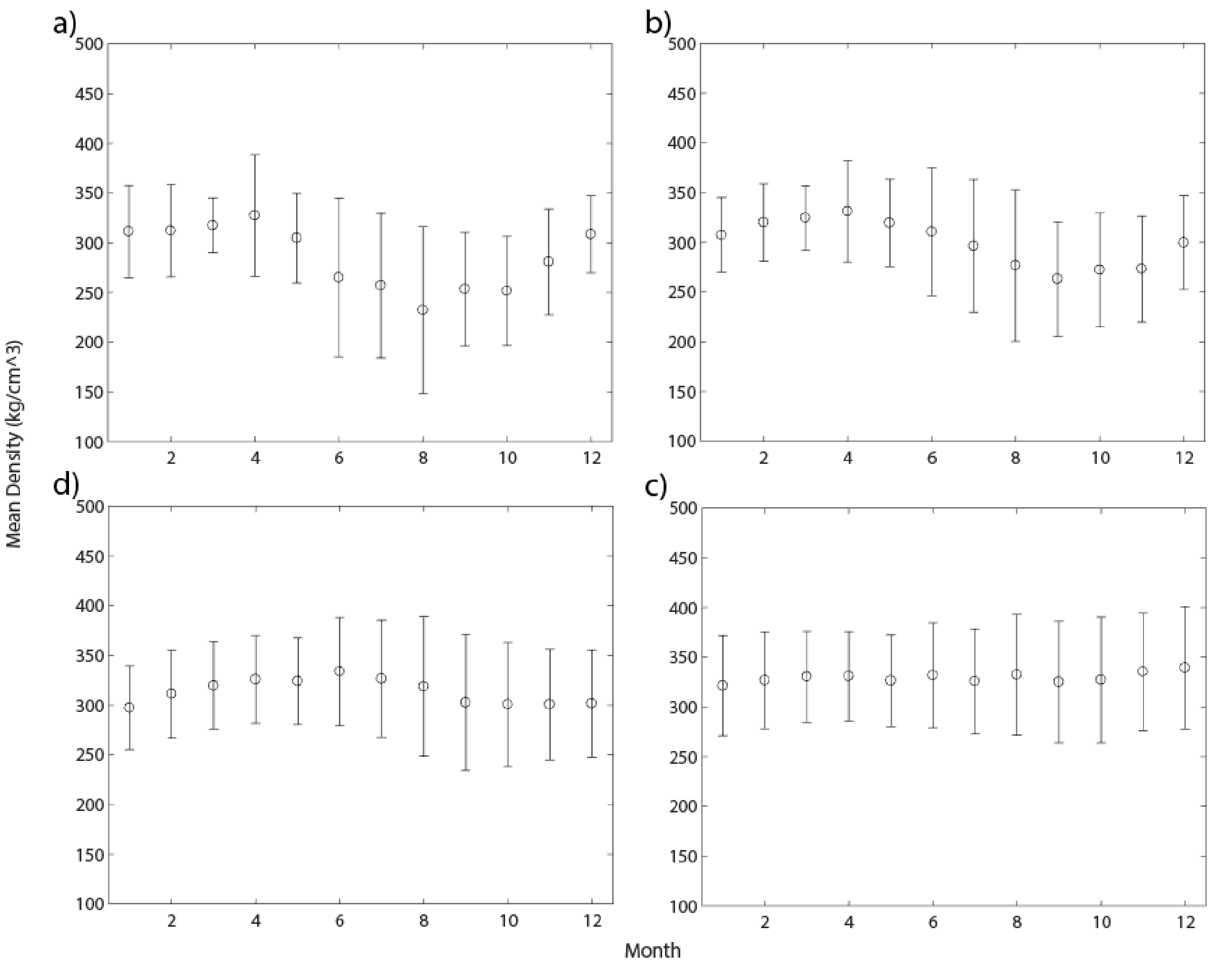

Figure 13: Plot of mean density (circle) and +/- 1 standard deviation (whiskers) for each month at Summit Station, Greenland for A) 10 cm b) 25 cm c) 50 cm d) 100 cm

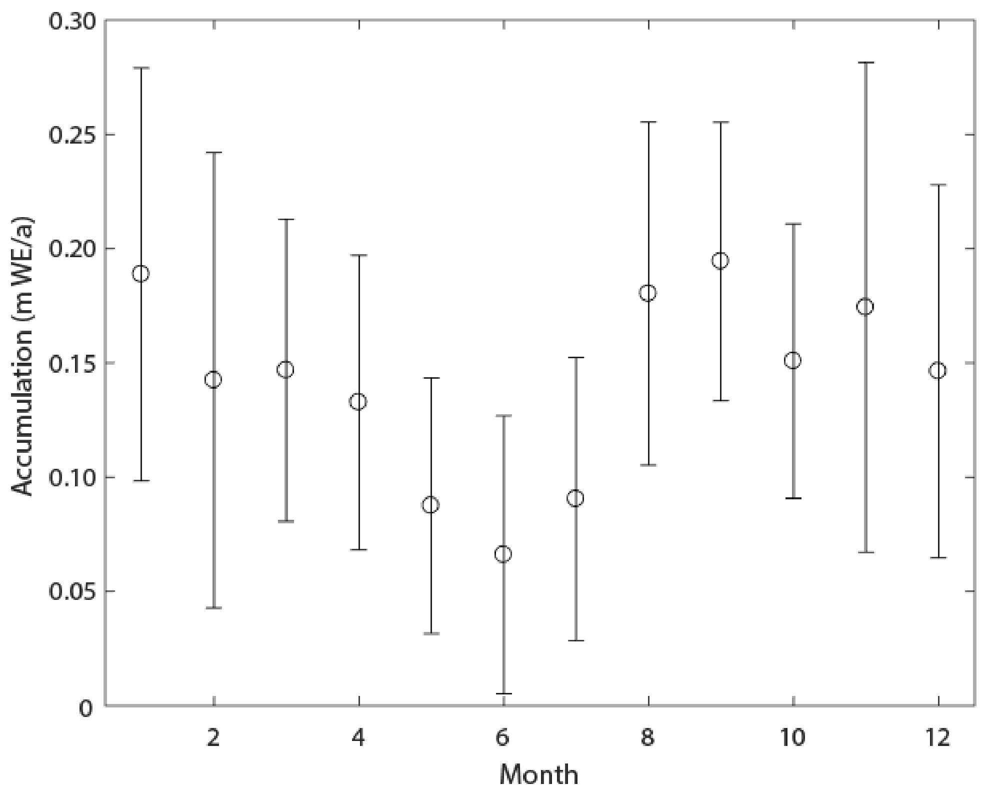

Figure 14: Plot of mean accumulation (circle) and +/- 1 standard deviation (whiskers) for each month at Summit Station, Greenland.