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Results
Observations

Overview

This document shows an overview of the data that is available for the project. It provides a first look at the processed data and provides figures that visualize the data. Section 1 examines the density data and uncertainty and potential systematic errors associated with measurements made in the snowpits and using a Federal Sampler. Section 2 briefly looks at the snow depths measured at the study glaciers. Section 3 visualizes the collected zigzag data. Section 4 examines the various ways to estimate snow water equivalent (SWE) at each measurement location. It focuses on options for how to interpolate density measurements and then visualizes estimated SWE at the measurement locations.

Contents

1 Density Estimates

1.1 Basic statistics

A summary of density data collected in snowpits and when using a Federal Sampler can be seen in Table 1. The standard deviation of each type of density measurement is less than 10% of the mean density. For snowpit derived densities, the mean density is indistinguishable between glaciers within one standard deviation. The densities estimated using the Federal Sampler differed with one standard deviation. Glacier 2 had a lower density than Glacier 4, while Glacier 13 had the same density as both. The mean of all Federal Sampler density values was likely skewed by the proportionally large number of measurements obtained on Glacier 13.

Table 1: Mean and standard deviation (std) of snow density (kg m^{-3}) as well as number of measurements (n) of snow density measured on study glaciers in snowpits and using a Federal Sampler.

Glacier	Snowpits			Federal Sampler		
	Mean	Std	n	Mean	Std	n
Glacier 4	348	13	3	355	18	7
Glacier 2	333	26	4	286	34	7
Glacier 13	349	26	3	316	40	17
All	342	26	10	318	42	31

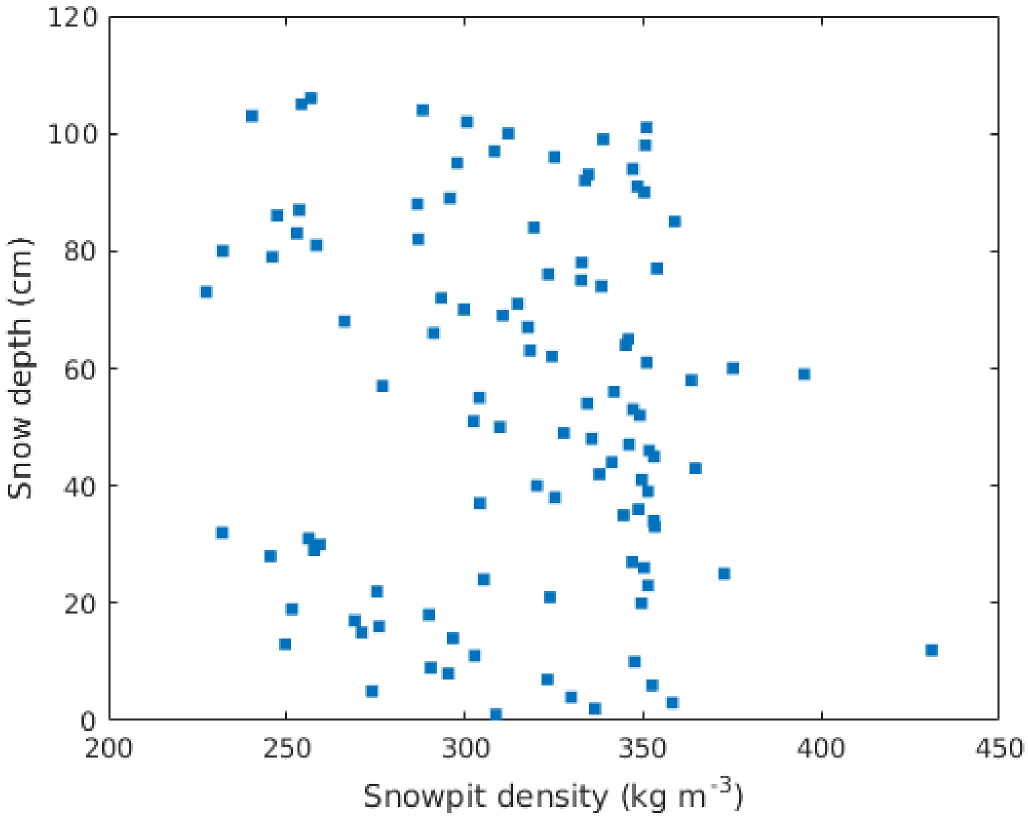


Figure 1: Plot of depth-detrended density and snow depth for all Federal Sampler measurements.

1.2 Federal Sampler measurements and snow depth

A plot of measured SWE and snow depth can be seen in Figure 2. A positive linear relation exists ($R^2 = 0.59$, $p<0.01$). This positive relationship could be a result of physical processes, such as compaction, and/or artefacts during data collection however, it seems more likely that this trend is a result measurement artefacts for a number of reasons. First, the range of densities measured by the Federal sampler is large (225–410 kg m^{-3}) and the extreme values seem unlikely to exist at these study glaciers, which experience a continental snowpack with minimal mid-winter melt events. Second, compaction effects would likely be small at these study glaciers because of the relatively shallow snowpack (deepest measurement was 340 cm). Third, no linear relationship exists between depth and snowpit-derived density ($R^2 = 0.05$) as can be seen in a plot of the depth-density relationship in snowpits in Figure 3. A plot of both Federal Sampler measurements and snowpit measurements can be seen in 4. Together, these reasons lead to the likely conclusion that the Federal Sampler measurements are biased.

To account for this likely artefact, the simplest form of linear detrending can be applied. The linear fit was subtracted from each data point and the original data mean was

Table 2: Summary of assumed and range of integrated snow density calculated in snowpits. The assumed density values arose from taking a density of 917 kg m^{-3} was applied to ice layers and a density of 600 kg m^{-3} was applied to layers that were described as 'hard' and were too difficult to sample. To determine the error in estimating integrated snow density, the values of ice density, ice thickness, and the 'hard' layer density was varied between 700 and 917 kg m^{-3}, ± 1 cm, and 500 and 600 kg m^{-3}, respectively.

	Depth (m)	**Density (kg m^{-3})**				**Range as %**
		Assumed value	*Minimum*	*Maximum*	*Range*	**of assumed value**
G02_LSP	44	360.9	328.6	377.3	48.7	13.5
G02_Z4A_SWE	35	325.8	307.9	344.7	36.8	11.3
G02_USP	119	344.0	327.1	361.9	34.8	10.1
G02_ASP	170	300.2	298.6	303.1	4.5	1.5
G04_LSP	190	350.9	343.2	359.1	15.9	4.5
G04_USP	160	333.4	316.6	349.6	33.0	9.9
G04_ASP	285	359.7	356.6	362.4	5.8	1.6
G13_LSP	20	383.0	383.0	383.0	0	0
G13_USP	100	355.4	345.6	366.9	21.3	6.0
G13_ASP	145	307.8	306.4	308.2	1.8	0.6

added to each point. A plot of the detrended density data can be seen in Figure 1. This detrended data will not be used for subsequent analysis but can be accessed by changing `options.TubeDensity` accordingly.

1.3 Density uncertainties

1.3.1 Snowpit density

Uncertainty in estimating density from snowpits is likely dominated by measurement errors and incorrect assumptions of density of layers that could not be sampled (i.e. ice lenses and 'hard' layers). To determine a possible range of density values from snowpit measurements, the original data was used and three parameters were varied. Ice layer density was varied between 700 and 900 kg m^{-3}, ice layer thickness was varied by ±1 cm, and the density of layers identified as being too hard to sample (but not ice) was varied between 600 and 700 kg m^{-3}. The resulting minimum and maximum possible densities for each snowpit can be seen in Table 2. The range of density values is always less than 15% of the reference density, with the largest ranges present on Glacier 2. Density values for shallow pits that contained ice lenses were particularly sensitive to changes in density and ice lens thickness.

1.3.2 Federal Sampler densities

Density values estimated from Federal Sampler measurements are shown in Table 3. Mean density has a larger spread of values over the study glaciers when compared to snowpit densities. The % range is also larger than snowpit densities for many of the measurement locations.

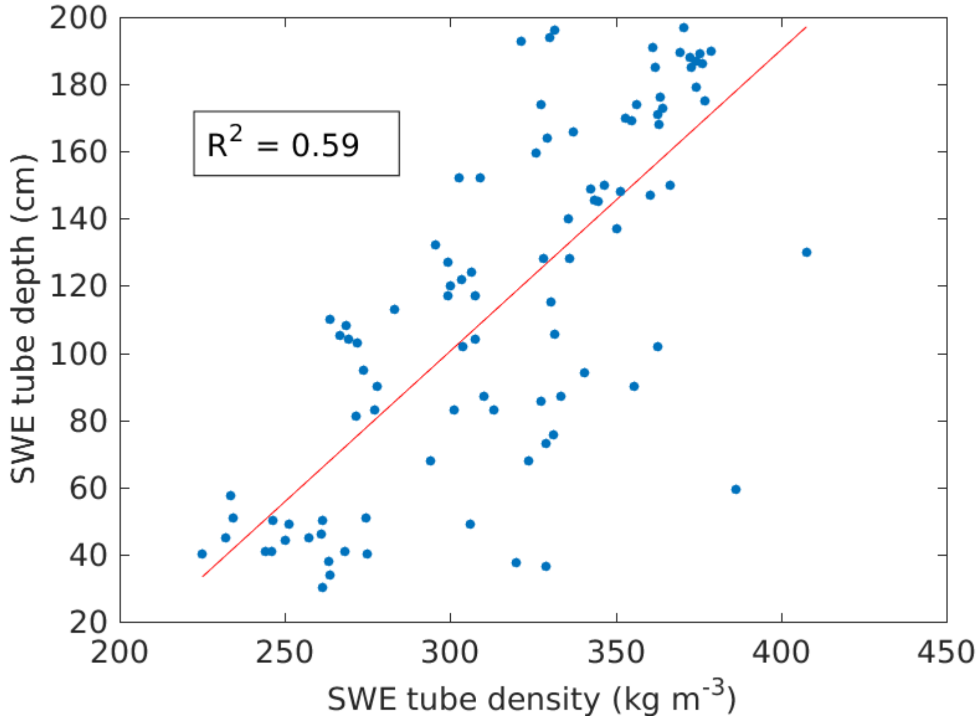


Figure 2: Relationship between measured density and snow depth for all Federal Sampler measurements.

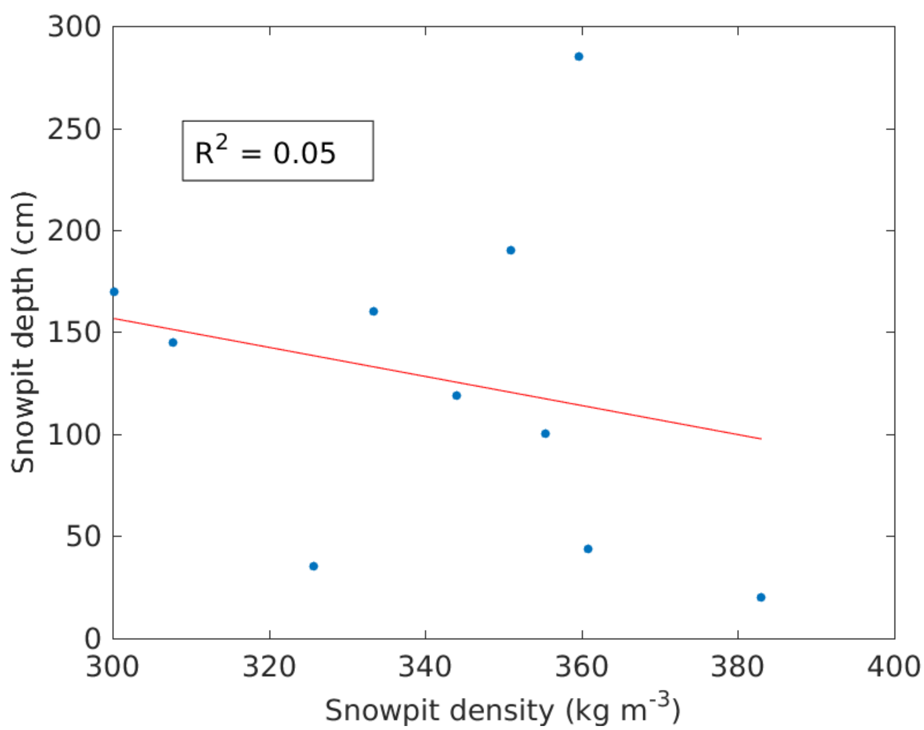


Figure 3: Relationship between measured density and snow depth for all snowpit locations.

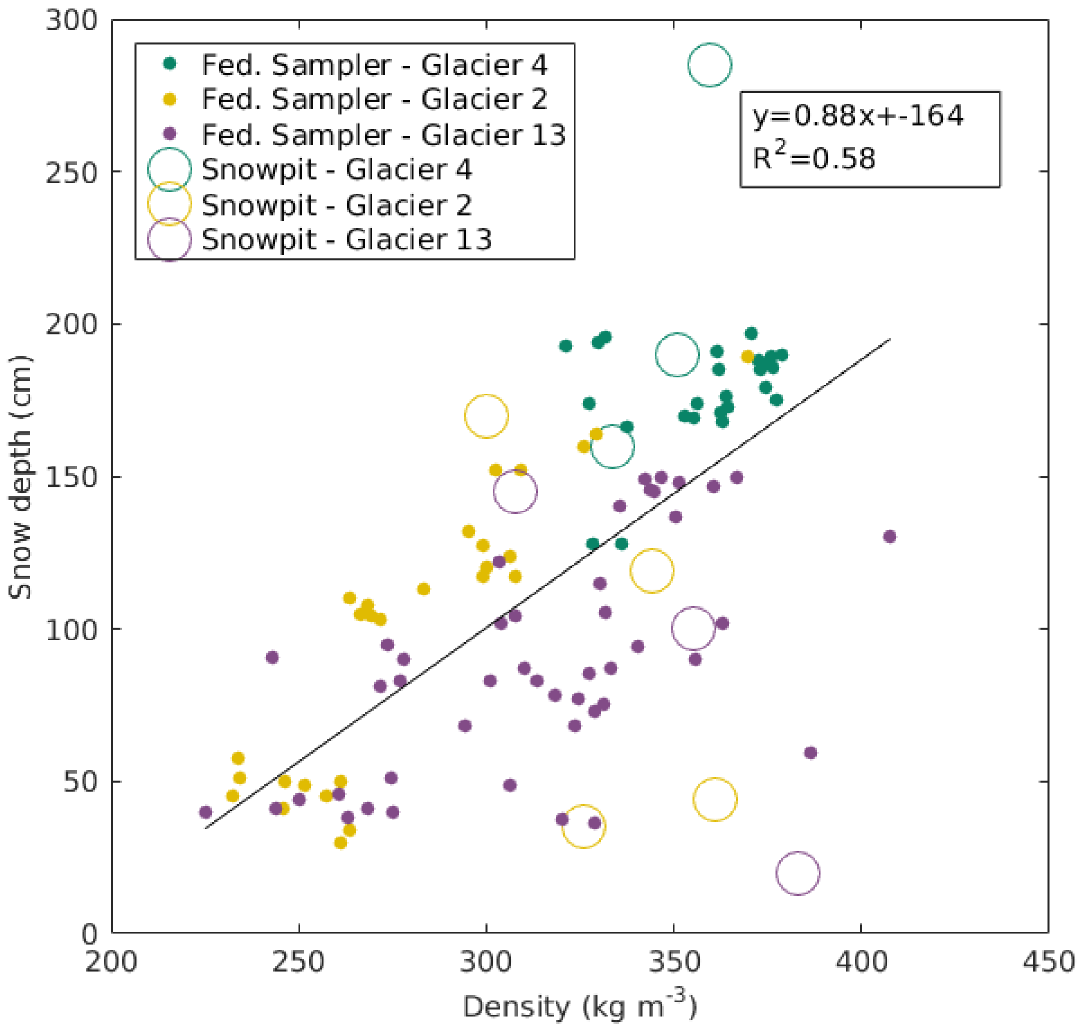


Figure 4: Relationship between measured density and snow depth for all Federal Sampler and snowpit locations.

Table 3: Range of densities estimated from Federal Sampler measuresments. The number (n) of good quality measurements, as well as the minimum, maximum, and mean density are shown. The density range given as a percent of the mean density is also shown.

Location	**n**	**Density (kg m^{-3})**			**Range as % of mean (%)**
		Mean	Minimum	Maximum	
GL4_Z3A_SWE	3	334	309	358	14
GL4_USP	6	311	274	353	22
G04_Z2A_SWE	3	360	303	431	35
G04_LSP	7	272	250	297	13
GL4_Z5B_SWE	2	337	324	350	7
GL4_Z5A_SWE	3	311	275	351	21
GL4_Z5C_SWE	2	361	350	373	6
GL02_Z5C_SWE	2	296	245	347	28
G02_USP	7	294	232	353	34
G02_Z7A_SWE	3	326	304	349	12
GL02_Z7B_SWE	2	336	320	351	9
GL02_Z7C_SWE	3	351	338	365	7
GL02_Z3B_SWE	3	349	341	353	3
GL02_LSP_SWE	7	331	302	349	13
GL13_ASP	8	343	277	395	33
G13_651	3	329	318	345	7
G13_652	2	319	291	346	15
G13_654	3	298	266	318	14
G13_655	1	300	300	300	0
G13_656	3	279	227	315	24
G13_657	3	331	323	338	4
G13_658	2	343	333	354	6
G13_659	3	245	232	258	7
G13_Z7C_SWE	2	270	253	287	9
G13_USP	6	294	247	359	31
G13_Z4C_SWE	4	342	334	350	5
G13_744	3	323	298	347	14
G13_Z3B_SWE	3	333	308	351	12
G13_Z4B_SWE	2	332	312	351	11
G13_Z5A_SWE	3	276	240	301	17
G13_Z5B_SWE	2	255	254	257	1

1.4 Comparing density from snowpit and Federal Sampler measurements

To compare snowpit-derived densities and Federal Sampler-derived densities, eight Federal Sampler measurements were taken around two snowpit locations on each study glacier. The results are shown in Figure 5. The overall range of Federal Sampler-derived densities is larger than that of the snowpit-derived density values. Within the range of possible values (minimum and maximum densities), the density values are indistinguishable for all snowpit locations, except for 'G13_ASP'.

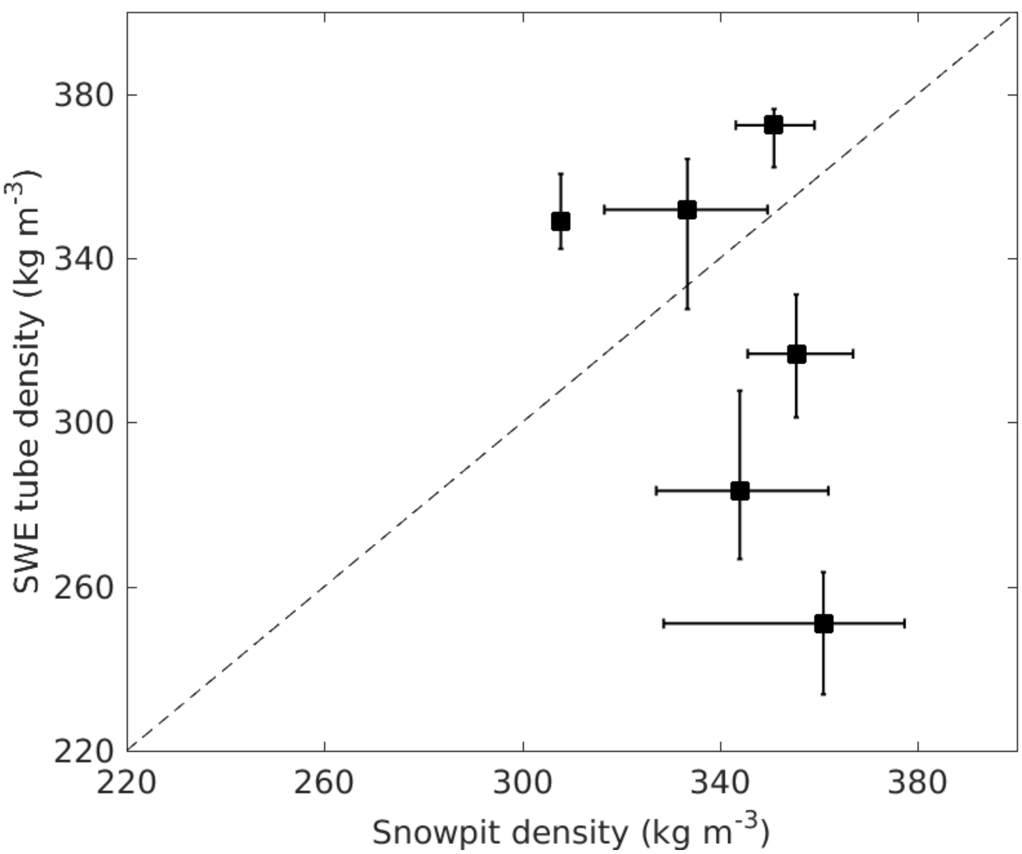


Figure 5: Comparison of density estimated using wedge cutters in a snow pit and Federal Sampler measurements for three study glaciers. Error bars are minimum and maximum values for each estimate as seen in Table 2 and 3. A 1:1 reference line is also shown.

1.5 Density and elevation

A linear fit between density and elevation is often used to interpolate density values between measurement locations. A summary of linear fits of the snowpit-derived and Federal Sampler-derived densities can be seen in Table 4. There seems to be no generalization of elevation regressions between study glaciers and even between sampling methods. Note

Table 4: Summary of linear regressions between snowpit-derived density and elevation (z) as well as Federal Sampler-derived densities and elevation (z) for the study area.

Location	**Snowpit Regression** Equation	R^2	**Fed. Sampler Regression** Equation	R^2
Glacier 4	$0.03z+274$	0.16	$-016z+714$	0.53
Glacier 2	$-0.14z+659$	0.75	$0.24z-282$	0.72
Glacier 13	$-0.19z+796$	1.00	$0.12z+33$	0.21
All	$-0.12z+618$	0.50	$-0.14z+659$	0.75

that since Federal Sampler measurements, which have been shown to have a significant relationship between snow depth and estimated density, are likely to have skewed regressions because snow depth is significantly correlated with elevation (as seen in Figure 6).

A plot of snowpit-derived density versus elevation can be seen in Figure 7 and a plot of Federal Sampler-derived density versus elevation can be seen in Figure 8.

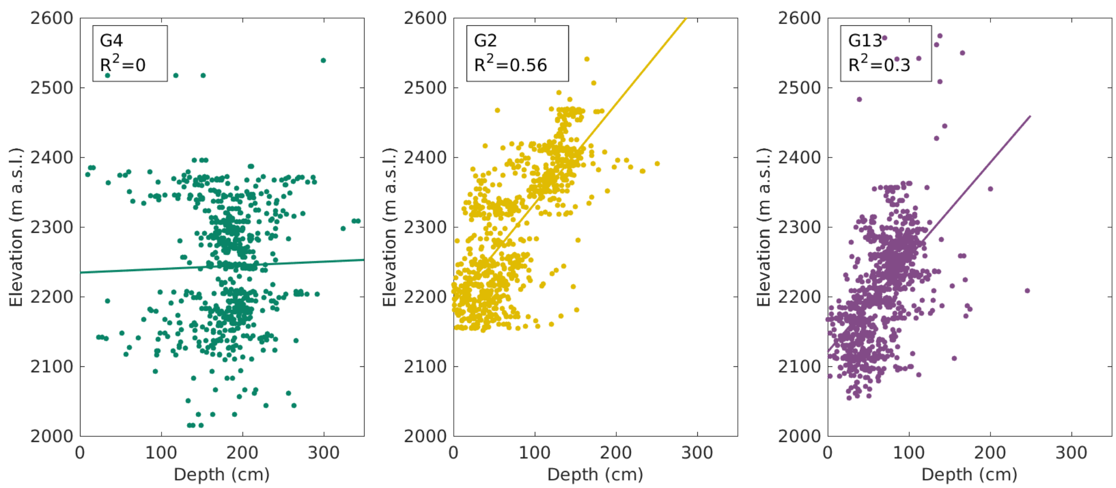


Figure 6: Relationship between measured snow depth and elevation at all sampling locations.

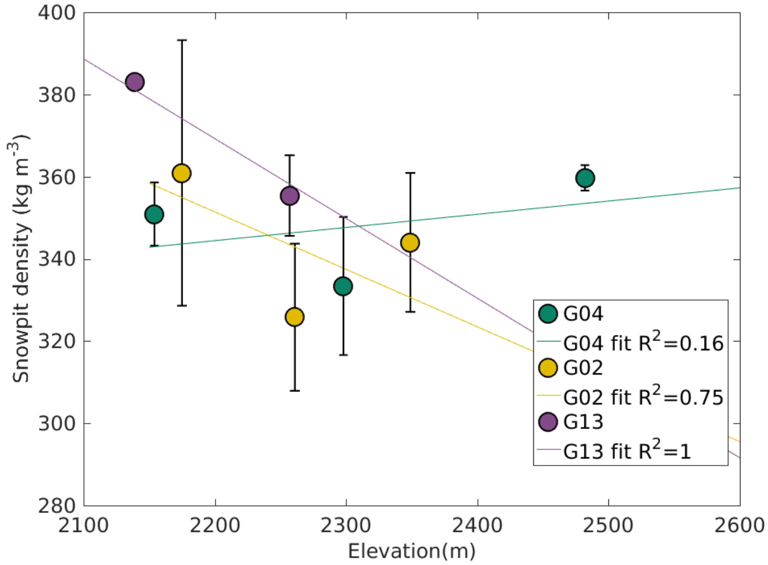


Figure 7: Relationship between snowpit-derived density and elevation for all study glaciers.

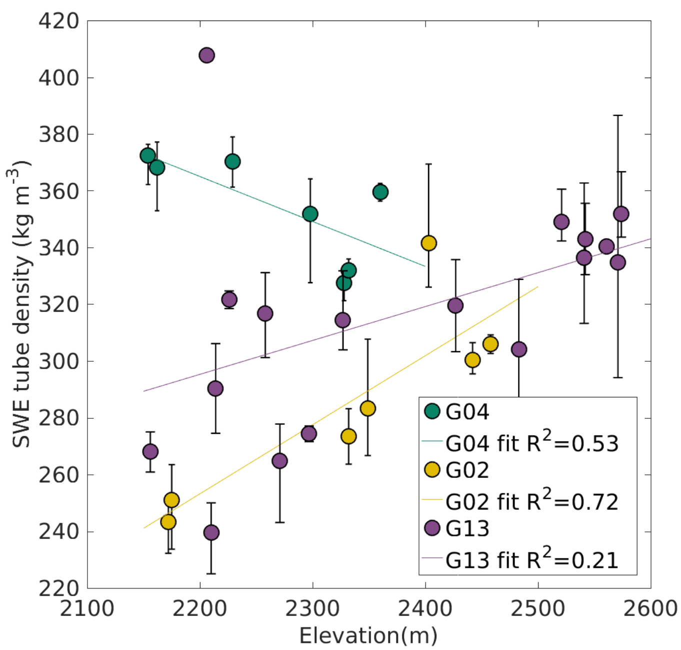
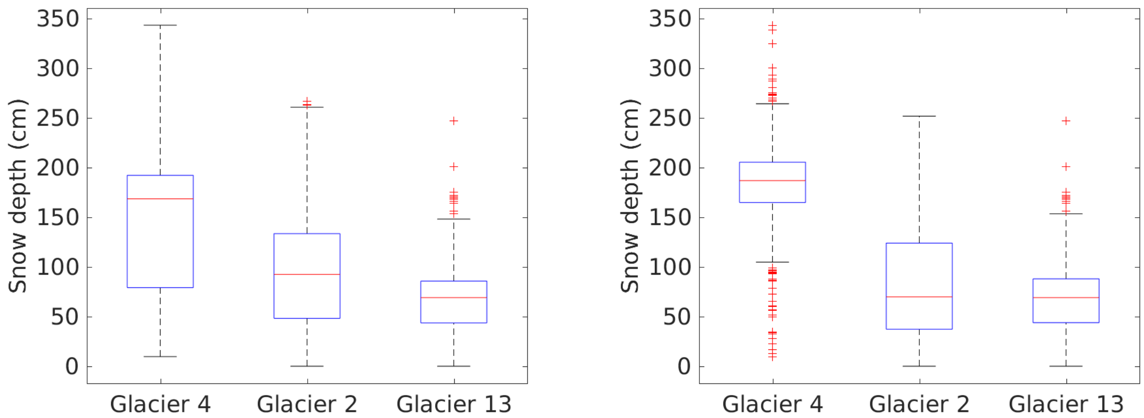


Figure 8: Relationship between Federal Sampler-derived density and elevation for all study glaciers.

2 Snow depth



(a) *All* snow depth values

(b) *Transect* snow depth values

Figure 9: Boxplots of snow depth measured ons tudy glaciers. Red line indicates median, blue box shows first quantiles (25the and 75th percentiles), bars indicate minimum and maximum values (excluding outliers), and red crosses show outliers, which are defined as being outside of the range of 1.5 times the quartiles (about $\pm 2.7\sigma$).

A summary of the measured snow depth on all study glaciers is shown in Figure 9 where 9a shows all snow depth measured (including zigzag values) and 9b shows snow depth values collected along curvilinear and linear transects. In both cases, Glacier 4 has the largest median and range of snow depth values, while Glacier 13 has the smallest.

3 Zigzag data

A comparison of measured snow depth for each zigzag is shown in Figure 10. The zigzags on Glacier 4 show minimal variability with a small range of values observed and few outliers. The mean depth is significantly larger at the upper most zigzag. Zigzags on Glacier 2 show more variability. The range on the mid zigzag is the largest of all the zigzags measured and the highest zigzag has many outliers. The zigzags on Glacier 13 do not vary considerably in range, although the lower zigzags show a large number of outliers which may be a results of these locations being close to a supraglacier meltwater channel.

The depth measured at each zigzag is shown in Figures 11, 12, and 13. There is considerable variability both between zigzags and within each zigzag. For example, in Figure 11, 'G04_Z5B' has a more uniform snow depth than 'G04_Z3A', which has a large range in depth values.

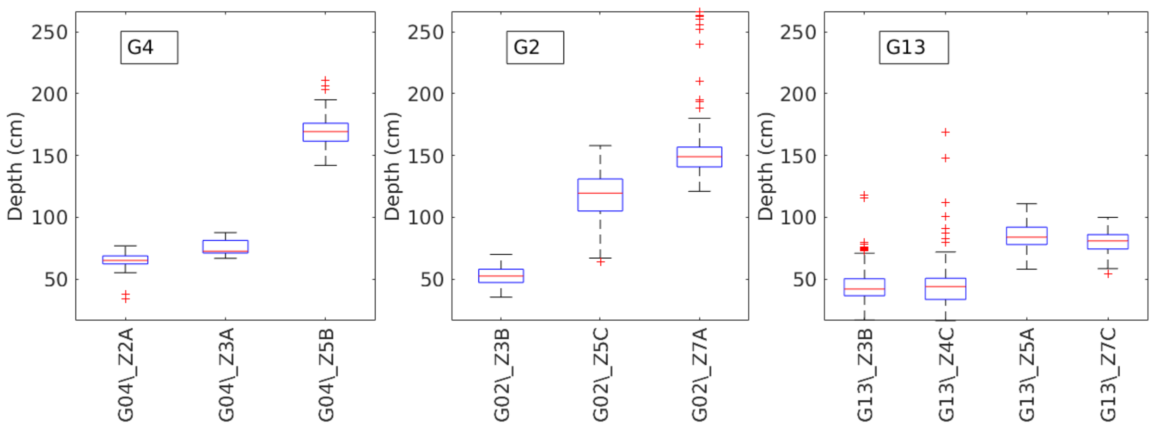


Figure 10: Boxplot of zigzag depths measured at each zigzag location.

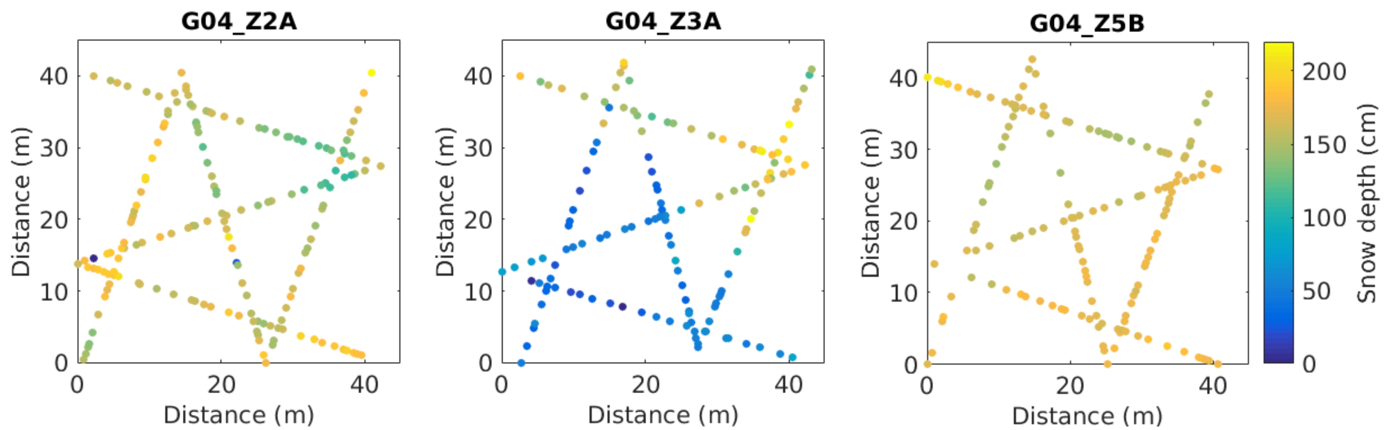


Figure 11: Plot of depth measured at zigzags on Glacier 4.

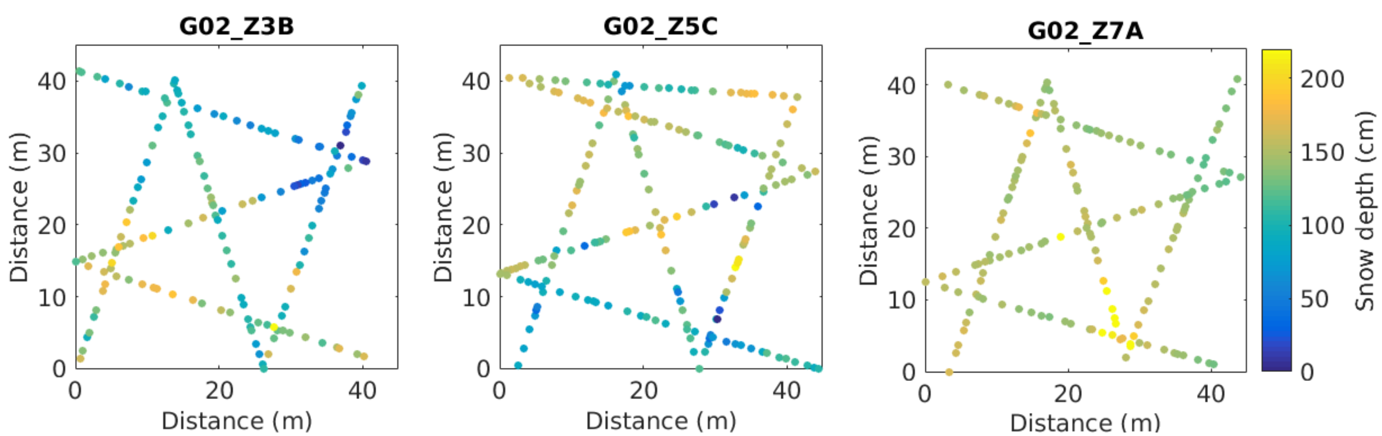


Figure 12: Plot of depth measured at zigzags on Glacier 2.

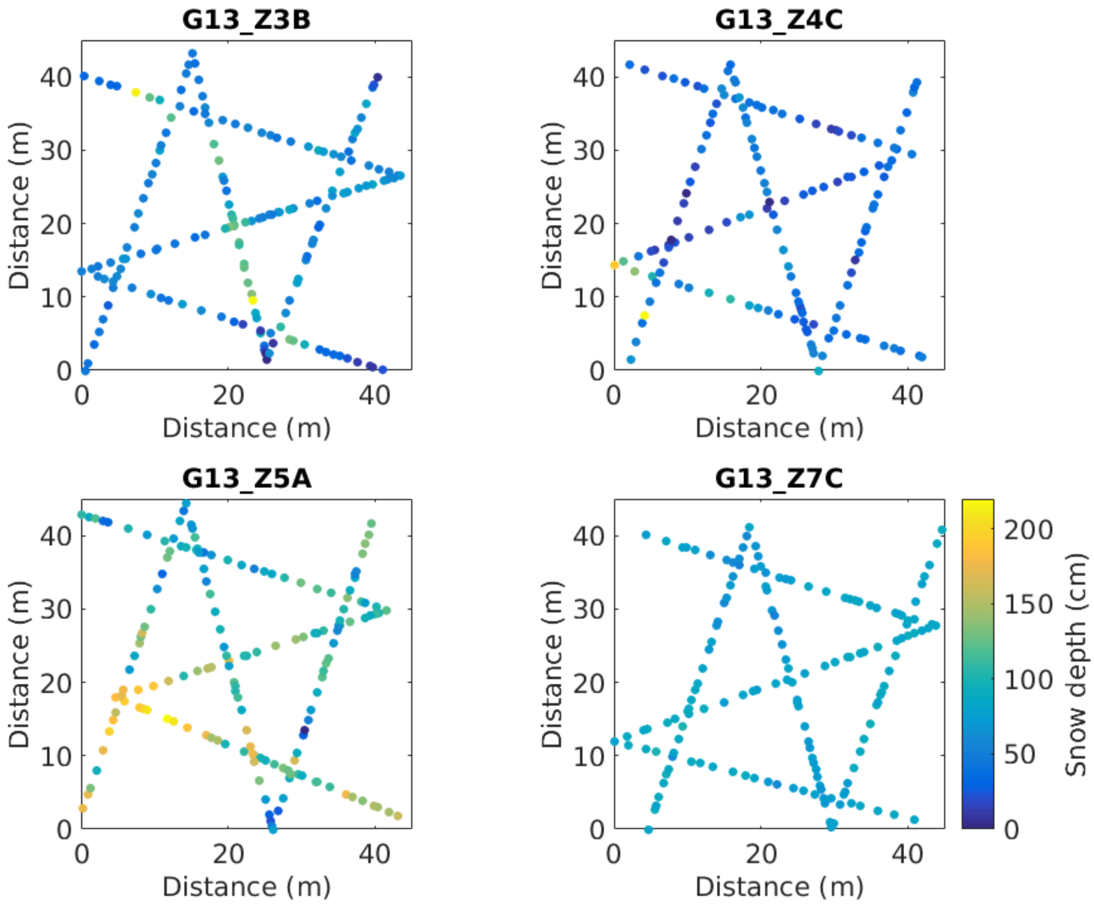


Figure 13: Plot of depth measured at zigzags on Glacier 13.

4 Snow water equivalent (SWE)

Snow water equivalent (SWE) estimated for each sampling location can be seen in Figure 14. For maps of SWE calculated for each density option see the Appendix. Generally, SWE is highest on Glacier 4 and lowest on Glacier 13. Glacier 4 also shows considerable SWE variability within the basin, with both high and low values seen along a single transect. Note that the individual measurement locations overlap on the figure.

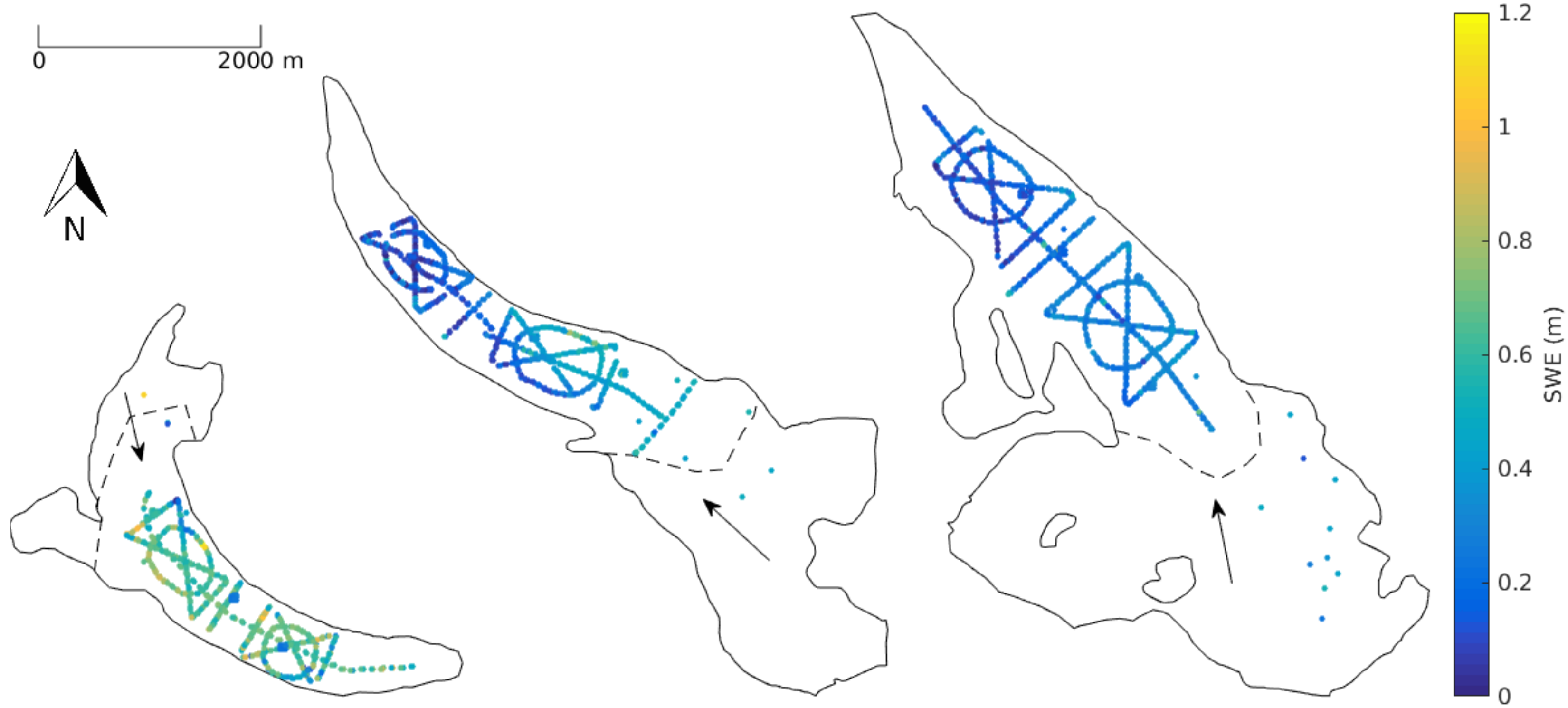


Figure 14: Estimated snow water equivalent (SWE) at measurement locations. Density was taken to be the average of three integrated, snowpit-derived densities for each glacier. Arrow shows ice flow direction. See Appendix for maps of SWE for other density options.

Appendix - SWE maps

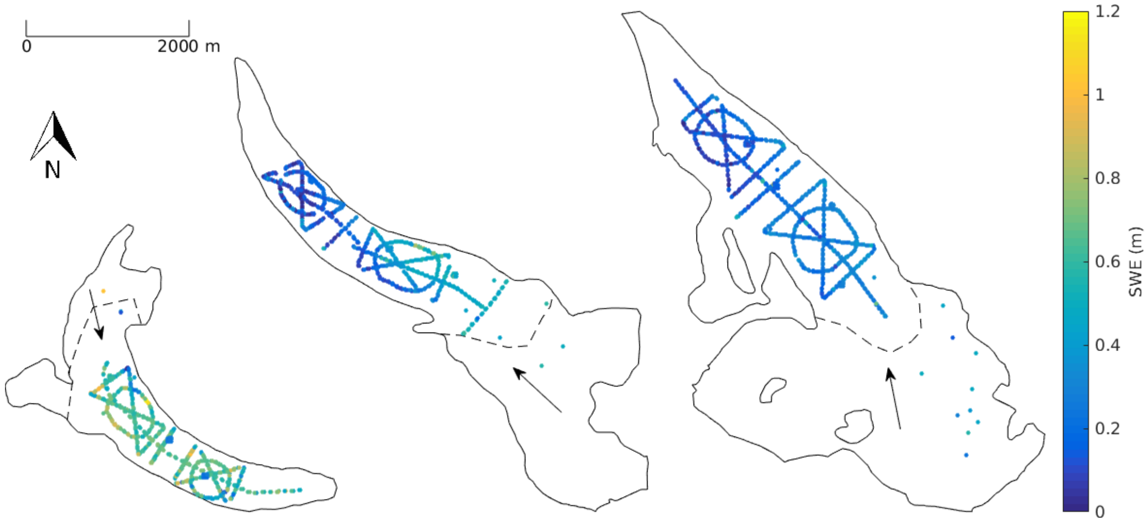


Figure 15: Estimated snow water equivalent (SWE) at measurement locations. Density was taken to be the mean value of all snowpit-derived densities (Option 2). Arrow shows ice flow direction.

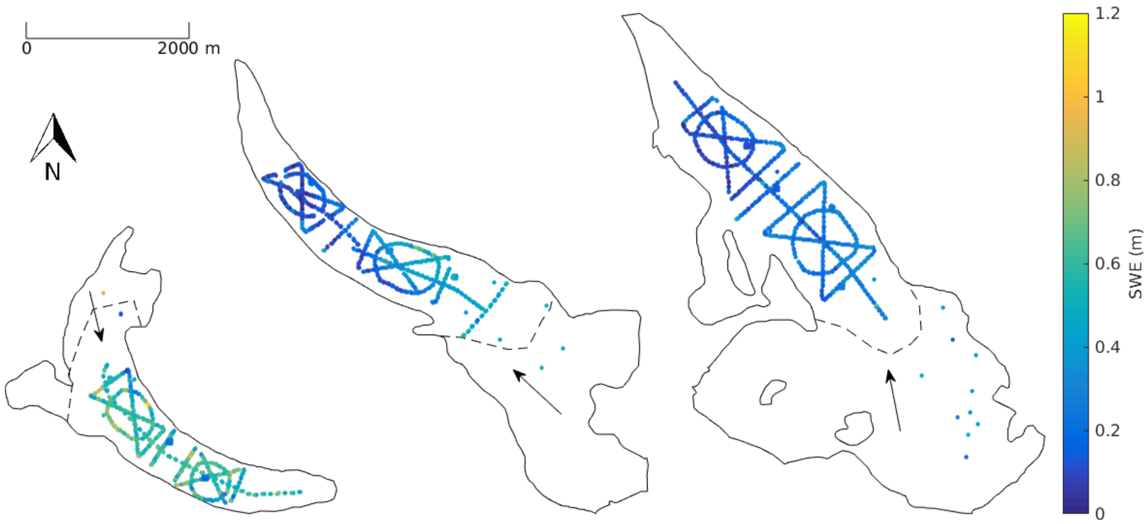


Figure 16: Estimated snow water equivalent (SWE) at measurement locations. Density was taken to be the mean value of all snowpit-derived densities (Option 3). Arrow shows ice flow direction.

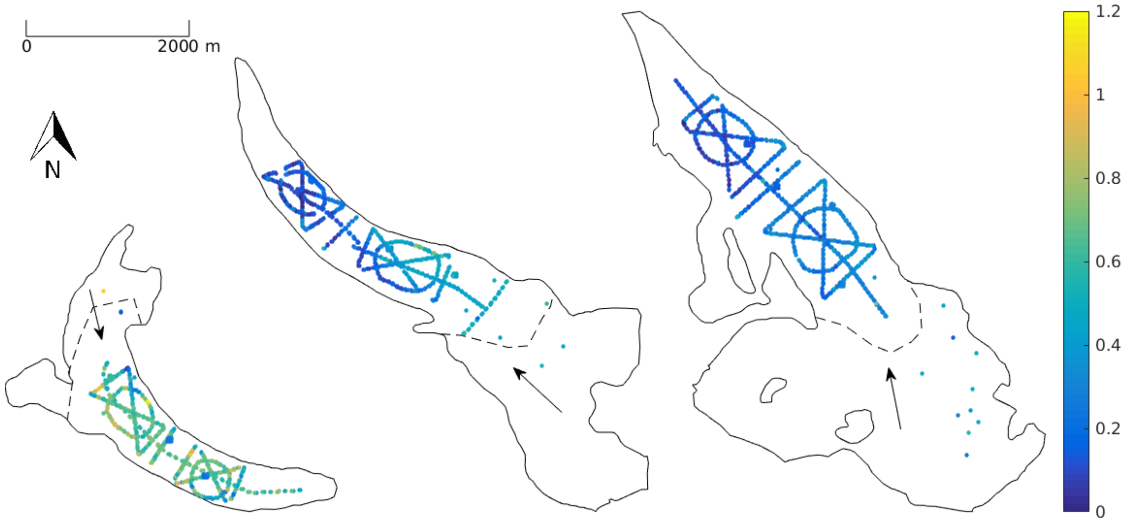


Figure 17: Estimated snow water equivalent (SWE) at measurement locations. Density was taken to be the mean value of snowpit-derived densities for each glacier (Option 4). Arrow shows ice flow direction.

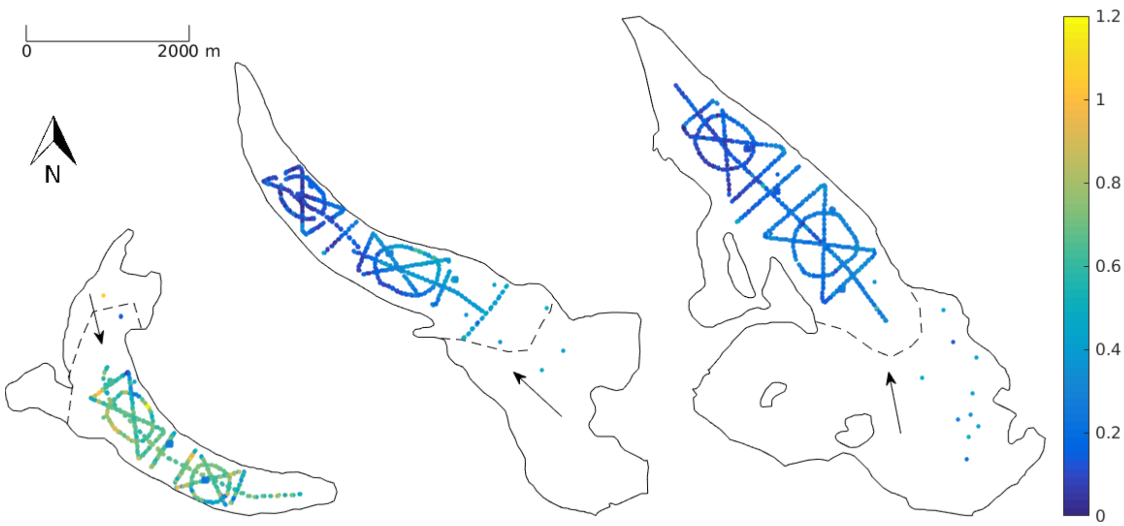


Figure 18: Estimated snow water equivalent (SWE) at measurement locations. Density was taken to be the mean value of Federal Sampler-derived densities for each glacier (Option 5). Arrow shows ice flow direction.

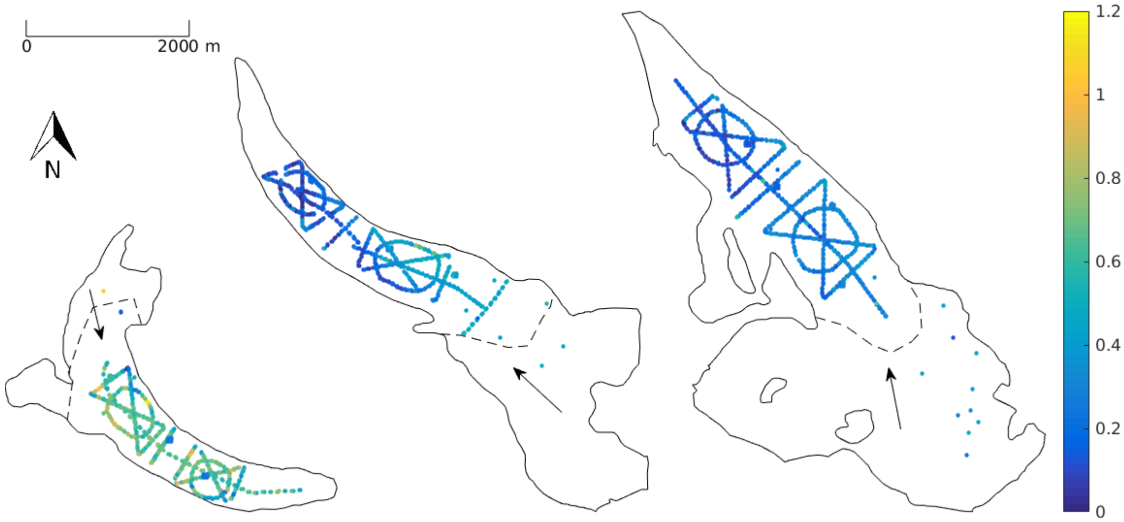


Figure 19: Estimated snow water equivalent (SWE) at measurement locations. Density was determined by using a linear fit between snowpit-derived density and elevation for each glacier (Option 6). Arrow shows ice flow direction.

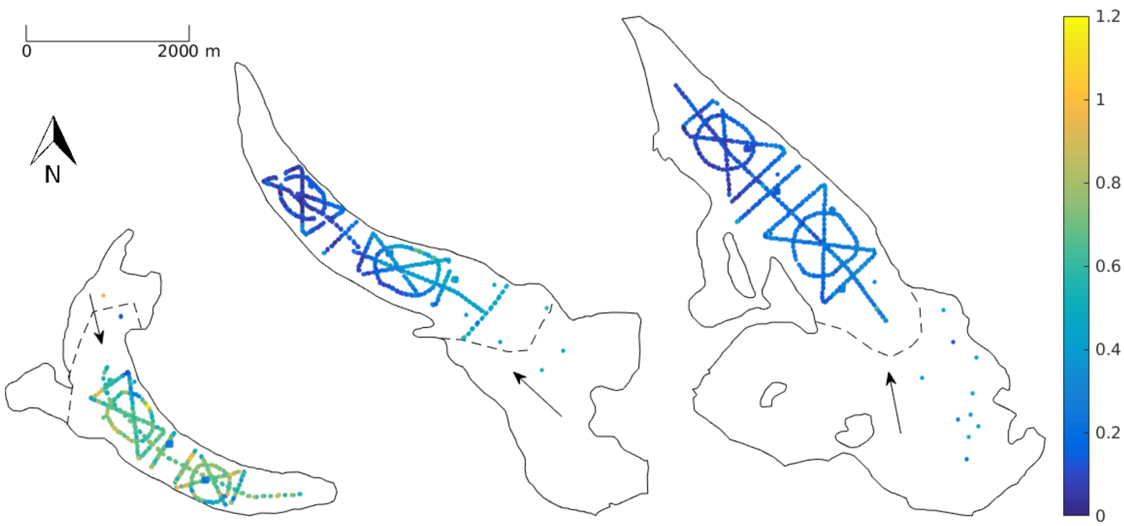


Figure 20: Estimated snow water equivalent (SWE) at measurement locations.Density was determined by using a linear fit between Federal Sampler-derived density and elevation for each glacier (Option 7). Arrow shows ice flow direction.

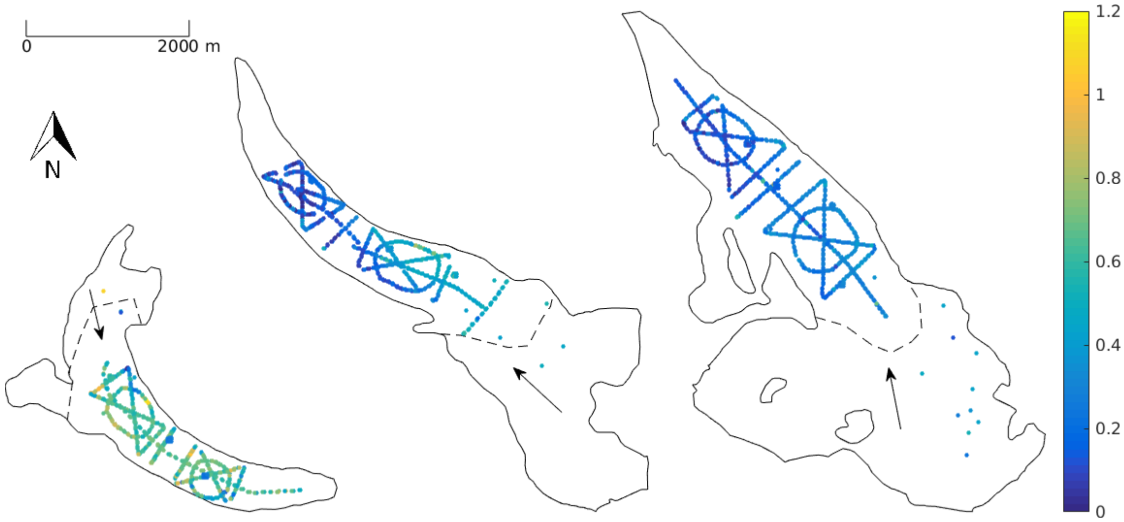


Figure 21: Estimated snow water equivalent (SWE) at measurement locations. Density was calculated using inverse distance weighting using all snowpit-derived densities (options 8). Arrow shows ice flow direction.

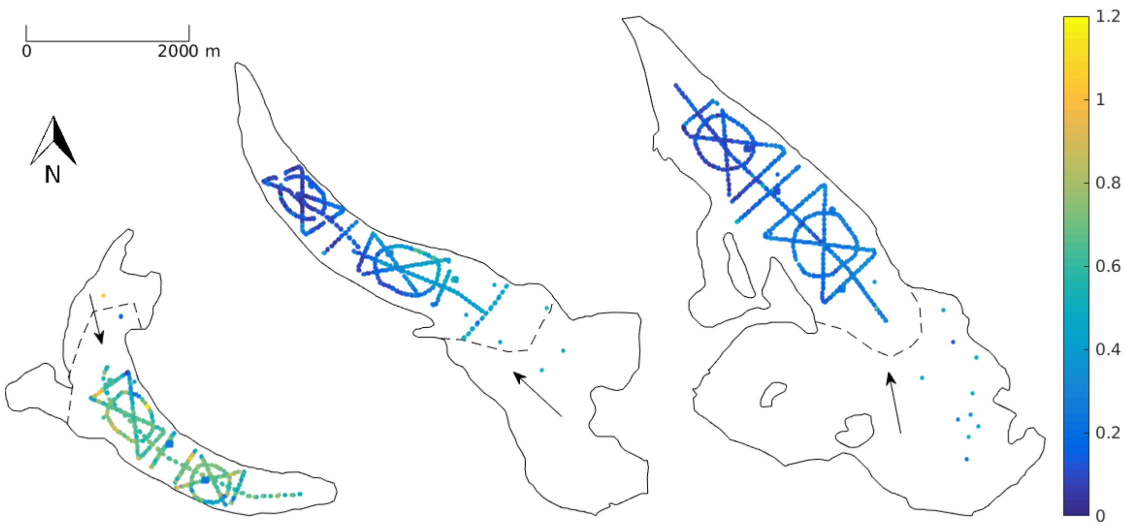


Figure 22: Estimated snow water equivalent (SWE) at measurement locations. Density was calculated using inverse distance weighting using all snowpit-derived densities (options 9). Arrow shows ice flow direction.

(a) Inserting the Federal Sampler into the snow. Photo credit: C. Ariagno

(b) Weighing the Federal Sampler with snow core on the spring scale (units of cm SWE). Photo credit: G. Flowers

Figure 23: Using the Federal Sampler to measure SWE