

Data Observations

Overview

This section documents the process of going from raw data to processed and consolidated data that will be used for analysis in subsequent components of the project. An overview of the various density interpolation methods and the eight group of SWE values is provided. An overview of the zigzag data is also included.

Contents

1	Initial Data Processing	2
1.1	Linear and Curvilinear Transects	2
1.2	Zigzag	3
1.3	Density	4
2	Density Estimates	4
2.1	Sampling Scheme and Naming System	11
2.2	Federal Snow Sampler	13

1 Initial Data Processing

1.1 Linear and Curvilinear Transects

Snow depth measurements along the linear and curvilinear transects were taken at locations a certain distance from marked waypoints. Since only the coordinates of the waypoints (WP) were recorded, the measurement coordinates needed to be estimated. The measurement locations were assumed to be 10, 20, and 30 m behind the marked WP, in a straight line between the marked WP and the previous WP. In cases with only two observers, locations were assumed to be 10 and 20 m behind the marked WP. For the first marked WP of a pattern, it was assumed that the locations were along the same line as that between the first and second WPs. The following methodology was used to determine measurement locations (each step corresponds with a section of the Matlab code ‘MeasurementLocations.m’):

1. Waypoint (WP) locations were exported from the GPS units using the BaseCamp program. They were then imported to QGIS and exported with UTM coordinates. This file was then used in the Matlab script and is entitled ‘GlacierWP_UTM.xlsx’.
2. In order to obtain the measurement locations for the first WPs of each pattern, an “imaginary” WP was created that was along the line between the first and second WPs, but located ahead of the first WP. These waypoints were then inserted into the original data.
3. A set of 1000 equally spaced points was created along a straight line between each set of subsequent WPs (including the “imaginary” WPs from the previous step) using the function `linspaceNDim.m` created by Steeve Ambroise and downloaded from the MathWorks File Exchange. The Euclidean distance between these interpolated points and the marked WP was then calculated and the points with distances closest to the assumed separation between observers were retained. The final matrix has the easting and northing of each measurement location and is labelled with the marked WP and a decimal that corresponds to the relative observer (e.g. label 45.2 means that the location was determined from the marked WP #45 and is 20 m behind this WP because it is the second observer).

The data recorded by each observer in the field books was transcribed to a spreadsheet format and then imported and processed in Matlab according to the following steps (each step corresponds with a section of the Matlab code ‘Import_Transect.m’):

1. A spreadsheet was created with a sheet for data from each field book (SD#1, SD#2, SD#3, and SWEDepth). For each reference WP there were values for all snow depth measurements and their quality (1 for good, 0 for bad), comments written, field book name, glacier name, observer, pattern, and date collected.
2. The quality, comments, book name, glacier name, observer, pattern, and date entries were categorized. This allows for efficient grouping and data searching in future analysis.

3. The depth data was then assigned the corresponding measurement location UTM from the ‘MeasurementLocations.m’ script. This was done by matching the WP number from the field books and that of the marked WPs and then assigning the coordinates from the WP ending with .1 to depths recorded in book SD#1, and likewise for the remaining books. The matrices for each set of observations were then made to be the same dimensions by inserting empty cells for WPs where no data was recorded in that set of observations.
4. The data was then arranged in a structure variable (called SD) with rows corresponding to each book (e.g. row 1 is data from book SD#1) and columns corresponding to the various types of data (e.g. depth values or glacier category). For example, the matrix with the glacier category for each value recorded in the book SD#1 can be accessed with ‘SD(1).glacier’.

Subsets of the transect data can be pulled using the function ‘pulldata.m’. The function is called with `pulldata(data, book, glacier, person, pattern, quality, format)`. Here, `data` is the full SD structure, `book`, `glacier`, `person`, and `pattern` are all strings that refer to desired categories, `quality` differentiates between good (1), bad (0), or ‘all’ data, and `format` specifies the formatting of the full depth matrix as being either a column vector (‘skinny’) or a matrix with depth values for one WP in a single row.

1.2 Zigzag

Data from zigzag measurements, which includes the measured snow depth and the distance of that measurement from the previous measurement or vertex, was transcribed to a spreadsheet. The data were then processed using the following procedure (each step corresponds with a section of the Matlab code ‘Import_Zigzag.m’):

1. Data were imported into Matlab.
2. Descriptive data, including glacier name, zigzag zone label, reference vertex, data quality, observer name, date collected, and book name were categorized.
3. A structure was created with the depth and categorical data.
4. The distance of each measurement point from it’s reference vertex was then calculated. These locations were assumed to be a cumulative sum of distances in a straight line between two subsequent vertices. Two options exist for the location of the reference vertex:
 - (a) Option 1 calculates the distance of each point from the UTM coordinates of the reference vertex.
 - (b) Option 2 calculates the distance of each point from the end of the previous line of measurements. Since the total distance measured with the avalanche probe did not always equal the distance between vertices (likely due to error in GPS units), this option takes the reference for each line to be from the end of the

previous line. The coordinates of the vertices were used for the start of each ‘Z’ shape (ZZ01 and ZZ05).

5. The final processing step involves removing bad quality data, obtaining the index for the start of each zigzag (needed for future analysis), as well as converting snow depth to snow water equivalent (SWE) based on the density calculated from the average SWE values measured with the Federal Sampler in each zigzag (if Option 2 is selected for that section).

1.3 Density

The density data from snowpit and Federal Sampler measurements were compiled into a spreadsheet and the density from each measurement was calculated and summarized in a spreadsheet.

Integrated snow density was calculated from snowpit measurements. This was done by multiplying the measured density from each wedge sample by the depth of the sample and summing these values. 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. When varying the ice density between 700 and 917 kg m^{-3} , the ice thickness by $\pm 1 \text{ cm}$, and the ‘hard’ layer density between 500 and 600 kg m^{-3} , a maximum error of 10% was found. This error was applied to all values of integrated snow density.

Density values determined from Federal Sampler measurements were filtered based on quality and then averaged for each measurement location. Measurements that were deemed to be unrepresentative of the local snow pack, which included measurements where the inner core length was less than 70% of the snow depth or where density values were exceptionally high (e.g. 490 kg m^{-3}), were marked as bad quality data. The data was processed in Matlab as follows (each step corresponds with a section of the Matlab code ‘Import_Density.m’):

1. Data were imported into Matlab and only good quality data were kept. Indices for data subsets (e.g. only density values from snowpits) were identified manually.
2. The mean density, standard deviation, and number of good measurements was calculated for the zigzag locations (Federal Sampler).
3. The mean density, standard deviation, and number of good measurements was calculated for the snowpit locations (Federal Sampler) and combined in a matrix with the corresponding snowpit derived density values.
4. A structure with the processed data was created.

2 Density Estimates

Federal Sampler measurements and snow depth

A plot of measured SWE and snow depth can be seen in Figure 1. A positive linear relation exists ($R^2 = 0.59$). This positive relationship could be a result of physical processes, such

as compaction, and/or artefacts during data collection. 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. Furthermore, compaction effects would likely be small at these study glaciers because of the relatively shallow snowpack (deepest measurement was 340 cm). A plot of the depth-density relationship in snowpits can be seen in Figure 2. No linear relationship exists between depth and snowpit-derived density ($R^2 = 0.05$). Together, these conditions lead to the likely conclusion that the Federal Sampler measurements are biased.

To account for this likely artefact, the simplest form of linear detrending was applied. The linear fit was subtracted from each data point and the original data mean was added to each point. A plot of the detrended density data can be seen in Figure 3. This detrended data will be used for all subsequent analysis.

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. This was also observed in the detrended densities derived from Federal Sampler measurements. 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, standard deviation (std), and 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	327	32	7
Glacier 2	333	26	4	326	23	7
Glacier 13	349	26	10	307	32	31
All	342	26	10	316	31	31

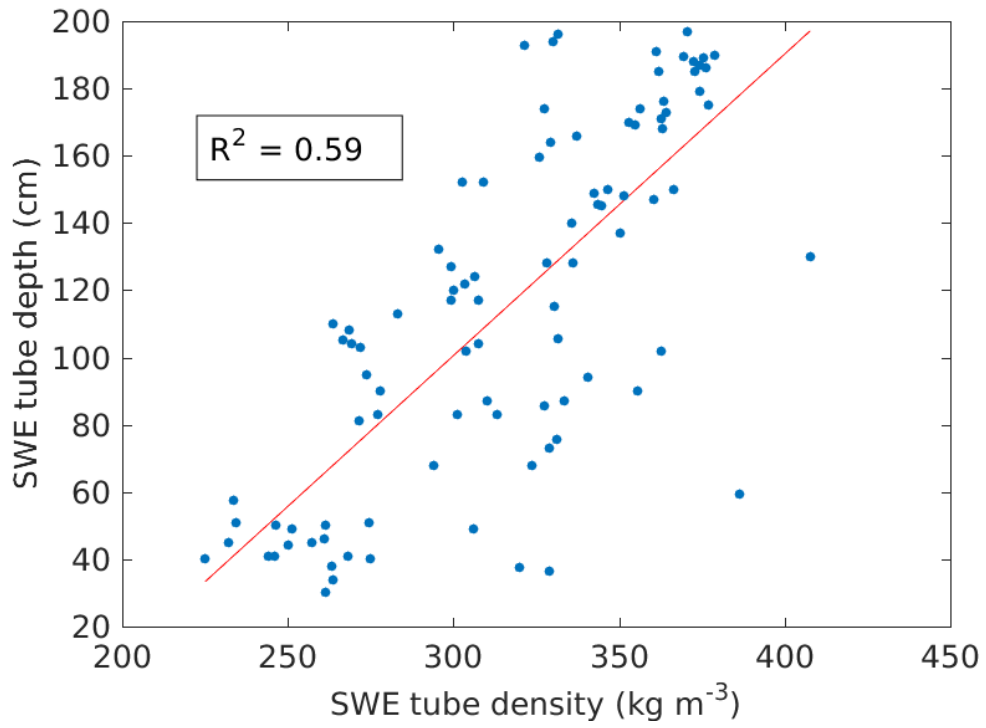


Figure 1: Relationship between measured density and snow depth for all Federal Sampler measurements.

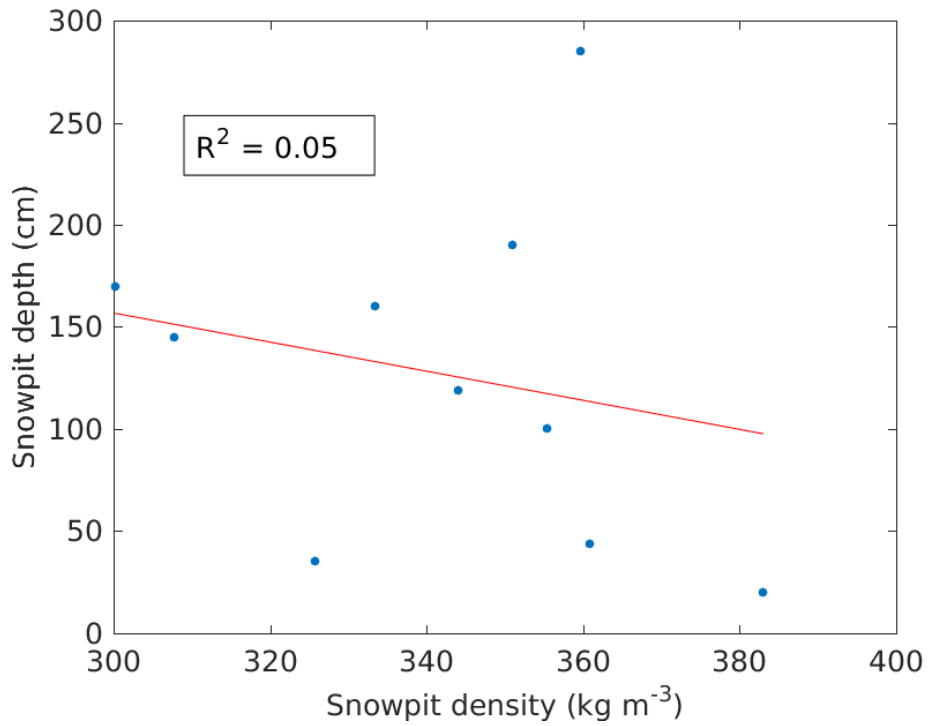


Figure 2: Relationship between measured density and snow depth for all snowpit locations.

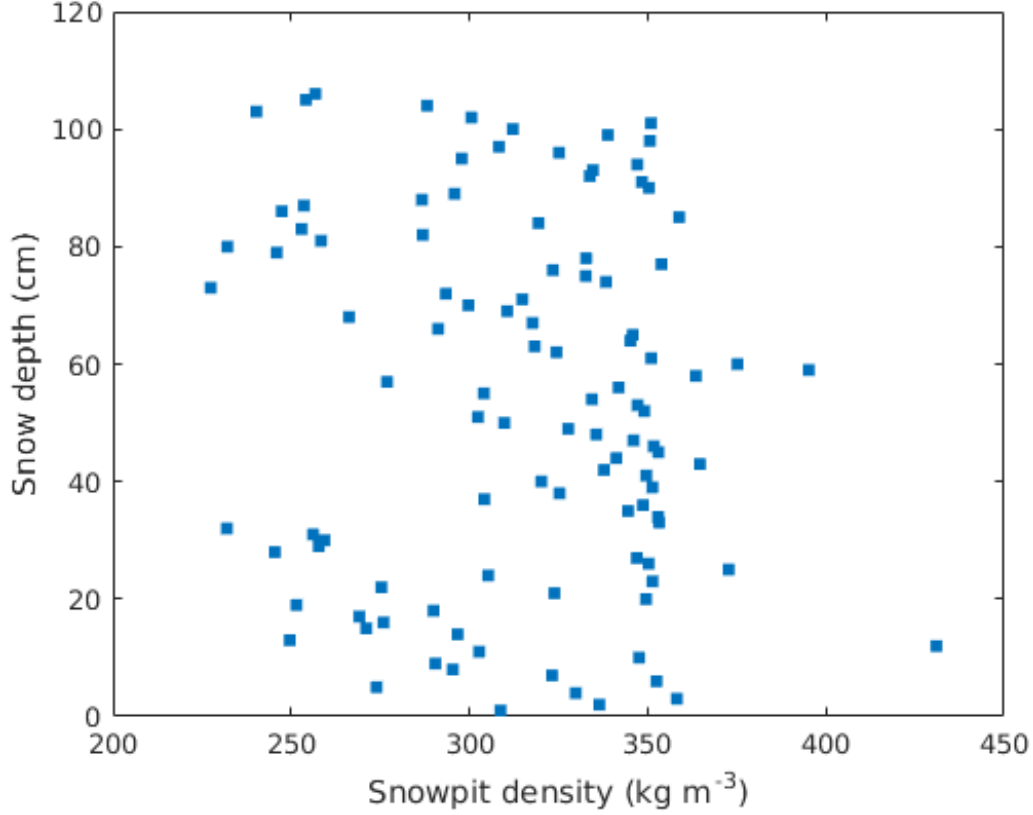


Figure 3: Plot of depth-detrended density and snow depth for all Federal Sampler measurements.

Density uncertainties

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 10% of the reference density (except for ‘G02.LSP’). Density values for shallow pits that contained ice lenses were particularly sensitive to changes in density and ice lens thickness.

Table 2: Range of snowpit density estimates. Minimum and maximum density values derived from varying ice layer density between 700 and 900 kg m⁻³, ice layer thickness by ± 1 cm, and the density of layers identified as being too hard to sample (but not ice) between 600 and 700 kg m⁻³. Reference values are those used in future analysis and were determined using an ice density of 900 kg m⁻³, the recorded ice thickness, and a ‘hard’ layer density of 600 kg m⁻³.

Snowpit	Density (kg m ⁻³)			Range as % of mean (%)	Snowpit depth (cm)
	Mean	Minimum	Maximum		
G02_LSP	361	329	377	13	44
G02_Z4A	326	308	345	11	35
G02_USP	344	327	362	10	119
G02_ASP	300	299	303	1	170
G04_LSP	351	343	359	5	190
G04_USP	333	317	350	10	160
G04_ASP	360	357	362	1	285
G13_LSP	383	383	383	0	20
G13_USP	355	346	367	6	100
G13_ASP	308	306	308	1	145

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.

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 4. The overall range of Federal Sampler-derived densities is larger than that of the snowpit-derived density values. A linear regression of the data gives a weak inverse relationship ($R^2 = 0.27$). Within the range of possible values (minimum and maximum densities), the density values are indistinguishable for all snowpit locations, except for ‘G13_ASP’.

Table 3: Range of densities estimated from Federal Sampler measurements. 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

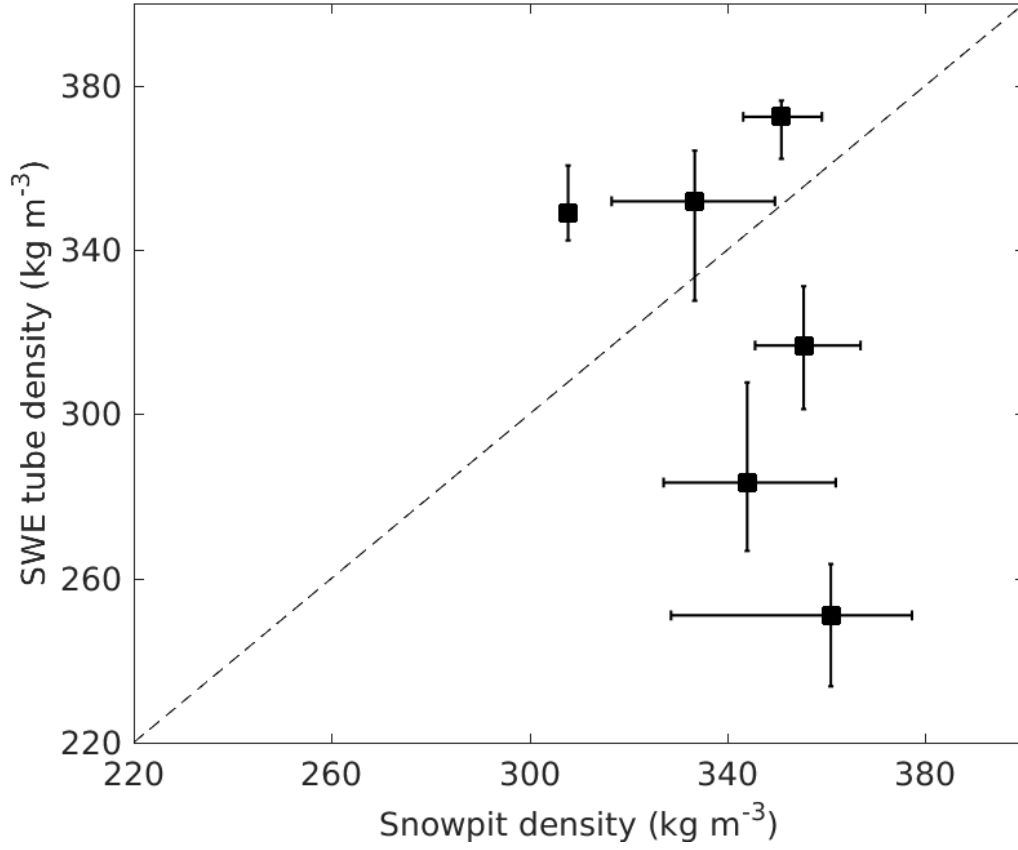


Figure 4: Comparison of density estimated using wedge cutters in a snow pit and Federal Sampler measurements for three study glacier (G04, G02, G13). Error bars are minimum and maximum values for each estimate as seen in Table 2 and 3.

Density and elevation

Snowpit density

A plot of snowpit-derived density and elevation can be seen in Figure 5.

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		Fed. Sampler Regression	
	Equation	R^2	Equation	R^2
Glacier 4	$0.03z+274$	0.16	$0.10z+111$	0.06
Glacier 2	$-0.14z+659$	0.75	$-0.01z+355$	<0.01
Glacier 13	$-0.20z+802$	1.00	$0.03z+248$	0.01
All	$-0.12z+618$	0.50	$0z+308$	<0.01

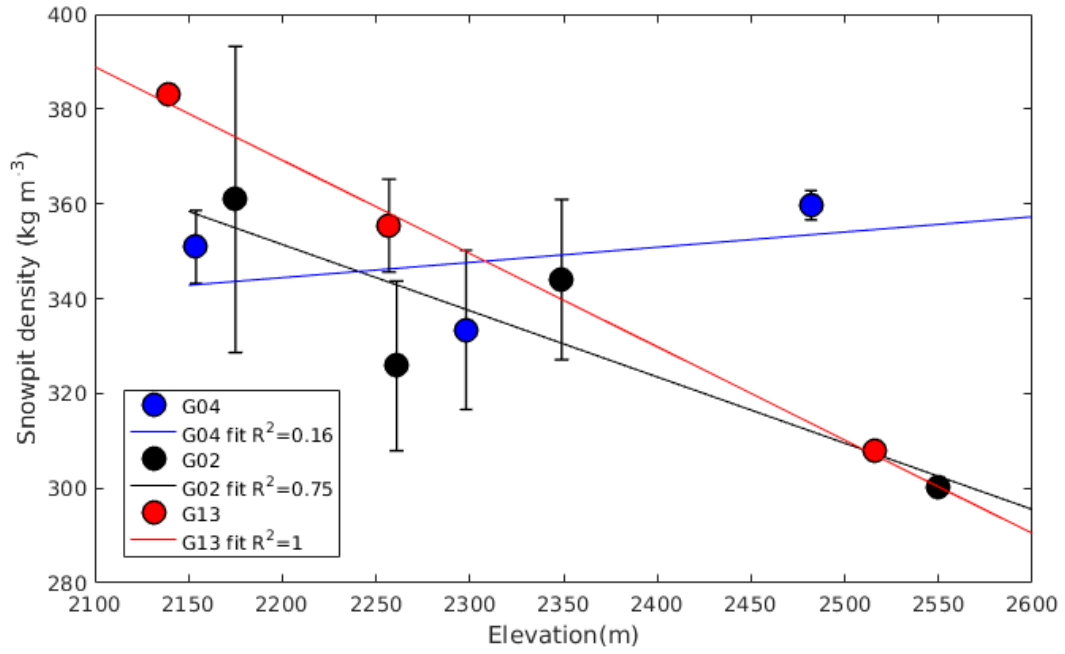


Figure 5: Relationship between snowpit-derived density and elevation for all study glaciers.

1.

2.1 Sampling Scheme and Naming System

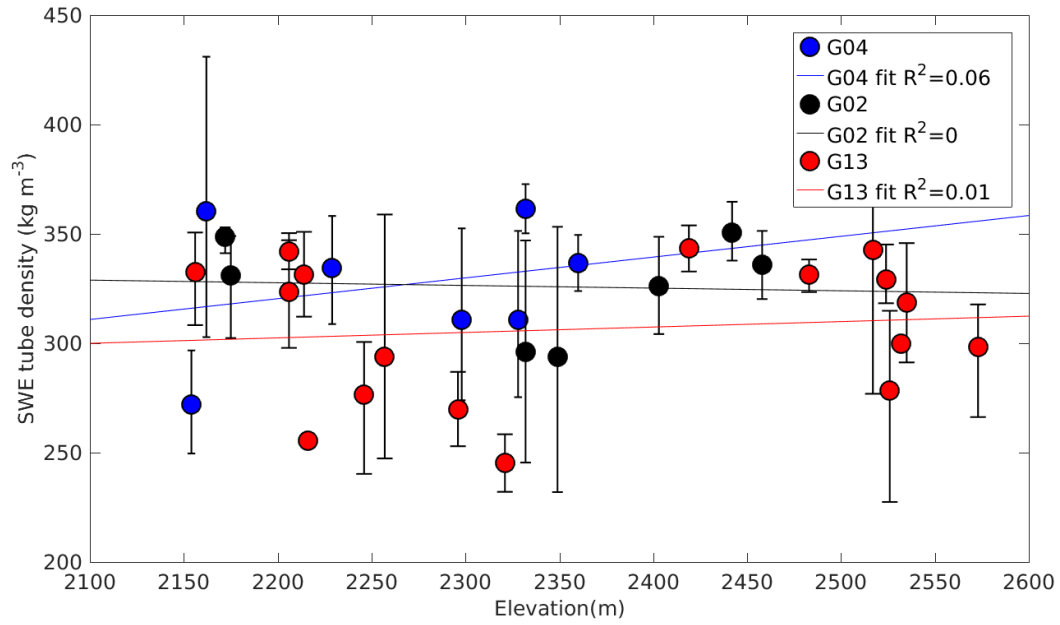


Figure 6: Relationship between Federal Sampler-derived density and elevation for all study glaciers.

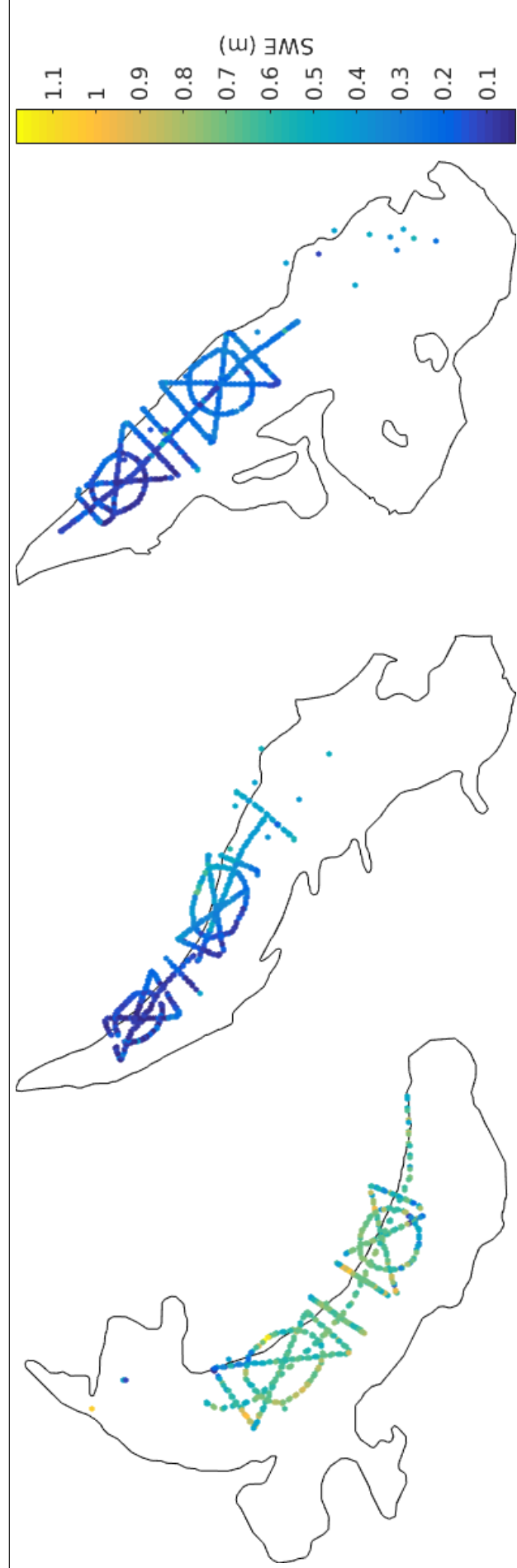
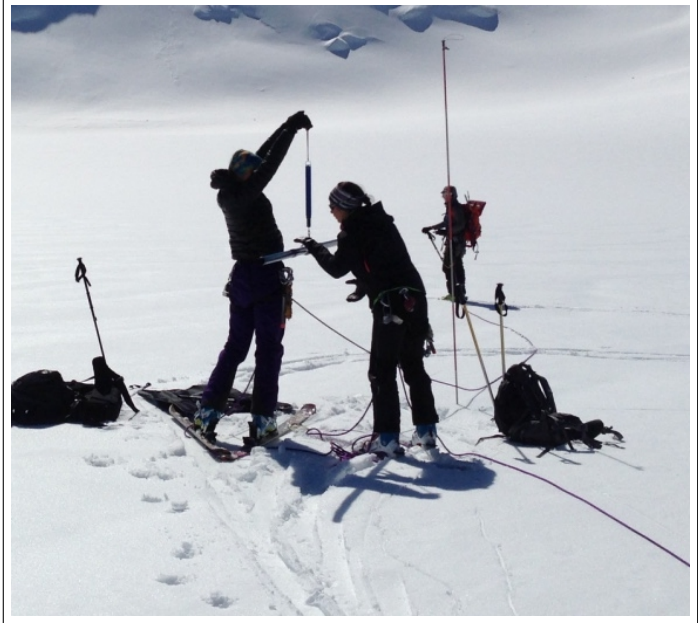


Figure 7: Estimated snow water equivalent (SWE) at measurement locations. Density was taken to be the average of three integrated, snowpit-derived densities for each glacier.



(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 8: Using the Federal Sampler to measure SWE

2.2 Federal Snow Sampler

References