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Appendix
Density

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

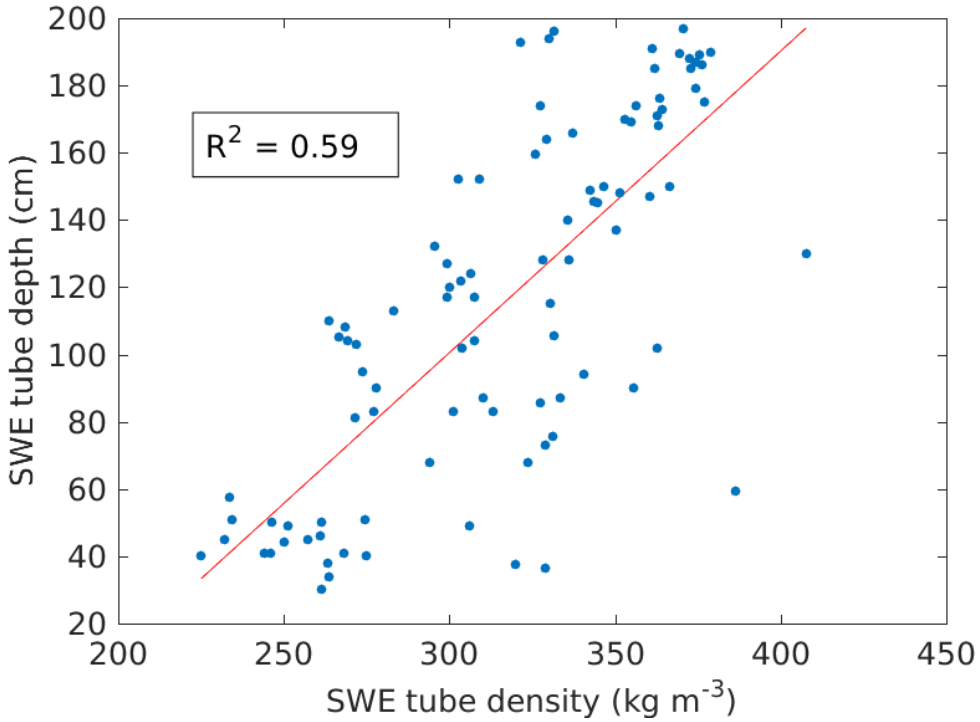

Figure 1: Relationship between measured density and snow depth for all Federal Sampler measurements.

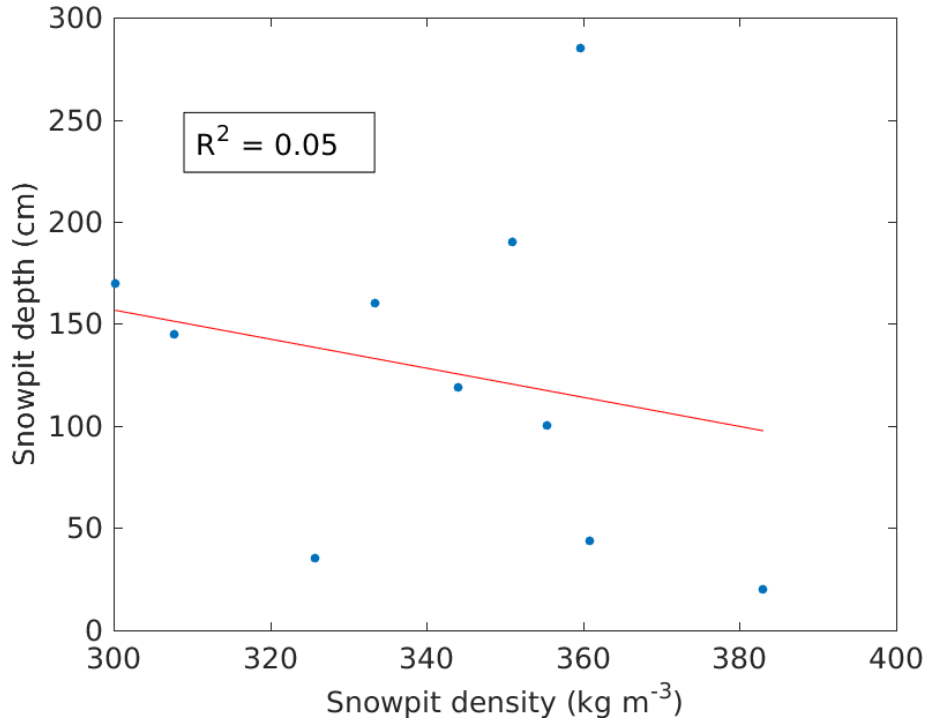

Figure 2: Relationship between measured density and snow depth for all snowpit locations.

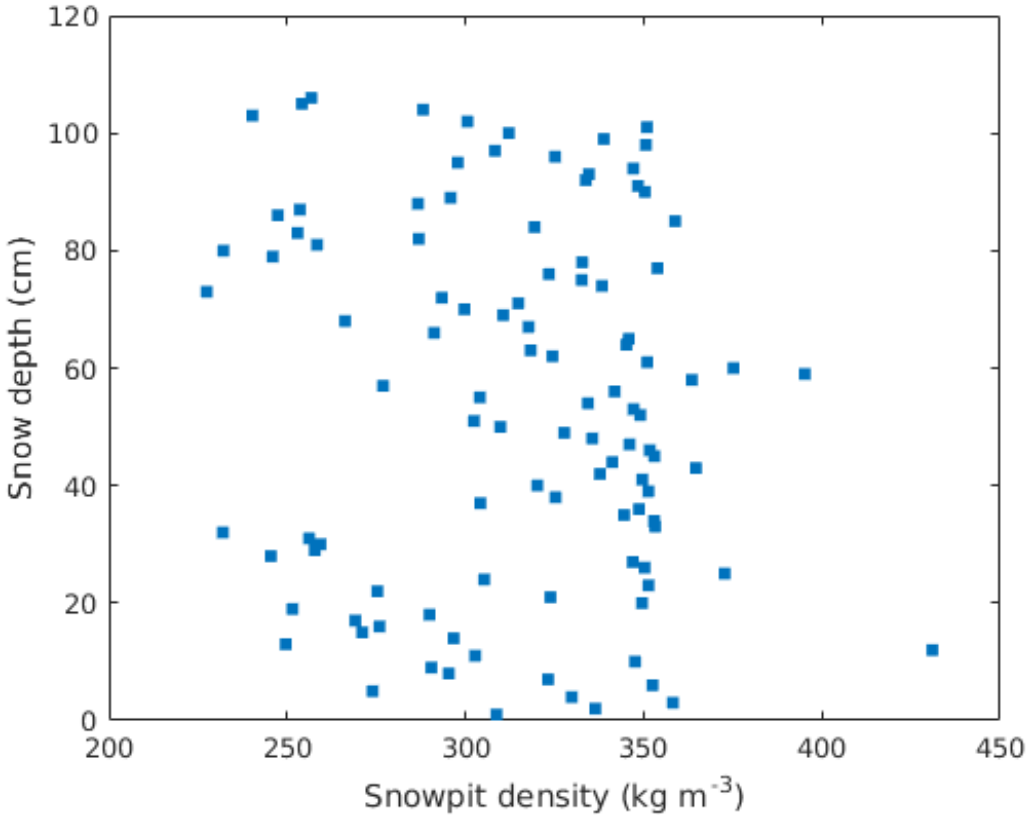

Figure 3: Plot of depth-detrended density and snow depth for all Federal Sampler measurements.

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 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

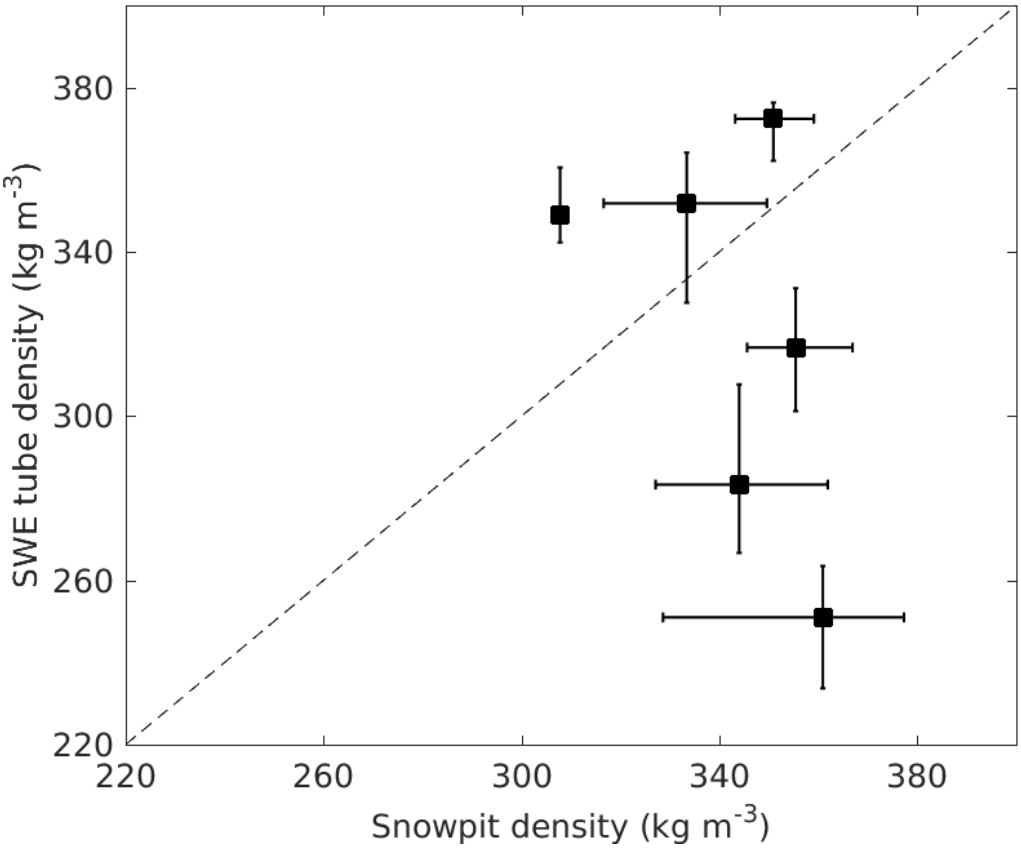

Figure 4: Comparison of density estimated using wedge cutters in a snow pit and Federal Sampler measurements for three study glacier (G04, G02, G13). Error bars are minimum and maximum values for each estimate as seen in Table 2 and 3.

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

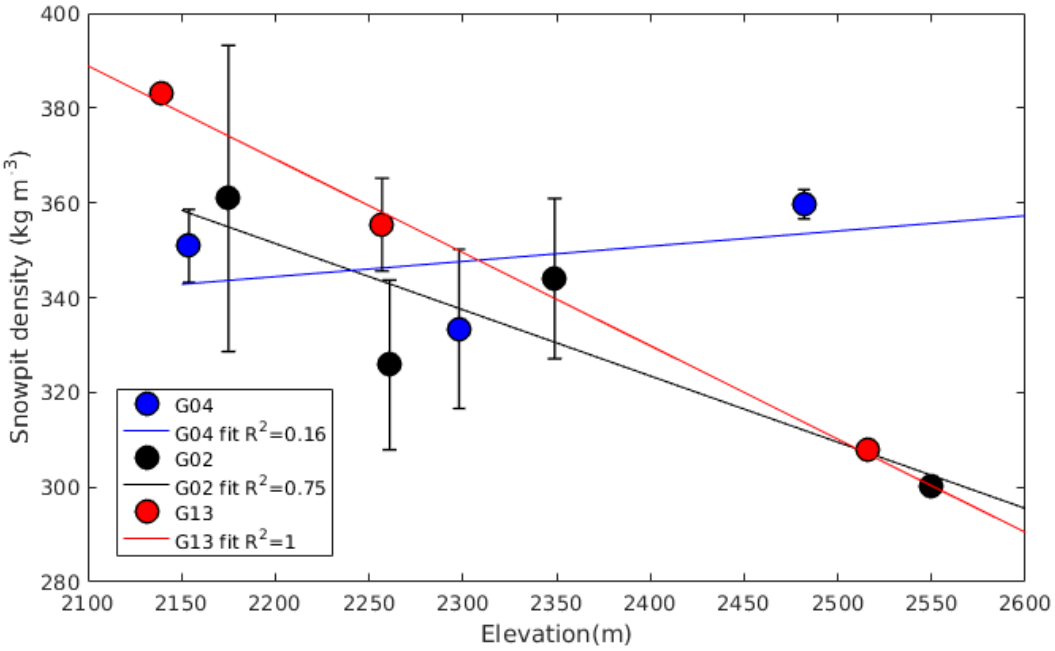

Figure 5: Relationship between snowpit-derived density and elevation for all study glaciers.

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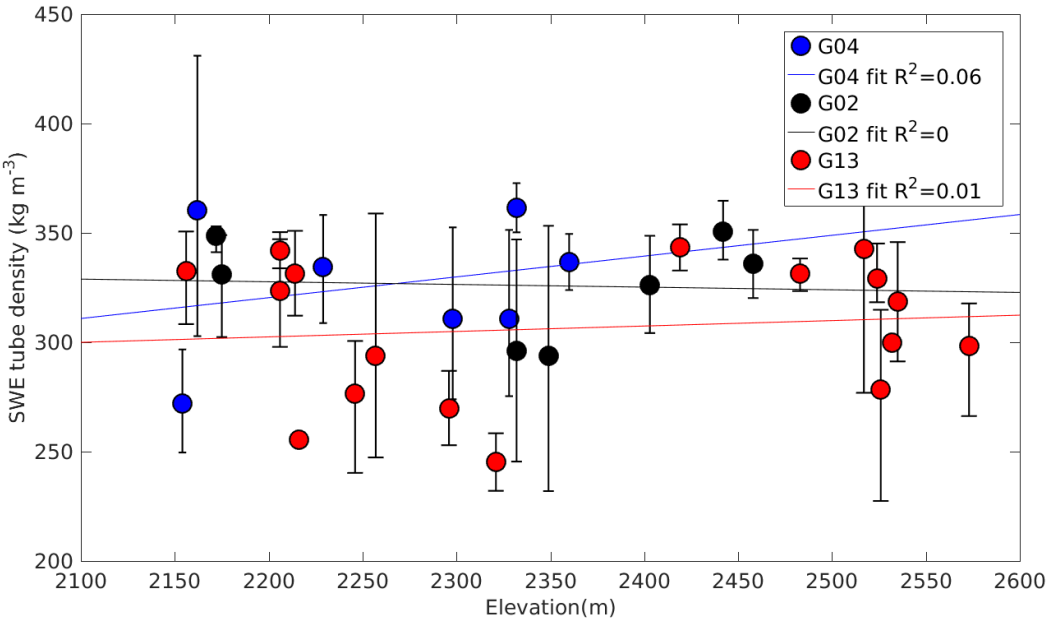

Figure 6: Relationship between Federal Sampler-derived density and elevation for all study glaciers.