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Appendix
Density

tube vs depth - correction, new SP vs tube elevation relation

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 also less than 10% of the mean density. For snowpit derived densities, the mean density is indistinguishable between glaciers within one standard deviation. This was not observed in densities derived from Federal Sampler measurements — Glacier 2 had the lowest mean density and Glacier 4 had the highest mean density. The mean of all Federal Sampler density values was likely skewed by the proportionally large number of measurements obtained on Glacier 13, and is thus indistinguishable from Glacier 13 mean density and different than both Glacier 4 and 2 mean density.

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) 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 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
G04	348	13	3	360	10	7
G02	333	26	4	275	18	7
G13	349	26	3	321	9	17
All	342	26	10	321	9	31

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_SWE	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 is has a larger spread of values when compared to snowpit densities across the study area. The % range is also larger than snowpit densities for many of the measurement locations.

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 ($R^2 = 0.55$), which indicates that there either snow does because more dense with depth (due to compaction) or that the instrument is biased. A plot of the depth-density relationship in snowpits can be seen

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.

Glacier	**n**	**Density (kg m^{-3})}**			**Range as**
		Mean	Minimum	Maximum	**% of mean (%)**
G04_Z3A_SWE	3	370	361	379	5
G04_USP	6	352	328	364	10
G04_Z2A_SWE	3	368	353	377	7
G04_LSP	7	372	362	376	4
G04_Z5B_SWE	2	359	356	363	2
G04_Z5A_SWE	3	328	321	332	3
G04_Z5C_SWE	2	332	328	336	2
G02_Z5C_SWE	2	273	264	283	7
G02_USP	7	283	267	308	14
G02_Z7A_SWE	3	342	326	369	13
G02_Z7B_SWE	2	306	303	309	2
G02_Z7C_SWE	3	300	295	306	4
G02_Z3B_SWE	3	243	232	251	8
G02_LSP	7	251	234	263	12
G13_ASP	8	349	342	361	5
G13_651	3	352	344	367	7
G13_652	2	343	330	356	8
G13_654	3	335	294	387	28
G13_655	1	340	340	340	0
G13_656	3	336	313	363	15
G13_657	3	304	263	329	22
G13_658	2	319	303	336	10
G13_659	3	314	304	332	9
G13_Z7C_SWE	2	274	272	277	2
G13_USP	6	317	301	331	9
G13_Z4C_SWE	1	408	408	408	0
G13_744	3	240	225	250	10
G13_Z3B_SWE	3	268	261	275	5
G13_Z4B_SWE	2	290	275	306	11
G13_Z5A_SWE	3	265	243	278	13
G13_Z5B_SWE	2	322	318	325	2

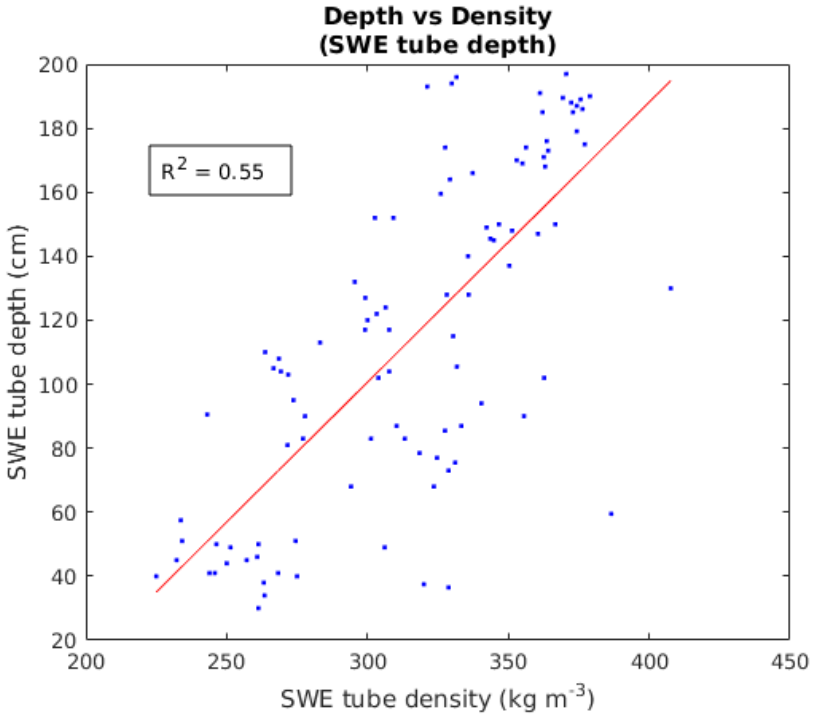

Figure 1: Relationship between measured density and snow depth for all Federal Sampler measurements.

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 seen in Figure 3. The overall range of Federal Sampler-derived densities is considerably larger than that of the snowpit-derived density values. A linear regression of the data gives a weak inverse relationship ($R^2 = 0.24$).

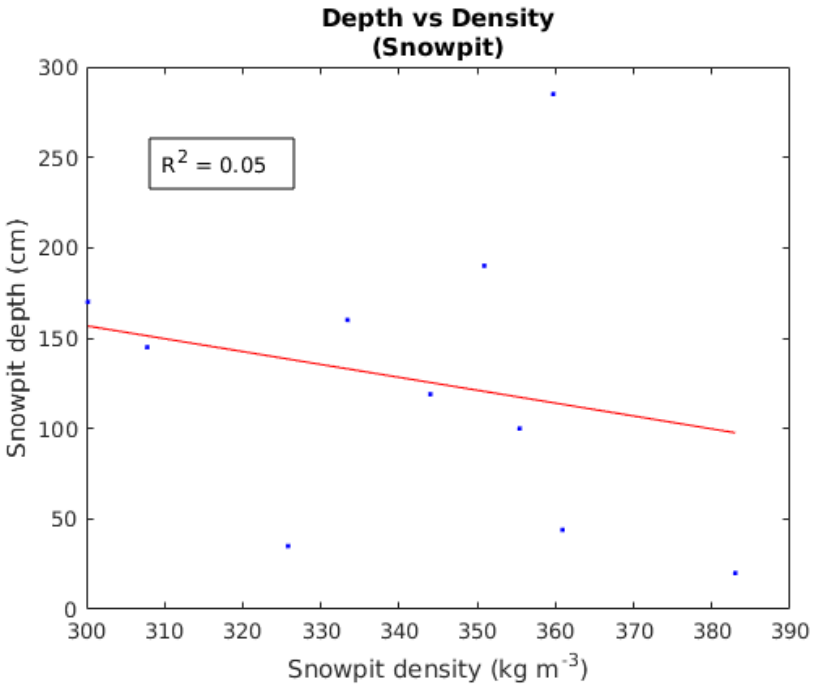

Figure 2: Relationship between measured density and snow depth for all snowpit locations.

1.

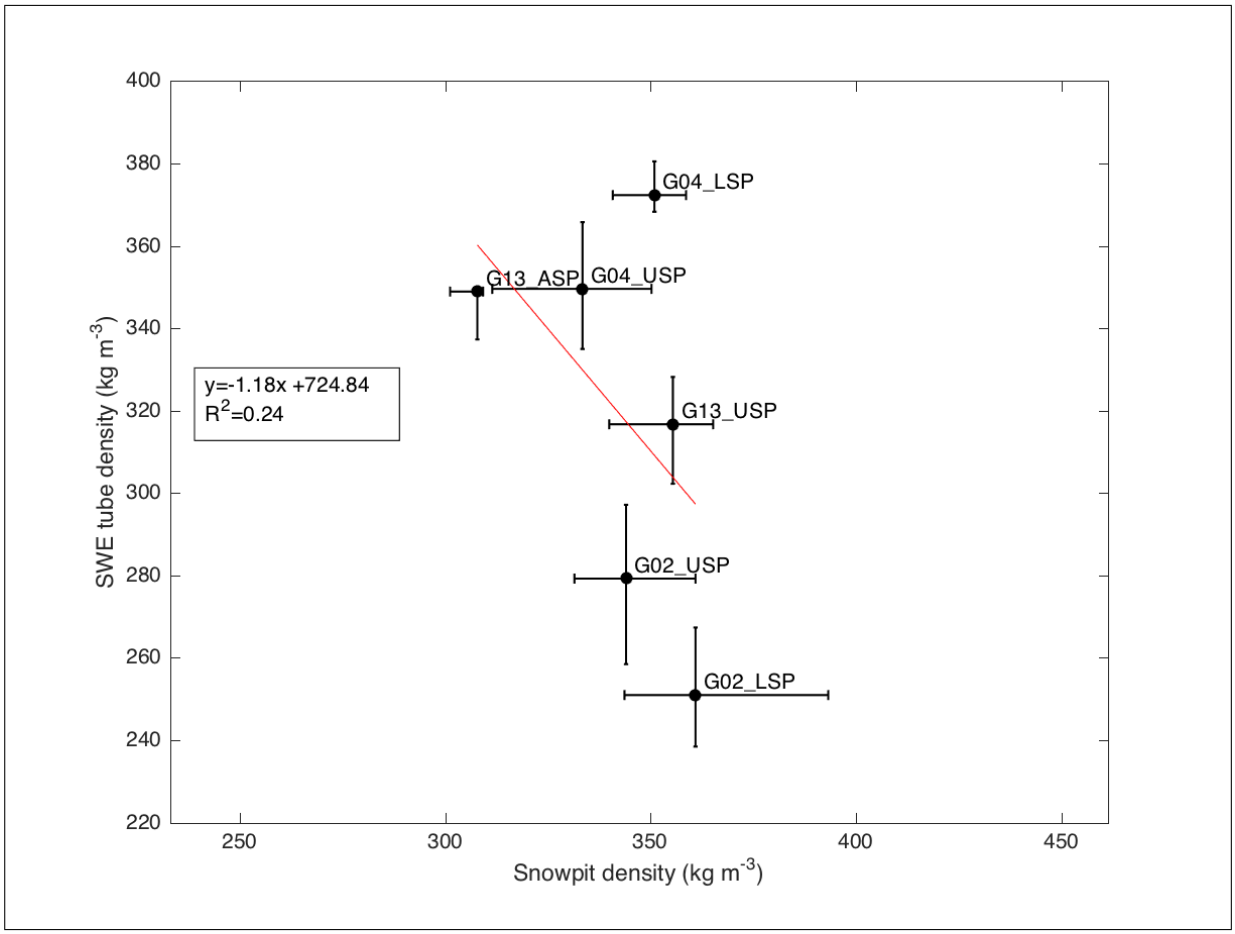

Figure 3: Comparison of density estimated using wedge cutters in a snow pit and Federal Sampler measurements for three study glacier (G04, G02, G13). Error bars are minimum and maximum values for each estimate as seen in Table 2 and 3.