Temporal Variability in Snow Accumulation and Density at Summit Camp, Greenland Ice Sheet

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SUPPLEMENTARY MATERIAL

SNOW BOARD MEASUREMENT PRECISION AND UNCERTAINTY

The measurement precisions and resulting uncertainties are listed in Table S1. The samples were weighed to the nearest 0.1 g and water the volume was measured to the nearest 5 mL prior to 9 November 2017, and to the nearest 1 mL thereafter. These precisions are less than 0.05% of the values for mass and less than 0.5% of volume (or 1.7% of volume prior to 9 November 2017).

The diameters of the core samplers are reported to the nearest 0.1 cm, with a 10.3 cm diameter core sampler used prior to 27 June 2017 and a 7.7 cm sampler used thereafter, resulting in uncertainties in core areas of 0.61 and 0.81 cm^2 or 0.98% and 1.30%, respectively. The uncertainty in the core area, therefore, dominates the measurement uncertainty in SWE. However, since a single measurement was made for each core sampler, this error is systematic for every sample using this core and, therefore, cancels when measuring changes in SWE.

Snow depth measurements are provided to the nearest 0.5 cm, giving an average uncertainty of ±1.2%, ranging from ±0.4 to ±3.1%. The combination of uncertainties in SWE and snow depth give uncertainties in density averaging ±0.01 g cm -3, or ±1.8%, with a maximum of ±3.4%.

The actual observational errors should be dominated by sampling errors, such as from difficulties in obtaining an intact sample or making depth measurements in strong winds and blowing snow conditions. I attempt to identify and mitigate these unconstrained errors in the next section.

Table *S1.* Measurement Values and Uncertainties

Measurement	**Values**	**Uncertainty**
Sample Mass	121.8 - 1063.7 g	±0.05 g
Sample Liquid Volume	123 - 1070 mL	±0.5 mL
Snow Depth	8 - 58 cm	±0.25 cm
Core Area	46.57; 83.32 cm^2	±0.61; ±0.81 cm^2
SWE (from mass)	2.62 - 18.40 cm w.e.	±1.0-1.3%
SWE (from volume)	2.6 - 18.1 cm w.e.	±1.0 -1.7%
Density	0.145 -0.524 g cm^{-3}	±1.2 - 3.4%

SNOW BOARD DATA QUALITY CONTROL

Measurements flagged as erroneous are listed, along with their mitigation approaches, in Table S2. Three outlier samples had differences between mass and volume derived SWE that exceeded three standard deviations (0.42 cm w.e.): 2 November 2017, 22 May 2018 and 27 November 2019, with differences of 0.53, -0.67 and 0.82 cm w.e., respectively.

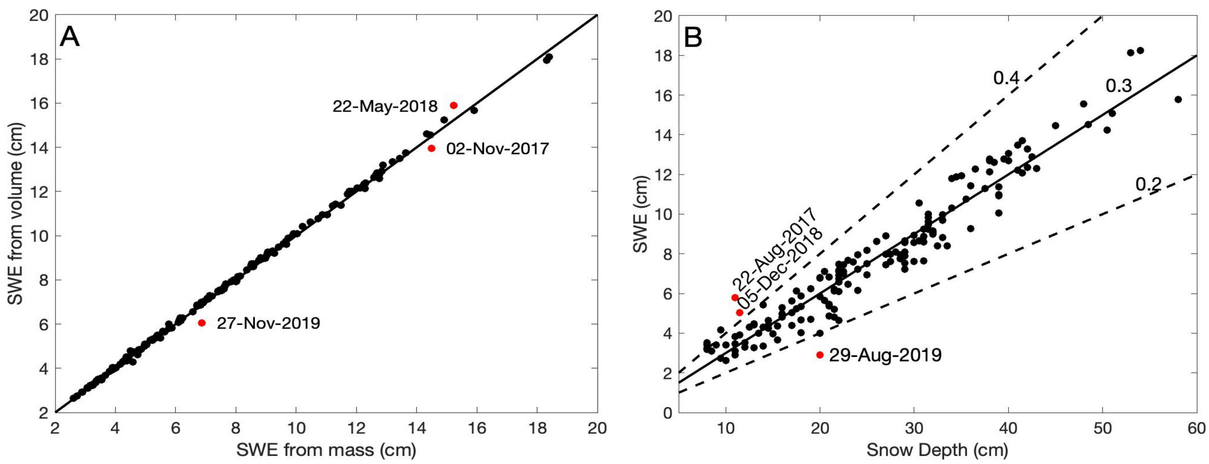


Fig. *S1*. (A) Comparison of SWE thickness measurements derived from samples mass and volume. Line is unity. Outliers shown in red with observation date. (B) Comparison of snow sample depth and SWE (average of mass and volume measurements). Lines show the equivalent densities in g cm^{-3}. Outliers shown in red with observation date.

For the 2 November 2017 measurement, the mass and volume-derived SWE measurements were respectively 2.20 and 1.83 cm w.e. larger than the previous measurement on 25 October, while the snow depth increased by 9.5 cm, giving respective accumulation densities of 0.231 and 0.192 g cm^{-3}. Since both estimates are within the range expected for new snow (Fausto et al., 2018), both are kept.

For the 22 May 2018 observation, the mass and volume-derived SWE measurements were respectively 0.89 and 1.3 cm w.e. larger than the previous measurement on 15 May, while the snow depth increased by 3 cm, giving respective accumulation densities of 0.300 and 0.430 g cm^{-3}. Since the later value is higher than typically measured for new accumulation (Fausto et al., 2018), I assume the volume-derived measurement was erroneous and use only the mass-derived estimate.

For the 27 November 2019 observation, the mass and volume-derived SWE measurements were respectively 1.24 and 0.41 cm larger than the previous measurement on 21 November, while the snow depth increased by 2.5 cm, giving respective accumulation densities of 0.496 and 0.164 g cm^{-3}. Thus, the mass-derived measurement is assumed erroneous and only the volume-derived estimate is used.

Another check of data quality is provided by comparing sample SWE and snow depth, which is related by the sample density, and which should be in the range 0.2 to 0.4 g cm^{-3} based on previous studies (e.g., Dibb and Fahnestock, 2004). Fig. 2b shows that, as expected, most values fall near the average of 0.2 to 0.4 g cm^{-3}. Anomalously high SWE and density values, reaching 0.42 g cm^{-3}, occur for snow depths less than 10 cm. These were recorded at the second sampling site between 20 June and 22 August 2017 during a period of anomalously low accumulation, when wind crust formation and densification are expected, which would comprise a larger fraction of the thinner sample. The density of thinner samples may also be more impacted by the presence of the plywood sample base, which would block exchange of vapor and heat with the underlying firn. During the summer, this may result in increased snow temperature and water content, and thus higher densities. Density values of sample depths less than 10 cm should therefore be viewed with caution.

Table 2. List of measurements suspected to be erroneous based on snow depth and density.

Observation Date	Measurement	Mitigation
22 August 2017 (old site)	Mass & Volume	Estimated from snow depth and new site density
22 May 2018	Volume	Removed, only mass used for SWE
5 December 2018 (new site)	Mass & Volume	Estimated from snow depth and new site density
27 June 2019	Snow Depth	Estimated from SWE and average density of neighboring measurements
29 August 2019	Mass, Volume & Snow Depth	Removed
24 October 2019 (new site)	Mass & Volume	Estimated from snow depth and new site density
27 November 2019	Mass	Removed, only volume used for SWE

Anomalously high-density values also occur at the site transition points, where concurrent measurements were made at each site to provide tie points for estimating cumulative SWE. In the first case, at the 22 August 2017 tie point, the density at the old site is the highest recorded (0.53 g cm^{-3}), and is 35% higher than the density at the new site. This corresponds to a large decrease in SWE while snow depth increased. A possible explanation is that the measurement was made in 22 knot winds with considerable blowing snow, making sampling difficult. Conversely, at the 5 December 2018 tie point, the density of 0.44 g cm^{-3} at the new site was almost 50% larger than the old. Finally, while neither of the densities obtained from the 24 October 2019 tie points are anomalous, measuring 0.258 and 0.341 g cm^{-3} for old and new samples, respectively, the value for the new site is 32% larger than at the old and similarly larger than the previous and next sample densities. Therefore, it is assumed that SWE values for the old site on 22 August 2017 and the new sites on 5 December 2018 and 24 October 2019 are erroneous. Since tie points are required for calculating cumulative SWE, the snow thickness value is used to replace the erroneous SWE measurement with that estimated from the density at the remaining tie point.

The lowest recorded density, 0.150 g cm^{-3} on 29 August 2019, resulted from a decrease in SWE that was 26% larger than the decrease in snow depth from the previous measurement. Since it's unclear whether the SWE or thickness measurement is in error, this measurement is assumed erroneous and removed from the time series.

Finally, an apparent erroneous snow depth measurement was recorded on 27 June 2019 (Fig. 1). Snow depth increased 4.5 cm from the prior measurement on 19 Jun and then dropped 3.5 cm by the next measurement on 3 July. This resulted in a density value ~15% less than the neighboring estimates. Based on this, and the anomalous increase and decrease, this measurement is replaced with an estimate of thickness obtained by dividing the SWE measurement by the average of the densities before and after this observation.

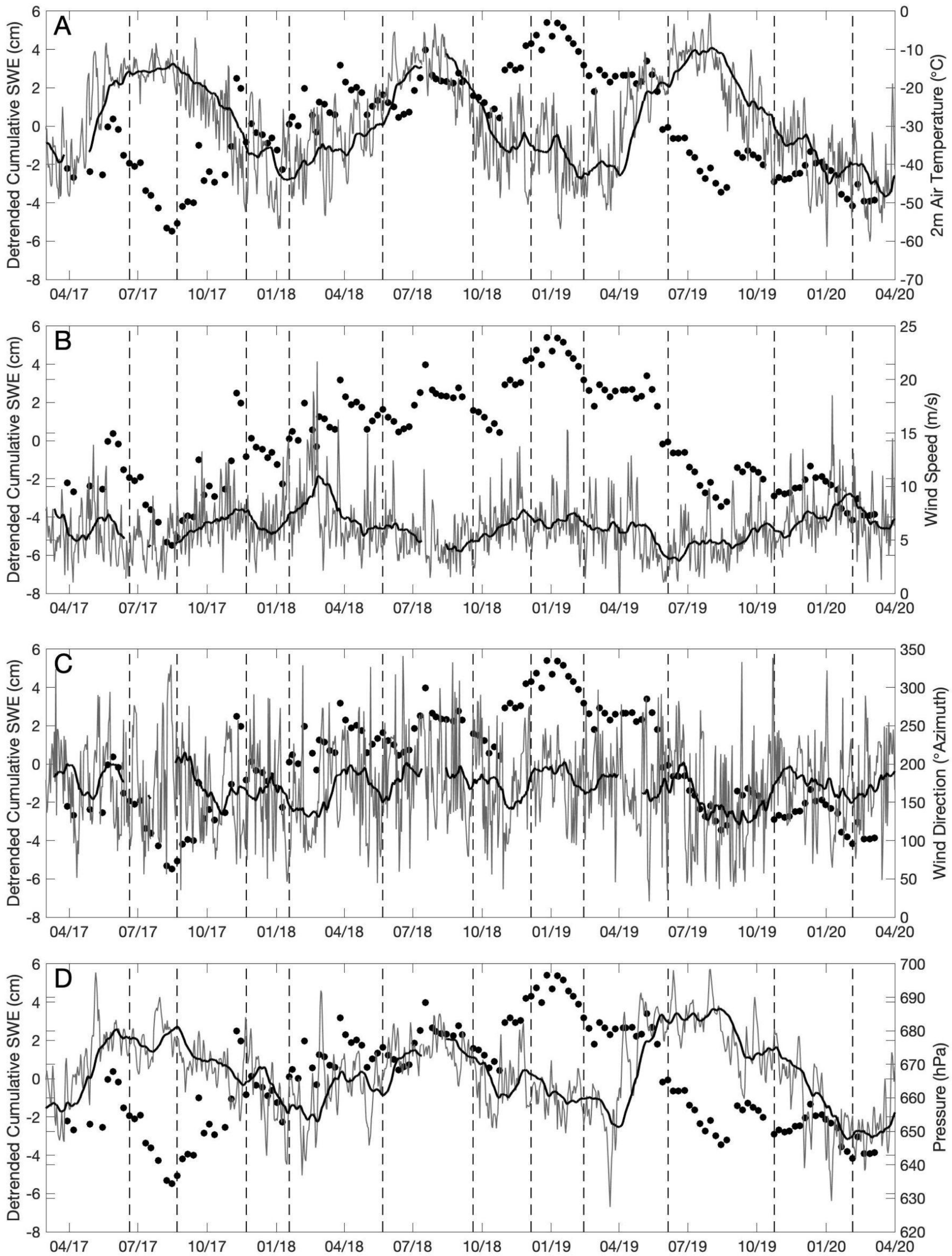
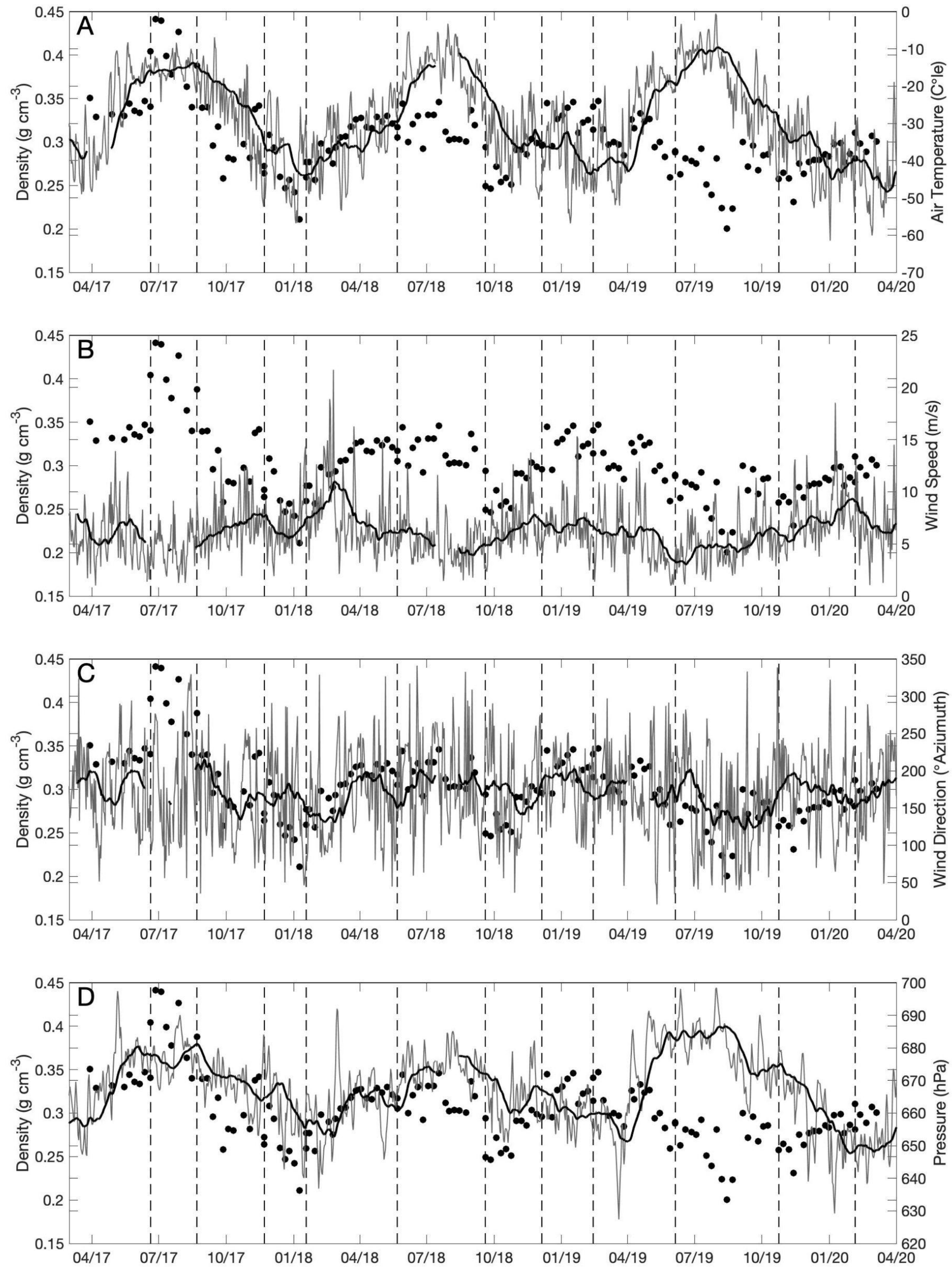


Fig. *S2.* (Points) Cumulative SWE from the Snowboard and (gray curve) (A) 2-meter air temperature, (B) wind speed, (C) wind direction, (D) barometric pressure. Black curve is the 30-day retrospective average.



94 **Fig. *S3*.** Same as Fig. S2 with points the sample density measured from thickness and SWE.