Uncertainty in Estimates of Net Seasonal Snow Accumulation on Glacier from In Situ Measurements

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Abstract

Accurately estimating the net seasonal snow accumulation (or "winter balance") on glaciers is central to assessing glacier health and predicting glacier runoff. However, measuring and modeling snow distribution is inherently difficult in mountainous terrain, resulting in high uncertainties in estimates of winter balance. Our work focuses on uncertainty attribution within the process of converting direct measurements of snow depth and density to estimates of winter balance. We collected more than 9000 direct measurements of snow depth across three glaciers in the St. Elias Mountains, Yukon, Canada in May 2016. Linear regression (LR) and simple kriging (SK), combined with cross correlation and Bayesian model averaging, are used to interpolate estimates of snow water equivalent (SWE) from snow depth and density measurements. Snow distribution patterns are found to differ considerably between glaciers, highlighting strong inter- and intra-basin variability. Elevation is found to be the dominant control of the spatial distribution of SWE, but the relationship varies considerably between glaciers. A simple parameterization of wind redistribution is also a small but statistically significant predictor of SWE. The SWE estimated for one study glacier has a short range parameter (90 m) and both LR and SK estimate a winter balance of ~0.6 m w.e. but are poor predictors of SWE at measurement locations. The other two glaciers have longer SWE range parameters (~450 m) and due to differences in extrapolation, SK estimates are more than 0.1 m w.e. (up to 40%) lower than LR estimates. By using a Monte Carlo method to quantify the effects of various sources of uncertainty, we find that the interpolation of estimated values of SWE is a larger source of uncertainty than the assignment of snow density or than the representation of the SWE value within a terrain model grid cell. For our study glaciers, the total winter balance uncertainty ranges from 0.03 (8%) to 0.15 (54%) m w.e. depending primarily on the interpolation method. Despite the challenges associated with accurately and precisely estimating winter balance, our results are consistent with the previously reported regional accumulation gradient.

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1. MOTIVATION

❄ Accurately estimating the net seasonal snow accumulation (or "winter balance") on glaciers is central to assessing glacier health and predicting runoff.

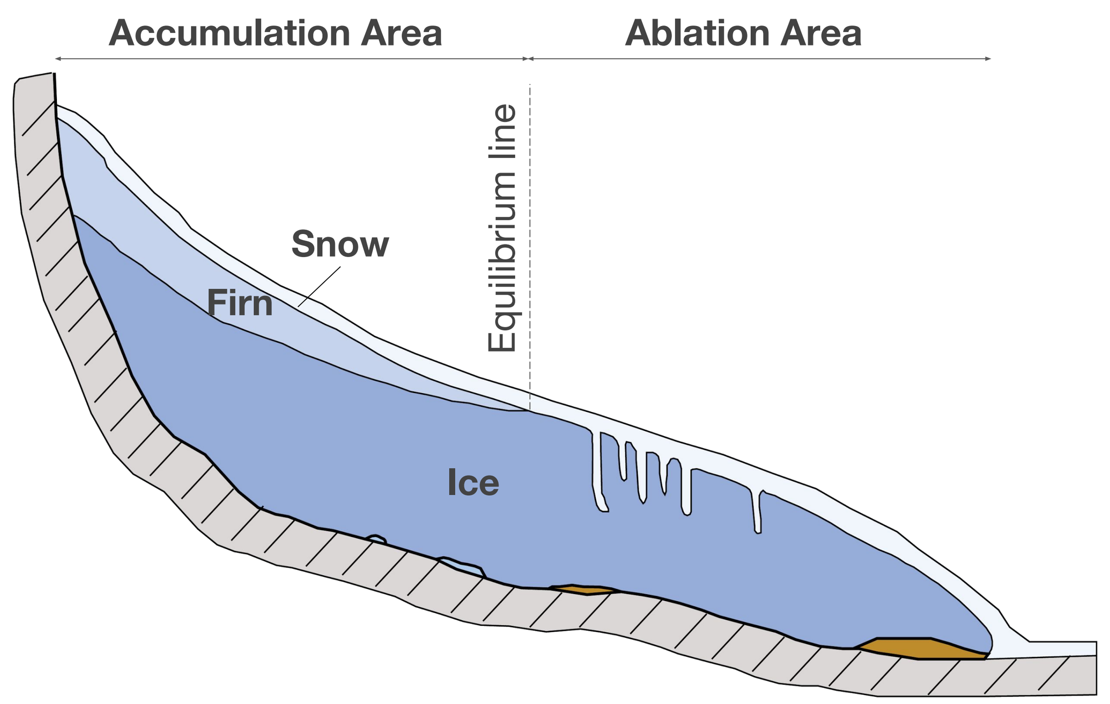
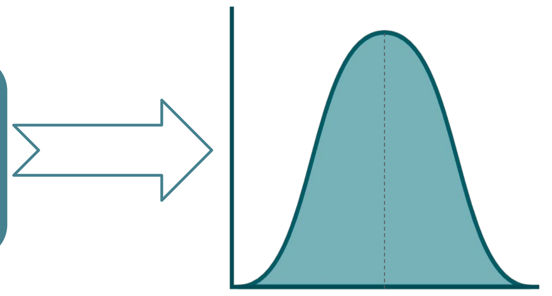


Fig. 1 Schematic of winter balance on an alpine glacier. Modified figure, original by Martin Funk

❄ Our **objective** is to quantify uncertainty in estimates of winter balance from three sources of uncertainty using a Monte Carlo method.

WINTER BALANCE = *DEPTH X DENSITY*

+0.7 m w.e.



3. ANALYSIS AND RESULTS

SNOW DEPTH

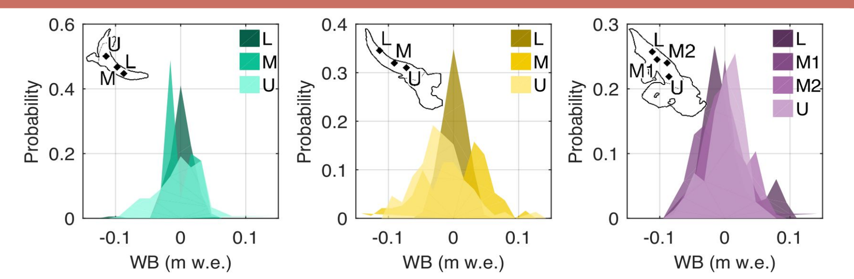
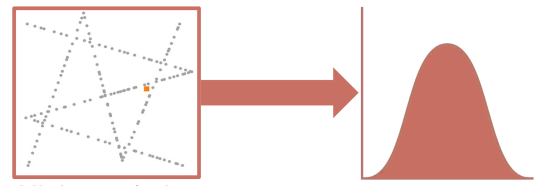


Fig. 3 Probability density functions of estimated winter-balance values for each zigzag survey in lower (L), middle (M) and upper (U) ablation areas (insets). See Fig. 12 for location of study glaciers.

❄ Gridcell-scale snow-depth distribution is similar across a glacier



SNOW DENSITY

❄ No correlation between density values derived from snow pit and Federal Sampler measurements

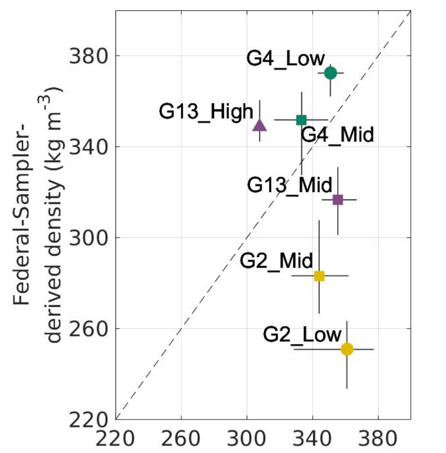
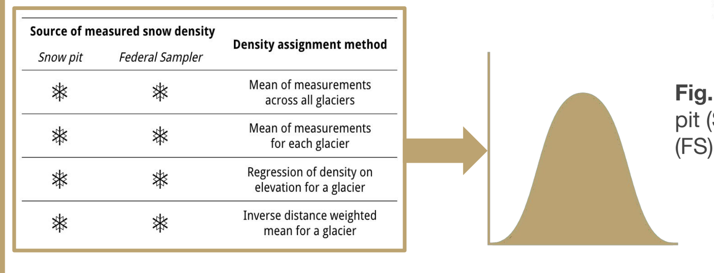


Fig. 4 Relation between co-located snow pit (SP)- and Federal Sampler (FS)-derived densities.



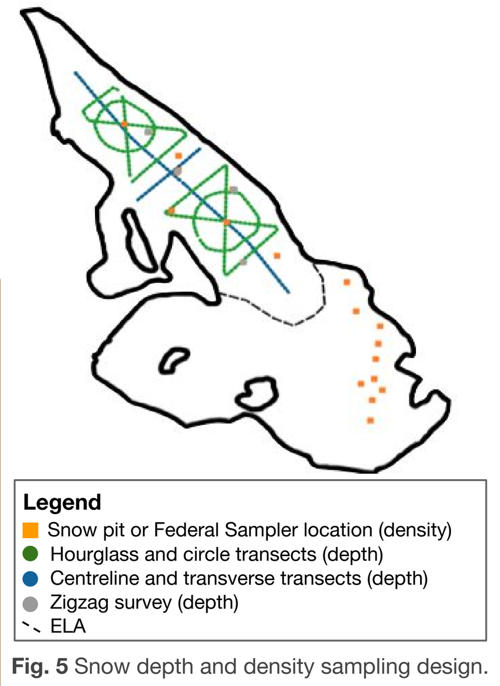


Fig. 5 Snow depth and density sampling design.

INTERPOLATION

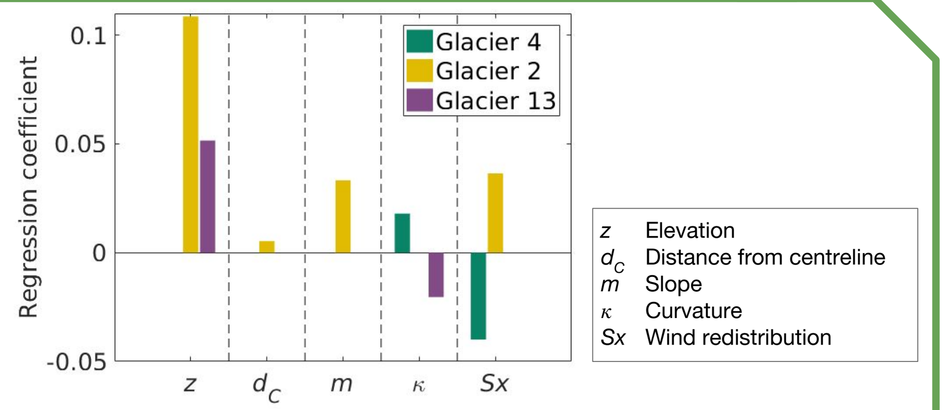


Fig. 6 Regression coefficients from linear regression of gridcell-scale winter balance on topographic parameters found with cross validation and model averaging (greater magnitude indicates great influence of topographic parameter).

❄ Controls on snow distribution differ between glaciers; elevation dominates & wind processes likely important
❄ Variance explained ranges from 7-58%

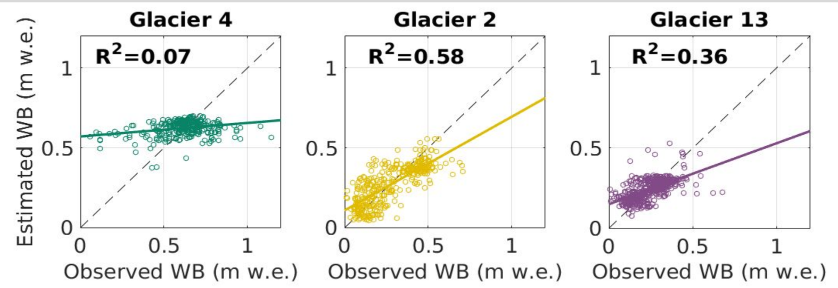


Fig. 7 Modeled versus observed winter balance (WB). Mean R^2 value is shown for each sub-plot with 1:1 line (dashed).

Fig. 8 A set of winter-balance distributions used to determine uncertainty in glacier-wide winter balance ($n \geq 1000$).

SPATIAL AVERAGE

WINTER BALANCE

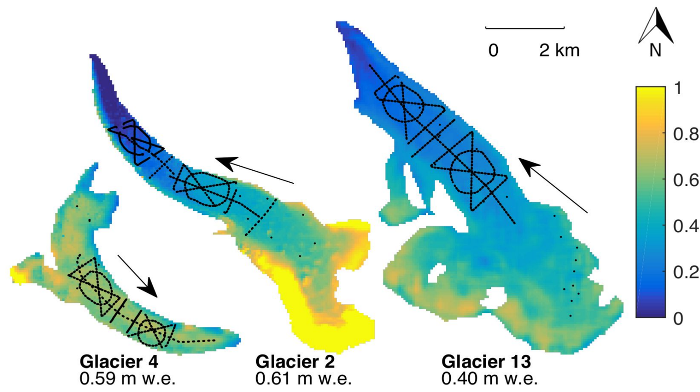


Fig. 9 Winter balance estimated with linear regression coefficients.

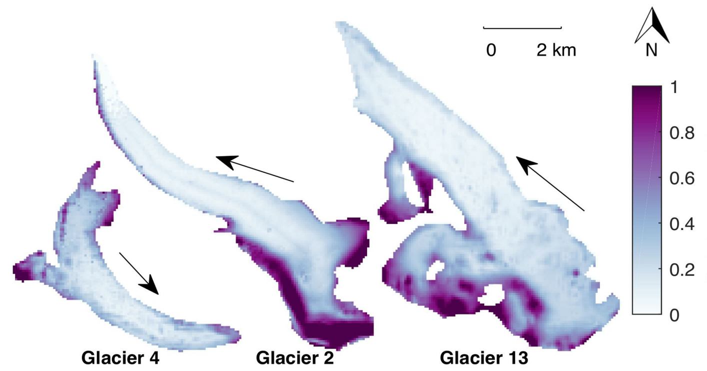


Fig. 10 Relative uncertainty in estimates of winter balance from three sources of uncertainty

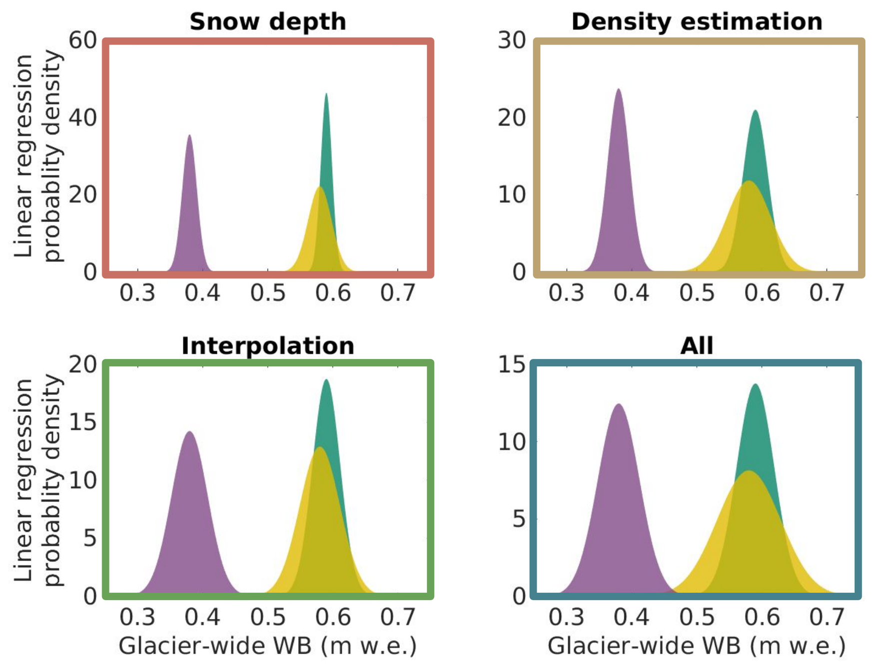


Fig. 11 Probability density functions of glacier-wide winter balance (WB) estimated with linear regression. Three sources of uncertainty are assessed to measure winter-balance precision.

❄ Interpolation is the largest assessed source of uncertainty in winter balance → use interpolated values with caution
❄ Uncertainty from snow depth variability and density estimation is low
❄ Total winter balance uncertainty ranges from 0.06 (10%) to 0.10 (20%) m w.e. on our study glaciers. This is a measure of the winter balance precision.

2. STUDY DESIGN

DATA COLLECTION
❄ We collected more than 9000 direct measurements of snow depth across three glaciers in the St. Elias Mountains, Yukon, Canada in May 2016.

INTERPOLATION
❄ We use linear regression (LR), combined with cross validation and model averaging, to interpolate estimates of snow water equivalent (SWE) from snow depth and density measurements.

UNCERTAINTY ANALYSIS
❄ We use a Monte Carlo method to quantify the effects of three sources of uncertainty: snow depth variability, density estimation, and data interpolation.

SCALES OF SNOW DEPTH VARIABILITY

Point scale | Gridcell scale | Basin scale | Regional scale

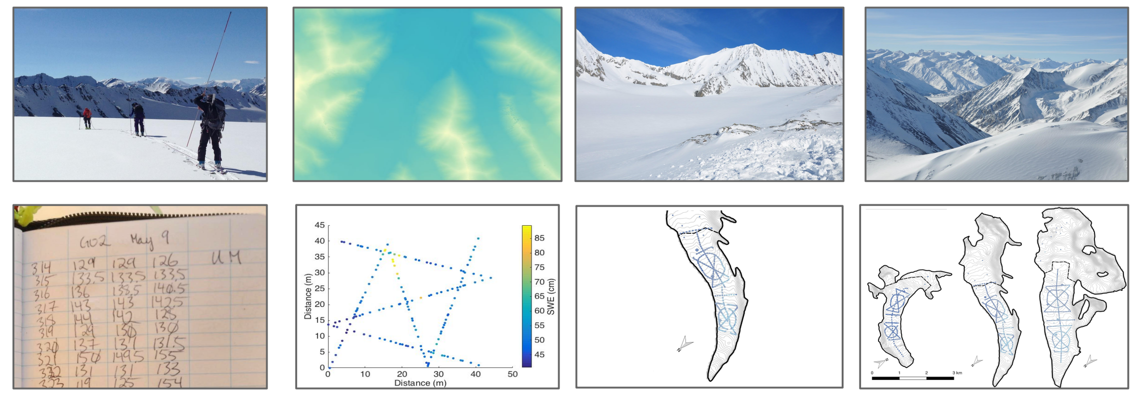
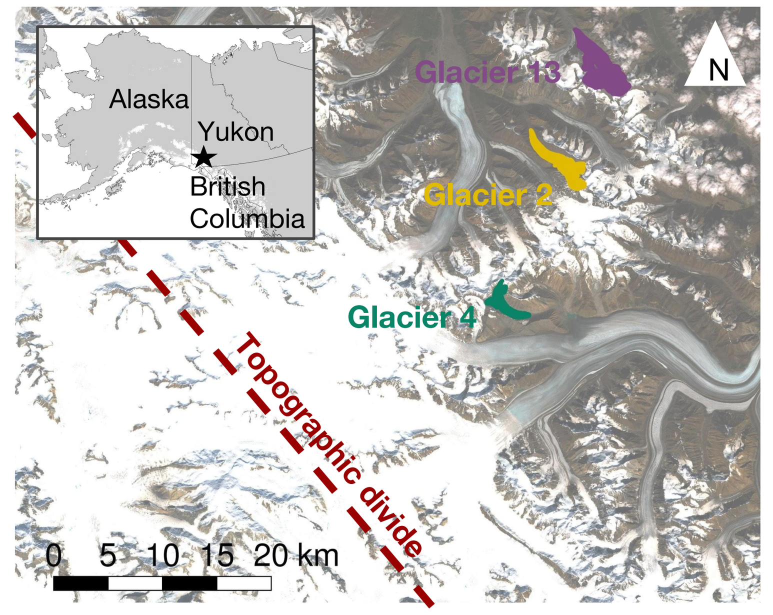
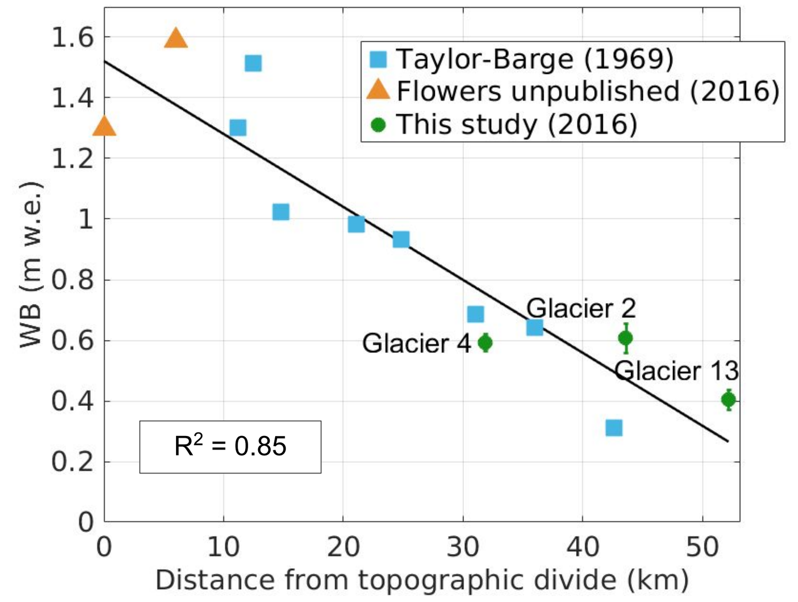


Fig. 2 Visual representation of the four scales of snow depth variability considered in this study and the sampling design used to obtain measurements at each scale

4. REGIONAL CONTEXT





❄ Our glacier-wide winter balance estimates are consistent with a regional accumulation gradient

Fig. 12 Regional context of winter-balance study. (Left) Location of study glaciers within the Donjek Range, St. Elias Mountains, Yukon, Canada. Dashed line indicates mountain-scale topographic divide. (Right) Winter balance of study glaciers along an accumulation gradient on the continental side of the St. Elias Mountains.

Taylor-Barge B (1969) *The summer climate of the St. Elias Mountain region.* Montreal: Arctic Institute of North America, Research Paper No. 53

5. KEY POINTS

METHODS
❄ We use linear regression to estimate winter balance from multiscale snow-depth and density measurements
❄ We use Monte Carlo analysis to quantify the contribution of three sources of uncertainty

RESULTS & IMPLICATIONS
❄ Quality of linear-regression fit differs considerably between glaciers
❄ Interpolation is a larger contributor to winter-balance uncertainty than snow depth variability or density estimation
❄ Basin coverage of measurements is more important than high resolution sampling

LIMITATIONS
❄ Few measurements in accumulation area and one year of data