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# Uncertainty in Estimates of Net Seasonal Snow Accumulation on Glaciers from *In Situ* Measurements

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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.

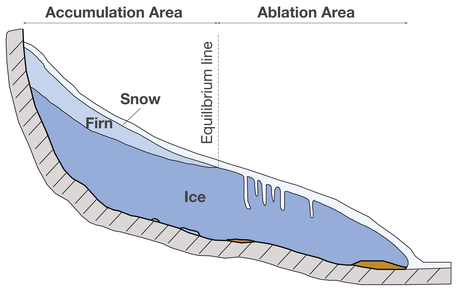
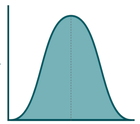



**Fig. 1** Schematic of winter balance on an alpine glacier. Modified figure, original by Martin Funk

❄ 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.**



**+0.7**
Winter balance (m w.e.)

## 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.

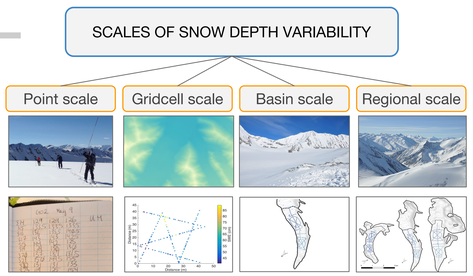



**Fig. 2** Visual representation of the four scales of snow depth variability considered in this study and the sampling design used to obtain measurements at each scale

## 3. ANALYSIS AND RESULTS

### SNOW DEPTH

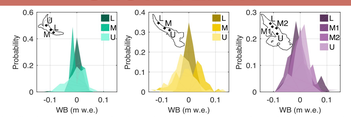
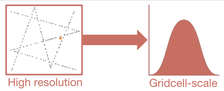



**Fig. 3** Probability density functions of estimated winter-balance values for each zigzag survey in lower (L), middle (M) and upper (U) ablation areas (insets). See Fig. 12 for location of study glaciers.

❄ 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

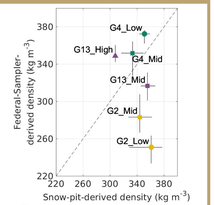
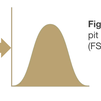
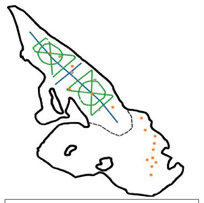



**Fig. 4** Relation between co-located snow pit (SP)- and Federal Sampler (FS)-derived densities.

| Source of measured snow density | | Density assignment method |
|---|---|---|
| *Snow pit* | *Federal Sampler* | |
| ❄ | ❄ | Mean of measurements across all glaciers |
| ❄ | ❄ | Mean of measurements for each glacier |
| ❄ | ❄ | Regression of density on elevation for a glacier |
| ❄ | ❄ | Inverse distance weighted mean for a glacier |



Methods to estimate density — Snow density



**Legend**
- Snow pit or Federal Sampler location (density)
- Hourglass and circle transects (depth)
- Centreline and transverse transects (depth)
- Zigzag survey (depth)
- ELA

**Fig. 5** Snow depth and density sampling design.

### INTERPOLATION

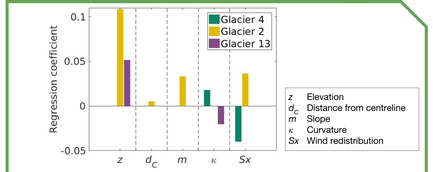



**Fig. 6** Regression coefficients from linear regression of gridcell-scale winter balance on topographic parameters found with cross validation and model averaging (greater magnitude indicates great influence of topographic parameter).

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

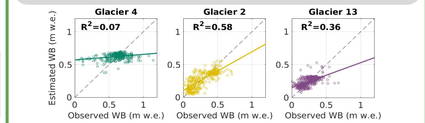



**Fig. 7** Modeled versus observed winter balance (WB). Mean $R^2$ value is shown for each sub-plot with 1:1 line (dashed).


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

**SPATIAL AVERAGE**

### WINTER BALANCE

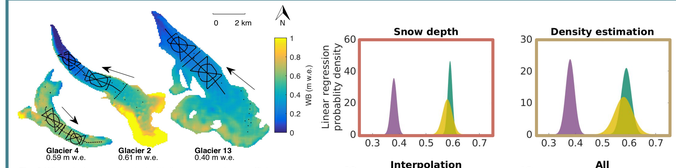



**Fig. 9** Winter balance estimated with linear regression coefficients.

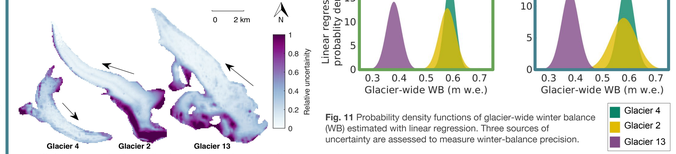
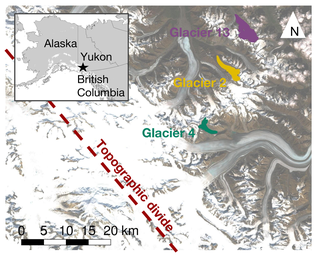



**Fig. 10** Relative uncertainty in estimates of winter balance from three sources of uncertainty

**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.

## 4. REGIONAL CONTEXT



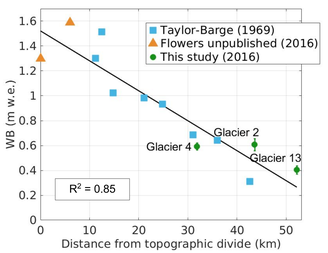




**Fig. 12** Regional context of winter-balance study. (Left) Location of study glaciers within the Donjek Range, St. Elias Mountains, Yukon, Canada. Dashed line indicates mountain-scale topographic divide. (Right) Winter balance of study glaciers along an accumulation gradient on the continental side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

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

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