Optimizing snow survey design for winter balance of alpine glaciers

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ABSTRACT.

INTRODUCTION

Estimates of basin-wide seasonal snow accumulation are critical for the availability and timing of surface runoff, especially in mountainous regions. On glaciers, the distribution of snow is half of the seasonally resolved mass balance, initializes ablation conditions and affects energy and mass exchange between the land and atmosphere (e.g. Hock, 2005; Réveillet and others, 2016). The net accumulation and ablation of snow on a glacier over a winter season is known as the winter surface mass balance, or "winter balance" (WB) (Cogley and others, 2011).

Snow distribution is spatially variable so properties, such as snow depth, must be measured over an extensive area. In addition, the period of peak accumulation is short so snow measurement must be completed quickly and efficiently. As a result, extensive and high-resolution measurements of snow depth are nearly impossible to obtain. Snow surveys must therefore be optimized in the extent and spacing of snow measurement locations, especially when labour-intensive methods like snow probing are used.

Optimal sampling schemes for snow probing are central to accurately estimating snow distribution and mass balance from *in situ* measurements. Measuring snow depth and travelling between measurement locations is both time consuming and can disturb the snow so care must be taken to choose a sampling scheme that avoids bias, allows for the greatest variability to be measured and minimizes distance travelled (Shea and Jamieson, 2010). There are a number of different designs that have been employed to obtain point measurements, including pure random (e.g. Elder and others, 1991), linear random (e.g. Shea and Jamieson, 2010), nested (e.g. Schweizer and others, 2008), gridded random (e.g. Bellaire and Schweizer, 2008; Elder and others, 2009; Bellaire and Schweizer, 2011) and gridded (e.g. Molotch and Bales, 2005; Kronholm and others, 2004; López-Moreno and others, 2011). Sampling designs that incorporate randomness are favourable because they limit sampling bias by varying sample spacing and direction. However, they are less efficient than sampling designs that incorporate grids. Grid-style sampling designs minimize travel distance but measurements are biased by regularly spaced intervals and linear orientations, which could result in an under representation of the snow variability (Kronholm and others, 2004) (check this ref??).

Snow surveys on glaciers are conducted to estimate winter balance and multi-year sampling programs are often established to monitor changes in winter balance with time. An optimized sampling design requires (1) a sampling pattern that captures spatial variability and minimizes travel distance and (2) knowledge of the minimum number of measurement locations needed to accurately estimate WB. The sampling pattern used for most winter balance programs does not included randomness and measurements are typically collected along the glacier midline. However, midline transects are known to underestimate winter balance so transverse transects are often added to improve the reliability of the sampling scheme (e.g. Walmsley, 2015). An hourglass with inscribed circle (personal communication from C. Parr, 2016) is an alternative sampling design that is attractive because it is able to capture changes in WB with elevation but is not biased along the midline and is easy to travel. To our knowledge, no study has yet compared the ability of these two sampling designs to capture spatial variability in WB. There are few studies that investigate the number of measurement locations needed to effectively sample WB distribution (c.f. Walmsley, 2015). Fountain and Vecchia (1999) investigated the number of measurement locations needed to estimate glacier mass balance, but snow is known to vary at much shorter length scales than melt, so an investigate into WB survey design is needed. (I think this paragraph need more citations...)

The goal of our work is to provide insight into ways to optimize WB sampling design by investigating various sampling patterns and number of measurement locations. The role of sub-gridcell variability in choosing a sampling design is investigated by varying the noise introduced to the assumed WB distribution. We examine three study glaciers with differing spatial patterns of WB to determine the applicability of our conclusions between glaciers.

STUDY SITE

We investigate sampling design for winter balance surveys on three unnamed glaciers in the Donjek Range of the St. Elias Mountains. Glacier 4, Glacier 2 and Glacier 13 (labelling adopted from Crompton and Flowers (2016)) are small alpine glaciers with simple geometries. The glaciers are generally oriented southeast-northwest in valleys with steep walls. A detailed analysis of estimating winter balance on these three glaciers is presented in Pulwicki and others (2017).

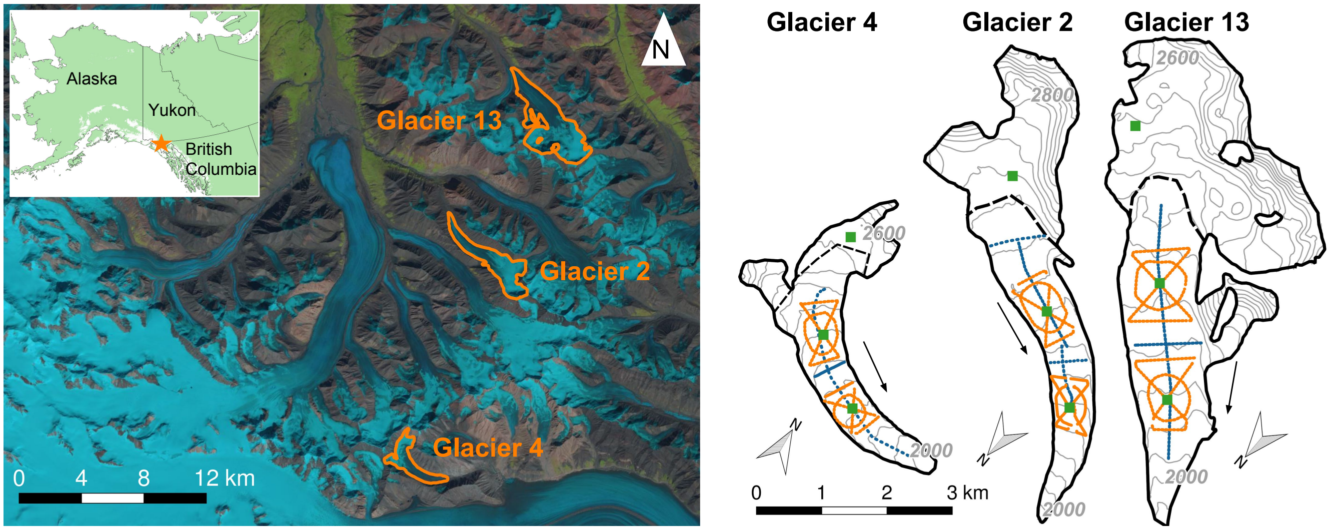

Fig. 1. Study area location and sampling design for Glaciers 4, 2 and 13. (Left) Study region in the Donjek Range of the St. Elias Mountains of Yukon, Canada (inset). Imagery from Landsat8 (29 August 2013, data available from the U.S. Geological Survey). (Right) Details of the snow-survey sampling design, with centreline and transverse transects (blue dots), hourglass and circle designs (orange dots) and locations of snow density measurements (green squares). Arrows indicate ice-flow directions. Approximate location of ELA on each glacier is shown as a black dashed line.

METHODS

Computer model WB

The computer model portion of our work uses a prescribed WB distribution to test possible sampling designs. Gridcell values of WB that fall within each sampling design are extracted from the prescribed WB distribution and then used to estimate a new WB distribution. The WB distribution derived from various sampling designs is then directly compared to the prescribed WB distribution to estimate spatially resolved error. For each study glacier, the prescribed WB distribution is equivalent to the distribution presented in Pulwicki and others (2017). The prescribed WB was estimated using a linear regression fitted to WB data on each glacier, which were obtained from direct measurements of snow depth and density.

We investigate numerous sampling designs. Sampling designs are based on a sampling pattern and number of measurement locations. We chose various sampling patterns that could be used for a snow survey (Figure 2). Midline (M) and midline with transverse transects (M+T) are the most common survey designs used in WB studies (e.g. **?**Machguth and others, 2006). The midline survey aims to capture changes in WB with elevation and transverse transects provide observation of lateral variations in WB. Hourglass (H) and inscribed circle (C) allow for sampling in multiple directions and are easy to travel (personal communication from C. Parr, 2016). We use hourglass and circle patterns separately and combined. Finally, a random pattern (R) of measurement locations is used. All sampling patterns are restricted to the ablation area, where terrain is accessible and direct measurements of snow depth are easy to obtain. For comparison, we also present results from a random sample pattern that spans the entire glacier, which is known to be the most accurate sampling pattern (ref?). For all sampling patterns we estimate WB using n measurement locations, where n ranges from a minimum of eight (constrained by using all seven topographic parameters for interpolation) to a maximum determined by the number of gridcells within a sampling pattern. The measurement locations are evenly distributed within the sampling pattern.

To simulate the process of measuring WB from the assumed distribution, we first obtain WB values from the prescribed WB distribution at selected measurement locations for each sampling pattern. Then, we add a low or high amount of noise to the WB data. Low noise is defined by a normal distribution that is centred at zero and has a standard deviation equal to the mean standard deviation of WB data from a series of high-density gridcell-scale surveys on each glacier (see Pulwicki and others, 2017, for details). High noise is defined in the same way as low noise but the standard deviation of the normal distribution is five times larger. The standard deviation of low noise is ∼5% of the glacier-wide WB, while high noise is ∼25% of the glacier-wide WB. A random number from the high or low noise distribution is chosen for each datum and added to the value of WB.

A linear regression is then used to interpolate the modified values of WB for each glacier. WB is regressed on topographic parameters that have been derived from a SPOT-5 digital elevation model (see Pulwicki and others, 2017, for details). The topographic parameters include elevation, slope, aspect, distance from glacier centreline, "northness", curvature and a wind redistribution parameter. The linear regression calculates regression coefficients that minimize the sum of squares between estimated WB and WB input data. The resulting regression coefficients are then applied to the topographic parameters associated with each gridcell to obtain distributed WB.

RMSE is calculated by taking the square root of the mean difference between all gridcells in the prescribed WB distribution and the WB distribution derived with the sampling design.

The process of adding random noise to sampled WB values and fitting a regression to estimate WB is repeated 100 times. Each repetition uses a different set of random noise resulting in a range of WB and RMSE values. A mean WB and RMSE from all runs is then calculated.

Measured values of WB

Measured values of WB are found by obtaining direct measurement of snow depth and density. Snow depth was measured using a 3.2 m graduated aluminium avalanche probe. Measurement locations followed linear and curvilinear transects, which were similar between study glaciers, with a sample spacing of 10–60 m. Spacing was constrained by protocols for safe glacier travel. Each observer made 3–4 depth measurements within ∼1 m at each transect measurement location. We restricted snow-depth sampling to the ablation area, where the clear districting between snow and ice ensure that only snow from the current accumulation season is measured. See Pulwicki and others (2017) for details on measuring snow depth along transects. In total, we collected more than 9000 snow-depth measurements throughout the study area. Snow density was measured using a wedge cutter in three snow pits that spanned a large portion of the elevation on each glacier. A mean density was then calculated for each glacier and this value was use dot convert snow depth at all measurement locations to values of point-scale WB. All point-scale WB values located within a common gridcell are averaged to obtain values of gridcell-scale WB, which are then used in the linear regression.

The process of estimating distributed WB using various sampling designs is then applied to measured values of WB. Sampling designs are derived from all measurement locations for each study glacier (Figure 1). As above, midline, midline with transects, circle, hourglass, circle with hourglass and random sampling patterns are used. All possible values of n are investigated, but the number of measurement locations is more limited when WB data are used. One hundred iterations of adding random noise, both low and high, and then executing a linear regression to estimate distributed WB are then completed, as above.

RESULTS AND DISCUSSION

CONCLUSION

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REFERENCES

Bellaire S and Schweizer J (2008) Deriving spatial stability variations from penetration resistance measurements. In *Proceedings ISSW*, 188–194

Bellaire S and Schweizer J (2011) Measuring spatial variations of weak layer and slab properties with regard to snow slope stability. *Cold Regions Science and Technology*, **65**(2), 234–241 (doi: 10.1016/j.coldregions.2010.08.013)

Cogley J, Hock R, Rasmussen L, Arendt A, Bauder A, Braithwaite R, Jansson P, Kaser G, Möller M, Nicholson L and others (2011) *Glossary of glacier mass balance and related terms*. UNESCO-IHP, Paris

Crompton JW and Flowers GE (2016) Correlations of suspended sediment size with bedrock lithology and glacier dynamics. *Annals of Glaciology*, **57**(72), 1–9 (doi: 10.1017/aog.2016.6)

Elder K, Dozier J and Michaelsen J (1991) Snow accumulation and distribution in an alpine watershed. *Water Resources Research*, **27**(7), 1541–1552 (doi: 10.1029/91WR00506)

Elder K, Cline D, Liston GE and Armstrong R (2009) NASA Cold Land Processes Experiment (CLPX 2002/03): Field measurements of snowpack properties and soil moisture. *Journal of Hydrometeorology*, **10**(1), 320–329 (doi: 10.1175/2008JHM877.1)

Fountain AG and Vecchia A (1999) How many stakes are required to measure the mass balance of a glacier? *Geografiska Annaler: Series A, Physical Geography*, **81**(4), 563–573 (doi: 10.1111/1468-0459.00084)

Hock R (2005) Glacier melt: a review of processes and their modelling. *Progress in Physical Geography*, **29**(3), 362–391 (doi: 10.1191/0309133305pp453ra)

Kronholm K, Schneebeli M and Schweizer J (2004) Spatial variability of micropenetration resistance in snow layers on a small slope. *Annals of Glaciology*, **38**(1), 202–208 (doi: 10.3189/172756404781815257)

López-Moreno JI, Fassnacht S, Beguería S and Latron J (2011) Variability of snow depth at the plot scale: implications for mean depth estimation and sampling strategies. *The Cryosphere*, **5**(3), 617–629 (doi: 10.5194/tc-5-617-2011)

Machguth H, Eisen O, Paul F and Hoelzle M (2006) Strong spatial variability of snow accumulation observed with helicopter-borne GPR on two adjacent alpine glaciers. *Geophysical Research Letters*, **33**(13), 1–5 (doi: 10.1029/2006GL026576)

Molotch NP and Bales RC (2005) Scaling snow observations from the point to the grid element: Implications for observation network design. *Water Resources Research*, **41**(11) (doi: 10.1029/2005WR004229)

Pulwicki A, Flowers G and Radić V (2017) Uncertainties in estimating winter balance from direct measurements of snow depth and density on alpine glaciers. *Journal of Glaciology*, (in submission)

Réveillet M, Vincent C, Six D and Rabatel A (2016) Which empirical model is best suited to simulate glacier mass balances? *Journal of Glaciology*, **63**(237), 1–16 (doi: 10.1017/jog.2016.110)

Schweizer J, Heilig A, Bellaire S and Fierz C (2008) Variations in snow surface properties at the snowpack-depth, the slope and the basin scale. *Journal of Glaciology*, **54**(188), 846–856 (doi: 10.3189/002214308787780058)

Shea C and Jamieson B (2010) Star: an efficient snow point-sampling method. *Annals of Glaciology*, **51**(54), 64–72 (doi: 10.3189/172756410791386463)

Walmsley APU (2015) *Long-term observations of snow spatial distributions at Hellstugubreen and Gråsubreen, Norway.* Master's thesis