I. Introduction

Objective: (1) Discuss choices made when moving from measurement to accumulation and (2) show how system variability and our choices interact to create uncertainty in our estimate of accumulation

- snow distribution in alpine regions is not uniform or static, but rather highly variable and influenced by diverse and dynamic processes operating on multiple spatial and temporal scales -> topographic effects (crevasses, surface topo, elevation aspect, precip grad across range), snow drift and preferential deposition - [22] note that studies of snow water equivalent (SWE) that have been conducted in alpine environments vary considerably in the extent and spacing of their measurements. - Snow accumulation is spatially variable on point scales (<5 m), hillslope scales (1âĂŞ100 m), basin scales (100âĂŞ10,000 m) and regional scales (10âĂŞ1000 km) [22]. -Point-scale variability is generally associated with surface roughness effects and the presence of small obstacles. -> take three measures Many parts of a glacier though are characterized by a relatively smooth surface, with roughness lengths on the order of centimeters [57]. In these areas, point-scale variability of snow depth is low. However, in heavily crevassed regions, point-scale variability can be large and thus exert a dominant control on snow distribution in the area [82]. -Hillslope-scale variability is caused by variations in the surface topography of the glacier. The curvature and slope of the surface as well as the presence of local ridges or depressions can affect where snow is located [15, 115]. Avalanching can also redistribute snow, especially on the margins of a glacier [17, 89]. Watershed-scale variability results mainly from the effects of changing elevation and aspect on atmopsheric conditions [22]. In particular, orographic lifting and shading can result in higher elevation and north-facing areas of the glacier having more snow than other areas [89, 115]. Gradients in temperature from elevation changes also affect the freezing level, which determines whether precipitation falls as snow or rain [17]. For example, [77] found a strong influence of elevation in determining accumulation on Findel Glacier in Switzerland. Regional variability occurs when areas within a mountain range have differing amounts of snow. Often, this results from horizontal precipitation gradients and rain shadows forming on the lee side of topographic divides. Areas with large, steep mountains are especially affected by these processes.

derived accumulation estimated winter surface mass balance distributed snow water equivalent

II. Methods

study area overview

i. Field Methods

Snow depth (d) and density (ρ) measurements are needed to estimate accumulation (SWE $= d \times \rho$). Snow depth is generally accepted to be more variable than density [38, 22] (cf??) so sampling designs are chosen to capture depth variability at multiple spatial scales and to account for known variation. Sampling designs need to avoids bias, allow for the greatest variability to be measured, and minimize distance travelled [110].

Snow depth was measured using an aluminium avalanche probe (3.2 m) at three glaciers, along linear and curvilinear transects, and with multiple measurements at each location to account for range-, basin-, and point-scale variability, respectively. The precipitation gradient in the St. Elias Mounatins, Yukon (Taylor-Barge, 1969) is sampled by selecting Glaciers 4, 2, and 13 (naming adopted from ??), which are located increasing far from the head of the Kaskawalsh Glacier. Centreline and transverse transects, with sample spacing of $10-60$ m, are selected to capture established correlation between elevation and accumulation as well as accumulation differences between ice-marginal and center accumulation [125]. An hourglass and circle design, which allows for sampling in all directions and is easy to travel (Parr, C., 2016 personal communication), with equivalent sample spacing was also implemented. At each measurement location, we took $3-4$ depth measurements, resulting in more than 9,000 snow depth measurements throughout the study area.

Our sampling campaign involved four people and occurred between May 5 and 15, 2015. Measurement locations were predefined with a 60 m spacing along transects. While roped-up for glacier travel, the lead person used a handheld GPS (Garmin GPSMAP 64s) to navigate as close to the predefined locations as possible. The remaining three people took $3-4$ snow depth measurements within $\sim$1 m of each other. Each observer was approximately 10 m behind the person ahead of them along the transect line. Location of each depth measurement was approximated based on the recorded location of the first person.

When estimating accumulation, snow depth variability at scales less than the grid-size of satellite derived elevation models is classified as being caused by random effects that are assumed to be unbiased and unpredictable [127]. A linear-random sampling design ('zigzag') was implemented to capture grid-scale variability [110].

Snow density was measured using a wedge cutter in three snowpits, as well as using a Federal Snow Sampler at $7-19$ locations at each glacier. We collected a continuous density profile by inserting a $5 \times 5 \times 10$ cm (250 cm^3) wedge-shaped cutter in 5 cm increments to extract snow samples and the weighted the sampled with a spring scale (**??**). While snow pits provide the most accurate measure of snow density, digging and sampling a snow pit is time and labour intensive. Therefore, a Federal Snow Sampler (FS) (**?**), which measures bulk SWE, was used to augment the spatial extent of density measurements. Three measurements were taken at each sampling location and eight FS measurements were co-located with each snow pit measurement.

ii. Analysis Methods

Estimating accumulation from measured values of snow depth and density requires a number of processing steps that reduces data. First, measured density is interpolated to estimate SWE. We chose four separate methods to interpolate density: (1) mean density for entire range, (2) mean density for each glacier, (3) density linear regression with elevation and (4) inverse-distance weighted density. Snow pit and Federal Sampler measures were used independently for each method – due to poor correlation between data sets (see Results) – so eight density interpolation options exist in this study.

Second, averages of data along SPOT-5 DEM-aligned grid (40×40 km) (Korona et al., 2009) are computed.

III. Discussion

[77] conducted an airborne GRP survey of two adjacent glaciers in Switzerland. The lower part of the larger valley glacier showed a clear correlation between altitude and snow accumulation. The upper part of the glacier and the adjacent smaller glacier had no alti- tudinal trend and the fluctuations in depth were large. Additionally, the accumulation was 40was thought to be a result of melt that occurred during warmer weather, which is more pronounced at lower elevations. Spatial variability of precipitation and redistribution of snow were believed to have resulted in the high spatial variability in higher parts of the study area. Since the majority of the precipitation events originated from one direction and the large glacier was on the lee side of a ridge, it experienced preferential deposition. Mean- while, the smaller glacier was further along the storm track so it received less precipitation. Overall, [77] showed that snow distribution on glaciers is not simply a function of altitude, which corroborated research done in other alpine catchments.

In most cases, the resolution of measurements over a large area is insufficient to approximate the true variability [15, 32].