Evaluating development of annual mass balance-accumulation area ratio relationship using annual and transient values

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ABSTRACT

Glacier annual mass balance (B_a) correlates well with the accumulation area ratio (*AAR*) for alpine glaciers. A key constraint in building a robust relationship is the total observations is limited to the number of years of mass balance assessment, which is typically limited. There is a 30-year record of B_a and *AAR* from Columbia Glacier and Lynch Glacier in the North Cascades, Washington. On Columbia Glacier at the beginning of August the transient mass balance (B_t) and transient AAR_t are determined in addition to the annual values. Here we compare the B_a –*AAR* relationship derived from using each data set alone, 30 data points and jointly 60 data points. In the case of Columbia Glacier the B_a –*AAR* has a correlation of 0.93, the B_t-AAR_t has a relationship of 0.95. On Lynch Glacier the B_a –*AAR* has a correlation of 0.97, the B_t-AAR_t has a relationship of 0.94. Both indicate that the transient values are comparable in accuracy and can be used to derive a stronger relationship. In this case both data records are long and robust without using the transient values; this is not usually the case.

INTRODUCTION

Annual mass balance (*Ba*) measurements are the most accurate indicator of short-term glacier response to climate change (Haeberli, 1995). The assessment of *Ba* is time and cost intensive and limited to approximately 100 glaciers around the globe (WGMS, 2013). The World Glacier Monitoring Service (WGMS) collects *Ba* data along with accumulation area ratio (*AAR*) annually for each glacier that is assessed. *AAR* is the percentage of a glacier that remains snowcovered at the end of the hydrologic year. The value of *AAR* as a measure of *Ba* is well documented and is the reason why WGMS derives a relationship plot between *AAR* and *Ba* for each glacier. *AAR* can be assessed using satellite imagery or photographs (Ostrem, 1975). This offers the potential for using the *AAR* to determine Ba once a relationship is derived. If only annual values of *Ba* and *AAR* are used developing the relationship will take a considerable period of time, which further restricts the number of glaciers where this can be used as many lack a long record of *Ba*. Utilizing transient values of *AAR* and *Ba* during the course of a balance year offers the opportunity to more readily develop a relationship. Here we contrast the *Ba*-*AAR* relationship on two glaciers from the end of the year measures and a transient date measurement in August.

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Dyurgerov (1996) proposed that the AAR-Ba relationship can be obtained from repeated mass balance measurements during one summer. From these measurements so-called "transient" (current) area-averaged mass balances, *Bt* can be computed and related to concurrent transient values of *AARt* and *ELAt.* Given the patchy nature of the snowline in the North Cascades ELA is not a good means of assessing mass balance. This method assumes that the relationship between transient values of mass balance *Bt* and AAR_t in the course of one season is identical to the relationship between *Ba* and *AAR* at the end of the mass balance year over many years. Here we test this method on two North Cascade glaciers with a 30 year record of both *Ba*, *Bt* and *AAR* and *AARt*. Hock and Koostra (2007) examined this method of *Bt-AARt* during one ablation season tested on Storglaciären, Sweden. They found the relationship worked except for low values of *AAR*. Hulth et al (2013) returned to the issue in concluding that.

STUDY AREA

The North Cascade region contains more than 700 glaciers, which covered 250 km^2 in the 1960's (Post et. al., 1971; Granshaw and Fountain, 2006). The North Cascade Glacier Climate Project (NCGCP) was founded in 1983 to monitor 10 glaciers throughout the range and identify the response of North Cascade Range, Washington glaciers to regional climate change (Pelto, 1988). The annual observations include mass balance, terminus behavior, glacier surface area and *AAR*. *Ba* measurements have been continued on the 8 original glaciers that still exist. Two glaciers have disappeared: the Lewis Glacier and Spider Glacier (Pelto, 2008). In 1990, Easton Glacier and Sholes Glacier were added to the annual balance program to offset the loss. All of the data have been reported to the World Glacier Monitoring Service (WGMS, 2009).

CLIMATE

The North Cascade region has a temperate maritime climate. From late spring to early fall, high pressure to the west keeps the Pacific Northwest comparatively dry. Climate west of the Cascade Crest is temperate with mild year-round temperatures, abundant winter precipitation, and dry summers. Average annual precipitation in the North Cascades typically exceeds 200 cm west of the divide. Climate east of the Cascade Crest is more continental, creating a sharp contrast with the maritime climate west of the Cascade Crest (Mote, 2003).

Approximately 70% of the region's precipitation occurs during the wet season (October-April) when the North Cascades are on the receiving end of the Pacific storm track (Elsner et al, 2010). Occasionally the warm fronts elevate temperatures, leading to rainfall and rapid snowmelt resulting in potential winter season flooding.

The North Cascades region experienced a substantial climate change beginning in 1976, to generally warmer conditions (Mote, 2003; Abatzoglou et al, 2013). A climate warming of 0.8 °C in mean annual temperature has been observed from 1901-2012 in the North Cascades (Abatzoglou et al, 2013**).** The warming has accelerated to 0.20 C per decade for the 1980-2012 period. Every season has experienced warming, particularly during the 1980-2012 period except spring (Abatzoglou et al, 2013**).**

From 1901-2012 precipitation has increased during the spring and declined during the summer and fall. No significant winter trend is evident. The 1980-2012 period features both some of the wettest and driest years, this high variability blurring any trend. Rains on snow events have increased in frequency (Elsner et al, 2010). This has led to an increase in the ratio of precipitation falling as rain versus snow (Barnett et al 2008; Pelto, 2008).

GLACIER MASS BALANCE

Surface mass balance is the difference between accumulation of snow and ice in winter and loss of snow and ice by ablation in summer. It is typically measured on a water year basis, beginning

October 1 and ending September 30 in the northern hemisphere yielding an annual mass balance (*Ba*) (Cogley et al (2011).

Since 1984, NCGCP has monitored the annual balance of ten glaciers (Pelto, 1996; Pelto and Riedel, 2001; Pelto and Brown, 2012). Eight glaciers have a 30-year record, Spider and Lewis Glacier melted away, and Sholes and Easton Glacier have a 24-year record.

Columbia Glacier is a southward oriented cirque glacier that is 1.6 km long, with a generally low surface slope on the centerline profile. The glacier is heavily avalanche fed with the main accumulation area being the avalanche fans and the upper basin at 1520 m (Figure 1). The tongue of the glacier is at 1440 m. The measurement network consists of 140-200 sites on the glacier (Figure 1).

Lynch Glacier is a north facing slope glacier that has limited avalanche accumulation and a steep overall slope ranging from 0.21 to 0.27. The glacier does receive wind drift accumulation in the upper basin above 2200 m. The terminus is on a steep slope just above Pea Soup Lake formed by the retreat of the glacier in the 1980's. The measurement network consists of 50-80 sites on the glacier (Figure 2).

METHODS

NCGCP essentially measures conditions on a glacier near the time of minimal mass balance at the end of the water year, using a fixed date method. Measurements are made at the same time each year in July-August and again in late September-early October near the end of the ablation season. Any additional ablation that occurs after the last visit to a glacier is measured during the subsequent hydrologic year. The methods are reviewed in detail by Pelto (1996, 1997), Pelto and Riedel (2001), Pelto (2008) and Pelto and Brown (2012).

NCGCP methods emphasize surface mass balance measurements with a relatively high density of sites on each glacier (>100 sites km^2), consistent measurement methods, applied on fixed dates, at fixed measurement locations with consistent supervision (Pelto, 1996; Pelto and Riedel, 2001). The average density of measurements NCGCP utilizes in the accumulation zone of each glacier ranges from 180-300 pointskm^{-2} (Pelto, 1996; Pelto and Brown, 2012). Columbia Glacier and Lynch Glacier are typical examples with the measurement network fixed using GPS (Figure 1 and 2).

RESULTS

Each glacier is measured in detail in August and revisited in late September or early October. The early visit to Columbia Glacier captures the variation of the snowline on the glacier on August 1 each year (Figure 3). On the first occasion both the *AARt* and *Bt* are determined, as well as the *Ba* and *AAR* at the end of the melt season visit. Thus, we have two data points each year for relating *AAR* and *Ba*. A plot of the values for each glacier of the *Bt-AARt* and *Ba-AAR* indicates a good agreement overall, the solid squares the *Bt-AARt* values and the open circles the *Ba-AAR* values. For Columbia Glacier the exception is for high *AAR* values for Columbia Glacier, since mass balance at an *AAR* of 100 can vary dramatically depending on how deeply buried the blue ice is. For Lynch Glacier the exception is for low values of *AAR*, where the *Bt-AARt* relationship drops below the trendline for the end of season relationship.

CONCLUSION

As Hock and Koostra (2007) noted the transient observations of *Bt* and *AARt* can be used to derive a *Ba-AAR* relationship on a glacier. Caution must be used at the highest and lowest values of *AAR*. This however offers the opportunity to more rapidly derive such a relationship that can be used in conjunction with satellite image identification of the AAR to determine a longer mass balance record.

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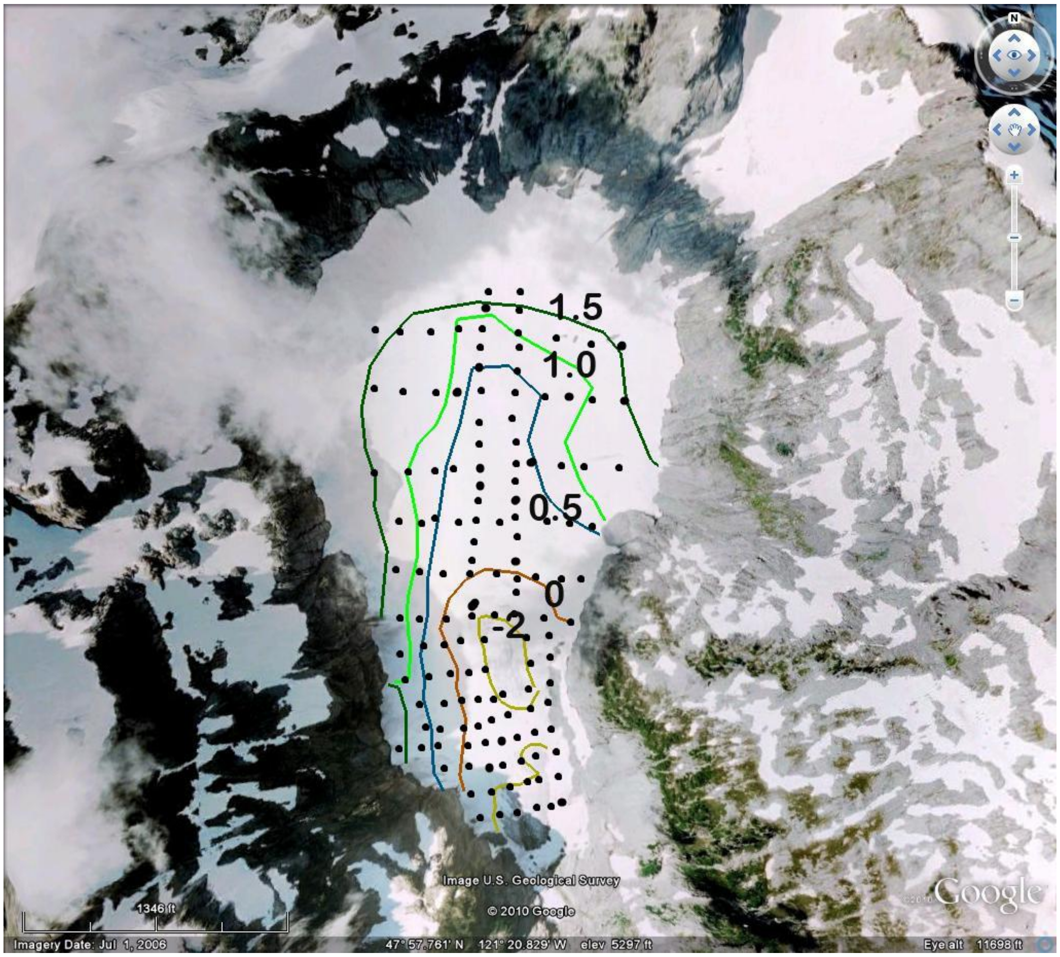

Figure 1. Columbia Glacier mass balance map and measurement network.

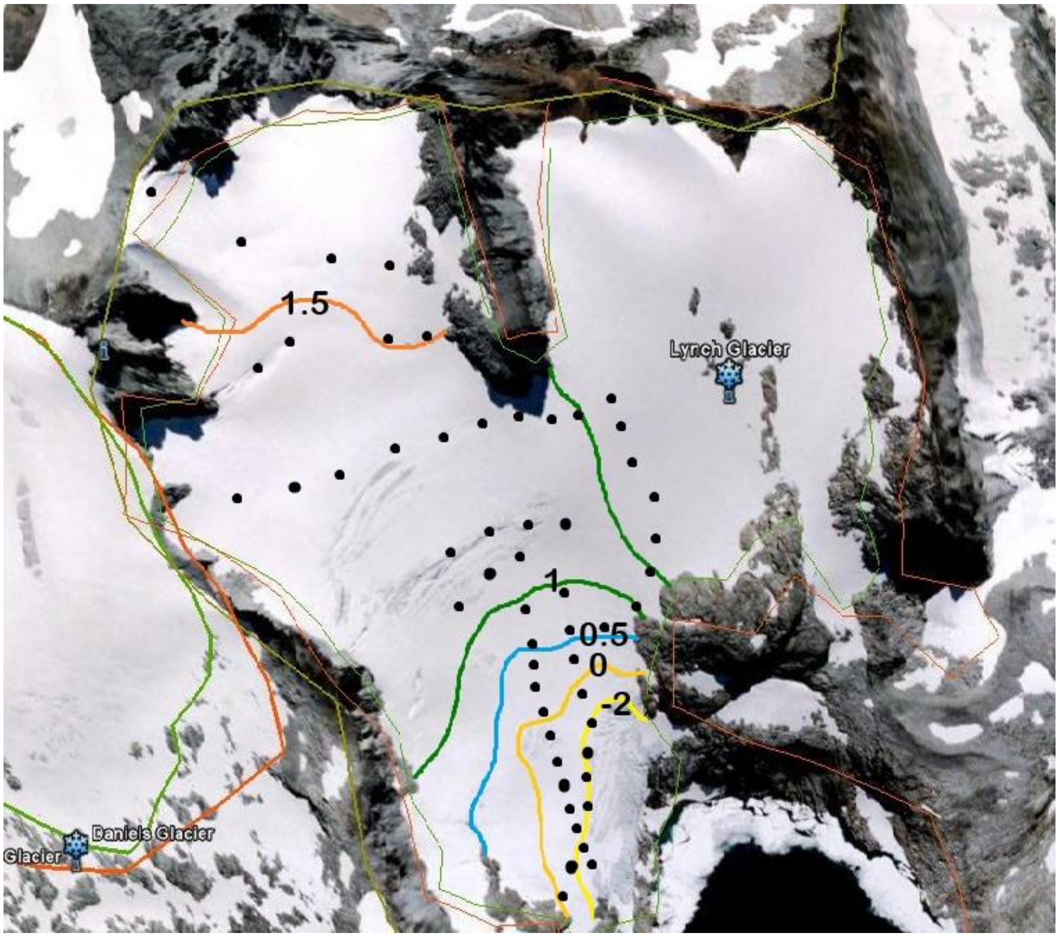

Figure 2. Lynch Glacier map and measurement network

Figure 3. Columbia Glacier annual August 1 snowline picture series 1985-1996.

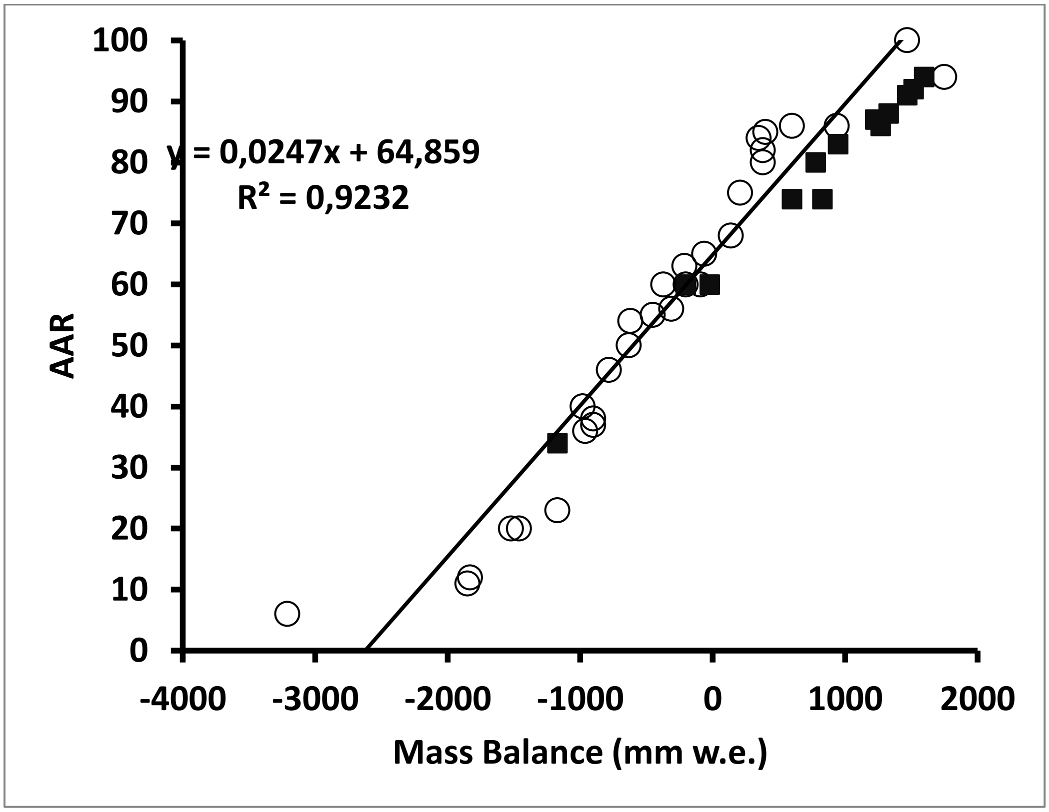

Figure 4. The *BA-AAR* (circles) and *Bt-AARt* (squares) relationship for Columbia Glacier.

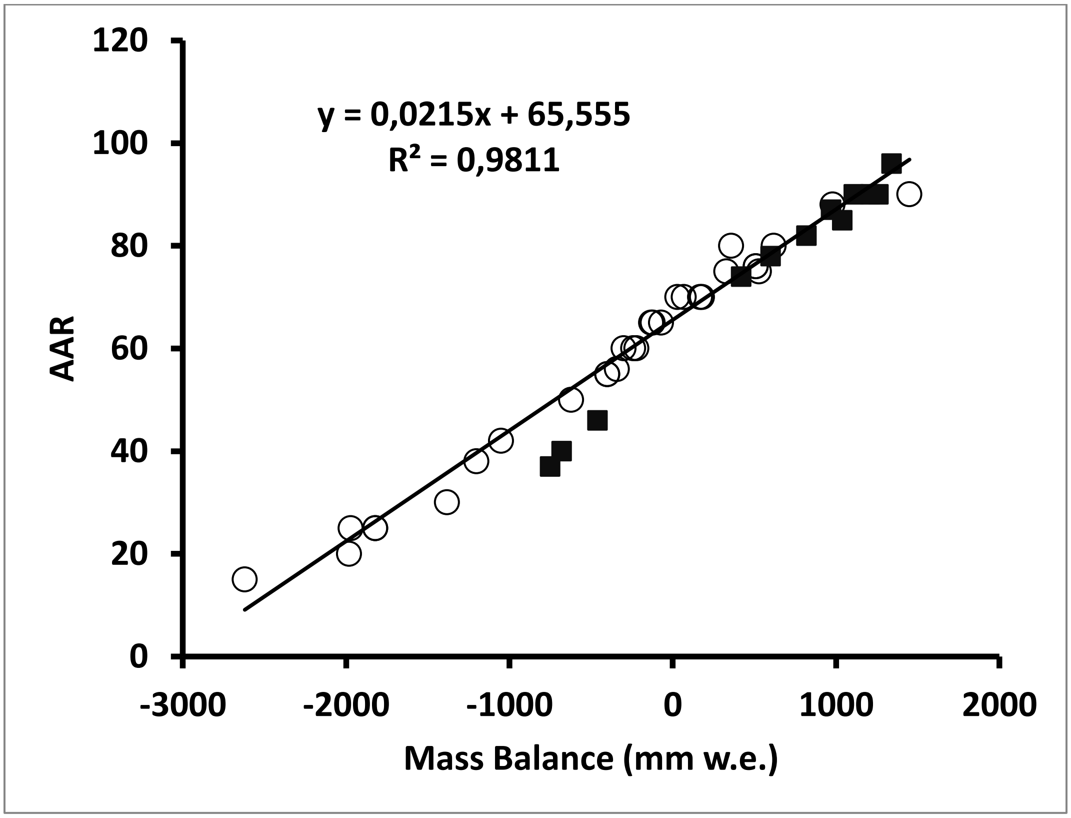

Figure 5. The *BA-AAR* (circles) and *Bt-AARt* (squares) relationship for Lynch Glacier.