[Handwritten note top right: Need to separate Background (climate geography, mass balance) from Methods and data sources from Results]

How unusual was 2015 in the 1984-2015 period of North Cascade Glacier Annual Mass Balance?

Mauri S. Pelto

[1]Environmental Science, Nichols College, Dudley, MA 01571 USA

5   *Correspondence to*: Mauri Pelto (mspelto@nichols.edu)

Abstract *[Handwritten: irrelevant to the abstract, delete.]*

In 1983 the North Cascade Glacier Climate Project (NCGCP) began annual monitoring 10 glaciers throughout the range, to identify their response to climate change.   The annual observations include mass balance, terminus behaviour, and accumulation area ratio (AAR).   Annual mass balance (Ba) measurements have ~~been~~ continued on 7 ~~original~~ glaciers ~~that~~

10   ~~still exist.~~ *[handwritten: and one]* Two glaciers have disappeared: ~~the Lewis Glacier and Spider Glacier~~ *[handwritten: two glaciers]*, Foss Glacier was discontinued in 2014 as it has separated into several sections. In 1990, ~~Easton Glacier and Sholes Glacier~~ were added to the annual balance program. *[handwritten: bring the total to 8]* This comparatively long record from glaciers in one region conducted by the same research program using the same methods offers some useful comparative data to place the impact of regional climate warmth of 2015 in perspective. The mean annual balance of the North Cascade glaciers is reported in water equivalent thicknesses to the World Glacier Monitoring Service

15   (WGMS). ~~From~~ *[handwritten: of the mean annual balance of 8-10 glaciers in the North Cascades]* 1984-2015 the mean Ba is -0.54 ma[-1], ranging from -0.44 to -0.67 ma[-1] for individual glacier's. This is equivalent to the WGMS global average for this period of -0.56 ma[-1]. The cumulative loss of 17.2 m w.e. and ~19 m of ice thickness represents more than 30% of the volume of the glaciers.   In 2015 the mean ~~Ba~~ *[handwritten: balance]* of nine North Cascade glaciers was -3.10 m w.e., the most negative in the 32 year record, with 2005 the previous maximum loss at -2.84 m. *[handwritten: annual balance]* The mean AAR of 3% was likewise a minimum, previous minimum was 16% in 2005. The correlation coefficient of ~~Ba is above 0.80~~ *[handwritten: >0.80]* between

20   all glaciers including the USGS benchmark glacier, South Cascade Glacier. This indicates that the response is regional and not controlled by local factors. The similar mass balance losses in alpine glacier regions globally suggest global climate change is the principal driving force.

1.0 Introduction

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Glaciers have been studied as sensitive indicators of climate for more than a century (Bojinski et al. 2014). Annual mass

25   balance measurements are the most accurate indicator of short-term glacier response to climate change (Zemp et al, 2015; WGMS, 2015).   The (WGMS) (2015) has recognized that changes in glacier mass are a key aspect of glacier monitoring, providing important information for assessing climatic changes, water resources, and sea level rise and has maintained the most extensive data set on global glacier mass balance. For the IGY in 1957 a number of benchmark glaciers around the

[1] *[Handwritten: Most of the glaciers were selected during the IHD.]*

world were chosen where mass balance would be monitored. This network has proven valuable, but in many areas the number of glacier is limited, for example. The WGMS has been working to expand the number of glaciers being monitored in-situ and reporting annual data WGMS (2015). The WGMS has recognized the long term programs with consistent measurement programs as reference glaciers (Zemp et al, 2015). There are two reference glaciers in the North Cascades and

5   in the conterminous United States, South Cascade Glacier (Fig. 1) monitored by the USGS (Fountain et al, 1991) and Columbia Glacier monitored by NCGCP.   Glacier mass balance varies due to geographic characteristics such as aspect, elevation and location with respect to prevailing winds. Since no single glacier is representative of all others to understand the causes and nature of changes in glacier surface mass balance throughout a mountain range, it is necessary to monitor a significant number of glaciers (Fountain et al, 1991).

10 The North Cascade region contains more than 700 glaciers, which are important to summer water supply (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 behaviour, glacier surface area and

15 accumulation area ratio (AAR). Annual mass balance (Ba) measurements have been continued on 7 original glaciers that still exist: Columbia, Daniels, Ice Worm, Lower Curtis, Lynch, Rainbow and Yawning. Two glaciers have disappeared: the Lewis Glacier and Spider Glacier (Pelto, 2008). One other glacier Foss Glacier has declined to the extent that continued measurements have been suspended. In 1990, Easton Glacier and Sholes Glacier were added to the annual balance program to offset the loss of Spider and Lewis Glacier. All Ba, AAR and terminus change data are reported annually to the World

20 Glacier Monitoring Service (WGMS). One glacier, Columbia Glacier is a reference glacier for the WGMS mass balance series. This network combined with South Cascade Glacier, is the also the most spatially concentrated group of glaciers where Ba has been monitored for at least 25 years, which provides a unique chance to compare the mass balance records to each other and climate records. This paper examines the exceptional 2015 mass balance year, placing the year in context of the thirty-two year mass balance record and local climate records.

25 **2.0 Climate**

The North Cascade region has a temperate maritime climate with mild year-round temperatures, abundant winter precipitation, and dry summers (Mote, 2003). The two key climate variables for the temperate maritime glaciers are accumulation season precipitation (November-April) and ablation season temperature (May-September) (Pelto, 1988; Josberger et al. 2007). A climate warming of 0.8 °C in mean annual temperature has been observed from 1901-2012 in the

30 North Cascades (Abatzoglou et al, 2014). The warming has accelerated to +0.20 C per decade for the 1980-2012 period. Every season except spring has experienced warming, particularly during the 1980-2012 period (Abatzoglou et al, 2014).

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). From late spring to early fall, high pressure to the west keeps the Pacific Northwest comparatively dry. Occasionally in the winter warm fronts elevate temperatures, resulting in

5 higher freezing levels, leading to rainfall even at glacier elevations. Rain 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, reducing snowpack storage efficiency (Mote et al 2008; Pelto, 2008). For the six USDA SNOTEL stations utilized in this study mean April 1 SWE declined 29% from 1946-2014. During the same period winter precipitation has increased slightly. The change in SWE is comparable with the change in snowpack storage efficiency indicating this is the primary cause of reduced April 1 SWE at

10 North Cascade SNOTEL stations. The freezing level is a key factor in determining snowpack storage efficiency and a North American Freezing Level Tracker was developed by Abatzoglou (2011) that is used here for comparison of the freezing level during the winter for Mount Baker.

The other key factor in glacier behaviour is the amount of ablation, which is primarily controlled by air temperature. That

15 air temperature is the key is indicated by the success of degree day factors (DDF) for assessing glacier ablation on glaciers in this region (Shea et al, 2008). The majority of ablation takes place during the June-September period, and nearly all ablation during the May-September period. The most reliable weather station in the region is Diablo Dam, which is used for DDF derivation on South Cascade Glacier (Rasmussen, 2009). An examination of trends in summer temperature at this station indicates a nearly identical pattern, for May-September and June-September. Six of the ten warmest summers during the

20 1946-2014 period have occurred since 2003. The long term summer warming is 0.7° C at Diablo Dam. The average June-September temperature from 2003-2014 is 0.6° C above the mean for the 1946-2002 period.

Bitz and Battisti (1999) noted the importance of PDO and MEI-ENSO to glaciers in the region, with PDO having a greater influence during the 1960-1995 period. Josberger et al (2007) indicate that the importance of PDO has declined recently.

25 Pelto (2008) used the indices as a first order forecast for annual glacier mass balance. Finding the impact was strongest when both indices were positive or negative.

The PDO Index is the leading principal component of North Pacific monthly sea surface temperature variability, poleward of 20N (Mantua et al., 1997). During the positive PDO phase warm weather is favored in the Pacific along the northwest coast

30 and over the Pacific Northwest. During the negative phase cool ocean water is found off the northwest coast and cooler temperatures across the Pacific Northwest (Mantua et al., 1997). In the past century: "cool" PDO regimes prevailed from 1890-1924 and again from 1947-1976, while "warm" PDO regimes dominated from 1925-1946 and from 1977-1998 (Mantua et al., 1997).

The El Niño/Southern Oscillation (ENSO) phenomenon is the most observable of the atmospheric circulation indices that lead to year-to-year climate variability. ENSO positive events (El Nino) herald abnormally warm sea surface temperatures (SST) over the eastern half of the equatorial Pacific. La Niña, is the opposite phenomenon, indicative of abnormally cold SST in the eastern half of the equatorial Pacific. ENSO is an east-west atmospheric pressure see-saw that directly affects

5 tropical weather around the globe and indirectly impacts a much larger area (Wolter and Timlin, 1998). The ENSO multivariate index used here is based on the principal observed climate variables over the tropical Pacific. The index is a weighted average of the main ENSO features contained in the following six variables: sea-level pressure, the east-west and north-south components of the surface wind, SST, surface air temperature, and total amount of cloudiness (Wolter and Timlin, 1998). Positive ENSO values are usually accompanied by sustained warming of the central and eastern tropical

10 Pacific Ocean. Negative values of the ENSO index are associated with stronger Pacific trade winds and warmer sea temperatures to the north of Australia (Wolter and Timlin, 1998).

2.1 Climate in 2015

The 2015 winter accumulation season featured 51% of mean (1984-2014) winter snow accumulation at six long-term USDA SNOTEL stations in the North Cascades; Fish Creek, Lyman Lake, Park Creek, Rainy Pass, Stevens Pass, and Stampede

15 Pass. This was exceptional in being the second lowest of the 32 years of the mass balance observation series. The winter season was exceptional for warmth, being the warmest winter season in the state of Washington (NOAA, 2015). The freezing level was high averaging 1645 m in the Mount Baker region from November-March compared to an average of 1077 m (Abatzoglou, 2011). No previous year exceeded a mean freezing level of 1500 m since the record began in 1948 (Figure 2). The result was snowpack at the six SNOTEL sites averaging 0.52 m w.e., 51% of the 1984-2014 average. The

20 minimum snowpack was in 2005 with 44% of mean snowpack, that year had less precipitation. The limited snowpack was not due to reduced precipitation as November-April precipitation at Diablo Dam and Concrete was 5-10% above the 1984-2014 mean. Mote et al (2008) noted a decline in snowpack storage efficiency in the Pacific Northwest the ratio between total precipitation and April 1 retained snowpack SWE, Pelto (2008) used the Diablo Dam and Concrete weather stations for total precipitation for November-March, the period of accumulating snowpack at the six SNOTEL sites with long term

25 records in the North Cascades, to determine snowpack storage efficiency. In 2015 the snowpack storage efficiency was the lowest with the mean April 1 retained SWE at six long-term SNOTEL stations being 19% of the November-March precipitation, compared to a 1984-2014 mean of 41%, the second lowest year was 2005 at 20%. The snowline by the end of April 2015, the end of the typical accumulation season, in the Mount Baker region was 1400 m, versus the 800 m average.

30 In 2015 the mean May-September temperature at Diablo Dam was 2.2 C above the long term mean, and the second warmest to 1958 in the record from 1950-2015. For June to September the mean temperature was 2.0 C above the long term mean and was also second to 1958 as the warmest. The mean 2015 July-August temperature recorded at the automatic weather station 100 m from the terminus of Sholes Glacier was 10.7 C. The combination of the warmest melt season in over 50 years

and the second lowest accumulation season snowpack in the last 30 years was a good indication that glacier mass balance would be quite negative.

In 2015 sea surface temperature waters that had developed in the winter of 2013/14 persisted off the coast of the Pacific

5   Northwest, with anomalies generally exceeding $2°C$ (Bond et al., 2015; Di Lorenzo and Mantua, 2016). Such conditions are associated with a positive PDO and warm air temperatures in the Pacific Northwest (Bond et al., 2015). From the winter of 2013/14 to 2014/15 the northeast Pacific experienced the largest marine heatwave ever recorded (Di Lorenzo and Mantua, 2016). In 2015 the warmest SST paralleled the entire Pacific North American coast exhibiting a PDO pattern (Di Lorenzo and Mantua, 2016).

10   A comparison of annual, winter and summer values for PDO 1984-2015 indicate that 2015 ranks in the top five for PDO for each seasonal measure. Examining the 1984-2015 period for ENSO indicates that in 2015 summer and annual values rank in the top 5. The 2015 hydrologic year had the most positive PDO of any year, but ENSO was not the most positive. The combined value of PDO + ENSO in 2015 ranked in the top five for both annual and seasonal rankings during the 1984-2015

15   period. Positive values for both ENSO and PDO are inversely related to glacier mass balance and also reinforce each other (Pelto, 2008). This illustrates that 2015 was predisposed for negative annual balance based solely on climate indices. The link between PDO and ENSO forced the anomalous atmospheric and sea surface temperature event in 2015 (Di Lorenzo and Mantua, 2016).

20   Overall 2015 was exceptional in terms of sea surface temperature in the northeast Pacific, air temperature in the North Cascade region and the positive values of the PDO, while ENSO was significantly positive.

3.0 Glacier Mass Balance Methods

Annual 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, approximately beginning October 1 and ending September

25   30 in the northern hemisphere yielding an annual mass balance (Ba) (Cogley et al (2011).

Since 1984, NCGCP has monitored the Ba of 9-10 glaciers every year (Pelto, 1996; Pelto and Riedel, 2001; Pelto and Brown, 2012). Seven glaciers have a 32-year record; Columbia, Daniels, Ice Worm, Lower Curtis, Lynch, Rainbow and Yawning. Foss Glacier has a 30 year record 1984-2013 and was discontinued due to the glacier separating into several

30   sections. Sholes and Easton Glaciers have a 26-year record 1990-2015. The glaciers represent a range of geographic characteristics and span the North Cascade Range (Table 1 and Figure 1). Key geographic variables are orientation of the

glacier, mean elevation, accumulation sources and distance to the mountain ranges watershed and climate divide. ~~Columbia Glacier in 2015 is one of the 37 reference glaciers used by the WGMS.~~

REF (Fixed date system)   *not identical, right*

NCGCP 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 using the same methods~~ *same period* from late July to mid-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 use of a high measurement density and consistent methods generates ~~errors resulting from an imperfectly representative measurement network that are largely consistent and correctable, the~~ *an* error range ~~has been observed~~ *of* at ± 0.10-0.15 ma⁻¹ (Pelto, 2000).

4.0 Results:

4.1 Annual Mass Balance

Glaciers in the North Cascades exhibit consistent Ba responses to climate from year to year (Pelto and Riedel, 2001; Pelto and Brown, 2012). Figure 3 illustrates the closely correlated pattern of Ba fluctuations from 1985 to 2015. In most years, all glaciers respond in step with each other to variations in winter retained snowpack and summer temperature. There is a mean annual range of 0.8 m from the maximum to the minimum Ba in a given year, but the inter-annual trend is the same for each glacier. This regional response is indicated by the high cross correlation values of Ba between individual glaciers ranging from r^2 of 0.80 to 0.98 between each glacier pair, including the South Cascade Glacier monitored by the USGS (Table 2) (Bidlake et al, 2010). Data for 2013-2015 has not been finalized for South Cascade Glacier; hence the comparison period ends in 2012 for this glacier.

confusing   *what is Max/min if only annual measured (t)? collected?*

mass balance

how does Bidlake provid 2012 data?

The mean Ba has been -0.54 ma⁻¹ for the 1984-2015 period on the glaciers monitored annually, ranging from a maximum of -0.44 ma⁻¹ to a minimum of -0.67 ma⁻¹ (Table 3). The mean Ba, -0.54 ma⁻¹ for North Cascade glaciers during the 1984-2015 period is quite similar to the WGMS global reference glacier mean Ba of 0.56 ma⁻¹ (Figure 6)(WGMS, 2017) The mean cumulative mass balance loss has been -17.2 m w.e, which is a 19-20 m of glacier thickness lost. North Cascade glacier *awk* average thickness ranges from 30-60 m (Post et al, 1971; Pelto and Hedlund, 2001; Finn et al, 2012). Thus, at least 30% of the volume of these glaciers has been lost since 1984. Observations by the USGS at South Cascade Glacier indicate that

Not well constrained either improve or delete

Decades apart skewing avg thickness

shows cross-correlations not Ba

Fig 5 needs to be cited first

Awkward

mean Ba from 1984-2012 is -0.75 ma^{-1} on South Cascade Glacier, 0.21 ma^{-1} more negative than the glaciers we monitor. South Cascade Glacier had a much less negative mean Ba of -0.15 ma^{-1} from 1956-1975 (Krimmel, 2001).

4.3 Accumulation Area Ratio

define   ?   why? it still depends on the ELA

At regional scales and on specific glaciers there are two common proxies for assessing mass balance without detailed

5 observations. They are the AAR and equilibrium line altitude (ELA) both can be derived from satellite imagery or photographs (Østrem, 1973; Racoviteanu et al, 2008). The ELA is the elevation at which ablation equals accumulation, on temperate alpine glaciers this is coincident with the TSL at the end of the melt season. The ELA is not typically an easily ? discernible line or elevation on North Cascades glaciers, due to variability of snow accumulation from impacts of wind and avalanche redistribution. AAR is a more accurately determined parameter and a better proxy in this case (Pelto and Brown, variable But this is part of the accumd pattern.

10 2012). Rabatel et al (2008) and Dyurgerov (1996) developed methods to derive mass balance from long term AAR observations. The AAR-Ba method has proven reliable for annual balance estimates (Hock et al., 2007; Racoviteanu et al, 2008; Pelto and Brown, 2012). A comparison of annual AAR and Ba observations in WGMS (2007; 2009) indicate correlation coefficients ranging from 0.70-0.92 for fifteen glaciers with at least 10 years of records. The World Glacier REF Monitoring Service (WGMS) has adopted the reporting of AAR with mass balance values (WGMS, 2007, 2009) and plotting

15 the relationship for each glacier. A combination of AAR observations and Ba measurements from 1984-2015 on North Cascade glaciers provides an opportunity to assess the relationship for each glacier and the variability between glaciers.

How was AAR estimated – aerial photos, mps?   Meier + Post said 0.65?

The AAR0 value is the AAR for a glacier with an equilibrium mass balance (Meier and Post, 1962). Braithwaite and Muller (1980) noted that the AAR0 for an alpine glacier with an equilibrium balance averaged 0.67. The mean AAR0 reported for

20 89 temperate alpine glaciers to the WGMS was 0.57 (WGMS, 2007: WGMS, 2009). The observed AAR0 on North Cascade glaciers ranges from a low of 0.60 on Ice Worm Glacier to 0.67 on Easton Glacier. The regression line from the plot of the AAR and Ba for the ten North Cascade glaciers indicates a mean AAR0 of 0.64 and a correlation coefficient of 0.89 between AAR and Ba (Fig. 4 and Fig. 5).

But not all had a Ba

Wait! You estimated AARo from fig 4?

Data table would be helpful here

year of Ba = 0 over the record. So you used a subset

4.3 Annual Mass Balance 2015

25 This is not clear from your description

On June 15th when the automatic weather station and discharge station were installed adjacent to Sholes Glacier the snowpack was similar to typical early August snowcover. On Sholes Glacier the AAR fell from 0.55 on July 9th to 0.00 on Sept. 9. In early August the AAR was below 0.10 in on all glaciers except for Easton Glacier Figure (7, 8 and 9). This was the first year since monitoring began in 1984 that the AAR in early August was below 0.25. The result was exposure of

30 older firn layers and a general decrease in albedo. In 2015 of the nine glaciers where Ba was examined the AAR was 0.00 on seven glaciers, 0.05 on Rainbow Glacier and 0.26 on Easton Glacier. This indicates the lack of a significant accumulation

need only one photo

zone in 2015 for all but Easton Glacier. The mean 2015 AAR of 0.03 is significantly less than the previous low of 0.16 in 2005 and the 1984-2015 mean of 0.53.

In 2015 the mean Ba of all nine glaciers North Cascade glaciers examined and reporting to the WGMS was -3.19 m, 2.65 m below the long term mean. The second most negative year for Ba was -2.84 m in 2005; no other year exceeded -2 m. The mean Ba 2015 data for WGMS reference glacier network is -1.12 m w.e., the second most negative to 2003 (WGMS, 2017). The mean BA of all WGMS reporting glacier in 2015 was -1.04 m. of the 11 glaciers globally reporting a loss of more than 3 m, nine were in the state of Washington, including in addition to the NCGCP glaciers Eel Glacier in Olympic National Park and Noisy Creek Glacier in North Cascades National Park reported by the National Park Service (WGMS, 2017). Of the WGMS reference glacier network Columbia Glacier had the most negative balance of any glacier. The Ba continues to trend negatively, both globally and in the North Cascades indicating that instead of approaching equilibrium as the glaciers retreat they continue to be in disequilibrium with current climate (Fig. 6). This mass balance loss represents the loss of 5-10% of the total glacier volume in a single year.

5.0 Climate Correlations

Examination of Pacific Northwest glacier mass balance for the full period of research for NCGCP and USGS benchmark glaciers indicate that winter balance fluctuations of maritime glaciers dominated the Ba fluctuations (Josberger et al, 2007). Looking at the full period of record 1984-2015 it is apparent that summer balances of the benchmark glaciers have become more negative during recent years, a result of warmer and drier summers, summer balance and have taken on a greater role in determining Ba (Josberger et al, 2007).

Bitz and Battisti (1999) noted the importance of PDO and MEI-ENSO to glaciers in the region, with PDO having a greater influence during the 1960-1995 period. Josberger et al (2007) suggested that there was a decoupling of winter balance and the PDO for the benchmark glaciers in the Pacific Northwest. They used three time periods, 1966-2004, 1966–1988 and 1989–2004, and found a significant change in the relationship between the PDO and the winter balances of Wolverine Glacier, but less so for South Cascade Glacier. Here we use two periods 1984-1998 and 1999-2014 comparing annual mass balance for each glacier to the PDO index for October-April (winter) and the annual mean October-September MEI-ENSO. During the first period the mean correlation was -0.34 for winter PDO and -0.59 for MEI-ENSO. During the latter period the mean correlation increased to -0.54 for winter PDO and -0.66 for MEI-ENSO. The annual MEI-ENSO index remains a better indicator of annual mass balance in the North Cascade Range than winter PDO. The annual PDO index has a significantly lower relation to annual balance than winter PDO. The correlation between the cumulative mass balance records of glaciers in various alpine glaciated regions around the globe, indicate the global climate signal is the dominant driver of mass balance losses (Zemp et al., 2015).
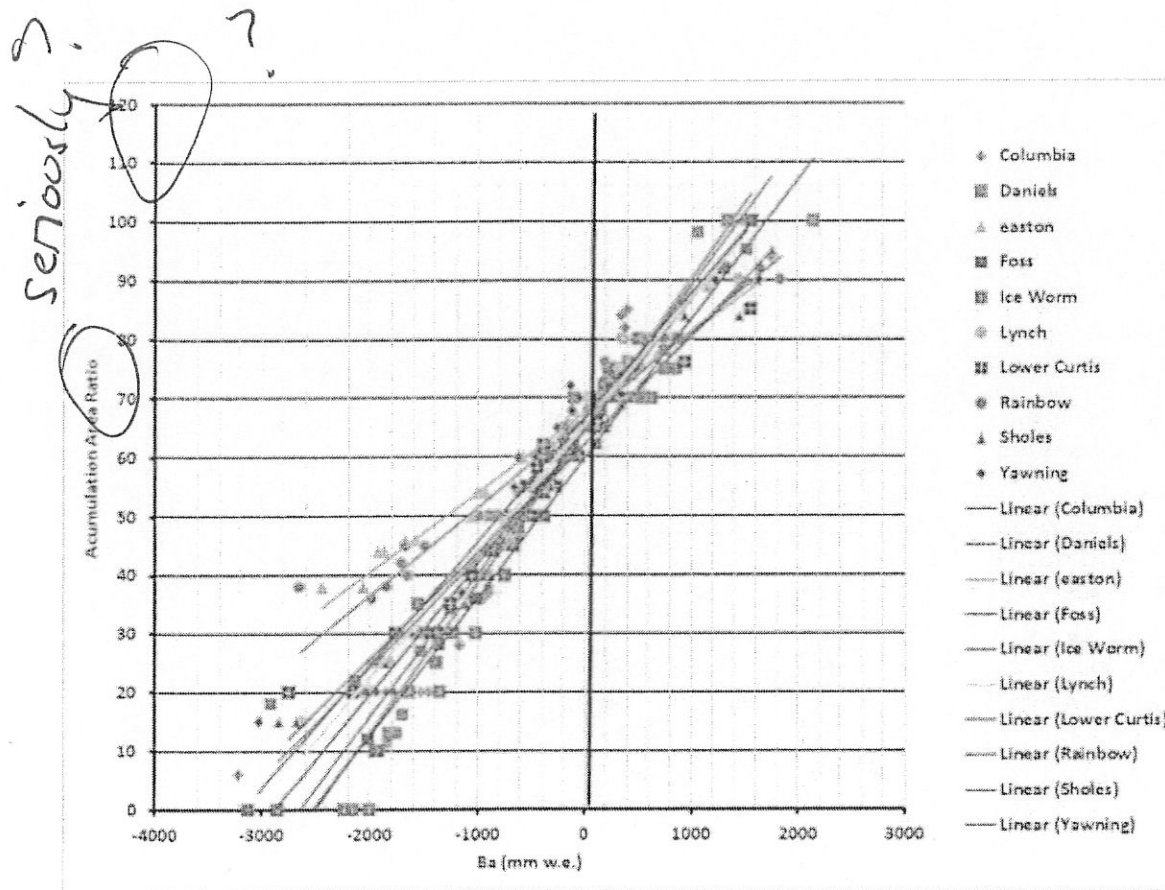
Figure 4. Relationship between annual balance and accumulation are ration on North Cascade glaciers.

seriously?
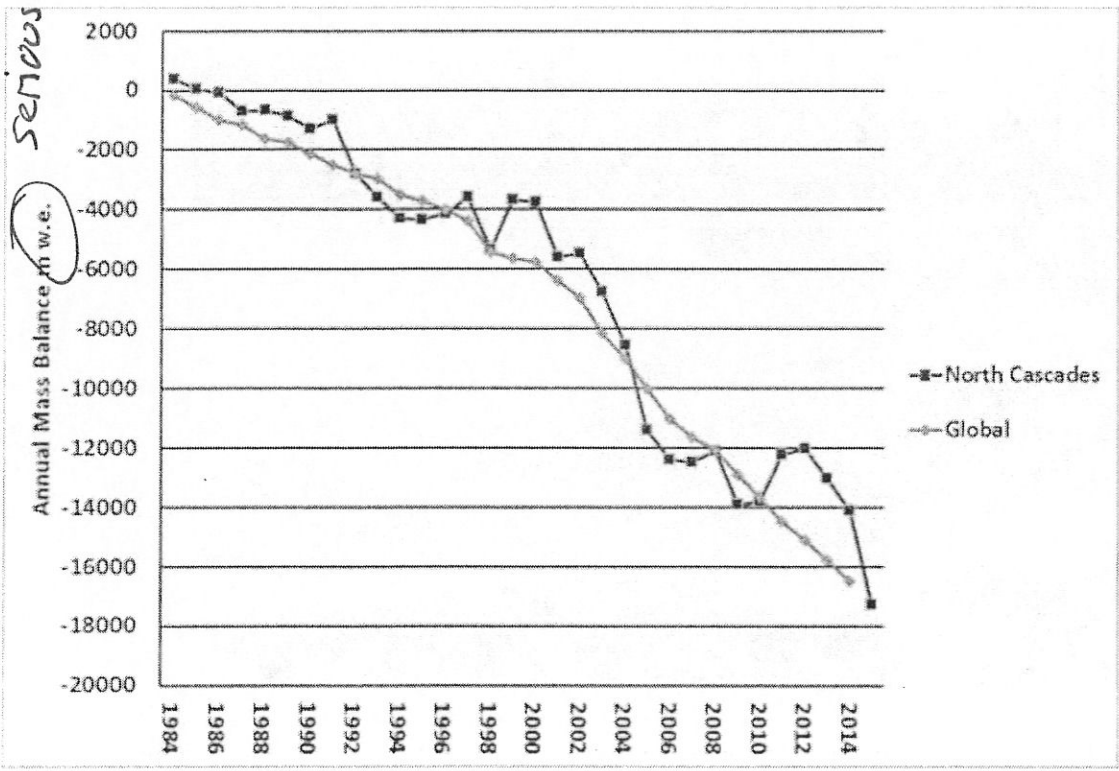
Figure 6. Cumulative mass balance for North Cascade glaciers observed by NCGCP and the WGMS Global reference glacier group.