

1 **Trends and variability in the global dataset of glacier mass balance.**

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6 **Abstract:**

7 Glacier mass balance (i.e., accumulation and ablation) is the most direct connection between climate
8 and glaciers. We perform a comprehensive evaluation of the available global network of mass-
9 balance measurements. Each mass-balance time series is decomposed into a trend and the variability
10 about that trend. Observed variability ranges by an order of magnitude, depending on climate setting
11 (i.e., maritime vs. continental). For the great majority of glaciers, variability is well characterized by
12 normally distributed, random fluctuations that are uncorrelated between seasons, or in subsequent
13 years. The magnitude of variability for both summer and winter is well correlated with mean
14 wintertime balance, which reflects the climatic setting. Collectively, summertime variability exceeds
15 wintertime variability, except for maritime glaciers. Trends in annual mass balance are generally
16 negative, driven primarily by summertime changes. Approximately 25% of annual-mean records
17 show statistically significant negative trends when judged in isolation. In aggregate, the global trend
18 is negative and significant. We further evaluate the magnitude of trends relative to the variability.
19 We find that, on average, trends are approximately -0.2 standard deviations per decade, although
20 there is a broad spread among individual glaciers. Finally, for two long records we also compare
21 mass-balance trends and variability with nearby meteorological stations. We find significant
22 differences among stations meaning caution is warranted in interpreting any point measurement
23 (such as mass balance) as representative of region-wide behavior. By placing observed trends in the
24 context of natural variability, the results are useful for interpreting past glacial history, and for
25 placing constraints on future predictability.

1. Introduction

Glacier mass balance (i.e., accumulation and ablation) reflects the sources and sinks of ice into and out-of a glacier. As such, it is the most direct connection between climate and glacier response. A surfeit of mass input will drive an advance; a deficit will drive a retreat. While there are variations among individual glaciers, there is a well-known consistency at the regional and global scale between the observed negative net mass balance and glacier retreat (e.g., IPCC 2013).

Most mass-balance measurements have been acquired from direct *in situ* snow-stake and snow-pit measurements extrapolated across the glacier (e.g., Braithwaite, 2002; Kaser et al., 2003). Such measurements are obviously laborious to make and, as such, mass-balance records are typically short, often fragmentary, and have a geographic bias reflecting their proximity to historical centers of research activity. The World Glacier Monitoring Service performs a critical role by archiving the available data in a common format and by promoting common measurement protocols (WGMS, 2014 and earlier reports).

Perhaps the main application of these glacier mass-balance records has been to relate them to anthropogenic climate change. Records (reported in m yr^{-1}) are often aggregated into regional averages and integrated in time to yield a cumulative mass balance (e.g., Dyurgerov and Meier, 2005; Lemke et al., 2007; WGMS, 2013). The purpose of the averaging is to represent the regional-scale behavior, and the cumulative mass-balance (with units of m) is often associated with volume loss and sea-level rise (e.g., Dyurgerov and Meier, 2005; Lemke et al., 2007). This latter association can be misleading as it fails to account for the dynamic response of the ice sheet. Ice is continuously being conveyed through the glacier, and so the glacier will forget its previous climate history on the timescale of the glacier's dynamic response time (e.g., Johanneson et al., 1989; Oerlemans, 2001;

1 Roe and Baker 2014). Moreover, as has been noted in this context previously (Braithwaite and
2 Zhang, 1999), integrating the random, stochastic component of mass balance produces the well-
3 known Drunkard's Walk effect (equivalent to Brownian motion), wherein the variance grows in time
4 without bounds, and which introduces a biased end-state (e.g., vonStorch and Zwiers, 1999). The
5 longer the mass-balance records, the less the cumulative mass-balance time series reflects the impact
6 on glacier thickness. Recent research estimating sea-level contributions incorporates a dynamic
7 adjustment to account for this effect (e.g., Marzeion et al., 2012).

8
9 In this study we use conventional times series analysis to perform a comprehensive evaluation of all
10 the mass-balance records that are long enough for stable statistical metrics to be estimated. The
11 starting point is to decompose each mass-balance time series into a trend and the variability about
12 that trend. The trend can be evaluated in the context of the well-documented secular trends in other
13 climate variables that are incontrovertibly associated with anthropogenic causes (e.g., IPCC, 2013).
14 The variability arises from the year-to-year vagaries of weather; unforced, internal climate
15 variability; and local stochastic effects such as wind blown snow and avalanching. Our analyses can
16 be grouped into addressing two main questions: 1) what is the best statistical characterization of the
17 mass balance records? 2) How large are the observed trends relative to the variability?

20 2. Glacier mass balance records

21
22 The World Glacier Monitoring Service (WGMS) is the main repository for standardized mass-
23 balance observations from around the world (WGMS 2013, 2014, and earlier issues). Net mass
24 balance is the difference between accumulation and ablation (i.e., mass loss via melting,
25 sublimation, calving), reported in m yr^{-1} of water equivalent. For a given year, the net-annual
26 balance, b_n , is determined by extrapolating from perhaps 10 to 15 individual snow-stake

1 measurements to estimate the area-averaged thickness change from the previous year's
2 measurement; or by summing up the separately measured winter and summer balances b_w and b_s
3 (Kaser et al., 2003). A minority of the mass-balance measurements are also accompanied by a
4 reported "maximum error". What that means formally is not clear, and is apparently left up to
5 individual groups to define. Reported accuracy for seasonal measurements are typically around
6 10% but vary widely, from an assuredly over-optimistic <1% to upwards of 25% in some cases.

7 We make a brief aside here to note that mass balance can be defined in different ways. In this
8 study we analyze the conventional mass balance (the direct measurements reported by the WGMS,
9 2014). The calculation involves the observed glacier area, which is typically also evolving over the
10 period of observations and so, to a degree, the mass balance also reflects glacier dynamics as well
11 as climate. Mass balance calculated in this way acts as a high-pass filter of climate variability (e.g.,
12 LeClerq et al., 2010). An alternative index, the "reference-surface" mass balance, extrapolates
13 observations over a fixed surface area, and has been proposed as a truer reflection of climate
14 (Elsberg et al., 2001, LeClerq et al., 2010). Several factors motivate our use of conventional mass-
15 balance data. There are additional uncertainties involved in extrapolating point measurements to
16 the hypsometry and area of the (nonexistent) reference surface. We analyze mass balance (rather
17 than cumulative mass balance), which minimizes the differences between the methods (e.g.,
18 Elsberg et al., 2001). Finally several studies have concluded that the two methodologies actually
19 agree quite closely, and especially so when applied to the relatively short records of a few decades
20 that are typical in the WGMS dataset (Elsberg et al., 2001; Huss et al., 2010). Thus, the differences
21 between the two methods are considerably smaller than both the uncertainties in the observations
22 themselves, and also much smaller than the statistical bounds on the two primary metrics we are
23 interested in -- the trend and the standard deviation.

24 The WGMS archive has at least one year of mass-balance data for over 250 glaciers. From this
25 complete dataset, we select records with at least 5 years of both winter and summer observations,

1 and/or at least 10 years of annual observations. We used the stricter cut-off of 10 years for annual
2 records because of their relative abundance compared to seasonal records. We found 130 records
3 with 5 years or more of seasonal data, and 158 records with 10 years or more of annual data.
4 Between these two datasets, there are 194 unique glaciers. Our statistical results are available for
5 all 194 glaciers in the online supplementary material. However, for the discussion and figures
6 presented in this paper, we further restricted the dataset based on some additional criteria.

7
8 First, many records are strewn with observational gaps, and any putative trend is less robust if
9 there are a large number of empty data points. Consequently, we eliminated records with
10 observational gaps that cover more than 20% of the record's length. Second, estimates of trends
11 and variability are very fragile when applied to short records. Even 10 year records yield large
12 uncertainties, but we believe that 10 years provides the best compromise between maximizing the
13 value of the available data while avoiding signals being obscured by short, noisy records. Thus in
14 the restricted dataset, we also eliminated winter and summer mass balance records less than 10
15 years. Finally, the relationship between mass balance and the dynamical response of rock glaciers
16 and ice fields, caps, sheets, and shelves is not straightforward. Hence we omitted all records that
17 are not associated with mountain and valley glaciers (we retain categories 4, 5, and 6 in the
18 WGMS classification).

19
20 Applying these extra filters to our dataset narrowed the number of records to 48 winter and
21 summer series, and 115 net-annual series. In general, and unless otherwise stated, any figures or
22 results discussed henceforth are from this vetted, higher-quality, list of mass-balance records,
23 hereafter referred to as the restricted dataset.

1 The locations of the 115 net-annual series are shown in Figure 1, together with a cumulative plot
2 of the record lengths. The distribution of records is global, although there is an obvious
3 concentration over Europe and North America. This bias in coverage should be borne in mind
4 when considering the representativeness of the data. The mean and median record lengths are 27
5 and 23 yrs, respectively. Although the number of records is small compared to the nearly 200,000
6 documented glaciers (RGI, Pfeffer et al., 2014), as time goes on the steady accumulation of
7 progressively longer records in the WGMS dataset is leading to much more accurate estimates for
8 mass-balance metrics. For example Braithwaite and Zhang (1999) analyzed 115 glaciers with at
9 least 5 years of data, which was all that was available at the time. Our complete analyses are
10 provided in a spreadsheet in the supplementary material, but we show a subsample of the records
11 and our analyses in Table 1.

13 3. Preliminary assessment of the data

15 We begin by analyzing the mass-balance records as a whole. Figure 2 shows histograms of the
16 time-averages of the seasonal and net-annual mass-balance records. From the restricted data set,
17 the average winter mass balance is 1.6 m yr^{-1} (ranging from 0.12 m yr^{-1} for glacier #1 in the Tien
18 Shan to 3.7 m yr^{-1} for Aalfotbreen, Norway). The average summer mass balance is -2.0 m yr^{-1}
19 (ranging from -0.71 m yr^{-1} for Johnsons glacier in the Antarctic Peninsula, to -4.2 m yr^{-1} for
20 Ossoue glacier in the Pyrenees). The average net annual balance is -0.44 m yr^{-1} (ranging from
21 -1.6 m yr^{-1} for Ossoue glacier in the Pyrenees to $+0.65 \text{ m yr}^{-1}$ for Eliot glacier, Cascade Range).
22 Thus the overall picture is one of an approximately order-of-magnitude spread in seasonal mass
23 balance depending on climatic setting and, in the aggregate, a net negative annual-mean mass
24 balance consistent with a warming climate.

25 3.1 Are the records normally distributed?

1 We focus first on the variability in the mass-balance records. To that end, we linearly de-trend the
2 winter, summer, and net-annual mass-balance time series using least-squares regression (e.g.,
3 vonStorch and Zwiers, 1999). This is standard practice in order to separate any trend due to
4 anthropogenically forced climate change, from the natural, interannual variability. We report the
5 trends and their uncertainties in a later section. Since it is unlikely that the anthropogenic forcing
6 of climate is exactly linear, it is probable that there remains some anthropogenic signature in the
7 records after removing the linear trend. However to attempt a more complete separation would
8 require a detailed model of anthropogenic climate forcing, which is of course subject to its own
9 uncertainties.

10 Each de-trended record was evaluated for normality (i.e., a Gaussian probability density function,
11 or PDF) of the variability using both the Jarque–Bera (JB) and the somewhat less-strict
12 Kolmogorov-Smirnov (KS) tests (Steinskog et al., 2007). For the full dataset, 144 out of 158
13 annual records were consistent with the null hypothesis of a normal distribution, evaluated using
14 the JB-test applied at the 5% significance level. For the summer and winter records, 113 and 119
15 respectively, out of 130 total were consistent with a normal distribution using the same test. For
16 the restricted dataset, the corresponding numbers are 108/115 and 44/48 and 43/48. Applying the
17 less-strict KS test did not reject the null hypothesis for any glacier.

18 Thus, the main result is that the variability in the vast majority of records is consistent with a
19 normal distribution. For the JB test, the number of records for which the null hypothesis is rejected
20 is slightly higher than expected by chance indicating some possible skewness (or kurtosis). For the
21 records that failed the JB test for normality, the skewness of the seasonal records showed no
22 preference towards positive or negative. However, all 14 annual records that failed the JB test
23 showed negative skewness (i.e., more extreme ablation than accumulation), with a mean skewness
24 of -1.0 and a standard deviation in skewness of 0.2. Potentially this reflects a genuine skewness in
25 variability, or it may result from having linearly detrended what is actually a nonlinear trend. But

1 in any event this skewness applies only to a small minority of records and may not deliver up a
2 clear or meaningful interpretation. Kurtosis tests were consistent with a Gaussian kurtosis of 3.

3 3.2 Is there persistence in the records? 4

5 Next, each mass-balance record was tested for autocorrelation (i.e., persistence in time). A time
6 series with no persistence is also known as a white noise process (e.g., Box et al., 2008). Perhaps
7 the most straightforward statistical test is due to Bartlett (1946). For data drawn from a white noise
8 process, the autocorrelation coefficient has a normal distribution with zero mean and variance $1/n$,
9 where n is the length of the record. The null hypothesis of no persistence can be rejected at the 5%
10 significance level if the lag-1yr autocorrelation exceeds $1.96/\sqrt{n}$. From this basic test, we cannot
11 reject the null hypothesis in 128 of 130 summer and winter records each, and 152 of 158 annual
12 records. (The corresponding numbers for the restricted data set are 47/48 summer, 47/48 winter,
13 111/115 annual). These results imply the mass-balance records are well described by a white-noise
14 process.

15 In addition to applying Bartlett's formula, we performed two more tests for persistence. Firstly, we
16 calculated the decorrelation time and 95% confidence bounds for each record using a first-order
17 autoregressive model (e.g., Box et al., 2008). For the full dataset we find 152 of 158 annual
18 records, and 126 and 128 out of 130 summer and winter records, respectively are consistent with
19 white noise. Secondly, we calculated the best-fit straight line and 95% confidence bounds through
20 the power spectrum (calculated from an unwindowed periodogram) of the data plotted on
21 logarithmic axes to test for power-law persistence (e.g., Box et al., 2008). A significant non-zero
22 slope in the regression equation indicates persistence (e.g., Percival et al., 2001). This test failed to
23 reject white noise in 123 and 122 respectively of 130 summer and winter records, and 146 of 158
24 annual records (the corresponding numbers for the restricted data set are 42/48 summer 43/48
25 winter, 108/115 annual records).

1 Since the exceptions are broadly within what one would have expected by chance, we hereafter
2 treat all records as uncorrelated in time, and proceed assuming that the degrees of freedom in each
3 record (needed for other statistical tests), are equal to the length of the record.

4 Given their typically short duration, it is hard to establish from the records themselves whether
5 persistence exists (Percival et al., 2001). It may be present but hard to detect. Other information
6 can be brought to bear. Long instrumental records (e.g., Pelletier, 1997; Fraedrich and Blender,
7 2003; Huybers and Curry 2006; Ault, 2013), paleoclimate proxies (e.g., Pelletier 1998; Huybers
8 and Curry, 2006; Laepple and Huybers, 2014), theory (e.g., Hoffert et al., 1980; Pelletier, 1997;
9 Fraedrich et al., 2004), and numerical models (e.g., Zhu et al., 2010; MacMynowski et al., 2011)
10 all suggest that a small degree of persistence does exist in other climate variables (e.g., annual-
11 mean precipitation and surface temperature), which varies as a function of location and climatic
12 setting. However such variables are only indirectly related to mass balance, which is subject to
13 other stochastic influences (such as avalanching, wind effects, and storminess). Thus these other
14 analyses cannot be straightforwardly carried-over to glacier mass balance.

15 In the present study we confine ourselves to simply characterizing the available mass balance data
16 as it stands. However, for a fuller discussion of the potential impact of climatic persistence on
17 glacier fluctuations, we refer readers to Roe and Baker (2015), which shows that a degree of
18 persistence that might not be detected in even the longest mass balance records can substantially
19 enhance the glacier fluctuations arising from mass-balance variability.

20 3.3 Is there correlation between winter and summer records? 21

22 Finally we examine the correlation between corresponding winter and summer records. Of the 130
23 seasonal records, 21 yield a statistically significant (5% level) Pearson correlation coefficient (e.g.,
24 vonStorch and Zwiers, 1999) between winter and summer records. In the restricted dataset, 8 of 48
25 records have a statistically significant correlation. Thus, for the majority of glaciers analyzed,

1 winter and summer mass balance are uncorrelated. However, slightly more records yield
2 significant correlation than can be explained by type I errors alone (i.e., a false positive, e.g.,
3 vonStorch and Zwiers, 1999). There are physical grounds for expecting an inter-seasonal
4 correlation: high winter snowfall might reduce the period of bare ice (and low albedo) during the
5 subsequent ablation season (e.g., Braithwaite and Zhang, 1999). However it is also possible that
6 correlations are an artifact of the observation protocols: extended or foreshortened accumulation
7 and ablation seasons mean that visits to measure the glacier mass balance may not coincide with
8 the maximum or minimum of that year's mass-balance seasonal cycle (e.g., Braithwaite 2002;
9 Kaser et al., 2003). With no more information, it is impossible to disentangle these effects.

11 4. Results

13 4.1 Standard Deviation of Mass Balance Series:

15 We characterize the interannual variability in net-annual, winter, and summer mass balance by
16 their standard deviations ($\equiv \sigma_{bn}, \sigma_{bw}, \sigma_{bs}$, respectively), presented in Figure 3. σ_{bn} has a mean value
17 of 0.7 m yr^{-1} , and ranges over nearly an order of magnitude, from 0.2 m yr^{-1} (Meikuang, China) to
18 1.6 m yr^{-1} (Echaurren Norte, Chile). σ_{bw} has a mean value of 0.4 m yr^{-1} , and ranges from 0.08 m yr^{-1}
19 (Shumskiy, Kazakhstan) to 1.2 m yr^{-1} (Echaurren Norte, Chile). σ_{bs} has a mean value of 0.5 m yr^{-1}
20 1 , and ranges from 0.2 m yr^{-1} (Waldemarbreen, Svalbard) to 1.3 m yr^{-1} (Ciardoney, Italy). Thus
21 there is a large spread in mass-balance variability depending on the setting, with the spread being
22 approximately equal in the winter and summer records.

24 The values of σ (dropping subscripts) calculated from the data are only an estimate of the true
25 standard deviation, σ_t (i.e., that of the true underlying distribution of which the data is only a

1 sample). For a record that is n years in length, and for significance level $1-p$, we have uncertainty
2 bounds given by:

$$3 \quad \sqrt{\frac{n-1}{\chi_{p/2}^2}} \leq \frac{\sigma|_t}{\sigma} \leq \sqrt{\frac{n-1}{\chi_{1-p/2}^2}} \quad (1)$$

4 where χ^2 is a chi-squared distribution with $n-1$ degree of freedom (e.g., vonStorch and Zwiers,
5 1999). For short records in particular, this means $\sigma|_t$ can be quite uncertain. For $n = 10$ years, the
6 95% bounds on $\sigma|_t$ are 69% to 183% of the sample value; for the median glacier length records of
7 around $n = 20$ years the bounds are 76% to 146%; while for $n = 50$ years, characteristic of the
8 longest records, the bounds are 84% to 125%. Thus for many of these glacier records (median
9 length = 23 yr) there is a factor of two or more uncertainty in the value of $\sigma|_t$. Note also that the
10 confidence bounds are asymmetric. The full list of uncertainties in the standard deviations of each
11 record is reported in the online supplementary information.

12 Figure 4 shows scatterplots of σ_{bw} and σ_{bs} against mean winter accumulation ($\equiv \mu_{bw}$), which
13 demonstrates the strong association between the variance and the mean. The records with the
14 largest σ_{bw} come from maritime climates, where μ_{bw} is also high (correlation coefficient, $r=0.81$).
15 This is consistent with accumulation variability tending to occur as a fraction of the mean. In the
16 long-term average, a large winter mass balance requires a large summer mass balance, and Figure
17 4 shows this also is typically accompanied by high summer variability, although the association is
18 less strong ($r = 0.44$). These analyses from our more comprehensive dataset echo and strengthen
19 the conclusions of Braithewaite & Zhang (1999).

20 4.2 Relative importance of winter and summer mass balance variability: 21

22 A series of recent studies has demonstrated that the interannual variability in glacier mass balance
23 is integrated by glacier dynamics to produce persistent glacier fluctuations, even in the absence of
24 persistence fluctuations in climate (e.g., Oerlemans, 2001; Roe and O'Neal, 2009; Roe 2011, Roe

1 and Baker, 2014). These studies find standard deviations of glacier length ($\equiv \sigma_L$) varying from a
 2 few hundred meters up to one kilometer depending on setting and modeling assumptions.
 3 Combined with a characteristic glacier response time of up to a few decades, the results
 4 demonstrate that century-scale, kilometer-scale fluctuations will occur, even in a constant climate.
 5 Such studies have used both numerical models of ice dynamics and also simple linear glacier
 6 models (e.g., Johanneson et al., 1989; Roe and Baker, 2014), which accurately emulate the
 7 numerical models. From the analytic solutions for the linear models, the variance in glacier length
 8 is related to the variance in mass balance via:

$$9 \quad \sigma_L^2 = K\sigma_{bn}^2,$$

10 where K is a constant that depends on glacier geometry (e.g., Oerlemans 2001; Roe and Baker
 11 2014). If r_{ws} is the correlation between winter and summer mass balance, then the above can be
 12 rewritten as:

$$13 \quad \sigma_L^2 = K(\sigma_{bw}^2 + \sigma_{bs}^2 + 2r_{ws}\sigma_{bw}\sigma_{bs}) \quad (x)$$

14 (e.g., Huybers and Roe, 2009). As we've seen, the great majority of glaciers are consistent with r_{ws}
 15 = 0. To simplify, we define R as the ratio of the winter variance to the sum of variances:

$$16 \quad R = \frac{\sigma_{bw}^2}{\sigma_{bw}^2 + \sigma_{bs}^2}. \quad (2)$$

17 For the case of $r_{ws} = 0$, R is equal to the fraction of the length variance attributable to winter mass-
 18 balance variance. Figures 5a,b shows the histogram and cumulative distribution for R for the 48
 19 seasonal records of the reduced dataset. The mean value of $R = 0.35$. Thus on average,
 20 summertime variance exceeds wintertime variance. We show the histogram of R grouped
 21 according to mean winter mass balance (Fig. 5a). For the wetter maritime climates, the value of R
 22 is generally greater than 0.5, meaning winter variance exceeds summer variance.

1 We note that, for any individual glacier, the value of R is quite uncertain, since it depends on both
2 σ_{bw} and σ_{bs} , which for short records are themselves uncertain. The 95% confidence bounds on R for
3 each glacier are reported in the supplementary material.

4 4.3 Mass balance trends: 5

6 In this section we evaluate the magnitude and significance of the trends in the records. We first fit
7 a simple linear regression to each record using least-squares minimization (e.g., vonStorch and
8 Zwiers, 1999). The difference between the end points of the regression line gives the magnitude of
9 the observed change, Δ . The length of the records will obviously affect the magnitude of Δ . For
10 example, the same trend for a 30 yr record will exhibit a larger Δ than a 10 year record. Because of
11 this, we report trends in normalized units of $\text{m yr}^{-1} \text{dec}^{-1}$.

12
13 The annual trends have a mean of $-0.17 \text{ m yr}^{-1} \text{dec}^{-1}$ and a median of $-0.18 \text{ m yr}^{-1} \text{dec}^{-1}$, and range
14 from $-1.1 \text{ m yr}^{-1} \text{dec}^{-1}$ (Ossoue Glacier, Pyrenees) to $+0.6 \text{ m yr}^{-1} \text{dec}^{-1}$ (Eliot Glacier, Cascade
15 Range). The summer trends have a mean of $-0.17 \text{ m yr}^{-1} \text{dec}^{-1}$ and a median of $-0.17 \text{ m yr}^{-1} \text{dec}^{-1}$,
16 ranging from $-0.9 \text{ m yr}^{-1} \text{dec}^{-1}$ (Hansebreen Glacier, Norway) to $+0.8 \text{ m yr}^{-1} \text{dec}^{-1}$ (Okstindbreen,
17 Norway). Finally, the winter trends have a mean of $-0.05 \text{ m yr}^{-1} \text{dec}^{-1}$ and a median of 0.0 m yr^{-1}
18 dec^{-1} , and range from $-0.7 \text{ m yr}^{-1} \text{dec}^{-1}$, (Okstindbreen again) to $+0.3 \text{ m yr}^{-1} \text{dec}^{-1}$ (Martial Este,
19 Andes). From these numbers and Figure 5 it can be seen that the strongest negative trends are in
20 the summer and annual records.

21
22 Which trends are statistically significant? To answer this, we use Student's t test. A test metric, t ,
23 may be calculated using the following formula (e.g., Lettenmaier, 1976; Casola et al., 2009; Roe
24 2011):

$$25 \quad t = \frac{\Delta}{\sigma} \sqrt{\frac{v-2}{12}} \quad (3)$$

1 Where Δ is the magnitude of the change attributable to the best-fit linear trend, σ is the standard
2 deviation, and v is the degrees of freedom--in this case the record length. In the absence of a trend
3 this metric follows a t distribution, which allows the null hypothesis of no trend to be evaluated
4 (e.g., vonStorch and Zwiers, 1999). Since we are interested in trends of either sign, we use a two-
5 sided test and require a significance level of $<5\%$. We note that this metric treats each glacier
6 independently, and so does not attempt to calculate combined probabilities.

7
8 Under this criteria, we find 27/115 and 16/48 of the annual and summer trends to be significant.
9 All of these are negative. On the other hand, just 4/48 winter records exhibit significant trends
10 (also negative). These results suggest that climate change has predominantly affected summer
11 ablation rather than winter accumulation.

12
13 It is important here to stress the difference between statistical and physical significance. An
14 observed trend should not be dismissed just because it is not statistically significant according to
15 one particular test. If the record is especially noisy it may not yield a statistically significant trend,
16 even if the observations are representative of a true underlying trend. It is likely that many of the
17 trends we find are real, but are not yet statistically discernable from background variability. In fact
18 we should expect this to be the case, given that most mass-balance records are short, and that there
19 is an established and widespread warming trend in the last century.

20
21 Finally we can apply Student's t -test to the whole distribution of trends shown in Figure 5. We find
22 that the mean of the summer and annual trends is different from zero at the 5% significance level,
23 but that the winter trends are not. It was somewhat surprising to find that the winter mass-balance
24 trends are not significant in the aggregate, given evidence of negative trends in winter snowpack
25 (Vaughn et al., 2013) and the physical expectation that warmer winter temperatures lift the winter
26 rain-snow line. However the effect of climate change on accumulation depends on elevation and

1 catchment hypsometry (e.g., Casola et al., 2009); and in many parts of the world changes in
2 average precipitation have yet to emerge from natural variability (Hartmann et al., 2013).

3 4.4 Trends in the Context of Variability: 4

5 A key objective of this study is to characterize mass-balance trends relative to natural variability.
6 Signal-to-noise ratio (SNR) can be defined as the ratio of Δ , the total change due to a trend, to σ ,
7 the standard deviation in the de-trended record. The SNR provides a simple, clear way to access
8 the sensitivity of a glacier to the trends it is subject to. However under the same trend, a longer
9 record yields an inherently larger SNR, making comparison between multiple records potentially
10 misleading. Consequently we chose to normalize the value of Δ by calculating the decadal trend,
11 as described in the preceding section. This leads to the normalized SNR, defined below:

$$12 \quad \Gamma = \frac{\Delta}{\sigma} \cdot \frac{1}{n \text{ yrs}} \cdot \frac{10 \text{ yrs}}{\text{decade}} \quad , \quad (4)$$

13 where n is the length of the record. While the standard definition of SNR is dimensionless, Γ can
14 be interpreted as the observed trend in units of σ per decade.

15
16 In the annual records Γ_{bn} has a mean of $-0.3 \sigma \text{ dec}^{-1}$, and ranges from $-1.4 \sigma \text{ dec}^{-1}$ (Zavisha Glacier,
17 British Columbia) to $+1.5 \sigma \text{ dec}^{-1}$ (Johnsons, Antarctic Peninsula). In the summer records Γ_{bs} has a
18 mean value of $-0.3 \sigma \text{ dec}^{-1}$ and ranges from $-2.2 \sigma \text{ dec}^{-1}$ (Waldemarbreen, Spitsbergen) to $+1.5 \sigma$
19 dec^{-1} (Okstindbreen, Norway). Finally, in the winter records Γ_{bw} has a mean value of $-0.04 \sigma \text{ dec}^{-1}$
20 and ranges from $-1.8 \sigma \text{ dec}^{-1}$ (Leviy Aktru, Altai Mtns) to $+1.8 \sigma \text{ dec}^{-1}$ (Hurd Glacier, Antarctic
21 Peninsula). As is to be expected the trends that are significant typically also have high values of Γ
22 and again are primarily associated with summer records.

23 24 5. Comparison with local climate records: two case studies. 25

1 How do the trends and variability in mass-balance records compare to the trends and variability in
2 other nearby indicators of climate? One can imagine, for example, that trends in precipitation and
3 temperature might have a compounding effect, producing stronger trends in mass-balance. Or it is
4 possible that because mass balance reflects a complex amalgam of meteorological influences, it is
5 noisier than other climate variables. Glaciers records are totemic symbols of climate change, but
6 because the observational network is so sparse it is important to establish the representativeness of
7 mass balance as a regional climate indicator. These issues are not the main focus of this paper, but in
8 this section we briefly explore them for two notable and long-studied glaciers: Nigardsbreen in
9 western Norway and South Cascade in Washington State. Monthly summaries of temperature and
10 precipitation were obtained from two stations near Nigardsbreen, and seven weather stations near
11 South Cascade. Data were obtained from the National Climatic Data Center
12 (<http://www.ncdc.noaa.gov/>). Mean summer temperature (defined June to September), and total
13 winter precipitation (defined November to March) were calculated for every year overlapping with
14 the glacier record. We applied the same analyses as for the mass-balance record, and the results are
15 summarized in Table 2. Representative time series are shown in Figure 8.

16
17 As might be expected, there is a general connection between mass balance and local climate records
18 for the two case studies. The stations near Nigardsbreen have experienced an average of 1.75 °C
19 increase in summer temperature over the period from 1962 to 2010, consistent with summer mass
20 balance becoming more negative, by -0.3 m yr^{-1} . Changes in precipitation and b_w are comparable. In
21 terms signal-to-noise, it is notable that the magnitude of Γ is larger, on average, for the station data
22 than for the mass balance (0.46 vs $-0.12 \sigma \text{ dec}^{-1}$ in summer, and 0.17 vs $0.05 \sigma \text{ dec}^{-1}$ in winter).

23

1 Stations near South Cascade glacier have warmed by an average of 0.7 °C between 1959 and 2011,
2 during which time summer mass balance became more negative by -1.0 m yr⁻¹. So both
3 Nigardsbreen and South Cascade regions have experienced warming and both have increased
4 ablation. However note that the regional-scale melt-factor (the ratio of ablation change to regional
5 temperature change) is not the same. Such melt factors are often used in predictions of mass-balance
6 change from the output of global climate models.

7
8 For South Cascades glacier, where the data is plentiful, for winter mass balance and station-based
9 precipitation, trends are generally weak and insignificant. However, for summer temperature, we
10 find a surprising variability in the trends and signal-to-noise ratios among the individual station
11 records. For the same reporting period, the station at Concrete shows a 0.5 °C *cooling* compared to a
12 2.4 °C *warming* at the Darrington station, located just 32 km away from Concrete. No doubt artificial
13 factors such as land-use and development may contribute to these intraregional differences (factors
14 which can also apply to glaciers, e.g., O’Neal et al., 2010), but it also serves to highlight that climate
15 records from individual point locations may not be representative of the regional averages. In terms
16 of signal-to-noise ratio, the magnitude of Γ_w is also highly variable (-0.14 to 0.61 σ dec⁻¹ for station
17 temperature vs. -0.37 σ dec⁻¹ for summer mass balance). Obviously this variability is a salutary
18 caution against interpreting isolated and sparse mass-balance records as indicative of regional
19 climate. This is particularly true if mass-balance records have a systematic bias on a landscape for
20 historical and accessibility reasons (e.g., Braithwaite, 2009).

22 6. Summary and Discussion

23

1 We've performed a statistical analysis of the complete global dataset of glacier mass-balance
2 records, with a particular focus on evaluating the magnitude of the signal (the observed trends
3 attributable to anthropogenic climate change), relative to the noise (the year-to-year natural
4 variability that occurs even in a constant climate due to the vagaries of weather).

5 Although analyses remain hampered by the short duration of most mass-balance records, we identify
6 115 annual and 48 seasonal records of mountain glaciers, with duration ten years or longer. This
7 represents a much larger dataset since the last assessment of mass-balance variability (Braithwaite
8 and Zhang, 1999). However there continues to be a significant bias in coverage towards Europe,
9 North America, and the former Soviet Union, and this bias should be borne in mind when
10 interpreting our results. The full set of analyses is available as a spreadsheet in the supplementary
11 material.

12 After linearly detrending the records, we find that they are almost all consistent with normally
13 distributed white noise (i.e., a Gaussian PDF, uncorrelated with time). A minority of glaciers (~15%)
14 shows some correlation between winter and summer, although we cannot distinguish whether this is
15 real or an artifact of the observational methodology.

16 We find that interannual variability in both winter and summer mass-balance records is closely
17 linked to the mean winter balance, being greatest in maritime climates and smallest in continental
18 climates. For the dataset as a whole, about 70% of records have summer variance that exceeds winter
19 variance. However for maritime climates, winter variance often exceeds summer variance.

20 Analyzing trends in mass balance, we find that negative mass-balance trends are primarily a summer
21 phenomenon. If a trend test is applied to each record individually, we nominally find that 25% of

1 net-annual records are significant at the 5% level. We want to be very clear that it would be incorrect
2 to infer that therefore 75% of the trends are not significant or not a result anthropogenic climate
3 change. There is a lot of information besides individual mass-balance records that inform about local
4 climate trends. Also when considered in the global aggregate, the trend in glacier mass balance is
5 negative and it is statistically significant.

6 We also evaluated the decadal signal-to-noise ratio, Γ , which can be interpreted as the mass-balance
7 trend in units of σ per decade. Such a metric is most reliable for the longest glacier records. For
8 annual-mean records exceeding 25 years, we found an average $\Gamma_{bn} = -0.2 \sigma \text{ dec}^{-1}$ (supplementary
9 material), but also a wide range, from $-0.8 \sigma \text{ dec}^{-1}$ (Careser, Italy, 46 yrs), to $+0.1 \sigma \text{ dec}^{-1}$
10 (Storglaciaeren, Sweden, 67 yrs). Important follow-up work would be to investigate these outliers,
11 by looking at nearby meteorological station data to establish if there is a discernible cause.

12 We also briefly investigated trends and variability in mass balance records relative to nearby station
13 records at two locations (Nigardsbreen and South Cascade). Although a proper analysis should be
14 much more comprehensive, we found that the relationship between regional temperature changes
15 and summer mass balance was different. And in the case of South Cascade we found considerable
16 differences among trends at nearby stations, the lesson being that caution is warranted in interpreting
17 any point record of climate (including mass balance) as indicative of regional trends.

18 There are some important qualifications to our analyses and results. Although the global dataset of
19 mass balance is improving year-by-year, the records are short and so the statistical resolving power
20 of our tests is not high. The analyses are therefore vulnerable to type II errors (i.e., the signal exists,
21 but was not detected, e.g., vonStorch and Zwiers, 1999). Here we've limited our analyses to what is
22 present in the mass-balance dataset. However mass balance is just a complicated combination of

1 other meteorological variables and, if done carefully, the presence of skewness, persistence, trends,
2 etc., can be evaluated from longer nearby meteorological station records where available.

3 A second issue is the quality of the data itself. Glacier mass balance is a brutally hard measurement
4 to make, and not only because of the physical effort involved. It requires a broad extrapolation from
5 a few point measurements, and involves a significant degree of subjectivity on the part of the
6 observers and analysts. Efforts have been made to standardize protocols (e.g., Kaser et al., 2003) but
7 despite this progress, the reporting of errors remains optional and rudimentary.

8 The complex relationship between meteorological variables and glacier mass balance makes
9 acquiring direct, globally representative mass-balance data all the more important. It will be the
10 work of future decades to sustain and expand an improving observation network. Increasingly,
11 technological advances mean that remote sensing of mass balance is possible (e.g., Bamber et al.,
12 2007), and work blending these new data sets with what already exists is ongoing (e.g., Cogley.,
13 2009; Gardner et al., 2013; Zemp et al., 2013).

14 Measurements of mass balance are important for monitoring the current state of glaciers. They are
15 also important for putting past and future glacier variability in context. For the past: by
16 characterizing the magnitude of natural mass-balance variability relative to the mass-balance trends
17 that have driven the observed glacier trends, one can use simple glacier models (e.g., Roe and Baker,
18 2014) to estimate the natural variability in glacier length that would occur even without climate
19 change; this provides an observationally derived baseline against which to evaluate the climatic
20 significance of past glacier variations. For the future: the magnitude of unforced internal variability
21 sets the irreducible lower bounds on the uncertainty of future climate projections (e.g., Hawkins and
22 Sutton, 2009; Deser et al., 2012); likewise, the observed natural variability in mass balance, together

1 with an assessment of its effect on glacier length, sets bounds on the predictability of future glacier
2 states. All of these applications will benefit from a growing, improving, and more comprehensive
3 global mass-balance dataset.

4 Acknowledgements:

6 References:

- 7 Ault TR, Cole JE, Pederson GT, Overpeck JT, St. George S, Otto-Bliesner B, Deser C, Woodhouse
8 C (2013) The continuum of hydroclimate variability in western North America during the last
9 millennium. *J Climate* 26:5863-5878. doi: 10.1175/JCLI-D-11-00732.1
- 10 Bamber JL, Rivera A (2007) A review of remote sensing methods for glacier mass balance
11 determination. *Global Planet Change* 59:138–148. doi: 10.1016/j.gloplacha.2006.11.031
- 12 Bartlett MS (1946) On the theoretical specification and sampling properties of autocorrelated time-
13 series. *Supplement to the Journal of the Royal Statistical Society* 8:27-41.
- 14 Box G, Jenkins G, Reinsel G (2008) *Time series analysis: Forecasting and control* (4th ed.). Wiley,
15 Hoboken, NJ 784 pp.
- 16 Braithwaite RJ, Zhang Y (1999). Relationships between interannual variability of glacier mass
17 balance and climate. *J Glaciol* 45:456–462.
- 18
- 19 Braithwaite RJ (2002) *Glacier Mass Balance: The First 50 Years of International Monitoring*.
20 *Progress in Physical Geography* 26:76-95.
- 21 Braithwaite RJ (2009) After six decades of monitoring glacier mass balance we still need
22 data but it should be richer data. *J Glaciol* 50:191-197.
- 23 Casola JH, Cuo L, Livneh B, Lettenmaier DP, Stoelinga MT, Mote PW, Wallace JM (2009)
24 Assessing the Impacts of Global Warming on Snowpack in the Washington Cascades. *J Climate*,
25 22:2758-2772.
- 26 Cogley JG (2009) Geodetic and direct mass-balance measurements: comparison and joint analysis.
27 *Ann Glaciol* 50:96–100.
- 28 Deser C, Phillips AS, Bourdette V, Teng H (2012) Uncertainty in climate change projections: The
29 role of internal variability. *Climate Dynamics* 38:527-546.

- 1 Dyurgerov M, Meier MF (2005) *Glaciers and the Changing Earth System: A 2004 Snapshot*.
2 Occasional Paper 58, Institute of Arctic and Alpine Research, University of Colorado, Boulder, CO,
3 118 pp.
- 4 Elsberg DH, Harrison WD, Echelmeyer KA, Krimmel RM (2001) Quantifying the effects
5 of climate and surface change on glacier mass balance. *J Glaciol* 47:649–658.
6
- 7 Gardner AS, Moholdt G, Cogley JG, Wouters B, Arendt AA, Wahr J, Berthier E, Hock R, Pfeffer
8 WT, Kaser G, Ligtenberg SRM, Bolch T, Sharp MJ, Hagen JO, van den Broeke MR, Paul F (2013)
9 A reconciled estimate of glacier contributions to sea level rise: 2003 to 2009. *Science* 340:852–857.
- 10 Fraedrich K, Blender R (2003) Scaling of atmosphere and ocean temperature correlations in
11 observations and climate models. *Physical Review Letters* 90:108501.
12 doi:10.1103/PhysRevLett.90.108501.
- 13 Fraedrich K, Luksch U, Blender R (2004) A 1/f-model for long time memory of the ocean surface
14 temperature. *Physical Review E* 70. doi:10.1103/PhysRevE.70.037301.
- 15 Hartmann DL, Klein Tank AMG, Rusticucci M, Alexander LV, Brönnimann S, Charabi Y, Dentener
16 FJ, Dlugokencky EJ, Easterling DR, Kaplan A, Soden BJ, Thorne PW, Wild M, Zhai PM (2013)
17 *Observations: Atmosphere and Surface*. In: *Climate Change 2013: The Physical Science Basis*.
18 *Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on*
19 *Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A.
20 Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United
21 Kingdom and New York, NY, USA.
- 22 Hawkins E, Sutton R (2009) The potential to narrow uncertainty in regional climate predictions. *Bull*
23 *Amer Met Soc* 90:1095-1107. doi:10.1175/2009BAMS2607.
- 24 Huss M, Hock R, Bauder A, Funk M (2010) Reply to the comment of Leclercq et al. on 100-year
25 mass changes in the Swiss Alps linked to the Atlantic Multi-decadal Oscillation. *The Cryosphere*
26 *Discussions* 4:258702592. doi:10.5194/tcd-4-2587-2592.
- 27 Huybers KM, Roe GH (2009) Glacier response to regional patterns of climate variability. *J Climate*
28 22:4606-4620.
- 29 Huybers P, Curry W (2006) Links between annual, Milankovitch, and continuum temperature
30 variability. *Nature* 41:329-32.
- 31 IPCC (2013) *Summary for Policymakers*. In: *Climate Change 2013: The Physical Science Basis*.
32 *Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on*
33 *Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A.
34 Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United
35 Kingdom and New York, NY, USA.
- 36 Jóhannesson T, Raymond CF, Waddington ED (1989) Timescale for adjustments of glaciers to
37 changes in mass balance. *J Glaciol* 35:355-369.

1 Kaser G, Fountain A, Jansson P (2003) A Manual For Monitoring the Mass Balance of Mountain
2 Glaciers. IHP-VI Technical Documents in Hydrology No. 59, UNESCO-IHP, Paris.
3

4 Laepple T, Huybers P (2014) Ocean surface temperature variability: Large model-data differences at
5 decadal and longer periods. *Proc Nat Acad Sci* 111:16,682-16,687.
6

7 Leclercq PW, van deWal RSW, Oerlemans J (2010) Comment on “100-year mass changes in the
8 Swiss Alps linked to the Atlantic Multidecadal Oscillation” by Matthias Huss et al. (2010). *The*
9 *Cryosphere Discuss* 4:2475–2481. doi:10.5194/tcd-4-2475-2010.
10

11 Lemke P, Ren J, Alley RB, Allison I, Carrasco J, Flato G, Fujii Y, Kaser G, Mote P, Thomas RH,
12 Zhang T (2007) Observations: Changes in Snow, Ice and Frozen Ground. In: *Climate Change 2007:*
13 *The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of*
14 *the Intergovernmental Panel on Climate Change* [Solomon, S., D. Qin, M. Manning, Z. Chen, M.
15 Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge,
16 United Kingdom and New York, NY, USA.
17

18 Lettenmaier DP (1976) Detection of trends in water quality data from records with dependent
19 observations. *Water Resour Res* 12:1037–1046.
20

21 MacMynowski DG, Shin H-J, Caldeira K (2011) The frequency response of temperature and
22 precipitation in a climate model. *Geophys Res Lett* 38:L16711.
23

24 Marzeion B, Jarosch AH, Hofer M (2012) Past and future sea-level change from the surface mass
25 balance of glaciers. *Cryosphere* 6:1295–1322.
26

27 Oerlemans J (2001) *Glaciers and climate change*. Lisse, etc., A.A. Balkema.

28 O'Neal MA, Roth LB, Hanson B, Leathers DJ (2010) A Field-Based Model of the Effects of
29 Landcover Changes on Daytime Summer Temperatures in the North Cascades.
30 *Physical Geography* 31:137-155. doi:10.2747/0272-3646.31.2.137

31 Percival DB, Overland JE, Mofjeld HO (2001) Interpretation of North Pacific Variability as a Short-
32 and Long-Memory Process. *J Climate* 14:4545-59.
33

34 Pelletier JD (1997) Analysis and modeling of the natural variability of climate. *J Climate* 10:1331-
35 1342.

36 Pelletier JD (1998) The power-spectral density of atmospheric temperature from time scales of 10^2
37 to 10^6 yr. *Earth and Planetary Science Letters* 158:157-164.
38

39 Pfeffer WT, Arendt AA, Bliss A, Bolch T, Cogley JG, Gardner AS, Hagen J-O, Hock R, Kaser
40 G, Kienholz C, Miles ES, Moholdt G, Mölg N, Paul F, Radić V, Rastner P, Raup BH, Rich J, Sharp
41 MJ (2014) The Randolph Glacier Inventory: a globally complete inventory of glaciers. *J Glaciology*
42 60:537-552.
43

1 Roe GH, O'Neal MA (2009) The response of glaciers to intrinsic climate variability: observations
2 and models of late-Holocene variations in the Pacific Northwest. *J Glaciology* 55:839-854.

3 Roe GH (2011) What do glaciers tell us about climate variability and climate change? *J Glaciology*
4 57:567-578.

5 Roe GH, Baker MB (2014) Glacier response to climate perturbations: an accurate linear geometric
6 model. *J Glaciology* 60:670-684

7 Roe GH, Baker MB (2015) The response of glaciers to climatic persistence. Submitted to *J*
8 *Glaciology*.

9 Schneider T, Neumaier A (2001) Algorithm 808: ARFIT - A Matlab package for the estimation of
10 parameters and eignemodes of multivariate autoregressive models. *ACM Trans Math Soft* 27:58-65.
11

12 Steinskog DJ, Tjøstheim DB, Kvamstø NG, (2007) A cautionary note on the use of the Kolmogorov-
13 Smirnov test for normality. *Mon Wea Rev* 135:1151-1157.

14 Vaughan DG, Comiso JC, Allison I, Carrasco J, Kaser G, Kwok R, Mote P, Murray T, Paul F, Ren J,
15 Rignot E, Solomina O, Steffen K, Zhang T (2013) Observations: Cryosphere. In: *Climate Change*
16 *2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report*
17 *of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor,*
18 *S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University*
19 *Press, Cambridge, United Kingdom and New York, NY, USA.*

20 vonStorch H, Zwiers FW (1999) *Statistical Analysis in Climate Research.* Cambridge University
21 Press,484pp.

22 WGMS (2013) *Glacier Mass Balance Bulletin No. 12 (2010-2011).* Zemp, M., Nussbaumer, S.U.,
23 Naegeli, K., Gärtner-Roer, I., Paul, F., Hoelzle, M. and Haeberli, W. (eds.), ICSU

24 WGMS (2014): *Fluctuations of Glaciers Database.* World Glacier Monitoring Service, Zurich,
25 Switzerland. DOI:10.5904/wgms-fog-2014-09. Online access: [http://dx.doi.org/10.5904/wgms-fog-](http://dx.doi.org/10.5904/wgms-fog-2014-09)
26 [2014-09](http://dx.doi.org/10.5904/wgms-fog-2014-09)

27 Zemp M, Thibert E, Huss M, Stumm D, Rolstad Denby C, Nuth C, Nussbaumer SU, Moholdt G,
28 Mercer A, Mayer C, Joerg PC, Jansson P, Hynek B, Fischer A, Escher-Vetter H, Elvehøy H,
29 Andreassen LM (2013) Reanalyzing glacier mass balance measurement series. *The Cryosphere*
30 7:1227–1245.

31 Zhu X, Fraedrich K, Liu Z, Blender R (2010) A demonstration of long-term memory and climate
32 predictability. *J Climate* 23:5021-5029.

33

Figure Captions

Figure 1: Locations of 158 glaciers with 10 years or more annual mass balance data. Marker size is proportional to record length. Note the preponderance of European and Scandinavian glaciers. The inset panel shows the cumulative distribution plot of glacier length.

Figure 2. Histograms of the average seasonal and net-annual mass balances for the restricted data set.

Figure 3. Histograms of the standard deviations of the winter, summer, net annual mass-balance records in the restricted data set.

Figure 4. From the restricted data set: standard deviation in winter and summer balance as a function of mean winter accumulation. Correlation between μ_{bw} and σ_{bw} is 0.81, correlation between μ_{bw} and σ_{bs} is 0.44.

Figure 5. (a) Histogram of R values divided into three groups according to the mean winter mass balance (colors). A value of $R > 0.5$ indicates winter mass-balance variance exceeds that in summer. Note the increased importance of winter mass balance in maritime climates. (b) same data represented as a cumulative distribution.

Figure 6. Decadal mass-balance trends in the restricted data set. Trends that are nominally significant ($p < 0.05$) are red, all other trends are blue.

Figure 7. Decadal signal-to-noise ratio, I (equivalent to the observed trend in units of σ per decade). Trends that are nominally significant ($p < 0.5$) are red, all other trends are blue.

Figure 8. A comparison of the summer mass balance at South Cascade with summer (JJAS) temperature data from nearby meteorological stations (see Table 2 for proximity). Note that the temperature scale is reversed (i.e., warmer temperatures towards the bottom). Tick marks are every plotted every 2 °C. Each temperature record is offset by 2 °C for clarity. Best-fit trend lines are plotted for the period of the mass balance record. To compare trends, the mass-balance scale on the right hand side has been chosen so that the plotted slope is equal to the average trend for the station data.

1

Table 1. Selected glacier records, with selected mass-balance metrics. Data columns report the mean net annual balance (μ_{bn}); the standard deviation (σ_{bn}) and 95% confidence bounds; the change in net annual balance over the record based on least-squares estimate (Δ_{bn}); the implied trend in $\text{m yr}^{-1} \text{dec}^{-1}$; the p -value of the trend based on Students t-test (p values (in bold) outside of $0.025 < p < 0.975$ implies significance at 95% level based on a two-sided test); the decadal signal-to-noise ratio (I) in units of σdec^{-1} .

Glacier	Length (yrs)	Location	μ_{bn} (m yr^{-1})	σ_{bn} (95% CI) (m yr^{-1})	Δ_{bn} (m yr^{-1})	Trend ($\text{m yr}^{-1} \text{dec}^{-1}$)	p value	I (σdec^{-1})
Storglaciären	67	N. Sweden	-0.3	0.7 {0.6, 0.9}	0.5	0.1	0.04	0.1
Hintereis Ferner	60	E. Alps	-0.6	0.5 {0.4, 0.6}	-1.1	-0.2	0.00	-0.4
S. Cascade	59	N. Cascade Mtns	-0.6	1.0 {0.9, 1.2}	-0.5	-0.1	0.14	-0.1
Ts. Tuyuksuyskiy	56	Tien Shan	-0.4	0.5 {0.4, 0.6}	-0.4	-0.1	0.04	-0.1
Nigardsbreen	51	W. Norway	0.4	1.0 {0.9, 1.3}	-0.2	-0.04	0.34	-0.04
Gulkana	47	Alaska Range	-0.5	0.5 {0.4, 0.7}	-1.0	-0.2	0.00	-0.4
Careser	46	Central Alps	-1.0	0.6 {0.5, 0.8}	-2.1	-0.5	0.00	-0.8
Peyto	46	Rocky Mtns	-0.6	0.6 {0.5, 0.8}	-0.7	-0.2	0.01	-0.3
Echuarren Norte	38	Central Andes	-0.4	1.6 {1.3, 2.0}	-0.9	-0.2	0.17	-0.1

2

3

Table 2. Comparing mass-balance records to nearby station records. σ_s is the standard deviation of the detrended summer records (Jun to Sept mean temperature for the station data); σ_w is the standard deviation of the detrended winter records (Nov to March total precipitation for the station data); Δ_s and Δ_w are the total changes of the summer and winter records attributable to the best-fit linear trend over the duration of the Nigardbreen (59 yrs) and South Cascade (62 yrs) records; Γ_s and Γ_w are the summer and winter signal to noise ratios in units of σ per decade. Data were obtained from National Climatic Data Center (<http://www.ncdc.noaa.gov/>)

Record/Station	Dist. to glacier	σ_s	σ_w	Δ_s	Δ_w	Γ_s ($\sigma \text{ dec}^{-1}$)	Γ_w ($\sigma \text{ dec}^{-1}$)
Nigardbreen	-	0.6 myr ⁻¹	0.6 myr ⁻¹	-0.3myr ⁻¹	0.2 myr ⁻¹	-0.12	0.05
Tafjord	60 km	0.9 °C	0.2 m	1.5 °C	0.1 m	0.38	0.17
Takele	122 km	0.7 °C	0.5 m	2.0 °C	0.4 m	0.55	0.17
South Cascade	-	0.6 myr ⁻¹	0.7 myr ⁻¹	-1.0 myr ⁻¹	0.2 myr ⁻¹	-0.37	0.07
Diablo Dam	40 km	0.7 °C	0.3 m	0.6 °C	0.03 m	0.15	0.02
Ross Dam	41 km	0.8 °C	0.2 m	1.0 °C	0.1 m	0.24	0.06
Darrington	42 km	0.8 °C	0.3 m	2.4 °C	0.01 m	0.61	0.003
Concrete	54 km	0.6 °C	0.2 m	-0.5 °C	0.1 m	-0.14	0.05
Startup	75 km	0.6 °C	0.2 m	0.4 °C	-0.01 m	0.11	-0.01
Sedro Woolley	87 km	0.5 °C	0.2 m	1.1 °C	-0.1 m	0.42	-0.07
Monroe	88 km	0.7 °C	0.1 m	-0.1 °C	-0.03 m	-0.04	-0.04

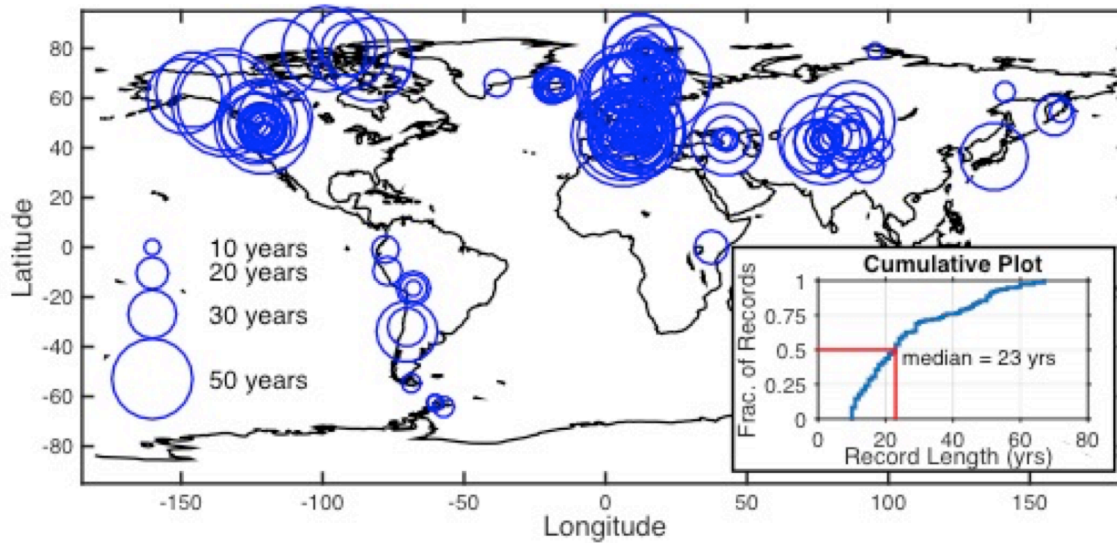


Figure 1: Locations of 158 glaciers with 10 years or more annual mass balance data. Marker size is proportional to record length. Note the preponderance of European and Scandinavian glaciers. The inset panel shows the cumulative distribution plot of glacier length.

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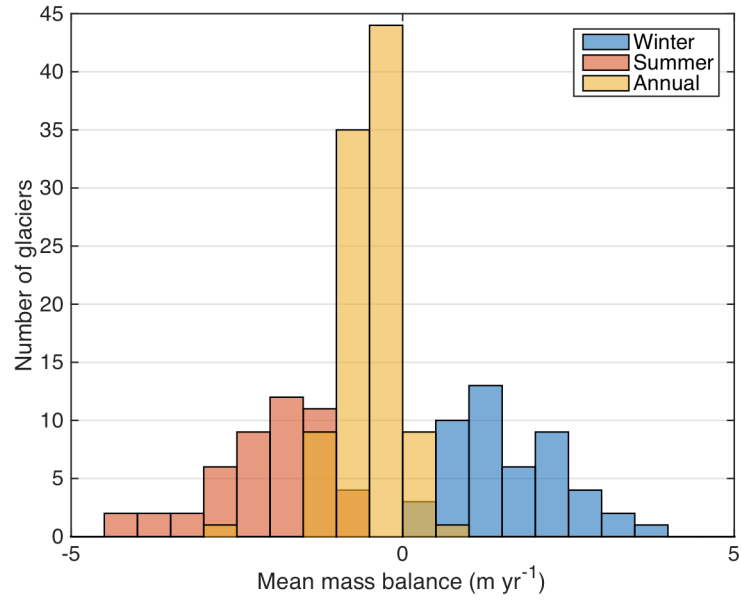


Figure 2. Histograms of the average seasonal and net-annual mass balances for the restricted data set.

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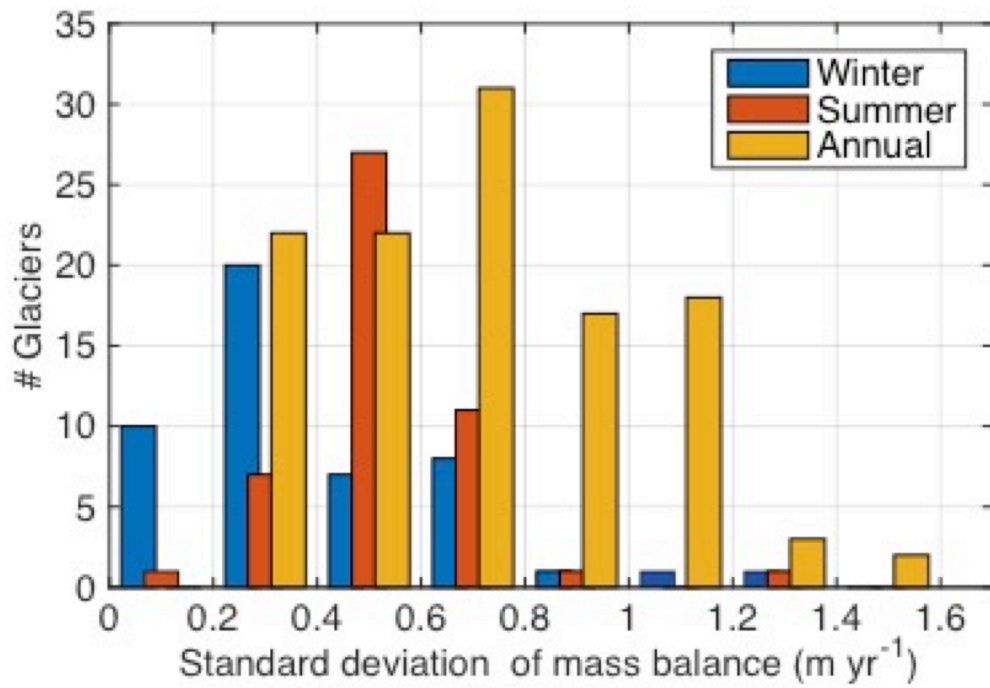


Figure 3. Histograms of the standard deviations of the winter, summer, net annual mass-balance records in the restricted data set.

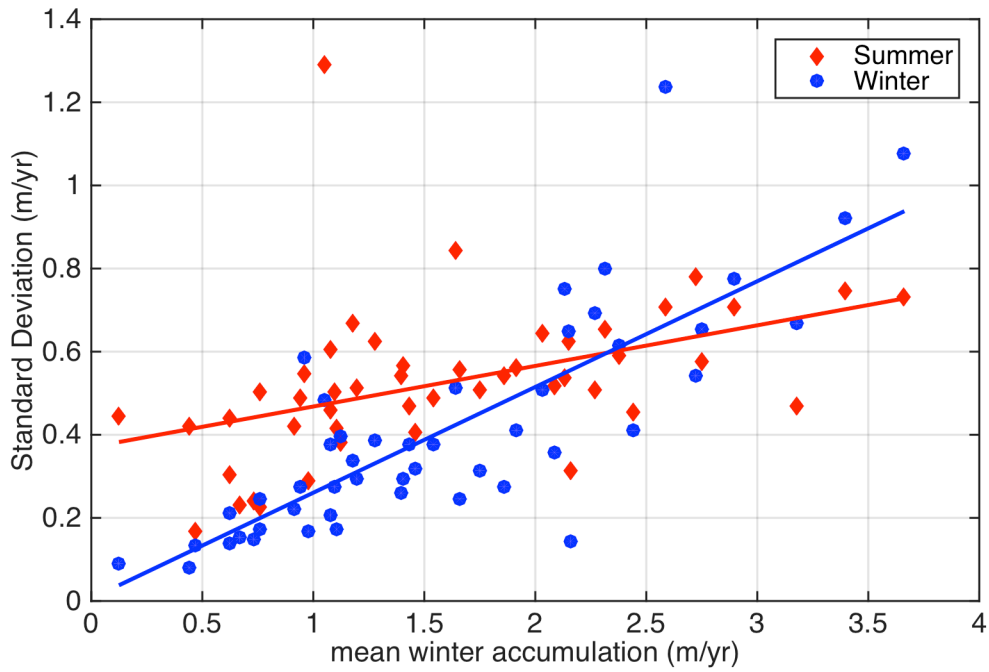


Figure 4. From the restricted data set: standard deviation in winter and summer balance as a function of mean winter accumulation. Correlation between μ_{bw} and σ_{bw} is 0.81, correlation between μ_{bw} and σ_{bs} is 0.44.

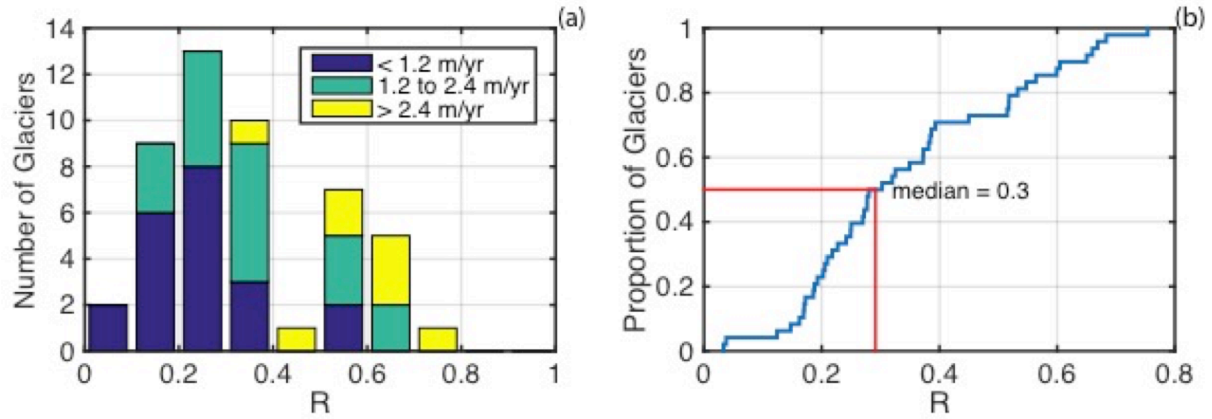


Figure 5. (a) Histogram of R values divided into three groups according to the mean winter mass balance (colors). A value of $R > 0.5$ indicates winter mass-balance variance is exceeds that in summer. Note the increased importance of winter mass balance in maritime climates. (b) same data represented as a cumulative distribution.

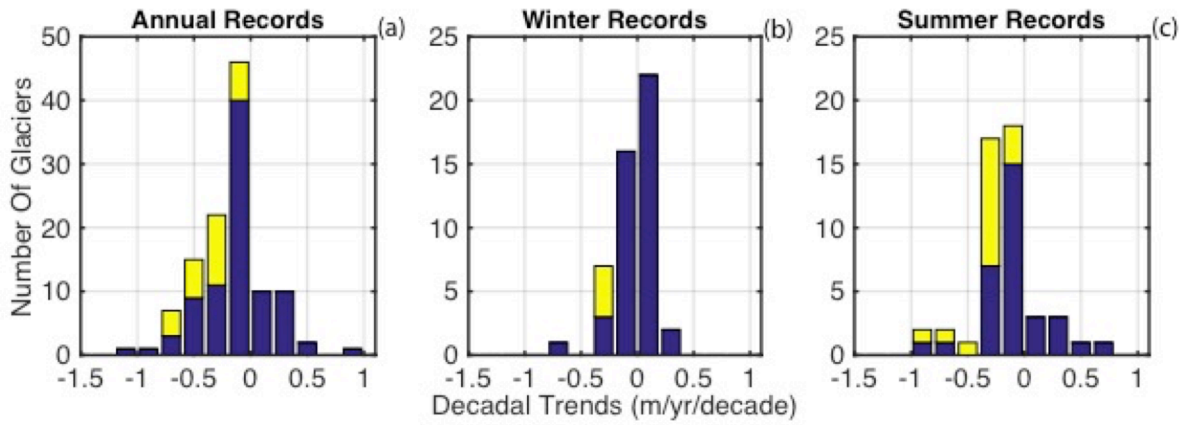


Figure 6. Decadal mass-balance trends in the restricted data set. Trends that are nominally significant ($p < 0.05$) are red, all other trends are blue.

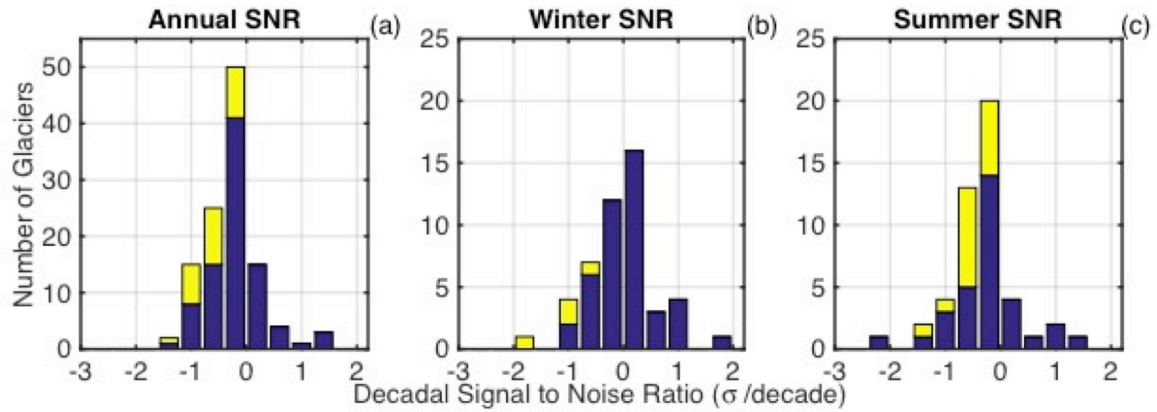


Figure 7. Decadal signal-to-noise ratio, Γ (equivalent to the observed trend in units of σ per decade). Trends that are nominally significant ($p < 0.5$) are red, all other trends are blue.

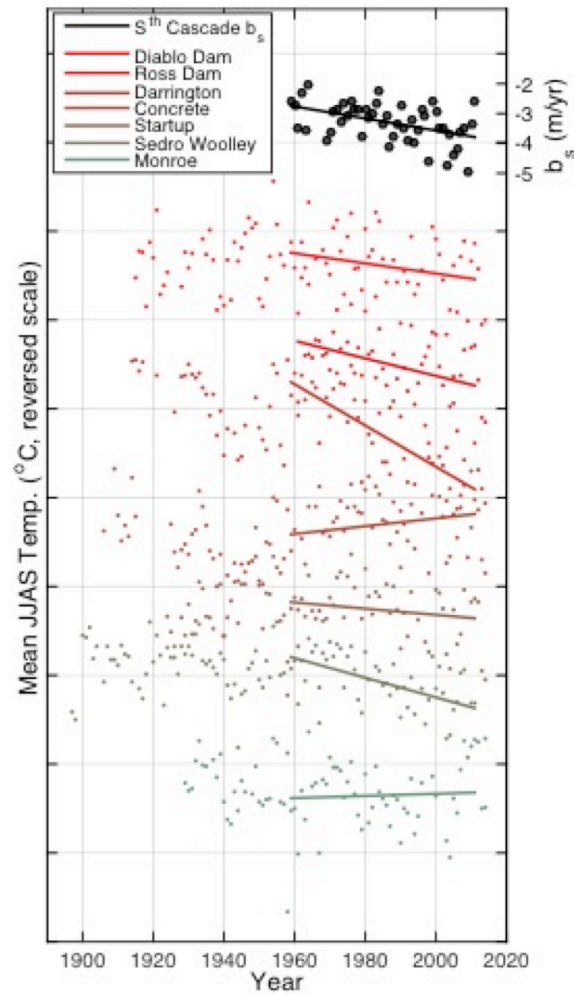


Figure 8. A comparison of the summer mass balance at South Cascade with summer (JJAS) temperature data from nearby meteorological stations (see Table 2 for proximity). Note that the temperature scale is reversed (i.e., warmer temperatures towards the bottom). Tick marks are every plotted every 2 °C. Each temperature record is offset by 2 °C for clarity. Best-fit trend lines are plotted for the period of the mass balance record. To compare trends, the mass-balance scale on the right hand side has been chosen so that the plotted slope is equal to the average trend for the station data.