Clim Dyn
DOI 10.1007/s00382-016-3253-x

Trends and variability in the global dataset of glacier mass balance

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Received: 28 July 2015 / Accepted: 20 June 2016
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Abstract Glacier mass balance (i.e., accumulation and ablation) is the most direct connection between climate and glaciers. We perform a comprehensive evaluation of the available global network of mass-balance measurements. Each mass-balance time series is decomposed into a trend and the variability about that trend. Observed variability ranges by an order of magnitude, depending on climate setting (i.e., maritime vs continental). For the great majority of glaciers, variability is well characterized by normally distributed, random fluctuations that are uncorrelated between seasons, or in subsequent years. The magnitude of variability for both summer and winter is well correlated with mean wintertime balance, which reflects the climatic setting. Collectively, summertime variability exceeds wintertime variability, except for maritime glaciers. Trends in annual mass balance are generally negative, driven primarily by summertime changes. Approximately 25 % of annual-mean records show statistically significant negative trends when judged in isolation. In aggregate, the global trend is negative and significant. We further evaluate the magnitude of trends relative to the variability. We find that, on average, trends are approximately −0.2 standard deviations per decade, although there is a broad spread among individual glaciers. Finally, for two long records we also compare mass-balance trends and variability with nearby meteorological stations. We find significant differences among stations meaning caution is warranted in interpreting any point measurement (such as mass balance) as representative of region-wide behavior. By placing observed trends in the context of natural variability, the results are useful for interpreting past glacial history, and for placing constraints on future predictability.

Electronic supplementary material The online version of this article (doi:10.1007/s00382-016-3253-x) contains supplementary material, which is available to authorized users.

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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 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 year^{-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., Jóhannesson et al. 1989; Oerlemans 2001; Roe and Baker 2014). Moreover, as has been noted in this context previously (Braithwaite and Zhang 1999), integrating the random, stochastic component of mass balance produces the well-known Drunkard's Walk effect (equivalent to Brownian motion), wherein the variance grows in time without bounds, and which introduces a biased end-state (e.g., von Storch and Zwiers 1999). The longer the mass-balance records, the less the cumulative mass-balance time series reflects the impact on glacier thickness. Recent research estimating sea-level contributions incorporates a dynamic adjustment to account for this effect (e.g., Marzeion et al. 2012).

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

Whilst most previous studies evaluating mass balance have aggregated observations into regional or global averages (e.g., Greene 2005; Zemp et al. 2015) we also characterize individual mass-balance records and their interannual variability. This focus allows us to document several important metrics of these mass-balance records: the magnitude of interannual variability sets the lower bound of the predictability of future mass balance (e.g., Hawkins and Sutton 2009); we establish the relative importance of winter versus summer mass-balance variability as a function of the mean climate state; we calculate the signal-to-noise ratio in individual records, from which the statistical significance of trends can be determined, and we deconstruct trends into separate winter and summer contributions. Our analyses represent a significant extension of Braithwaite and Zhang (1999), both for the variety of metrics documented, and the amount of new data available.

2 Glacier mass balance records

The World Glacier Monitoring Service (WGMS) is the main repository for standardized mass-balance observations from around the world (WGMS 2013, 2014, and earlier issues). Annual mass balance is the sum of accumulation (i.e., mass gain) and ablation (i.e., mass loss via melting, sublimation, calving), reported in m year^{-1} of water equivalent averaged over the glacier area, for the mass-balance year (Cogley et al. 2011). For a given year, the annual balance, b_n, is determined by extrapolating from perhaps 10 to 15 individual snow-stake measurements to estimate the area-averaged thickness change from the previous year's measurement; or by summing up the separately measured winter and summer balances b_w and b_s (Kaser et al. 2003). A minority of the mass-balance measurements are also accompanied by a reported "maximum error". What that means formally is not clear, and is apparently left up to individual groups to define. Reported accuracy for seasonal measurements are typically around 10 % but vary widely, from an assuredly over-optimistic <1 % to upwards of 25 % in some cases.

We make a brief aside here to note that mass balance can be defined in different ways. In this study we analyze the conventional mass balance (the direct measurements reported by the WGMS 2014). The calculation involves the observed glacier area, which is typically also evolving over the period of observations and so, to a degree, the mass balance also reflects glacier dynamics as well as climate. Mass balance calculated in this way acts as a high-pass filter of climate variability (e.g., Leclercq et al. 2010). An alternative index, the "reference-surface" mass balance, extrapolates observations over a fixed surface area, and has been proposed as a truer reflection of climate (Elsberg et al. 2001; Leclercq et al. 2010). Apart from the ready availability of conventional mass balance data, several other factors motivate our use of conventional mass-balance data: there are uncertainties involved in extrapolating point measurements to the hypsometry and area of the (nonexistent) reference surface. Furthermore, we analyze mass balance (rather than cumulative mass balance), which minimizes the differences between the methods (e.g., Elsberg et al. 2001). Finally, several studies have concluded that the two methodologies actually agree quite closely, and especially so when applied to the relatively short records of a few decades that are typical in the WGMS dataset (Elsberg et al. 2001; Huss et al. 2010). Thus, the differences between the

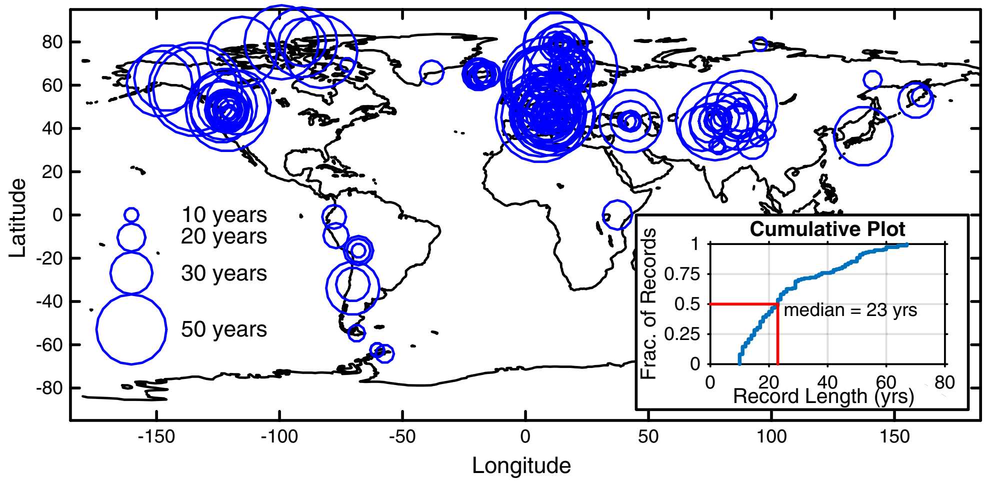

Fig. 1 Locations of 158 glaciers with 10 years or more annual mass-balance data. Marker size is proportional to record length. Note the preponderance of European and Scandinavian glaciers. The *inset panel* shows the cumulative distribution plot of glacier length

two methods are considerably smaller than both the uncertainties in the observations themselves, and also much smaller than the statistical bounds on the two primary metrics we are interested in—the trend and the standard deviation.

The WGMS archive has at least one year of mass-balance data for over 250 glaciers. From this complete dataset, we select records with at least 5 years of both winter and summer observations, and/or at least 10 years of annual observations. We used the stricter cut-off of 10 years for annual records because of their relative abundance compared to seasonal records. We found 130 records with 5 years or more of seasonal data, and 158 records with 10 years or more of annual data. Between these two datasets, there are 194 unique glaciers. Our statistical results are available for all 194 glaciers in the online supplementary material. However, for the discussion and figures presented in this paper, we further restricted the dataset based on some additional criteria.

First, many records are strewn with observational gaps, and any putative trend is less robust if there are a large number of empty data points. Consequently, we eliminated records with observational gaps that cover more than 20 % of the record's length. Second, estimates of trends and variability are very fragile when applied to short records. Even 10-year records yield large uncertainties, but we believe that 10 years provides the best compromise between maximizing the value of the available data while avoiding signals being obscured by short, noisy records. Thus in the restricted dataset, we also eliminated winter and summer mass balance records less than 10 years. Finally, we omitted all records that are associated with mountain and valley glaciers (we retain categories 4, 5, and 6 in the WGMS classification). These Alpine glaciers have a dynamical response to climate that is simpler than ice caps or tidewater glaciers, and as a result, have been the focus of most studies documenting and understanding the response to climate change. Applying these extra filters to our dataset narrowed the number of records to 48 winter and summer series, and 115 annual series. In general, and unless otherwise stated, any figures or results discussed henceforth are from this vetted, higher-quality, list of mass-balance records, hereafter referred to as the restricted dataset.

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

3 Preliminary assessment of the data

We begin by analyzing the mass-balance records as a whole. Figure 2 shows histograms of the time-averages

Table 1 Selected glacier records, with selected mass-balance metrics

Glacier	Length (years)	Location	μ_{bn} (m year^{-1})	σ_{bn} (95 % CI) (m year^{-1})	Δ_{bn} (m year^{-1})	Trend (m year^{-1} decade^{-1})	*p* value	Γ (σ decade^{-1})
Storglacieren	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	**1.00**	−0.4
S. Cascade	59	N. Cascade Mtns	−0.6	1.0 {0.9, 1.2}	−0.5	−0.1	0.86	−0.1
Ts. Tuyuksuys-kiy	56	Tien Shan	−0.4	0.5 {0.4,0.6}	−0.4	−0.1	0.96	−0.1
Nigardsbreen	51	W. Norway	0.4	1.0 {0.9, 1.3}	−0.2	−0.04	0.66	−0.04
Gulkana	47	Alaska Range	−0.5	0.5 {0.4, 0.7}	−1.0	−0.2	**1.00**	−0.4
Careser	46	Central Alps	−1.0	0.6 {0.5, 0.8}	−2.1	−0.5	**1.00**	−0.8
Peyto	46	Rocky Mtns	−0.6	0.6 {0.5, 0.8}	−0.7	−0.2	**0.99**	−0.3
Echuarren Norte	38	Central Andes	−0.4	1.6 {1.3, 2.0}	−0.9	−0.2	0.83	−0.1

Data columns report the mean annual balance (μ_{bn}); the standard deviation (σ_{bn}) and 95 % confidence bounds; the change in annual balance over the record based on least-squares estimate (Δ_{bn}); the implied trend in m year decade^{-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 (Γ) in units of σ decade^{-1}

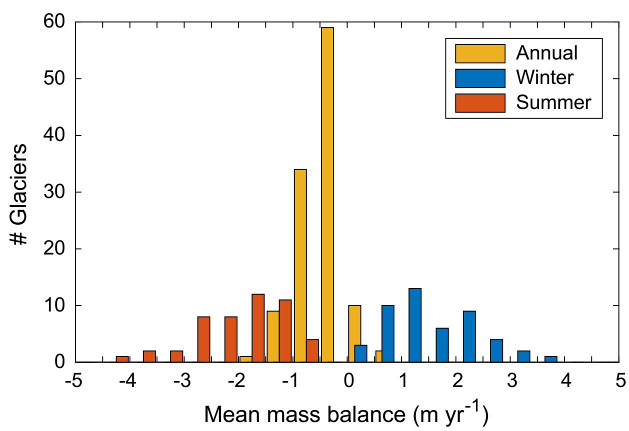

Fig. 2 Histograms of the average seasonal and annual mass balances for the restricted data set

of the seasonal and annual mass-balance records. From the restricted data set, the average winter mass balance is 1.6 m year^{-1} (ranging from 0.12 m year^{-1} for glacier #1 in the Tien Shan to 3.7 m year^{-1} for Aalfotbreen, Norway). The average summer mass balance is −2.0 m year^{-1} (ranging from −4.2 m year^{-1} for Ossoue glacier in the Pyrenees to −0.71 m year^{-1} for Johnsons glacier in the Antarctic Peninsula). The average annual balance is −0.44 m year^{-1} (ranging from −1.6 m year^{-1} for Ossoue glacier in the Pyrenees to +0.65 m year^{-1} for Eliot glacier, Cascade Range). Thus the overall picture is one of an approximately order-of-magnitude spread in seasonal mass balance depending on climatic setting and, in the aggregate, a negative annual mass balance consistent with a warming climate.

3.1 Are the records normally distributed?

We focus first on the variability in the mass-balance records. To that end, we linearly de-trend the winter, summer, and annual mass-balance time series using least-squares regression (e.g., von Storch and Zwiers 1999). This is standard practice in order to separate any trend from the natural, interannual variability. We report the trends and their uncertainties in a later section.

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

Thus, the main result is that the variability in the vast majority of de-trended records is consistent with a normal distribution. For the JB test, the number of records for which the null hypothesis is rejected is slightly higher than expected by chance indicating some possible skewness (or kurtosis). For the records that failed the JB test for normality, the skewness of the seasonal records showed no preference towards positive or negative. However, all 14 annual records that failed the JB test showed negative skewness (i.e., more extreme ablation than accumulation), with a mean skewness of −1.0 and a standard deviation in skewness of 0.2. Potentially this reflects a genuine skewness in variability, or it may result from having linearly detrended what is actually a nonlinear trend. But in any event this skewness applies only to a small minority of records and may not deliver up a clear or meaningful interpretation. Kurtosis tests were consistent with a Gaussian kurtosis of 3.

3.2 Is there persistence in the records?

Next, each de-trended mass-balance record was tested for autocorrelation (i.e., persistence in time). A time series with no persistence is also known as a white noise process (e.g., Box et al. 2008). The presence of persistence reduces the degrees of freedom in a time series, which affects the statistical significance of any trends and the uncertainty bounds on estimated metrics of the time series such as the standard deviation. Perhaps the most straightforward statistical test is due to Bartlett (1946). For data drawn from a white noise process, the autocorrelation coefficient has a normal distribution with zero mean and variance $1/n$, where n is the length of the record. The null hypothesis of no persistence can be rejected at the 5 % significance level if the lag-1 year autocorrelation exceeds $1.96/\sqrt{n}$. From this basic test, we cannot reject the null hypothesis in 128 of 130 summer and winter records each, and 152 of 158 annual records. (The corresponding numbers for the restricted data set are 47/48 summer, 47/48 winter, 111/115 annual). These results imply that the de-trended mass-balance records are well described by a white-noise process.

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

Since the exceptions are broadly within what one would have expected by chance, we hereafter treat all records as uncorrelated in time, and proceed assuming that the degrees of freedom in each record (needed for other statistical tests), are equal to the length of the record. Thus for the timescales covered by the glacier records (years to decades), on the basis of the mass-balance records alone, one cannot conclude that persistence exists in the climatic variability experienced by glaciers (see also Burke and Roe 2014; Roe and Baker 2016).

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

In the present study we confine ourselves to simply characterizing the available mass balance data as it stands. However, for a fuller discussion of the potential impact of climatic persistence on glacier fluctuations, we refer readers to Roe and Baker (2016), which shows that a degree of persistence that might not be detected in even the longest mass balance records can nonetheless substantially enhance the glacier fluctuations arising from mass–balance variability.

3.3 Is there correlation between winter and summer records?

Finally we examine the correlation between corresponding de-trended winter and summer records. Of the 130 seasonal records, 21 yield a statistically significant (5 % level) Pearson correlation coefficient (e.g., von Storch and Zwiers 1999) between winter and summer records. In the restricted dataset, 8 of 48 records have a statistically significant correlation. Thus, for the majority of glaciers analyzed, winter and summer mass balance are uncorrelated. However, slightly more records yield significant correlation than can be explained by type I errors alone (i.e., a false positive, e.g., von Storch and Zwiers 1999). There are physical grounds for expecting an inter-seasonal correlation: high winter snowfall might reduce the period of bare ice (and low albedo) during the subsequent ablation season (e.g., Braithwaite and Zhang 1999). However, it is also possible that correlations are an artifact of the observation protocols: extended or foreshortened accumulation and ablation seasons mean that visits to measure the glacier mass balance may not coincide with the maximum or minimum of that year's mass-balance seasonal cycle (e.g., Braithwaite 2002; Kaser et al. 2003). With no more information, it is impossible to disentangle these effects.

4 Results

4.1 Standard deviation of mass balance series

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

The values of σ (dropping subscripts) calculated from the data are only an estimate of the true standard deviation, $\sigma|_t$ (i.e., that of the true underlying distribution of which the data is only a sample). For a record that is n years in length, and for significance level 1-p, we have uncertainty bounds given by:

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

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

Figure 4 shows scatterplots of σ_{bw}, σ_{bs}, and σ_{bn} against mean winter accumulation ($\equiv \mu_{bw}$), which demonstrates the strong association between the variance and the mean. The records with the largest σ_{bw} come from maritime climates, where μ_{bw} is also high (correlation coefficient, $r = 0.81$). This is consistent with accumulation variability tending to occur as a fraction of the mean. In the long-term average, a large winter mass balance requires a large summer mass balance, and Fig. 4 shows this is typically accompanied by high summer variability, although the association is less strong ($r = 0.44$). The annual-mean variability is also highly correlated with mean winter balance ($r = 0.79$). This last correlation is sufficiently strong that the mean accumulation may be used to estimate annual-mean variability

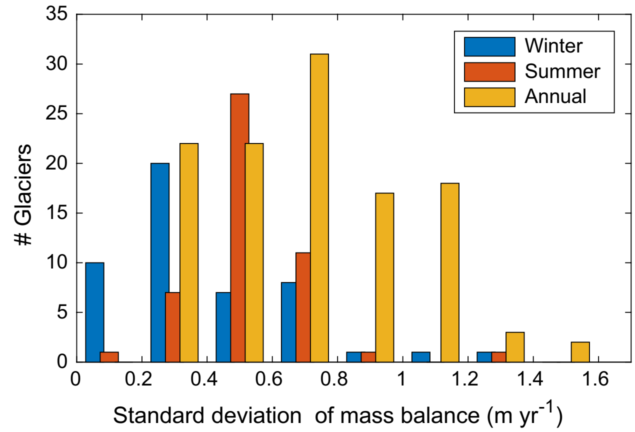

Fig. 3 Histograms of the standard deviations of the winter, summer, annual mass-balance records in the restricted data set

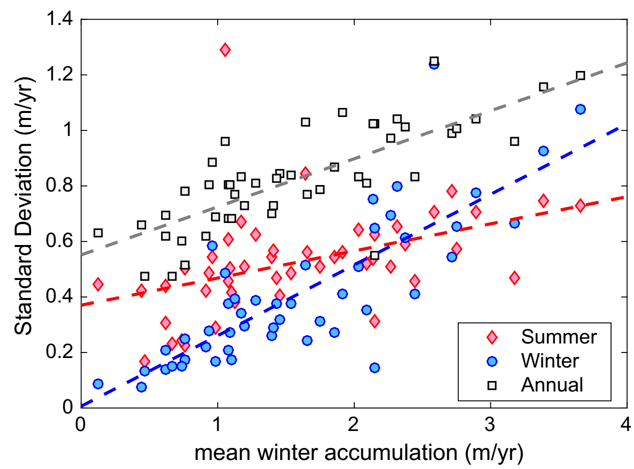

Fig. 4 From the restricted data set: standard deviation in winter, summer, and annual balance as a function of mean winter accumulation. The correlation between μ_{bw} and σ_{bw} is 0.81; correlation between μ_{bw} and σ_{bs} is 0.44; and correlation between μ_{bw} and σ_{bn} and 0.79. Also shown are the least-squares best-fit lines through each scatter plot. Note, some outliers (e.g., Ciardoney glacier, with $\mu_{bw} \sim 1$ m/year, has $\sigma_{bs} > \sigma_{bn}$) reveal possible inconsistencies among the seasonal and annual datasets, which result from either genuine measurement issues, or post-processing effects on short records

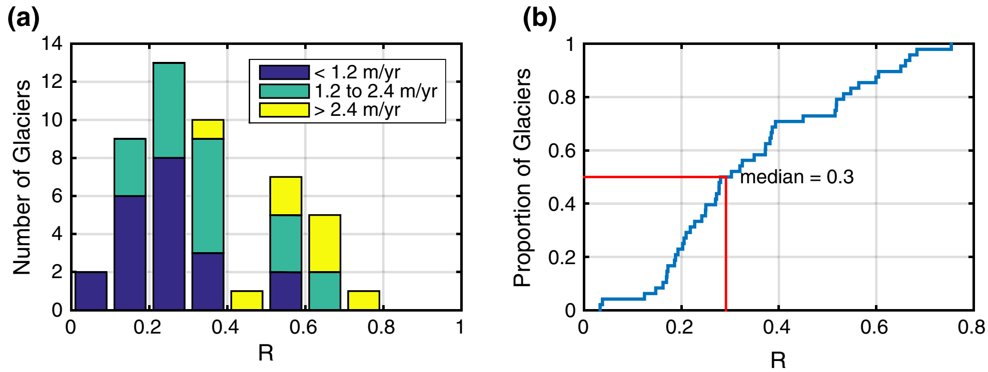

Fig. 5 **a** Histogram of R values divided into three groups according to the mean winter mass balance (*colors*). A value of $R > 0.5$ indicates winter mass-balance variance is exceeds that in summer. Note the increased importance of winter mass balance in maritime climates. **b** same data represented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

even where observations are not long enough to estimate variability directly. These analyses from our more comprehensive dataset echo and strengthen the conclusions of Braithwaite and Zhang (1999). It is worth noting that interannual variability of both winter and summer mass balance have important implications for variability of streamflow, especially in the upper reaches of glacier-fed catchments. Winter accumulation reflects regional snowpack, which typically contributes to streamflow in spring and early summer, whereas melt water from summer ablation of glacier ice can be the most important contribution to late-summer streamflow (e.g., Cuffey and Paterson 2010). The results in Fig. 4 and the on-line supplementary results table provide some information about how these factors vary as a function of mean climate, and geographic location.

4.2 Relative importance of winter and summer mass balance variability

A series of recent studies has demonstrated that the interannual variability in glacier mass balance is integrated by glacier dynamics to produce persistent glacier fluctuations, even in the absence of persistence fluctuations in climate (e.g., Oerlemans 2001; Roe and O'Neal 2009; Roe 2011, Roe and Baker 2014). These studies find standard deviations of glacier length ($\equiv \sigma_L$) varying from a few hundred meters up to one kilometer depending on setting and modeling assumptions. Combined with a characteristic glacier response time of up to a few decades, the results demonstrate that century-scale, kilometer-scale fluctuations will occur, even in a constant climate. Such studies have used both numerical models of ice dynamics and also simple linear glacier models (e.g., Jóhannesson et al. 1989; Roe and Baker 2014), which accurately emulate the numerical models. From the analytic solutions for the linear models, we can relate variance in glacier length to variance in mass balance via:

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

where K is a constant that depends on glacier geometry (e.g., Oerlemans 2001; Roe and Baker 2014). These relationships allow us to use mass-balance observations to estimate the relative importance of winter and summer mass balance for driving glacier variations. If r_{ws} is the correlation between winter and summer mass balance, then the above can be rewritten as:

$$\sigma_L^2 = K\left(\sigma_{bw}^2 + \sigma_{bs}^2 + 2r_{ws}\sigma_{bw}\sigma_{bs}\right)$$

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

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

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

We note that, for any individual glacier, the value of R is quite uncertain, since it depends on both σ_{bw} and σ_{bs}, which for short records are themselves uncertain. The 95 %

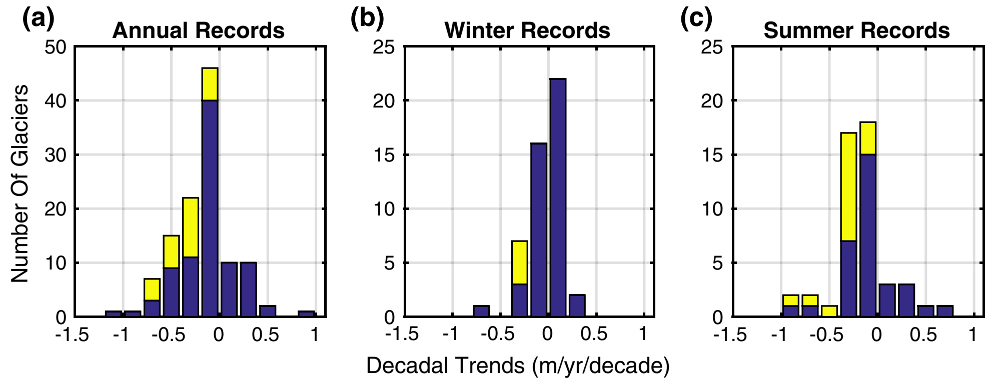

Fig. 6 Decadal mass-balance trends in the restricted data set. Trends that are nominally significant ($p < 0.05$) are *yellow*, all other trends are *blue*

confidence bounds on R for each glacier (generated using an F-test, von Storch and Zwiers 1999) are reported in the supplementary material.

4.3 Mass balance trends

In this section we evaluate the magnitude and significance of the trends in the records. We first fit a simple linear regression to each record using least-squares minimization (e.g., von Storch and Zwiers 1999). The difference between the end points of the regression line gives the magnitude of the observed change, Δ. Because the length of the records will obviously affect the magnitude of Δ, we report trends in normalized units of m year^{-1} decade^{-1}.

The full distributions of trends are shown in Fig. 6. The annual trends have a mean of -0.17 m year^{-1} decade^{-1} and a median of -0.18 m year^{-1} decade^{-1}, and range from -1.1 m year^{-1} decade^{-1} (Ossoue Glacier, Pyrenees) to $+0.6$ m year^{-1} decade^{-1} (Eliot Glacier, Cascade Range). The summer trends have a mean of -0.17 m year^{-1} decade^{-1} and a median of -0.17 m year^{-1} decade^{-1}, ranging from -0.9 m year^{-1} decade^{-1} (Hansebreen Glacier, Norway) to $+0.8$ m year^{-1} decade^{-1} (Okstindbreen, Norway). Finally, the winter trends have a mean of -0.05 m year^{-1} decade^{-1} and a median of 0.0 m year^{-1} decade^{-1}, and range from -0.7 m year^{-1} decade^{-1}, (Okstindbreen again) to $+0.3$ m year^{-1} decade^{-1} (Martial Este, Andes). From these numbers it can be seen that the strongest negative trends are in the summer and annual records.

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

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

where Δ is the magnitude of the change attributable to the best-fit linear trend, σ is the standard deviation, and ν is the degrees of freedom–in this case the record length. In the absence of a trend this metric follows a Student's t distribution (e.g., von Storch and Zwiers 1999). Since we are interested in trends of either sign, we use a two-sided test and require a significance level of <5 %. We note that this metric treats each glacier independently, and so does not attempt to calculate combined probabilities.

Under this criteria, we find 27/115 and 16/48 of the annual and summer trends to be significant. All of these are negative (Fig. 6a, c). On the other hand, just 4/48 winter records exhibit significant trends (also negative, Fig. 6b). These results suggest that climate change has predominantly affected summer ablation rather than winter accumulation. It is perhaps interesting to note the preponderance of statistically significant trends in summer rather than winter, despite the generally higher summertime variability.

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

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

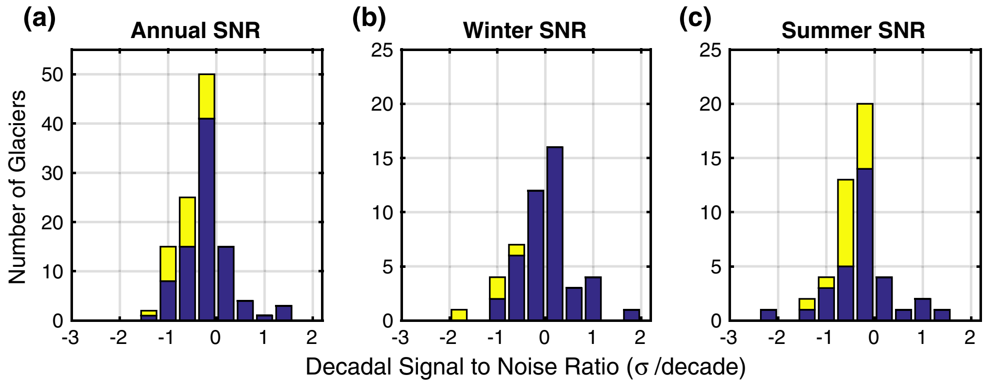

Fig. 7 Decadal signal-to-noise ratio, Γ (equivalent to the observed trend in units of σ per decade). Trends that are nominally significant ($p < 0.5$) are *yellow*, all other trends are *blue*

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

4.4 Trends in the context of variability

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

$$\Gamma = \frac{\Delta}{\sigma} \cdot \frac{1}{\text{n years}} \cdot \frac{10\,\text{years}}{\text{decade}}, \tag{4}$$

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

Results for Γ are shown in Fig. 7. In the annual records Γ_{bn} has a mean of -0.3 σ decade^{-1}, and ranges from -1.4 σ decade^{-1} (Zavisha Glacier, British Columbia) to $+1.5$ σ decade^{-1} (Johnsons, Antarctic Peninsula). In the summer records Γ_{bs} has a mean value of -0.3 σ decade^{-1} and ranges from -2.2 σ decade^{-1} (Waldemarbreen, Spitsbergen) to $+1.5$ σ decade^{-1} (Okstindbreen, Norway). Finally, in the winter records Γ_{bw} has a mean value of -0.04 σ decade^{-1} and ranges from -1.8 σ decade^{-1} (Leviy Aktru, Altai Mtns) to $+1.8$ σ decade^{-1} (Hurd Glacier, Antarctic Peninsula). As is to be expected the trends that are significant typically also have high values of Γ and again are primarily associated with summer records.

5 Comparison with local climate records: two case studies

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

As might be expected, there is a general connection between mass balance and local climate records for the two case studies. The stations near Nigardsbreen have experienced an average of 1.75 °C increase in summer temperature over the period from 1962 to 2010, consistent

Table 2 Comparing mass-balance records to nearby station records

Record/station	Dist. to glacier	σ_s	σ_w	Δ_s	Δ_w	Γ_s (σ decade^{-1})	Γ_w (σ decade^{-1})
Nigardsbreen	–	0.6 m year^{-1}	0.6 m year^{-1}	−0.3 m year^{-1}	0.2 m year^{-1}	−0.12	0.05
Tafjord	60 km	0.9 °C	0.2 m	1.5 °C	0.1 m	0.38	0.17
Takle	122 km	0.7 °C	0.5 m	2.0 °C	0.4 m	0.55	0.17
South Cascade	–	0.6 m year^{-1}	0.7 m year^{-1}	−1.0 m year^{-1}	0.2 m year^{-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

σ_s is the standard deviation of the detrended summer records (Jun to Sept mean temperature for the station data); σ_s 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 (49 years) and South Cascade (53 years) 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/)

with summer mass balance becoming more negative, by −0.3 m year^{-1}. Changes in precipitation and b_w are comparable. In terms of signal-to-noise, it is notable that the magnitude of Γ is larger, on average, for the station data than for the mass balance (0.46 vs −0.12 σ decade^{-1} in summer, and 0.17 vs 0.05 σ decade^{-1} in winter).

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

For South Cascades glacier, nearby station data is more abundant (see Fig. 8). We find winter trends (both mass balance and station-based precipitation) are generally weak and insignificant. However, for summer temperature, we find a surprising variability in the trends and signal-to-noise ratios among the individual station records. For the same reporting period, the station at Concrete shows a 0.5 °C *cooling* compared to a 2.4 °C *warming* at the Darrington station, located just 32 km away from Concrete. No doubt artificial factors such as land-use and development may contribute to these intraregional differences (factors which can also apply to glaciers, e.g., O'Neal et al. 2010), but it also serves to highlight that climate records from individual point locations may not be representative of the regional averages. In terms of signal-to-noise ratio, the magnitude of Γ_w is also highly variable (−0.14 to 0.61 σ decade^{-1} for station temperature vs −0.37 σ decade^{-1} for summer mass balance). Obviously this variability is a salutary caution against interpreting isolated and sparse mass-balance records as indicative of regional climate. This is particularly true if mass-balance records have a systematic bias on a landscape for historical and accessibility reasons (e.g., Braithwaite 2009), and such caution is only amplified by uncertainty in other factors unique to the glaciers (e.g., ice microclimates, avalanches, surface debris, changes in geometry, etc.)

6 Summary and discussion

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

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

After linearly detrending the records, we find that they are almost all consistent with normally distributed white noise (i.e., a Gaussian PDF, uncorrelated with time). A

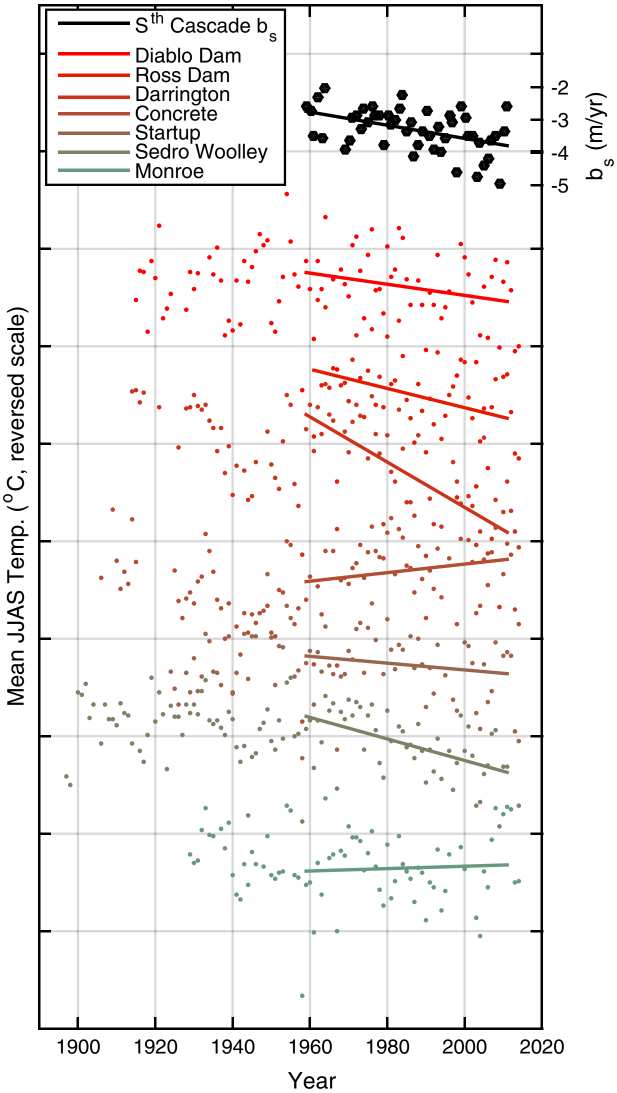

Fig. 8 A comparison of the summer mass balance at South Cascade with summer (JJAS) temperature data from nearby meteorological stations (see Table 2 for proximity). Note that the temperature scale is reversed (i.e., warmer temperatures towards the bottom). Tick marks are every plotted every 2 °C. Each 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 trend slope is equal to the average trend slope for the station data

minority of glaciers (~15 %) shows some correlation between winter and summer, although we cannot distinguish whether this is real or an artifact of the observational methodology.

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

Analyzing trends in mass balance, we find that negative mass-balance trends are primarily a summer phenomenon. If a trend test is applied to each record individually, we nominally find that 25 % of annual records are significant at the 5 % level. We want to be very clear that it would be incorrect to infer that therefore 75 % of the trends are not significant or not a result anthropogenic climate change. There is a lot of information besides individual mass-balance records that inform about local climate trends. Also when considered in the global aggregate, the trend in glacier mass balance is negative and it is statistically significant.

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

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

There are some important qualifications to our analyses and results. Although the global dataset of mass balance is improving year-by-year, the records are short and so the statistical resolving power of our tests is not high. The analyses are therefore vulnerable to type II errors (i.e., the signal exists, but was not detected, e.g., von Storch and Zwiers 1999). Here we've limited our analyses to what is present in the mass-balance dataset. However mass balance is just a complicated combination of other meteorological variables and, if done carefully, the presence of skewness, persistence, trends, etc., can be evaluated from longer nearby meteorological station records where available.

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

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

Measurements of mass balance are important for monitoring the current state of glaciers. They are also important for putting past and future glacier variability in context. For the past: by characterizing the magnitude of natural mass-balance variability relative to the mass-balance trends that have driven the observed glacier trends, one can use simple glacier models (e.g., Roe and Baker 2014) to estimate the natural variability in glacier length that would occur even without climate change; this provides an observationally derived baseline against which to evaluate the climatic significance of past glacier variations. For the future: the magnitude of unforced internal variability sets the irreducible lower bounds on the uncertainty of future climate projections (e.g., Hawkins and Sutton 2009; Deser et al. 2012); likewise, the observed natural variability in mass balance, together with an assessment of its effect on glacier length, sets bounds on the predictability of future glacier states. All of these applications will benefit from a growing, improving, and more comprehensive global mass-balance dataset.

Acknowledgments We are grateful to Kurt Cuffey and one anonymous reviewer for constructive and useful guidance, and to Ed Schneider, the editor.

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