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RESEARCH ARTICLE

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Key Points:

- We propose a nonlinear statistical model to extract a robust and consistent climatic signal for each glacier
- Our method has been tested from glacier mass balance observations for four glaciers located in very different climatic regimes
- This model, available for the whole community, can be used to assess the impact of climate change in different regions of the world

Supporting Information:

- Supporting Information S1

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A Nonlinear Statistical Model for Extracting a Climatic Signal From Glacier Mass Balance Measurements

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Abstract Understanding changes in glacier mass balances is essential for investigating climate changes. However, glacier-wide mass balances determined from geodetic observations do not provide a relevant climatic signal as they depend on the dynamic response of the glaciers. In situ point mass balance measurements provide a direct signal but show a strong spatial variability that is difficult to assess from heterogeneous in situ measurements over several decades. To address this issue, we propose a nonlinear statistical model that takes into account the spatial and temporal changes in point mass balances. To test this model, we selected four glaciers in different climatic regimes (France, Bolivia, India, and Norway) for which detailed point annual mass balance measurements were available over a large elevation range. The model extracted a robust and consistent signal for each glacier. We obtained explained variances of 87.5, 90.2, 91.3, and 75.5% on Argentière, Zongo, Chhota Shigri, and Nigardsbreen glaciers, respectively. The standard deviations of the model residuals are close to measurement uncertainties. The model can also be used to detect measurement errors. Combined with geodetic data, this method can provide a consistent glacier-wide annual mass balance series from a heterogeneous network. This model, available to the whole community, can be used to assess the impact of climate change in different regions of the world from long-term mass balance series.

1. Introduction

Surface mass balance observations on a large sample of glaciers are crucial to assess climate changes in different regions of the world (e.g., Gardner et al., 2013; Intergovernmental Panel on Climate Change, 2013). The surface mass balance offers a more direct response to climate than changes in glacier length as it is directly related to solid precipitation and energy fluxes between the glacier surface and the atmosphere (Oerlemans, 2001). For the sake of simplicity, most studies use glacier-wide surface mass balance data for comparison with regional climatic variables (e.g., Marzeion et al., 2014; Zemp et al., 2015).

However, several issues are encountered when attempting to use glacier-wide mass balances as a climatic indicator. First, glacier-wide mass balance depends not only on changes in climate but also on changes in glacier geometry that are controlled by the dynamic response of each glacier (Huss et al., 2012). Second, glacier-wide mass balances are calculated from heterogeneous observation networks (World Glacier Monitoring Service, 2015). The locations of mass balance measurements may change with time, especially if a series covers several decades. In addition, some point mass balance observations are often missing due to broken stakes or loss of stakes under snow. The result is a loss of information in space and in time, leading to large uncertainties in the quantification of glacier-wide mass balances.

Numerous studies have investigated the spatial-temporal mass balance distribution at glacier-wide scale (e.g., Huss & Bauder, 2009; Kuhn, 1984; Rasmussen, 2004; Thibert et al., 2013; Vincent et al., 2004) in an attempt to infer a climatic signal from surface mass balance changes and/or to calculate a glacier-wide mass balance from a reduced and heterogeneous sample of measurements. For instance, several studies analyzed mass balance changes from elevation gradients. Using this method, Meier and Tangborn (1965) concluded that vertical profiles of mass balance observed on South Cascade Glacier remained unchanged with time

and could be translated from one year to another by adding or subtracting a fixed value that corresponds to the mass balance change. Kuhn (1984) found similar results on Hintereisferner glacier in Austria. Studying 13 glaciers spread all over the globe, Dyurgerov and Dwyer (2000) found little variation of gradient from year to year for glaciers in maritime climates but significant variation for those in continental climates. From an analysis of 10 glaciers in Norway, Rasmussen (2004) and Rasmussen and Andreassen (2005) found that vertical profiles of annual and seasonal balances were remarkably linear and the elevation gradient did not change over time. Rasmussen concluded that one measurement on a glacier, near the middle of its elevation range, is sufficient to assess the glacier-wide mass balance and can be extended to nearby glaciers. Conversely, other studies (Dyurgerov & Dwyer, 2000; Oerlemans & Hoogendoorn, 1989) found steeper vertical gradients in warm years. However, all these studies used an averaged point mass balance for a given elevation (or elevation range) and did not take into account spatial variations other than those related to elevation. Further studies showed a strong spatial variability in the same range of elevation (Funk et al., 1997; Vincent & Six, 2013). In consequence, the relationship of point mass balances with elevation alone is not sufficient to investigate mass balance changes.

In a different approach, Lliboutry (1974) developed a linear statistical model to take into account the spatial and temporal changes of point mass balances, whatever the causes of spatial variability. He tested his model on the ablation area of Saint Sorlin Glacier (French Alps) assuming similar temporal changes of the mass balance over the whole area. He found the standard deviation of the residuals to be in the order of 20 cm of ice, which is almost within the uncertainty of the measurements. Using a similar approach, Funk et al. (1997) showed that the linear model of Lliboutry gives satisfying results if the accumulation and the ablation areas are treated separately. Using a linear statistical model similar to Lliboutry's (1974) and a reduced cluster of stakes selected in the ablation area of six glaciers, Vincent et al. (2017) showed a very consistent regional common signal from an analysis of point mass balances over the entire European Alps with a common variance of 52% for glaciers 400 km apart and 80% for glaciers less than 10 km apart. This previous study concluded that the signal derived from clusters of stakes on glaciers shows a climatic signal that is unbiased by the dynamic glacier response (Vincent et al., 2017).

Although the linear model of Lliboutry (1974) is valid over a limited elevation range, as shown by several studies (Funk et al., 1997; Kuhn, 1984; Vallon et al., 1998), it is unable to account for the decreasing temporal variability of the mass balance with elevation (Oerlemans, 2001). Indeed, the temporal changes of annual mass balance cannot be considered constant over the whole surface of the glacier (Kuhn, 1984). Thus, the linear model of Lliboutry (1974) is not sufficient to extract a common signal from point mass balance measurements distributed over a wide elevation range.

The main objective of this paper is to propose a method to extract a consistent climatic signal from heterogeneous and discontinuous mass balance measurements spanning a wide elevation range. Our study analyzes the point mass balances at glacier-wide scale for four glaciers located in different climatic regions of the world using a statistical model in order to take into account the main source of nonlinearity: the decrease of point mass balance temporal variability with elevation. For this purpose, we selected glaciers in different climatic regimes for which (i) point annual mass balances and coordinates of each measurement are available, (ii) the elevation range was large enough to observe this non linearity, and (iii) independent geodetic mass balances are available.

The general framework of our study is an evaluation of the extent to which we can extract a consistent signal from a network of point mass balance observations in order to assess the effect of climate change in different regions of the world. More specifically, the objectives of this study are (i) to account for the spatiotemporal variability of point mass balances on glaciers from a statistical approach, (ii) to calculate the glacier-wide mass balances for any glacier using this statistical model, and (iii) to provide a tool to detect measurement errors.

2. Data

We selected four glaciers in different climatic regions of the world taking into account the length of each mass balance series and the elevation range of measurements. The glaciers were also selected according to the availability of the point annual mass balances and the coordinates of each mass balance measurement. We used the point mass balance measurements for Argentière (France), Zongo (Bolivia), Chhota Shigri (India), and Nigardsbreen (Norway) glaciers. The series of Zongo and Chhota Shigri are the longest

Table 1
Location, Elevation Range, Surface Area, and Dominant Aspect for Each Investigated Glacier

	Glacier			Studied area				
	Location (lat/long) Aspect	Elevation range (m above sea level)	Surface area km^2 (year)	Period of measurements	Number of stakes and pits (elevation range)	Positioning method for stake coordinates	DEM dates	References
Argentière (FR)	45°55 N, 6°57°E North	1,700–3,500	12.4 (2003)	1975–2016	40–50 (1,800–3,050)	1976–2000: Theodolite 2000–2016: DGPS or handheld GPS	1980, 1994, 1998, 2003, 2008, 2012	Vincent (2002), Vincent et al. (2009); Six and Vincent (2014)
Zongo (BOL)	16°S, 68°W South-East	4,900–6,000	1.9 (2013)	1991–2016	20 (4,900–5,650)	1991–2004: Theodolite 2005–2016: DGPS or handheld GPS	1997, 2006, 2013	Soruco et al. (2009); Rabatel et al., 2012
Chhota Shigri (INDIA)	32°20′N, 77°30′E North	4,300–5,830	15.5 (2015)	2002–2016	15–30 (4,300–5,500)	DGPS or handheld GPS	2005, 2014	Azam et al. (2012, 2016); Vincent et al. (2013) Brun et al. (2017)
Nigardsbreen (NOR)	61°42′N, 7°08′E South	320–1,960	46.6 (2016)	1961–2016	10–40 (330–1,950)	1962–2000: Theodolite 2000–2016: DGPS or handheld GPS	1964, 1984, 2009, 2013	Kjøllmoen (2016); Andreassen et al. (2016)

Note. Various characteristics are also given for the studied area for each glacier, including the number of stakes and pits and the years with available digital elevation models (DEMs).

series of mass balances in the Andes and Himalayas, respectively. Glaciers of the European Alps and Scandinavia are represented by Argentière and Nigardsbreen, respectively, where point mass balance measurements cover large elevation ranges. Detailed information on these glaciers and the studied areas is given in Table 1. These glaciers cover very different climatic regions: tropical conditions in the Andes (Zongo), near subtropical conditions in the Himalayas (Chhota Shigri), temperate climate in the Alps (Argentière), and a high-latitude maritime climate in Scandinavia (Nigardsbreen). The number of stakes selected for this study is different for each glacier and ranges from 10 to 50 depending on the year and glacier (Table 1 and Figure 1). The stake positions have an uncertainty of ±0.05 to ±80 m depending on the glacier and year of measurement. The point annual mass balance uncertainty is estimated as ±0.15 and ±0.25 m w.e./a in the ablation and accumulation zones, respectively (Thibert et al., 2008). The methods used to measure the coordinates of the point measurements are also given in Table 1.

The geodetic mass balances of these glaciers were assessed on the basis of repeated digital elevation models. Elevation changes are known within an uncertainty of ±0.5 m to several meters per year from photogrammetric surveys depending on the quality of the aerial photographs or satellite images and the time intervals of acquisition (Andreassen et al., 2016; Azam et al., 2016; Brun et al., 2017; Kjøllmoen, 2016; Soruco et al., 2009; Vincent, 2002; Vincent et al., 2009). The digital elevation model years are also listed in Table 1.

3. Methodology

3.1. Linear Model

Annual point mass balance data have been collected from stake and pit measurements distributed over each glacier. Unfortunately, the measurement networks differ from year to year because mass balance measurements are not performed exactly at the same locations due to the movement of ice, possible changes in positioning methods, and the different researchers involved over the decades. For these reasons, it is not possible to extract a point mass balance at a fixed location for each year over several decades on the basis of the field measurements. To address this issue, Lliboutry (1974) suggested using a multivariate statistical analysis. This analysis requires the locations of each stake for each year but accepts estimates of missing values at some locations for some years. The model assumes that the mass balance can be decomposed into two independent variation terms, one spatial (α_i) and one temporal (β_t), which can be written as

$$b_{i,t} = \alpha_i + \beta_t + \varepsilon_{i,t} \tag{1}$$

where $b_{i,t}$ is the point mass balance recorded at site i for year t, α_i is the spatial effects at location i (i.e., the average balance at the site over the whole study period), and β_t is the annual deviation from this average balance (centered balance; therefore, $\Sigma\beta_t = 0$). The $\varepsilon_{i,t}$ term represents residuals corresponding to both measurement errors and discrepancies between the model and data (unexplained variance).

3.2. Temporal Variability of Point Mass Balance

The linear-model shows strong limitations for most glaciers when the analysis is performed over a large elevation range, as explained below. Indeed, the spatio-temporal decomposition described above implies that β_t is the same at each location for any given year t and has a glacier-wide significance. It also implies that temporal variations are the same at all locations on the glacier surface. The

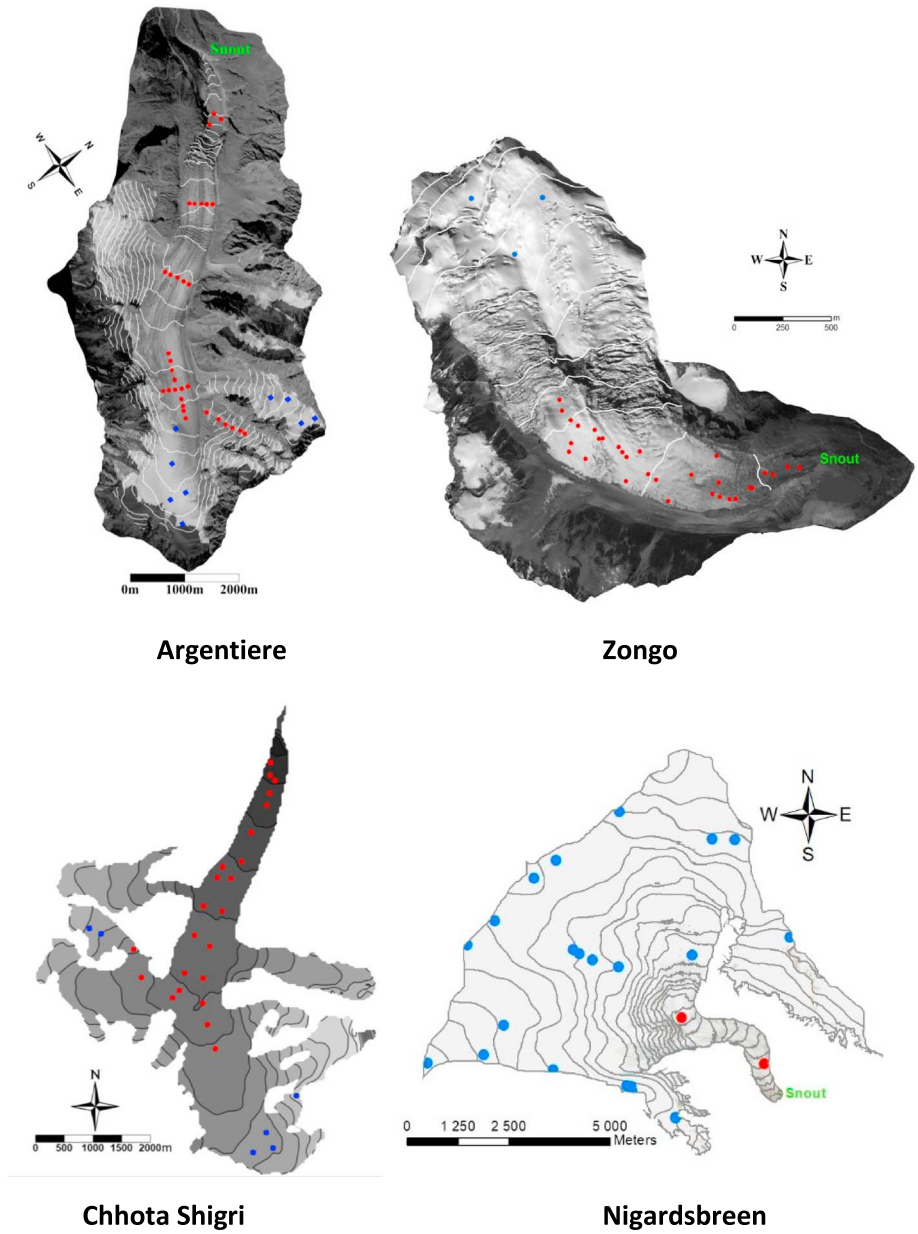

Figure 1. Maps of glaciers used in this study. The blue and red points are some examples of measurement points in the accumulation and ablation zones, respectively.

cross terms that account for nonlinear effects and deviate from separating the time and space variables are neglected in equation (1) (Lliboutry, 1974; Thibert & Vincent, 2009). Based on the analysis of observed mass balance in the reduced fraction of the ablation area of Saint Sorlin Glacier, Lliboutry (1974) concluded that the results obtained from a nonlinear (including cross time-space terms) model are not, significantly better, statistically speaking. The same conclusion was drawn on the small glacier of Sarennes (Thibert & Vincent, 2009). However, using the linear model of Lliboutry over the whole surface of Griesgletscher, Funk et al. (1997) showed that the results were improved if the accumulation and ablation areas were treated separately. Moreover, other studies performed on wider elevation ranges (e.g., Basantes-Serrano et al., 2016; Kuhn, 1984; Six & Vincent, 2014; Soruco et al., 2009; Vallon et al., 1998) reported that the sensitivity of annual mass balance to climate strongly decreases with elevation on numerous glaciers. In other words, except for some glaciers (Rasmussen, 2004), the temporal changes of annual mass balance (β_t in equation (1)) vary with elevation and cannot be considered constant

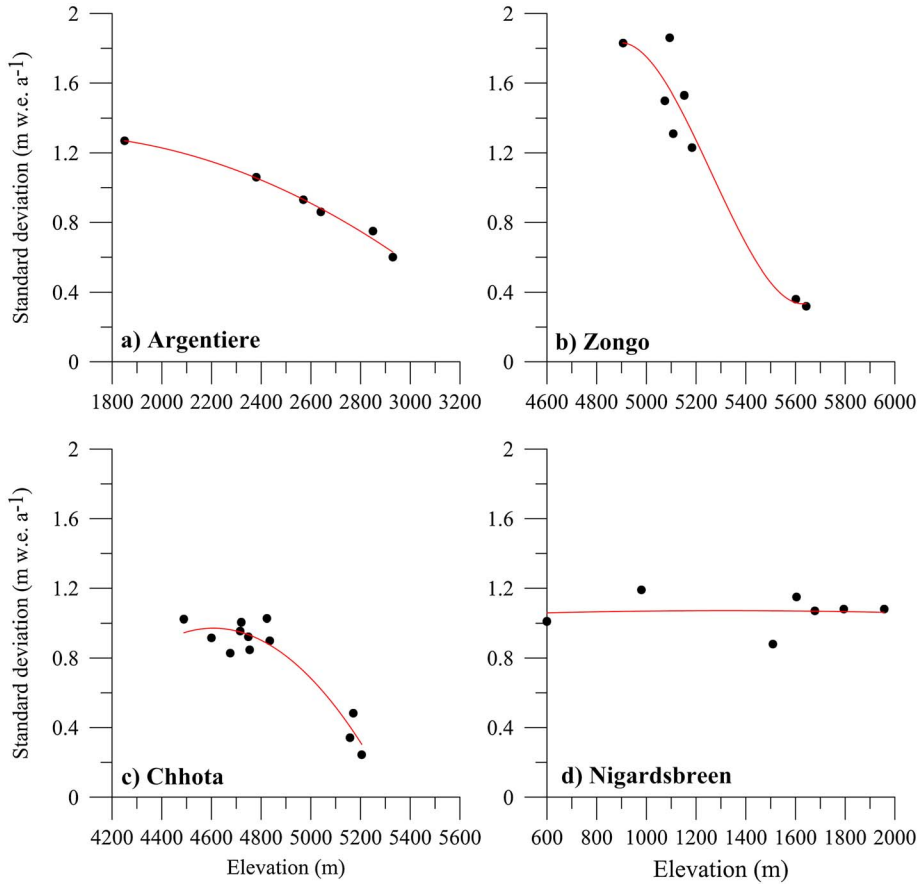

Figure 2. Mass balance standard deviations versus elevation for the four studied glaciers. The red lines correspond to polynomial functions. For easy comparison, the elevation ranges (1,400 m) and the vertical axes (standard deviation) are the same.

over the whole surface of glacier, as shown in Figure 2. The standard deviations shown in Figure 2 were calculated only when point mass balance measurements were available for more than 10 years at a given site. We assume that the standard deviation obtained from a period of 10 years of observations is representative of the whole observed period. This constraint explains why so few values are reported in Figure 2.

The standard deviations of annual point mass balance of Argentière, Zongo, and Chhota Shigri glaciers decrease with elevation. Indeed, the standard deviations are multiplied by a factor from 2 to 6 between the top of the glacier and the snout, depending on the glacier. On the other hand, those of Nigardsbreen glacier are similar over the whole surface area in agreement with previous studies (Rasmussen, 2004; Rasmussen & Andreassen, 2005).

3.3. Nonlinear Model

Here we consider a nonlinear model with a temporal term that depends on the site *i*, that is weighted by the standard deviations of mass balance at the site *i*. This reads

$$b_{i,t} = \alpha_i' + \beta_t'\gamma_i + \varepsilon_{i,t}' \tag{2}$$

where $b_{i,t}$ is the mass balance recorded at site *i* for year *t*, α_i' is the spatial effects at location *i* (i.e., the average balance at the site over the whole study period), β_t' is the annual deviation from this average balance (therefore $\Sigma\beta_t' = 0$), and $\gamma_i = \sigma_i/\sigma_{max}$ is a scaling factor defined as the ratio of the standard deviation of mass balance at site *i* by the maximum standard deviation found from the stake measurements on the glacier (generally at the lowest elevation).

The $\varepsilon_{i,t}'$ term represents residuals corresponding to both measurement errors and discrepancies between the model and data. Weighting the temporal term $\beta_t'$by σ_i/σ_{max}, instead of σ_i, gives a dimensionless value γ_i between 0 and 1, meaning that β_t' can provide the temporal change at the site of highest variance (the lowest elevation).

In our study, based on the results of Figure 2, we assume that the standard deviation of mass balance σ_i is a function of elevation only. In this way, the standard deviation is written as a second- or third-degree polynomial function of elevation z.

For Nigardsbreen glacier, the standard deviation is similar over the whole area. Consequently, $\gamma_i = 1$ at all locations and equation (2) is similar to the classical formulation of Lliboutry (1974) given in equation (1) for the linear model. In practice, to estimate the α_i', β_t', and $\varepsilon_{i,t}'$ variables from the $b_{i,t}$ data set, all terms of equation (2) are first divided by γ_i, which is calculated from the data with the classical estimation of the variance. In this way, we obtain a formulation similar to equation (1) and can use the classical Lliboutry algorithm to estimate all variables. Consequently, the input point mass balance data $b_{i,t}$ are divided by σ_i/σ_{max}. To account for missing values at some locations, changes in stake position or inconsistencies over the years, instead of treating each stake as an observation site, the surface of the glacier is here divided into cells of 0.2 × 0.2 km, in which the surface mass balance is assumed to be the same for a given year. If there is more than one observation within one of these squares, the mass balance value used is the average of the available measurements. The size of the cells has been chosen as a compromise between the spatial variability and the density of measurements. Consequently, we assume that spatial variability is weak within a cell of 0.2 × 0.2 km. Some numerical experiments performed on Saint Sorlin glacier, where the density of observations is high with cells of 0.1 × 0.1 km, provide similar results.

4. Results

4.1. Spatial Mass Balance Changes

Using the nonlinear statistical model described, the α_i' and β_t' terms were calculated from stakes, snow-pits, and shallow cores observations in the ablation and accumulation zones of each glacier (Table 1). The statistical model ensures independence with respect to changes in the observational network with time (lost stakes, changes of stake locations, etc.). Note that data are available for 29, 52, 42, and 14% of the 0.2 × 0.2 km cells on Argentière, Zongo, Chhota Shigri, and Nigardsbreen glaciers, respectively. Note also that the cells containing at least one measurement for one year do not cover the entire surface area of the glacier. The calculated and observed point mass balances are plotted in Figure 3 for the four studied glaciers. For the sake of clarity, we report only the average mass balances and the two most positive and two most negative mass balance years for each glacier. The calculated point mass balances of Argentière glacier are very similar in 1995 and 2001, as shown in Figure 3. Note that for Argentière glacier, the calculations were performed between 2,400 and 2,950 m above sea level (a.s.l.) only (Figure 3). Indeed, below 2,400 m a.s.l., the tongue of glacier has become debris-covered over the last 15 years and the network of observations from stakes has been discontinued. As shown in several previous studies (e.g., Kuhn, 1984; Rasmussen, 2004; Six & Vincent, 2014), the point annual mass balance increases strongly with elevation (Figure 3). However, a significant part of the spatial variability of mass balance does not depend on elevation and is related to solar radiation (Giesen et al., 2009; Vincent & Six, 2013) or other features (Hock, 1999, 2005; Réveillet et al., 2017). This spatial variability is fully taken into account by our statistical model although it cannot be shown properly in Figure 3. An example of mass balance spatial variability within elevation ranges is given in Figure S1 for Saint Sorlin glacier where numerous mass balance measurements performed over 60 years allow us to show the ability of the model to describe in detail the complex spatial pattern of mass balances.

The temporal variability decreases with elevation except for Nigardsbreen, where the standard deviation is the same for the whole glacier. The standard deviations of the residuals of the linear and nonlinear models are shown in Table 2. Using a nonlinear model decreases the standard deviation of the residuals (Table 2). This reduction of the variance is significant for Argentière, Zongo and Chhota glaciers (at the 5% error risk) as demonstrated by a Snedecor *F* test of variance comparison (see Figure S2 and Table S1 in the supporting information). The explained variances are higher than 91% when we compare the variance of mass balance observations and residuals. However, these encouraging results are strongly related to the range of elevation, because the point mass balances are strongly related to elevation. Hence, the correlation is improved

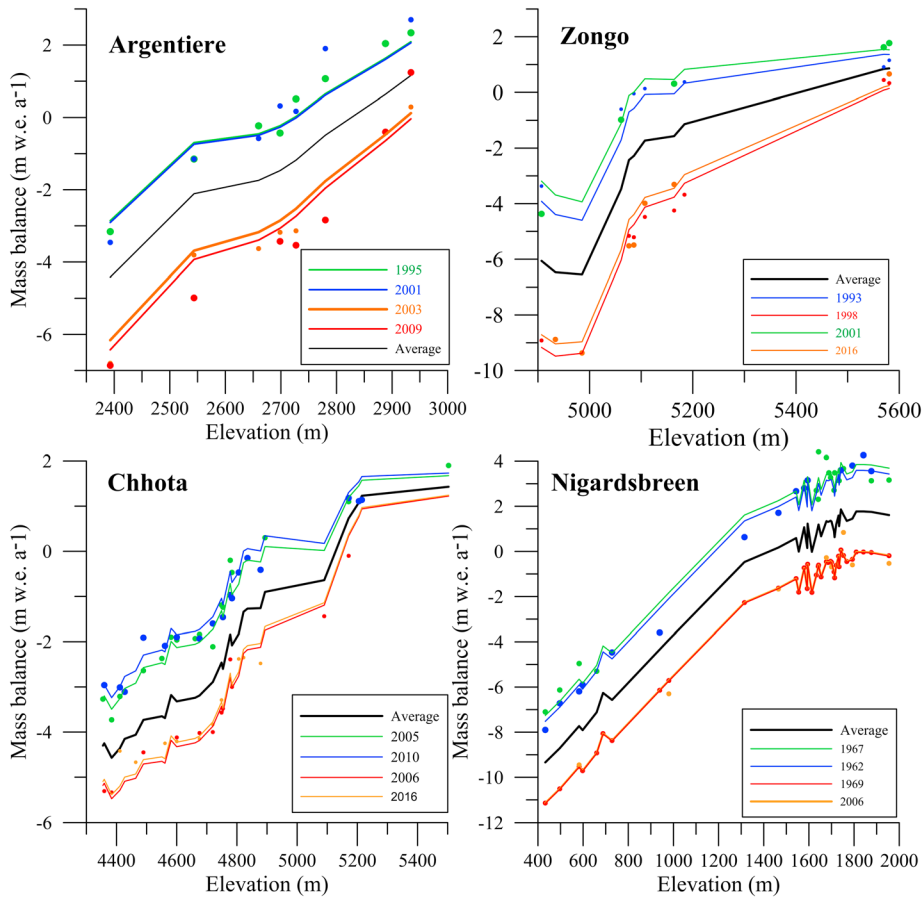

Figure 3. Observed (dots) and calculated (lines) point annual mass balances versus elevation for the four studied glaciers using the nonlinear model. The blue and green lines show the two most positive years, while the red and orange lines show the two most negative years. The black line shows the average point annual mass balance calculated over the whole observed period (Table 1). Note that the calculated annual mass balances for 1969 and 2006 for Nigardsbreen are very similar; hence, only one line is visible.

artificially when the elevation range is higher. For a more relevant comparison of model performance, we compared the variance of β_t' with those of the residuals. We obtained lower explained variances ranging from 75.5 to 91.3% with a nonlinear model (Table 2) but probably these values are probably more realistic, because they do not depend on the elevation. More importantly, there is a strong improvement between the linear model and the nonlinear model. This clearly shows that the nonlinear structure extracts more temporal information than the linear model. For all glaciers, residuals with the nonlinear model are in the

Table 2
Standard Deviation of the Residuals of the Linear and Nonlinear Models (Lines 2 and 3) Argentière, Zongo, Chhota Shigri, and Nigardsbreen

		Argentiere	Zongo	Chhota Shigri	Nigardsbreen
Standard deviation of the residuals (m w.e./a)	Linear model	0.40	0.66	0.34	0.54
	Nonlinear model	0.37	0.47	0.28	
Reduction of the standard deviation		8%	29%	18%	
Explained variances (mass balance observations/residuals)	Linear model	91.3%	91.4%	95.0%	97.6%
	Nonlinear model	92.5%	95.6%	97.7%	
Explained variances (β_t'/residuals)	Linear model	79.3%	64.6%	81.5%	75.5%
	Nonlinear model	87.5%	90.2%	91.3%	

Note. Reduction of the standard deviation between the linear and nonlinear models (line 4). Explained variances when the variances of mass balance observations and residuals are compared (lines 5 and 6). Explained variances when the variance of β_t' and the residuals are compared (lines 7 and 8).

range (just slightly above) of the measurement errors. Moreover, residuals can be considered as Gaussian for Chhota and Zongo glaciers (see Table S2 in the supporting information). This shows that the nonlinear model is well suited to capture the spatiotemporal structure of the variance of mass balances.

The efficiency of the nonlinear model is highest when the temporal variability of mass balance as a function of elevation is the largest. For instance, in the case of Argentière Glacier, this variability is from 1.05 to 0.6 m w.e./a (a factor of 1.75 only) over the surveyed area between 2,950 and 2,400 m a.s.l. Although this difference reaches a factor 1.75, it is not significantly different from the averaged temporal variability assumed by the linear model (i.e., 0.85 m w.e./a) taking into account the uncertainties. As a consequence, the results with a nonlinear model are barely improved for Argentière glacier. On the other hand, for Zongo and Chhota Shigri, the fact that the difference in temporal variability easily exceeds the mass balance uncertainties explains the great improvement of the nonlinear model compared with the linear model (from 64.6 to 90.2% and from 81.5 to 91.3% of explained variance for Zongo and Chhota Shigri, respectively).

4.2. Temporal Mass Balance Changes

For a better comparison, the calculated and observed point annual mass balances have also been reported against time for selected areas (Figure 4) for all studied glaciers. For each glacier, the reconstructed temporal fluctuations shown by the continuous lines are the same whatever the site *i* when weighted only by the scaling factor $\gamma_i = \sigma_i/\sigma_{max}$. In other words, the temporal term β_t' has a glacier-wide significance over the whole surface area of the glacier. Given that the standard deviations tend to zero at very high elevations at Zongo and Chhota Shigri glaciers (Figure 2), the temporal mass balance fluctuations are very small in the highest part of these glaciers. For Nigardsbreen glacier, the reconstructed temporal fluctuations are exactly the same whatever the sites given that the standard deviation is equal over the whole glacier, because $\gamma_i = 1$.

In some cases, we note large differences between the reconstructed and observed values. This could be due to special features such as avalanches, snowdrifts, or debris covered zones, which are not constant with time, although we normally excluded these zones from the data set used.

For a complete comparison of these glaciers, the annual deviation β_t' from the average mass balance for each glacier is plotted in Figure 5. For a relevant comparison, all the series of β_t' have been adjusted for the common period 2002–2016. From Figure 5, it is obvious that the annual mass balance fluctuations are very different from one glacier to another. Although there is a strong regional consistency of mass balance changes within a mountain range (Vincent et al., 2017), one cannot expect similar signals for glaciers located in very different climatic regions of the world.

4.3. Glacier-Wide Mass Balances

The glacier-wide mass balance is calculated as follows. First, we calculate a mean annual mass balance deviation β_{mt} for each year *t* of the series from:

$$\beta_{mt} = \beta_t' \int_{Z\min}^{Z\max} \frac{\sigma_z}{\sigma_{\max}} \frac{s_t(z)}{S_t} dz \tag{3}$$

where $s_{t(z)}$ is the surface area of each elevation range z, S_t is the total surface area of glacier at year *t*, σ_z/σ_{max} is the ratio between the standard deviation of mass balance within the elevation range *z* and the maximum standard deviation found on the glacier (Figure 2), and β_t' is the annual deviation from the average balance obtained from equation (2).

Combined with the geodetic balance, $B_{phot.}$, obtained from photogrammetry over N years, the glacier-wide average, B_t, is expressed as

$$B_t = \frac{B_{\text{phot.}}}{N} + \beta_{mt} \tag{4}$$

Geodetic data are needed because in situ mass balance measurements cannot cover the entire area of the glacier due to access difficulties such as crevasses and seracs. Indeed, due to the absence of in situ measurements, the term α_i' remains unknown at many locations on the glacier. Consequently, the sum of $b_{i,t}$ (equation (2)) does not allow us to obtain an accurate value of the glacier-wide mass balance. Geodetic data are required to get an unbiased value of the glacier-wide mass balance. Note that a similar issue is

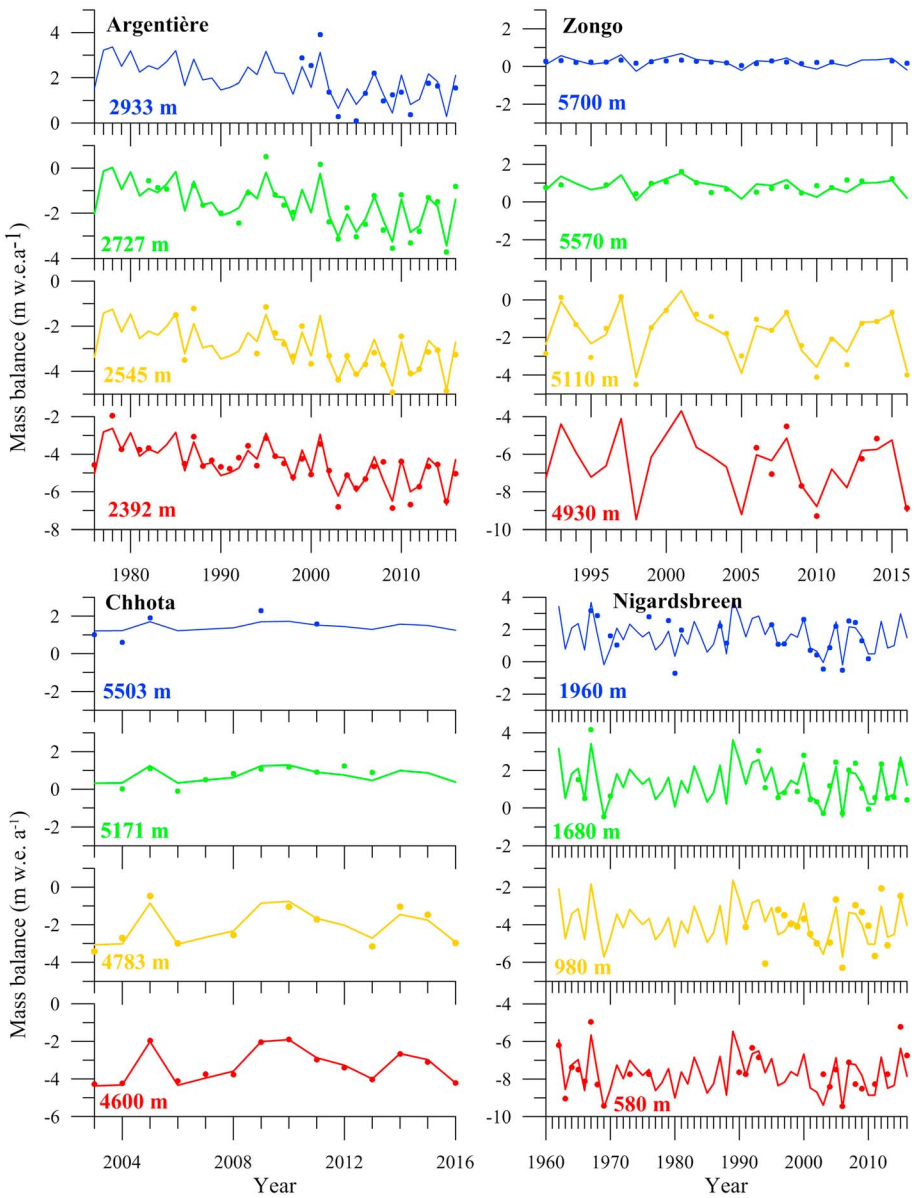

Figure 4. Point annual mass balance fluctuations for different elevations, obtained from the nonlinear statistical model (continuous line) and from measurements (dots) on the four studied glaciers.

encountered with the classical glaciological method. The sum of annual glaciological mass balance is generally a crude approximation of the glacier-wide mass balance if it is not corrected with geodetic data (Zemp et al., 2013). In this way, the series of β_{mt} is summed and adjusted linearly to match geodetic data obtained between two dates (usually the oldest and most recent available dates, except for Nigardsbreen). The accuracy of the method has been assessed using the other geodetic data available over the studied period.

In Figure 6, we plot the glacier-wide mass balances calculated using the nonlinear model (red lines), a linear model (blue lines), and the glaciological method (black lines).

As shown in Figure 6, the glacier-wide mass balances calculated from the nonlinear model and the numerous geodetic data obtained on Argentière glacier are very consistent. The results obtained from the nonlinear model provide the best agreement with the geodetic mass balances. The differences do not exceed 0.93 m w.e. compared to differences of up to 1.91 m w.e. from the linear model and 3.21 m w.e. from the classical glaciological method. Note further that the values of deviations depend on the length of the period given that the cumulative mass balances are calibrated between the oldest geodetic mass balance of 1980

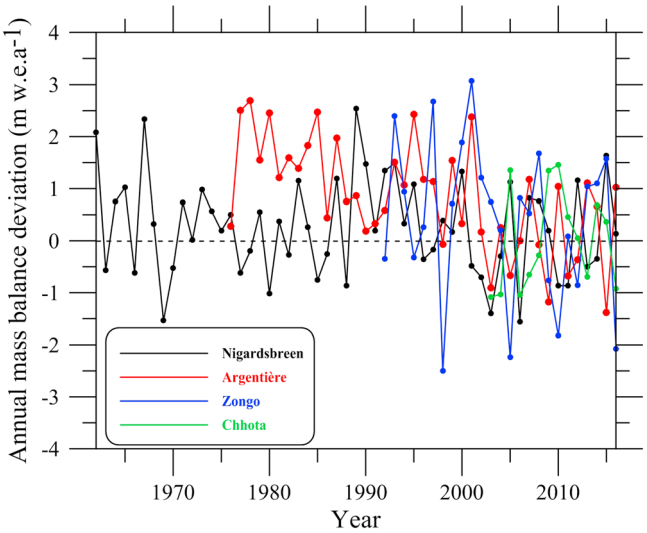

Figure 5. Annual deviation β_t' from the average mass balance for the common period 2002–2016.

and the most recent geodetic mass balance of 2012. However, the comparison shows the improvement obtained with the linear model.

The same is true for the Zongo results, although there is only one set of geodetic data to assess the performance of the model. The calculated glacier-wide mass balances cannot be checked for Chhota Shigri glacier given the lack of intermediate geodetic data. The mass balances of Nigardsbreen have not been adjusted on the oldest and most recent dates. The calibration period of the Nigardsbreen series is 1984–2013, given that the oldest geodetic data of 1964 is likely to have high uncertainty (Andreassen et al., 2016). Note that the calculated mass balance from the nonlinear model (red line) and homogenized mass balances (Andreassen et al., 2016) have been adjusted on the geodetic mass balances to obtain the cumulative glacier-wide mass balances. This explains the large differences with the cumulative glaciological mass balances obtained by Andreassen et al. (2016). The differences come from the internal ablation, which has been estimated at 0.16 m w.e./a at Nigardsbreen (Andreassen et al., 2016). Consequently, the cumulative glaciological mass balance is positive over the period 1961–2016, although the glacier-wide mass balance is negative. Our results are very similar to those obtained by Andreassen et al. (2016). As already shown (Andreassen et al., 2016), there is a large discrepancy with the geodetic measurements of 1964.

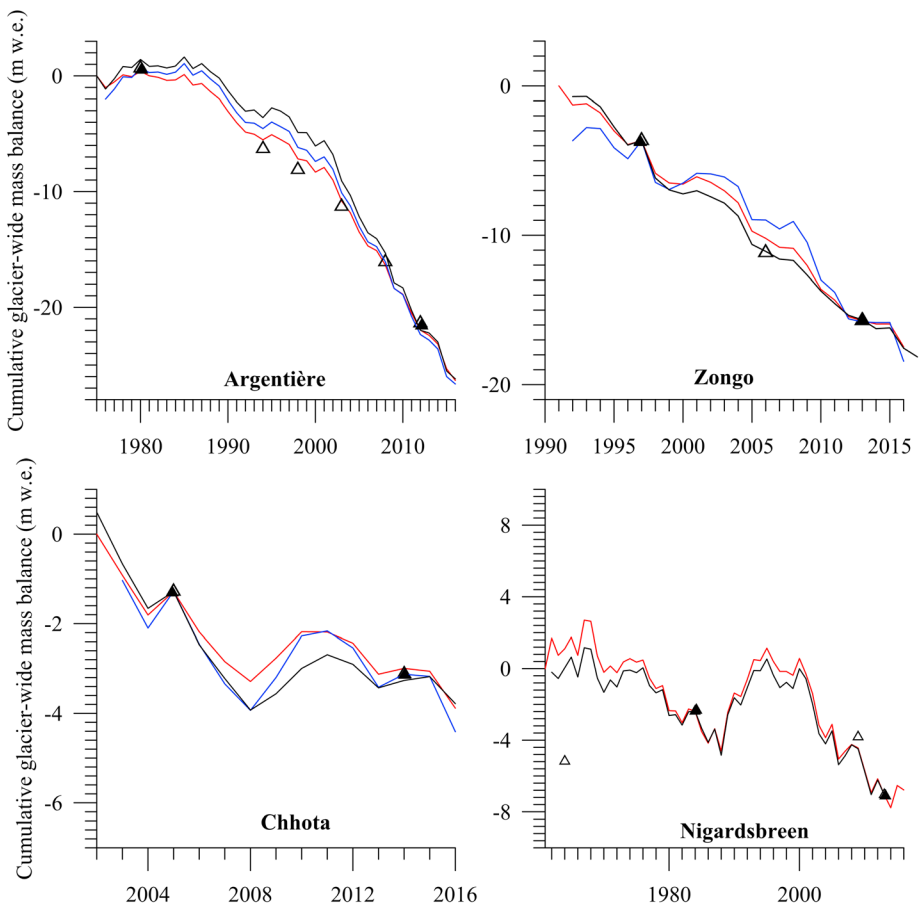

Figure 6. Glacier-wide mass balances for each glacier. The red (blue) lines show the mass balance obtained using the nonlinear (linear) model. The black lines show the mass balance calculated using a classical glaciological method. The triangles show the geodetic mass balances; the black triangles are those used for the calibration.

4.4. Detection of Measurement Errors

This statistical method can also be used to detect measurement errors. Our model allows us to calculate the deviation between the measured and theoretical value for each measured point mass balance. As shown in equation (2), the theoretical value is the sum of the spatial term α_i' and the temporal term $\beta_t'\gamma_i$. For ease, we first consider a linear model in which $\gamma_i = 1$ at each site *j*. Imagine an error in measurements e at stake *j* for year *t*. In a perfect model at the first order, the temporal term β_t' would be affected by e/n_t, where n_t is the number of measurements performed for the year *t*, which is different from the number of years of the whole period, given that the sum of β_t' is forced to zero. In the same way, the spatial term $\alpha_i{}'$ is affected by e/n_j where n_j is the number of measurements performed for site *j*, given that the term α_i' is obtained from the averaged measured point mass balance at site *j* with a complete set of measurements. Consequently, the deviation calculated on the erroneous value is reduced by $e/n_t + e/n_j$ at first order. In other words, the model shows a deviation of $e - (e/n_t + e/n_j)$ for a measurement error e. The deviation shown by the model is thus reduced compared to the initial measurement error *e*. The question is then which error can be detected with our method. Numerical tests were performed for Argentière glacier. Introducing an error of 1.60 m w.e. (about 4 $\varepsilon_{i,t}$) in annual mass balance on an individual stake measurement leads to a deviation of 1.34 m w.e. for $n_t = 25$ and $n_j = 13$. Thus, a measurement error can be suspected if the difference between theoretical and observed values exceeds 1.34 m w.e. The conclusions are very similar with the nonlinear model. Obviously, the higher the number of measurements, the greater is the deviation provided by the statistical model. Consequently, on a site with numerous annual measurements, it should be easy to detect an error of 4 $\varepsilon_{i,t}$ equivalent to 1.6 to 2.0 m w.e./a, depending on the glacier. On the other hand, when the number of measurements in a cell is low, it is very hard to detect a measurement error. Assuming that deviations should not exceed 4 $\varepsilon_{i,t}$, numerical tests can be performed on data set to reveal a deviation greater than 4 $\varepsilon_{i,t}$ $(n_t\, n_j - n_j - n_j)/(n_t\, n_j)$. If a deviation is greater than this threshold value, then the field measurement can be further investigated for accuracy (e.g., stake reading error and recording error) and retained or discarded as appropriate.

5. Discussion

5.1. Model Performance

Lliboutry (1974) analyzed the spatial and temporal changes of annual point mass balances on the Saint Sorlin glacier and noticed a strong spatiotemporal variability. In this way, he first proposed a linear statistical model to calculate a temporal signal of annual mass balance that would not depend on the site. Due to the lack of observations at this time, the model was developed on a reduced fraction of ablation zone of Saint Sorlin using a short mass balance series. The analysis of the long annual mass balance series used in the present study over a large range of elevations for several glaciers located in different climatic regime shows that a linear model is not sufficient to explain all the spatial and temporal variability. On the basis of the residuals analysis, the climatic signal extracted from each glacier is more consistent with a nonlinear model except for Nigardsbreen glacier.

However, a nonlinear model is not always justified (Eckert et al., 2011; Thibert & Vincent, 2009). In the case of limited elevation ranges, the linear model is sufficient. In the Alps, this is the case when the elevation range does not exceed about 400 m. Indeed, for this elevation range, the variation of the standard deviation of annual mass balance change is roughly ±0.15 m between the lower and upper elevation band, which is close to the uncertainty of point mass balance observations (Thibert et al., 2008). In addition, a nonlinear model would appear to be unjustified for glaciers in maritime climates for which the vertical profiles of annual balances are almost parallel (Dyurgerov & Dwyer, 2000; Rasmussen, 2004). Rasmussen and Andreassen (2005) noted that for each surveyed glacier in Norway, the difference in balance from year to year is nearly the same over the entire glacier, except near the very top and bottom of its elevation range. Our analysis of Nigardsbreen confirms that the standard deviation of mass balance is uniform from the bottom to the top of the glacier.

The residuals of the nonlinear model range from 0.28 to 0.54 m w.e./a depending on the glacier. For the Chhota Shigri and Argentière glaciers, the residuals hardly exceed the point annual mass balance uncertainty. The large residual obtained for Zongo glacier (0.47 m w.e./a) and Nigardsbreen (0.54 m w.e./a) could be due to the inaccurate geographical positions of mass balance measurements, in particular in the accumulation zone. Prior to the global positioning system, it was difficult to obtain accurate positions and to perform the

mass balance at the same locations. Given the strong spatial variability of mass balance, especially in the accumulation zone (Sold et al., 2013; Vincent et al., 2007), a deviation in geographical position leads to a significant bias in the temporal signal. In addition, most of the measurements of Nigardsbreen have been made in the accumulation zone for which nonclimatic processes (e.g., snow drift) could have significantly affected the spatial variability. Finally, the uncertainty of observation is larger in the accumulation zone (0.25 m w.e./a; Thibert et al., 2008), which could explain part of the large uncertainty on residuals in this region.

5.2. Glacier Wide Mass Balance Assessments

The comparison reported in Figure 6 shows that glacier-wide mass balances obtained from the nonlinear model are close to glaciological glacier-wide mass balances and intermediate geodetic mass balances when they are available. However, this only comparison does not show a significant improvement between linear and nonlinear models. Note that the glacier-wide mass balances obtained from the nonlinear model appear to be smoothed compared to those of the linear model.

Although it is not the main purpose of this model, the use of the nonlinear model for glacier-wide mass balance calculations offers several advantages compared to classical glaciological methods. Indeed, the nonlinear model enables us to take into account the spatial variability of mass balance even from a heterogeneous and noncontinuous in situ network. It is a significant improvement compared to the glaciological methods that ignore the spatial variability of mass balance within each elevation band or that use isolines of surface mass balance, which is very subjective when data are missing.

Compared to the linear model, the nonlinear model enables us to take into account the decrease of temporal variability with elevation. Finally, the model can be used easily from an executable code using an input file, which contains annual mass balance measurements and their coordinates (see the supporting information).

5.3. Elevation Gradient of Mass Balance

The elevation gradient of mass balance is recognized as an indicator of the climatic setting of a glacier. It is usually steeper for glaciers with a large mass turnover typical of wet climates and lower for glaciers located in drier and colder regions (e.g., Oerlemans, 2001). However, this is not the case for Zongo glacier for which the elevation gradient is much steeper although it is not located in a wet environment. Indeed, from our analysis, we found average elevation gradients of 1.0, 1.9, 0.75, and 0.88 m w.e. $\cdot$ (100 m)$^{-1}$ $\cdot$ a^{-1} over the ablation areas of Argentière, Zongo, Chhota Shigri, and Nigardsbreen glaciers, respectively. Kuhn (1984) showed that this gradient decreases with the duration of the ablation season from maximum in the tropics (>2 m w.e. $\cdot$ (100 m)$^{-1}$ $\cdot$ a^{-1}; e.g., Rabatel et al., 2013) to minimum in dry climates (0.3 m w.e. $\cdot$ (100 m)$^{-1}$ $\cdot$ a^{-1}) with typical values of 0.6–0.9 m w.e. $\cdot$ (100 m)$^{-1}$ $\cdot$ a^{-1} observed in the Alps (e.g., World Glacier Monitoring Service, 2015), in Scandinavia (e.g., Rasmussen, 2004), or in Western Himalaya (e.g., Azam et al., 2016).

Concerning the temporal variability of vertical gradients of mass balance, observations show a steepening of this gradient in warm years (Dyurgerov & Dwyer, 2000; Funk et al., 1997), probably related to the fact that the sensitivity of the surface energy balance to warming decreases with elevation (Oerlemans & Hoogendoorn, 1989). For Scandinavian glaciers, Rasmussen (2004) explains the absence in variability of mass balance gradient over time by two factors. First, summers in Scandinavia are neither hot nor long and as a consequence, there is never any strong or even extreme ablation at low elevation, which is responsible for a curvature of point mass balance in other regions of the world. Second, winters are usually cold with a lot of snow, covering the entire glacier due to the low elevations and in turn lower vertical extent of glaciers. Our results show that the temporal variability of mass balance profiles is maximum for glaciers located in tropical environments (Zongo), lower in the subtropics (Chhota Shigri) or in the Alps (Argentière), and insignificant in Scandinavia (Nigardsbreen). Hence, this is probably due to the fact that the duration of the ablation season is maximum in the tropics (the entire year) and decreases regularly as the latitude of the glacier increases. Indeed, since the mass balance in the lower part of a glacier is very sensitive to the surface energy balance controlling the melt, the longer the ablation season, the more variability in the point mass balance in this area and, as a consequence, the higher the mass balance profile temporal variability. Moreover, since vertical gradients are steeper during warm years, probably due to the fact that ablation is enhanced in the lower part of the glacier (longer ablation period and increased melt), glaciers out of balance with the present climate may experience steeper and steeper vertical profiles than those in equilibrium when conditions are more stable. This may explain the difference in behavior between Scandinavian glaciers (Andreassen et al., 2016) and

glaciers in the Alps that have been rapidly shrinking since the middle of the 1980s due to longer ablation periods (Thibert et al., 2018), and Himalayan (Azam et al., 2016) or Andean glaciers (Rabatel et al., 2013).

5.4. Contribution of each Elevation Range to the Glacier-Wide Mass Balance

In order to assess the relative contribution of each elevation range z to the temporal change of the glacier-wide mass balance, we calculated the values $(\sigma_z^2\, S_z^2)/(\sigma_{max}^2\, S_t^2)$ for each glacier. This points out a large contribution of low elevation ranges to the glacier-wide mass balance change, except for Nigardsbreen. Indeed, the relative contribution of the ablation zone is 70, 69, 76, and 35% for Argentière, Zongo, Chhota Shigri, and Nigardsbreen, respectively. This contribution obviously increases with the standard deviation of mass balance and the surface area of the ablation zone. Consequently, this contribution can change significantly with the surface area reduction of the tongue of glaciers. For these calculations, we used the averaged hypsometry over the whole observed period. Given that the temporal mass balance change on Nigardsbreen is similar over the whole surface of the glacier and that this glacier has been almost in equilibrium over the last 50 years, it is not surprising to find a value close to one minus the Accumulation Area Ratio needed for mass equilibrium (i.e., 1-AAR) found in the literature (Dyurgerov et al., 2009).

6. Conclusions

The main purpose of our statistical model is to extract a consistent climatic signal β_t' from heterogeneous and discontinuous mass balance measurements. Here we tested the robustness of the model for four glaciers in very different climatic regimes. When we compared the variance of temporal mass balance fluctuations and those of residuals, we obtained explained variances of 87.5, 90.2, 91.3, and 75.5% on Argentière, Zongo, Chhota Shigri, and Nigardsbreen, respectively. The standard deviations of the model residuals are close to measurement uncertainty.

It has been shown previously that analysis of point mass balances reveals remarkable regional consistencies over the European Alps with a common variance of 52% for glaciers 400 km apart (Vincent et al., 2017). It is obviously not the case in our study for which we selected four glaciers located in very different climatic regions of the world. However, using our nonlinear statistical model, the analysis could be extended to different regions of the world to analyze the impact of climate change on glacier mass balances and to obtain a consistent signal for each mountain range of the world. The model can be used easily from an executable code available in the supporting information. The input file requires only the annual mass balance measurements and their coordinates.

The nonlinear model reveals improvements compared to the linear model (Lliboutry, 1974) especially for glaciers with a strong decrease in temporal variability of mass balance with elevation. A previous study showed a common variance of 97% and 93% for point mass balances in two neighboring areas in the ablation zone of a single glacier (Saint Sorlin and Gries respectively), which demonstrates the strong relationship between point mass balances observed on the same glacier (Vincent et al., 2017). This shows that a linear model is very robust and sufficient for glaciers spanning a limited elevation range.

Our model could be used to detect measurement errors. Finally, our model enables the calculation of the glacier-wide mass balance from a heterogeneous in situ observation network taking into account the spatial variability within each elevation band. Note that as for the glaciological method, the geodetic mass balance is required to calibrate the results over long periods.

Author Contributions

C. Vincent designed the study and led the writing of the paper. A. Soruco, F. Azam, M. Jackson, B. Kjøllmoen, P. Wagnon, D. Six, A. Rabatel, A. Ramanathan, D. Cusicanqui, A. Mandal and P. Vincent acquired the field measurements. E. Thibert performed the statistical tests. All authors discussed the results and contributed to the writing of the paper.

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