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Climate Reconstructions Derived from Global Glacier Length Records

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Abstract

As glacier length fluctuations provide useful information about past climate, we derived historic fluctuations in the equilibrium-line altitude (ELA) on the basis of 19 glacier length records from different parts of the world. We used a model that takes into account the geometry of the glacier, the length response time and the mass balance–surface height feedback. The results show that all glaciers of the data set experienced an increase in the ELA between 1900 and 1960. Between 1910 and 1959, the average increase was 33 ± 8 m. This implies that during the first half of the 20th century, the climate was warmer or drier than before. The ELAs decreased to lower elevations after around 1960 up to 1980, when most of the ELA reconstructions end. These results can be translated into an average temperature increase of 0.8 ± 0.2 K and a global sea-level rise of about 0.3 mm a^{-1} for the period 1910–1959.

Introduction

Glacier length records contain information on how climate has changed. This information often complements historical meteorological data, as glacier length records generally extend farther back in time. Besides, glacier records are often from remote areas and higher altitudes, for which meteorological data are scarce (Intergovernmental Panel on Climate Change [IPCC], 2001). Hence, glacier length records form an alternative method for climate reconstruction for periods and locations for which instrumental or proxy indicators are inadequate or contradicting.

From many glaciers in Europe, we know how they have retreated or advanced since 1850 or even earlier. In an earlier study (Klok and Oerlemans, 2003), we used 17 European length records to retrieve climate reconstructions. The reconstructions were described in terms of changes in the equilibrium-line altitude (ELA). ELA fluctuations resemble transient climate changes more properly than glacier length changes, as the glacier length is subject to the length response time and the sensitivity of a glacier. The model that we developed for extracting ELA reconstructions from glacier length fluctuations is a simple analytical one, based on the assumption that the change in length can be described by a linear response equation. Its advantage is that it takes the length response time and the geometry of the glacier as well as the mass balance–surface height feedback into account. The length response time expresses the speed of the glacier response to a change in climate or mass balance. Results from this model indicate that the ELA of 17 European glaciers increased on average 54 m between 1920 and 1950 (Klok and Oerlemans, 2003). ELA reconstructions modeled with this analytical model agree well with mass-balance reconstruction derived from numerical flowline models and from historical temperature and precipitation records (Klok and Oerlemans, 2003). In this study, we extend this investigation to glaciers in other parts of the world.

So far, the climatic interpretation of worldwide glacier length fluctuations has been studied occasionally. More frequently, length fluctuations of single glaciers or glaciers in one specific region were investigated, e.g., the European Alps (Haeberli and Hoelzle, 1995), the Central Italian Alps (Pelfini and Smiraglia, 1997), Scandinavia (Bogen et al., 1989), the Patagonian Ice Fields (Warren and Sugden, 1993; Aniya, 1999), the North Cascade glaciers (Pelto and Hedlund, 2001), Northern Eurasia (Solomina, 2000), Tien Shan (Savoskul, 1997), New Zealand (Chinn, 1996), and the tropics (Kaser, 1999). However, Oerlemans (1994) compared the retreat of 48 glaciers from different regions. He estimated from this a global linear warming trend of 0.66 K per century, but did not take the response time of the glaciers into account. Hoelzle et al. (2003) also investigated 90 glaciers worldwide. They estimated, from cumulative glacier length changes, a global mean specific mass balance of –0.25 m w.e. a^{-1} since 1900. Furthermore, the IPCC (2001) analyzed a collection of glacier length records from different parts of the world quantitatively. They argued that glacier retreat already began around 1850 in the low and mid-latitudes, but started later at high latitudes.

This study thus focuses on the climatic interpretation of worldwide glacier length changes and uses a more sophisticated model than those used by Oerlemans (1994) and Hoelzle et al. (2003), because we correct for the length response time and treat the geometry of each glacier more comprehensively. Building a data set of useful length records was difficult because most non-European glaciers have only been measured since the beginning of the 20th century. The first criterion for populating our data set was to only use records that predate AD 1900. A second screening criterion of our data set was that the length fluctuations must be small ($<\sim$20%) compared to the total glacier length, to justify the assumption of a quasi-linear response. Third, only valley or outlet glaciers are included. Lastly, we also needed information about the geometry and the mass balance to calculate the response time and the climate sensitivity. This led to a collection of 19 glaciers: 14 from countries other than European, and 5 European yielding a global sample (Fig. 1).

In the following section, we describe the glaciers of our data set in more detail. To these glaciers, we applied the analytical model as explained in Klok and Oerlemans (2003), without any modifications, and we only explain the model briefly here. As we did not have accurate data on the glacier geometry or the mass-balance regime for some glaciers, we investigated the effects of the uncertainties in the input data on the ELA reconstruction. The results of the ELA and mass-balance reconstructions are also described and interpreted in terms of changes in air temperature.

Glaciers and Their Length Records

The glaciers of our data set are located in six regions: Canada, U.S.A., South America, Europe, Asia, and New Zealand. All of them

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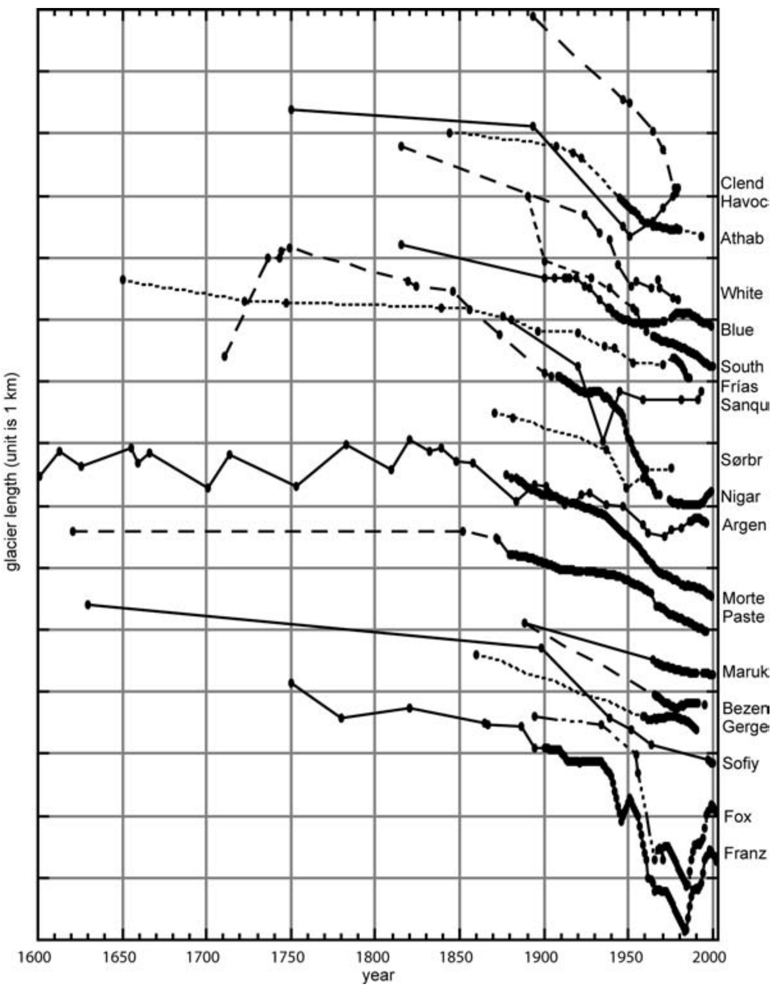

FIGURE 1. Glacier length fluctuations of the 19 glaciers of our data set. The first five letters of their names abbreviate the glacier names.

have retreated over the previous century, but 60% of them also slightly advanced after 1950 (Fig. 1). Retreat rates, total retreat and periods of retreat vary widely between the glaciers. Table 1 gives information about the geometry and the mass balance of the glaciers. These parameter values were used as model input. The length records and the input data were either collected or estimated from data of the World Glacier Monitoring Service, the World Glacier Inventory, from Dyurgerov (2002) or from other references mentioned in the text.

CANADA

The three Canadian glaciers of the data set are Athabasca (Rockies), Clendenning (Coast Mountains), and Havoc (Coast Mountains). Athabasca is an outlet glacier of the Columbia Ice Field, an ice cap of roughly 325 km^2. The glacier flows over three icefalls into an alpine valley (Reynolds and Young, 1997). It has retreated rapidly since 1910 until 1960, after which a slowdown in the retreat rate occurred. Clendenning and Havoc, two valley type glaciers, are located closer to the ocean and their glacier termini reach a lower elevation (~1000 m a.s.l.) than Athabasca (~1950 m a.s.l.). The length records of Clendenning and Havoc do not show similar patterns, although both are located in the Clendenning valley. This could be attributed to differences in glacier geometry: Havoc is much steeper and narrower.

U.S.A.

White and Blue Glaciers are located in the Olympic Mountains, about 55 km from the Pacific Ocean. The climate of the Olympic Mountains is strongly maritime and receives the greatest precipitation of any area in the U.S.A., excluding Alaska and Hawaii (Armstrong, 1989). Blue Glacier is steeper and narrower than White Glacier and has retreated less. South Cascade is in the North Cascade Range, 250 km from the ocean. This glacier receives less snow (~3 m w.e.) than White and Blue Glaciers (~4 m w.e.) (Rasmussen and Conway, 2001). Mass-balance measurements have been made on Blue Glacier (Conway et al., 1999) and South Cascade (Krimmel, 2000). Armstrong (1989) showed that Blue Glacier had a slightly positive mass balance between 1956 and 1986 (0.3 m) and Krimmel (1989) found a mean negative balance for South Cascade (–0.22 m) for 1959 to 1985. Blue Glacier has not retreated significantly since 1950, while the length record of South Cascade shows an ongoing retreat. Rasmussen and Conway (2001) concluded that South Cascade has been more out of balance than White Glacier because of differences in geometry between the two glaciers.

SOUTH AMERICA

Frías Glacier (Argentina) is an outlet glacier on the east side of Mount Tronador. This ice cap is the northernmost ice body in Argentina. Measurements from a weather station in the Rio Frías Valley of Frías Glacier indicated that the annual precipitation amounts to 4300 mm a^{-1} (Perez Moreau, 1945). The glacier fluctuations have been recorded since 1976 and Villalba et al. (1990) dated oscillations of Frías Glacier using tree rings. Between 1850 and 1900, the retreat rate was 7 m a^{-1} and increased to 10 m a^{-1} between 1910 and 1940. San Quintín is farther south than Frías Glacier and is the largest glacier of our data set. It is a piedmont outlet glacier of the North Patagonian

TABLE 1

Model parameters of the 19 glaciers, the calculated length response time (t_{rL}), climate sensitivity (c), an the mean annual precipitation (Zuo and Oerlemans, 1997b). The first five letters of their names abbreviate the glacier names. (L_0: reference glacier length, A_0: reference glacier area, s: mean surface slope, s_f: surface slope of the glacier snout, w_f: characteristic width of the glacier snout, B_f: melt rate at the glacier terminus, β_E: mass balance gradient at the ELA, β: mass balance gradient of the glacier)

Glacier	L_0 (km)	A_0 (km)	s (%)	s_f (%)	w_f (m)	B_f (m w.e.a^{-1})	β	β_E	tr_L (a)	c	P_{ann} (m a^{-1})
Clend	11.1	26.5	15	8	500	−8	0.0052	0.0065	80	49	2.5
Havoc	7.0	9.5	19	30	250	−6.9	0.0052	0.0065	46	36	2.5
Athab	9.3	15.0	17	8	550	−4.7	0.0058	0.0064	102	43	0.75
White	3.3	3.8	27	35	290	−5.6	0.010	0.010	18	16	4
Blue	4.3	5.5	27	160	400	−5.7	0.010	0.010	8	10	4
South	3.1	2.9	16	10	400	−6	0.0105	0.023	27	26	2.5
Frias	6	10.5	21	10	400	−12	0.0110	0.017	33	38	3
Sanqu	60	765.0	3	5	8500	−15.8	0.0150	0.015	76	128	2
Sørbr	9	15	20	8	800	−4	0.005	0.006	105	32	0.7
Nigar	9.6	48.2	17	23	500	−10	0.0079	0.0086	68	84	4
Argen	9.4	15.6	16	16	400	−12.2	0.0078	0.0071	34	25	2
Morte	7.0	17.2	29	6	650	−6.5	0.0046	0.0065	88	29	2
Paste	9.4	19.8	17	10	750	−5.8	0.004	0.007	62	32	2
Maruk	4.0	3.1	17	10	500	−2.5	0.0100	0.0061	91	19	1.5
Bezen	17.6	31.1	17	10	450	−7.2	0.0014	0.0042	85	42	1.5
Gerge	8.5	7.1	30	20	200	−3.9	0.0014	0.0042	78	37	1.5
Sofiy	7.0	20	20	10	500	−5	0.0054	0.0073	97	63	0.375
Fox	13.2	34.7	24	5	350	−23	0.011	0.017	56	92	1.87
Franz	10.3	32.6	25	8	425	−22	0.011	0.017	38	72	1.87

Ice Field in Chile. San Quintín flows to the west onto an outwash plain. It receives between 3700 and 6700 mm precipitation per year. Winchester and Harrison (1996) investigated fluctuations of the ice front and concluded that precipitation is the main factor controlling the terminus position. The length record of San Quintín shows a peculiar glacier retreat just before 1935 from which it recovers after 1935, which does not show up in the other length records.

EUROPE

Sørbreen is a glacier on Jan Mayen, the northernmost island on the Mid-Atlantic Ridge (71°N, 8°W). This glacier flows southwards to the ocean, from the 2277-m high Beerenberg volcano. The climate is cool oceanic with a mean annual air temperature of −1.2°C at sea level. The island is surrounded with pack ice during winter and spring (Anda et al., 1985). Nigardsbreen is an outlet glacier in Norway, flowing from the largest ice cap of continental Europe (Jostedalsbreen) in a southeasterly direction. It is a maritime glacier, located close to the Atlantic Ocean. It advanced very rapidly between 1710 and 1748 and after 1988, it slightly advanced again. Pohjola and Rogers (1997) claimed that this advance was due to enhanced westerly maritime flow after 1980 leading to high winter accumulation and low summer ablation. Glacier d'Argentière (France), Morteratschgletscher (Switzerland), and Pasterzenkees (Austria) are valley glaciers in the European Alps, where the climate is more continental. Glacier d'Argentière has been well documented and numerous fluctuations were registered before 1850. Its length record is the longest of our data set and has been studied by Huybrechts et al. (1989). Glacier d'Argentière advanced after 1970, in contrast to Morteratschgletscher and Pasterzenkees. Pasterzenkees is the longest glacier of the Austrian Alps. It has experienced two periods of retreat: between 1870 and 1910 and after 1930 (Zuo and Oerlemans, 1997a).

ASIA

Marukskiy, Bezengi, and Gergeti are valley glaciers in the Caucasus Mountains. Their length records contain only a few measurements, which explains the straight lines in Figure 1. The mass-balance gradient of these glaciers is relatively small and the melt rate at the glacier terminus is low (Table 1). The maximum elevation of Bezengi and Gergeti is over 5000 m a.s.l. Sofiyskiy glacier is located in the Altai Mountains of central Asia, a border region between Russia and Mongolia. It is a so-called continental, summer-accumulation type glacier. Sofiyskiy glacier is a valley type glacier consisting of three basins. The most rapid retreat of Sofiyskiy glacier occurred between 1900 and 1940 (De Smedt and Pattyn, 2003; Pattyn et al., 2003).

NEW ZEALAND

Fox and Franz Josef are valley glaciers in the maritime climate of the Southern Alps of New Zealand. They receive between 5 and 15 m precipitation per year. The glaciers reach very low elevations: 425 and 305 m a.s.l. for Franz Josef and Fox Glaciers, respectively (Hooker and Fitzharris, 1999). The length records show similar patterns: a rapid retreat after 1940 and a major advance after 1982. The advance phase is characterized by higher precipitation and is also related to a higher frequency of El Niño events (Hooker and Fitzharris, 1999).

Explanation of the Model

A comprehensive description of the model that we used is given in Klok and Oerlemans (2003) and Oerlemans (2001). In this section, we explain only the important aspects. The model is based on the following equation that relates changes in the ELA to glacier length fluctuations:

$$E'(t) = -\frac{1}{c}\left(L'(t) + t_{rL}\frac{dL'(t)}{dt}\right) \tag{1}$$

$E'(t)$ is the ELA with regard to a reference altitude, $L'(t)$ is the glacier length with regard to a reference length (L_0), t is time, t_{rL} is the length response time, and c the climate sensitivity of the glacier. The latter

TABLE 2

Parameters of the fictitious glacier

Parameter	Value
L_0	15 km
A_0	20 km^2
s	10°
s_f	10°
w_f	500 m
B_f	-5 m w.e.a^{-1}
β	0.005 m w.e.a^{-1} m^{-1}
β_E	0.007 m w.e.a^{-1} m^{-1}

relates the change in the glacier's steady-state length to a change in the ELA. We calculated t_{rL} and c from:

$$t_{rL} = -\frac{\eta A_0 + w_f H_f}{\eta \beta A_0 + w_f B_f} \tag{2}$$

$$c = \frac{\beta_E A_0}{\eta \beta A_0 + w_f B_f} \tag{3}$$

η is a constant that relates the change in glacier thickness to a change in glacier length. We derived this parameter from the mean glacier slope (s) and L_0. A_0 is the reference area, w_f is the characteristic width of the glacier snout, and H_f the characteristic thickness of the glacier snout, which we estimated from s and the surface slope of the glacier snout (s_f). β is the average mass-balance gradient over the glacier, β_E the mass-balance gradient at the equilibrium-line altitude, and B_f the melt rate at the glacier terminus.

Since the length records contain data gaps and a continuous length record is needed for application of equation (1), we applied linear interpolation between the data points of the length records. The reference length (L_0) was then defined as the mean length of this interpolated record. We applied a Gaussian filter to the records and calculated time derivatives with central differences to obtain a smooth series of time derivatives ($dL'(t)/dt$). As we concentrated on fluctuations in the ELA occurring on a decadal timescale, the timescale of the Gaussian filter was taken as 10 yr.

This model thus takes into account the length response time of the glacier. This implies that the ELA reconstruction shifts backward in time as the length response time increases and also influences the amplitude of the ELA fluctuations. The geometry of the glacier is included in the model, mainly defined by the characteristic width of the glacier snout and the glacier area. Glaciers with relatively narrow tongues compared to the total surface area will have larger climate sensitivities and response times (eqs. 2, 3). Furthermore, the effect of the mass balance–surface height feedback is included, by the integration of η. For steep glaciers, η is small (the surface height changes little when the glacier length changes), implying a weak mass balance–surface height feedback, resulting in smaller length response times and lower climate sensitivities.

Sensitivities

Climate sensitivity and length response time are determined by eight parameters (Table 1). The values for these parameters in Table 1 may contain errors because some of them were unknown or difficult to estimate. We therefore investigated the effect of a change in these parameters on length response time and climate sensitivity and, finally, on the ELA reconstruction of a fictitious glacier. Table 2 lists the parameter values of this fictitious glacier. The values represent an average valley glacier and they yield a length response time of 85 yr and a climate sensitivity of 70. We changed each of these parameters by 30%. The resulting length response times and climate sensitivities are plotted in Figure 2. They are most sensitive to changes in the melt rate at the glacier terminus, the width of the glacier snout and the mass-balance gradient at the equilibrium-line altitude. Also, the glacier area seems to influence the value of t_{rL} and c substantially. Nevertheless, we do not expect the surface area to be an important contributor to the uncertainties in t_{rL} and c, as it is often known within 10%. An increase in the melt rate at the glacier terminus or an increase in its width both lead to smaller response times, as both of them cause a larger mass turnover. However, an increase in the characteristic width of the glacier snout also implies that more ice needs to be transported down the glacier to make up for an equal change in glacier length. This counterbalances the effect of a larger mass turnover on t_{rL}. Therefore, the length response time is more sensitive to melt rate than to width of the glacier snout. Regarding climate sensitivity, changes in the characteristic width of the glacier snout or melt rate at the glacier terminus lead to the same effect. Generally, t_{rL} and c vary in the same direction when one of the input parameters is varied.

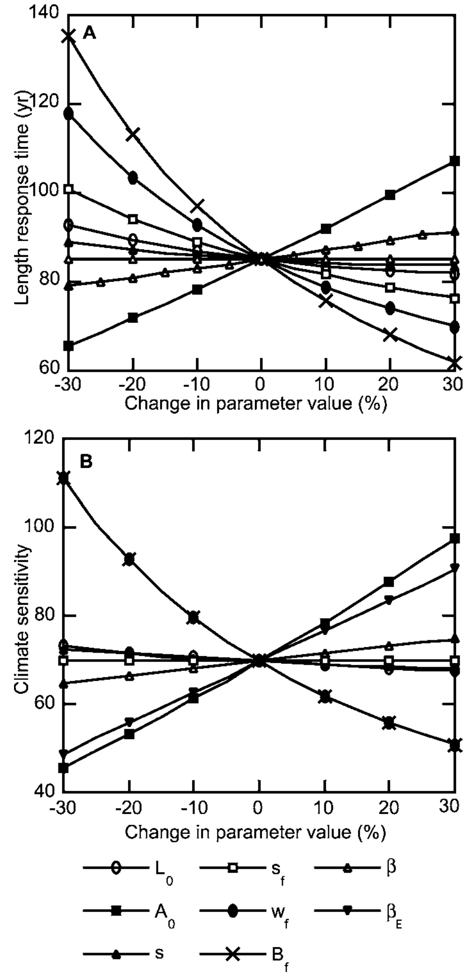

FIGURE 2. Length response time (A) and climate sensitivity (B) as function of a change in the input parameters. In B, B_f and w_f coincide. (L_0: reference glacier length, A_0: reference glacier area, s: mean surface slope, s_f: surface slope of the glacier snout, w_f: characteristic width of the glacier snout, B_f; melt rate at the glacier terminus, β_E: mass balance gradient at the ELA, β: mass balance gradient of the glacier).

As a second step, we determined the effect of a change in length response time and climate sensitivity on the ELA reconstruction of this fictitious glacier. We derived historic ELAs from a (fictitious) length record, which we defined as a sine function with an amplitude ($L'_{\max}$) of 1.5 km and a period (P) of 300 yr. Instead of smoothing this record with a Gaussian filter and calculating the derivatives with central

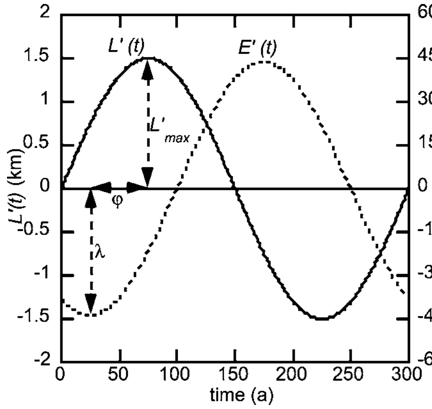

FIGURE 3. Length record and reconstructed ELAs of the fictitious glacier. The length response time is 85 yr and the climate sensitivity 70.

differences, we directly inserted this function and its time derivative in equation (1). This leads to:

$$E'(t) = -\lambda \sin\left(2\pi \frac{t + \varphi}{P}\right) \tag{4}$$

where λ and φ are the amplitude and the phase difference of the ELA reconstruction (see Fig. 3 for explanation of the symbols) described by:

$$\lambda = \frac{1}{c}\sqrt{1 + \left(2\pi \frac{tr_L}{P}\right)^2} L'_{\max} \tag{5}$$

$$\varphi = \frac{1}{4}P - \frac{P}{2\pi}\arctan\left(\frac{P}{2\pi tr_L}\right) \tag{6}$$

Figure 3 shows the length and the reconstructed ELA as function of time. The amplitude of the ELA reconstruction thus depends on the period of the length record, the length response time and the climate sensitivity. The reconstruction experiences a phase difference depending on the length response time. For very large length response times, the phase difference approaches $0.25P$.

We varied the length response time between 65 and 123 yr and the climate sensitivity between 53 and 101. These numbers are the limits set by a change of 25% (plus or minus) in the most sensitive parameter, melt rate at the glacier terminus (Fig. 2). The effects on the amplitude and phase difference of the ELA reconstruction are plotted in Figure 4. The amplitude varies roughly from 30 to 59 m and the phase difference from 18 to 30 yr. Note that an increase in t_{rL} leads to larger amplitudes and an increase in c to lower amplitudes. The total effect on the ELA reconstruction constitutes the sum of both, and is therefore smaller than the individual effects. Figure 4C shows that the total effect on the amplitude of the ELA reconstruction is at maximum 10%, when the melt rate at the glacier terminus is varied by 25%.

On the basis of this sensitivity test, we conclude that the length response time and the climate sensitivity are most sensitive to uncertainties in the characteristic width of the glacier snout, the melt rate at the glacier terminus and the mass-balance gradient at the equilibrium-line altitude. The effect of these uncertainties on the final ELA reconstruction is, at most, 10% in the amplitude, and a phase difference of 6.

Of course, this test provides no evidence that an uncertainty in the input parameters always leads to small changes in the ELA reconstructions because other glaciers may have different input parameters and length records than our fictitious glacier. Therefore, we also carried out a sensitivity test for Nigardsbreen, a glacier for which we had a long length record. We investigated the effect on the ELA reconstruction when the most sensitive parameters (B_f, w_f and β_E) were changed within their uncertainty ranges (Fig. 5). This test

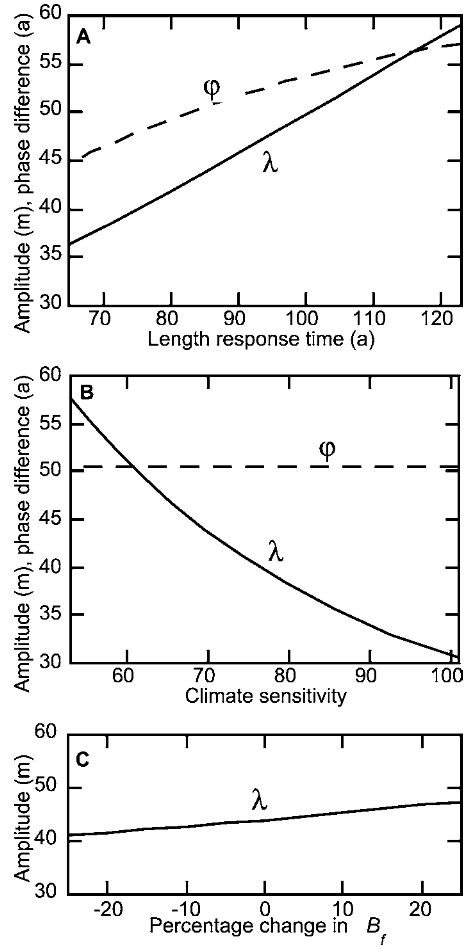

FIGURE 4. Amplitude (solid) and phase (dashed) of the ELA reconstruction of the fictitious glacier, when tr_L *is varied and c kept at 70 (A), when c is varied and* tr_L *is kept constant at 85 a (B), and when* B_f *is varied by 25% (C).*

indicates that the uncertainty in the characteristic width of the glacier snout has the largest impact on the ELA reconstruction of Nigardsbreen, leading to a standard deviation of 4 m in $E'(t)$, and a maximum deviation in the ELA of 9 m for the maximum ELA, which occurred in 1978.

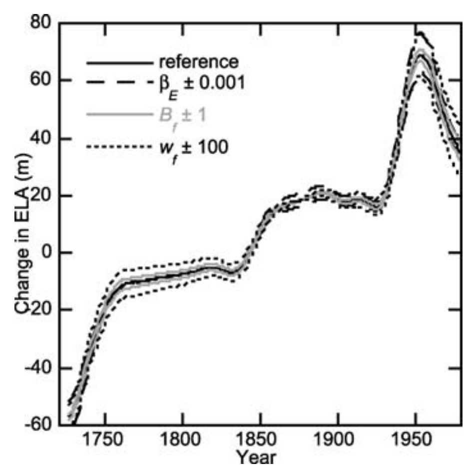

FIGURE 5. ELA reconstruction for Nigardsbreen for different values of the input parameters.

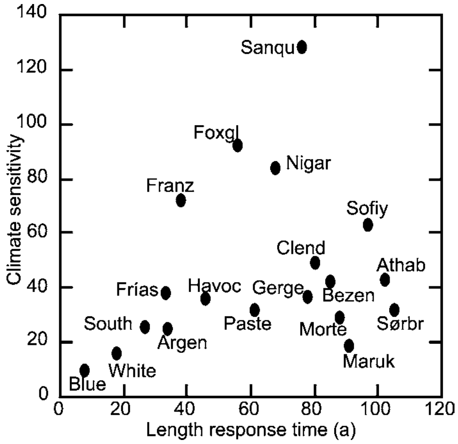

FIGURE 6. Climate sensitivity and length response time for all glaciers. The first five letters of their names abbreviate the names of the glaciers.

Results

LENGTH RESPONSE TIME AND CLIMATE SENSITIVITY

We calculated the length response time (eq. 2) and climate sensitivity (eq. 3) for all 19 glaciers and plotted the values in Figure 6 (see also Table 1 for the precise values of t_{rL} and c). Maritime glaciers often have high climate sensitivities (San Quintín, Fox, Nigardsbreen, and Franz Josef), since they have large mass-balance gradients. However, the glaciers of the U.S.A. (South Cascade, White, and Blue), which are also located in maritime areas, have low climate sensitivities. This is due to their small surface areas and relative wide glacier tongues. Athabasca Glacier has the largest length response time, which is partly caused by its low melt rate at the glacier terminus. Blue Glacier has the smallest length response time and the lowest climate sensitivity. Since this glacier is situated on a steep slope, the contribution of the mass balance–surface height feedback to t_{rL} and c is small. The calculated length response times and climate sensitivities generally agree well with values calculated from numerical flowline models, as was shown for European glaciers in Klok and Oerlemans (2003).

ELA RECONSTRUCTIONS

Figure 7 shows the reconstructed ELAs. Athabasca and Havoc show similar fluctuations in the ELA although the ELA of Havoc started to increase some years before 1900 and that of Athabasca some years after 1900. The ELA reconstruction of Clendenning shows neither any resemblances with the other Canadian ELAs nor with the reconstructions for the U.S.A. because the ELA does not stabilize around 1950. The reconstructed ELAs of White and Blue Glaciers are similar, but the fluctuation in White Glacier's ELA is larger.

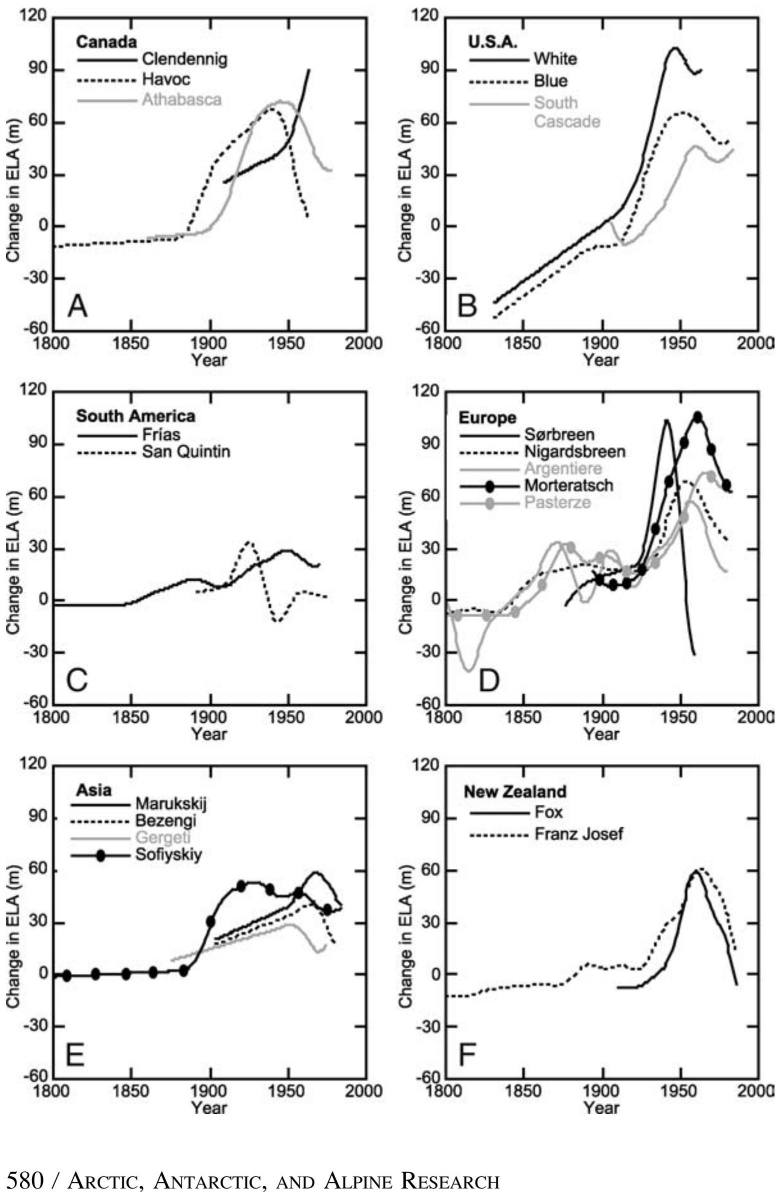

FIGURE 7. ELA reconstructions for all glaciers plotted separately for six regions.

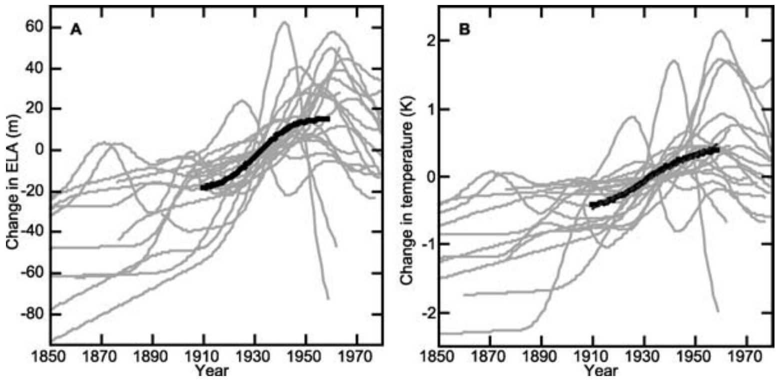

FIGURE 8. (A) All ELA reconstructions (gray) an the average ELA reconstruction (black). The ELA reconstruction of each glacier is shifted compared to Figure 7 in order to get a mean $E'(t)$ of zero over the period 1910 to 1959. (B) Same as Figure 8A, but for temperature reconstructions.

The ELAs of Frías and San Quintín show hardly any correspondence. The ELA of San Quintín decreases exceptionally after 1920. As San Quintín is a piedmont glacier and not a valley glacier, it could be argued whether its ELA reconstruction is reliable. However, the rapid decrease could be explained by an increase in precipitation between 1919 and 1935 (Winchester and Harrison, 1996). Winchester and Harrison (1996) also found that precipitation is a more dominant factor than air temperature in controlling the fluctuations of San Quintín.

The ELA of the European glaciers increased between 1920 and 1950. Sørbreen reached a maximum ELA before 1950 and the other glaciers after 1950. Morteratschgletscher's increase in the ELA is large compared to the other ELA reconstructions in the European Alps. Bogen et al. (1989) found that the increase in the ELA of Nigardsbreen that occurred between 1925 and 1955 is related to a series of excessive warm summers.

Marukskij, Bezengi, and Gergeti all show slowly increasing ELAs until 1950–1970 and a decrease afterwards. The ELA of Sofiyskiy increases rapidly around 1900 and starts decreasing already after 1930.

The reconstructed ELAs of Fox and Franz Josef show very similar patterns, with a rapid increase in the ELA after 1920 until 1960. The high ELAs around 1960 are strongly linked with changes in the circulation patterns over the southwest Pacific region (Fitzharris et al., 1992). At that time, summer pressures over New Zealand were higher than normal due to a pole-ward shift of the subtropical high, favoring clearer skies and more ablation. Moreover, snow accumulation was unusually low in the 1960s and 1970s.

WORLDWIDE PATTERN IN ELA FLUCTUATIONS

For all glaciers, ELA reconstructions were calculated for the period between 1910 and 1959. We therefore estimated an average worldwide change in the ELA for this period (Fig. 8A). The average ELA increase was 33 m between 1910 and 1959, with a standard error of 8 m. According to Figure 7, this increase was most pronounced in the U.S.A. and New Zealand and less in Asia. Generally, the reconstructed ELAs increased strongly during the first 50 yr of the 20th century. Except for San Quintín, they all decreased again in the second half of the 20th century until 1980, when most of our ELA reconstructions end. This implies that the first half of the 20th century was warmer or drier than the period before 1900. After 1960, the climate returned to a situation that favors lower ELAs.

RECONSTRUCTIONS OF TEMPERATURE

If we assume that the changes in the ELA were solely due to temperature variations, we can derive historic trends in air temperature from the ELA reconstructions. We then only need to know the sensitivity of the glacier mass balance to the temperature. A change in the ELA ($E'(t)$) can be easily translated into a mass-balance change ($B'(t)$) by multiplying it with the mass-balance gradient, given in Table 1. We estimated for each glacier the sensitivity of the mass balance to a change in temperature ($T'(t)$) by using a parameterization of Oerlemans (2001):

$$\frac{B'(t)}{T'(t)} = -0.271(P_{ann})^{0.597} \tag{7}$$

Oerlemans (2001) based this parameterization on calculations with a mass-balance model applied to a set of 13 glaciers. The sensitivity is a function of mean annual precipitation (P_{ann}; in m w.e.) and increases for wetter climates. We chose, for each glacier, a value for the annual precipitation, based on the compiled data of Zuo and Oerlemans (1997b) (Table 1). Figure 8B shows the calculated temperature reconstructions for each glacier and an average temperature trend. Between 1910 and 1959, the average increase in air temperature was 0.8 K and the standard error in the mean 0.2 K. The calculated linear trend in temperature was 0.19 K per decade.

Discussion

Our results agree with those of the IPCC (2001) on an increase in the global surface air temperature between 1910 and 1945, if we assume that the ELA fluctuations were solely explained by changes in temperature. In addition, cooling during the period 1946 to 1975 in the Northern Hemisphere (IPCC, 2001) is consistent with the observed lowering in our reconstructed ELAs. However, the warming rate reported by the IPCC for the period 1910–1945 was less (0.14 K per decade) than estimated from the ELA reconstructions for 1910 to 1959 (0.19 K per decade). This may be associated with the fact that we excluded precipitation and cloudiness as possible causes of the ELA fluctuations. Besides, we estimated this global temperature increase from only a few glacier records that are also not evenly distributed over the globe.

The IPCC (2001) also concluded that the Southern Hemisphere has been warming more uniformly during the 20th century compared with the Northern Hemisphere and also shows warming between 1946 and 1975. This is in contrast with the decreasing ELAs of the glaciers in New Zealand, unless precipitation has increased simultaneously. Regional differences from the hemispherical mean could also account for this discrepancy.

Our results do not give rise to the conclusion that there was a second period (1976 to 2000) of global warming, as claimed by the IPCC (2001). This is because most of our reconstructed ELAs do not extend beyond 1980, due to the time span of the length records and the Gaussian filter that we applied.

As we related changes in the ELA to changes in the specific mass balance, we could as well determine the mean specific mass balance for each glacier between 1910 and 1959. Averaged over all glaciers, this resulted in a mean specific mass balance of –0.18 m w.e. a^{-1} with a standard error of 0.04 m w.e. a^{-1}. If we assume this value to be representative for all glaciers in the world, the mean rise in sea level due to the retreating glaciers can be roughly estimated. Assuming an area of 527 900 km^2 for all of the world's small ice caps and glaciers excluding Greenland and Antarctica (Zuo and Oerlemans, 1997b), we derived a total rise in sea level of 1.3 cm over the period 1910–1959 and a mean rate of about 0.3 mm a^{-1}. This rate is in accordance with the estimated contribution of glaciers to sea-level rise for the period 1910–1990 reported by the IPCC (2001): 0.2 to 0.4 mm a^{-1}. However, we should realize that this estimate, and likewise the estimate for the global temperature increase, is not very accurate, as we did not include any information from glaciers in Alaska and northeast Canada, which are highly glacierized areas. Neither did we use a weighted average to account for the size of each glacierized region. Besides, the accuracy of the estimates of course depends on the data quality, and the errors in the model results.

Summary

The purpose of this study was to extract information on the past climate from glacier length fluctuations by means of deriving historical ELAs. We did this for 19 glaciers from different parts of the world. We used a simple model that takes into account the geometry of the glacier, the length response time, and the mass balance–surface height feedback (Klok and Oerlemans, 2003). Because we did not always know the input parameters of each glacier accurately, we carried out a sensitivity test for a fictitious glacier. We found that the uncertainty in the characteristic width of the glacier snout, the melt rate at the glacier terminus and the mass-balance gradient had the largest impact on the ELA reconstruction. More specifically, for Nigardsbreen, the standard deviation in the ELA reconstruction due to uncertainties in the input parameters was estimated to be 4 m.

The results show that all glaciers of our data set experienced an increase in the ELA between 1900 and 1960. The average increase between 1910 and 1959 was 33 m, with a standard error of 8 m. After around 1960 until 1980, the ELAs decreased to lower elevations. This implies that during the first half of the 20th century, climate was warmer or drier than before. From the ELA reconstructions, we estimated an average temperature increase of 0.8 ± 0.2 K and a sea-level rise of about 0.3 mm a^{-1}. These results support the evidence that an average global temperature increase took place between 1910 and 1945 and a sea-level increase of 0.2 to 0.4 mm a^{-1} (IPCC, 2001). However, care should be taken when interpreting the global estimates since we did not include length records of glaciers in the highly glacierized areas Alaska and northeast Canada, neither did we use a weighting function to account for the size of each glacierized region. The modeled ELA reconstructions reveal regional differences. Changes in the ELA are most pronounced for North America, Europe, and New Zealand.

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