Extracting a Climate Signal from 169 Glacier Records

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I constructed a temperature history for different parts of the world from 169 glacier length records. Using a first-order theory of glacier dynamics, I related changes in glacier length to changes in temperature. The derived temperature histories are fully independent of proxy and instrumental data used in earlier reconstructions. Moderate global warming started in the middle of the 19th century. The reconstructed warming in the first half of the 20th century is 0.5 kelvin. This warming was notably coherent over the globe. The warming signals from glaciers at low and high elevations appear to be very similar.

The worldwide retreat of many glaciers during the past few decades is frequently mentioned as a clear and unambiguous sign of global warming (*1*, *2*). Recent glaciometeorological field experiments and modeling studies have led to a much improved understanding of the link between climate processes and glacier mass balance (*3*, *4*). Yet, the climatic information contained in records of glacier geometry, particularly glacier length, has only partly been exploited. This is perhaps due to the nature of the data. Because data points on glacier length are irregularly spaced in time (Fig. 1), the data are more difficult to handle than some other proxies. Therefore, in most temperature reconstructions of the late Holocene climate, glacier records are not included and most information comes from tree rings (*5*, *6*).

Compared with biogenic climate indicators like tree rings, glacier systems react in a relatively simple way to climate change. The transfer function does not change in time and geometric effects can be addressed. Interestingly, many glaciers are found at high elevations. This implies that a climate signal reflected in glacier fluctuations can be studied as a function of height. The recent discussion on the possible discrepancy between surface-temperature observations and satellite measurements (*7*) and the problems involved in analyzing radiosonde temperature data (*8*) demonstrates the importance of climate proxies from high-elevation sites.

Although glacier retreat is mentioned in almost all assessments on climate change, the number of systematic studies of longer records is quite small. Some glaciers have been studied in great detail [including Storglaciären, Sweden (*9*); Nigardsbreen, Norway (*10*); Rhonegletscher, Switzerland (*11*); and Untere Grindelwaldgletscher, Switzerland (*12*)], but the methods used cannot be applied to a large sample because the required input data are not available. Direct mass-balance observations have been analyzed to estimate the contribution of glaciers to sea-level change (*13*). Unfortunately, such observations started only in the second half of the 20th century and do not provide information about the transition from the Little Ice Age to the current climatic state.

Here, I present an objective climatic interpretation of glacier length records from all over the world. A linear inverse model provides the basis for an individual treatment of all length records. Differences in the climate sensitivity and response time of glaciers are taken into account.

Records of glacier length were compiled from various sources, building on a data set from an earlier study (*14*). It was possible to extend the set of 48 records to a set of 169 records from glaciers found at widely differing latitudes and elevations. The core of the data set comes from the files of the World Glacier Monitoring Service in Zürich (*15*). Records were then included from glaciers in Patagonia (*16*), southern Greenland (*17*), Iceland (*18*), and Jan Mayen (*19*). Additional information was taken from the Satellite Image Atlas of Glaciers of the World (*20*) and from reports of the Swiss Academy of Sciences (*21*). The character of the records differs widely (Fig. 1). Some start in 1600 and have typically 10 data points until 1900 and more afterward. Other records start around 1900 but have annual resolution throughout. The longest record is that of the Untere Grindelwaldgletscher, which starts in 1534 (*22*).

Data points in the earlier parts of glacier records are sparse but normally quite reliable. The information on maximum stands from sketches, etches, paintings, and photographs can be checked with moraine systems that are still in place today. However, records based on information from moraines dated by lichenometry or fossil wood without any additional evidence have not been used in the present study.

The records are not spread equally over the globe. There is a strong bias toward the European Alps, where a wealth of documents exists and glacier monitoring was introduced relatively early. Fluctuations of some glaciers in Iceland and Scandinavia before 1800 have also been documented well (*18*, *23*, *24*). Glacier records in North America have not been kept up to date and many series do not extend beyond 1985. The 169 glaciers in the data set are located in the European Alps (93 records), Caucasus (8), tropical Africa (5), Central Asia (9), Irian Jaya (2), New Zealand (2), Patagonia (6), Northwest America (27), South Greenland (1), Iceland (4), Jan Mayen (1), Svalbard (3), and Scandinavia (8). In discussing the results, glaciers are grouped into regions, which are referred to as the Southern Hemisphere (tropics, New Zealand, and Patagonia), Northwest America (mainly Canadian Rockies), the Atlantic sector (South Greenland, Iceland, Jan Mayen, Svalbard, and Scan-

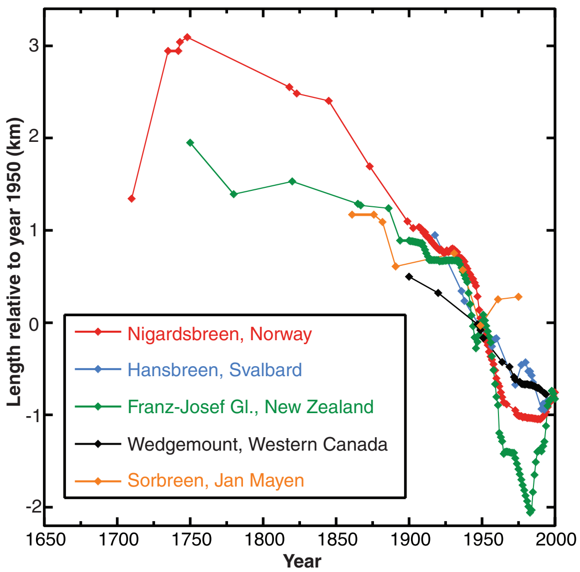

Fig. 1. Examples of glacier length records from different parts of the world. Each dot represents a data point. Data points are scarce before 1900; after 1900 a considerable number of records have annual resolution.

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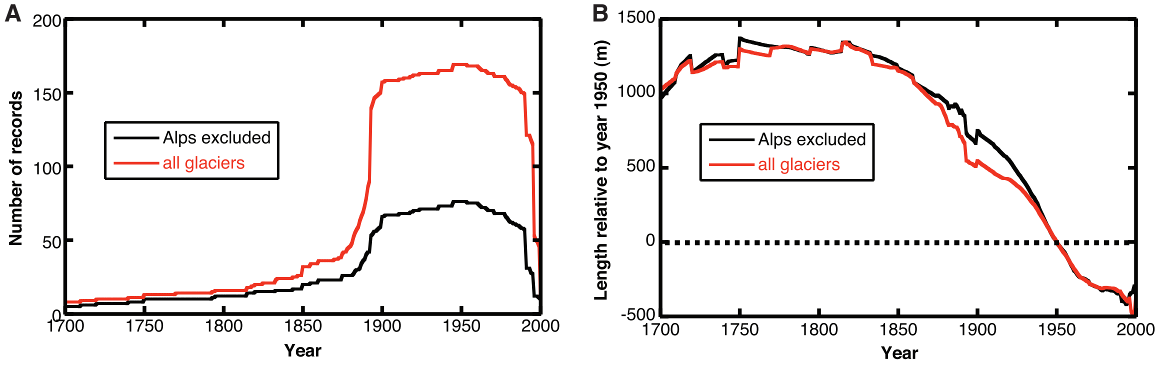

Fig. 2. (**A**) Number of records for the last 300 years. The decline after 1990 is due to a large delay in the reporting and publishing of data in a suitable form. (**B**) Stacked records of glacier length. Irregularities occur when a glacier with a large length change is added. However, this does not necessarily involve a large change in climatic conditions because glaciers exhibiting large changes are normally those that have a large climate sensitivity (and thus respond in a more pronounced way to, for instance, a temperature change). After 1900, the irregularities disappear because the number of glaciers in the sample increases strongly.

dinavia), and the Alps and Asia (Caucasus and Central Asia).

In all records, data points were connected by interpolation. Normally cubic splines were used. However, in some cases a combination of linear interpolation and fitting with splines performed better. All interpolated records were visually checked for spurious effects.

The number of records reveals a strong increase at the end of the 19th century, both for the Alps and for all other glaciers (Fig. 2A). Stacking all records yields a curve for the change in mean glacier length (Fig. 2B). The curve was not smoothed, implying that some irregularities occur when a glacier with a large change in length is added to the sample (or disappears from the sample at the very end). The curve for all glaciers outside the Alps is notably similar to the curve for the entire sample. This reflects the notion that glacier retreat on the century time scale is rather uniform over the globe. Around 1800, mean glacier length was decreasing and this decrease accelerated gradually. The present data set thus suggests that the Little Ice Age was at its maximum around 1800 rather than at the end of the 19th century as indicated by some other temperature proxies (*6*).

Histograms of mean retreat rates for selected periods show that very few glaciers in the sample actually became longer (fig. S1). For the period from 1860 to 1900 (36 records), one glacier advanced and all of the others retreated. For the period from 1900 to 1980, 142 of the 144 glaciers retreated.

The response of a glacier to climate change depends on its geometry and on the climatic setting. To unravel the climate signal contained in the glacier length records, it is necessary to discriminate with respect to the climate sensitivity c and to the response time τ (the time a glacier needs to approach a new equilibrium state). Similar to other climate proxies, glacier length fluctuations are the product of variations in more than one meteorological parameter. Glacier mass balance depends mainly on air temperature, solar radiation, and precipitation. Extensive meteorological experiments on glaciers have shown that the primary source for melt energy is solar radiation but that fluctuations in the mass balance through the years are mainly due to temperature and precipitation (*25*, *26*). Mass-balance modeling for a large number of glaciers has shown that a 25% increase in annual precipitation is typically needed to compensate for the mass loss due to a uniform 1 K warming (*3*, *27*). These results, combined with evidence that precipitation anomalies normally have smaller spatial and temporal scales than those of temperature anomalies (*2*), indicate that glacier fluctuations over decades to centuries on a continental scale are primarily driven by temperature. Here, the climate sensitivity c is therefore defined as the decrease in equilibrium glacier length per degree temperature increase.

The simplest approach that deals with lag effects is a linear response equation:

$$\frac{dL'(t)}{dt} = -\frac{1}{\tau}[cT'(t) + L'(t)] \qquad (1)$$

Here, t is time, L' is the glacier length with respect to a reference state, and T' is a temperature perturbation (annual mean) with respect to a reference state. The inverse model is now obtained by solving for T':

$$T'(t) = -\frac{1}{c}\left[L'(t) + \tau\frac{dL'(t)}{dt}\right] \qquad (2)$$

For any glacier length record, the corresponding temperature history can be obtained with Eq. 2 once the climate sensitivity and response time are known.

A number of glaciers have been studied by explicit numerical modeling (*28*) or more refined linear inverse modeling (*29*). However, the input data required for these methods is not available for most glaciers considered here. Therefore, c and τ were determined from a simple theory of glacier dynamics, calibrated with results from numerical studies (*30*). Climate sensitivity depends in particular on the surface slope (a geometric effect) and the annual precipitation (a mass-balance effect). Glaciers in a wetter climate are more sensitive (*31*, *3*), and this is taken into account (*30*). As a result, in the sample of 169 glaciers, c varies by a factor of 10, from ~1 to ~10 km K^{-1} (fig. S2). The response time is to a large extent determined by the slope and the balance gradient (the rate at which the mass gain or loss changes with elevation). Values of τ vary from about 10 years for the steepest glaciers to a few hundreds of years for the largest glaciers in the sample with a small slope (the glaciers in Svalbard). Most of the values are in the range of 40 to 100 years (fig. S2).

Because the right-hand side of Eq. 2 contains the time derivative of glacier length, the calculated temperature curves can be noisy. This noise was removed by filtering, which effectively smoothed out the variability on time scales shorter than about a decade.

Reconstructed temperatures for five regions are shown in Fig. 3A. The interpretation of the temperature curves before 1800 should be done with caution, because the number of records is small (Fig. 2A). From 1860 onward, most regions show a temperature increase. In the first half of the 20th century the temperature rise is notably similar for all regions: about 0.5 K in 40 years. After 1945, the global mean temperature drops slightly until 1970, when it starts to rise again. For North America, the reconstruction shows a marked cooling after 1940, which seems to be at odds with the substantial retreat observed for most glaciers during the past 20 years. This apparent discrepancy is due to the fact that many records from North America are not up to date and end in the period of 1975 to 1990 (table S1).

The global mean temperature shown in Fig. 3A is a weighted mean for the period from 1834 to 1990. To obtain a curve for the period from 1600 to 1990, it can be combined with a stacked temperature reconstruction for all glaciers before 1834 (Fig. 3B). The major sources of error for the global mean temperature reconstruction are (i) the influence of meteorological variables other than temperature, (ii) uncertainty in the climate sensitivity of the glaciers (which affects the amplitude

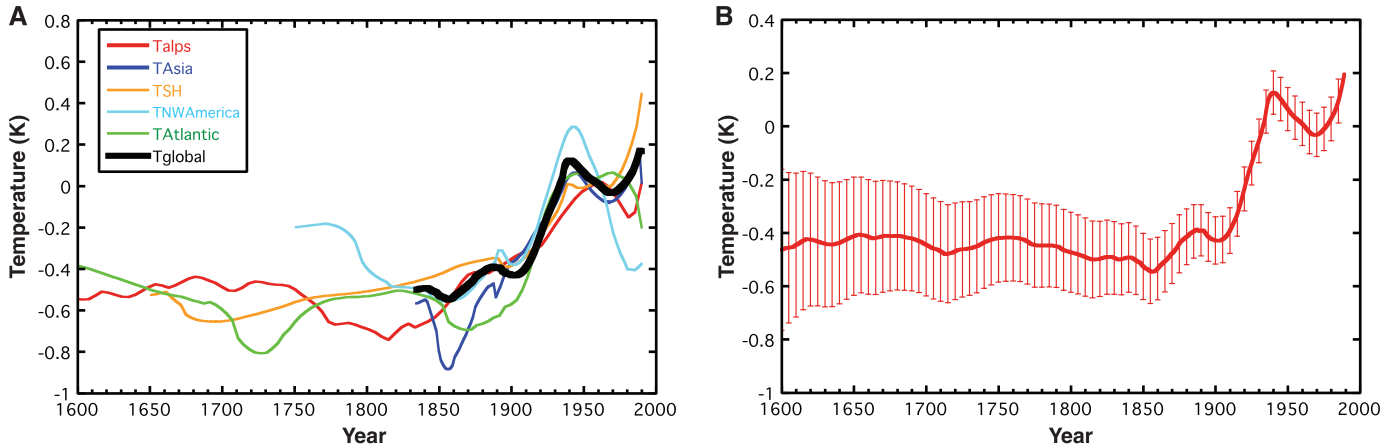

Fig. 3. (**A**) Temperature reconstruction for various regions. The black curve shows an estimated global mean value, obtained by giving weights of 0.5 to the Southern Hemisphere (SH), 0.1 to Northwest America, 0.15 to the Atlantic sector, 0.1 to the Alps, and 0.15 to Asia. (**B**) Best estimate of the global mean temperature obtained by combining the weighted global mean temperature from 1834 with the stacked temperature record before 1834. The band indicates the estimated standard deviation.

of the temperature reconstruction), (iii) uncertainty in the response times (which affects the phase of the temperature reconstruction), and (iv) the number of glacier length records and degree of global coverage. An error estimate was made by assigning ±20% errors to climate sensitivities and response times of individual glaciers and by making 10 subsamples of glacier length records (randomly removing 50% of the records). In total, 100 alternative temperature reconstructions were generated. The standard deviation calculated from this set of reconstructions is taken as an estimate of the error in the best estimate based on all records. This standard deviation has been smoothed in time. Changes in the resulting bandwidth reflect first of all the effect of the steadily increasing number of glacier records (Fig. 3B). The possibility that changes in precipitation are responsible for part of the observed glacier fluctuations cannot be excluded. However, a very large drying on a global scale would be needed to explain the worldwide glacier retreat, and there is no independent evidence at all of such a phenomenon (*2*).

The derived global temperature record is in broad agreement with other reconstructions and for the last part also with the instrumental record (fig. S3). However, the glacier reconstruction shows a somewhat larger amplitude on the century time scale. Because glaciers need time to react and the number of records drops sharply after 1995, the warming seen in the instrumental record over the past 15 years is not yet reflected in the reconstruction.

Temperature curves appear to be very similar for glaciers with low and high median elevation (fig. S4A). Low and high glaciers are classified as glaciers with median elevation below and above 2850 m, respectively (fig. S5). For this threshold, the number of glaciers in both classes is approximately equal. Although the evidence is not conclusive because only a limited altitudinal range is considered, the glacier record does not show any sign of a height dependence of the global warming signal.

Glaciers witnessed a particularly strong warming at high northern latitudes in the first decades of the 20th century (fig. S4B). Unlike the global mean signal, reconstructed temperature shows a minimum in the second half of the 19th century, when the Northern Hemisphere mid-latitudes were already warming up.

The temperature reconstruction presented here is fully independent of other sources (proxy or instrumental). It thus provides complementary evidence on the magnitude of the current global warming, on the time that this warming started, and on the notion that in the lower troposphere the warming appears to be independent of elevation.

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30. Climate sensitivity c and response time τ are modeled as $c = 2.3P^{0.6}s^{-1}$ and $\tau = 13.6\,\beta^{-1}s^{-1}(1 + 20s)^{-1/2}L^{-1/2}$. Here, P is the climatological annual precipitation in m/year, s is the mean surface slope of the glacier, β is the altitudinal mass-balance gradient, and L is the glacier length in the reference case in meters. These formulations were obtained by calibrating a simple model of glacier dynamics [(*3*), pages 61 and 73] with more explicit numerical modeling of a limited set of glaciers [(*3*), pages 83 to 92]. Values for P were obtained from climate stations and climate atlases. The balance gradient has been related to P by $\beta = 0.006P^{1/2}$ (here P is in m/year).
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Figs. S1 to S5
Tables S1 and S2
References

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