Deriving global temperature from glacier length records (draft)

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Background and method

From different parts of the world there is a wealth of information on glacier fluctuations. Systematic and precise measurements of glacier area and volume are relatively new (the past few decades). However, the length of a valley glacier is a relatively simple parameter to measure or to infer from sketches, paintings and early maps. In many cases moraines and trimlines provide very useful additional information (Fig. 1).

Fig. 1. The snout of the Morteratschgletscher, Switzerland. The former position of the glacier front has left clear marks in the landscape.

Compared to biogenic climate indicators, glacier systems react in a relatively simple way to climate change. The transfer function does not change in time and geometric effects can be dealt with.

Like 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 trough the years are mainly due to temperature and precipitation (Oerlemans, 2001). To compensate for the mass loss due to a 1 °C warming, a 25 % increase in annual precipitation is typically needed, which is a large number. Since precipitation anomalies normally have a smaller spatial and temporal scale than temperature anomalies (this is a fundamental property due to the nature of the processes involved), it is likely that glacier fluctuations over *decades to centuries* on a *continental scale* are primarily driven by temperature.

Glaciers react slowly and thus integrate climate fluctuations. E-folding response times for valley glaciers vary from ten to hundreds of years, depending on the geometry and climatic setting. This implies that annual resolution of a climate proxy from glacier records can never be achieved [on the other hand, 'annual climate resolution' is a rather meaningless concept anyway].

To calculate with a simple model (linear response equation) an annual temperature record that can explain the fluctuations of a certain glacier, two parameters characterising that glacier are needed: the response time τ referred to above, and the climate sensitivity c (conveniently expressed as the decrease in equilibrium glacier length for a 1 °C warming). It is possible to estimate c and τ with glacier models (Oerlemans, 2001); c and τ depend mainly on the surface slope of the glacier and the climatic regime. Steeper glaciers have a smaller response time and are less sensitive. Glaciers in a wet climate are also faster, but at the same time are more sensitive than glaciers in a dry climate.

In the analysis 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. An example of a derived temperature signal from a glacier length record is shown in Fig. 2.

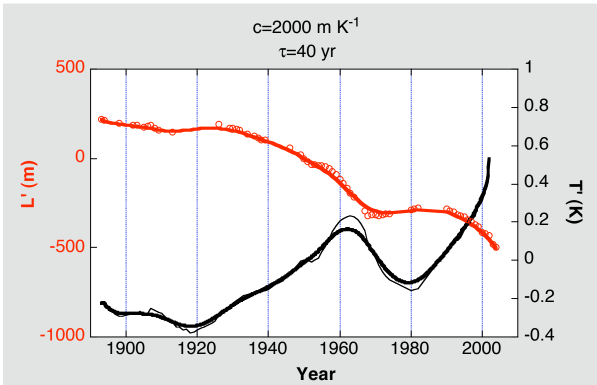

Fig. 2. Illustrating the linear backward model for given values of c and τ. The black curve shows the (smoothed) temperature signal that produces the observed glacier length record (in red - circles are individual measurements; note that there are significant gaps).

Data

169 records of glacier length were compiled from various sources. The core of the dataset comes from the files of the World Glacier Monitoring Service (WGMS, Zürich). Records were then included from glaciers in Patagonia, southern Greenland, Iceland and Jan Mayen. Additional information was taken from the Satellite Image Atlas of Glaciers of the World (U.S. Geological Survey) and from reports of the Swiss Academy of Sciences (for references, see Oerlemans, 2005). The character of the records differs widely (Fig. 3). Some start in 1600 and have typically 10 data points until 1900, and more afterwards. Other records start around 1900, but have annual resolution throughout. 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.

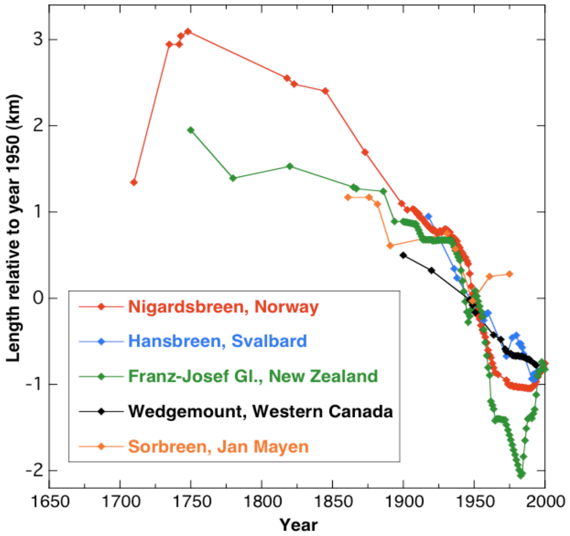

Fig. 3. Examples of glacier length records from different parts of the world. Each symbol represents a data point (from Oerlemans, 2005).

The records are not spread equally over the globe (Fig. 4). There is a strong bias towards the European Alps, where a wealth of documents exists and glacier monitoring has been introduced relatively early. Fluctuations of some glaciers in Iceland and Scandinavia before 1800 have also been documented well. Glacier records in North America have not been kept up to date and many series do not extend beyond 1985.

In deriving a global mean temperature signal, different regions have been given differents weights. These are defined as (weighing factor in brackets): Southern Hemisphere and tropics (0.5), Northwest America (0.1), Atlantic (0.15), Central Europe (0.1), Asia (0.15).

Fig. 5A shows the available number of records after interpolation. The number of records reveals a strong increase at the end of the 19th century, both for the Alps and for all other glaciers. After 1990 a strong decline can be seen; apparently many records have not been continued (or at least data have not been documented in the 'public domain').

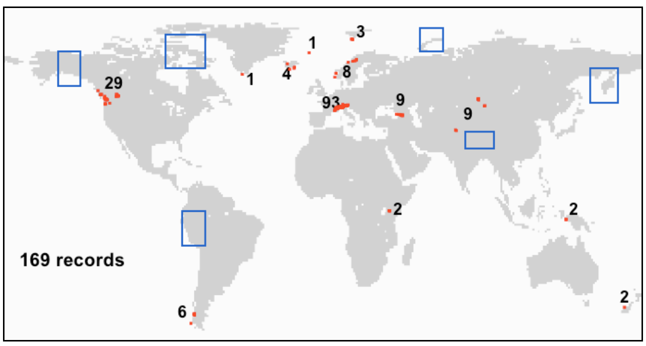

Fig. 4. Locations of the 169 glaciers from which length records are available. Numbers refer to numbers of glaciers 'regions'. Blue rectangles indicate areas where glacier records can probably be reconstructed from moraines, documentary evidence, old photographs and recent satellite images.

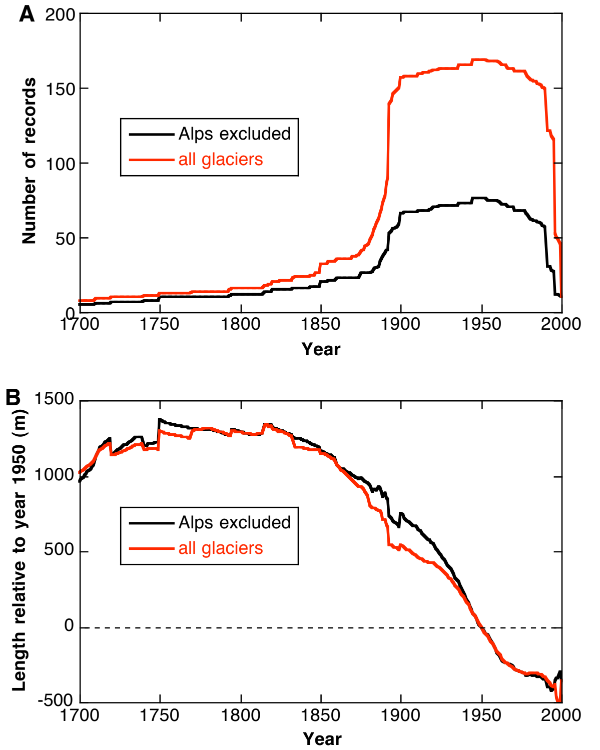

Fig. 5. A. Number of records. Note the gradual decline after 1950 and the very strong reduction of records after 1990. B. Stacked glacier length records. From Oerlemans (2005).

All glacier length records were adjusted to give length relative to the year 1950. The resulting stacked length record is shown in Fig. 5B. Irregularities appear when records from glaciers with large changes start or end.

There is a broad maximum in glacier length between 1750 and 1850. In the second half of the 19th century the global picture is already one of retreating glaciers everywhere, except at high northern latitudes.

It should be noted that for the period 1860-1900 (36 records) one glacier advanced and all the others retreated. For the period 1900-1980, 142 of the 144 glaciers retreated.

Result

The global mean temperature as reconstructed from the 169 glacier length records is shown in Fig. 6. It is a combination of an area-weighted mean for the period 1834 – 1990 and a stacked record for all glaciers before 1834 (because before this year there is no record for all regions as defined above).

To make an error estimate 100 alternative temperature reconstructions were generated by subsampling and varying the parameters c and τ. 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 band-width reflect first of all the effect of the steadily increasing number of glacier records.

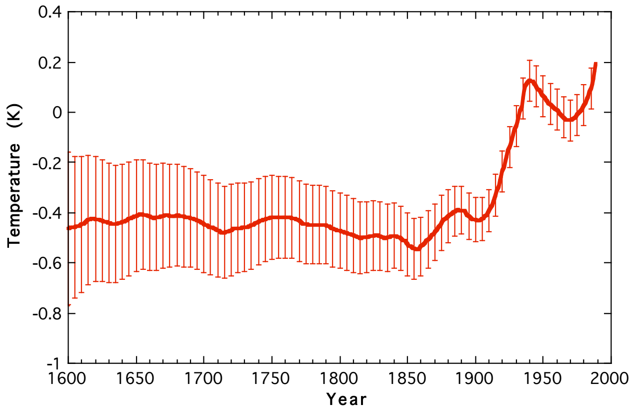

Fig. 6. Reconstructed global mean temperature anomaly. Due to the delayed response of glaciers and the strongly decreasing number of records, temperature cannot be reconstructed for the period after 1990.

It should be stressed that the temperature reconstruction presented here is fully independent of other sources (proxy or instrumental). Although in modelling of the climate sensitivity of glaciers extensive use has been made of meteorological observations on glaciers (process studies), it is not feasible to carry out a real 'calibration', in which a local temperature record could be compared with a local glacier length record. On smaller scales there are too many factors that have an influence on glacier mass balance.

Comparison with other studies using glacier data

To the knowledge of the author no earlier attempts have been made to derive a *global mean* temperature signal from data on glacier fluctuations. A number of studies are of a regional nature and have attempted to reconstruct equilibrium-line altitudes with a dynamic approach (e.g. Klok and Oerlemans, 2003). In another study equilibrium has been assumed between glacier length and climate (Hoelzle et al. 2003), by averaging the glacier length records over periods of estimated response time. This seems to be an inaccurate approach. Methods in which a constant phase lag between climate signal and glacier length is assumed (e.g. Nordli et al., 2003) should also not be supported, because such an approach is incorrect from a physical point of view: if a glacier has a characteristic response time the phase lag between forcing and response will depend on the period of the forcing.

Possible improvements

There are obvious ways to make the temperature reconstruction from glacier length records more accurate. As indicated in Fig. 4, it should be possible to obtain records from other reagions to improve global coverage. Many existing records could be brought up to date by using recent high-resolution satellite images (e.g. Landsat, ASTER).

Within the framework of the simple linear backward model (Oerlemans, 2005), it would also makes sense to refine the theory for deriving estimates of response times and climate sensitivities, without going to numerical models with full spatial resolution for individual glaciers.

References

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