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Solving the paradox of the end of the Little Ice Age in the Alps

Christian Vincent, Emmanuel Le Meur, and Delphine Six

Laboratoire de Glaciologie et de Géophysique de l'Environnement, Centre National de la Recherche Scientifique, Saint Martin d'Hères, France

Martin Funk

Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie, Zurich, Switzerland

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[1] The causes and timing of the Little Ice Age (fifteenth to nineteenth centuries) are still unclear (Crowley, 2000; Bond et al., 2001; Shindell et al., 2001). During the last part of this event (1760–1830), the advance of glaciers in the Alps conflicts with the summer temperature signal (Intergovernmental Panel on Climate Change, 2001). This paper attempts to solve this paradox. From glacier fluctuations and monthly temperature data, we show that mean winter precipitation was higher by at least 25% during this final phase compared to the twentieth century average and that glacier recession after 1830 clearly resulted from a winter precipitation decrease and not a temperature increase. Conversely, since the beginning of the twentieth century, glacier changes have been driven mainly by temperature change. **Citation:** Vincent, C., E. Le Meur, D. Six, and M. Funk (2005), Solving the paradox of the end of the Little Ice Age in the Alps, *Geophys. Res. Lett.*, *32*, L09706, doi:10.1029/2005GL022552.

1. Introduction

[2] Mountain glaciers are recognized as excellent tools to investigate the climate variability over the decadal to centennial timeframe [*Intergovernmental Panel on Climate Change* (*IPCC*), 2001; *Oerlemans and Fortuin*, 1992; *Haeberli et al.*, 2002]. The global extension of Northern Hemisphere glaciers between the fifteenth and nineteenth centuries, known as the Little Ice Age, is a good illustration of centennial variability [*Grove*, 2001]. However, the causes and the timing of glacier extension during the Little Ice Age are still unclear [*IPCC*, 2001; *Crowley*, 2000; *Bond et al.*, 2001; *Shindell et al.*, 2001]. For instance, Northern Hemisphere mean annual temperature estimates [*Jones et al.*, 1998, 2001; *Mann et al.*, 1998, 1999; *Crowley and Lowery*, 2000] indicate that temperatures from the fifteenth to the nineteenth centuries were only 0.2°C cooler than those from the eleventh to fourteenth centuries [*IPCC*, 2001], insufficient to explain the large advance of glaciers. Moreover, the timing of the onset of glacier retreat (mid-nineteenth century) conflicts with mean annual temperatures based on instrumental data [*Jones et al.*, 2001] and with paleo-temperature reconstructions [*Mann et al.*, 1999] that show no clear warming until the beginning of the twentieth century.

[3] In this paper, glacier mass balance fluctuation data were investigated in an attempt to solve this paradox. Mass balance data are direct climatic indicators as they directly record solid precipitation in the form of winter mass balances and surface energy fluxes via summer ablation [*Oerlemans*, 2001]. Moreover, it has been shown that ablation variations are closely related to temperature changes in the Alps [*Vincent*, 2002]. The relationships between mass balance and climate over the twentieth century have been analyzed throughout the Alps from the longest annual mass balance series in the Austrian, Swiss, and French Alps [*Vincent*, 2002; *Haeberli et al.*, 1998; *Vincent et al.*, 2004]. In this study, glacier reconstructions since the end of the eighteenth century were used to address the climate change leading to the large recession of alpine glaciers after 1830.

2. Data

[4] Figure 1 shows the locations of the longest annual mass balance series in the Austrian, Swiss, and French Alps. As depicted in Figure 2a, cumulative mass balances come from direct field measurements over the last 50 years (small dots). Old maps and photogrammetric measurements provide additional volume variations estimates from the beginning of the twentieth century (large triangles) for the Argentière, Saint Sorlin, and Sarennes glaciers [*Vincent*, 2002]. Since the cumulative mass balances of the Hintereisferner and Gries glaciers are unknown over the first half of the twentieth century, the first value have been artificially set to −20 m w.e. in 1953 and 1962, respectively, for easy reading on the graph. In fact, the oldest series of direct mass balance measurements in the world is from the Claridenfirn in Switzerland [*Vincent et al.*, 2004; *Müller and Kappenberger*, 1991; *Müller-Lemans et al.*, 1994] where observations have been carried out since 1914. Unfortunately, the cumulative mass balance of the Claridenfirn glacier could not be reported in Figure 2a because measurements come from two sites only and thus do not allow for computation of the total mass balance. However, these unique data are very useful to analyze the mass balance fluctuations over the twentieth century (see below). For the beginning of the nineteenth century, glaciers extensions are known from old maps and moraines positions [*Mougin*, 1912; *Lliboutry*, 1965; *Grove*, 1988]. Volume differences have been estimated for two glaciers, Saint Sorlin and Argentière, using two different methods. The volume of the Saint Sorlin glacier has been calculated by an ice flow model [*Le Meur and Vincent*, 2003] using the maximum glacier extension (close to 1830), deduced from an old topographic map and mapping of front moraines from the end of the Little Ice Age. In order to reconstruct the volume

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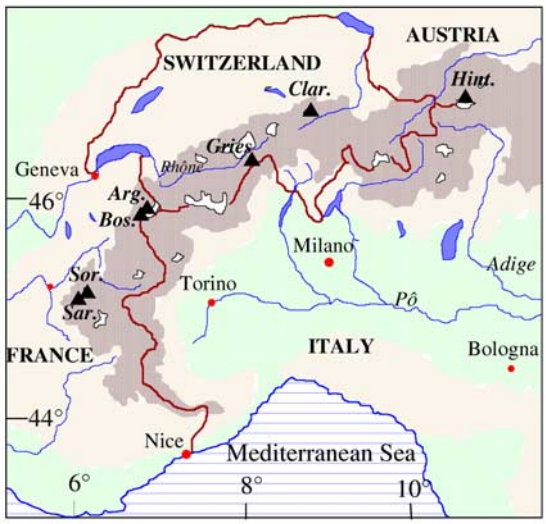


Figure 1. Map of the Alps. The glaciers of Sarennes (Sar.), Saint Sorlin (Sor.), Argentière (Arg.), Bossons (Bos.), Gries, Clariden (Clar.), and Hintereisferner (Hin.) are plotted on the map.

of this glacier, an extra 1.0 m w.e. yr^{-1} must be added to the present surface mass balance values (averaged over the last 50 years). This figure is consistent with other results found in the literature [*Schmeits and Oerlemans*, 1997]. With this method, the cumulative mass balance since 1830 reads −63.6 m w.e. The uncertainties arising from the ice flow modeling and from steady state assumptions can reach a maximum value of 10 m w.e. on the cumulative mass balance between 1830 and present.

[5] The topographic surface of the Argentière glacier for the last extension of the Little Ice Age has been reconstructed geometrically from the detailed topographic measurements of the large lateral moraines. This method does not allow for the determination of thickness variations in the accumulation zone; therefore, we assume that the slight thickness variations at high elevations decrease linearly with altitude. With this method, the cumulative mass balance since 1830 here reads −22.9 m w.e. The assumptions relative to the surface shape and to the thickness change at high elevations lead to a maximum uncertainty of 10 m w.e. on the cumulative mass balance.

3. Data Analysis

3.1. Evolution Over the Twentieth Century

[6] Figure 2a shows that these glaciers have been receding in response to the climate of the twentieth century. However, the twentieth century averaged cumulative mass balances are very different from place to place and range from −0.15 m w.e. yr^{-1} for the Argentière glacier to −0.62 m w.e. yr^{-1} for the Sarennes glacier. These trends result from their respective geometric and geographic characteristics, i.e., the size of the glaciers, altitude of the accumulation zones, and exposure. In order to reduce the effects of these specific trends and to investigate the mass balance fluctuations alone, the average rate of decrease (over the last 50 years) has been removed and replaced by that of the Saint Sorlin glacier (Figure 2b). For this purpose, each glacier mass balance has been reduced by subtracting the last 50 years average mass balance of each glacier from the annual values and by adding the average mass balance of the Saint Sorlin glacier. In addition to the glaciers shown in Figure 2a, Figure 2b also includes data from Claridenfirn. This figure shows a striking consistency for these data coming from glaciers spread over the whole Alps area (Sarennes and Hintereisferner are located 400 kms apart); it shows that cumulative mass balance fluctuations are very similar over the last 50 years, and it reveals a common climatic signal over the entire region. A detailed winter and summer mass balance analysis [*Vincent et al.*, 2004] reveals that (1) the average annual mass balance is essentially driven by the summer mass balance term and (2) melting rate variations since 1949 are very similar for two glaciers located 290 km apart.

[7] In order to reconstruct the long-term annual mass balance of these glaciers, meteorological data (precipitation and temperature) have been used together with a degree-day model, taking into account the change in the surface area of the glaciers [*Vincent*, 2002]. Given that sensitivity of mass balance to climatic parameters has been properly assessed from numerous field measurements, it becomes easy to

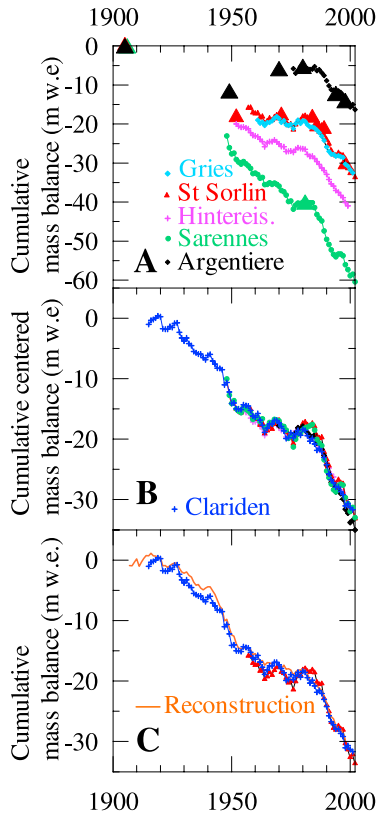


Figure 2. Cumulative mass balance of alpine glaciers in meters of water equivalent. (a) Observed cumulative mass balance for five glaciers in Austria, Switzerland, and France. (b) Cumulative centered mass balance series of the same glaciers (plus Claridenfirn) adjusted to the Saint Sorlin trend. (c) Cumulative mass balance from reconstruction (solid line) using degree-day model compared with Saint Sorlin and Claridenfirn observations (triangles and cross).

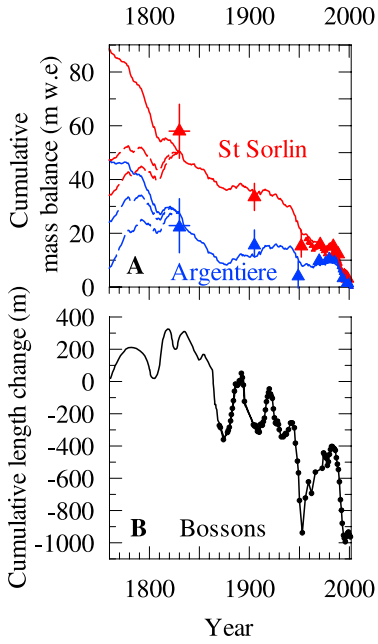


Figure 3. (a) Cumulative mass balance of two alpine glaciers since 1760, in meters of water equivalent, from direct measurements (small triangles), old maps or photogrammetric measurements (large triangles), and reconstructions using a degree day model with the twentieth century precipitation average (solid line). Between 1760 and 1830, tests have been carried out to increase winter precipitation by 25 and 35% (dashed lines). Error bars represent maximum uncertainties relative on these data. (b) Front fluctuations of the Bossons glacier in the French Alps over the same period, from direct measurements (dots) or from paintings and historical reports (solid line).

reconstruct annual mass balances in the Alps from winter precipitation (October to May) and summer temperature (May to September) [*Vincent*, 2002]. Homogenized summer temperature data (45°N; 6°E) [*Böhm et al.*, 2001] and average winter precipitation from Besse en Oisans (French Alps, Meteo France) have been used to reconstruct Saint Sorlin mass balance (Figure 2c). Here winter precipitations have been set deliberately to the mean value of the twentieth century in order to remove the influence of its variation with time. In addition, data from Saint Sorlin and Claridenfirn glaciers have been reported in Figure 2c for comparison. From these results, we can conclude that during the twentieth century, decadal variations of the annual mass balance can be largely explained by summer temperature change and that winter precipitation changes play a minor role on the long term (several decades). From these results and previous studies [*Vincent*, 2002; *Haeberli et al.*, 1998; *Vincent et al.*, 2004], it appears that, for the twentieth century, pluri-decadal mass balance fluctuations in the Alps result essentially from the summer energy balance change whereas the short-scale fluctuations result from winter precipitations.

3.2. Evolution Since 1760

[8] This analysis can extend back in time to 1760 using the homogenized alpine monthly temperature series [*Böhm et al.*, 2001]. The cumulative mass balances of these glaciers have been reconstructed for the period since 1760 using the degree-day model with homogenized summer temperature data and the average twentieth century winter precipitation from Besse en Oisans. The reconstructed values from the summer temperatures (Figure 3a, solid line) agree roughly with volume variations obtained from moraine positions and maps. Conversely, the very negative trend observed between 1760 and 1830 is quite the opposite of what would be expected from field observations and reports; indeed, length observations of alpine glaciers [*Vincent et al.*, 2004; *Grove*, 1988] show a general extension between the mid-eighteenth and mid-nineteenth centuries. For comparison, Figure 3b shows the length fluctuations of the Bossons glacier (Mont Blanc area) over the same period. Although these length variations cannot be directly interpreted in terms of climate change, it has been shown [*Martin*, 1977; *Reynaud*, 1984] that this glacier has a very short response time and that these snout fluctuations are closely related to cumulative mass balance variations. From this series, the glacier extension between 1760 and 1830 is clearly observable except for a regression phase between 1790 and 1805. This extension, visible on most glaciers in the Alps [*Grove*, 1988] contrasts with summer temperature data: Between the mid-eighteenth and mid-nineteenth centuries, the mean summer temperatures obtained from either homogenized observations in the Alps [*Böhm et al.*, 2001] or from multiproxy reconstructions for Europe [*Luterbacher et al.*, 2004] appear higher than the twentieth century average. Consequently, the last extension of alpine glaciers at the end of the Little Ice Age is the consequence of a winter precipitation increase. Given that this extension concerns the entire Alps [*Grove*, 1988] and that summer temperature trends are similar throughout the area [*Böhm et al.*, 2001], this conclusion is probably valid over the whole Alps. Using our degree-day model, we can estimate the precipitation increase required to offset the summer temperature effect between 1760 and 1830. These estimates have been based on the following criteria: (1) The 1760 glacier volume is larger than that of the beginning of the twentieth century and (2) the cumulative mass balance shows a positive trend between 1760 and 1830, and reveals a maximum in 1830. To respect these criteria, tests carried out using the degree-day model show that it is necessary to increase twentieth century average winter precipitation by at least 25% (Figure 3a, dashed lines). Modeling of Saint Sorlin and Argentiere glaciers gives similar results. Therefore the large alpine glacier recession that started not later than the mid-nineteenth century is clearly due to a winter precipitation decrease and not a temperature increase. The advance of glaciers (1760–1830) must be caused by a period of winter precipitation at least 25% higher than the twentieth century average. These results seem to agree with the change in the seasonal distribution of precipitation at the beginning of the nineteenth century as revealed by tree ring isotopic records obtained in western Europe [*Masson-Delmotte et al.*, 2005].

4. Conclusions

[9] Our study shows that the observed glaciers advance between 1760 and 1830 conflicts with the summer temper-

ature signal. From glaciers data measurements, mass balance reconstructions, and homogenized instrumental temperatures, we can conclude that this advance is caused by a period of higher winter precipitation of at least 25% compared to the twentieth century average. Indeed, alpine glacier recession at the end of the Little Ice Age started after 1830, largely before the temperature increase based on instrumental data or on paleo-temperature reconstructions. Thus this recession clearly results from winter precipitation decrease. The effect of summer warming on this glacier recession is visible only after the beginning of the twentieth century.

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M. Funk, Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie, Zurich, Switzerland.

E. Le Meur, D. Six, and C. Vincent, Laboratoire de Glaciologie et de Géophysique de l'Environnement, Centre National de la Recherche Scientifique, 54 rue Molière, Saint Martin d'Hères, F-38402 France. (vincent@lgge.obs.ujf-grenoble.fr)