Summary

The history of the *Mer de Glace* AD 1570–2003 according to pictorial and written documents

The *Mer de Glace* is a valley glacier 12 km long that is situated at the northern exposition of the Mont Blanc (France). Including all tributaries, it covers an area of about 32 km^2 and spans an altitudinal range from 1500 to 4000 m asl. It is the longest and largest glacier of the western Alps. During the Little Ice Age (LIA), the *Mer de Glace* nearly continuously reached the bottom of the valley of Chamonix at 1000 m asl. The attractiveness of the landscape and the easy accessibility soon made the glacier a desirable object of study for scientists, artists and tourists, leading to a large number of historical documentary data.
For the *Mer de Glace*, there exists a glacier length curve for the period from AD 1590 to 1911, compiled by Mougin (1912). Further investigations of glacier fluctuations during the late Holocene were made by Wetter (1987). The aim of this study is to establish a revised and refined glacier length curve for the *Mer de Glace*, using newly available documentary data.
The analysis and interpretation of historical documents allows the determination of former glacier extents. Excellent examples of glacier representations of the *Mer de Glace* are given by the drawings of Jean-Antoine Linck (1766–1843) and Samuel Birmann (1793–1847), and the maps by James David Forbes (1809–1868) and Eugène Viollet-le-Duc (1814–1879). Additionally, moraines have been mapped for the determination of former glacier extents. The analysis of old topographical maps (from 1906, 1939, 1958, and 1967) and a photogrammetric evaluation of recent aerial photographs (from 2001) yield a detailed description of the present state of the glacier. The calculation of digital elevation models (DEMs) allows the quantification of volume changes for the *Mer de Glace* for the 20th century.
The revised and refined glacier length curve for the *Mer de Glace* goes as far back as AD 1570. Not surprisingly, the glacier shows a generally large extent during the LIA. The largest glacier extension, documented by several archive texts and moraines, occurred around 1644. The largest glacier advance in the 19th century culminated in 1821 and is roughly 40 m smaller than the 1644 advance. A second advance in the 19th century occurred in 1852, with the glacier still lying roughly 70 m behind the well-formed 1821 moraines. Other major glacier advances are documented around 1600, 1720, and 1778. Since the 1850s, the glacier has retreated more or less continuously (except for some minor advances) by more than 2 km until the present. During the 20th century, the *Mer de Glace* shows a remarkable ice volume loss which mainly took place in the lower part of the glacier.
The new glacier length curve is in good agreement with the curve proposed by Mougin (1912). However, significant differences occur around 1850, when the glacier extent seems to have been much larger than assumed by Mougin. Furthermore, the new documentary data allow a more detailed

description of glacier fluctuations for the 1750–1820 period. The glacier extension around 1644 is roughly 100 m smaller than shown by the Mougin curve.
A comparison of the *Mer de Glace* length curve with that of the *Unterer Grindelwaldgletscher* (Zumbühl, 1980; Zumbühl *et al.*, 1983) yields an astonishing simultaneity between the glaciers, despite the different settings in the western and central Alps. Small differences occur around 1855 (19th century maximum of the *Unterer Grindelwaldgletscher*) as well as between 1650 and 1750 (generally greater extension of the *Mer de Glace* with more variability).

The application of a neural network to the length record of the *Mer de Glace*

A new suitable statistical approach to simulating glacier variations is the application of a neural network model, especially in this study, a non-linear back-propagation neural network model is successfully applied to simulate glacier variations of the *Mer de Glace* (Mont Blanc area, France), using multiproxy reconstructions of seasonal temperature and precipitation back to 1500 (Casty *et al.*, 2005).
The neural network model is trained with high-resolution climate data (input data) and glacier length variations of the *Mer de Glace* (output data). In the absence of glacier length data before 1570, the application of a neural network model yields plausible qualitative reconstructions of glacier fluctuations for the 16th century (glacier maximum around 1565, minima around 1552 and 1575).
Future glacier length variations of the *Mer de Glace* are simulated using two climate scenarios. The first scenario assumes no changes in mean climate, the second scenario embodies higher temperature and changing precipitation values. Confronting current climate change, the more likely scenario 2 shows a continuous and remarkable retreat of the *Mer de Glace* until the end of the simulation period in 2042. The prediction for scenario 1 indicates a glacier front position in 2042 around that of the present-day. For both scenarios, the simulation period ranges from 1900 to 2042, showing a very good accordance between the simulated curve and the measured glacier front values for the 20th century. The glacier responses significantly distinguish between the two scenarios, showing the key role of glaciers for the detection of climate change.
Moreover, the utilization of the neural network model as a sensitivity analysis tool suggests that the *Mer de Glace* is more influenced by temperature than precipitation, in contrast to the *Unterer Grindelwaldgletscher* (Bernese Alps, Switzerland). Finally, this non-linear neural network approach is a new contribution to the various investigations of the complex glacier-climate system, which allows finding explanations for several glacier advances and retreats. Even though the relationship between glacier length and climate parameters is not easy to determine, clear statements concerning glacier reaction to climate variables are possible.

The LIA history of the *Glacier des Bossons* (Mont Blanc area, France): a new high-resolution glacier length curve based on historical documents

Historical and proxy records document that there is a substantial asynchronous development in temperature, precipitation and glacier variations between European regions during the last few centuries. The causes of these temporal anomalies are yet poorly understood. Hence, highly resolved glacier reconstructions based on historical evidence can give valuable insights into past climate, but they exist only for few glaciers worldwide.

Here, we present a new reconstruction of length changes for the *Glacier des Bossons* (Mont Blanc area, France), based on unevaluated historical material. More than 250 pictorial documents (drawings, paintings, prints, photographs, maps) as well as written accounts have been critically analysed, leading to a revised picture of the glacier's history, especially from the mid-18th century up to the 1860s. Very important are the drawings by Jean-Antoine Linck, Samuel Birmann and Eugène Viollet-le-Duc, which depict meticulously the glacier's extent during the vast advance and subsequent retreat during the 19th century.
The new glacier reconstruction extends back to AD 1580 and proves maxima of the *Glacier des Bossons* around 1610/1643, 1685, 1712, 1777, 1818, 1854, 1892, 1921, 1941, and 1983. The LIA maximum extent was reached in 1818. Until the present, the glacier has lost about 1.5 km in length, and it is now shorter than at any time during the reconstruction period.
The *Glacier des Bossons* reacts faster than the nearby *Mer de Glace* (glacier reconstruction back to AD 1570 available). The Mont Blanc area is, together with the valley of Grindelwald in the Swiss Alps (two historical glacier reconstructions available back to AD 1535, and 1590, respectively), among the two regions that are probably best-documented in the world regarding historical glacier data.

Historical glacier fluctuations of *Jostedalsbreen* and *Folgefonna* (southern Norway) revisited according to pictorial and written documents

European alpine glaciers are sensitive indicators of past climate and thus valuable sources of climate history. Unfortunately, direct determinations of glacier changes (variations in length and mass balance) did not start with increasing accuracy before the end of the 19th century. Therefore, historical and physical methods have to be used to reconstruct glacier variability for preceding time periods.
Here we present new glacier length reconstructions for selected outlet glaciers of *Jostedalsbreen* and *Folgefonna* (two ice caps in southern Norway). A wealth of different historical sources (drawings, paintings, prints, photographs, maps, written accounts; about 400 documents) allow reconstruction of glacier length variations for the last 300 (*Jostedalsbreen*), and 200 years (*Folgefonna*), respectively.
We present historical material newly collected for *Briksdalsbreen*, *Bøyabreen*, *Store Supphellebreen*, *Bergsetbreen*, *Nigardsbreen*, *Lodalsbreen* (all *Jostedalsbreen*), and *Bondhusbrea*, *Buerbreen* (both southern *Folgefonna*).
At *Jostedalsbreen*, glaciers reached their Little Ice Age (LIA) maximum extent around AD 1750. *Nigardsbreen* is best-documented, where also the advance in the mid-18th century can be quantified. However, the nearby *Bergsetbreen* shows more distinct glacier advances and retreats since the LIA maximum extent. A minor peak is documented in the 1870s for all outlet glaciers of *Jostedalsbreen* studied.
At southern *Folgefonna*, the LIA maximum was attained in the late 1870s (second peak around 1890). So far, there is no direct historical evidence for the time before AD 1800.

Asynchronous development of glacier variations in Europe

There is a striking asynchrony between Alpine and Scandinavian glaciers during the LIA and in the 20th century (LIA maximum peaks around 1600/1640 and 1820/1850 in the Alps, and around 1750 (1870–1890) in southern Norway). In the second half of the 20th century, southern Norwegian glaciers showed a major advance due to enhanced winter precipitation.

Changes in the large-scale atmospheric circulation over the northern North Atlantic/European area and Eurasia lead to differences in temperature and precipitation distribution responsible for the different glacier behaviour. Sea surface temperature (SST) changes may be important at low frequency time scales, too. For southern Norway, the influence of the North Atlantic Oscillation (NAO) on glacier mass balance is evident, as they are highly affected by winter precipitation. For the Alps on the other hand, other large-scale weather patterns seem to be of great importance.