Summary

Glacier fluctuations are sensitive indicators of climate variability. Glacier mass balance is a direct function of temperature and precipitation and determines, among other factors, the dynamical behaviour and fluctuations of a glacier. Glacier length on the other hand is an indirect and delayed signal of climate information, but much easier to determine than mass balance. Glacier length is thus a useful and pragmatic tool for the examination of the glacier – climate relationship. At the end of the 19th century, the first accurate measurements of glacier length fluctuations were carried out. Unfortunately, the preceding time of the Little Ice Age (LIA) is not documented by instrumental data, and interdisciplinary approaches that use both historical and physical methods are needed to reconstruct the behaviour of glaciers back in time. Such an approach has been chosen in this study to investigate the fluctuations of the *Mer de Glace*.

Glacier length curve for the *Mer de Glace*

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 LIA, the *Mer de Glace* nearly continuously reached the bottom of the Vallée de 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 1590 to 1911, made by Mougin (1912). Further investigations of glacier fluctuations during the late Holocene were made by Wetter (1987). The aim of the present study is to establish a revised and refined glacier length curve for the *Mer de Glace*, using newly available documentary data. This new curve then serves as a basis for simulations using climate data and a new neural network approach.

Historical and physical methods

The analysis and interpretation of historical documents allow the determination of former glacier extents. Documents containing pictorial information on the glacier terminus (e.g., drawings, paintings, prints, photographs, and maps) as well as texts (descriptions of the valley, etc.) are used. A serious selection of the documentary data (e.g., dating of a painting) is necessary in order to get reliable information. The comparison of an old picture with today's situation in the field and the mapping of moraines is helpful for 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).

A new suitable statistical approach to simulating glacier variations is the application of a neural network model (NNM), especially in combination with high-resolution climate data (Steiner, 2005). In the present study, a non-linear back-propagation NNM is applied to the *Mer de Glace*, using multiproxy reconstructions of seasonal temperature and precipitation back to 1500 (Casty *et al.*, 2005).

Finally, the analysis of old topographical maps (from 1906, 1939, 1958, and 1967) and a photogrammetric evaluation of recent aerial photographs (from 2001) give 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.

Results and discussion

The revised and refined glacier length curve for the *Mer de Glace* dates back to 1570 (Appendix 4, Figure 7.25). 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, e.g. in 1995) by more than 2 km until the present-day. 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.

In the absence of data before 1570, the application of a NNM yields qualitative plausible reconstructions of glacier fluctuations for the 16th century (glacier maximum around 1565, minima around 1552 and 1575, respectively). In addition, future glacier length variations of the *Mer de Glace* are simulated using two climate scenarios. 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 (no change in mean climate) 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. Moreover, the utilization of the NNM as a sensitivity analysis tool suggests that the *Mer de Glace* is more dominated by temperature than precipitation, in contrast to the *Unterer Grindelwaldgletscher*.

The new glacier length curve is in good agreement with the curve made by Mougin (1912). However, significant differences occur around 1850, when the glacier extent seems to have been much more extensive than assumed by Mougin. Furthermore, the new documentary data allows 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 the one 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 1850 (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).

A non-linear statistical glacier model was successfully applied to the *Mer de Glace*. Even though the relationship between glacier length and climate parameters is not easy to determine, it was possible to make clear statements concerning glacier reaction to climate variables. In order to further confirm the knowledge gained, it would be interesting to consider more Alpine glaciers, and also to extend the comparison by studying LIA glacier fluctuations in other parts of the world.