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# Two Alpine Glaciers over the Past Two Centuries

## A SCIENTIFIC VIEW BASED ON PICTORIAL SOURCES

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For centuries high mountains and glaciers have been a source of both paralyzing fear and strange fascination. Natural scientists first began to show interest in Alpine glaciers at the beginning of the eighteenth century, but although the first simple observations of glacier movements and moraines were made, no systematic scientific investigations were carried out (Zumbühl 1980).

The nineteenth century witnessed the Ice Age hypothesis and the beginning of modern experimental glaciology. Initial detailed studies of glacier-related phenomena were undertaken on the Unteraar Glacier, in Switzerland, in the 1840s by Louis Agassiz (1807–73). His contributions to the newly established scientific field earned him the title of the "Father of Glaciology" (Lurie 1960). Impressive glacier advances affecting the majority of Alpine glaciers at about the same time can be recognized from archives and documentary evidence (Maisch et al. 1999; Nicolussi and Patzelt 2000). In addition, new kinds of documentary data that could be used to study glacier fluctuations appeared. The technical progress of photography made it possible to record a glacier's position without any artistic distortion (Gernsheim 1983), and the first geometrically exact topographic map of Switzerland, the so-called Dufour map, was published between 1844 and 1864 (Wolf 1879; Graf 1896; Locher 1954).

In general, all these historical records can give a very detailed picture of glacial fluctuations in the Swiss Alps during the Late Holocene. They allow the extension of the study of glacier history farther into the past than would be possible with the use of direct measurements alone (e.g., Holzhauser, Magny, and Zumbühl 2005). Empirical qualitative and/or quantitative data, mainly on the length but also on the area and volume of glaciers, can be derived from these sources.

With methods based on historical records, a temporal resolution of decades or, in some cases, even individual years can be achieved in the reconstruction of glacier time series. Probably the best example in this context is Switzerland's Unterer Grindelwald Glacier. Fluctuations in its length have been reconstructed with the aid of numerous texts and

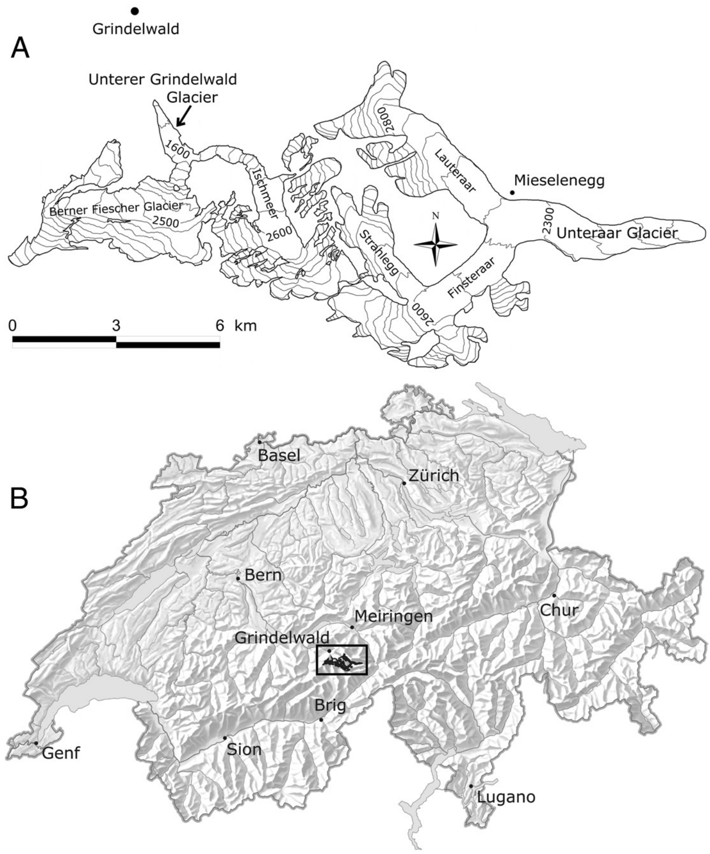


FIGURE 6.1. (A) The outlines of the Unterer Grindelwald and the Unteraar Glaciers and their main branches and tributaries and (B) the Unteraar Glacier and the Grindelwald region (*area with solid outline*) in Switzerland.

pictorial representations back to 1535 (Zumbühl 1980; Zumbühl, Messerli, and Pfister 1983; Holzhauser and Zumbühl 1996, 1999, 2003). For many other glaciers in the European Alps (e.g., the Mont Blanc region) the historical material appears exceptionally rich, but there may be untapped documentation for similar research in many other areas of the world.

The objective of this article is to bring together documentary data to quantify the fluctuations of the Unteraar and the Unterer Grindelwald Glaciers since their mid-nineteenth-century maximum extent. Whereas many other studies of glacier change focus on the regional or even global scale, our study deals with two exemplary glaciers in a relatively small area. In addition to having comparable climatic conditions and similar characteristics (e.g., area), the two glaciers are documented by a particularly rich sample of data. However, obtaining reliable results requires considerable effort in calibrating these data.

Finally, as a background to the beginning of modern glaciology, we also analyze the remarkable development of representation techniques from drawings and topographic surveys to the first scientific photographs within a few centuries.

## THE LOCAL SETTING

The Unteraar and the Unterer Grindelwald Glaciers are located within a few kilometers of each other in the Bernese Alps (Figure 6.1).

The Unteraar (latitude 46°35′N, longitude 8°15′E) is a valley glacier 13.5 km long and covering 24.1 km$^2$. A prominent feature is its large

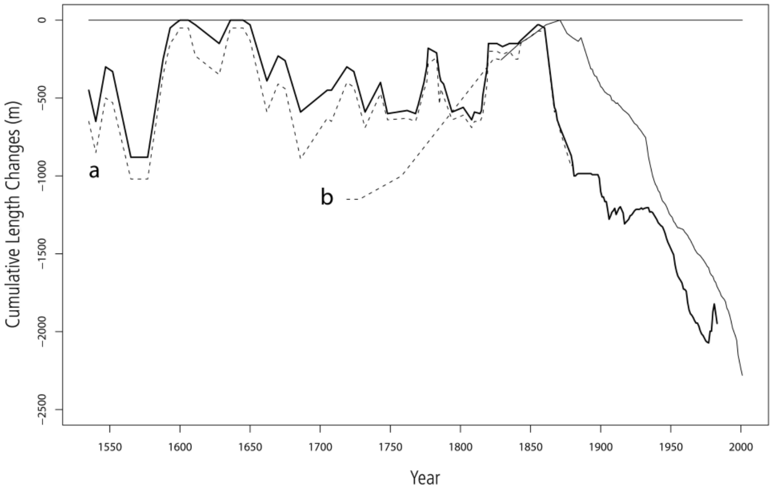


FIGURE 6.2. Cumulative length variations of (*a*) the Unterer Grindelwald Glacier from 1535 to 1983, relative to the 1600s maximum extent (=0), and (*b*) the Unteraar Glacier from 1719 to 2001, relative to 1871 (=0). Maximum extensions of the Unterer Grindelwald are represented by a thick line, minimum extensions by a dashed line. The Unteraar is represented by a solid line for the 1830–2001 period and a dashed line for the possible position between 1719 and 1829 (Zumbühl 1980; Zumbühl and Holzhauser 1988; Holzhauser and Zumbühl 1996, 2003; VAW/SANW 1881–2002).

ice-cored medial moraine and extensive debris cover, typically 5–15 cm thick (Bauder 2001; Schuler, Fischer, and Gudmundsson 2004). The tongue of the Unteraar is formed by the two main tributaries the Lauteraar and the Finsteraar. Mass balance measurements indicate that the present equilibrium line altitude of Unteraar is at 2,850 m a.s.l. (Bauder 2001). The present glacier terminus, 1.5 km from Lake Grimsel, is at an elevation of 1,950 m a.s.l. The cumulative length fluctuations of the Unteraar (Figure 6.2, *b*) show a continuous retreat of the glacier since the first observations in the 1880s (VAW/SANW 1881–2002; Zumbühl and Holzhauser 1988).

The Unterer Grindelwald Glacier (latitude 46°35'N, longitude 8°05'E) is a valley glacier 8.85 km long and covering 20.6 km$^2$. Ischmeer in the east and the Berner Fiescher Glacier in the west join to form its tongue. The main contribution of ice nowadays originates from the Berner Fiescher Glacier (Schmeits and Oerlemans 1997).

The approximate equilibrium line altitude (AAR [accumulation area ratio] = 0.67; Table 6.1), derived from digital elevation models and confirmed by the maximum elevation of lateral moraines (Gross, Kerschner, and Patzelt 1976; Maisch et al. 1999), is situated at 2,640 m a.s.l. in relatively flat areas. As a consequence of this specific hypsography, the relatively small ca. 40-m rise of the equilibrium line altitude in the past 140 years has resulted in a large increase of the ablation area and thus a large glacier retreat since the mid-nineteenth century (Nesje and Dahl 2000). Today the Unterer Grindelwald Glacier terminates at about 1,297 m a.s.l. in a narrow gorge, and reliable observations are difficult to obtain.

The last-published quantitative observation was made in 1983 (VAW/SANW 1881–2002). Because of the extraordinarily low position of its terminus and its easy accessibility, the Unterer Grindelwald is probably the best-documented glacier in the Swiss Alps. Figure 6.2, *a*, shows its cumulative length fluctuations, derived from documentary evidence, for the period 1535–1983 (Zumbühl 1980; Holzhauser and Zumbühl 1996, 2003).

The geometry of the two glaciers differs from that of the "model" glacier in having a wide variety of surface slopes and many basins that deliver ice to the main streams.

TABLE 6.1

*Topographical Characteristics of the Unterer Grindelwald Glacier in 1860/61/72 and 2004*

| | 1860/61/72 | 2004 |
|---|---|---|
| Length (measured along the longest flowline 1; see Figure 6.10) | 10.8 km | 8.85 km |
| Elevation of head (Mönch) | 4,107 m a.s.l. | 4,107 m a.s.l. |
| Elevation of terminus | 972 m a.s.l. | 1,297 m a.s.l. |
| Surface area[a] | 26.1 $km^2$ | 20.6 $km^2$ |
| Estimation of equilibrium line altitude (accumulation area ratio = 0.67) | 2,600 m a.s.l. | 2,640 m a.s.l. |
| Average slope in % | 29% | 31.8% |
| Average slope in degrees | 16.1° | 17.6° |
| Exposure | N-NW | N-NW |
| Absolute ice volume change 1860/61/72–2004 | $-1.56$ $km^3$ | |
| Average thickness change rate 1860/61/72–2004 | $-0.42$ m $a^{-1}$ | |

NOTE: The calculations are based on digital elevation models for 1861 and 2004 (Table 6.2, *a*).
[a]Including all subglaciers connected with major streams in 1860/61/72.

## FROM FIRST OBSERVATIONS TO DETAILED STUDIES

Systematic observations on the Unteraar Glacier began with the field work of the naturalist Franz Josef Hugi (1796–1855) between 1827 and 1831. It was he who made the first observations on the surface velocity of the glacier (Hugi 1830). When his successor, Louis Agassiz (1807–73), visited the glacier in 1839, he found to his surprise that Hugi's hut on the medial moraine had moved since 1827, an important indication of glacier movement (Agassiz 1885; Portmann 1975). Agassiz's observations were also aimed at supporting his theory of ice ages. The idea that glaciers transported erratic material was not new and probably originated with the mountain farmer Jean-Pierre Perraudin (1767–1858), who explained it in 1815 to the geologist Jean de Charpentier (1786–1855) (Haeberli and Zumbühl 2003). Charpentier's argument that the Swiss glaciers had once been much more extensive was taken up by Agassiz, who further postulated that the whole Northern Hemisphere had once been covered with a gigantic glacier. This Ice Age hypothesis was rejected by many people because it challenged the prevailing Bible-based Christian worldview, which does not include huge glaciers. In addition to this, comparable glaciers or ice sheets had not yet been discovered (Bolles 1999; Haeberli, this volume).

Between 1840 and 1845 Agassiz conducted a research program on the glacier that constituted the beginning of modern experimental glaciology. He initially acted as a leader and program manager of his interdisciplinary team and was also responsible for the climatic data. His secretary and friend, the naturalist Jean Édouard Desor (1811–82), conducted the glaciological and geomorphological research. The results of their numerous observations were comprehensively documented in Agassiz (1847). Besides these extensive glaciological studies, the artists and engineers on the team produced the first outstanding representations of the glacier, among them the panorama of Jacques Bourkhardt (1811–67) and the glacier

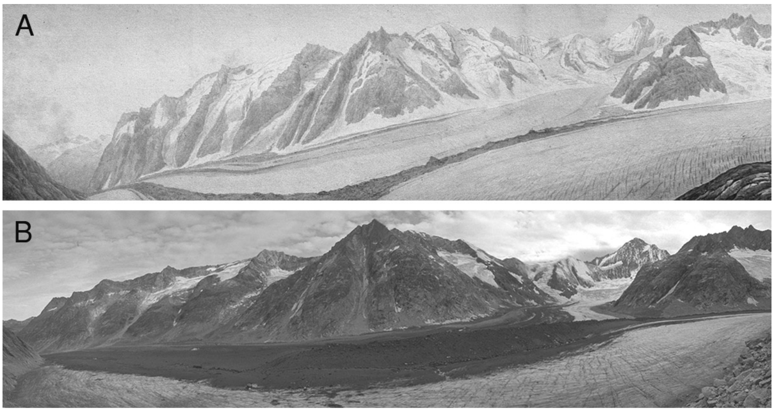


FIGURE 6.3. (A) Bourkhardt's drawing (24.4 × 126 cm; pencil, pen, ink, watercolor, gouache) of the chromolithograph "Panorama de la mer de glace du Lauteraar et du Finsteraar–Hôtel des Neuchâtelois" from the Mieselenegg (Swiss national coordinates approx. 657′500/158′700, altitude approximately 2,620 m a.s.l.) in 1842 (*detail*). Private collection. (B) Recent panorama taken east from the Mieselenegg (Swiss national coordinates approximately 657′600/158′600, altitude approximately 2,520 m a.s.l.) on August 22, 2004. (Photos Daniel Steiner and Heinz J. Zumbühl.)

maps of Johannes Wild (1814–94) and Johann Rudolf Stengel (1824–57).

## BOURKHARDT'S (1842) PANORAMA

Jacques Bourkhardt's drawing of the chromolithograph "Panorama de la mer de glace du Lauteraar et du Finsteraar–Hôtel des Neuchâtelois," which had been missing for a long time (Figure 6.3, A) is probably the most beautiful and topographically richest panorama ever done of the Unteraar Glacier. In it the different mountain peaks were named for the first time. The partial panorama includes the main mountain peaks in the background and the confluence area of the Finsteraar and Lauteraar Glaciers. Desor (1847) praised the panorama and pointed to the time-consuming drawing process that had produced it. The significance of the panorama may be judged from its use as the background for the portrait (Figure 6.4) of Agassiz and Desor by Fritz Berthoud (1812–90) as a reminder of the great scientific work done by the two naturalists.

On the medial moraine, below the confluence area, the panorama shows the "Hôtel des Neuchâtelois," a huge metamorphic boulder that served Agassiz and his team as accommodation and as a shelter during the summer field seasons. It also shows the newly built tent (20 m long and 5 m high) constructed by the guides and used for sleeping, drawing, and study (see Haeberli, this volume).

## FIRST PHOTOGRAPHS OF GLACIERS

Besides portraiture, early photographers paid special attention to architecture, travel views, and landscapes. One possible reason that scientific and public interest focused specifically on glacier photographs is probably the dramatic Greenland expedition of the Arctic explorer Elisha Kent Kane (1820–57) from 1853 to 1855. During his search for survivors of another expedition, Kane's ship became icebound and his objective changed to one of survival. After two years of hardship and a difficult journey over ice and open water to Greenland, he and his shipmates were finally rescued (Kane 1856). His reports of an "ice-ocean of boundless dimensions" confirmed the existence of huge ice masses and brought final acceptance of the Ice Age hypothesis after 40 years of discussion and opposition. This prompted curiosity and attracted more and more tourists to locations where they could admire even "little" glaciers such as those of the Swiss Alps.

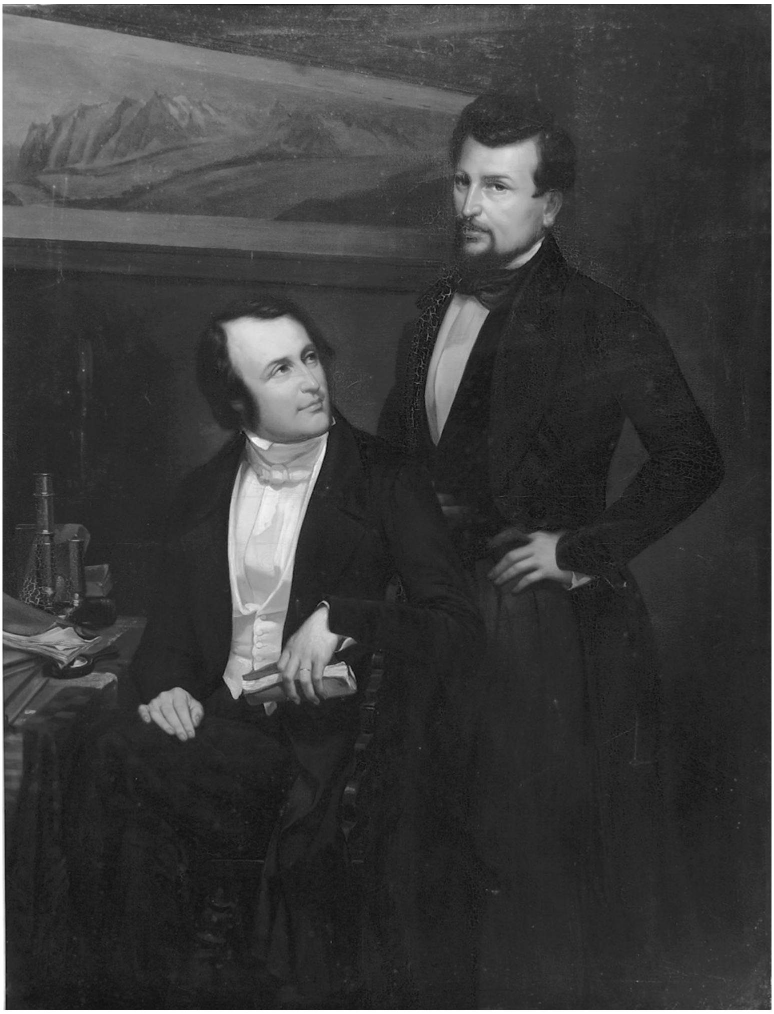

FIGURE 6.4. Portrait (in oil) of Louis Agassiz (*seated*) and Jean Édouard Desor by Fritz Berthoud (1812–90), with Bourkhardt's panorama (Figure 6.3, A) in the background. Musée d'Art et d'Histoire Neuchâtel, Switzerland (Inv.-Nr. 762).

Probably the earliest photos of Swiss glaciers were made in summer 1849/50 by Jean-Gustave Dardel (1824–99) and Camille Bernabé (1808–?) (Lagoltière 1989; Morand and Kempf 1989). In September 1855, Auguste-Rosalie Bisson took a panoramic photo of the Unteraar Glacier of the remarkable width of 1.85 m that was praised as "a gigantic ensemble with a wonderful effect" (Chlumsky, Eskildsen, and Marbot 1999). The Bisson Brothers, Auguste-Rosalie (1826–1900) and Louis-Auguste (1814–76), were among the best-known European photographers of the 1850s and 1860s. Their most famous body of work is made up of the high-altitude photographs they made in the Alps, among them the first photographs from the peak of Mont Blanc. Photography opened up regions that were not usually accessible (Guichon 1984; de Decker Heftler 2002). It is probable that the photo of Unteraar Glacier was shown at the Exposition Universelle of 1855 in Paris, where the Bisson Brothers' huge photos were among the major attractions and received first prize (Bonaparte 1856; Chlumsky, Eskildsen, and Marbot 1999). The Bisson photo "Glacier

FIGURE 6.5. The Unterer Grindelwald Glacier on the valley floor, exactly at its mid-nineteenth-century maximum extent. The black ink stamp "Bisson frères" at the edge of the photo, the snow-free glacier front, and an advertisement of the Bisson Brothers in the journal *L' Artiste* (December 14, 1856) show that the photo was taken in summer/autumn 1855/56. (Photograph "Glacier inférieur du Grindelwald [Oberland bernois]," Bisson Brothers, Alpine Club Library, London.)

inférieur du Grindelwald (Oberland bernois)" (Figure 6.5) was probably the first photograph of the Unterer Grindelwald Glacier.

After Queen Victoria took a fancy to the stereoscope at the Crystal Palace Exhibition in 1851, stereo viewing became the rage (Gernsheim 1983). The stereoscope slides that were produced allowed people to sit in their own homes and tour the world. Furthermore, because of their small size they were not too expensive. The most popular slides showed the world from the countrysides of Europe to the pyramids and tombs of ancient Egypt (Schönfeld 2001). However, both travelogue slides and books such as Kane's expedition reports produced increased interest in natural phenomena that had previously been inaccessible. Thus, these historical sources of glacier data also provide cultural information on social attitudes toward glaciers over time. The perception of glaciers ranges from fear and romantic transfiguration to broad scientific interest and nonscientific curiosity at a safe distance. In a similar way, representations of glacier retreat today could be interpreted as a social danger signal in a changing climate.

The earliest stereo views of the Unterer Grindelwald Glacier were taken by Adolphe Braun (1812–77) in summer/autumn 1858 (Figure 6.6, A). A list of Swiss stereo views by Braun published in the journal *La Lumière* (May 21, 1859), including Figure 6.6, A, shows that Braun had begun to market his series of depictions of chic tourist destinations in Switzerland a year earlier than was assumed by Kempf (1994, and personal communication, December 19, 2003). Figure 6.6 is a good example of the changes that can be observed in the forefield of the glacier since the mid-nineteenth century.

Braun's stereo views were taken two to three years after the mid-nineteenth-century maximum extent of the glacier in 1855/56. Because of the incomplete stereographic effects in the background of the photographs, the stereo views could not yield detailed topographic data. Nevertheless, a qualitative comparison of the stereo views with the Bisson photo of 1855/56 shows no significant

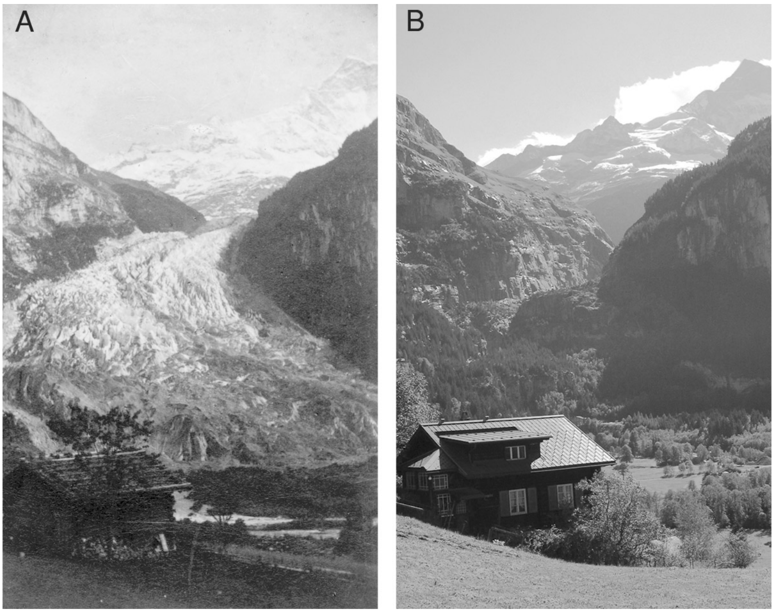


FIGURE 6.6. (A) The Unterer Grindelwald Glacier on the valley floor in 1858, two to three years after the maximum extent in 1855/56. Photograph on visiting card by Adolphe Braun (1812–77) at Dornach, Haut-Rhin ("510. Glacier inf. de Grindelwald"). Private collection of Richard Wolf, Fribourg, Switzerland. (B) Recent view of the glacier gorge and the Fiescherhorn/Pfaffestecki from Upper Stotzhalten (Swiss national coordinates approximately 645′900/163′700, altitude approximately 1,030 m a.s.l.) on September 25, 2003. (Photo Daniel Steiner.)

differences in the extent of the glacier. In fact, Zumbühl (1980) computed a change in length of less than −10 m for the 1855/56–1858 period. In contrast, the following two to three years brought a slightly accelerated tendency toward retreat. This can be seen in a projection of the 1855/56 moraine ridges extracted from an ortho photo map (Zumbühl 1980) onto the original plane-table sheet "Grindelwald 1860/61" (Figure 6.7). According to this, the glacier had withdrawn 30–60 m from the outer 1855/56 moraines. Furthermore, the arrangement of the moraine ridges and the glacier extent of 1870, extracted from the Siegfried map of 1870 ("Grindelwald 1870"), suggest that the glacier had been retreating in a rapid and asymmetric way since 1860/61.

## EARLY TOPOGRAPHIC MAPS AND DIGITAL ELEVATION MODELS

The Unteraar Glacier was the subject of the first topographic map of a glacier with scientific value, generated by Wild in 1842. The lithography (scale: 1:10,000), published by Agassiz (1847), shows the tongue of the glacier, which was more than 8 km long, east of the confluence area and designated by a system of hachures. At that time, the glacier ended in a steep, partially ice-covered ice front (Zumbühl and Holzhauser 1988; VAW/SANW 1881–2002; Haeberli and Zumbühl 2003). Because of the absence of contour lines, no reliable interpretation in terms of glacier volume changes can be deduced. The glacier map "Carte Orographique du Glacier de l'Aar Montrant les détails de la Stratification et l'origine des glaciers de second ordre," surveyed by Stengel in 1846 and also published by Agassiz (1847), shows the same glacier extent as on the Wild map, but in it for the first time we find contour lines of the glacier surface.

The leading role of Swiss cartography is mainly based on the first modern official map series of Switzerland, produced between 1832 and 1864 under the supervision of General Guillaume-Henri Dufour (1787–1875). The 25-sheet series


FIGURE 6.7. Forefield of the Unterer Grindelwald Glacier, extracted from the original plane-table sheet "Grindelwald 1860/61" by Wilhelm August Gottlieb Jacky (1833–1915), with a projection of the 1855/56 moraine ridges (from a 1:2,000 ortho photo map [Zumbühl 1980]). The glacier extents in 1860/61 (from "Grindelwald 1860/61"; contour lines) and 1870 (from "Grindelwald 1870"; dashed outline) are also shown.

(scale: 1:100,000) is an admirable specimen of cartography. After the Dufour map was published, there was demand for 1:25,000 or 1:50,000 maps. The depiction of some areas surveyed by regional topographic surveys was no longer considered satisfactory, and the areas had to be completely resurveyed. In contrast, most surveys carried out by the federal topographic survey met the requirements with minor revisions. These efforts resulted in the first official map series of high resolution and continuous scale, known as the Siegfried map and published from 1870 on (Oberli 1968). Two plane-table sheets of the Dufour map and two first editions of the Siegfried map, covering the Unterer Grindelwald Glacier, were available in the mid-nineteenth century. The Siegfried maps were often based on a revision of the Dufour surveys (Zölly 1944), and this was the case for the Siegfried edition "Jungfrau 1872" (Table 6.2; Bundesarchiv E 27 20040, Geschäftsberichte des Eidg. Stabsbureaus, 1872), which was used as a basis for the development of the digital elevation model instead of Stengel's original plane-table sheet from 1851 because of the latter's inaccurate glacier texture.

TABLE 6.2

*Digital Elevation Models (DEMs) Used in this Study and their Sources, Unterer Grindelwald Glacier*

| DEM NAME | DEM1861 | DEM1926 | DEM1993 | DEM2000 | DEM2004 |
|---|---|---|---|---|---|
| Data basis | Plane-table sheet, topographic map | Topographic maps | Digital photogrammetry | Digital photogrammetry | Digital photogrammetry |
| Name | Grindelwald, Jungfrau | Interlaken, Jungfrau | DHM25 (Level 2) | | |
| Survey/ revision date | Terrestrial survey 1860/61, 1872 | Terrestrial photographs 1926/1934 | Aerial photographs 1993 | Aerial photographs 1999/2000 | Aerial photographs 2004 |
| Scale | 1:50,000 | 1:50,000 | | | |
| Contour interval | 30 m | 20 m | | | |

Both the original plane-table sheet "Grindelwald 1860/61" of Wilhelm August Gottlieb Jacky (1833–1915) and the Siegfried map "Jungfrau 1872" have been geo-referenced on the basis of the current Swiss geodetic datum CH1903. Figure 6.8 shows the composite of the two topographic maps used. The detailed correspondence between the two maps at the junction is remarkable. The early topographic maps were based on the Schmidt's 1828 ellipsoid equivalent conical projection and have not been converted to the present geodetic reference system. The shifts in *xy*-direction between the two reference systems are negligible for our purposes (Bolliger 1967; Urs Marti, personal communication, June 5, 2002). Because the origin of the elevation measurements has changed from 376.2 m a.s.l. (Dufour map) or 376.86 m a.s.l. (Siegfried map) to 373.6 m a.s.l. (CH1903) the *z*-coordinates of the historical data have been corrected by −3 m to obtain a comparable database.

A comparison of a recent pixel map (PK50©swisstopo) and the geo-referenced maps shows that the accuracy lies within the expected range (15 m in *xy*-direction, 1 m in *z*-direction; Urs Marti, personal communications, November 25, 2002, and August 16, 2004). This result testifies to the extraordinary work of many topographers of the time. Jacky's sheet, for example, was judged faultless and exemplary by the cartographic commission in 1862 (Locher 1954). The digital elevation model 1861 was generated by digitalizing contour lines and reference points from the composite map of Figure 6.8 (Hoinkes 1970; Funk, Morelli, and Stahel 1997; Wipf 1999; Bauder 2001). The high quality of the early maps makes it possible to develop modern digital elevation models from them and allows very precise calculations of surface and volumetric glacier loss in the Alps.

Using the first and completely revised edition of the official Swiss maps (scale: 1:50,000), based on terrestrial stereo-photogrammetry in 1926 and additional field surveys in 1934, the digital elevation model 1926 was developed (Bundesarchiv E 27 20042, Geschäftsberichte der Eidg. Landestopographie, 1926 [Vol. 2], 1934 [Vol. 3]). Additional models of the current state of the glaciers have been extracted from a recent set of aerial photographs by applying digital stereo-photogrammetry (Kääb and Funk 1999; Kääb 2001). Digital color aerial photos of the Unterer Grindelwald Glacier were produced in 1999 (accumulation area), 2000 (ablation area), and 2004 (©swisstopo). The photogrammetric interpretation and automatic generation of the

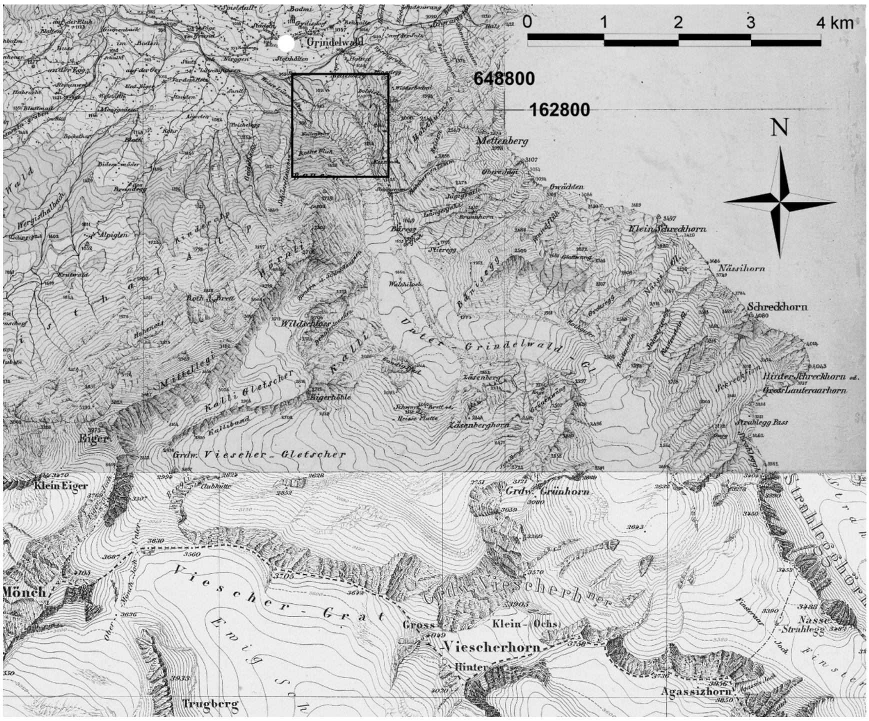


FIGURE 6.8. Composite map of the Unterer Grindelwald Glacier. *Above,* “Grindelwald 1860/61.” *Below,* “Jungfrau 1872.” The area outlined represents the region shown in Figure 6.7. The white dot indicates the approximate location of the photographer of Figure 6.6.

digital elevation model were performed with standard photogrammetric software. In order to improve the detail in the deglaciated glacier forefield, the digitalized contour lines of the aforementioned ortho photo map were merged with the models of 2000 and 2004. The automatic procedures for model generation are limited in areas with low texture, such as flat snowfields, and therefore points were checked manually and either deleted or corrected where necessary. The resulting high-resolution models 2000 and 2004 show an average grid width of ~10 m. Finally, the DHM25 (Level 2) of the Federal Office of Topography (DHM25©swisstopo) has been interpreted as the status of the Unterer Grindelwald Glacier in 1993 (Swisstopo 2004).

For the Unteraar Glacier there are five plane-table sheets of the Dufour map and four first editions of the Siegfried map. The quality of the maps covering the firn areas was inadequate for model construction, and we restricted our study to the ablation area below the confluence of Lauteraar and Finsteraar, where the major changes were expected (Table 6.3). Four additional digital elevation models, dating from 1927, 1947, 1961, and 1997, respectively (Bauder 2001), exist for this glacier. They are based on digitalized contours of two original photogrammetric analyses, a map of a regional cadastral survey, and recent digital photogrammetric analysis as presented before (Bauder 2001).

## RESULTS

On the basis of these models, it is possible to calculate changes in glacier volume, area, and length (Wipf 1999; Maisch et al. 1999). The spatial distributions of volume and thickness changes have been calculated for both glaciers. They are based on the area of greatest extension, including areas of complete retreat and new advance. The results are summarized in Tables 6.4 and 6.5. After the well-documented maximum extents of the Unterer Grindelwald

TABLE 6.3

*Digital Elevation Models (DEMs) Used in this Study and their Sources, Unteraar Glacier*

| DEM NAME | DEM1880 | DEM1927 | DEM1947 | DEM1961 | DEM1997 |
|---|---|---|---|---|---|
| Data basis | Plane-table sheet | Photo-grammetrical contour analysis | Photo-grammetrical contour analysis | Cadastral map | Digital photogrammetry |
| Survey/revision date | Terrestrial survey 1879/80 | Terrestrial photographs 1927 | Aerial photographs 1947 | Aerial photographs 1961 | Aerial photographs 1997 |
| Scale | 1:50,000 | 1:25,000 | 1:25,000 | 1:10,000 | |
| Contour interval | 30 m | 20 m | 20 m | 10 m | |

TABLE 6.4

*Changes in Glacier Parameters, Unterer Grindelwald Glacier, 1860–2004*

| YEAR | AREA ($KM^2$) | LENGTH (KM) | VOLUME CHANGE ($KM^3$) | THICKNESS CHANGE (M) | AVERAGE THICKNESS CHANGE (M/YR) |
|---|---|---|---|---|---|
| 1860/61/72 | 26.1 | 10.8 | – | – | – |
| 1926 | 24.3 | 9.8 | −0.94 | −36.0 | −0.55 |
| 1993 | 22.3 | 9.0 | −0.42 | −17.3 | −0.26 |
| 1999/2000 | 21.4 | 8.9 | −0.14 | −6.3 | −0.90 |
| 2004 | 20.6 | 8.85 | −0.06 | −2.8 | −0.70 |
| 1860–2004 | – | – | −1.56 | −59.8 | −0.42 |

TABLE 6.5

*Changes in Glacier Parameters, Unteraar Glacier, 1880–1997*

| YEAR | AREA ($KM^2$) | VOLUME CHANGE ($KM^3$) | THICKNESS CHANGE (M) | AVERAGE THICKNESS CHANGE (M/YR) |
|---|---|---|---|---|
| 1880 | 28.4 | – | – | – |
| 1927 | 27.5 | −0.32 | −11.3 | −0.24 |
| 1947 | 27.4 | −0.42 | −15.3 | −0.76 |
| 1961 | 25.5 | −0.34 | −12.4 | −0.89 |
| 1997 | 24.1 | −0.51 | −20.0 | −0.56 |
| 1880–1997 | – | −1.59 | −56.0 | −0.48 |

Glacier in 1855/56 and the Unteraar Glacier in 1871 (Zumbühl and Holzhauser 1988), we find a relatively high rate of thickness change of −0.55 m per year for the former and a lower rate of −0.24 m per year for the latter until the late 1920s. From then on we find a lower rate of thickness change for the Unterer Grindelwald Glacier and an increasing mass loss for the Unteraar Glacier.

A rapid volume loss of −0.90 m per year in the 1990s can be calculated for the Unterer Grindelwald Glacier. It is striking that this mass loss occurred almost without any substantial change in glacier length (Table 6.4). This is probably due to the fact that the glacier terminus is in a narrow gorge. Down-wasting of the glacier surface in the front basin of the glacier (Figure 6.9) is known from other glaciers (Paul et al. 2004) and primarily leads to a decrease in glacier width/area and not in length. The observed cumulative mass balance of three Swiss Alpine glaciers (Gries, Basòdino, Silvretta) amounts to −2 m for the period 1993–2000 and −2.6 m for the period 2001–2004, which includes the European heat wave of 2003 (VAW/SANW 1881–2002; unpublished data from Andreas Bauder). Therefore, the total decrease of the Unterer Grindelwald Glacier of −6.3 m for the period 1993–1999/2000 was significantly above average and the total thickness change of −2.8 m for the period 1999/2000–2004 was comparable to the mass balance of other Alpine glaciers.

The decrease of glacier area between 1860/61 (Unterer Grindelwald Glacer) or 1880 (Unteraar Glacier) and the end of the twentieth century amounts to approximately −20%. Furthermore, the overall mass loss is −1.56 $km^3$ ice (–1.4 $km^3$ water; assumed ice density 0.9 kg $m^{-3}$) for the Unterer Grindelwald Glacier and −1.59 $km^3$ ice (–1.43 $km^3$ water) for the Unteraar Glacier. The sum of this mass loss (2.83 $km^3$ water) is nearly equivalent to three years' water consumption (1.06 $km^3$ in the year 2000) in Switzerland (SVGW 2002). Both the glacier area and the volume loss correspond to studies based on inventory data (Zemp et al., this volume).

Finally, the calculated average thickness changes are similar to those revealed by investigations of other Alpine glaciers such as the Aletsch, the Rhône, and the Trift. Generally, an increased mass loss since the 1980s has been observed (see also Zemp et al., this volume). The rates and timing depend on the available digital elevation models.

Figure 6.10 shows the spatial distribution of the thickness change for the Unterer Grindelwald Glacier between DEM1861 and DEM2004. The average overall thickness change for this period amounts to −0.42 m per year. In general, the widespread decrease of glacier thickness expected since 1860 can be determined from Figure 6.10. Absolute negative thickness changes of up to −330 m can be seen in the ablation area, the upper Ischmeer, and south of the Berner Fiescher Glacier. The latter differences are much larger than we would expect in the accumulation areas (Bauder 2001). Nevertheless, there are some regions where a totally unexpected increase of glacier surface height is found. In some of these cases, such as the upper part of the Berner Fiescher Glacier, we can assume a lower quality of both DEM1861 and DEM2004 due to low snow/ice surface contrasts and/or complex terrain and perhaps the sparse point density of DEM1861 and DEM2004 in such areas.

This argument does not, however, apply to the lower part of the Berner Fiescher Glacier, which shows a large area of surface height increase of up to +100 m since the mid-nineteenth-century maximum extent (see also Figure 6.9, *b*, for the surface profile along flowline 2). According to the newly discovered field book, the topographer Jacky, one of the best topographers of his time, surveyed the Grindelwald region in July 1861 and worked very close to the area of increase, which is also a relatively flat region that is easy to survey. He measured a large number of trigonometric points with full spatial information on or close to the Unterer Grindelwald Glacier, including a profile crossing exactly the assumed area of increase. Because he measured these points in

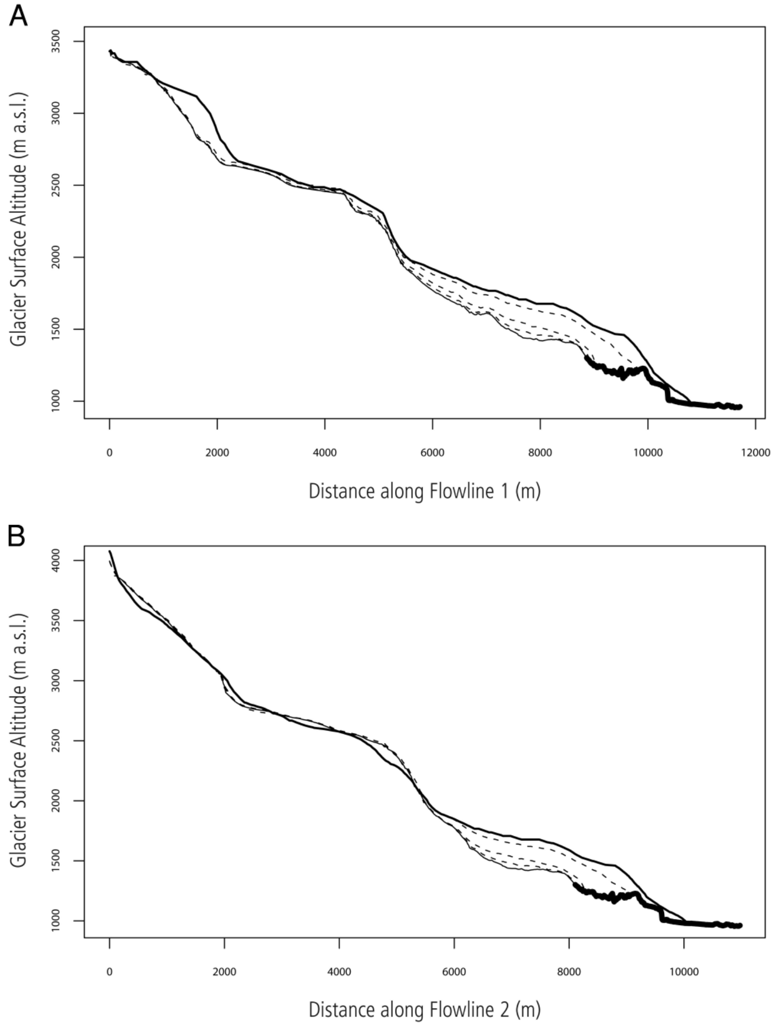


FIGURE 6.9. Surface profiles along (A) flowline 1 and (B) flowline 2 of the Unterer Grindelwald Glacier for 1860/61 (*thick line*), 1926 (*dashed line*), 1993 (*dashed line*), 1999/2000 (*dashed line*), and 2004 (*solid line*), derived from digital elevation models. The thick line downvalley indicates the exposed glacier forefield with the two pronounced "Schopf Rocks."

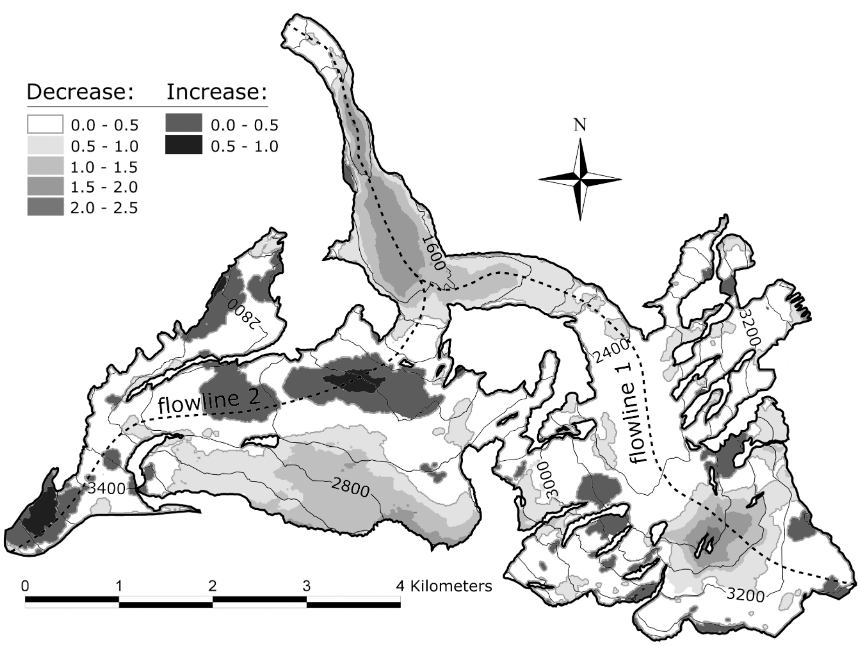


FIGURE 6.10. Average changes of surface heights (m per year) between 1860/61/72 and 2004 (DEM1861–DEM2004). The glacier outlines of 1860/61/72 and the contour lines of 2004 are also given.

situ to use them for drawing the contour lines (Martin Gurtner, personal communication, August 28, 2003), major systematic errors in his survey are very doubtful. It is possible that the area of increase could be dynamically linked with the decrease of surface heights in the previous mentioned southern part of the Berner Fiescher Glacier, but in the absence of detailed investigations of the dynamics of the Unterer Grindelwald Glacier this linkage cannot be investigated.

## SUMMARY AND CONCLUSIONS

The first systematic investigations on the Unteraar Glacier marked the beginning of modern glacier research and represented an important proof of the Ice Age theory. Louis Agassiz was the motive force behind both the first systematic and scientific glaciological studies and the development of representations of glaciers in the form of drawings and topographic maps. A few years later, the first glacier photographs provided the means to show glacier changes in a relatively easy way. Thus, the photographic technique marked a new era of scientific representation of glaciers because even inaccessible areas could now be recorded quickly and easily. This change of scientific representation techniques from paintings and maps to photographs within only 15 years can be studied against the background of the inception of modern glaciology.

During the same period an increased glacier cover can be detected in many regions all over the world. This last glacier maximum extent is well documented for a few glaciers, among them the Unterer Grindelwald and the Unteraar. Therefore we were able to conduct this unique case study of research on two of the best-known glaciers in Europe and to demonstrate its development from the very beginnings to the present. We have also noted that the quality of the documentary evidence from these two glaciers is a benchmark against which other glaciers and studies should be measured.

The maximum extents of the two glaciers around the mid-nineteenth century and their subsequent retreat have been studied by combining a critical discussion of documentary data with the application of recent technical possibilities in photogrammetry. New photographic material and the evaluation of old topographic maps confirm that the retreat of the Unterer Grindelwald Glacier was relatively slow in a first period after the mid-nineteenth-century maximum extent and then accelerated in the 1861–70 period. Digital elevation model comparisons show reliable rates of thickness change of −0.42 m per year for the Unterer Grindelwald Glacier and −0.48 m per year for the Unteraar Glacier since their mid-nineteenth-century maximum extent.

Finally, the Unterer Grindelwald Glacier's spatial distribution of thickness changes shows some surprising patterns. Either the basic data are much less accurate than has been assumed, or this glacier demonstrates some interesting dynamic behavior that affected only parts of the area. Because a mass shift could have taken place within less than a decade, additional information between the 1860 and 1926 models is needed for further investigation of this question.

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## REFERENCES CITED

Agassiz, E.C. 1885. *Louis Agassiz: His life and correspondence*. Boston: Houghton, Mifflin.

Agassiz, L. 1847. *Système glaciaire ou recherche sur les glaciers, leur mécanisme, leur ancienne extension et le rôle qu'ils ont joué dans l'histoire de la terre.* Pt. 1. *Nouvelles études et expériences sur les glaciers actuels: Leur structure, leur progression et leur action physique sur le sol.* Paris: V. Masson/Leipzig: L. Voss.

Bauder, A. 2001. *Bestimmung der Massenbilanz von Gletschern mit Fernerkundungsmethoden und Fliessmodellierungen: Eine Sensitivitätsstudie auf dem Unteraargletscher.* Zurich: Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie der Eidgenössischen Technischen Hochschule Zürich.

Bolles, E. B. 1999. *The ice finders: How a poet, a professor, and a politician discovered the Ice Age.* Washington, DC: Counterpoint Press.

Bolliger, J. 1967. *Die Projektionen der Schweizer Plan- und Kartenwerke.* Winterthur: Druckerei Winterthur.

Bonaparte, Napoléon-Joseph-Charles-Paul, Prince. 1856. *Exposition Universelle de 1855: Rapports du jury mixte international.* Paris: Imprimerie Impériale.

Chlumsky, M., U. Eskildsen, and B. Marbot. 1999. *Die Brüder Bisson. Aufstieg und Fall eines Fotografenunternehmens im 19. Jahrhundert: Katalog zur gleichnamigen Ausstellung, Museum Folkwang, Essen, 7.2.–28.3.1999; Fotomuseum im Münchner Stadtmuseum, 11.4.–30.5.1999; Bibliothèque nationale de France, Paris, 15.6.–15.8.1999.* Amsterdam: Verlag der Kunst.

de Decker Heftler, S. 2002. *Photographier Le Mont Blanc: Les pionniers.* Collection Sophie et Jérôme Seydoux. Chamonix: Éditions Guérin.

Desor, J. E. 1847. *Agassiz' und seiner Freunde geologische Alpenreisen in der Schweiz, Savoyen und Piemont,* ed. C. Vogt. Frankfurt am Main: Literarische Anstalt.

Funk, M., R. Morelli, and W. Stahel. 1997. Mass balance of Griesgletscher 1961–1994: Different methods of determination. *Zeitschrift für Gletscherkunde und Glazialgeologie* 33:41–56.

Gernsheim, H. 1983. *Geschichte der Photographie: Die ersten 100 Jahre.* Frankfurt am Main: Ullstein, Propyläen Verlag.

Graf, J. H. 1896. *Die Schweizerische Landesvermessung 1832–1864: Geschichte der Dufourkarte.* Bern: Buchdruckerei Stämpfli & Cie.

Gross, G., H. Kerschner, and G. Patzelt. 1976. Methodische Untersuchungen über die Schneegrenze in alpinen Gletschergebieten. *Zeitschrift für Gletscherkunde und Glazialgeologie* 12:223–51.

Guichon, F. 1984. *Montagne: Photographies de 1845 à 1914.* Paris: Denoël.

Haeberli, W., and H. J. Zumbühl. 2003. Schwankungen der Alpengletscher im Wandel von Klima und Perzeption. In *Welt der Alpen–Gebirge der Welt: Ressourcen, Akteure, Perspektiven,* ed. F. Jeanneret, D. Wastl-Walter, and U. Wiesmann, 77–92. Bern: Jahrbuch der Geographischen Gesellschaft Bern.

Hoinkes, H. 1970. Methoden und Möglichkeiten von Massenhaushaltsstudien auf Gletschern. *Zeitschrift für Gletscherkunde und Glazialgeologie* 6:37–90.

Holzhauser, H., M. Magny, and H. J. Zumbühl. 2005. Glacier and lake-level variations in west-central Europe over the last 3500 years. *The Holocene* 15:791–803.

Holzhauser, H., and H. J. Zumbühl. 1996. To the history of the Lower Grindelwald Glacier during the last 2800 years–palaeosols, fossil wood, and historical pictorial records–new results. *Zeitschrift für Geomorphologie,* n.s., suppl. 104:95–127.

———. 1999. Glacier fluctuations in the western Swiss and French Alps in the 16th century. *Climatic Change* 43: 223–37.

———. 2003. Nacheiszeitliche Gletscherschwankungen. In *Hydrologischer Atlas der Schweiz,* ed. R. Weingartner and M. Spreafico. Bern-Wabern: Bundesamt für Landestopographie.

Hugi, F. J. 1830. *Naturhistorische Alpenreise.* Solothurn: Amiet-Lutiger.

Jacky, W. A. G. 1861. *Feldbuch: Blatt Grindelwald, topographische Aufnahme 1:50000, 1860/61.* Bern-Wabern: Bundesamt für Landestopographie.

Kääb, A. 2001. Photogrammetric reconstruction of glacier mass balance using a kinematic ice-flow model: A 20-year time series on Grubengletscher, Swiss Alps. *Annals of Glaciology* 31: 45–52.

Kääb, A., and M. Funk. 1999. Modelling mass balance using photogrammetric and geophysical data: A pilot study at Griesgletscher, Swiss Alps. *Journal of Glaciology* 45:575–83.

Kane, E. K. 1856. *Arctic explorations: The Second Grinnell Expedition in Search of Sir John Franklin, 1853, '54, '55.* Philadelphia: Childs and Peterson.

Kempf, C. 1994. *Adolphe Braun et la photographie 1812–1877.* Illkirch: Éditions Lucigraphie/Valblor.

Lagoltière, R. M. 1989. Mulhouse et la conquête photographique des Alpes et du Mont-Blanc. *Annuaire Historique de la Ville de Mulhouse* 2:39–63.

Locher, T. 1954. Bernische Kartierung zur Zeit der Dufourkarte und Vorarbeiten zum bernischen Kataster. Ph.D. diss., University of Bern.

Lurie, E. 1960. *Louis Agassiz: A life in science.* Chicago: University of Chicago Press.

Maisch, M., A. Wipf, B. Denneler, J. Battaglia, and C. Benz. 1999. *Die Gletscher der Schweizer Alpen: Gletscherhochstand 1850, Aktuelle Vergletscherung, Gletscherschwund-Szenarien.* Zurich: vdf Hochschulverlag.

Morand, S., and C. Kempf. 1989. *Le temps suspendu: Le daguerréotype en Alsace au XIXe siècle, 150e anniversaire de la divulgation de la photographie*. Strasbourg: Éditions Oberlin.

Nesje, A., and S. O. Dahl. 2000. *Glaciers and environmental change*. London: Arnold.

Nicolussi, K., and G. Patzelt. 2000. Untersuchungen zur holozänen Gletscherentwicklung von Pasterze und Gepatschferner (Ostalpen). *Zeitschrift für Gletscherkunde und Glazialgeologie* 36:1–87.

Oberli, A. 1968. Vor 100 Jahren: Wie es zur Herausgabe der Siegfriedkarte kam. *Hauszeitung der Eidg. Landestopographie (Wabern)* 23:7–22.

Paul, F., A. Kääb, M. Maisch, T. Kellenberger, and W. Haeberli. 2004. Rapid disintegration of Alpine glaciers observed with satellite data. *Geophysical Research Letters* 31:L21402.

Portmann, J. P. 1975. Louis Agassiz (1807–1873) et l'étude des glaciers. *Denkschriften der Schweizerischen Naturforschenden Gesellschaft* 89:113–42.

Schmeits, M. J., and J. Oerlemans. 1997. Simulation of the historical variations in length of Unterer Grindelwaldgletscher, Switzerland. *Journal of Glaciology* 43:152–64.

Schönfeld, J. 2001. Die Stereoskopie: Zu ihrer Geschichte und ihrem medialen Kontext. Master's thesis, University of Tübingen.

Schuler, T., U. H. Fischer, and G. H. Gudmundsson. 2004. Diurnal variability of subglacial drainage conditions as revealed by tracer experiments. *Journal of Geophysical Research* 109:F02008.

SVGW (Schweizerischer Verein des Gas- und Wasserfaches). 2002. Der Trinkwasserkonsum in der Schweiz sinkt weiter. *Trinkwasser Informationsblatt* 9:1–2.

Swisstopo. 2004. *DHM25: The digital height model of Switzerland: Product information*. Bern-Wabern.

VAW/SANW (Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie der Eidgenössischen Technischen Hochschule Zürich/Schweizerischen Akademie der Naturwissenschaften). 1881–2002. *Die Gletscher der Schweizer Alpen*. Jahrbücher der Glaziologischen Kommission der Schweizerischen Akademie der Naturwissenschaftern 1–122.

Wipf, A. 1999. *Die Gletscher der Berner, Waadtländer und nördlichen Walliser Alpen: Eine regionale Studie über die Vergletscherung im Zeitraum "Vergangenheit" (Hochstand 1850), "Gegenwart" (Ausdehnung 1973) und "Zukunft" (Gletscherschwundszenarien, 21. Jhdt.)*. Zurich: Geographisches Institut der Universität Zürich.

Wolf, J. R. 1879. *Geschichte der Vermessungen in der Schweiz*. Zurich: Commission von S. Höhr.

Zölly, H. 1944. *Geodätische Grundlagen der Vermessungen im Kanton Bern: Geschichtlicher Überblick*. Schweizerische Zeitschrift für Vermessungswesen und Kulturtechnik, special issue.

Zumbühl, H. J. 1980. *Die Schwankungen der Grindelwaldgletscher in den historischen Bild- und Schriftquellen des 12. bis 19. Jahrhunderts: Ein Beitrag zur Gletschergeschichte und Erforschung des Alpenraumes*. Denkschriften der Schweizerischen Naturforschenden Gesellschaft 92. Basel, Boston, and Stuttgart: Birkhäuser.

Zumbühl, H. J., and H. P. Holzhauser. 1988. Alpengletscher in der Kleinen Eiszeit: Sonderheft zum 125jährigen Jubiläum des SAC. *Die Alpen* 64:129–322.

Zumbühl, H. J., B. Messerli, and C. Pfister. 1983. *Die Kleine Eiszeit. Gletschergeschichte im Spiegel der Kunst*: Katalog zur Sonderauss tellung, Schweizerisches Alpines Museum, Bern, 24.8.–16.10.1983; Gletschergarten-Museum, Luzern, 9.6.– 14.8.1983.