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# Glacier Fluctuations in the European Alps, 1850–2000

## AN OVERVIEW AND A SPATIOTEMPORAL ANALYSIS OF AVAILABLE DATA

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Fluctuations of mountain glaciers are among the best natural indicators of climate change (Houghton et al. 2001). Changes in precipitation and wind lead to variations in accumulation, while changes in temperature, radiation fluxes, and wind, among other factors, affect the surface energy balance and thus ablation. Disturbances in glacier mass balance, in turn, alter the flow regime and, consequently, after a glacier-specific delay, result in a glacier advance or retreat such that the glacier geometry and altitude range change until accumulation equals ablation (Kuhn et al. 1985). Hence, mass balance is the direct and undelayed signal of annual atmospheric conditions, whereas changes in length are an indirect, delayed, and filtered but enhanced signal (Haeberli 1998).

The modern concept of worldwide glacier observation is an integrated and multilevel one; it aims to combine in-situ observations with remotely sensed data, understanding of process with global coverage, and traditional measurements with new technologies. This concept uses detailed mass and energy balance studies from just a few glaciers, together with length change observations from many sites and inventories covering entire mountain chains. Numerical models link all three components over time and space (Haeberli 2004). The European Union–funded ALP-IMP Project focuses on multicentennial climate variability in the Alps on the basis of instrumental data, model simulations, and proxy data. It represents a unique opportunity to apply this glacier-monitoring concept to the European Alps, where by far the most concentrated amount of information about glacier fluctuations over the past century is available. The World Glacier Monitoring Service (WGMS) has compiled, within the framework of the ALP-IMP Project, an unprecedented data set containing inventory data (i.e., area, length, and altitude range) from approximately 5,150 Alpine[1] glaciers and fluctuation series from more than 670 of them (i.e., more than 25,350 observations of annual front variation and 575 of annual mass balance) dating back to 1850.

In this chapter we offer an overview of the available glacier data sets from the European Alps and analyze glacier fluctuations between

1850 and 2000. To achieve this, we analyze glacier size characteristics from the 1970s, the only time period for which a complete Alpine inventory is available, and extrapolate Alpine glaciation in 1850 and in 2000 from size-dependent area changes from Switzerland. We go on to examine mass balance and front variation series for the insight they provide into glacier fluctuations, the corresponding acceleration trends, and regional distribution patterns at an annual resolution. Finally, we discuss the representativeness of these recorded fluctuation series for all the Alpine glaciers and draw conclusions for glacier monitoring.

## BACKGROUND

The worldwide collection of information about ongoing glacier changes was initiated in 1894 with the founding of the International Glacier Commission at the Sixth International Geological Congress in Zurich, Switzerland. At that time, the Swiss limnologist F. A. Forel began publishing the periodical *Rapports sur les variations périodiques des glaciers* on behalf of the commission (Forel 1895). Up until 1961, data compilations constituting the main source of length change data worldwide were published in French, Italian, German, and English. Since 1967, the publications have all been in English. The first reports contain mainly qualitative observations except for the glaciers of the European Alps and Scandinavia, many of which have had extensive documentation and quantitative measurements recorded from the very beginning. After World War I, P. L. Mercanton edited the publications, which began to appear less than annually. From 1933 to 1967 they were published on behalf of the International Commission on Snow and Ice (ICSI), part of the International Association of Hydrological Sciences (IAHS). Since then they have been published at five-year intervals under the title *Fluctuations of Glaciers*, at first by the Permanent Service on the Fluctuations of Glaciers (PSFG [Kasser 1970]) and then, after the merger of the PSFG with the Temporary Technical Secretariat for the World Glacier Inventory (TTS/WGI) in 1986, by the WGMS. An extensive overview of the corresponding literature is given by Hoelzle et al. (2003).

The need for a worldwide inventory of perennial snow and ice masses was first considered during the International Hydrological Decade declared by the United Nations Educational, Scientific, and Cultural Organization (UNESCO) from 1965 until 1974 (UNEP/GEMS 1992). Preliminary results and a thorough discussion of the techniques and standards employed in glacier inventorying were given in IAHS (1980). A status report and the corresponding national literature of all national glacier inventories compiled at that time was published by Haeberli et al. (1989a). More detailed reports on glacier area changes for specific regions or countries, often with special emphasis on developments since 1850, can be found in CGI/CNR (1962) for Italy, Gross (1988a) for Austria, Maisch et al. (2000) for Switzerland, Vivian (1975) for the Western Alps, Maisch (1992) for the Grisons (Switzerland), Böhm (1993) for the Goldberg region (Hohe Tauern, Austria), and Damm (1998) for the Rieserferner group (Tyrol, Austria).

## THE DATA

The Alpine glacier information available is of three types: the World Glacier Inventory (WGI), the Swiss Glacier Inventory 2000 (SGI2000), and Fluctuations of Glaciers (FoG). The geographical distribution of the different data sets is shown in Figure 11.1.

### THE WORLD GLACIER INVENTORY

The WGI contains attribute data on glacier area, length, orientation, and elevation as well as a classification of morphological types and moraines linked to the glacier coordinates. The inventory entries are based upon specific observation times and can be viewed as snapshots of the spatial glacier distribution. The data are stored in the WGI database (part of the WGMS database) and are published in Haeberli et al. (1989*a*), which summarizes the national inventories for the entire Alps.

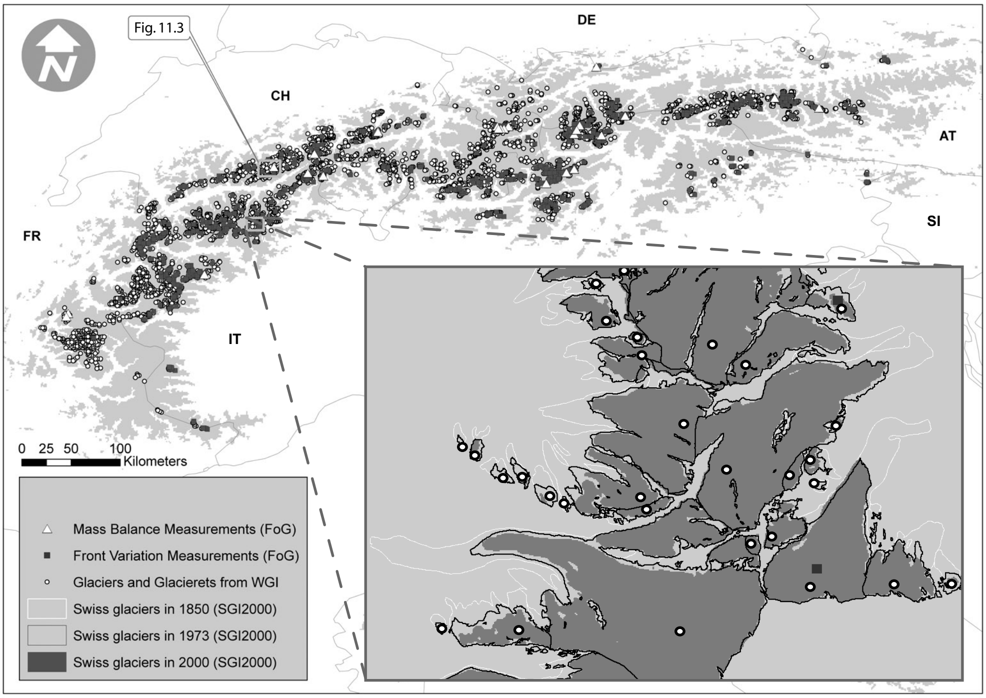


FIGURE 11.1. Geographical distribution of available glacier information in the Alps: WGI data (*white circles*) and mass balance (*white triangles*) and front variation (*dark gray squares*) data from the FoG database. Elevations above 1,500 m a.s.l. are in light gray. *AT*, Austria; *FR*, France; *DE*, Germany; *IT*, Italy; *SI*, Slovenia; and *CH*, Switzerland. The inset shows Swiss glacier polygons for 1850, 1973, and 2000 from the SGI2000.

Complete national inventories for the European Alps are available for Austria (1969), France (1967–71), Switzerland (1973), Germany (1979), and Italy (1975–84). The inventories for Austria, Switzerland, and Germany refer to a single reference year, while the records of France and Italy are compiled over a longer period of time to achieve total coverage (Figure 11.2). However, in every inventory there is a certain percentage of glaciers for which no data from the corresponding reference period/year could be obtained and information from earlier years has been substituted. For example, in the Swiss inventory, data from only 1,550 glaciers date from 1973, while the information for the remaining 274 glaciers refers to earlier years. Glacier identification, assignment, and partitioning (due to glacier shrinkage) are the main challenges for comparisons of inventories overlapping in space or time. Therefore, the total number and areas of glaciers may vary in different studies. Haeberli et al. (1989*a*) sum the area of the 5,154 Alpine glaciers from Austria (542 km²), France (417 km²), Switzerland (1,342 km²), Germany (1 km²), and Italy (607 km²) as 2,909 km². Because of the inconsistencies just mentioned, the data set used in this study differs slightly from these numbers; the Italian inventory sums up to only 602 km² and the number of Alpine glaciers to 5,167. These differences, however, are smaller than 0.3% and therefore negligible.

## THE SWISS GLACIER INVENTORY 2000

The SGI2000 has been compiled from multispectral Landsat Thematic Mapper (TM) data acquired in 1998–99 (path-row 194/5-27/8). Glacier information (e.g., area, slope, aspect) was obtained from a combination of glacier outlines with a digital elevation model and the related analysis by a Geographic Information

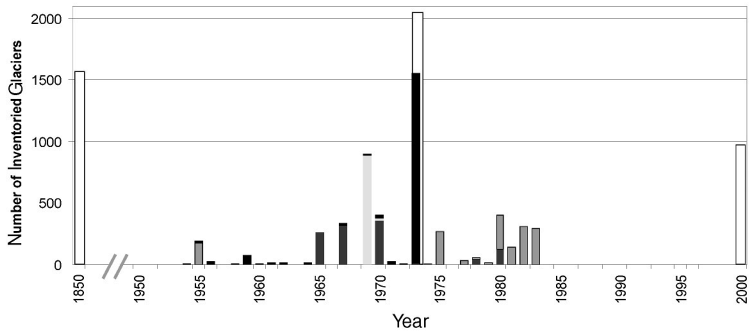


FIGURE 11.2. Numbers of inventoried glaciers in the Alps by year, country, and data source. (For 1973, for example, there are data in the WGI from 6 Italian, 2 Austrian, and 1,550 Swiss glaciers and data in the SGI2000 from 2,057 Swiss glaciers.)

System (Kääb et al. 2002; Paul et al. 2002; Paul 2004). Several glaciers were not properly identified because of cast shadow, snow cover, and debris and were excluded from the statistical analysis. New areas for 938 glaciers were obtained for 2000 and the related topographical information extracted. The glacier inventories from 1850 and 1973 were digitized from the original topographic maps and are now a major part of the SGI2000 (Figure 11.3). The 1973 outlines are also used to define the hydrological basins of individual glaciers in the satellite-derived inventory, in particular the ice-ice divides. However, because different identification codes were used in the inventories of Müller, Caflisch, and Müller (1976), Maisch et al. (2000), and the SGI2000, a direct comparison of glacier areas is not yet possible. Moreover, glacier retreat has caused severe changes in glacier geometry (tongue separation, disintegration, etc.) that prevent direct comparison. For this reason our analysis of glacier changes was based on different samples. The major results of this study have been summarized by Paul et al. (2004).

## FLUCTUATIONS OF GLACIERS

The FoG database contains attribute data on glacier changes over time—front variations, mass balance, and changes in area, thickness, and volume—linked to glacier coordinates. The data are stored in the FoG database (part of the WGMS database) and published in the *Fluctuations of Glaciers* series at five-year intervals (latest edition, Haeberli et al. 2005*b*) and biannually in the *Glacier Mass Balance Bulletin* (latest edition, Haeberli et al. 2005*a*).

Regular glacier front variation surveys in the Alps started around 1880. The number of glaciers surveyed and the continuity of series changed over time because of world history and the perceptions of the glaciological community (Haeberli and Zumbühl 2003; Haeberli, this volume). Direct measurements of glacier mass balance in the Alps started at Limmern (Switzerland) and Plattalva (Switzerland) in 1948, followed by Sarennes (France) in 1949, Hintereis (Austria) and Kesselwand (Austria) in 1953, and others. In the last reporting period (1995–2000) 297 glacier front measurements were made, along with measurements of the mass balance of 18 Alpine glaciers (Haeberli et al. 2005*b*). For the analysis here only front variation series with more than nine survey years and mass balance series longer than three years have been considered (Figure 11.4).

There are some reconstructed front variation series for several Alpine glaciers, spanning time periods from centuries to millennia (e.g., Holzhauser and Zumbühl 1996; Holzhauser 1997; Nicolussi and Patzelt 2000; Holzhauser,

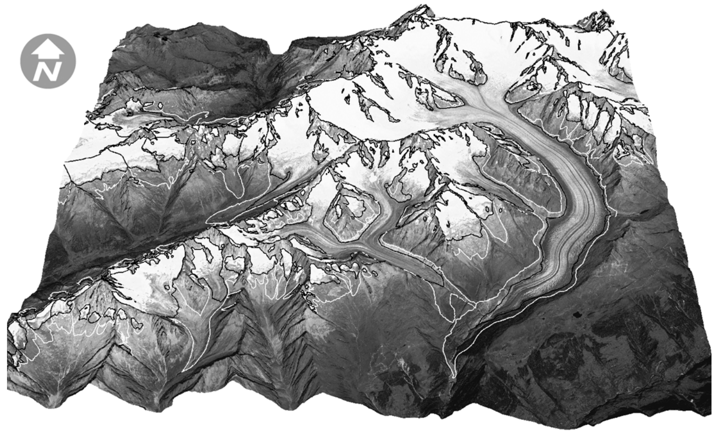

FIGURE 11.3. Synthetic oblique-perspective of the Aletsch Glacier region, Switzerland, generated from a digital elevation model (DEM25; reproduced by permission of swisstopo, BA057338) overlaid with a fusion of satellite images from Landsat TM (1999) and IRS-1C (1997) in a grayscale rendition. The Grosser Aletsch Glacier retreated about 2,550 m from 1850 (*white lines*) to 1973 (*black lines*) and another 680 m by 2000.

Magny, and Zumbühl 2005). In addition, there are some studies that estimate secular mass balance trends from cumulative glacier length changes (e.g., Haeberli and Holzhauser 2003; Hoelzle et al. 2003) or from glacier surfaces reconstructed from historical maps (cf. Haeberli 1998; Steiner et al., this volume). These studies, however, have not been prepared within an international framework, and most of the data are not publicly available, so we have not considered them here.

## ANALYSIS AND RESULTS

### ALPINE GLACIERIZATION IN THE 1970s

The only complete Alpine inventory available is from the 1970s, with 5,154 glaciers and an area of 2,909 km$^2$ (Haeberli et al. 1989*a*). Paul et al. (2004) have estimated the total ice volume to be about 100 km$^3$, much lower than the 130 km$^3$ suggested earlier by Haeberli and Hoelzle (1995). The latter estimated the total ice volume from the total Alpine glacier area and an averaged thickness from all the glaciers (in accordance with semielliptical cross-sectional glacier geometry). Paul et al. (2004) calculated the total volume loss ($-25$ km$^3$) for the period 1973–1998/99 from the mean Alpine glacier area (2,753 km$^2$) and the average cumulative mass balance for eight Alpine glaciers ($-9$ m water equivalent). Assuming that the relative change in volume is likely to have been larger than the corresponding relative change in area (for geometric reasons), the estimated relative volume loss is roughly $-25$% and, therefore, the total Alpine ice volume in the 1970s was about 100 km$^3$.

Eighty-two percent of Alpine glaciers are smaller than 0.5 km$^2$ and cover 21% of the total glaciated area (Figure 11.5). Glacierets and névés (perennial snowbanks) do not normally show dynamic reactions and therefore are usually excluded from glacier studies. However, neglecting these small glaciers in inventories could introduce significant errors in the assessment of regional glacier change. Only seven glaciers (Grosser Aletsch, Gorner, Fiescher, Unteraar, Unterer Grindelwald, and Oberaletsch in Switzerland and Mer de Glace in France) are larger than 20 km$^2$ but represent 10% of the total area. Glaciers between 1 and 10 km$^2$ account for 46% of the Alpine glacier area.

The regional distribution of numbers and areas of Alpine glaciers can be calculated for each Alpine country. Most of the glaciers are located in Switzerland (35%), followed by Italy (27%), France (20%), and Austria (18%). Regarding total glacier area, the majority of European ice is located in Switzerland (46%) and Italy (21%). Austria ranks third, with 19% of the Alpine glacier area, followed by France with

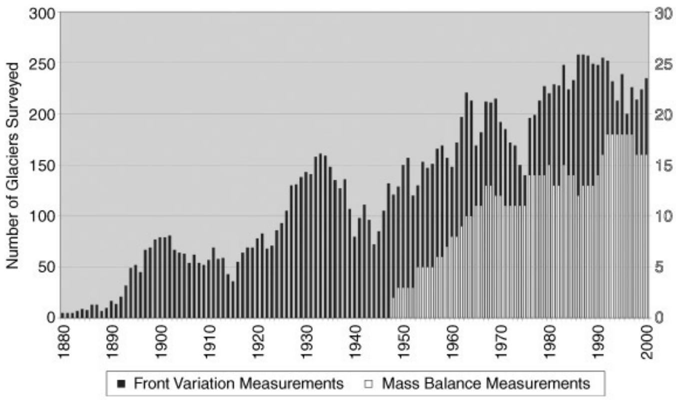


FIGURE 11.4. Frequency of front variation (*black bars, left axis*) and mass balance (*white bars, right axis*) measurements in the Alps, 1880–2000. Only glaciers with more than 18 front variations or three mass balance surveys are considered.

14%. The five German glaciers, with a total area of 1 $km^2$, and the two small Slovenian glaciers are not considered in the tables.

Tables 11.1 and 11.2 show the glacier size characteristics in the 1970s. The numbers of glaciers in each area-class are very similar in all countries except for France, where 50% of the glaciers are smaller than 0.1 $km^2$. The area distribution in Austria and Italy is dominated equally by small- and middle-sized glaciers. Mer de Glace, with an area of 33 $km^2$, corresponds to almost 8% of the French glacierization. In Switzerland the 22 largest glaciers ($>$ 10 $km^2$) account for 37% of the total glacier area.

## ALPINE GLACIERIZATION IN 1850 AND 2000

Using the Alpine inventory of the 1970s, the Alpine glacier areas in 1850 and in 2000 can be extrapolated by applying the relative area changes (1850–1973, 1973–2000) of the seven glacier size classes from the SGI2000 to the corresponding Alpine glacier areas in the 1970s (Table 11.3). The estimated Alpine glacier areas amount to 4,474 $km^2$ in 1850 and to 2,272 $km^2$ in 2000. This corresponds to an overall glacier area loss from 1850 until the 1970s of 35% and almost 50% by 2000—or an area reduction of 22% between the 1970s and 2000. Dividing the total area loss by time provides estimates of area change per decade of 2.9% between 1850 and 1973 and 8.2% between 1973 and 2000. Several methods exist for calculating glacier volume from other variables, based either on statistical relationships (e.g., Müller, Caflisch, and Müller 1976), empirical studies (e.g., Maisch et al. 2000), or physical parameters (e.g., Haeberli and Hoelzle 1995). However, all of them employ glacier size as a scaling factor, and the deviations between individual methods are large. As the individual glacier sizes for the year 2000 are not yet available for all glaciers, we have not attempted to present glacier volume evolution over time. However, a current estimate of Alpine glacier volume in 2000 indicates that approximately 75 $km^3$ remain (Paul et al. 2004).

## ALPINE FRONT VARIATIONS

Large valley glaciers have retreated continuously since the Little Ice Age maximum around 1850. Smaller mountain glaciers show marked periods of intermittent advances in the 1890s, the 1920s, and the 1970–80s. The front variations of the smallest glaciers have a high annual variability. In Figure 11.6 front variation series with more than 18 measurement years are plotted and sorted according to glacier size. The advance periods of the 1920s and the 1970–80s and the retreat periods in between and after 1990 show up very clearly. However, on the individual level the climate signal from variations in the front position of glaciers is much more complex. This noise prevails even when the data set is sorted according to

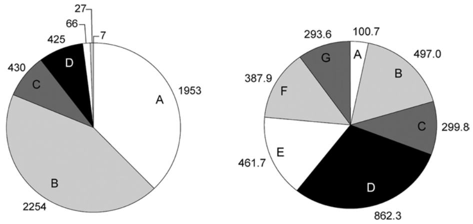


FIGURE 11.5. Distribution of glaciers by number (*left*) and size (*right*) in the Alps for the 1970s. Pie charts give percentages with absolute values indicated. (A) < 0.1 km²; (B) 0.1–0.5 km²; (C) 0.5–1.0 km²; (D) 1.0–5.0 km²; (E) 5.0–10.0 km²; (F) 10.0–20.0 km²; (G) > 20.0 km². The five German and two Slovenian glaciers are not considered in this figure.

response time (see Johannesson, Raymond, and Waddington 1989; Haeberli and Hoelzle 1995) or analyzed in geographical subsamples. Figure 11.6 is dominated by the smaller mountain glaciers, and therefore the signals of the large valley glaciers and the smallest glaciers (including absolute retreat values) are more visible in the graphs of individual cumulative front variation (e.g., Haeberli et al. 1989*b*; Hoelzle et al. 2003).

### ALPINE MASS BALANCES

Fifty years of direct mass balance measurements show a clear trend of mass loss. Although some of the glaciers measured gained mass from the 1960s to the 1980s, ice loss has accelerated in the past two decades (Figure 11.7). With respect to the geographical distribution, years with a uniformly positive (e.g., 1965, 1977, 1978) or negative (e.g., 1964, 1973, 1983) Alpine mass balance signal, as well as years with a clear spatial gradient in net balance (e.g., 1963, 1976) or with heterogeneous signals, can be found mainly before 1986. After 1981, uniformly negative mass balance years dominate. Nine Alpine reference glaciers (Careser in Italy, Gries and Silvretta in Switzerland, Hintereis, Kesselwand, Sonnblick, and Vernagt in Austria, and Saint Sorlin and Sarennes in France) with continuous mass balance series over more than 30 years show a mean annual loss of ice thickness close to 37-cm water equivalent per year, resulting in a total thickness reduction of about 13 m water equivalent between 1967 and 2001. The corresponding values for the period 1980–99 are 60 cm water equivalent and 12.3 m water equivalent per year, respectively (Table 11.4).

## DISCUSSION

### DATA COVERAGE

Glacier studies have a long tradition in the Alps that began with the establishment of systematic observation networks in the 1890s (Haeberli, this volume). In comparison with the rest of the world, the European Alps have the densest and most complete spatial glacier inventory over time (Haeberli et al. 1989*a*). Thus, the inventory data contain information on spatial glacier distribution at certain times, whereas the fluctuation series provides high-resolution temporal information for specific locations. Interestingly, the 1970s is the only period in which an Alpine inventory with total spatial coverage can be compiled, most glaciers being relatively close to steady-state conditions (Figure 11.7; Patzelt 1985). The reconstructed glacier extents at the end of the Little Ice Age (around 1850) and the glacier outlines derived from multispectral satellite data around 2000 from the SGI2000 cover the major parts and the full range of area-classes of Swiss glaciation. Thus, they can be used to extrapolate Alpine glaciation in 1850 and 2000 on the assumption that the relative losses of the different area-classes in Switzerland are representative of other Alpine countries as well. This, of course, is not necessarily the case. The fluctuation series are numerous and well distributed over the Alps, with a minimum number of front variation series in the southwestern part of the Alps. For the fluctuation series, length and completeness of the time series are most relevant.

### GLACIER SHRINKAGE

The inventory for the 1970s and the extrapolated area estimates for 1850 and 2000 show dramatic shrinkage of the Alpine glaciers. Despite the high degree of variability in individual glaciers, the European Alps have experienced a 50% decrease

TABLE 11.1

*Distribution of Glaciers by Number and Area (Absolute Values) in the Alps in the 1970s*

| AREA-CLASS ($KM^2$) | | ALPS WGI | AT WGI | CH WGI | FR WGI | IT WGI | ALPS FOG, FV | ALPS FOG, MB |
|---|---|---|---|---|---|---|---|---|
| 0.0–0.1 | Number | 1,953 | 287 | 636 | 522 | 508 | 16 | 0 |
| | Area ($km^2$) | 100.7 | 16.2 | 29.4 | 24.5 | 30.5 | 1.0 | 0.0 |
| 0.1–0.5 | Number | 2,254 | 416 | 826 | 361 | 651 | 130 | 3 |
| | Area ($km^2$) | 497.0 | 92.3 | 185.5 | 77.0 | 142.2 | 36.2 | 0.9 |
| 0.5–1 | Number | 430 | 112 | 156 | 73 | 89 | 92 | 4 |
| | Area ($km^2$) | 299.8 | 77.6 | 108.4 | 51.4 | 62.5 | 64.0 | 2.8 |
| 1–5 | Number | 425 | 95 | 152 | 79 | 99 | 198 | 13 |
| | Area ($km^2$) | 862.3 | 213.2 | 294.8 | 153.6 | 200.7 | 446.6 | 35.2 |
| 5–10 | Number | 66 | 10 | 32 | 7 | 17 | 56 | 3 |
| | Area ($km^2$) | 461.7 | 71.8 | 223.0 | 51.0 | 115.9 | 392.1 | 24.6 |
| 10–20 | Number | 27 | 5 | 16 | 2 | 4 | 27 | 2 |
| | Area ($km^2$) | 387.9 | 71.2 | 240.1 | 26.1 | 50.5 | 396.0 | 33.0 |
| >20 | Number | 7 | 0 | 6 | 1 | 0 | 7 | 0 |
| | Area ($km^2$) | 293.6 | 0.0 | 260.5 | 33.1 | 0.0 | 293.5 | 0.0 |
| Total | Number | 5,162 | 925 | 1,824 | 1,045 | 1,368 | 526 | 25 |
| | Area ($km^2$) | 2,902.9 | 542.2 | 1,341.7 | 416.6 | 602.4 | 1,629.3 | 96.5 |

NOTE: *AT*, Austria, *CH*, Switzerland, *FR*, France, *IT*, Italy; *FV*, front variation surveys (more than nine measurements); *MB*, mass balance surveys (more than three measurements).

in ice coverage over the past 150 years. The area loss over each decade (in percent) between the 1970s and 2000 is almost three times greater than the related loss of ice between 1850 and the 1970s. Variations in glacier front position provide a higher-resolution assessment of the glacier retreat over the past 150 years. Though glaciers have generally been retreating since 1850, there have been several periods of documented readvances—in the 1890s, the 1920s, and the 1970s and 1980s (Patzelt 1985; Müller 1988; Pelfini and Smiraglia 1988; Reynaud 1988; Haeberli et al. 1989b). The area reduction after the 1970s occurred mainly after 1985 (see also Paul et al. 2004), and therefore the acceleration of the glacier retreat in the past two decades was even more pronounced. Mass balance measurements are available only for the past five decades and confirm the general trend of glacier shrinkage. While some glaciers gained mass between 1960 and 1980, ice loss has accelerated in the past two decades. The mean specific (annual) net balance of the 1980s is 18% below the average of 1967–2001, and the value for the 1990s doubles that average ice loss. The most recent mass balance data show a continuation of the acceleration trend after 2000, with a peak in the extraordinary year of 2003, when the ice loss of the nine Alpine reference glaciers was about 2.5-m water equivalent—exceeding the average of 1967–2000 by a factor of nearly seven. Estimated total glacier-volume loss in the Alps in 2003 corresponds to 5–10% of the remaining ice volume (Zemp et al. 2005). The acceleration of glacier shrinkage after 1985 indicates a transition toward rapid down-wasting rather than a dynamic glacier response to a changed climate (cf. Paul et al. 2004).

The general glacier retreat since 1850 corresponds well with the observed warming trend in

TABLE 11.2

*Distribution of Glaciers by Number and Area (Percentage) in the Alps in the 1970s*

| AREA-CLASS (KM$^2$) | | ALPS WGI | AT WGI | CH WGI | FR WGI | IT WGI | ALPS FOG, FV | ALPS FOG, MB |
|---|---|---|---|---|---|---|---|---|
| 0.0–0.1 | Number (%) | 37.8 | 31.0 | 34.9 | 50.0 | 37.1 | 3.0 | 0.0 |
| | Area (%) | 3.5 | 3.0 | 2.2 | 5.9 | 5.1 | 0.1 | 0.0 |
| 0.1–0.5 | Number (%) | 43.7 | 45.0 | 45.3 | 34.5 | 47.6 | 24.7 | 12.0 |
| | Area (%) | 17.1 | 17.0 | 13.8 | 18.5 | 23.6 | 2.2 | 0.9 |
| 0.5–1 | Number (%) | 8.3 | 12.1 | 8.6 | 7.0 | 6.5 | 17.5 | 16.0 |
| | Area (%) | 10.3 | 14.3 | 8.1 | 12.3 | 10.4 | 3.9 | 2.9 |
| 1–5 | Number (%) | 8.2 | 10.3 | 8.3 | 7.6 | 7.2 | 37.6 | 52.0 |
| | Area (%) | 29.7 | 39.3 | 22.0 | 36.9 | 33.3 | 27.4 | 36.5 |
| 5–10 | Number (%) | 1.3 | 1.1 | 1.8 | 0.7 | 1.2 | 10.6 | 12.0 |
| | Area (%) | 15.9 | 13.2 | 16.6 | 12.2 | 19.2 | 24.1 | 25.5 |
| 10–20 | Number (%) | 0.5 | 0.5 | 0.9 | 0.2 | 0.3 | 5.1 | 8.0 |
| | Area (%) | 13.4 | 13.1 | 17.9 | 6.3 | 8.4 | 24.3 | 34.2 |
| >20 | Number (%) | 0.1 | 0.0 | 0.3 | 0.1 | 0.0 | 1.3 | 0.0 |
| | Area (%) | 10.1 | 0.0 | 19.4 | 7.9 | 0.0 | 18.0 | 0.0 |
| Total | Number (%) | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |
| | Area (%) | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |

NOTE: *AT*, Austria, *CH*, Switzerland, *FR*, France, *IT*, Italy; *FV*, front variation surveys (more than nine measurements); *MB*, mass balance surveys (more than three measurements).

this period (e.g., Oerlemans 1994, 2001: 110–11; Maisch et al. 2000; Zemp, Hoelzle, and Haeberli 2007). However, the onset of the Alpine glacier retreat after 1850 may have been triggered by a negative winter precipitation anomaly (relative to the mean of 1901–2000) during the second half of the nineteenth century (Wanner et al. 2005). The intermittent periods of glacier advances in the 1890s, the 1920s, and the 1970s and 1980s can be explained by earlier wetter and cooler periods, with reduced sunshine duration and increased winter precipitation (Patzelt 1987; Schöner, Auer, and Böhm 2000; Laternser and Schneebeli 2003). Schöner, Auer, and Böhm (2000) concluded from the study of a homogenized climate data set and mass balance data from the Austrian part of the eastern Alps that the more positive mass balance periods show a high correlation with winter accumulation and a lower correlation with summer temperature, while more negative mass balance periods are closely correlated with summer temperature and show no correlation with winter accumulation. In addition they found that the positive mass balance period between 1960 and 1980 was characterized by negative winter North Atlantic Oscillation index values, which caused an increase of the meridional circulation mode and a more intense northwesterly to northerly precipitation regime (see Wanner et al. 2005). The observed trend of increasingly negative mass balances since 1980 is consistent with accelerated global warming and correspondingly enhanced energy flux toward the earth's surface (Haeberli et al. 2005*b*).

## REPRESENTATIVENESS OF THE SGI2000 AND THE FLUCTUATION SERIES

When analyzing national inventories or individual fluctuation series, the question of representativeness often arises. Are the subsample

TABLE 11.3

*Alpine Glaciation, 1850, 1970s, and 2000*

| | SWITZERLAND (SGI2000) | | | | | | | | ALPS | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1850 | | 1973 | | 2000 | | 1850–1973[a] | 1973–2000[a] | 1970s | | 1850[b] | 2000[b] |
| AREA-CLASS ($KM^2$) | *Number* | *Area ($km^2$)* | *Number* | *Area ($km^2$)* | *Number* | *Area ($km^2$)* | *Area Change (%)* | *Area Change (%)* | *Number* | *Area ($km^2$)* | *Area ($km^2$)* | *Area ($km^2$)* |
| < 0.1 | 297 | 17.3 | 1,022 | 40.1 | 164 | 3.6 | –55.4 | –64.6 | 1,953 | 100.7 | 225.5 | 35.6 |
| 0.1–.5 | 715 | 181.3 | 673 | 153.9 | 448 | 60.3 | –52.9 | –45.6 | 2,254 | 497.0 | 1,055.0 | 270.4 |
| 0.5–1 | 249 | 172.5 | 151 | 104.1 | 131 | 63.5 | –44.3 | –29.1 | 430 | 299.8 | 538.0 | 212.6 |
| 1–5 | 253 | 524.4 | 157 | 296.0 | 141 | 217.1 | –33.2 | –17.9 | 425 | 862.3 | 1,291.1 | 707.9 |
| 5–10 | 26 | 195.5 | 35 | 249.4 | 36 | 232.6 | –19.7 | –10.8 | 66 | 461.7 | 574.8 | 412.1 |
| 10–20 | 18 | 259.9 | 14 | 216.3 | 13 | 192.8 | –14.8 | –8.2 | 27 | 387.9 | 455.1 | 356.1 |
| > 20 | 9 | 270.5 | 5 | 225.9 | 5 | 213.0 | –12.3 | –5.7 | 7 | 293.6 | 334.8 | 276.9 |
| Total | 1,567 | 1,621.4 | 2,057 | 1,285.7 | 938 | 982.9 | –27.1 | –16.1 | 5,162 | 2,902.9 | 4,474.3 | 2,271.6 |

[a]The relative area changes in Switzerland are calculated from the comparable subsamples: 1,567 glaciers for 1850–1973 and 938 glaciers for 1973–2000, respectively.
[b]Alpine glacier area in 1850 and 2000 is extrapolated from the glacier area in the 1970s (WGI) and relative area changes of the seven glacier area-classes in Switzerland (SGI2000).

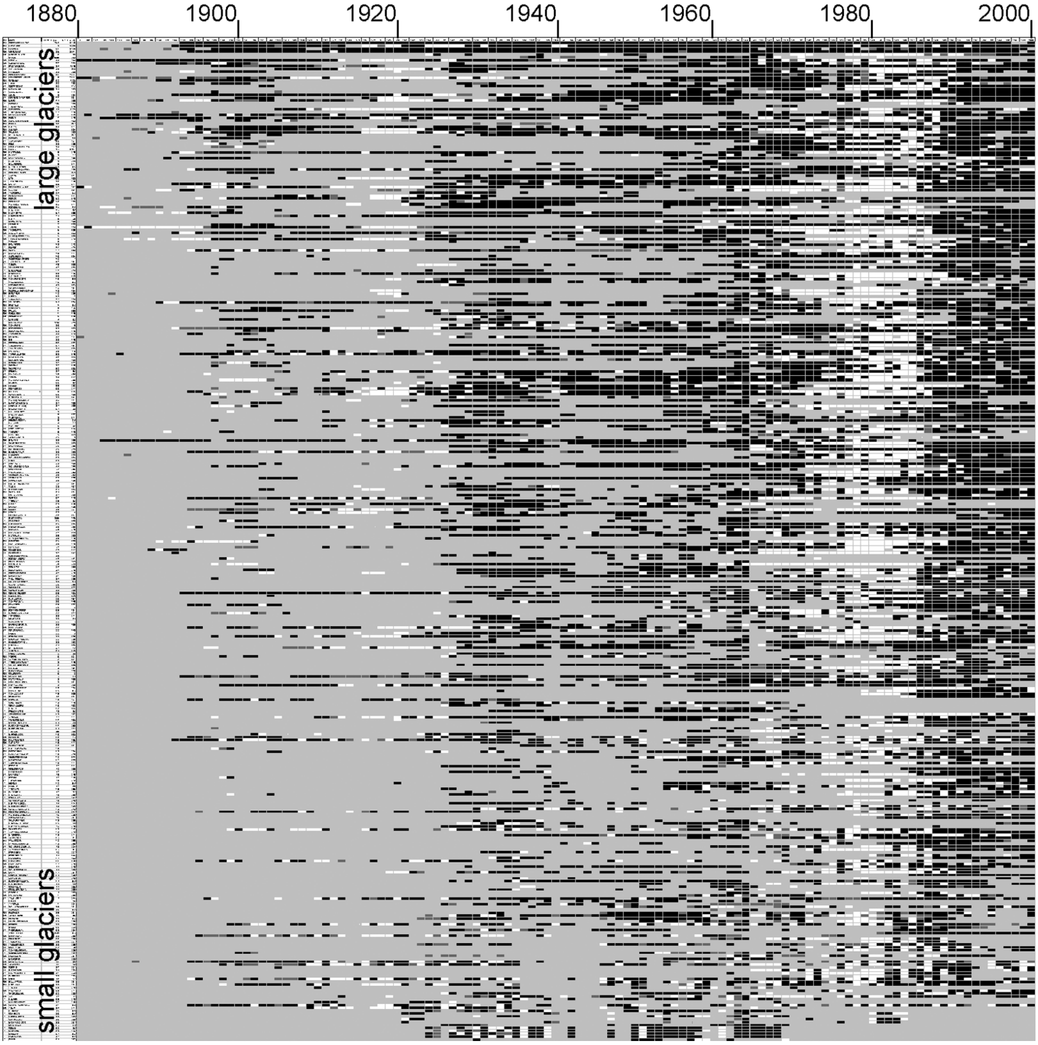


FIGURE 11.6. Alpine front variation series, 1880–2000. Annual front variation values from glaciers with more than 18 measurements are colored white after an advance, black after a retreat; dark gray indicates no apparent variation and light gray no data. Each row represents one glacier. The glaciers are sorted according to length in the 1970s (y-axis).

investigated and the glaciers surveyed representative of the entire glacierization? Comparison of the area characteristics of the 1850 and 2000 subsamples of the SGI2000 (on which the extrapolation of the Alpine areas of 1850 and 2000 is based) with the complete Swiss inventory in the WGI shows that the distributions of the area-classes are similar. Nevertheless, small glaciers (<0.1 km$^2$) are underrepresented, and glaciers in northeastern Switzerland are poorly represented (Paul et al. 2004). However, the SGI2000 subsamples for 1850 and 2000 include 86% of the Swiss glaciers covering 88% of the total area and 51% of the Swiss glaciers covering 87% of the total area, respectively. Thus, the SGI2000 can be considered a representative subsample of Swiss glaciation, which is very similar to the glaciation of the other Alpine countries. The ice coverage of the European countries is equally distributed with respect to the number of glaciers in each area-class, with the largest glaciers being overrepresented in the area distribution. Therefore, the different area-classes were considered when the

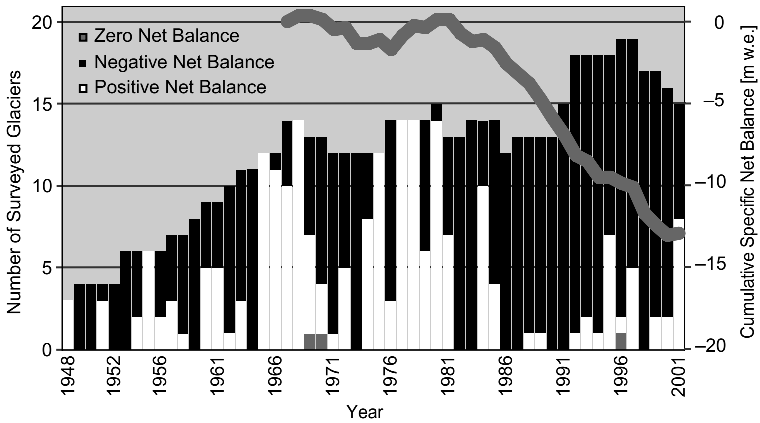


FIGURE 11.7. Alpine mass balance measurements, 1948–2001, showing annual numbers of glaciers (*left axis*) with a zero net balance (*dark gray*), positive net balance (*white*), or negative net balance (*black*) and the mean cumulative specific net balance of the nine Alpine reference glaciers from 1967 to 2001 (*right axis*).

extrapolation was applied to all Alpine glaciers. The large relative area change of the smaller glaciers leads to a more pronounced area change in the entire Alps than in Switzerland (assuming a uniform climate change across the region) because of the greater frequency of large glaciers in the latter.

Front variations are measured mainly on middle-sized and large glaciers, while glaciers smaller than 0.5 km$^2$ are underrepresented. This is to be expected because glacierets and névés are often unsuitable for this kind of measurement in terms of their limited accessibility and their low dynamic response. Front variation series with more than nine measurement years exist for about 10% of all Alpine glaciers, which cover more than 50% of the total glacier area. The dynamic response to climatic forcing of glaciers with variable geometry results in striking differences in the recorded curves, reflecting the considerable effects of size-dependent filtering, smoothing, and enhancing of the delayed tongue response with respect to the input (mass balance) signal (Oerlemans 2001). Dynamic response time depends mainly on glacier length, slope, and mass balance gradient (Johanneson, Raymond, and Waddington 1989; Haeberli and Hoelzle 1995). As a consequence, large valley glaciers with a dynamic response time of several decades show the secular climate trend, while smaller mountain glaciers show marked periods of intermittent advances and retreats on a decadal scale. The smallest, somewhat static, low-shear-stress glaciers (cirque glaciers) have altitude ranges that are comparable to or smaller than the interannual variation in equilibrium line altitude and hence, in general, reflect yearly changes in mass balance without any delay (Hoelzle et al. 2003).

Mass balance measurements are labor-intensive and are therefore available from only 25 glaciers, mainly from 0.5 to 10 km$^2$ in size, covering only 3% of the glacier area. In spite of their small number, they are geographically well distributed over the entire Alps. Mass balance is the direct and undelayed response signal to annual atmospheric conditions. It documents degrees of imbalance between glaciers and climate due to the delay in dynamic response caused by the characteristics of ice flow (deformation and sliding). Over long time intervals mass balance variations indicate trends of climatic forcing. With constant climatic conditions (no forcing), balances would tend toward zero. Long-term nonzero balances are therefore an expression of ongoing climate change (Haeberli et al. 2005). Summer and winter balance even provide intraannual climate information and should therefore be surveyed on all mass balance glaciers (Dyurgerov and Meier 1999; Vincent 2002). In general, fluctuation series are well distributed across the Alps and represent the range of area-classes quite well. In view of the large contribution of

TABLE 11.4
*Mean Specific (Annual) Net Balance of the Alpine Reference Glaciers*

| TIME PERIOD | NUMBER OF REFERENCE GLACIERS | NET BALANCE (MM W.E.) |
|---|---|---|
| 1950–59 | 1–5 | –536 |
| 1960–69 | 6–9 | –26 |
| 1970–79 | 9 | –69 |
| 1980–89 | 9 | –437 |
| 1990–99 | 9 | –767 |
| 1949–2001 | 1–9 | –412 |
| 1967–2001 | 9 | –369 |

glaciers smaller than 1 km² to glacier shrinkage in the past and the prediction of ongoing global warming (e.g., Schär et al. 2004; Beniston 2005), future work should include studies on the influence of atmospheric warming on small glaciers and on current down-wasting processes (see also Paul et al. 2004). However, the climatic sensitivity of glaciers depends not only on glacier size but also on sensitivity to variations in regional climate versus local topographic effects, which potentially complicates the extraction of a regional or global climate signal from glacier fluctuations (Kuhn et al. 1985; Vincent et al. 2004). Mass balance and ice flow models calibrated with available fluctuation data are needed to quantify these effects (Oerlemans et al. 1998; Oerlemans 2001; Paul et al., this volume).

## CONCLUSIONS

In the European Alps the growth of the glacier monitoring network over time has resulted in an unprecedented glacier data set with excellent spatial and temporal coverage. The WGMS has compiled information on spatial glacier distribution from approximately 5,150 Alpine glaciers and fluctuation series (front variation and mass balance) from more than 670 of these glaciers. National inventories provide complete Alpine coverage for the 1970s, when the glaciers covered an area of 2,909 km². This inventory, together with the SGI2000, is used to extrapolate Alpine glacier-covered areas in 1850 and 2000 of about 4,470 km² and 2,270 km², respectively. This corresponds to an overall glacier area loss from 1850 of 35% by the 1970s and almost 50% by 2000.

Annual mass balance and front variation series provide a better time resolution of glacier fluctuations over the past 150 years than the inventories. During the general retreat, intermittent periods of glacier advances in the 1890s, the 1920s, and the 1970s and 1980s can still be seen. Increasing mass loss, rapidly shrinking glaciers, and disintegrating and spectacular tongue retreats are clear warnings of the atmospheric warming observed in the Alps during the past 150 years and the acceleration observed over the past two decades.

While inventory data contain information on spatial glacier distribution at certain times, fluctuation series provide temporal information at specific locations. Continuity and representativeness of fluctuation series are thus essential for the planning of glacier monitoring. Furthermore, modeling should be enhanced and integrated into monitoring strategies. It is very important to continue with long-term fluctuation measurements and to extend the series back in time with reconstructions of former glacier geometries. Additionally, it is necessary to integrate glacier monitoring and reconstruction activities into the framework of the Global Land Ice Measurements from Space (GLIMS) project and the WGMS.

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