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MASS BALANCE OF RHONEGLETSCHER DURING 1882/83–1986/87

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ABSTRACT. The glaciological investigations on Rhonegletscher were started in 1874. The mass-balance data measured during 1884/85–1908/09 and during 1979/80–1981/82 are presented. Two methods are used for estimating the mass changes. During 1882/83–1968/69, the cumulative specific net balance is -24 ± 6 m w.e. at the 90% confidence level by the regression model of annual mass balance, annual precipitation, and summer air temperature (the PT model), while the thickness change revealed by the maps is -23 ± 5 m w.e. The cumulative specific net balance during 1882/83–1986/87 is -26 ± 6 m w.e. at the 90% confidence level.

The study shows that Rhonegletscher generally experienced mass loss, especially during the periods from the late 1920s through the early 1960s with some short periods of positive balance. The glacier tongue retreated by 970 m during 1882–1986, that is, from 1780 m a.s.l. (1882) to 2130 m a.s.l. (1986). During 1882–1969, the ice-covered area decreased by 4.37 km^2 and the volume by 4.71×10^8 m^3.

The PT models of Rhonegletscher and other alpine glaciers suggest that the contribution of the temperature changes to the mass balance is of more importance than that of the precipitation changes. The great mass loss reflects the climatic warming after the end of the Little Ice Age, with the warmest period occurring around the 1940s in this region.

INTRODUCTION

Mass balance of a glacier is a key element for understanding a glacier's behaviour and history. The processes of the mass exchange between snow/ice and the atmosphere are essential for knowing those of energy (heat) exchange associated with, and the effect of, snow/ice changes in the climatic systems (Ohmura, 1988). Mass balance also serves as an element of the water balance. Therefore, an accurate data base of the glacier mass balance both measured and reconstructed becomes essential (Martin, 1978; Tangborn, 1980; Reynaud and others, 1986).

Rhonegletscher is located in the middle of the Swiss Alps (lat. 46°37′ N., long. 08°24′ E.). It is the source of the Rhone River. This valley glacier is 10.2 km long with an area of 17.38 km^2, and the terminus was at 2140 m a.s.l. in 1969 (Müller and others, 1976). The exposure of both the accumulation and ablation areas is to the south. Its mean thickness is about 100 m (Haeberli and others, 1983; Waechter, unpublished).

In this paper, the mass-balance data of Rhonegletscher measured during 1884/85–1908/09 (Mercanton, 1916) and during 1979/80–1981/82 (Funk, 1985) are presented. Furthermore, the mass change of Rhonegletscher since 1882–83 is estimated by using a regression model of the specific net balance, the precipitation, and the air temperature (the PT model). To check the accuracy of the model, the results are compared with the mean thickness change of the glacier during 1882–1969 as revealed by the topographical maps. The PT models and the vertical gradients of the net balance of this glacier are analyzed in relation to the mass changes. Finally, the climatic implications of the mass changes of this glacier are briefly discussed.

An overview of the studies on Rhonegletscher

Rhonegletscher is one of the glaciers with the longest record of terminus fluctuations in the world and it still serves as a reference glacier for monitoring by the "Glacier Commission" (Gletscher-Kommission) of the Swiss Academy of Natural Sciences (SANW, earlier known as SNG — Schweizerische Naturforschende Gesellschaft) and the World Glacier Monitoring Service.

The record of the fluctuations of Rhonegletscher goes back to 1869. In 1874, Rhonegletscher was selected for systematic glaciological studies by the "Glacier Committee" (Gletscher-Kollegium) of the SANW and of the Swiss Alpine Club (SAC). The aim of the study at that time was to understand the historical development of the glacier and its flow, as well as the waxing and waning of the glacier due to the changes occurring at the glacier surface. The studies covered: (1) topographical survey of changes of the ice surface and the tongue, (2) ablation and accumulation, (3) glacier flow, (4) glacier run-off, and (5) the structures of the glacier. The main studies were funded and guided by the Glacier Committee during 1874–88, and the Glacier Commission during 1888–1915. The measurements were done by P. Gosset during 1874–80, L. Held during 1881–88, and L. Held, H. Wild, S. Simonett, and E. Leupin during 1888–1915. Some of the research reports were published (Rütimeyer, 1880–81, 1881–84, 1886–88; Coaz, 1885; Hagenbach-Bischoff, 1894–1910; Heim, 1910–15; Held, 1889). The results were summarized by Mercanton (1916).

The fluctuations of this glacier have been monitored continuously by the Glacier Commission (Kasser and Aellen, 1986). A new comprehensive glaciological, climatological, and hydrological research project on Rhonegletscher (Rhonegletscher Project) was initiated in 1979 by the Department of Geography of the Swiss Federal Institute of Technology (ETH Zürich) with the aim of studying the combined balances of ice, water, and energy in a strongly glacierized basin (Müller and others, 1980). The mass-balance study was a part of this project in which both winter balance and summer balance of the glacier had been measured (Funk, 1985). Other studies on Rhonegletscher concerned the ablation gradient (Haefeli, 1962), radio-echo sounding (Haeberli and others, 1983; Waechter, unpublished), hydrology (Bernath, unpublished), length variations (Kasser and Aellen, 1986; Müller, 1988), and the mechanical characteristics of the historical glacier in 1850 (Haeberli and Schweizer, 1988). A general survey of this glacier has been given by Röthlisberger (1963).

Maps

The first topographic map of Rhonegletscher was made by H. Siegfried and L. Held between 1874 and 1882. The tongue was drawn at a scale of 1 : 5000, and the rest of the glacier at a scale of 1 : 25 000, with a contour interval of 10 m (Mercanton, 1916). In 1959 and 1969, Rhonegletscher was mapped again at a scale of 1 : 25 000 and with a contour interval of 20 m. It was printed on two sheets: Guttannen (Map No. 1230, 1969) and Urseren (Map No. 1231, 1959) of the Swiss Federal Topographical Survey. The accuracy of the topographical maps of the glacier is within ±5 m (better in the lower ablation area than in the upper accumulation area).

MASS-BALANCE DATA

Mass-balance measurements

The following profiles were established for the velocity, elevation, and mass-change measurements (Fig. 1): four in 1874–75 called black, green, yellow, and red; another four in 1881–82 (Upper- and Lower-Grossfirn and Upper- and Lower-Thaeli), and one in 1895 (blue). Due to glacier retreat, the lowest three profiles disappeared in 1882–83, 1899–1900, and 1911–12.

For the period 1884/85–1909/10, the mass changes were measured by observing ablation and/or accumulation using stakes. The changes in the surface elevation only were measured without density determinations. The positions of the stakes of the upper four profiles are shown in Figure 1. More than 11 stakes were installed in the profiles I-IV, but these stakes moved with time and some even disappeared. There are three stakes for each of the profiles V–IX, which were newly installed each year at the initial profile positions.

The annual mass change was defined as "accumulation" when the glacier had gained mass during a hydrologic year and as "ablation" when mass was lost. The original data for ablation or accumulation should be translated into the specific annual balance or the specific net balance by the fixed date system, as defined by Meier (1963), Østrem and Stanley (1966), and Mayo and others (1972).

For the period 1979/80–1981/82, measurements of mass balance were made by Funk (1985) at 50 points selected so as to provide a good representation of the spatial mass-balance distribution (Fig. 2). The data were analyzed by a multiple-regression model to discover the relationships between the specific net balance and the morphological parameters of the glacier surface.

Calculation of the specific net balance

In the present approach, annual net balance of a point as measured by a stake will be denoted as b while the specific annual net balance over an area (an altitude interval, the ablation area, the accumulation area, or the whole glacier) is specified as $\langle b \rangle$. $\langle\rangle$ specifies the mean of b over the whole area. To calculate the mean specific net balance $\langle b \rangle$ of a glacier, the commonly applied formula is

$$\langle b \rangle = (1/S) \sum_{i=1}^{N} \langle b \rangle_i s_i \qquad (1)$$

where s_i is the area of the glacier within the ith altitude interval of 100 m, and $\langle b \rangle_i$ is the specific net balance of that interval.

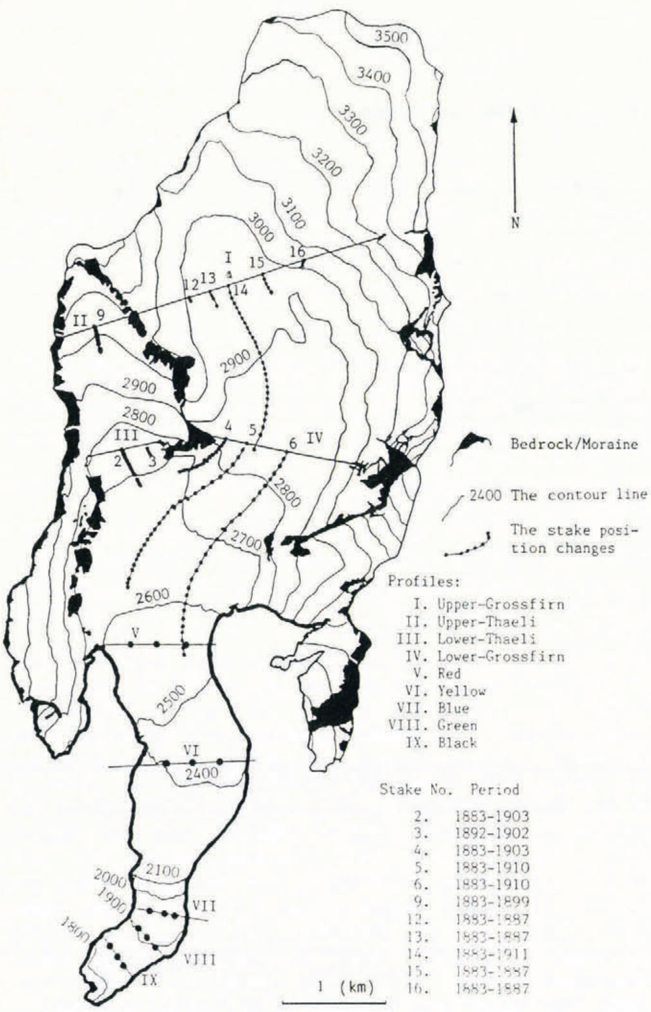

Fig. 1. A sketch showing the profiles and the stakes for mass-balance measurements during 1884/85–1908/09, reduced after Mercanton (1916, pl. I).

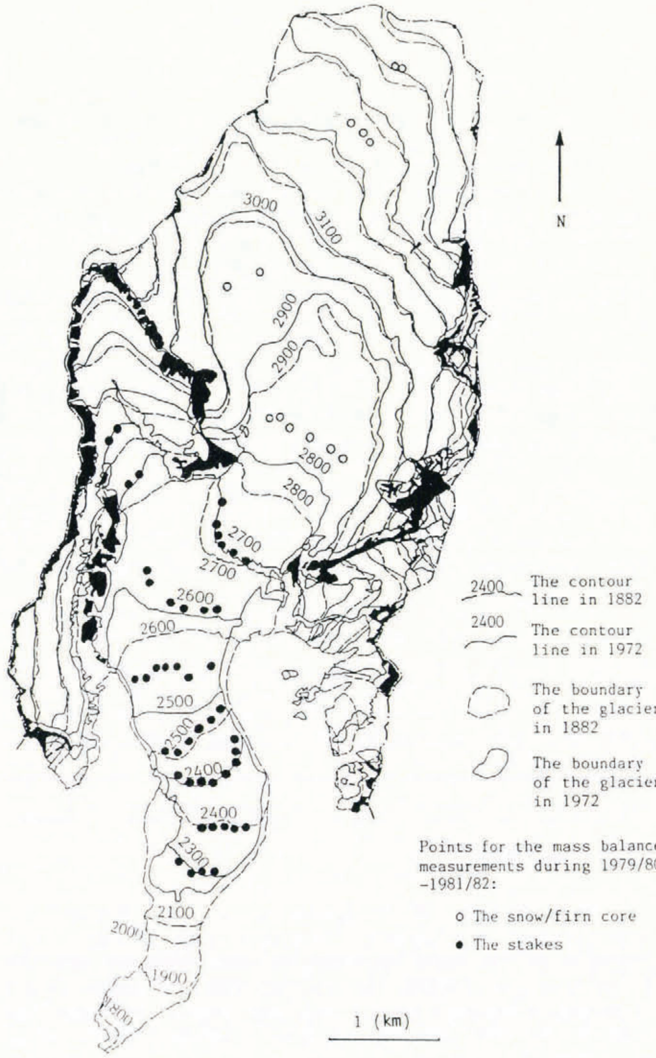

Fig. 2. Positions for mass-balance measurements during 1979/80–1981/82 and comparison of the contour lines in 1882 and 1969 for Rhonegletscher.

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When calculating $\langle b \rangle$ with Equation (1), $\langle b \rangle_i$ can be approximated as the arithmetic mean of the b values of the stakes in the ith altitude interval. s_i changes from year to year, especially in the ablation area, but it is not measured annually in most cases. By taking s_i as the area of the glacier or as that of the ice-covered area (i.e. including the area of small ice patches in the same altitude interval, which are separated from the glacier), some differences in the calculation of $\langle b \rangle$ may be introduced. The ice-covered area is used for the $\langle b \rangle$ calculation for the period 1884/85–1908/09 while the glacier area is used for the calculation of $\langle b \rangle$ 1979/80–1981/82. For Rhonegletscher in 1969, the glacier area was 17.38 km^2 and the ice-covered area was 18.42 km^2. This is a difference of 1.04 km^2. No corrections were made for this and the resultant error is judged to be small. In the present study, "area" always refers to "ice-covered area".

Correction of the 1884/85–1908/09 mass-balance data

The original data are point values of stake measurements giving ablation or accumulation. They need to be corrected before they can be used for the following reasons: (1) the length of the annual measurement period changed with time, (2) the position of the stakes changed with time, (3) the snow/firn densities are unknown, and (4) in some areas of the glacier, there are no measurements.

The times of stake readings for mass-balance measurements varied from late August to late September. Therefore, part of the original records of mass balance shows a time deviation of about 1 month, by the end of a hydrological year, from the period of the generally used hydrological year (the fixed-date system) in the mid-latitudes (beginning of October–end of September). The time deviations introduced some errors to the calculation of $\langle b \rangle$ for the years when intense ablation or accumulation occurred by the end of the year and were not considered.

Stake position. The stakes were used for the simultaneous measurements of both ice flow and mass balance. In the lower part of the glacier they had to be replaced or newly installed due to ice flow and intense ablation. Therefore, the coordinates of the stakes or observation points changed with time. This can easily be considered by using the information on the positions of the measurement points as given by Mercanton (1916).

Densities of snow/firn/ice. Densities of snow/firn/ice are basic data for mass-balance calculations, especially in the accumulation area. As no original density measurements are available, the data are treated in the following way: the positive mass-balance data (almost all stakes with positive b in the accumulation area) are multiplied by a constant of 0.6 (the mean density of firn), according to the field measurements on Rhonegletscher by Funk (1985), and the negative mass balance in the ablation area by 0.9 (the density of ice).

Data extrapolation. Above the two "upper" profiles in the accumulation area, there are about four 100 m altitude intervals which extend from 3200 to 3629 m a.s.l. and covered 4.28 km^2 in 1874–82 (18.8% of the total area). Their area remained almost unchanged until 1930. For this area, $\langle b \rangle$ values are extrapolated using a vertical gradient of $\langle b \rangle$ (hereafter referred to as $\langle db/dz \rangle$) of 6.3 mm/m which is the mean gradient for the accumulation area measured during the period 1979/80–1981/82 (Table I). In some years, the stakes were lost in the lower part of the tongue due to strong ablation. For example, the mass-balance data for the five altitude intervals between 2600 m a.s.l. and the terminus (1780 m a.s.l.) were lost in 1884–85. Missing data from the ablation area are extrapolated according to the mass-balance data of neighbouring altitude intervals and $\langle db/dz \rangle$ for that year or 9.1 mm/m, which is the mean value for the ablation area during the period 1979/80–1981/82 (Table I) in the case (1884–85) where b data are insufficient for calculating db/dz. The year with only a few measurement points is not used for the caculation (1909–10). The reason for using the given values of $\langle db/dz \rangle$ will be discussed in the following section.

Analysis of the measured mass-balance data

The data for the measured $\langle b \rangle$ versus the altitude interval, compiled as explained above based on the original data (Mercanton, 1916), are listed in Table II. Despite the fact that the vertical gradient of $\langle b \rangle$ is larger in the lower part of the ablation area and becomes smaller towards the accumulation area, the maximum amplitude of the vertical shift in $\langle b \rangle$-isolines can be observed in the altitude interval where the equilibrium line appears (Fig. 3). The amplitude of the vertical shift of the $\langle b \rangle$ = 0 m w.e. isoline is 500 m (2600–3100 m a.s.l.). Moreover, it is larger in the accumulation area than in the ablation area.

The specific net balance $\langle b \rangle$ during 1884/85–1908/09 and 1979/70–1981/82 (Funk, 1985) and some other data from Rhonegletscher are listed in Table I. The mass balance for the period 1884/85–1908/09 is generally negative, and the cumulative $\langle b \rangle$ during those 25 years is −3240 mm w.e. Some short periods with a positive $\langle b \rangle$ occurred in the late 1880s, the mid-1890s, and the late 1900s.

For the period 1979/80–1981/82, the specific summer balance of Rhonegletscher is −1350 mm w.e. in its accumulation area and −3800 mm w.e. in the ablation area. The specific winter balance is 2610 mm w.e. in the accumulation area and 1660 mm w.e. in the ablation area. The specific net balance $\langle b \rangle$ (in mm w.e.) of Rhonegletscher was 890 in 1979–80, 90 in 1980–81, and −380 in 1981–82.

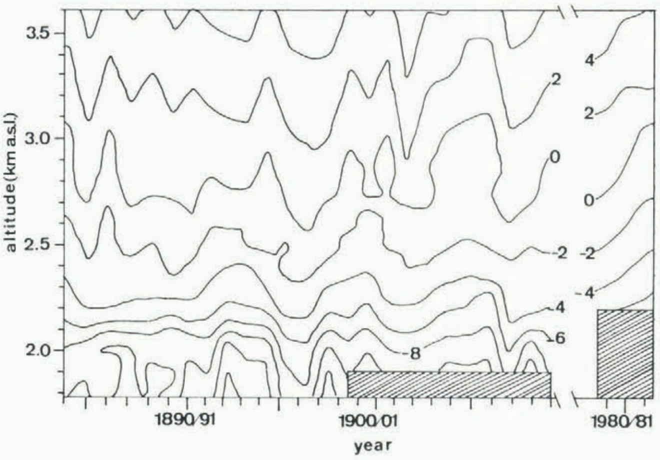

Fig. 3. Changes of specific net balance (in m w.e.) with altitude and time for Rhonegletscher during 1884/85–1908/09 and 1979/80–1981/82.

THE VERTICAL GRADIENT OF THE SPECIFIC NET BALANCE

The vertical gradient of the specific net balance $\langle db/dz \rangle$ reflects the net balance change with altitude or the form of the specific net balance–elevation curve ($\langle b \rangle$–z curve). For some glaciers the $\langle b \rangle$–z curves for different years have a similar form, i.e. the $\langle b \rangle$–z curve for a glacier for one year can be approximated by a parallel displacement of the $\langle b \rangle$–z curve of that glacier of the reference year (Meier and Tangborn, 1965; Hoinkes, 1970). This reference $\langle b \rangle$–z curve is usually taken as the mean $\langle b \rangle$–z curve or the $\langle b \rangle$–z curve for the near-balance situation. If such a feature applies universally, it implies that mass-balance measurement field work could be reduced. The $\langle b \rangle$–z curve for Rhonegletscher also shows this feature for the years 1979–80, 1980–81, and 1981–82 (Fig. 4). However, detailed examination shows that the vertical gradient of the mass balance of Rhonegletscher is not strictly a constant in time.

The spatial distribution of b values of Rhonegletscher during 1979/80–1981/82 has been investigated by Funk (1985) using multiple-regression analysis with morphological parameters of the glacier surface (elevation, surface slope, azimuth, and concavity and convexity index) as independent variables. These morphological variables have been

TABLE I. SPECIFIC NET BALANCE $\langle b \rangle$(IN mm w.e.), EQUILIBRIUM LINE ALTITUDE ELA (IN m a.s.l.), AND VERTICAL GRADIENT OF MASS BALANCE $\langle db/dz \rangle$ (IN mm w.e./m) OF RHONEGLETSCHER

Year	$\langle b \rangle$	*ELA*	$\langle db/dz \rangle_g$ (1)	$\langle db/dz \rangle_g$ (2)	$\langle db/dz \rangle_a$ (1)	$\langle db/dz \rangle_a$ (2)	$\langle db/dz \rangle_c$ (1)	$\langle db/dz \rangle_c$ (2)
1884–85	−1210	3124	7.4	6.9	7.8	7.3	6.6	6.6
1885–86	590	2812	8.3	8.5	10.6	9.6	6.6	5.5
1886–87	−1160	3098	5.7	6.7	5.5	6.9	6.6	6.9
1887–88	910	2795	9.6	10.0	11.8	11.4	7.4	6.8
1888–89	−270	2845	6.4	7.1	7.8	7.9	5.5	4.6
1889–90	280	2830	6.8	7.9	7.6	8.7	6.5	5.9
1890–91	140	2772	8.1	8.9	11.0	10.9	4.9	4.4
1891–92	−360	2920	8.6	8.5	9.9	9.1	7.2	7.3
1892–93	−340	2872	10.3	11.1	12.6	13.0	6.6	6.6
1893–94	−500	2869	9.2	9.6	11.4	11.2	5.3	5.4
1894–95	−860	3018	8.9	9.3	10.0	10.5	7.0	7.4
1895–96	740	2804	8.0	7.7	9.1	8.1	6.8	6.5
1896–97	920	2726	7.6	7.2	9.1	7.7	6.1	6.3
1897–98	370	2825	9.8	10.0	12.5	11.5	7.4	6.3
1898–99	−380	2920	8.3	8.1	9.5	8.6	6.5	6.5
1899–00	−420	2838	8.7	9.3	11.7	10.4	5.9	5.7
1900–01	−600	3029	6.9	7.1	7.2	7.7	4.9	5.7
1901–02	380	2833	7.8	8.2	9.2	8.9	5.6	6.3
1902–03	150	2791	7.3	7.6	9.3	8.6	4.2	5.2
1903–04	−710	3003	8.0	8.4	8.9	9.3	4.9	6.6
1904–05	−1190	3105	7.8	8.0	8.2	8.5	5.1	7.0
1905–06	−980	3075	8.1	8.4	8.8	9.4	4.7	6.0
1906–07	760	2795	6.9	6.9	7.4	7.1	5.2	6.3
1907–08	320	2811	8.0	8.8	10.1	10.1	5.1	5.9
1908–09	170	2926	7.2	7.3	7.7	7.5	5.1	7.4
Mean (1884/85–1908/09)	−130	2897	8.0	8.2	9.4	9.2	5.9	6.1
1979–80	890	2764	9.1	7.0	12.4	9.9	5.7	6.3
1980–81	90	2875	8.7	6.7	10.5	8.8	5.8	6.4
1981–82	−380	3035	8.7	7.4	9.8	8.6	6.7	7.1
Mean (1979/80–1981/82)	200	2890	8.8	7.1	10.9	9.1	6.1	6.3

The subscripts for $\langle db/dz \rangle$, a, c, and g, specify the ablation area, the accumulation area, and the entire glacier. (1) and (2) denote that corresponding db/dz are calculated by Equations (2) and (3), respectively.

determined with a digital elevation model. It has been shown that the most suitable morphological variables for expressing the spatial distribution of the mass balance are the elevation and slope of the surface.

The values of $\langle db/dz \rangle$ for Rhonegletscher are calculated in two ways, first by:

$$\langle db/dz \rangle_i = (\langle b \rangle_{i+1} - \langle b \rangle_{i-1})/z_{i+1} - z_{i-1}) \qquad (2)$$

where $\langle b \rangle$ is defined as above and z is the altitude. The subscript i denotes the ith altitude interval. The mean $\langle db/dz \rangle$ of the ablation and accumulation areas, as well as the entire glacier, which are referred to as $\langle db/dz \rangle_a$, $\langle db/dz \rangle_c$, and $\langle db/dz \rangle_g$, respectively, is the arithmetic mean over all the altitude intervals in the corresponding area. The second method is to find a linear regression relationship between the specific net balance $\langle b \rangle_i$ and the altitude z_i:

$$\langle b \rangle_i = \beta_0 + \beta_1 z_i \, . \qquad (3)$$

If the correlation of $\langle b \rangle_i - z_i$ is significant, the value of β_1 can be taken as that of $\langle db/dz \rangle$.

Both Equations (2) and (3) are used for calculating $\langle db/dz \rangle_a$, $\langle db/dz \rangle_c$, and $\langle db/dz \rangle_g$ for Rhonegletscher. The $\langle db/dz \rangle$ values calculated by Equation (3) agree with those calculated by Equation (2) for the years when the $\langle b \rangle - z$ curves do not deviate much from the linear form (Table I). It can be seen from the data for 1979/80–1981/82 that the value of $\langle db/dz \rangle_a$ is usually different from that of $\langle db/dz \rangle_c$. It follows that extrapolation of missing b values should be done by using $\langle db/dz \rangle_c$ for the accumulation area and $\langle db/dz \rangle_a$ for the ablation area. Although the results suggest that annual $\langle db/dz \rangle$ changes with time, the mean of $\langle db/dz \rangle$ over a long time remains stable (7–9 mm/m for the entire glacier, 9–10 mm/m for its ablation area, and about 6 mm/m for its accumulation area). The $\langle db/dz \rangle$ values from the measurements during 1979/80–1981/82, covering the whole glacier, are considered to be relatively accurate and are therefore used for extrapolation purposes.

MEAN ELEVATION CHANGES

Changes in elevation and volume of glaciers can be determined by using the digital elevation model or the contour method (Finsterwalder, 1954; Reinhardt and Rentsch, 1986). Both methods are used here.

Method I. The topographical maps (1 : 25 000) completed during 1874–82 and in 1969 have been digitized by hand with a grid-point interval of 100 m in order to obtain the elevation change $\langle \Delta h \rangle$ of Rhonegletscher during 1882–1969. The accuracy of the elevation is estimated to be within ±5 m for each grid point. $\langle \Delta h \rangle$ of Rhonegletscher during 1882–1969 is obtained from the Δh of all grid points. The area change is determined by planimetry. The results are given in Table III and shown in Figure 5. Elevation changes are mapped in Figure 6. Areas with intensive shrinkage during 1882–1969 include the central and lower parts of the glacier. $\langle \Delta h \rangle$ of the ice surface during

TABLE II. SPECIFIC NET BALANCE IN 100 m ALTITUDE INTERVALS OF RHONEGLETSCHER FOR THE PERIODS 1884/85–1908/09 AND 1979/80–1981/82

Altitude interval m a.s.l.		*Annual specific net balance* cm w.e.								
		1884–85	85–86	86–87	87–88	88–89	89–90	90–91	91–92	92–93
3500	3629	(276)	(477)	(299)	(570)	(345)	(450)	(381)	(432)	(456)
3400	3500	(213)	(414)	(236)	(507)	(282)	(387)	(318)	(369)	(393)
3300	3400	(150)	(351)	(173)	(444)	(219)	(324)	(255)	(306)	(330)
3200	3300	(87)	(288)	(110)	(381)	(156)	(261)	(192)	(243)	(267)
3100	3200	(24)	(225)	(47)	(318)	(93)	(198)	(129)	(180)	(204)
3000	3100	−67	162	−44	255	30	135	66	117	141
2900	3000	−76	192	−113	192	108	114	144	54	78
2800	2900	−84	64	−182	(75)	(8)	(24)	(65)	−129	(−22)
2700	2800	−216	−105	−251	−61	−140	−97	−18	−171	−161
2600	2700	(−298)	(−166)	−245	(−155)	(−210)	(−129)	(−130)	(−261)	(−287)
2500	2600	(−380)	(−266)	−239	(−248)	(−285)	−161	−242	−350	−413
2400	2500	(−462)	−287	−233	−341	−359	(−361)	−337	(−453)	−521
2100	2400	(−585)	(−500)	(−554)	(−595)	(−582)	(−661)	(−561)	(−607)	(−808)
1900	2100	(−790)	−854	−1016	−953	−935	−863	(−1286)	−863	−1286
1800	1900	(−913)	(−977)	−728	(−1139)	−706	−755	(−1058)	(−986)	(−1409)
1789	1800	(−994)	(−1059)	(−810)	(−1221)	(−788)	(−837)	(−1140)	(−1068)	(−1491)
Mean		−121	59	−116	91	−27	28	14	−36	−34

1893–94	94–95	95–96	96–97	97–98	98–99	99–00	1900–01	01–02	02–03	03–04
(375)	(374)	(511)	(503)	(501)	(405)	(411)	(334)	(473)	(401)	(358)
(312)	(311)	(448)	(440	(438)	(342)	(348)	(271)	(410)	(338)	(295)
(249)	(248)	(385)	(377)	(375)	(279)	(285)	(208)	(347)	(275)	(232)
(186)	(185)	(322)	(314)	(312)	(216)	(222)	(145)	(284)	(212)	(169)
(123)	(122)	(259)	(251)	(249)	(153)	(159)	(82)	(221)	(149)	(106)
60	(29)	(196)	(188)	(186)	(90)	(96)	(19)	(158)	(86)	(43)
96	−62	(133)	(125)	(123)	27	33	−72	95	23	−48
(−23)	(−142)	(42)	62	60	−64	48	−17	32	90	−99
−190	−223	−49	16	−180	−131	−336	−161	−153	−62	−150
−190	−156	−215	−51	−108	−272	−254	−181	−162	−94	−177
−431	−313	−152	−163	−288	−332	−368	−332	−204	−233	−305
−485	−430	(−255)	−253	−450	−476	−548	−353	−348	−368	−521
(−725)	(−690)	(−409)	(−386)	(−662)	(−602)	(−710)	(−511)	(−510)	(−523)	(−674)
−1124	−1123	(−665)	(−607)	(−1013)	(−810)	(−980)	(−773)	(−773)	(−778)	(−927)
(−1247)	(−1246)	−818	−739	−1224	−935	−1142	−930	−940	−935	−1079
(−1329)	(−1328)	(−900)	(−820)	(−1306)	(−1017)	(−1225)	–	–	–	–
−50	−86	74	92	37	−38	−42	−82	38	15	−71

1904–05	05–06	06–07	07–08	08–09	Mean 1	1979–80	80–81	81–82	Mean 2
(321)	(320)	(495)	(456)	(451)	415	476	392	375	414
(258)	(257)	(432)	(393)	(388)	352	431	332	328	364
(195)	(194)	(369)	(330)	(325)	289	355	259	250	288
(132)	(131)	(306)	(267)	(262)	226	318	230	210	253
(41)	(68)	(243)	(204)	(199)	162	203	124	106	144
(−50)	(−23)	(180)	(141)	(136)	93	110	43	5	53
−141	−114	117	(78)	26	45	90	21	−28	28
−111	−29	54	(67)	−84	−12	79	−8	−67	1
−143	(−109)	(−45)	(−104)	(−113)	−134	−13	−103	−164	−93
−218	−188	−144	−195	−142	−185	−81	−170	−240	−164
−364	−269	−229	−265	−329	−284	−143	−213	−298	−219
−557	−692	−269	−224	−313	−396	−250	−304	−390	−315
(−690)	(−793)	(−378)	(−480)	(−518)	−589	−361	−431	−513	−435
(−911)	(−961)	(−559)	(−905)	(−641)	−896	–	–	–	–
−1043	−1061	−667	−1160	(−732)	−993	–	–	–	–
–	–	–	–	–	–	–	–	–	–
−119	−98	76	32	17	−13	89	9	−38	20

Values in brackets are either interpolated or extrapolated.
Mean 1: the mean for 1884/85–1908/09.
Mean 2: the mean for 1979/80–1981/82.

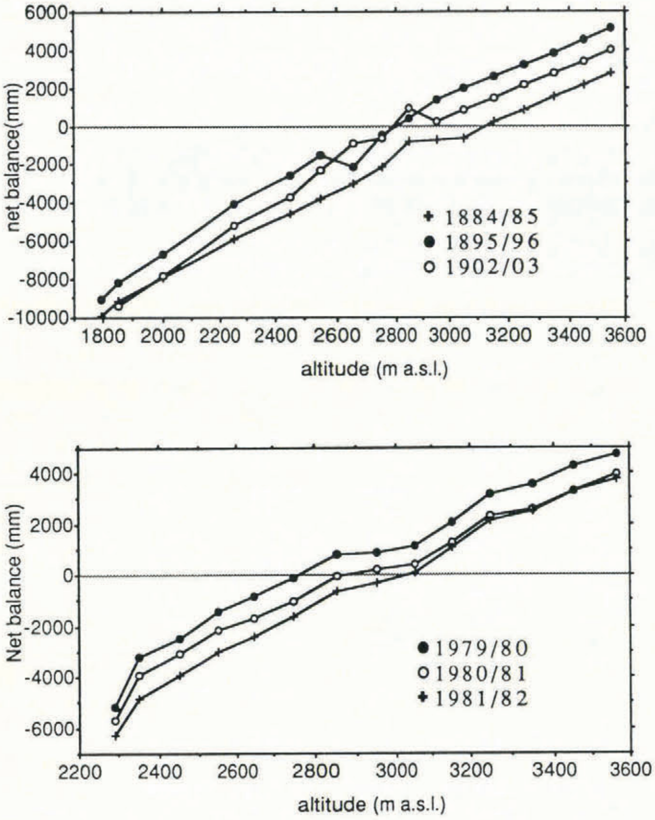

Fig. 4. Specific net balance versus altitude of Rhonegletscher for the years 1884–85, 1895–96, 1902–03, 1979–80, 1980–81, and 1981–82.

TABLE III. ICE-COVERED AREA S (IN km^2) IN 1882, CHANGES OF ICE-COVERED AREA ΔS (IN km^2), AND MEAN CHANGES OF THE SURFACE ELEVATION $\langle\Delta h\rangle$ (IN m w.e.) IN 100 m ALTITUDE INTERVALS OF RHONEGLETSCHER FOR THE PERIOD 1882–1969

H1	*H2*	*S(1882)*	ΔS	$\langle\Delta h\rangle$(1)	$\langle\Delta h\rangle$(2)
3500	3629	0.47	−0.05	−10	−22
3400	3500	0.82	0.00	−14	−17
3300	3400	1.32	−0.13	−11	−18
3200	3300	1.67	−0.03	−7	−13
3100	3200	2.11	−0.46	−4	−9
3000	3100	2.93	−0.87	−9	−13
2900	3000	3.51	−0.65	−13	−22
2800	2900	3.24	−1.37	−21	−28
2700	2800	1.54	−0.06	−27	−27
2600	2700	1.89	0.01	−25	−19
2500	2600	0.99	0.07	−26	−31
2400	2500	0.75	−0.16	−36	−52
2300	2400	0.69	0.03	−48	−41
2200	2300	0.20	0.01	−56	−56
2100	2200	0.08	−0.08	−36	−36
2000	2100	0.08	−0.08	−55	−55
1900	2000	0.23	−0.23	−86	−86
1800	1900	0.31	−0.31	−43	−43
1780	1800	0.05		−43	−43
Sum		22.80	−4.37		
Mean				−20	−23

(1) $\langle\Delta h\rangle$ is estimated as the mean elevation change of the grid points, and (2) $\langle\Delta h\rangle$ is determined from the volume change.

1882–1969 is −20 m as revealed by two maps. The errors in the $\langle\Delta h\rangle$ estimation by method I is mainly introduced by the interpolation of the elevation of some grid points.

Method II. The thickness change $\langle\Delta h\rangle$ of the glacier can also be estimated as

$$\langle\Delta h\rangle = \Delta V/\bar{S} \tag{4}$$

where ΔV is the volume change and $\bar{S}$ the mean area of the glacier during the considered period. ΔV is equal to

$$\Delta V = \sum_{i=1}^{N} \Delta V_i = \sum_{i=1}^{N} \Delta z_i(\Delta S_i + \Delta S_{i+1})/2 \tag{5}$$

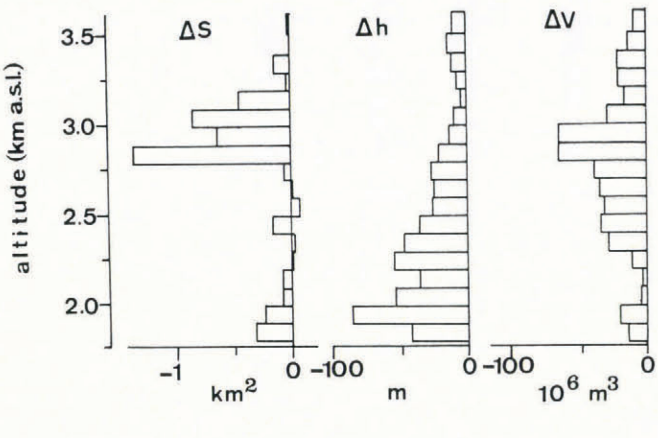

Fig. 5. Changes of ice-covered area and mean thickness of Rhonegletscher between 1882 and 1969. ΔS(1882–1969): change of ice-covered area during 1882–1969; Δh(1882–1969): mean thickness change during 1882–1969; ΔV(1882–1969): volume change during 1882–1969.

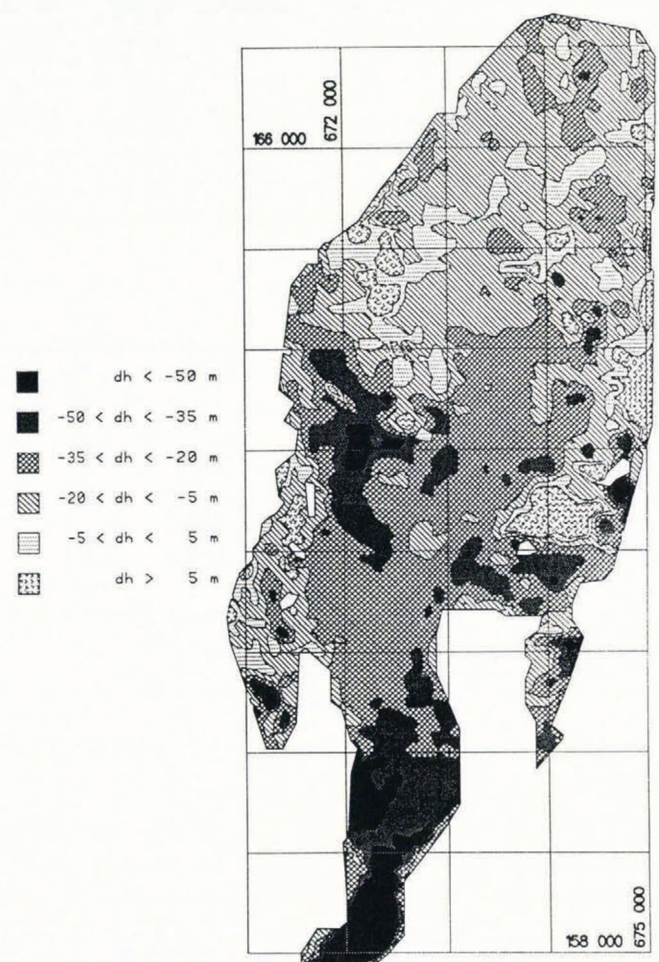

Fig. 6. The coordinates and thickness changes of Rhonegletscher between 1882 and 1969.

where Δz_i is the altitude interval (100 m) and ΔS_i is the area surrounded by the ith contour lines of the glacier surfaces at different times. The values of ΔS_i in Equation (5) are measured per 100 m altitude interval for Rhonegletscher during 1882–1969 (see Fig. 2). The values of $\langle \Delta h \rangle$ for individual altitude intervals of Rhonegletscher during 1882–1969 calculated by Equations (4) and (5) are given in Table III. $\langle \Delta h \rangle$ for the entire glacier is –23 m. This value agrees fairly well with the value of –20 m obtained by method I. In considering the accuracy of the maps, the mean elevation change during 1882–1969 is within 23 ± 5 m.

THE PT MODEL

In order to determine the mass changes of this glacier during 1909/10–1978/79 and for the period after 1982–83, it is necessary to estimate the annual mass balance for this period using the climatic data. The statistical parameterization of the PT models can be written as

$$\langle b \rangle = \beta_0 + \beta_1 \langle P \rangle + \beta_2 \langle T \rangle + \varepsilon \qquad (6)$$

where b, P, and T are the specific net balance, precipiation, and air temperature, respectively, and $\langle\ \rangle$ denotes their spatial mean over the entire glacier. β_0, β_1, and β_2 are the coefficients and ε is the residual. Another form of Equation (4) is

$$\langle b \rangle = \overline{\langle b \rangle} + \beta_1(\langle P \rangle - \overline{\langle P \rangle}) + \beta_2(\langle T \rangle - \overline{\langle T \rangle}) + \varepsilon$$

with the same variables as in Equation (4) (a bar indicating the mean over the time period). β_1 (or $\beta_1 \sigma \langle P \rangle / \beta_0$) represents the contribution of precipitation changes to $\langle b \rangle$ and β_2 (or $\beta_2 \sigma \langle T \rangle / \beta_0$) that of temperature changes to $\langle b \rangle$. $\delta \langle P \rangle$ and $\sigma \langle T \rangle$ are the standard deviations of $\langle P \rangle$ and $\langle T \rangle$, respectively. Ideally, precipitation and temperature series of the glacierized region should be used in Equation (6). However, none exists for a long period. P and T for single stations nearest to the glacier are generally used (Martin, 1978; Vallon and Leiva, 1982; Holmlund, 1987; Letréguilly, unpublished).

The climatic stations Reckingen (lat. 46°28′ N., long. 08°15′ E., 1338 m a.s.l. and 9 km south of Rhonegletscher) and Andermatt (lat. 46°38′ N., long. 08°36′ E., 1442 m a.s.l. and 15 km north-east of this glacier) are selected for analysis due to the more significant correlations of their climatic elements with the $\langle b \rangle$ of Rhonegletscher in comparison with other neighbouring climatic stations. With various combinations of the climatic data for Reckingen and Andermatt (Schuepp, 1961; Uttinger, 1965; Weilenmann, unpublished), three PT models for the period 1884/85–1908/09 and 1979/80–1981/82 are established through multiple-regression analysis (see PT models Nos 1–3 in Table IV). The PT model used for extrapolation purposes in this study is:

$$\langle b \rangle = 5365 + 1.215 \langle P_a \rangle - 587 \langle T_s \rangle \qquad (7a)$$

with $\langle P_a \rangle$ and $\langle T_s \rangle$ being the mean annual precipitation and mean summer temperature for Reckingen and Andermatt. The units of $\langle b \rangle$, $\langle P_a \rangle$, and $\langle T_s \rangle$ are in mm, and °C, respectively. The multiple-correlation coefficient for Equation (7a) is 0.85 and it is significant at the 90% confidence limit. The standard deviation of the residuals of Equation (7a) is 354 mm w.e.

The ranges (the difference between the maximum and the minimum) of $\langle P_a \rangle$ and $\langle T_s \rangle$ for Reckingen and Andermatt are 1029 mm and 3.0 °C. It can be estimated from the regression coefficients of Equation (7a) that the contribution of $\langle T_s \rangle$ to $\langle b \rangle$ is about 1.5 times that of $\langle P_a \rangle$. By the standard deviations σ_P and σ_T of the climatic elements during the measurement period, it can also be seen from PT models Nos 1–3 for Rhonegletscher (Table IV) that the influence of temperature changes on $\langle b \rangle$ is 1.3–1.8 times that of the precipitation changes. Similar studies on some other alpine glaciers suggest that the influence of the temperature on $\langle b \rangle$ is usually of the same significance as or more important than that of the precipitation.

The air temperature is obviously very important in PT models for glaciers in maritime climatic regions such as the Alps. The significance of the air temperature to the mass-balance processes has been recognized for a long time (Ahlmann, 1953). Under wet maritime climatic conditions, the sensible-heat flux and the long-wave radiation play a decisive role in the glacier ablation, and hence mass-balance processes. In the summer season, the net radiation (90 W/m²) and sensible-heat flux (81 W/m²) contribute almost equal amounts of energy to the heat input at the Rhonegletscher surface and nearly all of this heat input is used for melting (Funk, 1985). This is different from the situations of glaciers in dry continental climatic regions such as at Glacier No. 1 in the headwaters of the Urumqi River in Chinese Tian Shan, where 80–90% of the heat input is from net radiation with the remaining part (10–20%) mostly from sensible heat. About 10% of the available heat input is used for evaporation and the remaining 90% for melting (Bai and Xie, 1965).

TABLE IV. REGRESSION MODELS OF THE SPECIFIC NET BALANCE $\langle b \rangle$ (IN mm w.e.), PRECIPITATION P (IN mm), AND AIR TEMPERATURE T (IN °C) OF NEIGHBOURING CLIMATIC STATIONS FOR SOME ALPINE GLACIERS AND THE CORRELATION COEFFICIENTS r, COEFFICIENT $(\beta_2\sigma_T)/(\beta_1\sigma_P)$ SHOWS THE RELATIVE CONTRIBUTION OF TEMPERATURE TO THE NET BALANCE IN COMPARISON WITH PRECIPITATION

Glacier	*Station*	*Regression formula*	r	$(\beta_2\sigma_T)/(\beta_1\sigma_P)$
1. Rhone	Reckingen	$\langle b \rangle = 6320 + 1.094P_a - 601T_s$	0.90	1.8
2. Rhone	Andermatt	$\langle b \rangle = 3650 + 0.929P_a - 454T_s$	0.70	1.3
3. Rhone	Reckingen and Andermatt	$\langle b \rangle = 5365 + 1.215\langle P_a \rangle - 587\langle T_s \rangle$	0.85	1.4
4. Sarenne	St. BErnhard	$\langle b \rangle = -1307 + 1.649P_a - 333T_s$	0.80	0.6
5. Gries	Sion	$\langle b \rangle = 16024 + 1.021P_a - 941T_{ws}$	0.88	5.0
6. Limmern	Andermatt	$\langle b \rangle = 4204 + 1.844P_{wy} - 517T_s$	0.90	1.0
7. Silvretta	Davos	$\langle b \rangle = 1951 + 3.306P_a - 448T_s$	0.86	0.8
8. Hintereis	Vent	$\langle b \rangle = 2568 + 2.337P_a - 503T_{ws}$	0.82	1.5

The sources of mass-balance data of glaciers Nos 4–7 are Kasser (1967, 1973), Müller (1977), Haeberli (1985), and Haeberli and Müller (1988).

The periods for the regression analysis are: 1–3. 184/85–1908/09 and 1979/80–1981/82, 4. 1948/49–1984/85, 5. 1961/62–1984/85, 6. 1947/48–1984/85, 7. 1959/60–1984/85, 8. 1952/53–1984/85.

P_a: annual precipitation (October–September); P_{wy}: the winter half-year precipitation (October–April); T_s: the mean summer temperature (May–September); T_{ws}: the weighted summer temperature $T_{ws} = 1/4(T_{VI} + T_{VII} + T_{VIII} + 0.5(T_V + T_{IX}))$ where the subscripts VI, ... , and IX denote the month.

The mean values of $\langle P_a \rangle$ and $\langle T_s \rangle$ for Reckingen and Andermatt during 1884/85–1908/09 and 1979/80–1981/82 are 1164 mm and 11.7°C. Therefore, Equation (7a) can be written as:

$$\langle b \rangle = -98 + 1.215(\langle P_a \rangle - \overline{\langle P_a \rangle}) - 587(\langle T_s \rangle - \overline{\langle T_s \rangle}) . \quad (7b)$$

The mean $\overline{\langle b \rangle}$ in mm w.e./a (water equivalent per year) is therefore −98 from Equation (7a) and the measured $\langle b \rangle$ during 1884/85–1908/09 and 1979/80–1981/82 is −95 mm w.e./a. The comparison with the result from Equation (7a) is shown in Figure 7. The mean and cumulative values of $\langle b \rangle$ for the period 1884/85–1908/09 are −130 mm w.e./a and −3240 mm w.e. from the measured $\langle b \rangle$, and −128 mm w.e./a and −3197 mm w.e. as estimated by Equation (7a). Therefore, the $\langle b \rangle$ values calculated from Equation (7a) are close to the measured $\langle b \rangle$, although the results from PT models 1–3 in Table IV all agree well with the measured $\langle b \rangle$.

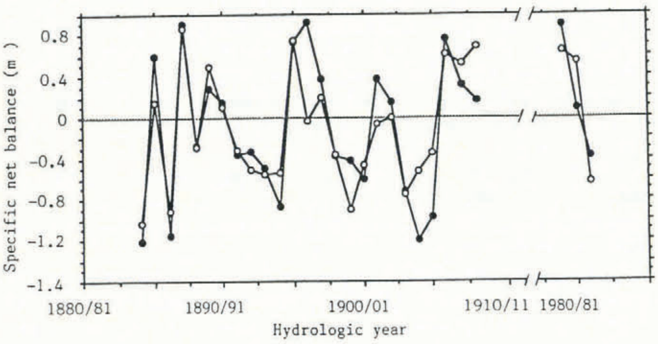

Fig. 7. Comparison of the measured specific net balance of Rhonegletscher (solid circles) with the values calculated by the PT model (open circles).

THE RECONSTRUCTED SPECIFIC NET BALANCE

To reconstruct the mass balance of the glacier by PT models, the statistical relationship established by the measured data is assumed to be valid for the period for which there are no mass-balance measurements (1909/10–1978/79 and 1982/83–1986/87). In fact, such statistical PT models do not remain strictly stable. The regression coefficients β_0, β_1, and β_2 will change with time. Therefore, $\langle b \rangle$ values estimated by using PT models may yield certain errors when long periods are considered.

The data for P_a in the years 1889–90, 1896–97, 1906–07, and 1929/30–1933/34 and T_s in 1929–30, 1931/32–1932/33 at Reckingen are reconstructed on the basis of data from neighbouring stations (Weilenmann, unpublished). The observations at Reckingen ceased after 1981 and the data after that are reconstructed using those from Grimsel, another station near Rhonegletscher. Considering the regional variability of the climatic elements and the comparison with the measured mass balance, Equation (7a) is used for the reconstruction of $\langle b \rangle$ for Rhonegletscher.

The reconstructed specific net balance $\langle b \rangle$ of Rhonegletscher is given in Table V. In spite of some short periods with a positive mass balance, this glacier generally experienced mass loss after 1908–09, especially during the periods from the late 1920s through the early 1960s, with the cumulative net balance being −26 ± 6 m w.e. at the 90% confidence level between 1882–83 and 1986–87 by the PT model (Fig. 8).

Errors introduced by the PT model calculation may be due to: (1) the inaccuracy of $\langle b \rangle$ during 1882/83–1908/09, upon which the PT models are based, and (2) the statistical property of the PT model and the inhomogeneity and the inaccuracy of T_s and P_a. The cumulative specific net balance of Rhonegletscher is estimated statistically to be within 24 ± 6 m w.e. at the 90% confidence level assuming that the $\langle b \rangle$ values for different years are independent from each other and that data for precipitation and temperature are free of error.

The great mass loss of Rhonegletscher since 1882–83 reflects the climatic warming after the end of the Little Ice Age. Some statistical values of the mean $\langle P_a \rangle$ and $\langle T_s \rangle$ for Reckingen and Andermatt, and those of $\langle b \rangle$ for Rhonegletscher in Table VI show a general increase in $\langle P_a \rangle$ and $\langle T_s \rangle$. A comparison of periods I (1882–1920) and II (1921–85) suggests that $\langle P_a \rangle$ increased by 47 mm and $\langle T_s \rangle$ by 0.9°C. This leads to the relatively negative value of the reconstructed $\langle b \rangle$ (−48 cm w.e./a) for period II by the PT model. Small temperature changes obviously influence the mass changes greatly, while the influence of precipitation on the changes of mass balance is smaller.

It shows that Rhonegletscher mostly experienced mass loss since 1882–83. This can also be seen on other glaciers (Table VII) (Martin, 1978; Finsterwalder and Rentsch, 1980; Vallon and Leiva, 1982; Meier, 1985; Reynaud and others, 1986; Holmlund, 1987; Letréguilly, unpublished). The intense and continuous retreat of the Rhonegletscher front also suggests a negative value of the cumulative mass balance.

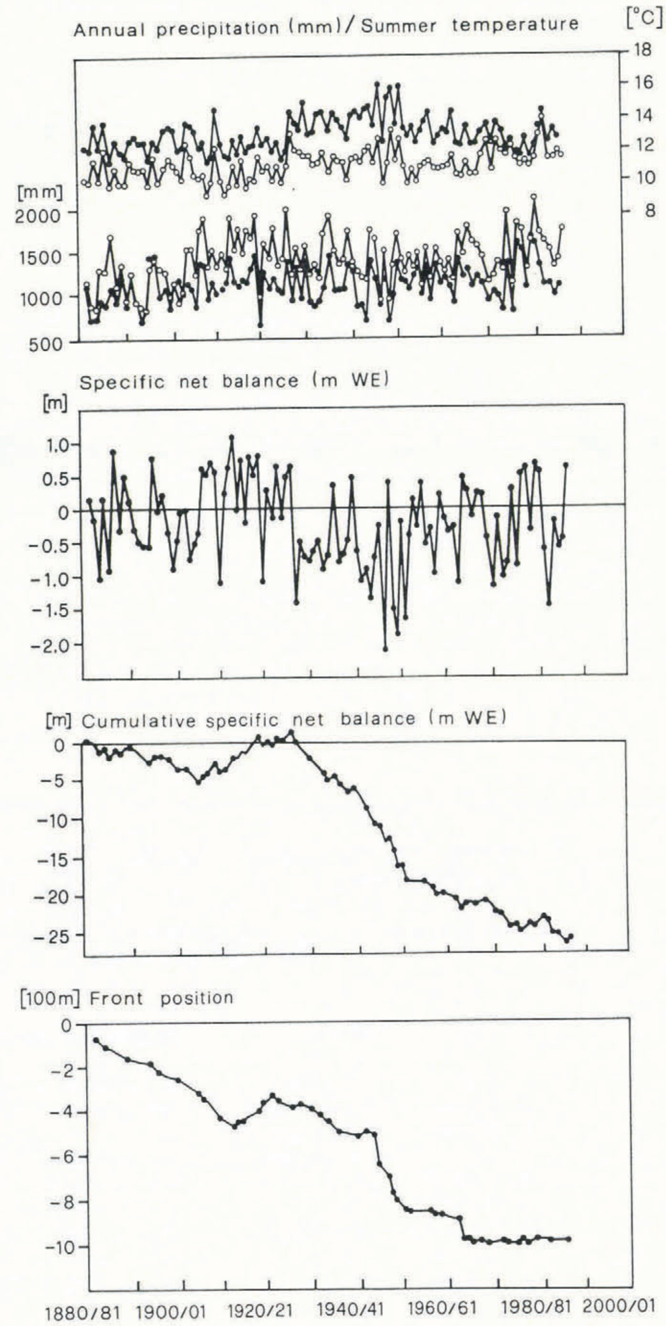

Fig. 8. Summer temperature and annual precipitation for Reckingen and Andermatt, and mass balance and front position of Rhonegletscher during 1882–1986. 1. Summer temperature and annual precipitation for Reckingen (solid circles) and Andermatt (open circles); 2. Calculated specific net balance of Rhonegletscher; 3. Cumulative specific net balance; 4. Changes of the frontal position of Rhonegletscher relative to 1881.

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TABLE V. MEAN ANNUAL PRECIPITATION $\langle P_a \rangle$ (IN mm) AND SUMMER TEMPERATURE $\langle T_s \rangle$ (IN °C) OF RECKINGEN AND ANDERMATT, AND THE CALCULATED SPECIFIC NET BALANCE $\langle b \rangle$ (IN cm w.e.) OF RHONEGLETSCHER

Year	$\langle P_a \rangle$	$\langle T_s \rangle$	$\langle b \rangle$	*Year*	$\langle P_a \rangle$	$\langle T_s \rangle$	$\langle b \rangle$
1882–83	1107	11.2	14	1935–36	1632	11.9	34
1883–84	778	11.0	−17	1936–37	1222	13.1	−81
1884–85	769	12.5	−103	1937–38	1144	12.7	−70
1885–86	1095	11.1	15	1938–39	1187	12.4	−47
1886–87	1065	12.9	−91	1939–40	1482	11.4	45
1887–88	1368	10.5	87	1940–51	1259	12.9	−64
1888–89	999	11.7	−28	1941–42	998	13.0	−108
1889–90	1250	10.9	49	1942–43	977	12.7	−90
1890–91	879	10.8	10	1943–44	883	13.2	−134
1891–92	1124	12.0	−31	1944–45	1503	13.5	−73
1892–93	880	11.9	−52	1945–46	1350	12.4	−27
1893–94	747	11.6	−56	1946–47	842	14.5	−212
1894–95	786	11.7	−54	1947–48	1326	11.2	38
1895–96	1344	10.6	75	1948–49	749	13.2	−150
1896–97	1401	12.1	−3	1949–50	1105	14.6	−189
1897–98	1108	11.1	20	1950–51	1481	12.6	−20
1898–99	1132	12.1	−36	1951–52	1223	14.5	−162
1899–1900	880	12.5	−90	1952–53	1138	12.2	−40
1900–01	1096	12.2	−46	1953–54	1192	11.4	13
1901–02	1014	11.4	−6	1954–55	1208	12.1	−27
1902–03	992	11.2	0	1955–56	1322	11.2	37
1903–04	1296	13.1	−75	1956–57	995	12.1	−52
1904–05	1264	12.6	−52	1957–58	1372	12.5	−30
1905–06	1019	11.9	−35	1958–559	997	12.9	−96
1906–07	1519	11.2	61	1959–60	1358	11.6	18
1907–08	1586	11.5	52	1960–61	1171	11.9	−16
1908–09	1102	10.2	69	1961–62	1150	12.1	−34
1909–10	1290	10.9	57	1962–63	1169	12.0	−28
1910–11	1144	13.4	−111	1963–64	973	13.1	−111
1911–12	1238	11.3	24	1964–65	1487	11.5	46
1912–13	1178	10.5	64	1965–66	1271	11.4	25
1913–14	1626	10.6	109	1966–67	1451	12.4	−12
1914–15	1294	11.9	−1	1967–68	1281	11.5	21
1915–16	1400	10.8	73	1968–69	1300	11.5	20
1916–17	1288	12.2	−20	1969–70	1207	12.4	−44
1917–18	1411	10.8	77	1970–71	954	13.1	−116
1918–19	1448	11.2	53	1971–72	1037	11.6	−15
1919–20	1650	11.2	77	1972–73	1090	13.1	−102
1920–21	768	12.6	−109	1973–74	976	12.6	−81
1921–22	1392	11.6	25	1974–75	1579	11.9	27
1922–23	1212	11.9	−14	1975–76	892	12.4	−86
1923–24	1438	11.0	63	1976–77	1632	11.6	51
1924–25	1158	11.8	−15	1977–78	1552	11.4	59
1925–26	1170	10.8	48	1978–79	1118	12.1	−35
1926–27	1650	11.5	62	1979–80	1569	11.3	64
1927–28	1036	13.7	−141	1980–81	1776	11.9	54
1928–29	1387	12.9	−52	1981–82	1446	13.2	−62
1929–30	1075	12.6	−72	1982–83	1278	14.2	−144
1930–31	1421	13.4	−77	1983–84	1228	12.0	−21
1931–32	1022	12.4	−64	1984–85	1078	12.4	−60
1932–33	1050	12.1	−49	1985–86	1169	12.4	−46
1933–34	1002	12.8	−90	1986–87	1673	11.6	59
1934–35	1329	13.1	−71				

TABLE VI. THE MEAN, RANGE *Ra*, AND STANDARD DEVIATION σ OF THE MEAN ANNUAL PRECIPITATION $\langle P_a \rangle$ (IN mm), AND MEAN SUMMER TEMPERATURE $\langle T_s \rangle$ (IN °C) OF RECKINGEN AND ANDERMATT, AND OF THE SPECIFIC NET BALANCE $\langle b \rangle$ (IN mm w.e.) OF THE RHONEGLETSCHER CALCULATED BY THE PT MODEL

		$\langle P \rangle$			$\langle T_s \rangle$			$\langle b \rangle$		
	Period	*Mean*	*Ra*	σ	*Mean*	*Ra*	σ	*Mean*	*Ra*	σ
I	1882–1920	1162	903	247	11.6	3.2	0.8	−10	2200	613
II	1921–60	1211	901	209	12.5	3.9	0.9	−480	2622	653
III	1961–85	1282	884	247	12.2	3.0	0.7	−230	2003	583

TABLE VII. MEAN MASS OR THICKNESS CHANGES $\overline{\langle b \rangle}$ (OR $\overline{\langle \Delta h \rangle}$) OF SOME GLACIERS (IN cm w.e./a) DURING THE CORRESPONDING PERIOD

	Sarenne*	Rhonegletscher	Hintereisferner†	N. Schneeferner†	S. Schneeferner†	Vernagtferner†	Guslarferner†	Storglaciären‡	WG§
$\overline{\langle b \rangle}$, $\overline{\langle \Delta h \rangle}$	−49	−25	−46	−39	−63	−21	−29	−25	−38
from	1882	1882	1894	1892	1892	1889	1889	1878	1900
to	1975	1986	1979	1979	1979	1979	1979	1986	1961

Data sources: * Martin (1978); † Finsterwalder and Rentsch (1980); ‡ Holmlund (1987); and § Meier (1985). WG specifies about 25 glaciers and small ice caps in 13 regions. ⟨ ⟩ denotes the mean over the entire glacier and a bar the mean over the given period.

The retreat of this glacier since the end of the Little Ice Age has been interrupted only by some short periods of advance (Fig. 8). It retreated by 970 m during 1882–1986, corresponding to a mean rate of −9.4 m/a. During 1882–1969, the ice-covered area decreased by 4.37 km^2 and the volume by 4.71×10^8 m^3. The reconstructed mass-balance history of the glacier agrees with this trend.

SUMMARY

The mass balance of Rhonegletscher for the period 1884/85–1984/85 was examined on the basis of measurements during 1884/85–1908/09 and 1979/80–1981/82, and on estimation by PT models: the regression models of the mean specific net balance over the entire glacier $\langle b \rangle$ and the climatic elements. The reconstructed $\langle b \rangle$ during 1884/85–1968/69 from the PT model was compared with the ice-thickness change of the same period based on the cartographic method. For Rhonegletscher during 1882/83–1968/69, the cumulative $\langle b \rangle$ is -24 ± 6 m w.e. by the PT model, while the mean thickness change is -23 ± 5 m by the cartographic method. The uncertainty ranges of the results from these two methods overlap each other.

Rhonegletscher has experienced relatively great mass loss since the end of the Little Ice Age. The cumulative specific net balance is −3.4 m w.e. during 1884/85–1908/09 according to the stake measurements and -26 ± 6 m w.e. during 1882/83–1986/87 according to the PT models. Some short periods of positive b are found in the late 1880s, the mid-1890s, the late 1900s to the late 1910s, and in the late 1970s. The other periods in between show negative b, especially during the period from the late 1920s through the early 1960s with maximum mass loss in the 1940s.

The influence of summer temperature on the mass balance is of more importance than that of precipitation for Rhonegletscher. This seems to apply also to other alpine glaciers under wet maritime climatic conditions. The temporal change of $\langle b \rangle$ for Rhonegletscher reflects a general trend of warming after the end of the Little Ice Age with the warmest period from the late 1920s to the early 1950s, especially in the 1940s.

The negative mass balance partly explains the continuous retreat of this glacier since the end of the Little Ice Age. Rhonegletscher retreated 970 m during 1882–1986, which is 9% of its length. For the period 1882–1969, this glacier decreased by 19% of the ice-covered area, by 20% of its thickness, and by 27% of its volume.

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