VARIATIONS IN THE MASS-BALANCE OF HINTEREISFERNER (OETZTAL ALPS), 1952-1961, AND THEIR RELATION TO VARIATIONS OF CLIMATIC ELEMENTS

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ABSTRACT

A short description is given of the mass balance studies carried out on the Hintereisferner (Oetztal Alps) between 1952 and 1961. An attempt is made to relate the variations in mass-balance to variations in climatic conditions, based on meteorological observations on or near the glacier on a total of 673 days. From these observations, reduction factors were deduced, which made it possible to give climatological data for the Hintereisferner deduced from the continuous observations of the climatological station at Vent. The relations between mass balance and climatic conditions are discussed in detail for the period under consideration. The result shows clearly that no single climatic element is responsible for the changing mass-balance of glaciers, but a rather complex combination of climatic variables. Although radiation is the main source of energy for ablation, a time factor has to be considered : the effective duration of the main ablation period. This typifies the weather, and is closely related to the total net ablation.

ZUSAMMENFASSUNG

Eine kurze Beschreibung der Untersuchungen des Massenhaushalts am Hintereisferner (Oetztaler Alpen) in den Jahren 1952-61 wird gegeben. Es wird der Versuch unternommen, die Veränderungen im Massenhaushalt mit den Veränderungen der klimatischen Elemente in Beziehung zu setzen. Mit Hilfe meteorologischer Beobachtungen, gewonnen am Gletscher selbst oder in seiner unmittelbaren Nähe an insgesamt 673 Tagen, werden Reduktionsfaktoren abgeleitet. Diese gestatten es, ausgehend von den Beobachtungen der Klimastation Vent, die klimatischen Verhältnisse für den Hintereisferner abzuleiten. Die Beziehungen zwischen Massenhaushalt und den klimatischen Verhältnissen werden für die Untersuchungsperiode sodann in Einzelheiten diskutiert. Die Ergebnisse zeigen deutlich, daß kein einzelnes klimatisches Element für die Veränderungen der Massenbilanz des Gletschers verantwortlich gemacht werden kann, sondern eine komplexe Kombination klimatischer Elemente. Obwohl die Strahlung die wichtigste Energiequelle für die Ablation darstellt, muß ein Zeitfaktor berücksichtigt werden. Diese effektive Dauer der Hauptablationsperiode ist typisch für den Witterungscharakter; sie steht in engem Zusammenhang mit der Nettoablation.

RÉSUMÉ

On donne une courte description des études du bilan des masses exécutées sur le Hintereisferner (Oetztal Alps) entre 1952 et 1961. Un essai est fait pour établir une relation entre le bilan des masses aux variations des conditions climatiques basées sur des observations météorologiques sur ou près du glacier sur une période totale de 673 jours. De ces observations, des facteurs de réduction ont été déduits qui rendent possible de présenter des données climatologiques pour le Hintereisferner déduites des observations continues de la station climatologique de Vent. Les relations entre le bilan des masses et les conditions climatiques sont discutées en détail pour la période considérée. Le résultat montre que le bilan des masses des glaciers n'est pas le fait d'un élément isolé, mais bien d'une combinaison assez complexe de variables climatiques. Bien que la radiation soit la source principale d'énergie pour l'ablation, un facteur durée doit être pris en considération : la durée effective de la période de l'ablation principale. Celle-ci caractérise les conditions du temps et est en relation serrée avec l'ablation totale nette.

Introduction

There is no doubt that variations in the size of glaciers are caused primarily by variations of climatic conditions. Although the problem seems to be simple, there is no generally agreed solution to it. This is in most cases due to the lack of adequate data. The mass-balance of a glacier is related to the amount of solid precipitation during the budget year, and to the heat balance during the ablation period. But variations in the position of the snout of a glacier are not clearly related to the mass-balance of that glacier, nor is it easy to deduce the precipitation conditions and the heat balance on glaciers from climatological observations of more or less distant stations. Among the best known glaciers of the Eastern Alps are the big glaciers near Vent (1900 m) in the Oetztal Alps, which have been under continuous observation for more than 70 years, viz. Vernagtferner since 1889, Hochjochferner and Hintereisferner since 1893, and Kesselwandferner. These glaciers, therefore, were chosen for a research programme in glacial meteorology, the outlines of which were given by Hoinkes (1959). Measurements of precipitation with totalizators began anew in 1948 (Hoinkes 1954; Hoinkes and Lang, in press A), investigations of the heat balance of glacier surfaces were taken up in 1950 (Hoinkes and Untersteiner, 1952), and those of the mass-balance of Hintereisferner in 1952 (Schimpp, 1959). All studies continue to the present day; in 1955, and again during the I.G.Y. and the I.G.C. they were carried out on an enlarged scale (Hoinkes and Lang, in press A, in press B).

Mass-balance

Net ablation of ice was measured with stakes, 54 of which were placed in 11 profiles across the surface of Hintereisferner in the autumn of 1952 by Schimpp (1959). An additional 40 stakes were placed by Rudolph (1961, in press) in the spring of 1954. Most of them were kept under observation until 1957, when the number of stakes was raised to a total of 117, 35 of which were set up on the Kesselwandferner. Since the autumn of 1959 only a reduced number of about 50 stakes was observed to the present date. Net accumulation of old snow as well as net ablation of firn snow (the term old snow is proposed for snow from the current budget year, in order to distinguish it from snow which has survived at least one budget year) was studied in pits, and by mapping of enduring accumulation patterns. In addition to the measurements of precipitation, run-off was measured in 1954 by Rudolph (1961), and again at the same spot between 1957 and 1959 by Lang (in press), when a recording stream-gauge was operating at 2287 m.a.s.l., only 1,65 km from the snout of Hintereisferner. For these three budget years the mass balance equation could be applied :

$$N - A - V = R - B$$

(N = total precipitation, A = run-off, V = total evaporation, R = total net accumulation, B = total net ablation). The drainage area of the stream gauge is marked in figure 1, comprising 26,62 km^2, 58 per cent of which were glacierized in 1959, viz. Hintereisferner 9.97 km^2, Kesselwandferner 4.06 km^2, slope glaciers 1.42 km^2 (according to photogrammetric surveys, carried out in 1953 and in 1958/59 by the Institut für Photogrammetrie, Topographie und allgemeine Kartographie, Technische Hochschule München, which were placed at our disposal by courtesy of Prof. Dr. R. Finsterwalder). The average height of the drainage area is 2981 m, the highest point is the Weisskugel (3739 m). The determination of the mass balance of the glaciers within the drainage area for the hydrological years 1957/58 and 1958/59 was dealt with in detail by Hoinkes and Lang (in press B).

In a recent paper by Hoinkes and Rudolph (in press) the mass balance of Hintereisferner was analyzed for the whole period 1952/53 to 1960/61. Table 1 gives a sum-

TABLE I

Mass-balance of the Hintereisferner, Oetztal Alps, 1952-61.
(millions of cubic metres of water)

Budget year	Total net accumulation of old snow		Total net ablation of firn and ice		Mass-balance		Average height of old snow line
	km^2	10^6 m^3	km^2	10^6 m^3	km^2	10^6 m^3	m
1952/53	5.44	+1.66	4.80	− 7.19	10.24	−5.53*	3000
53/54	7.04	+3.03	3.16	− 5.95	10.20	−2.92*	2910
54/55	7.57	+5.20	2.58	− 4.43	10.15	+0.77	2830
55/56	7.01	+3.19	3.10	− 5.97	10.11	−2.78	2900
56/57	6.51	+3.74	3.55	− 5.64	10.06	−1.90	2920
57/58	3.49	+1.49	6.53	−11.32	10.02	−9.83	3120
58/59	3.42	+1.26	6.55	− 8.87	9.97	−7.61	3120
59/60	7.15	+4.32	2.77	− 4.94	9.92	−0.62	2850
60/61	6.27	+4.11	3.61	− 6.14	9.88	−2.03	2900
Average 1952-61	5.99	+3.11	4.07	− 6.71	10.06	−3.60	2950
Max. error		±0.31		± 0.23		±0.54	

* The mass-balance figures as given by Schimpp (1959), viz. -8.84×10^6 m^3 for the budget year 1952/53 and -4.96×10^6 m^3 for the budget year 1953/54 are too high by about 60 to 70 per cent. The error was caused by extrapolating results of observations on a surface of about 6 km^2 to the whole surface of the glacier without taking into account the differences in the distribution of area versus height between surfaces with and without measurements. Because height zones above 2800 m are of much greater weight, the estimates of total net accumulation agree fairly well (in 10^6 m^3 of water : +1.36 versus +1,66. and +3.53 versus +3.03), whereas total net ablation was overestimated (in 10^6 m^3 of water : −10.20 versus −7.19, and −8.49 versus −5.95).

mary of the results. The average annual mass loss, viz. 3.60×10^6 m^3 of water, is strongly influenced by the two unfavourable budget years 1957 to 1959, during which 54 per cent of the total mass loss (32.45×10^6 m^3) occurred. The average annual mass loss for the three budget years 1952/53 and 1957/59 amounts to 7.66×10^6 m^3, whereas in the six remaining budget years 1953-57 and 1959-61 it is only 1.58×10^6 m^3. There is a large variation between the best budget year 1954/55 with a net mass gain of 0.77×10^6 m^3, and the worst 1957/58 with a net mass loss of 9.83×10^6 m^3. The corresponding variation in the average height of the old snow line (the term "old snow line" was proposed instead of the term "firn line" by Hoinkes and Rudolph (in press)) was nearly 300 metres, viz. between 2830 m and 3120 m. The ratio, area of nourishment to area of wastage was 2.94 in the budget year 1954/55, and 0.53 in the budget year 1957/58.

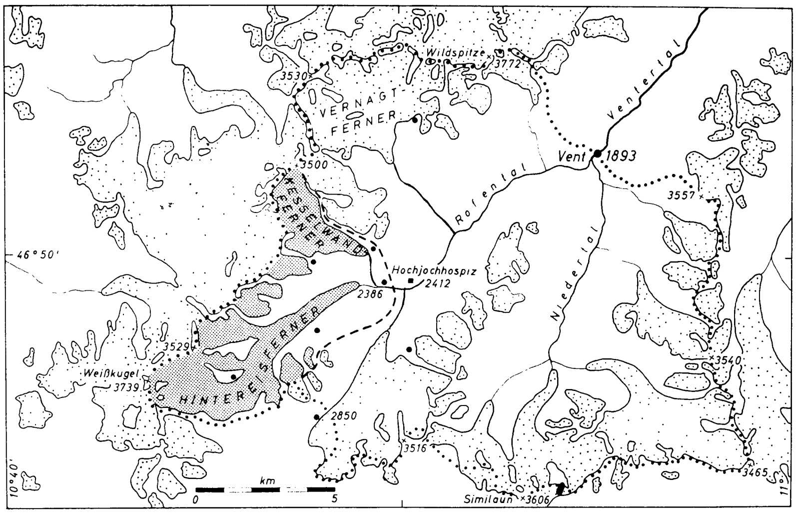

Fig. 1 — Map of the central part of the Oetztal Alps, showing the drainage areas of Vent (164.6 km^2) and of Hochjochhospiz (26.6 km^2). Glaciers are stippled, positions of precipitation gauges are marked by dots.

Climatic conditions

An attempt to relate the variations in the mass-balance of Hintereisferner to variations in climatic conditions can be based on the observations of the climatological station at Vent, 1900 m, only about 10 km downvalley from the snout of Hintereisferner (see fig. 1), which has been in continuous operation since 1934. In the immediate vicinity of the glaciers precipitation was measured with 4 to 6 totalizators, the first of which was set up in 1926 (Hoinkes, 1954). In order to check and support the precipitation measurements, systematic studies of the water content of winter snow cover on glaciers have been performed since 1954 (Hoinkes and Lang, in press A). On or near the glaciers meteorological observations were carried out between 1952 and 1959 in different periods, covering a total of 673 days, (Table II). All these observations were related to the simultaneous observations at Vent, and reduction factors deduced, which made it possible to find climatological data for the Hintereisferner, covering the period 1952 to 1961.

Experiences gained within the last 15 years showed that ablation on the Hintereisferner, which terminates at 2400 m a.s.l., rarely begins before mid May or continues

TABLE II

Periods with meteorological observations on or near the glaciers between 1952 and 1959
(T = temperature, R = radiation, C = other climatic elements, HB = heat balance, D = discharge)

Year	Period	No. of days	Site	Height	*T*	*R*	*C*	*HB*	*D*
1952	20 July-4 Aug.	16	Vernagtferner	2970	×	×	×	×	
1953	23 May-7 June	16	Hochjochhospiz	2360	×		×		×
	14-17 July	4	"	"	×		×		×
	23-29 Aug.	7	"	"	×		×		×
	8-17 Sept.	10	Gepatschferner	2350	×	×	×	×	
	13-16 Oct.	4	Hochjochhospiz	2360	×		×		×
	29-31 Oct.	3	"	"	×		×		×
1954	28 May-13 June	17	Hochjochhospiz	2410	×	×	×		×
	25 June-3 July	9	Hintereisferner	2430	×	×	×		×
	15 July-20 July	6	"	"	×	×	×		×
	21 July-8 Oct.	80	"	2750	×	×	×		×
	17 Oct.-20 Oct.	4	"	"	×	×	×		×
	23 Nov.-29 Nov.	7	Hochjochhospiz	2410	×				×
1955	25 July-8 Aug.	15	Hintereisferner	2950	×	×	×	×	
	27 July-7 Aug.	12	"	2570	×	×	×	×	
	23 July-9 Aug.	18	"	2370	×	×	×	×	×
1956	22 July-30 Aug.	40	Hintereisferner	2500		×			
	21-29 Aug.	9	Kesselwandferner	3240	×	×			
1958	25 Jan.-19 Oct.	268	Hochjochhospiz	2410	×	×	×		×
	9 Aug.-8 Sept.	31	Kesselwandferner	3240	×	×	×	×	
1959	1-5 March	5	Hochjochhospiz	2410	×		×		×
	1-4 April	4	"	"	×		×		×
	28-31 May	4	"	"	×		×		×
	28-29 June	2	"	"	×		×		×
	14 July-4 Oct.	82	"	"	×	×	×		×
		673							

TABLE III

Average total short-wave radiation of sun and sky, ly/day, Hochjochhospiz, 2410 m, and average air temperature, °C, terminus of Hintereisferner, 2400 m a.s.l.

Year	16-31 May		June		July		Aug.		1-15 Sept.		Average 16 May-15 Sept.		Approx. Duration of ablation period
	R ly/day	*T* °C	*R* ly/day	*T* °C	*R* ly/day	*T* °C	*R* ly/day	*T* °C	*R* ly/day	*T* °C	*R* ly/day	*T* °C	days
1953	582	5.5	464	4.1	481	7.3	449	6.2	440	5.9	477	5.8	120
1954	453	1.0	493	5.1	452	4.1	389	5.2	376	6.7	437	4.5	110
1955	547	−0.4	508	5.0	439	6.2	399	4.9	299	4.5	443	4.5	85
1956	570	3.9	456	2.1	501	6.5	440	6.0	368	6.3	467	4.9	105
1957	396	−0.5	531	5.7	452	5.8	446	4.9	339	3.1	449	4.4	100
1958	570	4.4	544	4.0	491	6.9	438	6.7	412	6.4	491	5.8	140
1959	511	2.8	457	4.6	497	8.0	400	5.4	419	3.8	455	5.3	135
1960	577	3.6	559	5.9	477	5.0	409	5.9	349	2.8	477	5.0	95
1961	488	0.0	580	6.5	508	5.9	499	5.7	367	5.2	503	5.1	105
Average 1953-61	522	2.3	510	4.8	478	6.2	430	5.7	374	5.0	467	5.0	111

after mid September. Therefore, the data were calculated for the summer or ablation season 16 May to 15 Sept., and for the winter or accumulation season 16 Sept. to 15 May. In the present paper all climatological data are given for a height of about 2400 m, corresponding to the Hochjochhospiz, which is situated quite close to the termini of Hintereisferner, Hochjochferner and Kesselwandferner (see Fig. 1), and served as our headquarters during field work. Reduction of the data to other levels is possible, and will be given in another report.

Air temperature was reduced with an average lapse rate of $-0.65\,^{o}C/100$ m for the period May to August, and with $-0.60\,^{o}C/100$ m for September. The temperature data given in Table III match the conditions on the terminus of Hintereisferner, whereas the nearby Hochjochhospiz at the same level but on a steep slope has slightly higher average temperatures, owing to the lack of inversions at night. As shown in various investigations of the heat balance of glacier surfaces in the Alps (Hoinkes, 1955) heat supply by radiative flux is far more important than the fluxes of sensible and latent heat from the air to the ice by turbulent mixing.

Total short-wave radiation of sun and sky was recorded on 328 days between May and September at the Hochjochhospiz or on the terminus of Hintereisferner (see Table II), using a Robitzsch bimetallic actinograph, which was calibrated in Innsbruck as well as in the field. A relation was established between recorded daily sums of total short-wave radiation at or near Hochjochhospiz, and relative duration of bright sunshine as recorded in Vent on the respective days. This was done for each month in steps of 20 per cent, overcast days without bright sunshine were treated as a separate group (singular point). The result is given graphically in figure 2; the differences between the relations for May and June were too small to show up clearly. Using a formula, derived by Hinzpeter (1958), the average daily total short-wave radiation at the Hochjochhospiz $\bar{R}$ was computed for each month of the ablation seasons 1952-61 from the average relative duration of bright sunshine $\bar{s}/s_0$ in Vent.

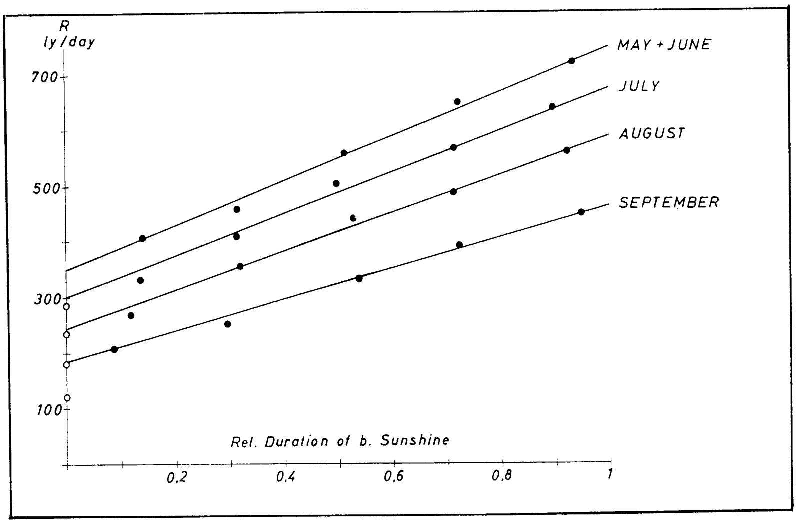

Fig. 2 — Relation between total short-wave radiation at the Hochjochhospiz (2410 m), R in ly/day, and the relative duration of bright sunshine at Vent (1900 m), May to September, 328 days.

$\bar{s}$ means average hours of bright sunshine as recorded with the sunshine recorder whereas $\bar{s}_0$ means the maximum possible duration of sunshine on cloudless days, i.e. hours between local sunrise and sunset as measured with Schmidt's (1933) "Tagbogenmesser". If R_1 denotes the daily total short-wave radiation on cloudless days ($s/s_0 = 1$), and R_0 the same on overcast days ($s/s_0 = 0$), and R_0' the value obtained by linear extrapolation of the linear relation ($s/s_0 \to 0$), and if the constant $\alpha = R_0/R_1$ (Ångström's definition), and if $\alpha' = R'_0/R_1$ (Prohaska's definition), n being the number of overcast days, and N the number of days of the representative period (month), then :

$$\bar{R} = R_1 \left[\alpha' + (1 - \alpha') \frac{\bar{s}}{s_0} - \frac{n}{N} (\alpha' - \alpha) \right].$$

For the computation of the average daily total short-wave radiation, as shown in Table III, the following constants taken from figure 2 were used :

	May and June	July	August	1-15 Sept.	
R_1	750	675	590	495	ly/day
R_0'	350	300	245	200	ly/day
R_0	285	235	180	135	ly/day
α	0.380	0.348	0.305	0.273	
α'	0.467	0.444	0.415	0.404	
	78	105	74	71	number of days

The only ablation season with continuously recorded total short-wave radiation at the Hochjochhospiz, i.e. 16 May to 15 September 1958, had a recorded average of 487 ly/day, whereas the computed average was 491 ly/day (table III). Thus, recorded and computed values of total short-wave radiation agree within one per cent; for shorter periods (months or half months) larger deviations are possible, but hardly exceeding five per cent. As long as the surface is melting snow or ice, having a constant outgoing long-wave radiation, and as long as albedo remains more or less constant a certain relation holds between total short-wave radiation and radiation balance. This was shown by Hoinkes and Untersteiner (1952), and by Hoinkes (1953). Therefore, the average total short-wave radiation as given in table III can be expected to be approximately proportional to the radiation balance, and serve the purpose of bringing out true relative differences between single ablation seasons.

Precipitation is given in table IV for the totalizator near the Hochjochhospiz (2360 m), which has been operating since 1934, and which was read an average of ten times a year. Although we do know that, during the accumulation season, owing to the shifting of snow by the wind, much more snow accumulates on the glaciers than in the precipitation gauges (Hoinkes and Lang, in press A), the figures for the period 16 Sept. to 15 May are at least proportional to the true accumulation. Precipitation during the ablation season 16 May to 15 September is partly in the solid form as well. This is important not so much because of mass accumulation, but because of the increase in albedo. From direct observations it was found that a day with more than 3.0 mm precipitation at Vent, and a temperature below 3 °C at the Hochjochhospiz would have at least 5 cm of fresh snow on glaciers down to a height of at least 2800 metres. According to the distribution of surface versus height (see figure 5 in Hoinkes and Lang, in press A) the more important parts of the glaciers within the drainage area are situated above that height. The number of days with more than 5 cm of fresh snow during each ablation season is given in table IV, together with the number of days with at least 0.1 mm of precipitation in Vent. The latter number, together with the amount of precipitation for that ablation season, characterizes to a certain degree the course of the weather. For the same reason the number of cloudy days ($C > 8$),

TABLE IV

Precipitation (mm) and number of days with precipitation > 0.1 mm, fresh snow on glaciers, and cloudiness $> 8/10$

Budget year	1952/53	53/54	54/55	55/56	56/57	57/58	58/59	59/60	60/61	Average
Precipitation, mm Hochjochhospiz, 2360 m winter : 16 Sept.-15 May summer : 16 May-15 Sept.	381 466	401 544	552 291	333 560	390 538	405 426	494 286	431 512	632 285	447 434
No. of days with precip. $\geqslant$ 0.1 mm, Vent, 1900 m, 16 May-15 Sept.	64	77	83	73	84	68	61	72	62	72
No. of days with more than 5 cm of fresh snow on glacier at least down to 2800 m 16 May-15 Sept.	13	25	17	21	26	14	11	20	15	18
No. of periods with at least 5 consecutive days of more than 50 per cent of possible sunshine, 16 May-15 Sept.	5	1	0	6	2	6	5	4	3	3.5
No. of cloudy days ($C > 8$) Vent, 16 May-15 Sept.	38	44	46	40	44	29	35	35	27	38
Ratio, cloudy/clear days	1.65	4.40	5.75	3.34	3.66	1.93	3.18	3.50	1.50	2.84

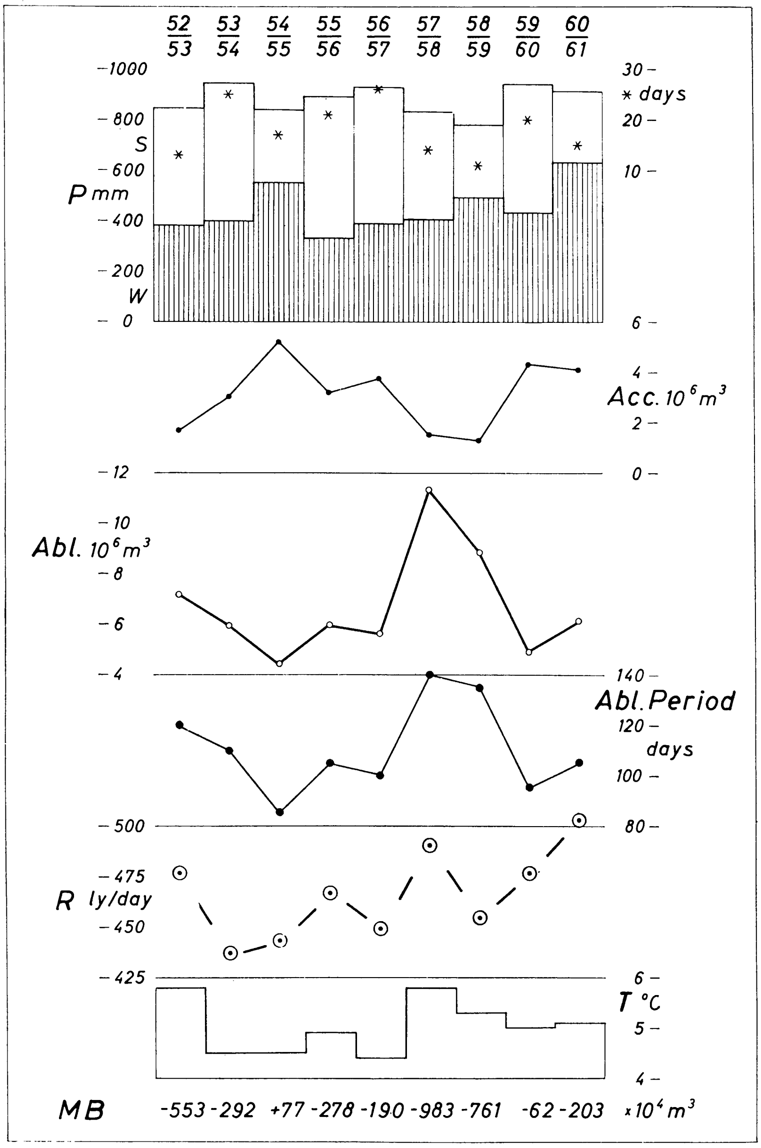

Fig. 3 — Net accumulation and net ablation on Hintereisferner in 10^6 m^3 of water, budget years 1952/53 to 1960/61, and climatic variables : P = Precipitation for winter (16 Sept. to 15 May) and summer (16 May to 15 Sept.), as measured by the totalizator at Hochjochhospiz (2360 m);
* = Number of days with at least 5 cm of fresh snow in summer;
Effective Duration of main Ablation Period;
R = average total short-wave radiation at Hochjochhospiz (2410 m) during summer;
T = average air temperature at the terminus of Hintereisferner (2400 m) during summer;
MB = Mass-Balance of Hintereisferner in 10^4 m^3 of water.

and the relation cloudy/clear days is included, as well as the number of periods with at least five consecutive days having more than 50 per cent of possible sunshine at Vent.

Relations between mass-balance and climate

Figure 3 gives a graphical representation of climatic variables governing accumulation and ablation, in order to facilitate interpretation of tables I, III and IV. In the budget year 1952/53 winter snow was below average, and so were days with fresh snow in summer. High radiation and high temperature on a large area with low albedo caused heavy ablation, and only little net accumulation was left for the budget year 1953-54, which again had winter snow below average. Because temperature and radiation were much below average and at the same time cloudy days and days with rain and fresh snow were above normal, more net accumulation was left and the resulting mass loss was smaller. In the budget year 1954/55 winter snow was above average, whereas radiation and temperature remained below average. In spite of low summer precipitation the number of days with precipitation was very high, the number of cloudy days was the highest observed during the nine ablation seasons, and there was no single period of at least five days of sunny weather. At the end of the 1955 ablation season the old snow line was found in its lowest position (2830 m average), and therefore the area with bare ice and low albedo was of minimum size. Accordingly, net ablation was exceeded by net accumulation and the mass-balance became slightly positive. In the budget year 1955/56 very little winter snow and even higher radiation would have caused a heavy mass loss, had there not been a high net accumulation left from the year before. Therefore, the average albedo for the whole glacier remained high, which was also due to frequent falls of fresh snow. The old snow line receded, only about 70 metres in height, the mass-balance became negative again, but not as much as one would have expected from the available radiation.

In the budget year 1956/57 radiation was low, and temperature lowest, and the highest number of days with fresh snow helped to preserve the smallest winter snow cover since 1954/55 (see fig. 4 in Hoinkes and Lang, in press A). The mass-balance was less negative than in the year before. In the summer of 1958 high radiation and high temperature led to a rapid removal of winter snow, and firn layers of at least five years became exposed to ablation (see figs. 2 and 3 in Hoinkes and Lang, in press B). There was only slight protection from falls of fresh snow or cloudy days. At the end of the budget year, with the heaviest mass loss in the period under consideration, the old snow line was found at an average height of 3120 metres. The summer of 1959 had much less radiation and a lower average temperature. Nevertheless the mass loss was again heavy, although there was more snowfall in winter. Because of the very low number of fresh snowfalls in summer the available energy was able to remove the winter snow cover, and then a large area with low albedo was again exposed to ablation (see fig. 7 in Hoinkes and Rudolph, in press). This demonstrates clearly the influence of the previous year upon the mass-balance. Had not such a large area with bare ice and old firn, i.e. with low albedo, been exposed in the summer of 1958, the energy supplied in the summer of 1959 could not have caused such a strong mass loss.

The mass-balance in the budget year 1959/60 is only slightly negative, which at first seems surprising because of the high amount of radiation. But there was more winter snow on the higher parts of Hintereisferner than in the year before (see fig. 4 in Hoinkes and Lang, in press A). A comparably high number of fresh snowfalls not only preserved winter snow, but terminated ablation practically at the end of August. Thus, the duration of the ablation period was only 95 days, forty days shorter than in the year before, and a high net accumulation remained at the end of the budget year. The summer of 1961 had the highest amount of radiation, but as the winter 1960/61 had the heaviest snow cover on record, net accumulation remained high, and the mass-balance was only moderately negative.

Comparing the budget years 1952/53 and 1957/58 one has about the same amount of winter snow, the same temperature during the ablation season, the same number of days with fresh snow, but higher radiation in the summer of 1958, which, together with a longer ablation period, was decisive for the mass-balance. The same radiation as in the summer 1953 is found in 1960, but the mass-balance in the budget year 1959/60 is only slightly negative, because of lower temperature, more winter snow, more days with fresh snow in summer, and a shorter ablation period. A comparison of the budget years 1953/54 and 1954/55 shows the same low average temperature, about the same low radiation, nearly the same number of cloudy days, and yet the mass-balance is negative in the first and positive in the second budget year. In this example the decisive factor is the heavy snow cover in the winter of 1954/55, and again the shorter ablation period. In the budget year 1955/56 the mass-balance is about the same as in 1953/54, despite higher radiation and temperature in the summer of 1956, which fact can only be understood by considering the previous year.

Conclusions

Obviously there is no single climatic element responsible for the changing mass-balance of glaciers, but rather a combination of climatic elements, which is signified by the German word "Witterungscharakter" (character of weather conditions). Different combinations of climatic variables may lead to the same mass-balance. This result is not a very satisfactory one, even though it does not contradict the findings of the heat balance studies, viz. radiation as the main energy source for ablation (Hoinkes 1955). The application of these findings is not possible without considering a time factor.i.e. the effective duration of the main ablation period. This was estimated from the daily climatological data of Vent and from the direct observations on the glacier, which was visited much more frequently than shown in table II. The shortest effective ablation period of only 85 days was observed in the summer of 1955, when owing to repeated snowfalls the glacier remained under a blanket of fresh snow of high albedo until mid June, and became snowed in as early as Sept. 10. The longest effective ablation period of 140 days was observed in the summer of 1958, when strong ablation started as early as May 7 and lasted until Sept. 23. Apparently, the effective duration of the ablation period is a good description of the "Witterungscharakter"; it is closely related to the total net ablation, as can be seen from figure 3.

Finally it must be pointed out that the mass-balance figures for the Hintereisferner, as given in the present report, are not readily applicable to other glacierized areas. As will be shown in another report, this is not even possible for the drainage area of Vent (164.6 km^2, about 43 per cent glacierized, see fig. 1), of which the drainage area of the Hintereisferner is only a small part.

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