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Hydrometeorological implications of the mass balance of Hintereisferner, 1952-53 to 1968-69

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Abstract. The mass balance of Hintereisferner correlates significantly with cumulative positive degree days reduced from the climatological station Vent (1900 m) to the elevation of the glacier. Correlation is greatly improved by considering the heat necessary to melt winter snow, and more importantly, fresh snow deposited on the glacier during the ablation period. Calculations were done for intervals of 5 days to show differences in the duration of the ablation period for different elevations on the glacier.

Résumé. Le bilan de masse de l'Hintereisferner est corrélé de façon significative avec la somme des moyennes journalières positives calculées pour l'altitude du glacier sur la base des données de la station climatologique de Vent (1900 m). La corrélation est nettement meilleure si l'on considère la chaleur nécessaire pour faire fondre la neige d'hiver et – ce qui est encore plus important – la neige fraîche déposée sur le glacier pendant la période d'ablation. Les calculs ont été effectués pour des périodes de cinq jours afin de mettre en évidence des différences dans la durée de la période d'ablation pour les différentes altitudes du glacier.

On the Hintereisferner (Ötztal Alps, Tyrol) mass balance has been determined by the glaciological method since the budget year 1952/53. During the 17 years of observation until 1968/69 the mass balance was positive three times, three times in equilibrium, and negative eleven times. Annual mean specific mass balance for the whole period was –0.268 m of water with an average equilibrium line altitude of 2960 m above sea level (Hoinkes, 1970). The combined balances project (UNESCO, 1970) is too demanding, in terms of the data currently available, and in these circumstances it is worthwhile to try a simpler approach to the old problem of relating variations of glaciers and climate.

In an earlier contribution to simple glacio-meteorology (Hoinkes *et al.*, 1968) it was shown that daily observations of air temperature at Vent (1900 m) and of precipitation falling as snow on the glacier could be used to assess net ablation on Hintereisferner. Taking as average a lapse rate of –0.6° C/100 m, melting conditions at the terminus of Hintereisferner (2400 m) commence when daily mean temperatures in Vent exceed 3° C; they prevail over the whole drainage basin with temperatures in excess of 10° C. Air temperature was reduced from Vent to the terminus of Hintereisferner by subtracting 3° C, and cumulative positive degree days were calculated for the potential ablation period May to September. Precipitation falling in Vent with air temperatures below 3° C was considered as fresh snow on the whole glacier. As a threshold for precipitation 3 mm was chosen, corresponding to about 5 mm of water equivalent on the glacier. To melt this amount of fresh snow two positive degree days were considered necessary, which were subtracted for each 3 mm of precipitation. Thus numerically degree days are equivalent to two-thirds of the below 3° C precipitation (in mm) at Vent. In this way a cumulative curve of degree days was obtained which is called the TS curve. In two recent papers it was shown that the TS(3°) sum at Vent could also be used to estimate the mean specific mass balance of Hintereisferner for the budget years following 1962/63. The connexion was clearly better than with the sum of positive degree days without considering the retardation of ice melt by falls of fresh snow (Hoinkes, 1970, 1971).

In this paper an attempt is made to improve the concept, and to apply it to the mass balance data from Hintereisferner for the whole observation period 1952/53 to 1968/69. Correlation coefficients of mean specific mass balance with the sum of positive degree days reduced to 2400 m elevation is –0.719, see upper plotting in Fig. 1; this improves to –0.764 by considering the heat necessary to melt fresh snow on the glacier as described. Frequently fresh snow occurs only on higher parts of the glacier. This was taken into account by subtracting from TS(3°) a smaller heat equivalent, namely one positive degree day for each 3 mm of precipitation fallen with temperatures at Vent between 3° and 6° C, and one-half positive degree day in the temperature interval from 6° to 9° C. In this way the correlation coefficient was improved to –0.807.

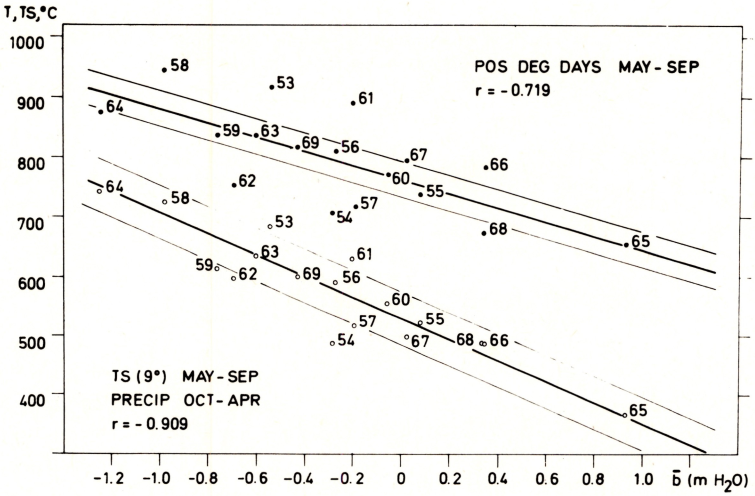

FIGURE 1. Scatter diagram and regression lines: mean specific mass balance of Hintereisferner and cumulative positive degree days May to September (upper plotting), including allowances for heat necessary to melt fresh snow deposited on glacier during ablation period May to September (TS9°) and amount of winter snow (lower plottting). Data in Table 1.

As the next step the amount of winter snow, which governs the onset of net ablation, was allowed for. This was done by adding algebraically to the TS(9°) number two-thirds of the average (250 mm) minus the current precipitation observed at Vent during the accumulation period October to April. This is equivalent to shifting the zero-point of the TS(9°) scale in a positive sense in dry winters, and in a negative sense in snowy winters. The correlation coefficient improved to –0.853. Finally the shorter duration of the ablation period in higher regions of the glacier was taken into account by giving full weight only to the summer months June-July-August, and a reduced weighting of two-thirds of positive degree days in the second half of May and first half of September, and one-third in the first half of May and second half of September. In this way the correlation coefficient was improved to –0.909. All correlation coefficients are above the significance level of 1%. In Fig. 1 the improvement is shown by the steeper slope of the lower regression line and by the reduced scatter.

In the first two budget years 1952/53 and 1953/54 accumulation was not measured as accurately, and in 1960/61 several ablation stakes were lost. In April 1962 a heavy dust deposit on glaciers caused increased net ablation. Omitting the years with inadequate data (53, 54, 61) the remaining 14 years give a correlation coefficient of

TABLE 1. Hydrometeorological data for Vent, derived degree days for Hintereisferner, and mass balance quantities for Hintereisferner 1 October-30 September

Hydrol. year 1 Oct-30 Sept	Precipitation. Vent (1900 m) mm; Precipitation. Hintereisferner (2960 m): Hydrol. year Oct-Sept V	Hydrol. year Oct-Sept H	Accum. period Oct-Apr V	Accum. period Oct-Apr H	Ablation period May-Sept V	Ablation period May-Sept H	T Vent Ablation period May-Sept	(a) positive deg days 2400 m May-Sept	(b) correction for fresh snow TS(3°)	(c) correction for fresh snow TS(9°)	(d) correction for winter snow	(e) Σ(+T) reduction V, IX	Hintereisferner $\bar{b}$ m	Hintereisferner EL m	Hintereisferner Sc/S
1952/53	675	1307	308	575	367	732	8.4	915	897	849	811	675	−0.540	3020	0.53
1953/54	759	1251	251	392	508	859	7.0	706	570	524	567	488	−0.286	2970	0.69
1954/55	667	1240	334	657	333	583	7.3	738	697	676	620	522	+0.076	2850	0.75
1955/56	667	1454	181	498	486	956	7.7	808	728	673	719	590	−0.275	2920	0.69
1956/57	746	1596	244	604	502	992	7.0	717	632	576	581	520	−0.189	2930	0.65
1957/58	583	1280	234	645	349	635	8.7	945	915	872	884	724	−0.981	3100	0.35
1958/59	593	1290	314	778	279	512	8.0	836	785	759	718	612	−0.763	3060	0.34
1959/60	751	1772	259	799	492	973	7.5	771	712	644	638	555	−0.062	2880	0.72
1960/61	573	1266	309	668	264	598	8.1	891	832	811	772	630	−0.205	2940	0.63
1961/62	527	1354	254	777	273	577	7.0	753	689	672	670	596	−0.696	3080	0.39
1962/63	600	1330	254	578	346	752	8.0	836	786	741	738	634	−0.603	3010	0.53
1963/64	485	990	190	456	295	534	8.3	874	840	808	848	741	−1.244	3180	0.25
1964/65	836	1873	274	598	562	1275	6.7	670	525	458	443	380	+0.925	2770	0.81
1965/66	726	1753	214	725	512	1028	7.4	783	641	582	606	488	+0.344	2850	0.76
1966/67	721	1592	349	851	372	741	7.5	793	685	663	593	498	+0.020	2920	0.69
1967/68	605	1436	197	609	408	827	7.0	673	570	531	568	488	+0.338	2850	0.73
1968/69	554	1359	216	641	338	718	7.7	817	736	713	737	599	−0.431	2960	0.56

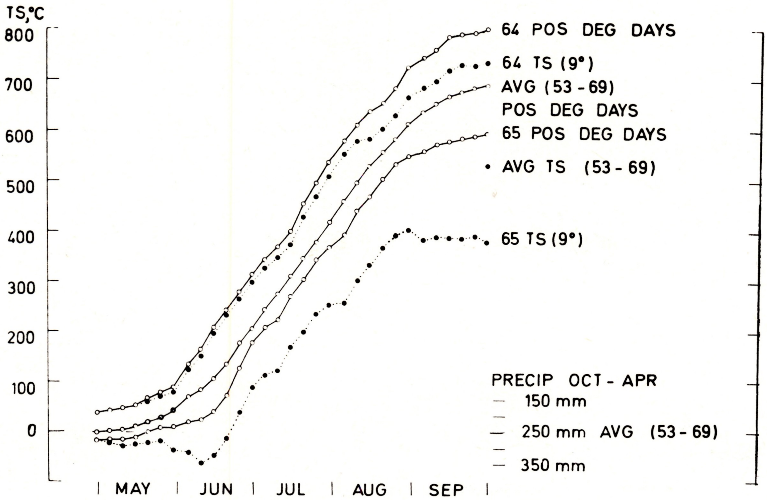

FIGURE 2. Positive degree days and TS(9°) calculated for five-day intervals, ablation periods May to September for 1964 and 1965. Winter snow considered as shift of zero for TS(9°) scale.

−0.965. For the most homogeneous part of the observation series, beginning with the budget year 1962/63, the regression equation of mass balance on TS becomes $\bar{b}$(mm) = 3221 − 6.058 TS. Hydrometeorological and glaciological data are given in Table 1.

The two most different years with respect to mass balance on Hintereisferner were 1963/64 ($\bar{b}$ = − 1.244 m, ELA = 3180 m, AAR = 0.25), and 1964/65 ($\bar{b}$ = + 0.925 m, ELA = 2770 m, AAR = 0.81). For these, calculations of TS(9°) were carried out in steps of five days, the results are shown in Fig. 2. At a first glance the difference in the duration of the ablation period becomes evident: 1 May to 30 September in 1964 versus 10 June to 30 August in 1965. To the difference of 361 TS(9°) days [741 (1964) − 380 (1965)] winter snow has contributed 55 days (15%), summer snow 150 days (42%), whereas the remaining 156 days (43%) were due to differing summer temperatures. The number of days with mean air temperature in Vent above 10°C was 60 in 1964, but only 37 in 1965. Again, summer snowfall proves to be more important for glacier mass budget than winter snowfall, as pointed out by Tronov (1962).

Instead of trying to approximate annual mean specific mass balance for the whole glacier by hydrometeorological data, it seems to be equally rewarding to calculate specific mass balance for different elevations on the glacier, by applying the TS

TABLE 2. Calculation of specific mass balance for important elevations on Hintereisferner, using hydrometeorological observations from Vent (1900 m)

Elevation on glacier (m)	Reduction from Vent to glacier of temperature	Reduction from Vent to glacier of precipitation	Calculated TS(°C) and b(m) for period 1 May to 30 Sept 1963/64 TS	1963/64 b	1964/65 TS	1964/65 b
2400	$T_V - 3°C$	$P_V(T_V \leq 3°C) \cdot 1.50$	776	−6.98	406	−3.65
2733	$T_V - 5°C$	$P_V(T_V \leq 5°C) \cdot 2.17$	372	−3.35	− 28	+0.07
2900	$T_V - 6°C$	$P_V(T_V \leq 6°C) \cdot 2.50$	186	−1.67	−261	+0.65
3067	$T_V - 7°C$	$P_V(T_V \leq 7°C) \cdot 2.83$	− 1	0	−533	+1.33
3150	$T_V - 7.5°C$	$P_V(T_V \leq 7.5°C) \cdot 3.00$	− 80	+0.20	−676	+1.69
3233	$T_V - 8°C$	$P_V(T_V \leq 8°C) \cdot 3.17$	−160	+0.40	−820	+2.05

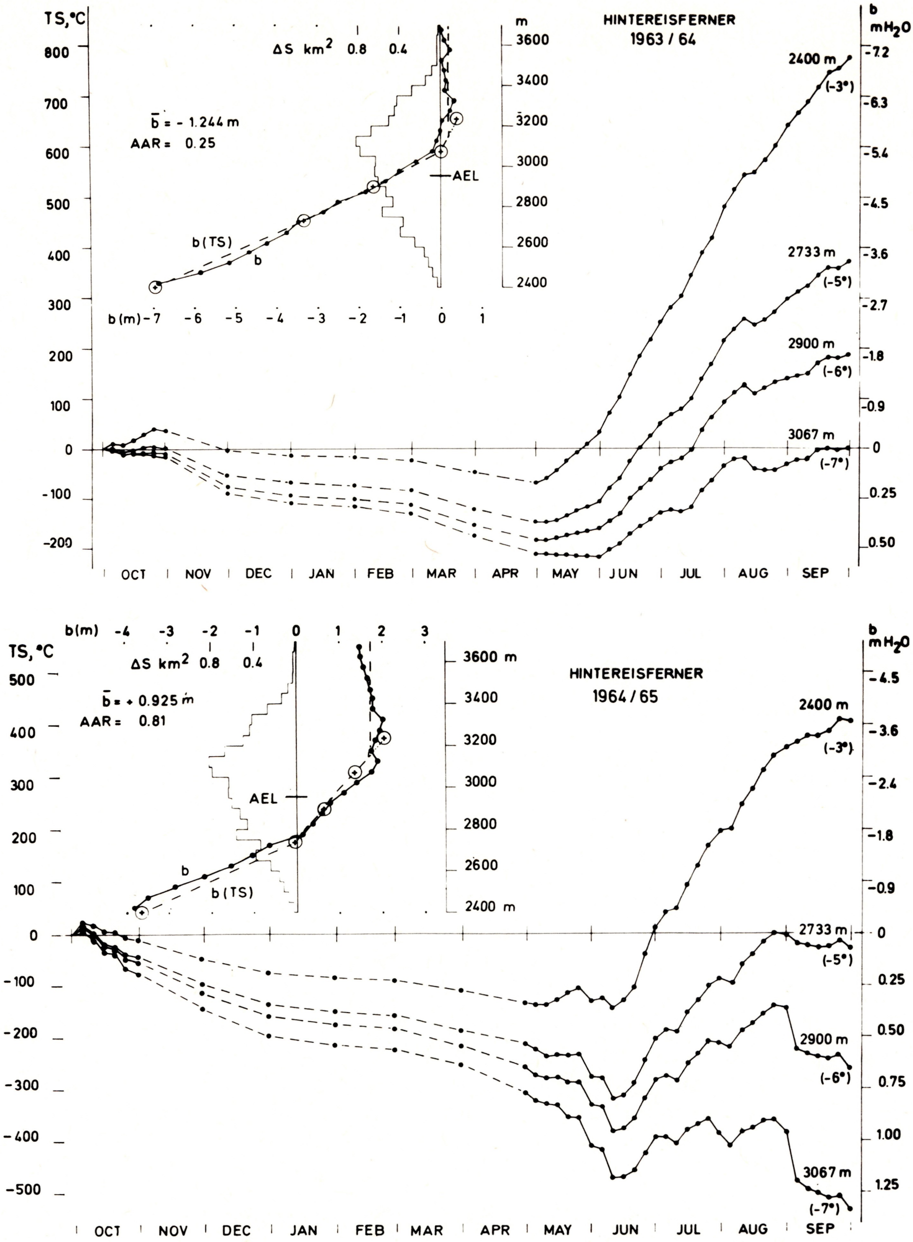

FIGURE 3. Calculation of TS (left-hand scale) at four elevations on Hintereisferner. Resulting specific mass balance on right-hand scale. For comparison with observed mass balance-altitude relation see inset.
(a) Budget year 1963/64; (b) budget year 1964/65. Data in Table 2.

concept. Temperature is easily reduced from Vent to arbitrary elevations; this is facilitated by the data from Station Hintereis (3026 m), and auxiliary stations at 2450 and 2800 m above sea level on the glacier. Precipitation in the Rofental is measured by 10 storage gauges, five of these in the vicinity of Hintereisferner, the oldest at 2960 m above sea level being in operation since 1926 (see data in Table 1). Extensive studies of winter snow cover since the winter of 1954/55, together with recordings of runoff, have provided additional information about the variation of precipitation with elevation in the drainage basin of Rofenache. Full details of the method were published by Hoinkes and Lang (1962); the reduction factors of precipitation as measured in Vent for different elevations, as given in Table 2, are in agreement with these results.

In addition to the terminus of Hintereisferner (2400 m) TS values were calculated for the following important elevations: 2733 m with maximum of $-b\Delta S$, 2900 m near the average equilibrium line where budget imbalance b_i is best determined, and 3150 m with maximum of $+b\Delta S$ (see Hoinkes, 1970). The course of TS values as calculated for five-day intervals (with the exception of winter where monthly values of precipitation were used) is shown in Fig. 3a for the hydrological year 1963/64, and in Fig. 3b for 1964/65. To convert TS (scale on left-hand side) into specific mass balance (scale on right-hand side of graph) one positive degree day was put equal to 2.5 mm of water equivalent for melting of snow, and to 9.0 mm of water equivalent for the melting of ice. This relation corresponds to an average albedo of 0.8 for snow and 0.3 for ice. Specific mass balance as calculated from TS agrees fairly well with specific mass balance as averaged over 50 m altitude increments from analysed observations (see inset in Figs. 3a, b). By linear connexion of the calculated points the observed balance-altitude relation is well matched. Above 3150 m because of steepening slopes the specific mass balance remains constant.

As a next step the method will be tested by computing the mean specific mass balance of Hintereisferner with hydrometeorological data from Vent back to the year 1940. A photogrammetric map of the glacier surveyed in that year will allow evaluation of the change in volume and verification of the result.

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