GLACIER MASS BUDGET AND MESOSCALE WEATHER IN THE AUSTRIAN ALPS 1964 TO 1966

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ABSTRACT

Mass budgets 1964-1966 of Hintereisferner and Kesselwandferner (Ötztal Alps, Tyrol), and of Stubacher Sonnblick-Kees (Granatspitzgruppe, Salzburg) are compared with climatological data. Net ablation as function of time, the net budget gradient in the ablation area, and the retreat of the transient snowline were calculated with the aid of nomographs. These were constructed from daily observations at Vent (1900 m), using reduced cumulative temperatures and taking into account the retardation of ice melt by falls of fresh snow. The duration of the ablation period of 150 days in 1963/64 corresponded to a strongly negative mass budget, whereas 64 days in 1964/65 were indicative of a highly positive mass budget. The mesoscale weather affecting glaciers is furthermore described by the frequency of selected weather types during the potential ablation season May to September. As a consequence of the more cyclonic character of the weather in the ablation season of 1965 temperatures at the 500 mbar level over the Alps were much lower. Characteristic deviations from the average height of the 500 mbar surface are used to correlate atmospheric circulation and glacier mass budget.

RÉSUMÉ

Une comparaison est faite entre les bilans de masse de 1964 à 1966 du Hintereisferner et du Kesselwandferner (Ötztaler Alpen, Tyrol) et du Stubacher Sonnblick Kees (Granatspitzgruppe, Salzburg) et les données climatologiques. Le bilan de la zone d'ablation en fonction du temps, le gradient du bilan net dans la zone d'ablation et le recul de la limite temporaire du manteau neigeux ont été calculés à l'aide de nomographes. Ces nomographes ont été construits sur la base d'observations effectuées à la station climatologique de Vent (1900 m) en tablant sur des températures cumulatives réduites et en tenant compte du retard de la fonte des glaces par des chutes de neige fraîche. La durée de la période d'ablation de 150 jours, en 1963/64, correspond à un bilan de masse fortement négatif, tandis que 64 jours, en 1964/65, relèvent un bilan de masse hautement positif. La situation météorologique à l'échelle moyenne influançant l'allure des glaciers est également démontrée par la fréquence de certains types de temps déterminés pendant la saison d'ablation potentielle de mai à octobre. Pendant la saison d'ablation de 1965 les températures, au niveau de 500 mbar, au-dessus des Alpes, ont été beaucoup plus basses par suite du caractère plus cyclonique du temps. Des déviations caractéristiques du niveau moyen de la surface de 500 mbar établissent des corrélations entre la circulation atmosphérique et le bilan de masse des glaciers.

Investigations of glacier mass budget began on Hintereisferner in the central part of the Ötztal Alps in the western Tyrol in the hydrological year 1952/53. These studies were part of a research programme in glacial meteorology and glacial hydrology initiated in 1948 in the Rofental, extending 17 km southwest of the village of Vent (46°52′N, 10°56′E, 1900 m.a.s.l.). In the hydrological year 1957/58 mass budget investigations were extended to Kesselwandferner, and in the hydrological year 1965/66 to Vernagtferner. The catchment area of Vent (see sketchmap in Hoinkes and Rudolph (1962)) was selected as a study site for the IHD project of combined water, ice, and heat budgets of selected glacierized basins. The second project of this type to be carried out in the Austrian Alps, which also forms part of the west-east chain of glacier basins around latitude 45 degrees N, was initiated in 1963 in the catchment area of the Weiss-See reservoir west of Rudolfshutte (47°08′N, 12°38′E, 2315 m.a.s.l.) on the northern slopes of the middle part of the mountain group of Hohe Tauern. Investigations of mass budget were also carried out on Stubacher Sonnblick Kees, a glacier on the northeastern slopes of the peaks of Sonnblick and Granatspitze. A description of this area has been given by W. and H. Slupetzky (1963).

Mass budget data for Hintereisferner, Kesselwandferner and Sonnblick Kees for the budget years 1963/64, 1964/65 and 1965/66 (see Table 1) were obtained by the surface budget method. A complete account of the work has been given by Hoinkes and others (unpublished). In the budget year 1963/64 the most negative mass budget, and in the budget year 1964/65 the most positive mass budget was observed since the mass budget investigations on Hintereisferner began in 1952/53. The same is the case on Aletschgletscher in the Swiss Alps according to Kasser (1967), where the budget year 1948/49 was the first with a more negative mass budget than the one observed in 1963/64 (−129 g/cm²). A more positive mass budget than the one observed in 1964/65 (+126 g/cm²) does not occur in the data recorded back to the budget year 1940/41. In the budget year 1965/66 a positive mass budget persisted so that the average mass budget for the three years 1964-1966 was balanced on Hintereisferner, but it was markedly positive on Kesselwandferner and even more so on Sonnblick Kees. The occurrence of two extremes of opposite sign in the mass budget of two consecutive years, makes it worthwhile to look again for relations between glacier mass budget and weather in the much neglected meso-scale.

TABLE 1

Mass budget data 1964 to 1966
Mean specific mass budget $\bar{b}$ (g/cm²)
accumulation area ratio S_c/S
altitude of equilibrium line *Ea* (m.a.s.l.)

Budget year	Hintereisferner			Kesselwandferner			Sonnblick Kees		
	$\bar{b}$	S_c/S	*Ea*	$\bar{b}$	S_c/S	*Ea*	$\bar{b}$	S_c/S	*Ea*
1963/64	−124,5	0.25	3180	− 53,7	0,60	3150	− 83,0	0,19	~2950
1964/65	+ 92,5	0,81	2770	+104,0	0,85	3000	+218,9	0,99	<2500
1965/66*)	+ 34,5	0,76	2850	+ 59,4	0,82	3040	+ 88,0	0,89	~2650
1963/66	+ 2,5			+109,7			+223,0		

Budget year for Hintereisferner and Kesselwandferner:
1 October to 30 September

for Sonnblick Kees: 26.9.63—16.9.64, 17.9.64—25.8.65, 26.8.65—17.10.66

*) Vernagtferner $\bar{b}$ = +82 g/cm², S_c/S = 0.94, *Ea* = 2900 m (H. Queck, pers. comm.)

Results of climatological observations of Vent and of Rudolfshütte 1964 to 1966 are included in Table 2. Both stations are situated in the immediate vicinity of the glaciers, and are representative of the respective areas. Because of the difference in altitude of 415 metres Rudolfshütte is at all periods (i.e. hydrological year, accumulation period, ablation period and summer) colder than Vent by 2.0 °C to 3.5 °C, with the greater differences in summer. The more cyclonic year 1965 results somewhat colder in all periods at Rudolfshütte than at Vent as compared to 1964. A comparison at both stations shows the summer months June to August to be colder by 1.1 °C and 1.7 °C in 1965, and by 1.2 °C and 1.4 °C in 1966, as compared to the summer of 1964. For seven stations in the Alps at altitudes above 2000 m, viz. Jungfraujoch (3576 m), Sonnblick (3106 m), Zugspitze (2962 m), Säntis (2500 m), St. Bernhard (2479 m), Villacher Alpe (2135 m) and St. Gotthard (2095 m), the respective differences are 1.3 °C in 1965, and 1.4 °C in 1966. This is a good proof of the representativeness of the observations carried out at Vent and Rudolfshütte for glacierized altitudes in the Alps. Summer temperatures as observed in Vent between 1964 and 1966 are not exceptional. Between 1901 and 1965 there were 18 summers with temperatures $\geq$ 9.5 °C., and 19 summers with temperatures $\leq$ 8.4 °C (see Lauffer, unpublished). A better agreement with mass budget data is obtained by considering the temperatures of the potential ablation period May to September. These temperatures are 1.6 °C and 1.9 °C colder in 1965, and only 0.9 °C and 0.7 °C colder in 1966, as compared to 1964. One has to go back 40 years in the temperature record of Vent to find an ablation period (1926) as cold as 1965, and the ablation periods of 1910, 1912, 1913 and 1916 were the only ones that were slightly colder in this century.

TABLE 2

Climatological Data 1964-1966

Vent (1900 m.a.s.l.) — Rudolfshütte (2315 m.a.s.l.)

	Hydrol. Year 1 Oct-30 Sept.		Accumulation Period 1 Oct-30 Apr.		Ablation Period 1 May-30 Sept.		Summer 1 Jun-31 Aug.	
	Vent	R. Hütte	Vent	R. Hütte	Vent	R. Hütte	Vent	R. Hütte
	Temperature (°C)							
1964:	1,9	−0,5	−2,7	−4,7	8,3	5,3	9,5	6,6
1965:	0,5	−2,7	−4,0	−6,7	6,7	3,4	8,4	4,9
1966:	1,7	−0,9	−2,4	−4,8	7,4	4,6	8,3	5,2
1901-50:	1,4	—	−3,1	—	7,7	—	9,0	—
	Precipitation (mm)							
1964:	485	1728	190	736	295	992	236	679
1965:	836	3075	274	1647	562	1428	311	819
1966:	726	2260	214	747	512	1513	410	1046
1901-50:	710	—	314	—	396	—	267	—

The Central Ötztal Alps are very dry as compared to the Hohe Tauern where between two and three times as much precipitation is measured in storage gauges (Lauscher 1961). The precipitation measured in the storage gauge at Hochjochhospiz (2360 m) in the Vent area is reduced to the values at Rudolfshütte (2315 m) by the factors 2.63, 2.72 and 2.58, respectively, in the three hydrological years under consideration. Precipitation of the three years is in relative agreement, even though the hydrological year 1963/64 had the smallest precipitation so far observed in Vent, i.e. since 1891

(Lauffer, unpublished), and the hydrological year 1964/65 is one of the nine wettest in the last 75 years. The same good relative agreement between both areas exists in the accumulation and ablation periods of the budget years 1963/64 and 1965/66. In the accumulation period 1964/65, precipitation measured at Rudolfshütte exceeded precipitation measured in the storage gauge at Hochjochhospiz by a factor of 4.4 and that at Vent by a factor of six. At Rudolfshütte the amount of winter snow in 1964/65 was exceptionally high, contributing essentially to the high positive mass budget of Sonnblick Kees in 1965. (Table 1). In Vent, on the contrary, all three accumulation periods had less than average precipitation (see Table 2), 1963/64 being the fourth driest and 1965/66 the sixth driest accumulation period since 1891/92. Both ablation periods in the years with positive mass budget had higher than average precipitation, 1965 being the second wettest and exceeded by only one mm in 1910, and 1966 was one of the five wettest ablation periods since 1891. In the Vent area, therefore, the positive mass budget must be attributed to the frequent falls of fresh snow on glaciers during the ablation periods. This was also clearly the case on Sonnblick Kees, where only in 1964/65 winter snow contributed appreciably to the positive mass budget. The larger number of days with snow and sleet that were observed in both areas in the ablation seasons 1965 and 1966, as compared to 1964, supports this view. In addition, the duration of bright sunshine was shorter in the ablation season of 1965 by 170 hrs in Vent, and by 216 hrs at Rudolfshütte than in the ablation season of 1964 (see Hoinkes and others, unpublished). Judging from climatological observations since 1891 the hydrological years 1963/64 and 1964/65 can definitely be classified as unusual, matching the equally unusual results of mass budget investigations.

In an earlier attempt to relate variations in the mass budget of Hintereisferner to variations of climatic elements as observed in Vent, Hoinkes and Rudolph (1962) obtained average monthly values of total shortwave radiation on Hintereisferner from monthly data of the relative duration of bright sunshine at Vent for the ablation periods 1953 to 1961. In this paper daily observations of temperature in Vent will be used to deduce ablation conditions on Hintereisferner. Temperature is merely a substitute for radiation, and can easily be reduced to other altitudes. From simultaneous observations carried out in Vent and on glaciers for about 300 days between the summers of 1950 and 1965 an average lapse rate of 0.60 °C to 0.65 °C/100 m was found. That is to say melting conditions at the terminus of Hintereisferner commence with daily mean temperatures in Vent exceeding 3°C; they prevail over all parts of the drainage basin with daily mean temperatures exceeding 10°C. It is interesting to note that in 1965 the lowest number of days (37) with mean temperatures at Vent exceeding 10 °C was observed for the period 1935 to 1965 (average 57 days, see Lauffer, unpublished); in 1966 there were 42 such days, and in 1955 with a slightly positive mass budget 41 days. In 1964, on the other hand, the number of days was 60; this is not exceptionally high as compared to the maximum numbers of 83 such days in 1947 and of 72 days in 1950. If temperature is used as an indication of radiation, the existence of fresh snow on the glacier has to be considered as well. The high albedo of a fresh snow cover will prevent ablation, especially with low humidity, and regardless of high air temperature or strong insolation there will be hardly any melting of ice.

From the mean daily temperature at Vent 3 °C was subtracted; these reduced temperatures were added together for the ablation season; taking negative values as zero. Snow was considered to occur on the glacier whenever there was precipitation in Vent and when the temperature during precipitation in Vent was below 3°C. As a threshold for precipitation 3 mm was chosen, corresponding to about 5 cm of fresh snow. It was estimated that about two positive degree days were necessary to melt this amount of snow before melting of the glacier ice could continue. From the onset of precipitation two positive degree days were subtracted from the cumulated temperature, for each 3 mm of precipitation. In this way for each ablation season a cumulative curve of

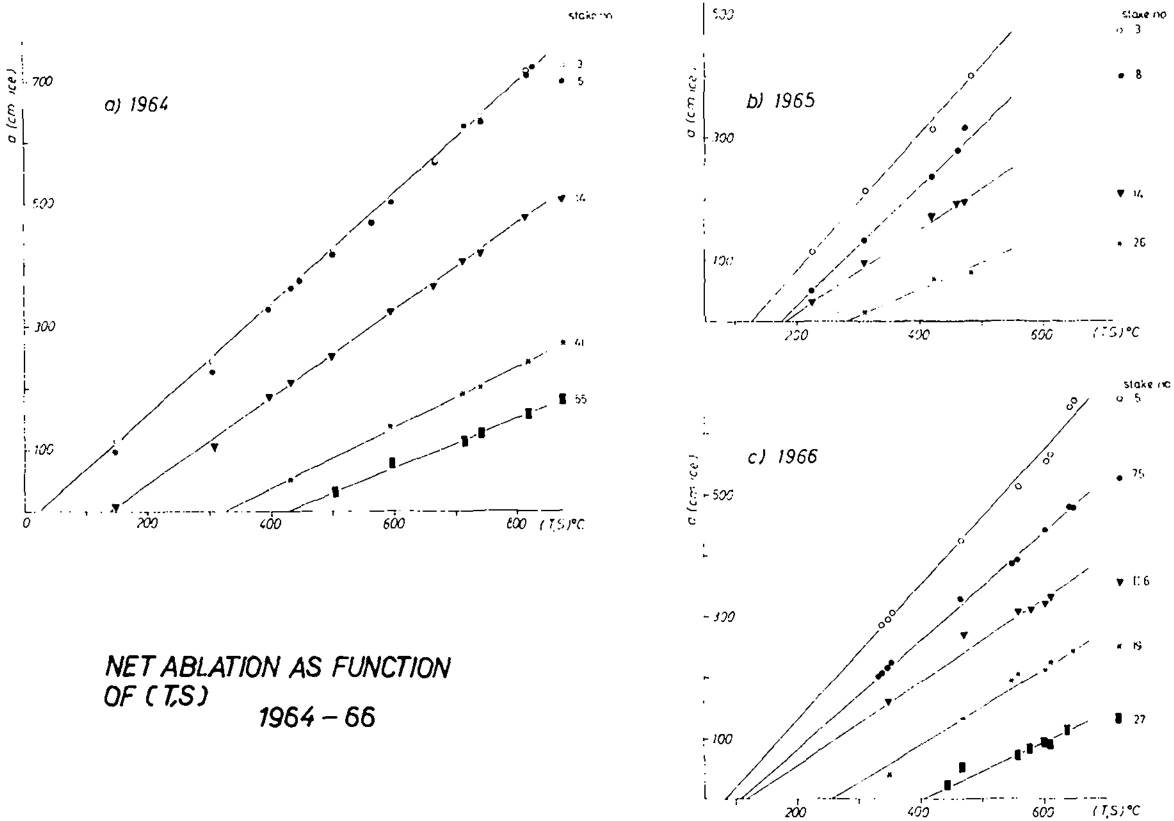

Fig. 1 — Net ablation as function of cumulative (*TS*)-values for selected stakes on Hintereisferner in the budget years 1963/64, 1964/65, and 1965/66.

degree-days was obtained which is called the (*TS*)-curve. The observed net ablations on Hintereisferner in cm of ice, when plotted as a function of the cumulated (*TS*)-values, yield a family of straight lines with the stake number, i.e. altitude, as a parameter, as can be seen from figure 1 for the years 1964 to 1966. To facilitate conversion of the (*TS*)-values into net ablation nomographs were constructed for each budget year, of which the one for 1963/64 is given as an example in figure 2. The left hand scale shows (*TS*) values with the corresponding dates, the right hand scale shows net ablation in cm of ice. By connecting the dates of stake readings with the measured net ablation, points of intersection are obtained and marked with the respective stake numbers. The points marking the stakes show only a moderate scatter around the diagonal straight line, due to local differences in ablation conditions caused by the microrelief and albedo. With the aid of the nomographs the course of net ablation has been plotted as a function of time for different altitudes during the ablation seasons of 1964 to 1966. Figure 3, for example, for the ablation season 1964 reveals surprisingly good agreement between observed and calculated net ablation considering the rather rough assumptions made.

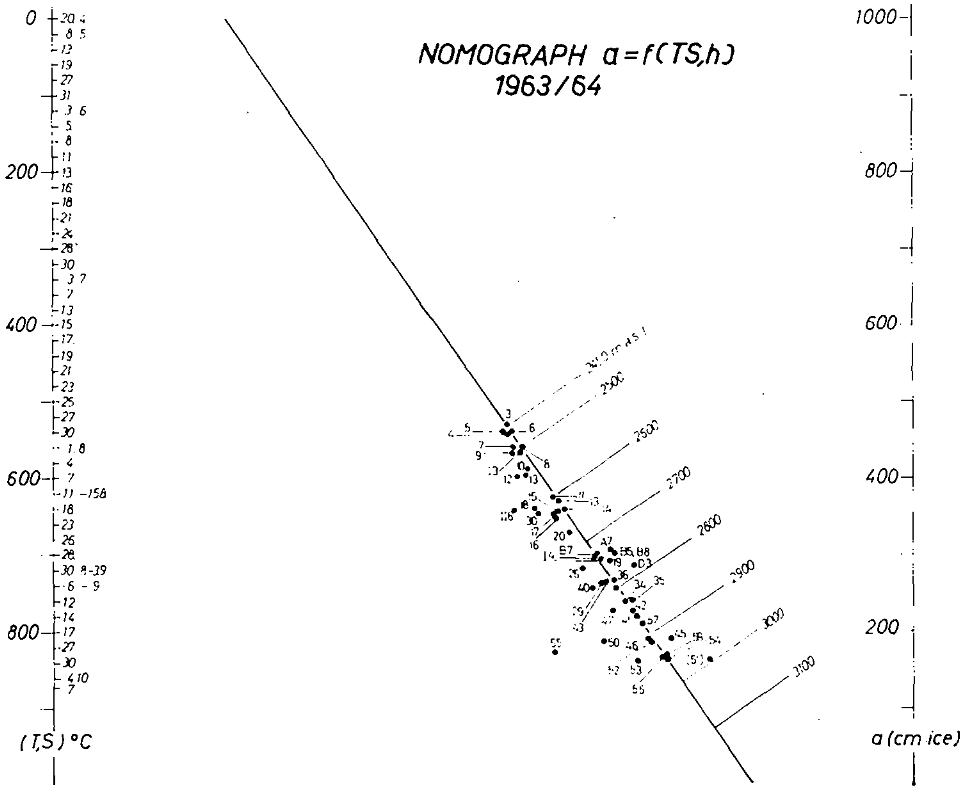

Fig. 2 — Nomograph $a = f(TS, h)$ for Hintereisferner, budget year 1963/64. To obtain net ablation in cm of ice connect linearily (*TS*)-value or respective date on left-hand scalle with stake number or respective altitude on diagonal middle scale. Read net ablation on point of intersection on right-hand scale.

From the geometry of the nomographs the relation between net ablation, altitude and (*TS*) values can be expressed by the following formulae:

$$1963/64 \quad a = (TS+330)\frac{3728-h}{h-1030} - 300$$

$$1964/65 \quad a = (TS+\ 60)\frac{3150-h}{h-1865} - 160$$

$$1965/66 \quad a = (TS+130)\frac{3080-h}{h-1830} - 180$$

with

a = net ablation in cm of ice

h = altitude in metres above sea level.

TS = the cumulated reduced positive degree days (°C) minus 2/3 of the precipitation (mm) at temperatures below 3°C in Vent

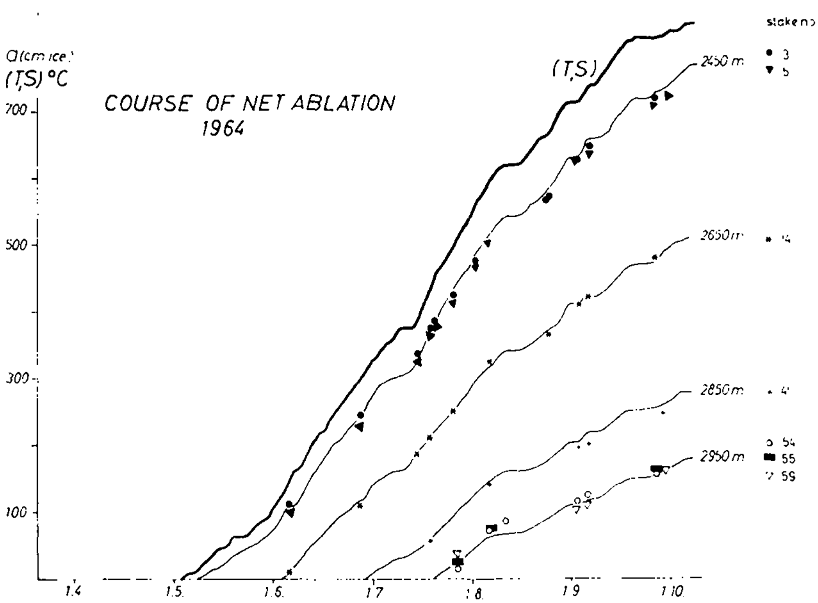

Fig. 3 — Course of net ablation (cm of ice) as function of date for different altitudes on Hintereisferner, ablation season 1964. Curves were obtained with the nomograph figure 2, actual readings of selected stakes entered for comparison.

Unfortunately the numerical values in single budget years are not constant although they are similar in the years with positive mass budget. They contain the influence of other factors than (*TS*), such as winter snow cover, which is different in single years.

As yet insufficient data are available for a statistical analysis, but it seems worthwhile to continue the study along these or similar lines. The estimation of the mass budget of a glacier or of a defined part of it (e.g. net ablation is the mass budget of the ablation area) from the results of meteorological observations carried out in the vicinity of that glacier would greatly reduce the amount of field work. In this respect a knowledge of the net budget gradient would be most desirable (LaChapelle 1962). The net budget gradient in the ablation area is obtained by dividing the difference of two net ablation values a_2-a_1 at two altitudes by the difference in altitude h_2-h_1. By inserting for h_2 the altitude of the equilibrium line and for (TS) the respective value at the end of the ablation season, one obtains in the budget year 1963/64

$$(a_2-a_1) = (TS+330)\left[\frac{3728-h_2}{h_2-1030} - \frac{3728-h_1}{h_1-1030}\right]$$

and

$$\frac{a_2-a_1}{h_2-h_1} = \frac{676}{670} = 1.01 \text{ m ice/100 m}$$

with

$$h_2 = 3170 \text{ m},\ h_1 = 2500 \text{ m},\ TS = 840.$$

Table 3 contains the values of net budget gradients for the ablation zone of Hintereisferner 1964 to 1966, calculated in steps of 100 m altitude increment. The net budget gradients as calculated from the above formulae agree well with the ones obtained from the analysis of mass budget (see Hoinkes and others, unpublished).

TABLE 3

Net budget gradients (m ice/100 m) in the ablation zone of Hintereisferner 1964 to 1966

Altitude interval	1963/64	1964/65	1965/66
2500-2600 m	1.38	1.43	1.78
2600-2700 m	1.19	1.14	1.39
2700-2800 m	1.06	0.88	1.09
2800-2900 m	0.95	—	—
2900-3000 m	0.87	—	—
2500-3170 m	1.01	—	—
2500-2800 m	—	1.15	—
2500-2830 m	—	—	1.38
from analysis	1.08	1.28	1.35

The retreat of the transient snow line as function of (TS) is calculated by putting the net ablation equal to zero. In 1964, e.g. one obtains from $(TS) = 300\,(h-1030)/(3728-h)-330$ the data included in Table 4. The great difference in the character of the three budget years becomes even more obvious from the graphic representation in Figure 4. An early beginning of net ablation and persistent intense ablation in Septem-

TABLE 4

Retreat of transient snowline as function of (TS) (reduced degree days) *on Hintereisferner*, 1964 *to* 1966

Altitude	1964 (TS)	1964 date	1965 (TS)	1965 date	1966 (TS)	1966 date
2450 m	3	3 May	74	24 June	47	16 May
2500 m	30	12 May	94	26 June	77	7 June
2550 m	47	16 May	123	28 June	112	11 June
2600 m	88	29 May	155	1 July	150	17 June
2650 m	120	3 June	192	13 July	214	2 July
2700 m	157	7 June	236	18 July	282	11 July
2750 m	197	13 June	294	29 July	389	2 Aug.
2800 m	244	19 June	360	11 Aug.	492	3 Sept.
2850 m	290	26 June	465	never	670	never
2900 m	348	4 July				
2950 m	410	16 July				
3000 m	480	23 July				
3050 m	565	2 Aug.				
3100 m	660	23 Aug.				
3150 m	770	13 Sept.				
3200 m	900	never				

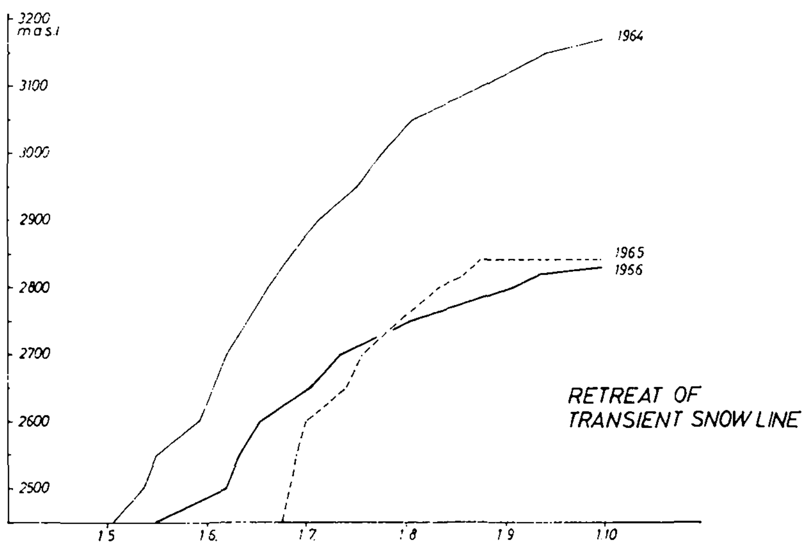

Fig. 4 — Retreat of transient snowline on Hintereisferner 1964, 1965, and 1966 as function of altitude and of date.

ber lead to the strongly negative mass budget in 1963/64. An exceptionally late beginning of net ablation and heavy falls of fresh snow as early as 25 August resulted in a strongly positive mass budget in 1964/65. In the year 1966 July and August were colder and wetter than in 1965, causing a very slow retreat of the transient snowline. The relatively early beginning of net ablation, therefore, was not indicative of a negative mass budget in 1965/66.

As pointed out by Hoinkes and Rudolph (1962) a good correlation was found between mass budget and the duration of the ablation period counted from the onset of net ablation at the terminus of Hintereisferner. In the budget year 1957/58 with a mean specific mass budget of -98 g/cm^2 the ablation period was 140 days, and in 1958/59 -76 g/cm^2 corresponded to 135 days. In 1963/64 the duration of the ablation period was 150 days, resulting in the most negative mass budget of -124 g/cm^2. The budget year 1964/65 had the most positive mass budget so far observed on Hintereisferner ($+92$ g/cm^2) as a consequence of the shortest ablation period on record, viz. 64 days. In the budget year 1954/55 ($+8$ g/cm^2) the duration of the ablation period was 85 days, whereas in 1959/60 (-6 g/cm^2) it lasted for 95 days. In the budget year 1965/66 ($+34$ g/cm^2) because of the special character of July and August this correlation was not valid. Again a longer series of mass budget data seems necessary in order to learn more about the frequency of such exceptions.

Marked differences in the duration of the ablation period, and a different character of the ablation season, as expressed by deviations from climatological averages, must be caused by the frequency of specific "Grosswetterlagen", i.e. fairly persistent synoptic situations which determine the form and sequence of weather events for periods of several days. The mesoscale weather affecting glaciers as expressed by the frequency of Grosswetterlagen or certain groups thereof, i.e. " weather types", should form the link between macroscale climate as caused by atmospheric circulation, and microscale

TABLE 5

Frequency of weather types in Central Europe
Ablation Periods May to September 1964 *to* 1966

Month	Weather type	Number of days		
		1964	1965	1966
May	cold spells	3	13	3
June	monsoon type	5	13	9
July	and	9	19	18
August	cyclonic	7	20	16
Sum of favourable weather types for glaciers		24	65	46
June	anticyclonic	17	14	9
July	anticyclonic	15	0	2
August	anticyclonic	8	7	10
September	warm advection	18	21	12
Sum of unfavourable weather types for glaciers		58	42	33
Sum of favourable types minus sum of unfavourable types of weather		-34	23	13

heat budget. Ablation seasons favourable for glaciers clearly have cold spells in May and monsoon type and cyclonic weather in summer. Anticyclonic weather in summer and warm advection in September are clearly unfavourable. From the publication "Grosswetterlagen Mitteleuropas", issued monthly by Deutscher Wetterdienst, Zentralamt Offenbach, the frequency of days representing these weather types was counted (for details of selected Grosswetterlagen see Hoinkes 1968). The result is shown in Table 5 for single months of the ablation periods 1964-66. There is an excess of 34 days with unfavourable weather types in the ablation season of 1964, as compared to an excess of 23 days with favourable weather types in the ablation season of 1965, and of 13 days in 1966. The great differences in the mass budget of glaciers in the Alps in the budget years 1963/64, 1964/65 and 1965/66 are thus well expressed by the frequency of selected weather types occurring in the respective ablation seasons. In the same way the pattern of glacier variations in the Alps since the year 1891 can be correlated with the statistics of weather types (Hoinkes, 1968).

From the differences in the mass budget it might be concluded that similar differences exist in the frequency of cool polar air masses and warm tropical masses. This is not the case as can be seen from Table 6 which summarizes the frequency of days with

TABLE 6

Frequency of air masses in Central Europe
Ablation periods May to September 1964 to 1966

May to Sept	Number of days with polar air			Number of days with tropical air			Weather situation	
	cycl.	anti-cycl.	all	cycl.	anti-cycl.	all	cycl.	anti-cycl.
1964	45	47	92	13	48	61	58	95
1965	72	28	100	22	31	53	94	59
1966	67	25	92	24	37	61	91	62

polar air masses (maritime, continental and modified) and with tropical air masses for the ablation periods May to September 1964, 1965, and 1966. While the total number of days with polar air masses is almost the same in the ablation periods of all three years, the differences in frequency become striking if only cyclonic weather situations are considered. In the ablation season of 1964 there is an excess of 37 days with anticyclonic weather situations, causing subsidence of air masses and consequently high temperatures aloft, combined with low cloudiness and strong insolation. On the other hand, in the ablation season of 1965, cyclonic weather situations are 35 days in excess of those with anticyclonic situations. Rising air masses cause lower temperatures aloft, combined with more cloudiness, more of the precipitation falling as snow, and less insolation. The same is the case in the ablation season of 1966, but to a smaller extent.

Temperature aloft is, therefore, a good indication of atmospheric stability. This is clearly reflected in the average monthly temperatures at the 500 mbar—level over the Alps, taken as the mean between the radiosondes of Munich and of Milan for the periods May to September 1964, 1965 and 1966. From Table 7 it can be seen that the

TABLE 7

Mean monthly temperatures at the 500 mbar level
(Munich + Milan)/2

	May	June	July	August	September	Aver. May-Sept.
1964	−18,2	−13,9	−12,7	−13,3	−14,4°C	−14,5°C
1965	−20,8	−15,9	−14,3	−14,4	−16,4°C	−16,4°C
1966	−19,0	−15,4	−14,8	−13,9	−13,3°C	−15,3°C

temperature for the ablation period is 1.9 °C colder in 1965, and 0.8 °C colder in 1966, as compared to 1964. The average thickness of the layer from 1000 mbar to 500 mbar over Munich for the period May to September is 5596 geopotential metres in 1964, 5554 gpm in 1965 and 5570 gpm in 1966 respectively. This means that the average temperature of the lower troposphere is 2.1 °C colder in 1965, and 1.3 °C colder in 1966, than in 1964. This is due to lifting and cooling of air masses in the more frequent cyclonic weather situations in the ablation periods of 1965 and 1966, as compared to the more frequent anticyclonic situations in 1964. As a consequence of tropospheric temperatures a good correlation between glacier mass budget and average height of the 500 mbar surface is to be expected. This is shown by means of deviations from the average 1951-60 height of the 500 mbar surface over Munich and over Payerne for the periods May to September 1964 to 1966 (see Table 8). Differences in the mass budget

TABLE 8

Deviations from the average 1951-60 height
of the 500 mbar surface in geopotential metres

	May	June	July	August	September	May-Sept.
	Munich					
1964	+41	+41	+35	+ 3	+34	+154 gpm
1965	−32	− 5	−37	−15	−45	−134 gpm
1966	+18	+ 8	−45	−22	+39	− 2 gpm
	Payerne					
1964	+32	+20	+17	+12	+46	+127 gpm
1965	−50	−30	−45	−15	−76	−216 gpm
1966	− 5	+21	−41	−14	+56	+ 17 gpm

data from different regions, as for instance the Alps and Scandinavia are, therefore, closely related to certain deviation patterns in the 500 mbar surface, that is to say to deviations from normal atmospheric circulation, as shown by Hoinkes (1964, 1968).

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DISCUSSION

H. LISTER

In your earlier work on the heat balance of glaciers in the Austrian Alps you found that the heat of thermal radiation was dominant in causing ablation. In moving from the micro to the macro scale of meteorology and glaciers you use air temperature and precipitation as the controlling variables. In this change compelled because of absence of radiation data; you are taking temperature and precipitation as parameters of a slab atmosphere through which radiation has to pass?

J.C. THAMS

I think, we all agree that there must be some relations between the meteorological conditions near the glacier and the general circulation on the one hand and the mass budget of the glacier on the other hand. The most difficult problem is to prove, whether these correlations are significant or not. For this purpose the period of some years is certainly too short. After all the methods Prof. HOINKES used have a statistical background. We all know by experience, that there are often very strong correlations between different phenomena for many years and then they disappear completely. Did you prove the significance of the correlations you found ?

H.C. HOINKES

In reply to Dr. LISTER's question there are two points to consider: one is really the lack of long-term radiation data for the Vent area, but it is well known that at least total short-wave radiation can be deduced from monthly values of the relative duration of bright sunshine, which are available. (HOINKES and RUDOLPH 1962.) In order to find at least the short-wave radiation budget, average albedo of glaciers has to be known. Temperature and precipitation during the ablation period decide how much of the precipitation falls as snow, and this is a decisive factor influencing average albedo. At least in summer, temperature shows a positive correlation with radiation, therefore temperature here is merely a substitute for radiation, and summer snow a substitute for albedo. The second point is to demonstrate, how changes in the mass budget of glaciers are pictured in simple daily climatological observations from stations in the close vicinity of glaciers, in order to learn how to use these data. One has to rely on available data, either from stations on the ground or from radiosondes, if the relations found are to be extended to the past.

To J.C. THAMS's contribution I may observe that all correlations used are based on the results of detailed studies of heat budget, carried out repeatedly since the year 1950 on different glaciers in the Alps. Knowing very well the difficulties in proving the significance of correlations derived from short-term observation series, I did, at this stage, refrain from calculating correlation coefficients. The positive result of a significance test by statistical means would not compensate for the lacking knowledge of the physical process. The physical processes governing ablation and accumulation are quite well understood, at least on alpine glaciers, and I don't think they will change, making the correlations "disappear completely". This, of course, does not mean that in my opinion the correlations used here are the best ones, and improvements are not only possible but definitely necessary.