THE HEAT BALANCE OF AN ALPINE SNOWFIELD
(Kesselwandferner, 3240 m, Oetztal Alps, August 11-Sept. 8, 1958)
Preliminary communication

W. AMBACH and H. HOINKES
Universität Innsbruck, Austria

ABSTRACT

The results are given of a heat-balance investigation carried out on the Kesselwandferner (3240 m, Oetztal Alps), between August 11, and September 8, 1958. Main emphasis was given to radiation observations, viz. normal incidence solar radiation, turbidity of the atmosphere, total short-wave radiation of sun and sky, albedo, net short-wave radiation and net long-wave radiation. The heat-balance was calculated for day- and night intervals during two ablation periods and for daily intervals during an accumulation period. The total heat available for melting as calculated from the heat-balance equation was 2615 ly, 68 per cent of which was supplied by net radiation.

ZUSAMMENFASSUNG

Es werden die Ergebnisse einer Untersuchung des Wärmehaushaltes mitgeteilt, die am Kesselwandferner (3240 m, Ötztaler Alpen) zwischen 11. August und 8. September 1958 durchgeführt wurde. Das Hauptgewicht wurde auf Strahlungsbeobachtungen gelegt. Gemessen wurde die direkte Sonnenstrahlung, und daraus die Trübung der Atmosphäre berechnet, die Globalstrahlung, die Albedo, und die Komponenten der Strahlungsbilanz. Der Wärmehaushalt wurde während der zwei Ablationsperioden für Tag- und Nachtabschnitte, während der Akkumulationsperiode nur für 24 Stunden-Intervalle berechnet. Aus der Wärmehaushaltsgleichung ergab sich eine Gesamtwärmemenge von 2615 ly für Schmelzung, die zu 68% von der Strahlungsbilanz gedeckt wurde.

RÉSUMÉ

On présente les résultats d'une étude du bilan thermique éxecutée sur le Kesselwandferner (3240 m, les Alpes d'Ötztal) entre le 11 août et le 8 septembre 1958. L'étude fut notamment concentrée sur l'observation du rayonnement. Le rayonnement solaire fut mesuré et on en déduisit par calculs le trouble de l'atmosphère, le rayonnement solaire global, l'albedo et les facteurs du bilan de rayonnement. Pendant les deux périodes d'ablation le bilan thermique fut calculé pour les heures de jour et de nuit, tandis que durant la période d'accumulation il ne fut calculé que pour les intervalles de 24 heures. De l'équation du bilan thermique, on déduit une quantité de chaleur totale de 2615 ly pour la fusion qui a été causés pour 68% par le bilan de rayonnement.

INTRODUCTION

In the summer of 1958 a detailed study of the heat-balance was carried out in the firn basin of the Kesselwandferner (ötztal Alps), as a part of the Austrian I.G.Y. Glaciology Programme. A meteorological station was set up on August 9, 1958, at an elevation of 3240 m, approx. geographic position 46°50.8′N, 10°47.1′E, and kept in operation until Sept. 8, 1958. The general location and some details of the glacier were shown in two recent papers (Hoinkes and Rudolph, 1962 A and B, Figs. 1 respectively); the mass-balance is dealt with in another report (Hoinkes and Lang, 1963). The measuring site is nearly level; it serves as a study site of net accumulation since 1956 (Hoinkes, 1957), and of winter snow cover since 1960 (Hoinkes and Lang, 1962).

TABLE 1

Meteorological conditions at the Kesselwandferner, 3240 m, Aug. 11 to Sept. 8, 1958.

	Air temp. (°C) at 110 cm			Vapour press. (mm Hg) at 110 cm			Wind speed (m/sec)		Precipitation mm		Cloudiness (tenths)
	avg.	max.	min.	avg.	max.	min.	120 cm	240 cm	rain	snow	
Aug. 11, 09 hrs., to Aug. 19, 18 hrs. (201 hrs.)	2.2	6.5	−0.8	4.3	5.3	3.3	2.95	3.20	39.2	4.0	6.0
Aug. 19, 18 hrs. to Aug. 28, 07 hrs. (205 hrs.)	−1.3	0.5	−4.6	3.4	4.0	2.6	3.70	3.90	8.0	54.1	6.8
Aug. 28, 07 hrs. to Sept. 8, 09 hrs. (266 hrs.)	3.3	8.5	−0.2	3.9	4.8	2.7	2.00	2.15	4.4	3.8	5.0
Aug. 11, 09 hrs. to Sept. 8, 09 hrs. (672 hrs.)	1.6	5.6	−1.6	3.8	4.8	2.8	2.75	2.97	51.6	61.9	5.9

METEOROLOGICAL CONDITIONS

Air temperature and relative humidity were observed with two ventilated psychrometers and recorded on a thermo-hygrograph in an instrument-screen at 110 cm; a second thermograph recorded during the night hours close to the snow surface. The average velocity of the wind was calculated from readings of counting anemometers Lambrecht at two levels (240 cm and 120 cm) for the day- and night-intervals. Cloudiness, visibility and weather events were frequently observed, and precipitation was measured every morning.

The period with full records from all instruments, including radiation, covers 28 days, i.e. August 11, 09 hrs., to Sept. 8, 09 hrs. The average air temperature at 110 cm, calculated from hourly values, amounted to 1.6 °C; there was a total precipitation of 113.5 mm, 55% of which fell as snow. With respect to ablation conditions the observation period was subdivided into three periods. In table 1 the respective average values of air temperature, vapour pressure, wind speed, precipitation and cloudiness are given. The first period covering 201 hrs. was rather warm, with moderate winds and only minor disturbances from southwest to west. The second period (205 hrs.) was cool (lowest temperature −7.6 °C on Aug. 27), with predominant snowfalls, and accumulation instead of ablation. This was caused by an invasion of maritime air due to a large cyclonic system. The third period (266 hrs.) was dominated by anticyclonic situations, with high temperatures (highest temperature 12.6 °C on Aug. 30) and only very light winds.

RADIATION OBSERVATIONS

Normal incidence solar radiation was measured in 42 series on six days with an actinometer Linke-Feussner (Kipp) in connection with a mV-meter in order to calibrate the recording radiation instruments in situ. In table 2 a summary is given of the results according to the optical air mass. The air pressure at the measuring site (average 520 mm Hg) was obtained by reduction from the nearby climatological station Vent (1900 m). Intensities are reduced to mean solar distances, and given in ly/min according to the IPS 1956. Readings with filters OG1 and RG2 were taken

TABLE 2

Intensity of normal incidence solar radiation, Kesselwandferner, 3240 m, Aug. 15, 27, 28, Sept. 1, 3, 5, 1958.

Optical air mass	Relative air mass	True solar elevation	Intensity (ly/min), MSD, IPS 1956	
			average	maximum
0.900	1.298	50.32	1.57	1.61
1.000	1.442	43.85	1.54	1.58
1.200	1.730	35.24	1.48	1.53
1.400	2.015	29.67	1.45	1.49
1.600	2.310	25.55	1.40	1.45
1.800	2.595	22.54	1.37	1.41
2.000	2.885	20.14	1.34	1.38

in order to obtain the turbidity of the atmosphere. Values of the turbidity coefficient β_p (reduced for standard pressure) and of the extrapolated turbidity factor T_p are given in table 3. For details of computation compare the IGY Instruction Manual Part VI (1957).

TABLE 3

Average turbidity of the atmosphere, Kesselwandferner, 3240 m, Aug. 15, 27, 28 Sept. 1, 3, 5, 1958.

day :	Aug. 15	Aug. 27	Aug. 28	Sept. 1	Sept. 3	Sept. 5
$\beta_p . 10^3$	6	7	8	20	14	5
T_p	2.14	2.03	2.00	2.20	2.28	1.95
range of optical air mass	0.82 – 1.96	0.86 – 2.10	0.86 – 1.98	0.88 – 1.25	0.88 – 0.90	0.90 – 1.17
number of observations	7	8	12	5	3	7

Short-wave radiation of sun and sky on a horizontal surface was observed with a solarimeter Moll-Gorczynski (Kipp), using a recording mV-meter (R_i 13Ω, 75μA) Hartmann and Braun. To the same recording instrument a second solarimeter was connected downfacing in order to get the reflected short-wave radiation. For a control additional measurements of the albedo were made at varying sites with a solarimeter in a cardanic mount.

The albedo of the snow surface over the whole period averaged 72%. This high value was due to the frequent falls of fresh snow during the second period, whose mean albedo was 89%. For periods one and three with a melting surafce of old snow an average albedo of 67% and 66% was obtained. There was a very well pronounced diurnal variation of the albedo, between 90% in the morning and 68% around noon. Figure 1, upper part, shows the average diurnal variation of the albedo for the accumulation period (92-88 per cent) and for the two ablation periods (91-61 per cent). This was mostly caused by the varying fresh water content of the snow due to the regular freezing over night; on some mornings the frozen surface was covered with frost crystals, which might cause reflection at low sun elevation. To a certain degree the diurnal variation of albedo is caused by the varying amount of scattered radiation emerging through the snow surfaces from below. This can be seen from figure 1 (lower part) : on August 27 the fresh snow remained dry throughout the day with wet-bulb temperatures below freezing, whereas on August 28 melting started after 8 hrs., and both effects combined.

The total (short- and long-wave) radiation was observed with a net radiometer Schulze, whose poly-ethylene — covered thermopiles were recorded separately on a mV-meter Hartman and Braun (R_i 500Ω, 20μA). The difference in the output from corresponding thermopiles of the net radiometer and of the solarimeters made it possible to determine the incoming and outgoing long-wave radiation. As shown in detail in another report (Ambach, Beschorner, Hoinkes, in press) the calibration factor for short-wave radiation of the thermopiles of the solarimeters and of the net radiometer Schulze depend on solar altitude (up to 16 degrees), and on temperature. The calibrations made on the Kesselwandferner were later confirmed with the same

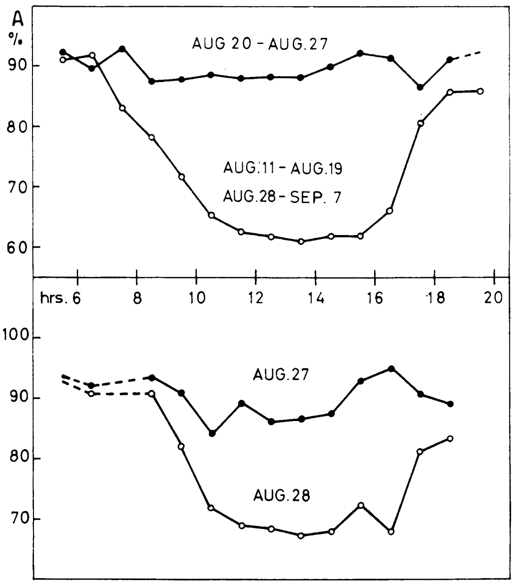

Fig. 1 — Upper part : average diurnal variation of albedo, accumulation period Aug. 20 to 27, and ablation periods Aug. 11-19, Aug. 28 — Sept.7. Lower part : diurnal variation of albedo on Aug. 27 (dry fresh snow) and on Aug. 28 (melting fresh snow). Kesselwandferner, 3240 m.

set of instruments in Greenland (Ambach, in press) and in Obergurgl (not yet published). For long-wave radiation the net radiometer Schulze is less sensitive; the respective calibration factor exceeds the one for short-wave radiation by a factor of 1.58 (upfacing) and 1.54 (downfacing), depending on the properties of the polyethylene bulbs. This requires a dissection of the recorded scale parts according to short-wave radiation (taken from the solarimeter) and long-wave radiation. Although the evaluation of the records from the net radiometer Schulze is certainly timeconsuming, the instrument has the true advantage to give complete results under the most adverse weather conditions.

For the whole period the recorded net long-wave radiation (NRL) amounted — 1935 ly or —2.88 ly/hr. at an average cloudiness of 5.9 tenth, and for the ablation period only —1384 ly or —2.98 ly/hr. at an average cloudiness of 5.5 tenth. NRL of snow- or icefields during the ablation season varies mostly with the atmospheric long-wave radiation, which latter is a function of cloudiness. Therefore a relation between NRL and cloudiness is to be expected, which might be useful for the purpose of estimates, when only records of net short-wave radiation (NRS) are available. The results of instantaneous measurements of NRL from the Vernagtferner (2973 m, summer of 1950, Hoinkes and Untersteiner, 1952, and summer of 1952, Ambach, 1955) and of records from the Kesselwandferner and from Obergurgl (1970 m, spring of 1962, melting snow surface, not yet published) are averaged in table 4 for different amounts of cloudiness. Only nighttime observations were used. The observed values of NRL are fitted best by the following expression :

$$NRL_c = NRL_0(1 - 0.060 \times c^{1.2})$$

where c = cloudiness in tenths. The agreement between calculated and observed values is rather good, except for a few points, where the number of observations is

TABLE 4

Net long-wave radiation of snow or ice (ablation season) as a function of cloudiness.

Cloudiness (tenths)	0	1	2	3	4	5	6	7	8	9	10
NRL observed ly/min.	0.0945	.0838	.0807	.0738	.0592	.0545	.0510	.0250	.0222	.0150	.0057
NRL calculated ly/min.	0.0945	.0890	.0815	.0733	.0645	.0553	.0458	.0358	.0257	.0150	.0048
Number of observations	64	25	22	15	15	6	7	9	14	8	38

not sufficient. Despite the fact that only nighttime observations were used in deducing the above expression, the *NRL* as recorded on the Kesselwandferner for the whole period fits the expression satisfactorily. This shows that no major error occurred in the analysis of the single components of the radiation balance.

HEAT BALANCE

The heat transferred in the following processes should be determined quantitatively. Sources or processes conveying heat to the snow surface are : net short-wave radiation, latent heat released during condensation of water vapour, and heat of fusion during the freezing of surface layers, the latter depending on the free water content of the snow. Transfer of sensible heat from the air is mainly a source, and net long-wave radiation only rarely, with a dense low overcast of a radiation temperature exceeding that of the ground. Sinks or processes conveying heat away from the surface or consuming heat are : heating of ice after the night-cooling, melting of ice, and latent heat used for evaporation. Net long-wave radiation is mainly a sink, and transfer of sensible heat from the surface to the air only rarely during the advection of cold air. Heat carried by precipitation is considered negligible.

Not all processes mentioned could be measured with the same degree of accuracy. Priority was given to the components of the radiation balance, i.e. short-wave incoming minus reflected, giving *NRS*, and long-wave outgoing plus incoming, giving *NRL*, and special care was taken of calibrations in the field. The exchange coefficient was derived from the wind-profile. Two carefully checked anemometers gave an average roughness parameter $z_0 = 0.0115$ cm, which is the same order of magnitude as the roughness parameter obtained at the Hintereisferner in the summer of 1955 with three anemometers for the same type of surface, i.e. fresh and old snow (not yet published). Lettau's correction for stable stratification was applied for a height $z =$ 10 cm, and the transfer of sensible and latent heat calculated, assuming logarithmic profiles of temperature and specific humidity, with $e_0 = 4.58$ mm and $t_0 = 0.1\,^{\circ}$C at z_0.

Only for the periods with melting snow surface was it therefore possible to distinguish between evaporation, condensation and sensible heat transfer. The amount of heat available for melting was then calculated from the heat-balance equation. Melting ceased regularly at about 18 hrs., when the surface began to freeze, and started anew the next morning around 08 hrs. There were only three nights with continued melting, namely Aug. 11-12, Aug. 14-15, and Sept. 7-8. The thickness of the frozen layer was measured every morning during the ablation period; it varied between 2 and 14 cm, average 8 cm. During the accumulation period the frozen surface layer gradually increased to a thickness of 24 cm. The thickness of the frozen layer depends not only on the heat balance of the night, but to a high degree on the free water content of the surface layers.

The free water content of the snow was measured frequently by means of electrical methods. The dielectric constant of the wet snow was determined with a condensor designed by W. Ambach (1958, in press). With plate dimensions of 10 × 10 cm, only average values of the free water content of a snow volume of about 1000ccm were available. These showed a wide range between 0.5 and 16 per cent for surface layers, and between 1.1 and 6 per cent for depths between 30 and 180 cm. Because freezing begins at the very surface and at the same time the water percolates to deeper layers, the heat of fusion released in the process of freezing was calculated with the following assumptions : If the amount of heat available for melting (M) in the preceding period exceeded 200 ly, a free water content of 2 per cent was used, for M between 200 and 100 ly 1.5 per cent, and for M less than 100 ly 1 per cent. The average temperature of the frozen layer was assumed to be $-2\,^{\circ}$C.

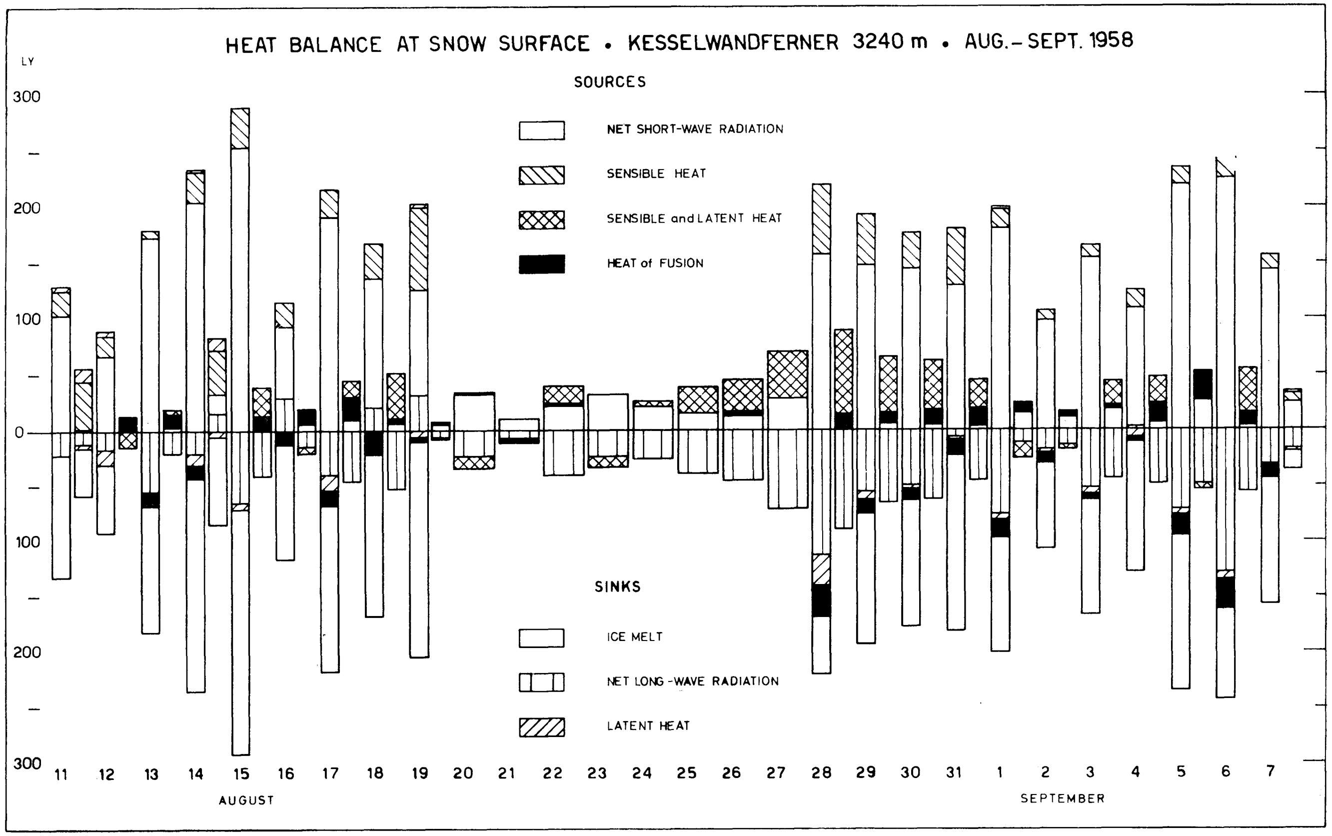

Fig. 2 — Components of heat exchange, Kesselwandferner, 3240 m, August 11, 09 hrs., to Sept. 8, 09 hrs., 1958. Time intervals for two ablation periods usually 08-18 hrs. and 18-08 hrs. For accumulation period 09-09 hrs.

The amount of heat necessary to bring the snow back to the original state, that is heating to melting temperature and thawing of an equivalent amount of snow, was considered as a sink for the period following the freezing, and consequently as a source for the freezing period. Now from the heat balance equation the net amount of convective heat, sensible and latent, could be determined as a residual for all periods with frozen surface. The single components of the heat-balance equation are represented in figure 2. For the two ablation periods a subdivision is made according to intervals with melting (usually 08 to 18 hrs.) and intervals with freezing (usually 18 to 08 hrs.). For the accumulation period only 24-hourly intervals (morning to

TABLE 5

Components of the heat balance for different periods, Kesselwandferner, 3240 m, Aug. 11 to Sept. 8, 1958.

	melting only 234 hrs.		ablation periods 467 hrs.		accum. period 205 hrs.		whole period 672 hrs.	
	ly	%	ly	%	ly	%	ly	%
Sources :								
Net short-wave rad.	3030	81.5	3162	78.5	364	66.0	3526	77.3
sensible heat	645	17.4	866*	21.5	172*	31.2	1037*	22.7
latent heat (condens.)	40	1.1						
Sinks ;								
latent heat (evap.)	−136	3.7						
heat of fusion (frozen layer)	−231	6.2	−29**	0.7	+15**	2.8	−13**	0.3
net long-wave rad.	−733	19.7	−1384	34.3	−551	100.0	−1935	42.4
melting	−2615	70.4	−2615	65.0	—	—	−2615	57.3
Sum of sources	+3715	100	+4028	100	+551	100	+4563	100
Sum of sinks	−3715	100	−4028	100	−551	100	−4563	100
ly/hr.	15.9		8.7		2.7		6.8	
melting 2615 ly =	100 %		100 %		—		100 %	
net radiation	87.9%		68.0%		—		60.9%	
net convection	20.9%		33.1%		—		39.6%	
multiple melting	−8.8%		−1.1%		—		−0.5%	

* = net convective heat
** = net heat of fusion.

morning) were calculated. Figure 2 reveals the similarities in the heat-balance of the two ablation periods and the striking difference to the heat-balance of the accumulation period, which is mainly caused by the much higher albedo of that period.

In table 5, the components of the heat-balance equation are summarized for the respective periods. During the two ablation periods on an average 6.8 ly/hr. were supplied by net short-wave radiation, and only 1.8 ly/hr. during the accumulation period, whereas net longwave radiation remained about equal for both periods (−3.0 ly/hr. and −2.7 ly/hr., respectively). Therefore net radiation was +3.8 ly/hr. during the ablation periods, and −0.9 ly/hr. during the accumulation period. The latter value was compensated by net convective heat, whereas the same source contributed +1.8 ly/hr. to the heat balance of the ablation periods, bringing the heat available for melting to a total of 2615 ly or +5.6 ly/hr. Of this amount 68 per cent were supplied by net radiation, and 32 per cent by net convection. These figures compare very well with the results obtained by E. LaChapelle (1960) on the Blue Glacier in 1958 and 1960.

ABLATION

Ablation was measured every morning and evening on stakes, but the results were not too satisfactory. This was not only caused by the well-known difficulties in short-period measurements of snow ablation (Hubley, 1954), but mainly due to a sinking in of the ablation stakes, as could be discovered in the last snow pit. Density and stratigraphy of the snow were examined in five deep pits, and in numerous shallow pits. Here the results of two adjacent pits are of main interest, dug at the beginning and at the end of the period covered by the heat-balance investigation. The fall 1957 horizon was found 207 cm below the surface on Aug. 11, 10 hrs., and marked with ochre. Two ablation stakes were placed in the corners of the pit to mark the profile, and the pit closed. On Sept. 8, 10 hrs., the 1957 horizon was found 157 cm below the surface, but the foot of the ablation stakes had sunk 20 cm below the dyed horizon. Figure 3 shows the average densities for indicated layers, as determined with a snow sampler of 50 cm^2 surface. There was a well defined ice band between 83 and 86 cm on Aug. 11, which was found between 38 and 40 cm on Sept. 8. Taking the 1957-horizon as a reference, a settling of the layer below the ice-band by 5 cm became apparent. The water content in this layer remained unchanged with 679 mm, therefore the ice band could be used as a reference level for an estimate of the ablation.

Above the ice band 83 cm of old snow with an average bulk density of 0.637 were found on Aug. 11, and 38 cm of old snow with an average bulk density of 0.631 on September 8, making the difference 28.89 g/cm^2. Thus 45 cm of old snow had disappeared, with a resulting bulk density of 0.642 g/cm^3, which is certainly too high because of the free water content of the snow. Unfortunately the free water content of the snow was not measured in these two pits. Assuming it within the limits found in the course of the investigation, i.e. 1 to 6 per cent for deeper layers, it is possible to estimate the ice density of the snow at least within probable limits. August 10 was clear and warm with intensive melting, and 6.4 mm of rain fell during the night (not included in Tab. 1). Therefore the free water content was presumably higher in the pit of Aug. 11, and not so high an Sept. 8 because of the smaller heat balance. During the investigation period 61.9 mm of precipitation fell in the form of snow and soft hail. Most of it was concentrated in the accumulation period, and ablated at the beginning of the second ablation period.

Table 6 contains the total ablation, calculated with different assumptions regarding the free water content. Assumptions (4) and (5), i.e. a free water content of 4 per cent in the upper 83 cm of snow on Aug. 11, and 2 or 3 per cent in the upper 38 cm of snow on Sept. 8, agree best with the amount of heat available for melting according to the

TABLE 6

Total ablation as a function of assumed free water content of the snow. Kesselwandferner, 3240 m, Aug. 11, 1958, to Sept. 8, 1958.

	1	2	3	4	5	6	7	8	9	10
Free water content of snow :										
83 cm on Aug. 11	5%	5%	4%	4%	4%	3%	3%	2%	1%	0%
38 cm on Sept. 8	1%	2%	1%	2%	3%	1%	2%	1%	0%	0%
Difference in ice mass of snow (g/cm^2)	25.12	25.50	25.85	26.33	26.71	26.78	27.16	27.61	28.06	28.89
Corresponding ice density of 45 cm of snow (g/cm^3)	0.558	0.567	0.574	0.585	0.594	0.595	0.604	0.614	0.624	0.642
Solid precipitation (g/cm^2)	6.19	6.19	6.19	6.19	6.19	6.19	6.19	6.19	6.19	6.19
Total ablation (g/cm^2)	31.31	31.69	32.04	32.52	32.90	32.97	33.35	33.80	34.25	35.08
Calories required	2505	2535	2563	2602	2632	2638	2668	2704	2740	2806

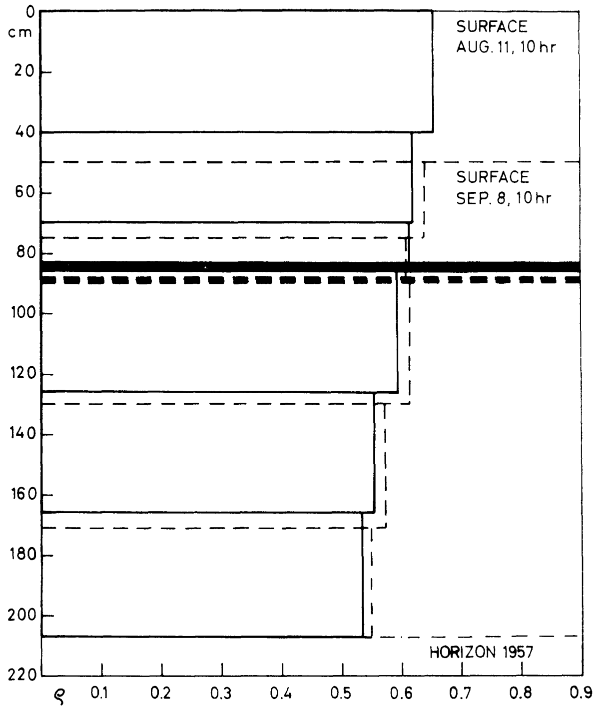

Fig. 3 — Bulk density of snow on Aug. 11, 1958, 10 hrs., and on Sept. 8, 1958, 10 hrs. Kesselwandferner, 3240 m.

heat-balance equation. On Aug. 27 and 28 seven shallow pits gave an average value of 6.01 g/cm^2 for the snow deposited during the accumulation period. It is not to decide whether this value is better than the 5.41 g/cm^2 measured with the precipitation gauge (Tab. 1), or not. In this case 48 ly more would be required for ablation, and therefore assumption.(3), i.e. a free water content of 4 per cent on Aug. 11, and of 1 per cent on Sept. 8, would yield the best value. The corresponding average ice density of the ablated 45 cm of old snow results within the reasonable limits 0.574 to 0.594 g/cm^3.

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