Band 19, Heft 2 (1983), S. 131—147

ZEITSCHRIFT FÜR
GLETSCHERKUNDE
UND GLAZIALGEOLOGIE

SNOW ACCUMULATION, FIRN TEMPERATURE AND SOLAR RADIATION IN THE AREA OF THE COLLE GNIFETTI CORE DRILLING SITE (MONTE ROSA, SWISS ALPS): DISTRIBUTION PATTERNS AND INTERRELATIONSHIPS

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With 10 figures

ABSTRACT

Distributional patterns of glaciological parameters at the Colle Gnifetti core drilling site are described and their interrelationships are briefly discussed. Observations within a stake network established in 1980 furnish information about snow accumulation (short term balance), submergence velocity of ice flow (long term balance), ram hardness (melt layer stratigraphy), and firn temperature. In addition, a numerical model was used to estimate local variations of available radiant energy.

Melt layer formation is considerably more intensive on the south facing parts of the firn saddle where incoming radiation is high. These melt layers seem to effectively protect some of the fallen snow from wind erosion. As a result, balance ist up to one order of magnitude larger on south facing slopes. Heat applied to the surface is therefore positively correlated with balance, whereas the relation between solar radiation and firn temperature is less clear. Distributional patterns of submergence velocity confirm that the observed spatial variability of surface balance is representative for longer time periods and greatly influences the time scale and the stratigraphy of firn and ice cores from Colle Gnifetti.

SCHNEEABLAGERUNG, FIRNTEMPERATUR UND SONNENSTRAHLUNG IM GEBIET DER KERNBOHRUNGEN AUF DEM COLLE GNIFETTI (MONTE ROSA, SCHWEIZER ALPEN): VERBREITUNGSMUSTER UND WECHSELBEZIEHUNGEN

ZUSAMMENFASSUNG

Verbreitungsmuster und gegenseitige Beziehungen von glaziologischen Parametern im Gebiet der Kernbohrstelle auf dem Colle Gnifetti werden beschrieben und diskutiert. Beobachtungen an einem 1980 eingerichteten Pegelnetz liefern Informationen über Schneezuwachs (kurzfristige Bilanz), Eintauchgeschwindigkeit des Firns (langfristige Bilanz), Rammwiderstand (Eislagenstratigraphie) und Firntemperatur. Zusätzlich wurden mit einem numerischen Modell lokale Variationen der verfügbaren Sonnenstrahlung abgeschätzt.

Die Eislagenbildung ist an südexponierten Hängen des Firnsattels bedeutend intensiver als in Schattenlagen. Die Eisschichten scheinen den gefallenen Schnee vor der Winderosion zu schützen. Der Schneezuwachs an südexponierten Hängen ist entsprechend bis zu einer Größenordnung höher als in Schattenlagen. Das Energieangebot an der Oberfläche des kalten Firnsattels ist deshalb positiv mit der Massenbilanz korreliert. Weniger klar ist dagegen die Beziehung zwischen Sonnenstrahlung und Firntemperatur. Das Verbreitungsmuster der gemessenen Eintauchgeschwindigkeit bestätigt, daß die beobachtete räumliche Variabilität der Oberflächenbilanz für längere Zeitabschnitte repräsentativ ist und sowohl die Zeitskala wie die Stratigraphie der Bohrkerne vom Colle Gnifetti stark beeinflußt.

ACCUMULATION DE NEIGE, TEMPÉRATURE DU NÉVÉ ET RAYONNEMENT SOLAIRE AUTOUR DU SITE DES CAROTTAGES SUR LE COLLE GNIFETTI (MONT ROSE, ALPES SUISSES): MODÈLE DE DISTRIBUTION ET RELATIONS

RÉSUMÉ

Des modèles de distribution de paramètres glaciologiques aux alentours du site de carottage du Colle Gnifetti sont décrits et leurs relations discutées. Des observations sur un réseau de balises installé en 1980 fournissent des informations sur l'accumulation de neige (balance à court terme), la vitesse de submersion du névé (balance à long terme), la résistance au battage (stratigraphie des couches de glace) et la température du névé. En plus, les variations locales du rayonnement solaire ont été estimées à l'aide d'un modèle numérique.

La formation de couches de glace est considérablement plus intensive sur les flancs du col exposés au sud que dans les zones plus ombragées. Ces couches semblent protéger la neige tombée de l'érosion éolienne. Il en résulte que l'accumulation de neige est plus importante jusqu'à un ordre de grandeur dans les zones exposées au sud que dans celle à l'ombre. L'offre d'énergie à la surface du névé froid est donc positivement corellée au bilan de masse, mais la relation entre le rayonnement solaire et la température du névé est moins claire. Le modèle de distribution des vitesses de submersion confirme que les variations spatiales du bilan à la surface sont représentatives pour des périodes plus longues et influencent fortement l'échelle de temps ainsi que la stratigraphie des carottes du Colle Gnifetti.

1. INTRODUCTION

Up until now, few data exist on the mass balance and its relation to topography and climate for altitudes above 3500 m a. s. l. Core drillings were performed on Colle Gnifetti, Monte Rosa, 4450 m a. s. l. (fig. 1) between 1976 and 1982 (Oeschger et al., 1978). The glacier bed was reached in 1982. Analysis of these cores using classical and isotope stratigraphy yielded information about some mass balance variations with time at high altitudes (Schotterer et al., 1981, Gäggeler et al., 1983). However, because of glacier flow, the ice in the deeper parts of the cores originates from a different area of Colle Gnifetti than the ice in the shallower parts. It is therefore necessary to know the accumulation distribution on Colle Gnifetti in order to correctly interpret the stratigraphy and time scale of the ice cores.

The aim of the present study is to present information about the spatial variability of glaciological parameters at and near the Colle Gnifetti core drilling site. Observed parameters are (1) short term balance, (2) long term balance (from submergence velocity of ice flow), (3) firn temperature (from measurements in shallow boreholes), and (4) melt layer stratigraphy (from profiles of ram hardness). In addition, local variations of the available radiant energy are estimated using a numerical model.

The reported data will be used as input for models which are presently being developed to simulate the ice flow to and the temperature distribution in different boreholes of the Colle Gnifetti.

Fig. 1: Colle Gnifetti from Zumsteinspitze, August 1981

2. FIELD MEASUREMENTS AND MODEL CALCULATIONS

2.1 NET BALANCE DISTRIBUTION

In August 1980, a network of 30 stakes was set up in a roughly rectangular pattern with mutual distances of approximately 50 m between stakes (fig. 2). By August 1981, some stakes were lost because they were covered by the unexpectedly large accumulation of snow on the north side of the col. 3 stakes could be dug out after resurveying their position, followed by an estimation of their displacement caused by glacier flow. In 1981 snow pits were dug at 3 locations (fig. 2). The snow stratigraphy as observed in the pits is shown in fig. 3.

Near all other stakes, net balance (b_a after Mayo et al., 1972) was determined by stake readings and bulk sampling with a core auger down to the surface level of the previous survey. Core sampling near the pits gives balance measurements which are within 15 % or better compared to the more reliable measurements in the pits. Parallel measurements of balances in the pits agreed to within 5 % or better.

Specific mass balance measurements are given in table 2 for the period 17. August 1980 till 14. August 1981. On 23. July 1982 only surface level readings were made on the 16 stakes which were still visible. Balance was estimated from surface level changes and snow densities determined in 1981.

For 1980/81 specific mass balance varied between +4 cm WE (stake 47) and +118 cm WE (stake 21, see fig. 4). Even higher values than +118 cm WE may have occured around the unrecovered stakes. In general, highest positive balance occurred on the south-exposed part of Colle Gnifetti; low, but still positive balance on the north-exposed part. The relatively small positive balance of stake 63 (+32 cm WE) may be partially a result of the extreme exposition to wind near the cliff. Very high horizontal gradients (approx. 1 cm WE/1 m horizontal distance) are found between the stakes 34 and 46.

Spectacular differences in the snow stratigraphy were observed in the pits (fig. 3). Apart from the large difference in thickness of the accumulated snowpack, numbers and thickness of ice lenses, ice layers and icy crusts vary drastically (table 1).

Table 1: Net balance and melt layers in the pits

pit at stake No.	net balance in cm WE	no. of ice layers and ice lenses	no. of icy crusts
21	+118	20	1
33	+110	9	2
36	+ 22	0	1

In the profile at stake 21, a massive, 7 cm thick, blue ice layer was encountered, from which a conspicuous percolation cylinder extended 43 cm downwards (fig. 3). The cylinder showed about 35 horizontal layers of alternating clear and increasingly white (bubble rich) layers of ice (cf., also fig. 5). It clearly shows that percolation does occur on the south-exposed part of Colle Gnifetti. However, it seems that in the level part of the col no percolation occurs from one year's accumulation down to the previ-

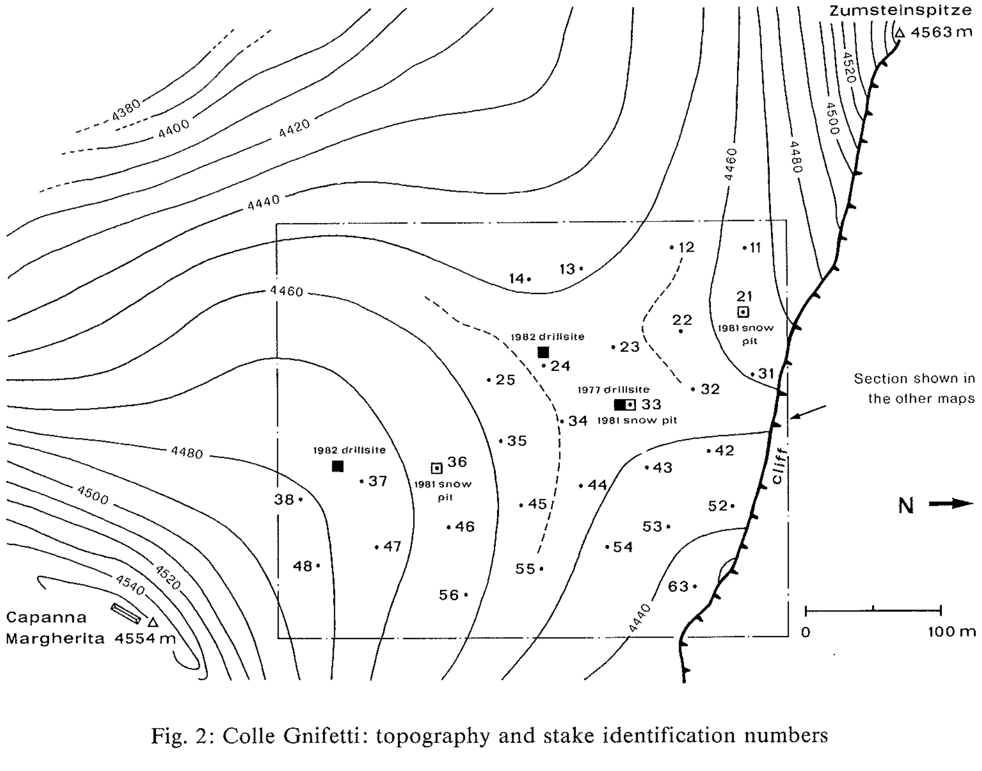

Fig. 2: Colle Gnifetti: topography and stake identification numbers

Table 2: Firn temperature, ram resistance, mass balance and submergence velocity measurements on Colle Gnifetti

stake no.	temperature (2 m)			Ram resistance				balance in cm WE		submergence velocity (cm/yr)
	date in 1980	borehole temp. (° C)	temp.diff. to hole 33 (° C)	average ram resistance (kg)		number of hard layers		17. 8. 80 till 14. 8. 81	14. 8. 81 till 23. 7. 82	
				of top 2 m	80/81 layer	of top 2 m	80/81 layer			
11	14. 8.	− 5.3	+5.0							
12	14. 8.	− 8.0	+2.3							
13	14. 8.	− 9.2	+1.1							
14	14. 8.	−10.1	+0.2					+ 105	− 12	− 122
21	14. 8.	− 8.0	+2.3	18	15.2 ?	7	> 7	+ 118		− 194
22	14. 8.	− 9.8	+0.5	17	16.6	11	11	+ 110		− 132
23	14. 8.	−10.5	−0.2	10	8.4	2	1	+ 103	− 13	− 101
24	14. 8.	−11.5	−1.2	24	12.8	8	4	+ 101	− 12	− 97
25	15. 8.	−10.6	−0.3	9	7.7	3	2	+ 79	− 13	− 105
31	14. 8.	− 7.9	+2.4							
32	14. 8.	− 8.5	+1.8							
33	14. 8.	−10.3	(0)	22	21.3 ?	12	> 12	+110		− 121
34	14. 8.	−10.7	−0.4					+ 103	− 2	− 106
35	15. 8.	−11.0	−0.7	8	8.5	2	2	+ 60	− 14	− 84
36	15. 8.	−11.3	−1.0					+ 21	− 12	− 47
37				13	10.8	1	1	+ 17	− 9	− 60
38	15. 8.	−10.6	−0.3	12	7.3	3	0	+ 26	− 8	− 63
42	14. 8.	− 8.7	+1.6							
43	14. 8.	−11.6	−1.3							
44	14. 8.	−11.0	−0.7					+ 96	− 4	− 114
45	15. 8.	−11.1	−0.8					+ 53	− 17	− 63
46	15. 8.	−10.1	+0.2					+ 13	− 14	− 49
47	15. 8.	− 9.8	+0.5					+ 4	− 11	− 51
48	15. 8.	−10.6	−0.3					+ 24	− 10	− 61
52	14. 8.	− 8.9	+1.4							
53	14. 8.	−10.2	+0.1							
54	14. 8.	−10.6	−0.3					+ 94	− 14	− 114
55	15. 8.	−10.7	−0.4					+ 51	− 15	− 43
56	15. 8.	−10.5	−0.2					+ 11	− 17	− 30
63	14. 8.	− 8.4	+1.9					+ 32		− 84
average		−9.84		14.8	12.1	5.4	4.4	+63.4	−11.6	−87.7
standard deviat.		±1.40		±4.8	±4.8	±4.2	±4.3	±40.5	± 4.1	±39.0

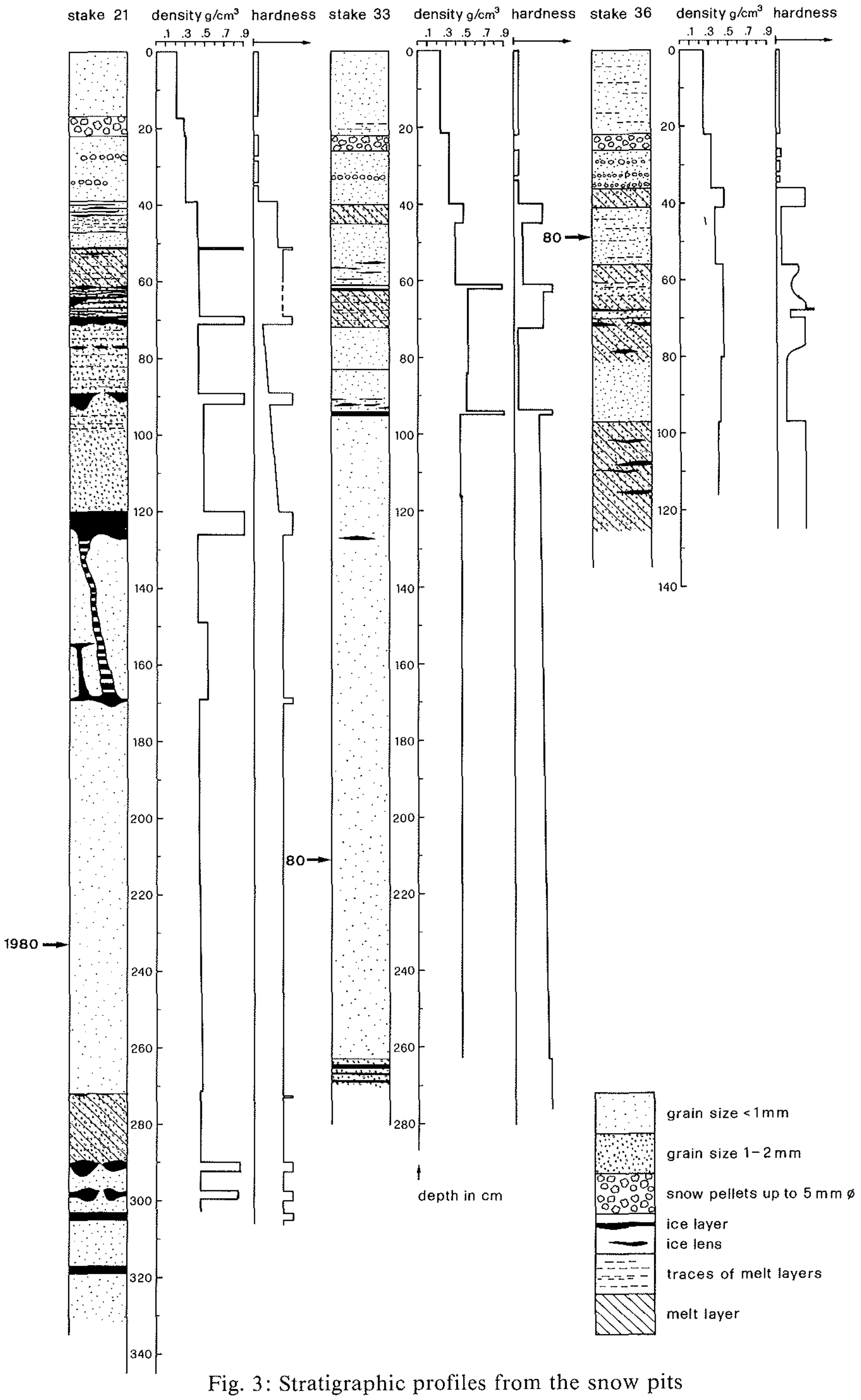

Fig. 3: Stratigraphic profiles from the snow pits

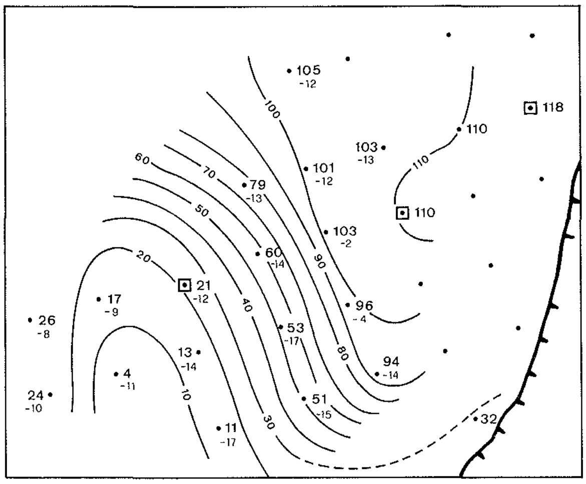

Fig. 4: Net balance in cm WE: Upper numbers near stakes and numbers on lines of equal net balance: balance period 17. August 1980 — 14. August 1981. Lower numbers near stakes: 14. August 1981 — 23. July 1982

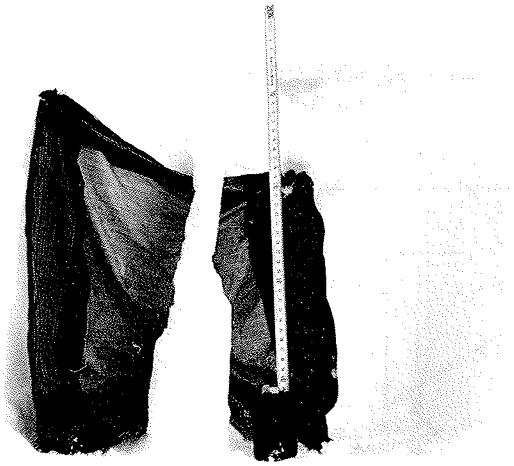

Fig. 5: Percolation cylinder found in the pit near stake 21. The exposed part of the tape is 41 cm long

ous year's. Consequently, the site of the core drillings can be considered to be located near the boundary between the infiltration-recrystallisation zone and the cold infiltration zone (cf., Shumsky, 1964, Haeberli, 1976, Oeschger et al., 1978).

Various snow layers visible near stakes 21 and 33 are missing near stake 36. However, the top two snow layers (the lower of the two consisting of snow pellets up to 5 mm in diameter) were encountered at all three sites, and had approximately the same thickness at each site. At all sites, slight melting within the top layer, but no percolation, was noticed during the exceptionally hot and calm days 13./14./15. August 1981.

The snow density of the top layers (approx. 0.26 g/cm^3) was identical at all three sites. This snow probably fell shortly before and is atypical of the normal variation of thicknesses and density of snow layers on the col. The densities of the deeper layers were somewhat higher (up to 0.50 g/cm^3) at stake 21 and were lowest at stake 36 (as low as 0.36 g/cm^3).

In 1982, Colle Gnifetti was visited on 23. July. Even though further accumulation may have occurred in August, the balance year is taken from 14. August to 23. July 1982. Surface lowering was observed at all stakes. Since significant melting is not expected to occur, wind erosion must have removed all new snow, and even some snow from the previous balance year.

Exposed rock outcrops outside the stake network such as the summits Signalkuppe (4554 m a. s. l.), Zumsteinspitze (4563 m a. s. l.) and Dufourspitze (4634 m a. s. l.) obviously experience no permanent snow accumulation. On the steep, south-exposed slopes of Zumsteinspitze and Dufourspitze intensive melting occurred in August 1981, and small wet snow avalanches slid off both peaks. However, the area of the stake network is well outside the reach of such avalanches.

2.2 SUBMERGENCE VELOCITY

The stakes were surveyed using a theodolite equipped with an electronic distance measuring device; readings were taken in 1980, 1981 and 1982 to an accuracy of ± 1 cm.

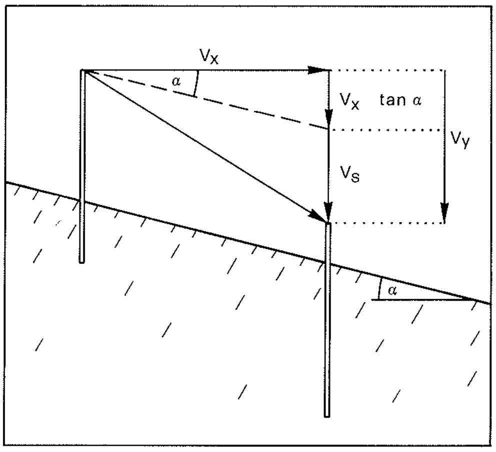

Fig. 6: Explanation of submergence velocity V_S (adapted from Paterson, 1981)

Submergence velocity V_s can be written as:

$$V_s = V_y - V_x \cdot \tan \alpha \qquad (1)$$

where V_y = vertical velocity of stake, V_x = horizontal velocity of stake and α = slope angle at stake. In order to avoid any confusion about the terms used, a diagram given by Paterson (1981, p. 61) is shown in fig. 6, albeit modified for the situation in an accumulation area. Assuming there are only minor changes in surface topography and flow over long periods of time at Colle Gnifetti, the submergence velocities are considered to reflect the long-term average of net balance at the respective positions. More detailed information about these geodetic measurements will be given in a forthcoming paper about the geometry and flow of the Colle Gnifetti firn saddle.

2.3 NEAR SURFACE FIRN TEMPERATURES

Temperature within the Colle Gnifetti firn saddle was measured in boreholes (33 and 60 m deep) drilled in 1976 and 1977. Recent measurements have also been carried out in a borehole which reaches the bedrock at a depth of 124 m. This hole was drilled in 1982. Observed temperatures are slightly below −12° C at the glacier bed, and around −14° C at a depth of 10 to 15 m; at this depth annual variations of temperature are negligable compared to the accuracy of the measurements themselves (Oeschger et al., 1978 and unpublished results).

The distribution of near surface temperatures on Colle Gnifetti was expected to reflect in some way the local variation of solar radiation. High firn temperatures might be found in areas with more intensive melt layer formation.

To study this assumed distributional pattern, temperature measurements were carried out on the 14. and 15. August 1980 in shallow boreholes. These 2 m deep holes were drilled mechanically with the purpose of installing the stakes for accumulation and velocity measurements. Thermistor readings in all boreholes were made exactly 20 minutes after the thermistor (always the same one) had been introduced into the holes to allow for equilibration of boreholes and thermistor temperatures. Open boreholes were protected with wooden planks in order to eliminate any disturbance due to direct

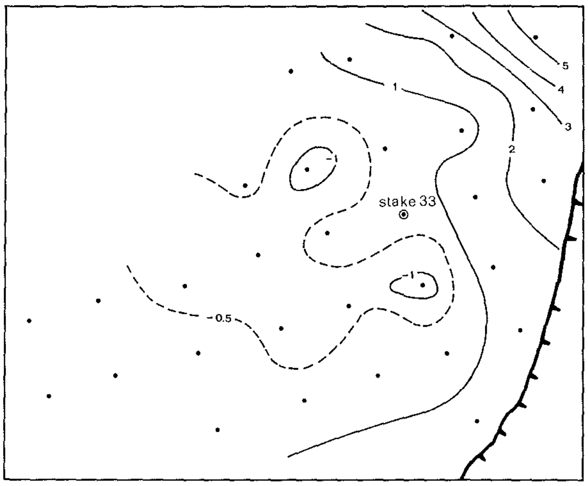

Fig. 7: Relative 2 m-firn temperatures in ° C. The numbers show the difference between measured temperatures and the temperature found at stake 33 (−10.3° C)

solar radiation and drifting snow. The accuracy of the temperature values measured is not exactly known. Temperature differences, however, which are the prime interest in this study, are estimated to be accurate within less than ±0.5° C.

Fig. 7 and table 2 represent the results obtained. Standard temperature (temperature difference = 0) is taken to be the one recorded at the position of the boreholes drilled in 1977 (= stake 33), where the 10 m-depth temperature is −14° C. From fig. 7 it is seen that significant temperature deviations mainly occur at the foot of the Zumsteinspitze, where slopes are exposed to the south. However, near surface firn temperatures do not seem to be a simple function of the slope aspect. Only minor temperature differences are observed at the foot of the Signalkuppe (Punta Gnifetti).

2.4 RAMMSONDE PROFILES

Ram resistance on Colle Gnifetti has been measured before in connection with a snow pit study in 1978 (Haeberli et al., 1983). Thin, hard layers representing wind crusts and refrozen melt layers appeared in the pit profile, and the relatively high average ram resistance values indicated the important influence of wind on the deposition of snow at the core drilling site.

Measurements for 9 rammsonde profiles were made in August 1981 at some stake positions. The main aims of this part of the study were

a) to investigate the possibility of correlating stratigraphic profiles from different places on the Colle Gnifetti by making use of patterns of ice lenses, wind crusts and soft layers in ram profiles (cf. Benson, 1959) and

b) to collect basic information about the distribution of ice layers and their possible relation to snow accumulation and snow temperature. Standard methods were used.

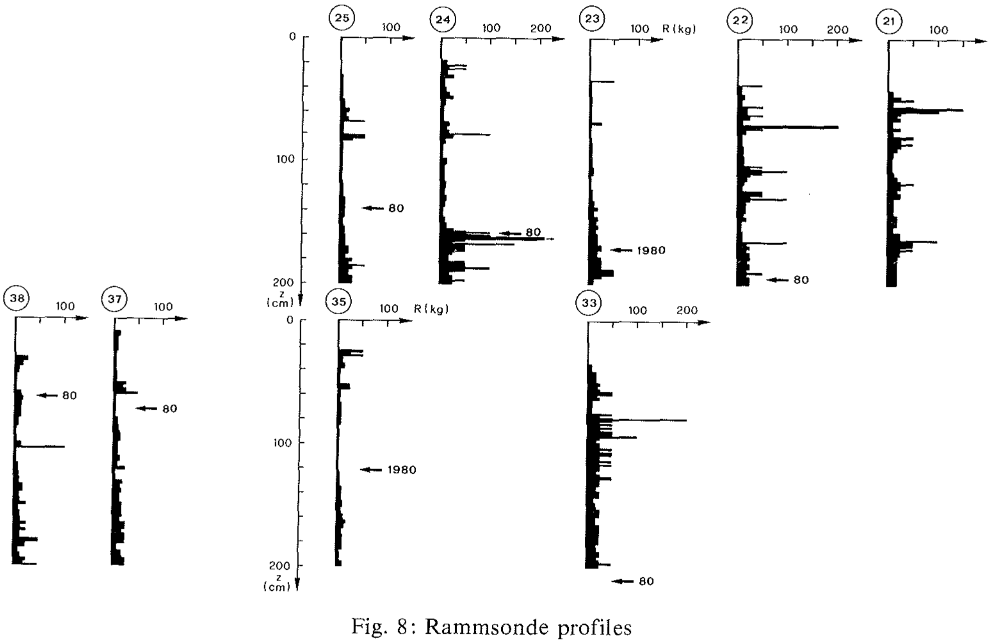

Fig. 8: Rammsonde profiles

Fig. 8 and table 2 illustrate the results. Ram hardness increases in general towards the sunny side of the firn saddle, as does the number of thin, hard layers which most probably represent melt layers. Both, ram hardness and melt layer frequency also seem to parallel the thickness of the snow layer which accumulated in the year 1980/81. There ist, however, one striking exception to this general tendency. Profile 23 has a low average ram resistance and a small number of melt layers despite a thick snow layer from the year 1980/81. The start of the balance year 1980/81 as determined at the stakes installed for accumulation measurements, is not marked by any obvious feature in the ram profiles and striking sequences of melt layers are not easily identified in the different profiles. Ram resistances vary between 7.3 and 21.3 kg within the snow layer accumulated in 1980/81; 0 to more than 11 melt layers or wind crusts had formed in the same layer.

2.5 ESTIMATION OF ENERGY AVAILABLE AT THE STAKES

Since firn temperature and ice layer formation are expected to depend on the amount of solar radiation available at a particular place on the col, an estimation of this energy had to be made. Of greater interest than the absolute values at each stake were the relative differences in the energy available for areas of Colle Gnifetti with different exposures.

Within the energy balance equation (2, given below) the net radiation has, without doubt, the most important influence on these differences:

$$R_n - Q_s - Q_l - Q_g = 0 \qquad (2)$$

where R_n = net (short and long wave) radiation, Q_s = sensible heat flux, Q_l = latent heat flux and Q_g = ground heat flux. The net radiation is itself dependent on the amount of direct shortwave radiation (I_s), since all other components of the radiation balance (3) are relatively little influenced by the exposure of the terrain.

$$R_n = (I_s + I_d) - I_r - I_a - I_{ar} - I_e \qquad (3)$$

whre I_s = direct incoming radiation, I_d = sky diffuse radiation ($I_s + I_d$ = global radiation), I_r = reflected shortwave radiation, I_a = incident atmospheric longwave radiation, I_{ar} = reflected longwave radiation and I_e = emitted longwave radiation.

Since no radiation measurements were done on Colle Gnifetti, a model was used to estimate not only radiant energy received, but also the influence of topography. The calculation of the potential direct incoming shortwave radiation on a horizontal surface is based on extraterrestrial radiation which is reduced by a turbidity coefficient dependent on altitude, time of the day and season (4):

$$I_s = I_0 \cdot \sin h \cdot (1/R^2) \cdot f(z, t, \delta) \qquad (4)$$

where f = turbidity coefficient, I_0 = solar constant, h = solar altitude, t = sun's hour angle, δ = solar declination, z = height above sea level and R = normed distance earth-sun. The turbidity coefficient was determined using an empirical function by Enders (1979), based on measurements done in the Alps by Steinhauser (1939). For the sky diffuse radiation, 11 % of the value of the direct radiation was used. This leads to the diffuse radiation being about 10 % of the global radiation ($I_s + I_d$); this figure is rather an upper limit for a clear sky at the altitude of Colle Gnifetti. Effects of clouds were not simulated.

The calculation of the incoming radiant energy at the points on Colle Gnifetti was done using a digital terrain model with a grid width of 50 m, and a numerical model DISMO (Escher, 1980), modified by Schädler (1982). This combination of programmes enables the incoming global radiation for any point in the terrain model to be calculated at any time. In order to calculate the incoming radiant energy for a particular day, one has to check at regular intervals (for example, every 10 mins) if the sun is above the horizon at a particular grid point. If the sun is visible, then the direct solar radiation as well as the diffuse radiation is taken into account; however, if the sun is below the horizon, only the contribution from the diffuse radiation is incorporated in the calculation. Both components are adjusted according to the slope at the particular location and the direction of the sum by means of the equations (5) and (6):

$$I'_s = \frac{I_s}{\sin h} \cdot \sin \psi \qquad (5)$$

where I'_s = direct short wave radiation over the terrain and ψ = angle between the slope and the direction to the sun.

$$I'_d = I_d \cdot \cos^2 (\alpha/2) \qquad (6)$$

where I'_d = sky diffuse radiation over the terrain and α = slope of the terrain. The sum of all values calculated over a whole day gives the total incoming shortwave radiant energy available at each grid point for the day in question.

Using these values, it is possible to compute the incoming energy for the stake positions where temperature measurements were done (stake positions do not coincide with grid points). In order to be able to study the influence of solar radiation on the temperature of the snow and on accumulation, values of potential radiant energy for days with very different sun positions (21. December, 21. March and 21. June) were calculated. Since local differences are most prominent for 21. December (low sun elevation) this situation is shown in fig. 9.

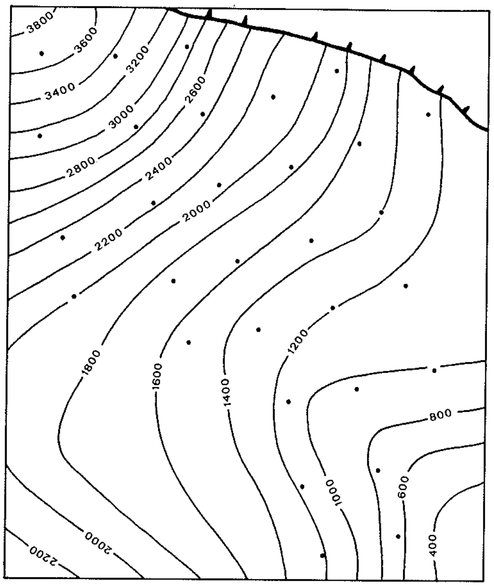

Fig. 9: Total radiation energy as calculated for 15. December in Wh/m²

3. DISCUSSION OF THE RESULTS

Core analysis (taken at the no. 33 site) yielded the following average annual mass balance values (Gäggeler et al., 1983):

Table 3: Average annual mass balance values from core analysis

period	1976 core	1977 core
1953/54 to 1958/59	28 cm WE	—
1958/59 to 1962/63	25 cm WE	30 cm WE
1962/63 to year of drilling	30 cm WE	36 cm WE

The balance year 1980/81 seems to have been one of exceptionally large positive balance (average b_a of 21 stakes: +64.4 cm WE), whereas the negative balance in 1981/82 (average b_a of 17 stakes = −11.6 cm WE) may be an exception also.

The balance measurements for 1980/81 dramatically illustrate the spatial variation of permanent snow accumulation on Colle Gnifetti. It is important to bear in mind that only net balance has been measured. There is, to date, no method of even roughly

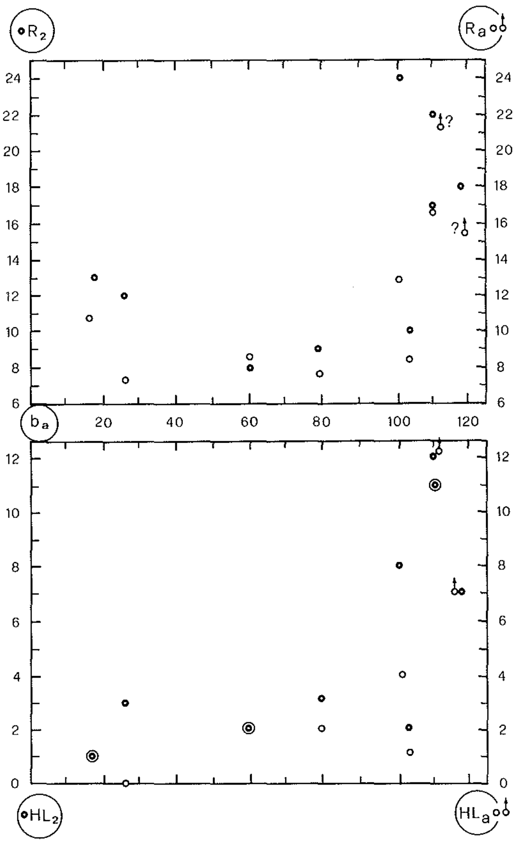

Fig. 10a + b: Ram resistance, number of thin hard layers and specific net balance 1980/81 as measured at the stakes.

b_a = Balance 1980/81 in cm WE

R_2 = Ram resistance of top 2 m in kg

R_a = Ram resistance of 1980/81 layer in kg

HL_2 = Number of thin hard layers ($\geqq$ 50 kg) in top 2 m

HL_a = Number of thin hard layers ($\geqq$ 50 kg) in 1980/81 layer

Arrows mark minimal values for stakes 21 and 33 since the 1980 horizon was below the depth reached by the soundings.

estimating semi-permanent snow deposition and subsequent erosion on the col. Small balance values could be a result of massive wind erosion rather than slight accumulation. Indeed W. Schmid (personal communication) observed sastrugis with a surface area of up to 1 m^2 being torn away during storms in April 1982.

The balance distribution on Colle Gnifetti for 1980/81 clearly shows the highest positive values on the south exposed slope where clearly the most radiation is received and where the thickest and most numerous ice layers or lenses were found in the pits. However, correlation of net balance values with rammsonde profiles is not as clear as expected. The connection between balance and ram resistance or number of thin, hard layers as determined by the rammsonde seems to be of a complex nature (fig. 10a and 10b). Highest ram resistance or largest numbers of hard layers occur in areas with very high mass balance (roughly $b_a > 100$ cm WE). However, no clear relationships are found for places with $b_a < 100$ cm WE. The most obvious (non linear) relation is the one between the number of melt layers per unit time and the balance. This seems to confirm that the frequency of melt layer formation influences the snow erosion and accumulation.

Linear regression analysis was performed on the firn temperature, net balance 1980/81 and the submergence velocity measurements incorporating the calculated radiative energy values. The 1981/82 balance year was not used for this statistical analysis since little meaningful variation in balance occurred between the stakes. The correlation coefficients (r) of this analysis are given in table 4. Non-linear analysis yielded only insignificant improvements of the correlation coefficients.

Table 4: Correlation coefficients (r) of measured and calculated variables on Colle Gnifetti

	b_a	V_s	T	R_m	R_j	R_d (*)	R_y
b_a	1.00	−0.86	0.07	0.80	0.76	0.81	0.82
V_s		1.00	−0.46	−0.83	−0.66	−0.87	−0.85
T			1.00	0.30	0.00	0.44	0.34

b_a = Specific net balance 1980/81
V_s = Submergence velocity
T = Firn temperature (2 m)
R_m = Radiation energy (March)
R_j = Radiation energy (June)
R_d = Radiation energy (December)
R_y = Radiation energy (year)

*: the higher correlations for December do not mean that melt features are formed in winter, but that relief effects may be best simulated by the model with low sun elevation.

The high correlation ($r = -0.86$) between net balance (b_a) and submergence velocity (V_s) shows that despite the unusually large positive values, the balance distribution of 1980/81 must have been fairly representative for the long term balance pattern on Colle Gnifetti.

It seems safe to assume that differences in ice layer formation are mainly controlled by differences in available radiative energy since the variability of sensible heat flux from the air to the snow must be very small within the stake network. Therefore, the higher radiative energy input on the south exposed parts of the col leads to the formation of ice layers or lenses which, later on, protect the snowpack from erosion by wind. In addition, destructive metamorphism and sintering might take place more rapidly also, adding to a higher erosion resistance of the snow on these parts of the col.

These mechanisms are thought to be the reason for the good correlation ($r = 0.76$ to 0.81) of radiative energies calculated with b_a.

Near surface firn temperatures, on the other hand, do not significantly correlate with the calculated radiation values. This apparent paradox can be explained by the fact that radiation values correlate positively with net balances: the larger amount of radiative energy available on the south facing slope needs to heat a much thicker annual snowpack. Differences in air permeability might also be important.

It seems improbable that the observed balance gradient can be attributed to higher snow deposition in the lee of the Zumsteinspitze brought about by northern winds, since the saddle is open to the east and to the west.

4. CONCLUSIONS

The results of this study may help (a) to understand the variation of net balance on Colle Gnifetti, (b) to interpret the ice core data more accurately and (c) to better understand processes in high glaciers in general.

(a) The very large variation of net balance on Colle Gnifetti over horizontal distances of only a few hundred meters can to some extent be attributed to the formation of ice layers and ice lenses on the south exposed part of the col. These melt layers effectively protect parts of the fallen snow from wind erosion. Hence, snow accumulation is related to solar radiation which favours melt layer formation. However, firn temperature and solar radiation are not correlated in a simple way. This is the main break in the chain of links between the considered parameters.

(b) The high local variation in net balance is also evident from the submergence velocity of glacier flow. It must be taken into account when interpreting data from ice core sections which originate more than a few tens of meters below the surface. Because of flow the lower sections of the core indeed originate from parts of Colle Gnifetti with different accumulation rates and snow characteristics than at the surface near the drill site.

Solar radiation can be considered to be the main factor influencing the variation in *space* of available energy and of snow characteristics on Colle Gnifetti. However, variations in *time* of snow characteristics and of climatic parameters are essential in ice core studies. At a given place, variations of air temperature may be as important as variations of radiation, but the effects of both parameters on ice layer formation and snow accumulation may be assumed to be similar. Results of the present study suggest that variations in the melt layer occurrence within ice cores are not only expressions of variation in heat applied to the snow surface (cf. Herron et al., 1981) but could also be related to accumulation rates and, hence, to the time scale of the ice cores. Moreover, variations in the heat applied to the surface do not necesarily show up markedly in firn temperature profiles, because more extensive melt layer formation may lead to higher accumulation rates. Thereby the influence of melt layer formation on firn temperature can be cancelled to a certain degree.

(c) Climatic variations are expected to have a considerable influence on the mass balance of high altitude glaciated areas in general; an increase in temperature, for example might lead to a pronounced increase of positive net balances, thus leading to a larger mass turnover. High hanging glaciers might eventually respond with an increased ice avalanche activity.

ACKNOWLEDGEMENTS

This study was carried out as a part of the research programme of the Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie (Professor Dr. D. Vischer) of the Eidgenössische Technische Hochschule, Zürich, Switzerland. Thanks are due to Professor Dr. H. Röthlisberger and Dr. D. Wagenbach for encouragement and criticism and to Dr. P. Felber, B. Ott and W. Schmid for their participation in the field work. P. Alean assisted in the preparation of this publication and Werner Nobs prepared the drawings.

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Manuscript received March 29, 1984

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