TEMPERATURE AND ACCUMULATION OF HIGH ALTITUDE FIRM IN THE ALPS

by

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ABSTRACT

Data on temperature and accumulation of high altitude firm in the Alps are compiled and discussed. Firm temperature varies with incoming radiation (slope aspect) at a given altitude. The altitudinal gradient of temperature in highly permeable firm bodies appears to be about twice as high as the mean lapse rate of air temperature. "Cold infiltration" takes place above about 3500 m a.s.l. Firm temperatures on the highest peaks are around -15°C. Accumulation (net balance) also decreases with increasing altitude from about 3 m H2O at 3500 m a.s.l. to around 0.5 m H2O at wind exposed sites between 4300 and 4800 m a.s.l. Probably this is strongly due to wind erosion and topographical effects. However, temperature and accumulation not only appear to be interrelated, but also seem to be positively correlated to temperature. "Cold infiltration" takes place above about 40 m below the surface (Schotterer and others 1981). The firm-ice transition in this cold firm saddle occurs about 40 m below the surface (Schotterer and others 1981). When presently-known firm temperatures are compiled (Figure 1) two groups seem to exist. Group I incorporates summits, crests and probably also very steep slopes which mainly consist of impermeable ice or high density firm with high concentrations of ice layers. Temperatures in such ice bodies decrease with increasing altitude at a rate (about 1°C/100 m) which is slightly higher than the assumed lapse rate of mean annual air temperature (0.65°C/100 m). No temperate firm bodies are known in such situations. In contrast, more gentle slopes and basins (group 2) where highly permeable firm accumulates, are temperate up to about 3600 m a.s.l. Above this upper boundary of the "warm infiltration zone" of the Alps, percolating meltwater cannot have been compiled by Haeberli (1976, cf also Hooke and others 1983). New information is available from Chli Titlis, Jungfraujoch, Sphinxgrat and Monte Rosa/Colle Gnifetti (all Swiss Alps). At Chli Titlis, 3070 m a.s.l., 15 m-temperature in the summit's 22 m thick firm and ice was -0.7°C (1979/80, cf. Haeberli and others 1979). Temperatures in the Sphinxgrat crest were measured in a 70 m borehole through firm, ice and perennially frozen rocks, in connection with recent construction work at the Jungfraujoch. The ice-rock interface, 10 m below the surface at 3525 m a.s.l., had a temperature close to -6°C (1981). Temperatures around -14°C at 15 m depth were registered in all core drilling boreholes made so far on Colle Gnifetti (4450 m a.s.l.). The firm-ice transition in this cold firm saddle occurred about 40 m below the surface (Schotterer and others 1981).

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completely warm up the firn bodies any more. Here in the "zone of cold infiltration" (Shumskii 1964), firn temperatures decrease with altitude at a rate which is at least twice the lapse rate of mean annual air temperature. At Colle Gnifetti, refrozen melt layers are commonly observed in snow layers which have been deposited during the same year (infiltration/recrystallization), and in some years no melt layers may form at all (dry snow zone). Melt layer formation is the exception rather than the rule on top of Mont Blanc, the highest point in the Alps. Mean firn temperature there is very close to the mean air temperature.

Details observations within a stake network around the core drilling site on Colle Gnifetti, Monte Rosa, throw more light on the connection between the variability of firn temperature and accumulation at a given altitude (cf. Alean and others 1983). Figure 2 illustrates the variability of some important parameters across the firn saddle which is exposed to strong winds, predominantly from the west. Firn temperature increases towards the sunny side of the col, as does the amount of available radiant energy and the number of refrozen melt layers. At a given altitude, therefore, firn temperature (local variability ± 2 to 4°C) seems primarily to depend on incoming solar radiation (slope and aspect). Latent heat exchange through percolating and refreezing meltwater thereby appears to be an important factor. However, the relation between energy input, melt layer formation and firn temperature is less clear than expected, because energy input and melt layer formation also seem to be correlated with accumulation.

**ACCUMULATION**

Accumulation (net balance) at high altitudes has been determined in only a small number of cases up to now. Figure 3 is a compilation of information available from Jungfraufirn/Aletsch glacier (Aellen and Rothlisberger 1981) and the Southern Hanging Glacier of Mönch (Alean 1983), from Jungfraujoch (Ambach 1969), from several places in the Mont Blanc area (Lliboutry and others 1976), and from Colle Gnifetti/Monte Rosa (Alean and others 1983). Below about 3500 m a.s.l. accumulation usually increases with increasing altitude because of higher amounts of solid precipitation and less melting. The highest mean accumulation rates in the Alps (around $3 \text{ m H}_2\text{O}$) have been measured at 3500 to 3550 m a.s.l. (Jungfraufirn and Vallée Blanche/Mont Blanc). At even higher altitudes, considerably smaller accumulation rates were observed. Values in the order of $0.5 \text{ m H}_2\text{O}$ seem most common at 4300 to 4800 m a.s.l.

Extreme local variability of accumulation rates can be observed at a given altitude. A detailed study around Colle Gnifetti core drilling site (Figure 2, cf. Alean and others 1983) indicates that melt layers protect the snow from wind erosion and that energy input and melt layer formation are probably positively correlated with net balance at wind exposed sites. In 1980/81, net balance on Colle Gnifetti varied between almost 0 in north exposed positions to more than $+1 \text{ m H}_2\text{O}$ on the sunny slope. In the following year probably only negative balance values occurred. This pronounced variability of accumulation is certainly due to wind effects and snowdrift. Accumulation rates are lower on wind-exposed crests and saddles than in protected places (slopes and basins), the latter becoming rare at very high altitudes. This may explain a major part of the decrease of accumulation with altitude above about 3500 m a.s.l.

**DISCUSSION AND CONCLUSIONS**

Despite the great scatter of the measured values, there appears a clear tendency for firn temperature and accumulation to decrease with altitude above the upper boundary of the "warm infiltration zone" in the Alps. In the case of firn temperatures, this altitudinal change can easily be assumed to be mainly the effect of decreasing air temperature (mainly by latent heat exchange from percolating and refreezing meltwater). The reasons for the decrease of accumulation with altitude are probably more complex. High wind speeds and a less suitable topography around mountain peaks certainly have an important influence. However, a temperature effect is also likely to exist, because cold and dry snow at high altitudes is more easily eroded by wind than temperate firn containing refrozen melt layers. This means that the temperature and accumulation of firn at high altitudes could be interrelated to some degree, and that both could be positively correlated to the heat applied to the surface. Similar observations are known from polar regions (Loewe 1970; Herron and Langway 1980).

It remains difficult to reach a better understanding of the complex processes and interactions behind the observed phenomena until more detailed information is available. However, the obvious influence of air temperature on firn temperature and probably even on accumulation might lead to speculations about developments in time. Mean annual air temperature has
risen by about 0.5 to 1.0 °C in the Alps since the last
century (Rudloff 1980). Correspondingly, temperature of
high altitude firm bodies may have increased by about 1
to 2 °C. A continuation or even acceleration of this
trend (e.g., as a consequence of CO₂-induced atmospheric
warming) could raise firm temperatures by several
degrees within a few decades and shift altitudinal belts
such as the "zone of warm infiltration" by several
hundred meters. If accompanied by a corresponding
increase in accumulation rates, such a development
would lead to a considerable change of mass turnover
and activity of high altitude ice bodies in the Alps.
However, since the processes involved are complex and
only few data are available, firm conclusions are
difficult to draw.

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