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Isotopic analysis of the snow cover at an alpine glacier as an indicator of local climatic variations and isotopic homogenization processes

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Abstract Stratigraphic variations of $^{18}O/^{16}O$ ratios of winter-accumulated snow at an alpine temperate glacier correspond to temporal patterns of local climatic variations. Although the snow is influenced by percolation and homogenization processes, the isotope stratigraphy in the glacier's accumulation area is not destroyed during the first part of summer. Below the equilibrium line altitude, rapid melting results in isotopic homogenization. Variation of $\delta^{18}O$ values in the firn are relatively small.

Key words isotopic analysis, snow cover, alpine glacier, climatic change.

1 Introduction

For some four decades, seasonal changes of the isotopic composition of deposited snow at polar ice caps have been used to date glacier ice and to determine past climatic conditions. In contrast, there have been few reports about isotopic composition of snow at alpine glaciers in relation to climatic conditions, principally because of the effects of meltwater percolation on the isotopic stratigraphy (Wagenbach 1989). Here, we discuss observations made at Austre Okstindbreen (66°00′N, 14°16′E), the largest glacier of Okstindan area, Norway, which covers about 14 km^2 between 1700 and 730 m above sea level (Fig. 1). The mean equilibrium line altitude (ELA) is about 1200 m.

Studies at Austre Okstindbreen have been made as a major part of Okstindan Glacier Project since 1976. Observations of stable isotopes and chemical ions in the glacier river (Theakstone 1988, Theakstone and Knudsen 1989, 1996a,b) and of the chemistry of the snowpack (He and Theakstone 1994, Raben and Theakstone 1994) have been reported. In July 1990, samples of snow and firn were collected at Austre Okstindbreen to elucidate problems concerning (1) Isotopic variations during snow accumulation on an alpine temperate glacier and their relations to changes of local climatic conditions, (2) The influence of meltwater percolation on the isotopic composition of snow at different altitudes, and (3) Processes of homogenization of the isotopic composition of melting

snow and firn. The investigations reported here were made at two sites, one above and one below the ELA (Fig. 1), They were part of a programme in which the isotopic composition of snow and firn present in different zones was related to climatic conditions (He 1993*). Samples were analyzed at the Geophysical Isotopic Laboratory of the University of Copenhagen. All samples of isotopes were measured twice, to get an accuracy of 0.6‰.

2 The sampling programme

Site 90.1 was at 1350 m (Fig. 1). A pit, 1.8 m deep, was excavated on 20 July and a core, 4.7 m deep, was also taken from the base of the pit to the underlying glacier ice. Sixty-five samples, each 0.1 m long, were collected from the pit wall and core. The 6.5 m deep profile (Fig. 2) provided the most significant data set from the glacier's accumulation area, as it included continuous and detailed data from two balance years of 1988/1989 and 1989/1990. The previous summer's surface was identified at a below-surface depth of 4.1 m, where there was a marked change of snow structure; its location was confirmed by extensive snow depth sounding undertaken as part of the annual mass balance programme at the glacier (Knudsen 1991). The isotopic composition of the material changed at the level of the 1989 summer surface.

The variations of oxygen isotope ratios in the snow were more complex than those in the underlying firn, with large differences of $\delta\,^{18}O$ values above 4.1 m depth (Fig. 2). In contrast, variations in the underlying firn were relatively small. The upper part of the firn was characterized by a progressive downwards enrichment in the heavy isotope, ^{18}O, whilst isotopic homogenization was evident in the lowest metre of the core. The mean $\delta\,^{18}O$ value of the 1989/1990 winter snow was −11.67‰ and that of the underlying firn was −10.96‰.

Site 90.2 was at 1000 m (Fig. 1). A pit, 1.96 m deep, was excavated to glacier ice on 16 July, and 39 samples, each 0.05 m long, were collected from the wall. Variations of $\delta\,^{18}O$ values were larger in the uppermost metre of the snowpack than that at greater depth (Fig. 3a). Ten days later, a second set of samples was collected. The thickness of the snowpack had decreased by 0.94 m, principally as a result of melting, although a small part of the change may have resulted from compaction. Ten of the eleven samples collected on 26 July were 0.1 m long; the length of the other samples was 0.06 m (Fig. 3b).

3 Isotopic variations in the snowpack and local climate variations

There are no permanent high-altitude meteorological stations in the Okstindan area. Accordingly, climatic data from Mo I Rana (30 m above sea level), about 28 km north of the glacier, have been used to present trends at Austre Oksindbreen. Data from an automatic weather station which was operating at an altitude of 1350 m within the

* He YQ (1993): Ph. D thesis: Isotopic, ionic and physical studies of snow and firn at the glacier Austre Okstindbreen, Okstindan, Norway, in relation to local climatic variations and to regional atmospheric circulations. The University of Manchester, England.

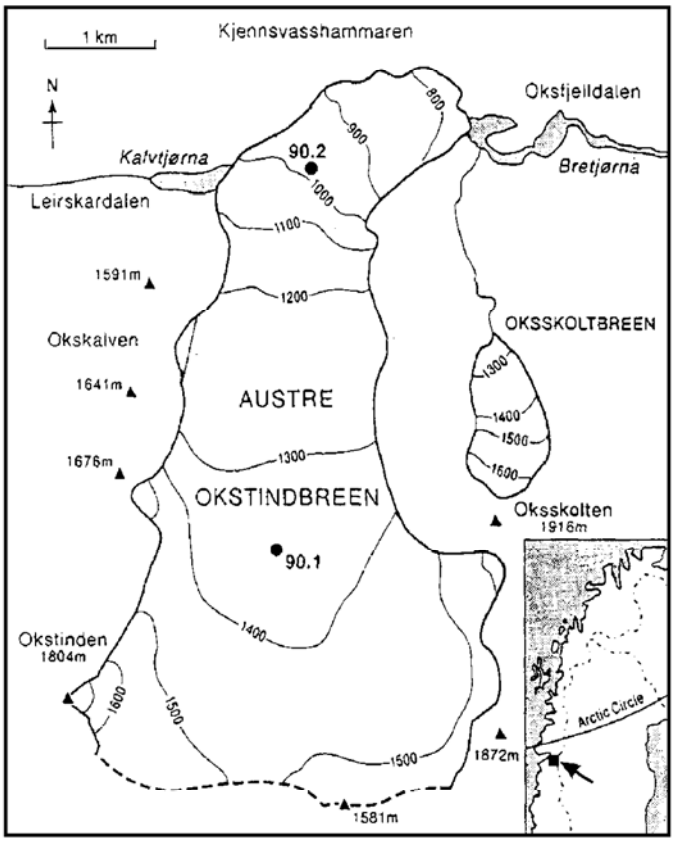

Fig. 1. The glacier Austre Okstindbreen, with the two sampling sites. Contours are in metres.

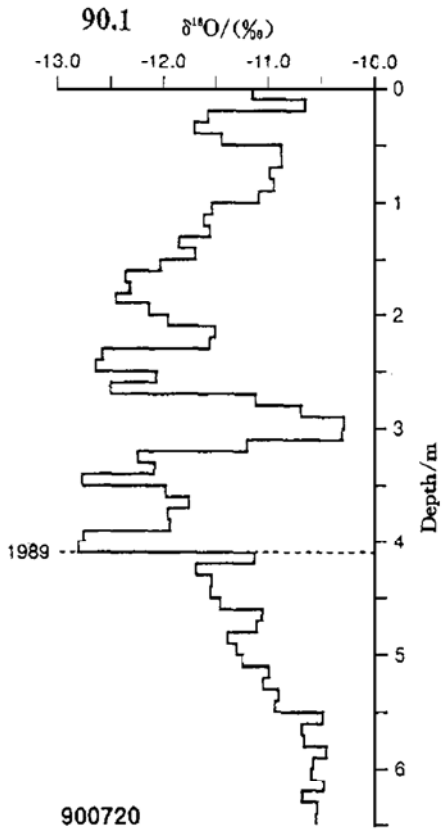

Fig. 2. Stratigraphic variations of $\delta^{18}O$ values at site 90.1, Austre Okstindbreen, 20 July 1990. The 1989 summer surface was at a depth of 4.1 m.

glacier's catchment during previous winter and summer seasons displayed a good correlation with data from Mo I Rana for the same period. Monthly mean temperature (T_m) at Mo I Rana for the accumulation season of the 1989/1990 mass balance year (October 1989 — May 1990) are shown in Table 1.

Table 1. Mean monthly temperatures (T_m), proportion of 1989/1990 winter (October — May) precipitation at Mo I Rana (P_m), and calculated monthly snow accumulation (S_m) at site 90.1, Austre Oktindbreen

Month	T_m/C	P_m/%	S_m/m
October	4.0	13.1	0.71
November	0.0	8.1	0.43
December	4.9	18.5	1.00
January	−4.5	10.0	0.54
February	1.4	16.9	0.91
March	0.5	17.6	0.95
April	3.5	12.7	0.69
May	6.4	3.2	0.17

The depth of the total winter-accumulated snow at Austre Okstindbreen was measured in May 1990, as part of the annual mass balance programme (Knudsen 1991); at site 90.1, the snow depth was 5.4 m. Monthly snowfall (S_m) was calculated as the product of this value, based on the percentage of the October — May precipitation for

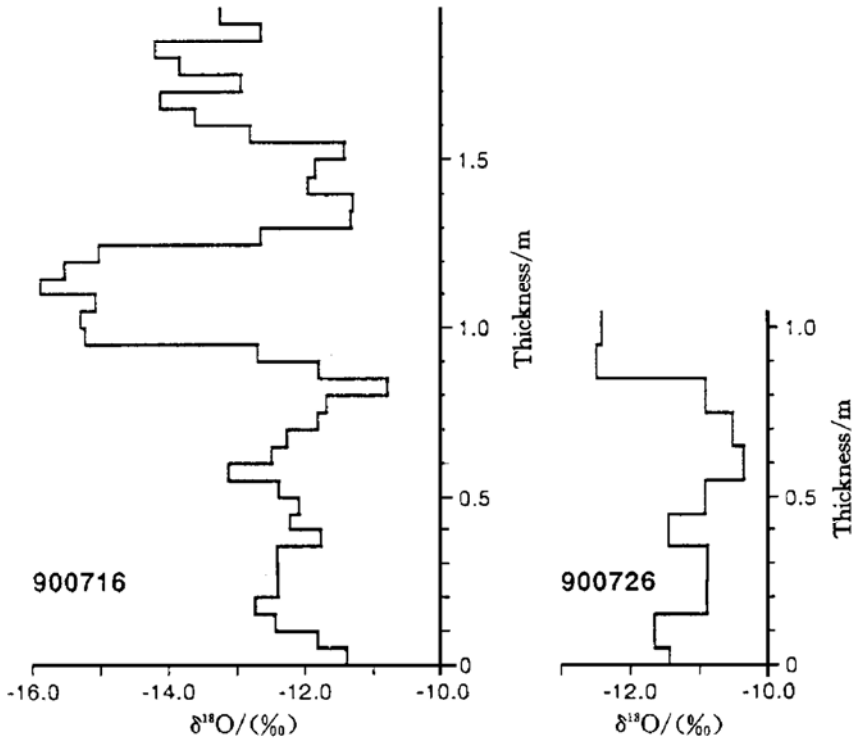

Fig. 3. Stratigraphic variations of $\delta^{18}O$ at site 90.2, Austre Okstindbreen, 16 July and 26 July 1990. Surface melting make snowpack thickness to reduce 0.94 m within 10 days.

each winter month at Mo I Rana (P_m) (Table 1). The relation between T_m and S_m is plotted in Fig. 4, together with the isotopic profile. The figure is based on the assumption that snow began to accumulate at the beginning of October and continued until the mass balance measurements in May; the effects of snow compaction are neglected.

Vertical variations of $\delta^{18}O$ values in snowpack profiles reflect temporal changes of air temperature during precipitation, the effects of percolating meltwater and the tendency towards isotopic homogenization of the snow stratigraphy. The isotopic variations within the uppermost 4.1 m of the snowpack at site 90.1 are related to the mean monthly temperatures. Temperatures in December and January were lower than those during the earlier part of the winter, and this is reflected in the lower $\delta^{18}O$ values from 1.2 m to 2.7 m above the 1989 summer surface, whist the increase of $\delta^{18}O$ values from 2.7 m to 3.6 m is related to the warmer conditions of February (Fig. 4). Because the mean temperature in March was lower than that in February, the $\delta^{18}O$ values are lower between 3.6 m and 3.8 m. The 1.4 m of snow which accumulated in April and May probably melted during June and July before samples were collected, and meltwater percolation is likely to have affected the $\delta^{18}O$ values at the top of the residual pack. Nevertheless, it is evident that the isotopic variations in the snow stratigraphy do reflect the general trends of air temperature at Mo I Rana between October 1989 and March 1990.

At site 90.2, almost a metre of snow melted during the ten days between collection of the two sets of samples; melting and meltwater percolation was accompanied by isotopic homogenization of the residual pack (Fig. 3). The variability of $\delta^{18}O$ values in

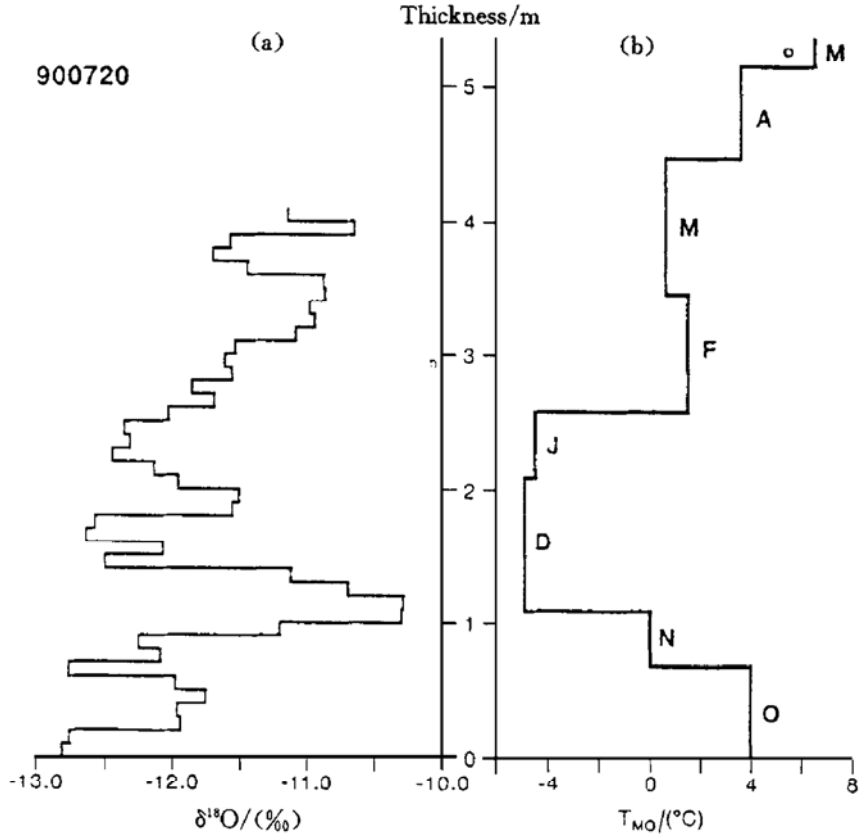

Fig. 4. Calculated October — May monthly snow accumulation at 1350 m and mean winter monthly temperatures at Mo I Rana in relation to the isotopic composition of the residual 1989/1990 winter snowpack at site 90. 1 on 20 July 1990.

the pack decreased as the mean increased from −12. 80‰ on 16 July to − 11. 25‰ on 26 July.

4 Discussion

The distribution of $\delta^{18}O$ values in accumulated snow changes as a result of processes of meltwater percolation and associated isotopic homogenization (Stichler 1987), but phases of melting and homogenization do not occur above the ELA (1200 m) during the winter at Austre Okstindbreen, and observations have shown that there are major stratigraphic differences in the snowpack for several weeks after the onset of surface melting (Raben and Theakstone 1994). The varitions of winter mean monthly temperature at Mo I Rana are reflected in the isotopic composition of the snowpack at Austre Okstindbreen deposited at the same period. Deviations from a simple relationship are to be expected because of the different altitudes and locations of the glacier and weather station, and because some spatial and temporal variability must characterize both the isotopic variations in accumulated snow and mean monthly temperatures between them: local geographcal conditions, such as topography and elevation, will influence the relationship between isotopic distributions at the glacier in winter and temperature changes at the meteorological station which is at a distant position and much lower altitude.

In contrast to the overlying stratigraphy, the variations of $\delta^{18}O$ values in the 2.4 m of firn between 4.1 m and 6.5 m depth at site 90.1 were slight (Fig. 2), indicating clearly the effects of homogenization of old snow which is at the melting point proceeds rapidly during the ablation season at lower altitudes on the glacier, as witnessed by the changes in ten days of intense ablation in July at site 90.2 (Fig. 3).

5 Conclusion

Although the relation between $\delta^{18}O$ values in the snowpack and mean monthly temperature during the winter (T_m) probably were affected by many natural factors, the isotopic variations above the ELA at Austre Okstindbreen provide fundamental information about the monthly periodic trends of local air temperature changes during the period of snow accumulation. Thus, the oxygen-isotope record in temperate snow at an alpine glacier is a satisfactory indicator of local climatic conditions, especially of local temperature variations, although it is likely to be influenced by more factors as compared with the records at polar glaciers. Isotopic research in the accumulation area of alpine glaciers can be used as a supplementary method for local climatic analysis where no climatic records exists. The isotopic record in temperate snow and firn during the ablation season changes as a result of meltwater percolation, but the effects in old snow after about one month of ablation at 1350 m at Austre Okstindbreen are not marked. However, isotopic homogenization is pronounced in firn less than 2 m below the previous summer's surface, and the degree of homogenization is likely to increase with time. Where ablation rates are relatively high, changes of isotopic composition and associated homogenization of old snow are apparent within a very short period of melting.

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