

**Changes of Ionic and Oxygen  
Isotopic Composition of the Snowpack  
at the Glacier Austre Okstindbreen, Norway, 1995**

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Marked vertical variations of ions and oxygen isotopes were present in the snowpack at the glacier Austre Okstindbreen during the pre-melting phase in 1995 at sites between 825 m and 1,470 m above sea level. As the first meltwater percolated from the top of the pack, ions were moved to a greater depth, but the isotopic composition remained relatively unchanged. Ions continued to move downwards through the pack during the melting phase, even when there was little surface melting and no addition of liquid precipitation. The at-a-depth correlation between ionic concentrations and isotopic ratios, strong in the pre-melting phase, weakened during melting. In August, concentrations of  $\text{Na}^+$  and  $\text{Mg}^{2+}$  ions in the residual pack were low and vertical variations were slight;  $^{18}\text{O}$  enrichment had occurred. The difference of the time at which melting of the snowpack starts at different altitudes influences the input of ions and isotopes to the underlying glacier.

## **Introduction**

Seasonal snow covers can be significant in the chemical dynamics of ecosystems in many temperate, alpine and subarctic regions (Unsworth and Fowler 1988). Dozier *et al.* (1991), discussing chemical processes in snow, noted that "In the future we must move towards larger scales – catchment, regional, global." The concentrations of ionic species in accumulated snow and the isotopic composition of the pack reflect the prevailing climatic/atmospheric conditions (He and Theakstone 1994), and short-term records of snow chemistry (single events to months) sampled over a wide

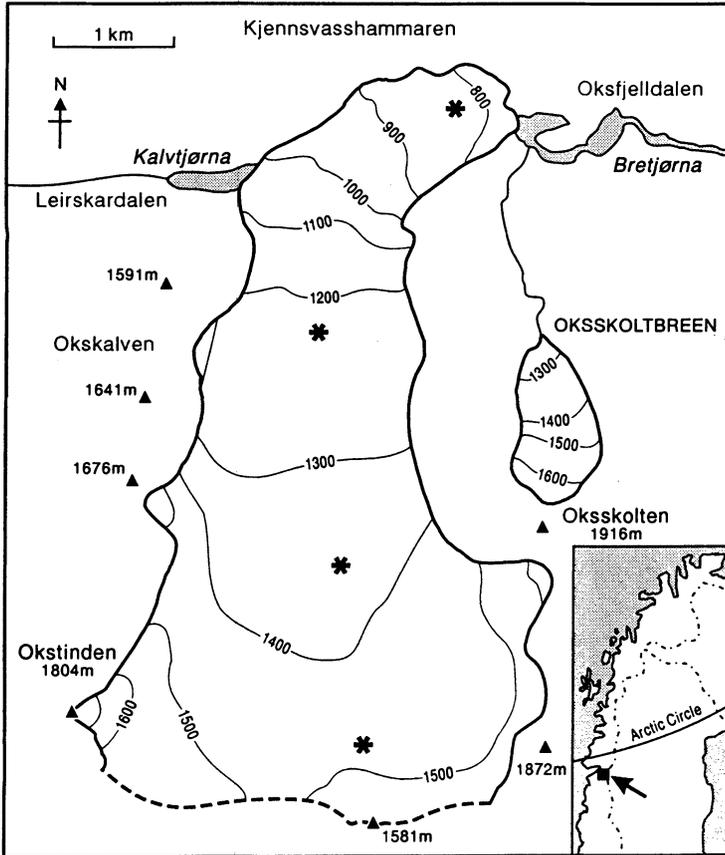


Fig. 1. The positions of snow sampling sites (\*) used in 1995 at the glacier Austre Okstindbreen.

spatial range (lateral and elevational) provide the basis for identifying discrete source areas and understanding the underlying processes responsible for the spatial variation in the chemical content of snow (Lyons *et al.* 1991). The relationship between changing micro- and macro-climatic conditions and the chemistry of the snowpack at the glacier Austre Okstindbreen is being investigated in a multi-year programme by the Okstindan Glacier Project. Studies of changes of ions and oxygen isotopes in the snowpack at different altitudes during the pre-melting stage and the first part of the 1995 melt season are reported here.

Austre Okstindbreen is the largest glacier (14 km<sup>2</sup>) of the Okstindan area, Norway, 40 km south of the Arctic Circle, at 66°01'N 14°18'E (Fig. 1). The highest parts of its accumulation area are more than 1,650 m above sea level, but most of the glacier surface is below 1,500 m. The glacier terminates at 730 m. The total 1994-95 winter-accumulated ionic inputs to the glacier catchment have been calculated (Ra-

ben and Theakstone 1997). The proximity of the Okstindan area to the Atlantic Ocean results in relatively-high inputs of sea-salt ions ( $\text{Na}^+$ ,  $\text{Mg}^{2+}$ ,  $\text{Cl}^-$ ), as either wet or dry deposition on the snowpack. The thickness variations of the snow layer deposited during a single event are relatively slight; in large part, they are determined by the local variations of surface topography, as drifting tends to smooth out irregularities. Horizontal at-a-site variations of both the ionic and the isotopic content of the snowpack are much less pronounced than the vertical variations, and the stratigraphic variations generally can be recognised when sets of samples are collected within a few weeks at sites which are a few metres apart (Raben and Theakstone 1994).

### **Study Sites, Sample Collection and Analytical Methods**

In 1995, more than 600 snow samples were collected between late-April and mid-August at four sites along the centre line of Austre Okstindbreen at 825 m, 1,230 m, 1,350 m and 1,470 m. The surface gradient was approximately  $10^\circ$  at 825 m and less than  $2^\circ$  at the other sites. Seasonal melting began on the lower part of the glacier at the beginning of May, but a cold period followed in mid-May. Melting on the upper part of the glacier began in late-May, as the temperature at the Okstindan Glacier Project base station (860 m a.s.l.) increased from around  $2^\circ\text{C}$  to  $10^\circ\text{C}$  (Fig. 2). High temperatures during the following days resulted in near-continuous melting conditions.

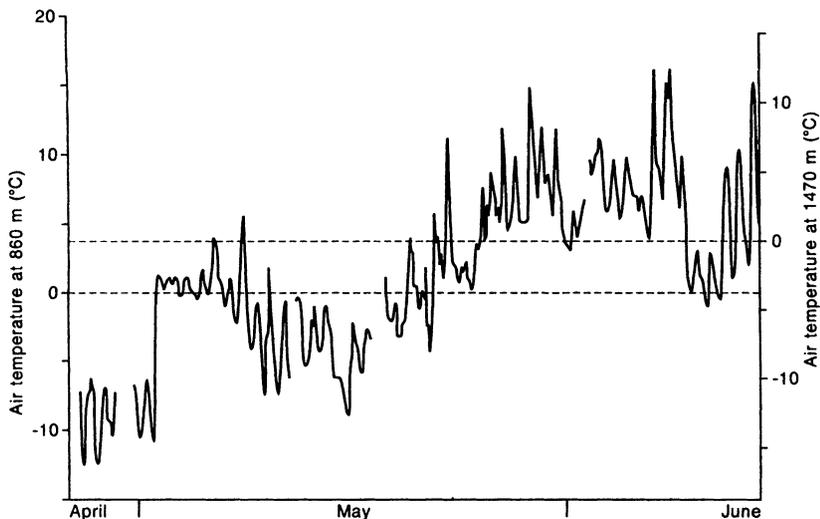


Fig. 2. Air temperatures at the Okstindan Glacier Project field station at 860 m above sea level. Temperatures at 1,470 m are estimated from the lapse rate,  $0.6^\circ\text{C}$  per 100 m.

When the pits were excavated in late-April, glacier ice was covered by snow to depths of 2.70 m and 2.33 m at 825 m and 1,230 m respectively. The two highest pits (1,350 m and 1,470 m) were taken to about 3 m below the surface and the underlying snow was sampled using a lightweight Polar Institute Core Office corer. The 1994 summer surface was found at a depth of 6.0 m (1,350 m pit) and 7.0 m (1,470 m). Samples from the top of the firm (1993-94 snowpack) were collected at each site.

On each visit to a site, the pit was extended sideways by 1 m and the depth and density of the snowpack were measured before samples were collected. At 825 m and 1,230 m, the surface of the underlying glacier ice was used as a reference datum; at 1,350 m and 1,470 m, the datum was the 1994 summer surface. Samples with a cross-section of 0.12 m x 0.12 m were taken downwards from the surface at the pit wall not exposed to direct solar radiation. The length of each sample except that at the top of the sequence was 0.10 m; the length of the uppermost sample varied with the overall thickness of the pack. A 0.20 m increment was used for samples collected by coring at the two highest sites. This strategy enabled samples to be taken in almost exactly the same position within the pack on each visit. Depth and density measurements confirmed that the compaction which occurred between visits was slight in relation to the sample length.

The density, temperature, liquid water content by volume, and visible stratification, including ice layers or lenses, were recorded each time the snowpack was sampled. Temperature (accurate to  $\pm 0.1^\circ\text{C}$ ) and liquid water content (error close to  $\pm 5\%$ ) were measured at intervals of either 0.05 m or 0.10 m. Density (estimated error about  $\pm 5\%$ ) was determined in 0.24 m increments. Protective clothing was worn during sampling, to avoid contamination. Samples were allowed to melt in sealed polythene bags before being transferred to pre-cleaned polyethylene flasks and vials. Before transport to the laboratories, they were kept in snow at  $0^\circ\text{C}$  in black plastic bags to prevent penetration of daylight. At the laboratories, samples were stored in a dark room at  $2\text{--}4^\circ\text{C}$ . Because of the low particulate content in the snow, filtration was not carried out.

The concentrations of the four major cations ( $\text{Na}^+$ ,  $\text{K}^+$ ,  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ) in all samples were determined by atomic absorption spectrometry at the Aarhus University Geological Institute, Denmark, and the University of Manchester Department of Geography, England. The detection limits of the cations  $\text{Na}^+$  and  $\text{Mg}^{2+}$  were  $0.001$  and  $0.003 \text{ mg L}^{-1}$ , respectively, with an error of  $\pm 5\%$ , whereas detection limits of  $\text{K}^+$  and  $\text{Ca}^{2+}$  were  $0.01$  and  $0.05 \text{ mg L}^{-1}$ , respectively, with an error of  $\pm 10\%$ . Values of both  $\text{Na}^+$  and  $\text{Mg}^{2+}$  in the pack generally were well above the detection limit. The content of  $\text{K}^+$  and  $\text{Ca}^{2+}$  generally was close to the detection limit, and these two elements therefore are not used here in describing in detail the movement of ions. Some 200 snow samples were analysed for three anions ( $\text{Cl}^-$ ,  $\text{NO}_3^-$ ,  $\text{SO}_4^{2-}$ ) by ion chromatography at the University of Manchester Department of Earth Sciences; the detection limit was  $0.05 \text{ mg L}^{-1}$ , with an error of  $\pm 5\%$ . The concentrations of  $\text{Cl}^-$  and  $\text{SO}_4^{2-}$  generally were above the detection limit.  $\text{NO}_3^-$  concentrations were close to the de-

tection limit and the ion was not used in the study reported here. Oxygen isotope analyses were undertaken at the Copenhagen University Geophysical Isotope Laboratory;  $\delta^{18}\text{O}$  values were determined by mass spectrometry with a precision of  $\pm 0.01\%$ .

### Pre-melting Conditions

Snowpack temperatures were below  $0^\circ\text{C}$  at all the sites when the first sets of samples were collected. Mean snow temperature decreased markedly with altitude (Figs. 3, 5 and 8). On 26 April, the temperature of the lowermost metre of snow at 825 m was very close to  $0^\circ\text{C}$  (Fig. 3) and metamorphic processes may have affected the pack already: ionic concentrations were lower in the bottom 0.5 m of the pack than in most of the overlying snow (Fig. 4).

The late-April temperature profiles at 1,230 m and 1,470 m (Figs. 5 and 8) indicated that the pack at those sites had been well below  $0^\circ\text{C}$  through the winter. The absence of ice layers also suggested that there had been few, if any, episodes of surface melting. No liquid water was detected at either site. The heterogeneity of the isotopic and ionic stratigraphy of the snowpack in the pre-melting stage (Figs. 6, 7 and 9) is considered to reflect the original variations in the precipitated material. Previous observations have shown that temporal variations of oxygen isotope inputs to the snowpack result principally from temperature differences, but that simple altitude effects may be masked by other factors (He and Theakstone 1994; Stichler 1987). A trend of increasing  $\delta^{18}\text{O}$  values in the top 30% of the pack indicated the influence of rising temperatures during the last part of the winter (March and April).

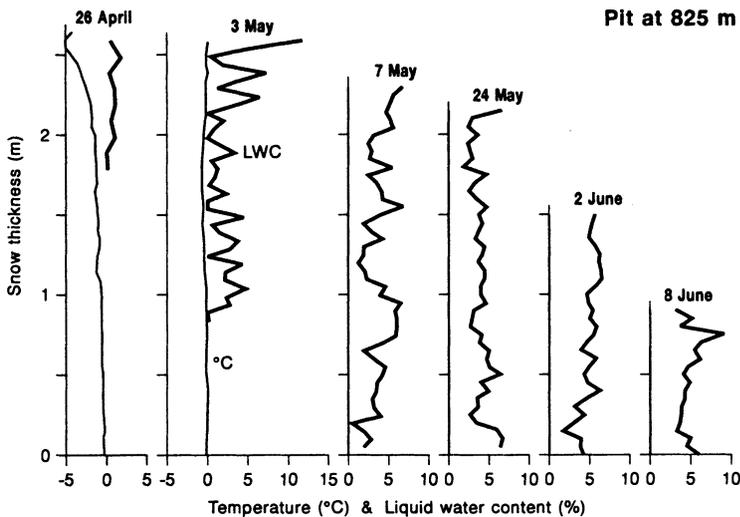


Fig. 3. Snow temperature and liquid water content at 825 m, Austre Okstindbreen, 1995.

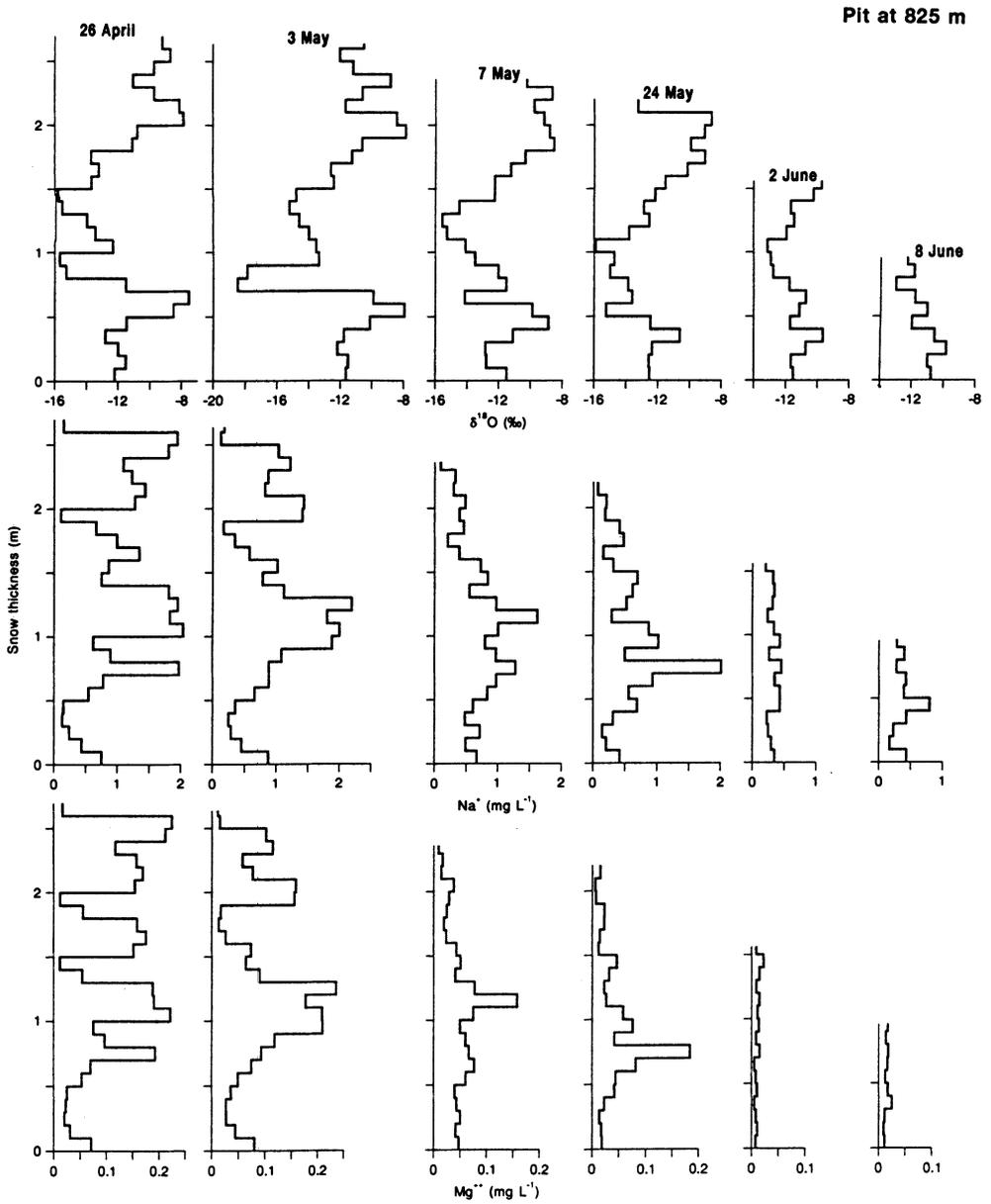


Fig. 4. Changes of snowpack thickness, ions and oxygen isotopes at 825 m, Austre Okstind-breen, 1995

## *Ions and Oxygen Isotopes in the Snowpack*

Table 1 - Mean  $\delta^{18}\text{O}$  values (‰) and concentrations of ions ( $\text{mg L}^{-1}$ ) in samples collected at Austre Okstindbreen in 1995 ( $\mu$ ), with standard deviations ( $\sigma$ ) and coefficients of variation ( $\sigma/\mu$ ). Homogenisation is reflected in a reduction of the coefficient of variation.

|           | $\delta^{18}\text{O}$ |          |              | $\text{Na}^+$ |          |              | $\text{Mg}^{2+}$ |          |              |
|-----------|-----------------------|----------|--------------|---------------|----------|--------------|------------------|----------|--------------|
|           | $\mu$                 | $\sigma$ | $\sigma/\mu$ | $\mu$         | $\sigma$ | $\sigma/\mu$ | $\mu$            | $\sigma$ | $\sigma/\mu$ |
| Pit 825   |                       |          |              |               |          |              |                  |          |              |
| 26 April  | -11.70                | 2.46     | -0.21        | 1.02          | 0.63     | 0.62         | 0.11             | 0.07     | 0.67         |
| 3 May     | -12.06                | 2.60     | -0.22        | 0.90          | 0.57     | 0.63         | 0.09             | 0.06     | 0.74         |
| 7 May     | -11.62                | 2.11     | -0.18        | 0.68          | 0.35     | 0.52         | 0.05             | 0.03     | 0.62         |
| 24 May    | -12.41                | 2.01     | -0.16        | 0.53          | 0.41     | 0.79         | 0.04             | 0.04     | 1.01         |
| 2 June    | -11.47                | 0.98     | -0.09        | 0.33          | 0.08     | 0.24         | 0.01             | <0.01    | 0.36         |
| 8 June    | -11.41                | 0.89     | -0.08        | 0.38          | 0.17     | 0.44         | 0.02             | <0.01    | 0.27         |
| Pit 1,230 |                       |          |              |               |          |              |                  |          |              |
| 27 April  | -11.88                | 1.84     | -0.16        | 0.82          | 0.65     | 0.79         | 0.09             | 0.07     | 0.76         |
| 9 May     | -11.40                | 1.82     | -0.17        | 0.79          | 0.92     | 1.17         | 0.09             | 0.09     | 1.10         |
| 25 May    | -11.70                | 1.88     | -0.16        | 1.01          | 1.16     | 1.14         | 0.12             | 0.13     | 1.16         |
| 31 May    | -11.18                | 1.81     | -0.16        | 1.11          | 1.13     | 1.02         | 0.12             | 0.12     | 1.03         |
| 8 June    | -10.80                | 0.57     | -0.05        | 0.39          | 0.18     | 0.46         | 0.01             | 0.01     | 0.58         |
| Pit 1,350 |                       |          |              |               |          |              |                  |          |              |
| 30 April  | -13.21                | 1.60     | -0.12        | 0.79          | 0.59     | 0.74         | 0.09             | 0.06     | 0.71         |
| 6 June    | -12.25                | 0.96     | -0.08        | 0.36          | 0.30     | 0.83         | 0.02             | 0.03     | 1.41         |
| Pit 1,470 |                       |          |              |               |          |              |                  |          |              |
| 29 April  | -13.04                | 2.10     | -0.16        | 0.68          | 0.74     | 1.09         | 0.08             | 0.08     | 1.05         |
| 2 June    | -13.33                | 1.34     | -0.10        | 0.57          | 0.30     | 0.53         | 0.05             | 0.03     | 0.47         |
| 12 June   | -12.39                | 1.13     | -0.09        | 0.21          | 0.27     | 1.26         | 0.02             | 0.02     | 1.40         |
| 12 Aug.   | -11.57                | 0.48     | -0.04        | 0.16          | 0.12     | 0.73         | 0.01             | <0.01    | 0.38         |

### **Melting of the Snowpack**

The thickness of the snowpack at 825 m decreased by 0.06 m between 26 April and 3 May as a result of melting and/or compaction. On 3 May, the temperature of the lowest 2.15 m was below  $0^\circ\text{C}$  whilst the higher part of the pack was at the melting-point (Fig. 3); some elution of ions from the uppermost half metre had occurred since 26 April (Fig. 4). Minor changes of isotopic composition at the very top of the pack probably were the result of evaporation, which causes  $^{18}\text{O}$  enrichment, and condensation, which reduces  $\delta^{18}\text{O}$  values; most of the underlying pack was unchanged. Rain fell on the lower part of the glacier during the following four days, when the weather was warmer; the snow thickness at 825 m decreased by 0.28 m (0.06 m water equivalent). Many ions were lost, particularly from the uppermost part of the pack (Fig. 4). In contrast, melting had only slight effects on the isotopic

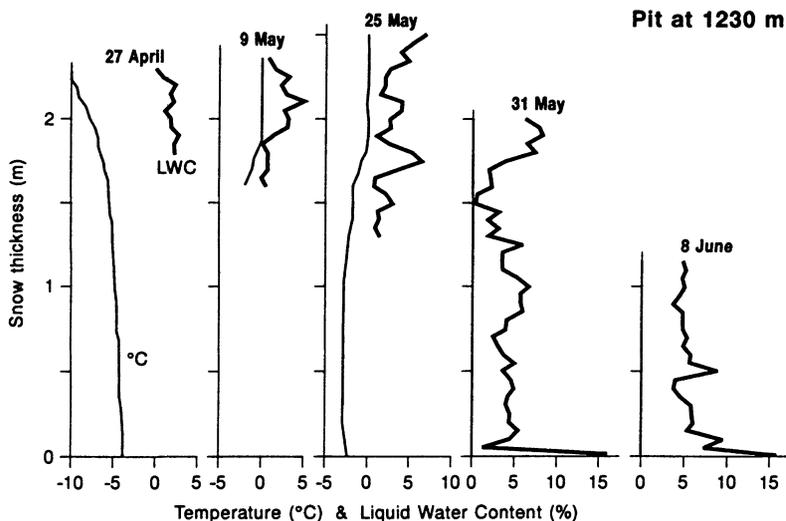


Fig. 5. Snow temperature and liquid water content at 1,230 m, Austre Okstindbreen, 1995.

composition, with some homogenisation of  $\delta^{18}\text{O}$  values to a depth of 0.56 m. On 7 May, the whole snowpack was isothermal at  $0^\circ\text{C}$ , with a generally high but variable liquid water content.

Colder weather dominated the next seventeen days. Both  $\text{Na}^+$  and  $\text{Mg}^{2+}$  ions were redistributed and the highest ionic concentrations on 24 May were 0.7 m above the base of the pack (Fig. 4). The isotopic stratigraphy was more or less unchanged from 7 May to 24 May (Fig. 4). The snowpack thickness decreased by some 0.65 m (0.31 m water) in the generally warm weather of the next eight days, when melt rates were high; by 2 June, most of the ions had been removed and those that were left were uniformly distributed (Fig. 4; Table 1). The rate of elution of  $\text{Mg}^{2+}$  was higher than that of  $\text{Na}^+$ . As meltwater moved through the pack during the phase of surface melting,  $^{18}\text{O}$  enrichment occurred and  $\delta^{18}\text{O}$  values became more homogeneous (Fig. 4). Between 2 June and 8 June, the calculated total melt was 0.70 m (0.38 m water equivalent).

Snow which accumulated at 1,230 m between 27 April and 9 May (Fig. 6) was almost free of impurities and was depleted in the heavy isotope of oxygen. Only the top 0.6 m of the pack was at  $0^\circ\text{C}$  on 9 May (Fig. 5). An ice layer at 0.83 m above the glacier ice surface reduced the permeability and may have been responsible for the increase of the ionic content 0.70-1.00 m above the ice (Fig. 6). Higher  $\delta^{18}\text{O}$  values coincided with the higher ionic concentrations and the presence of the ice layer (Fig. 6). During the colder weather between 9 May and 25 May, the snow depth increased by 0.12 m. The  $\delta^{18}\text{O}$  value of the new snow was low, and no significant heavy-isotope enrichment of the older part of the pack occurred (Fig. 6). The liquid water content immediately above the sub- $0^\circ\text{C}$  portion of the pack on 25 May was high (Fig.

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Pit at 1230 m

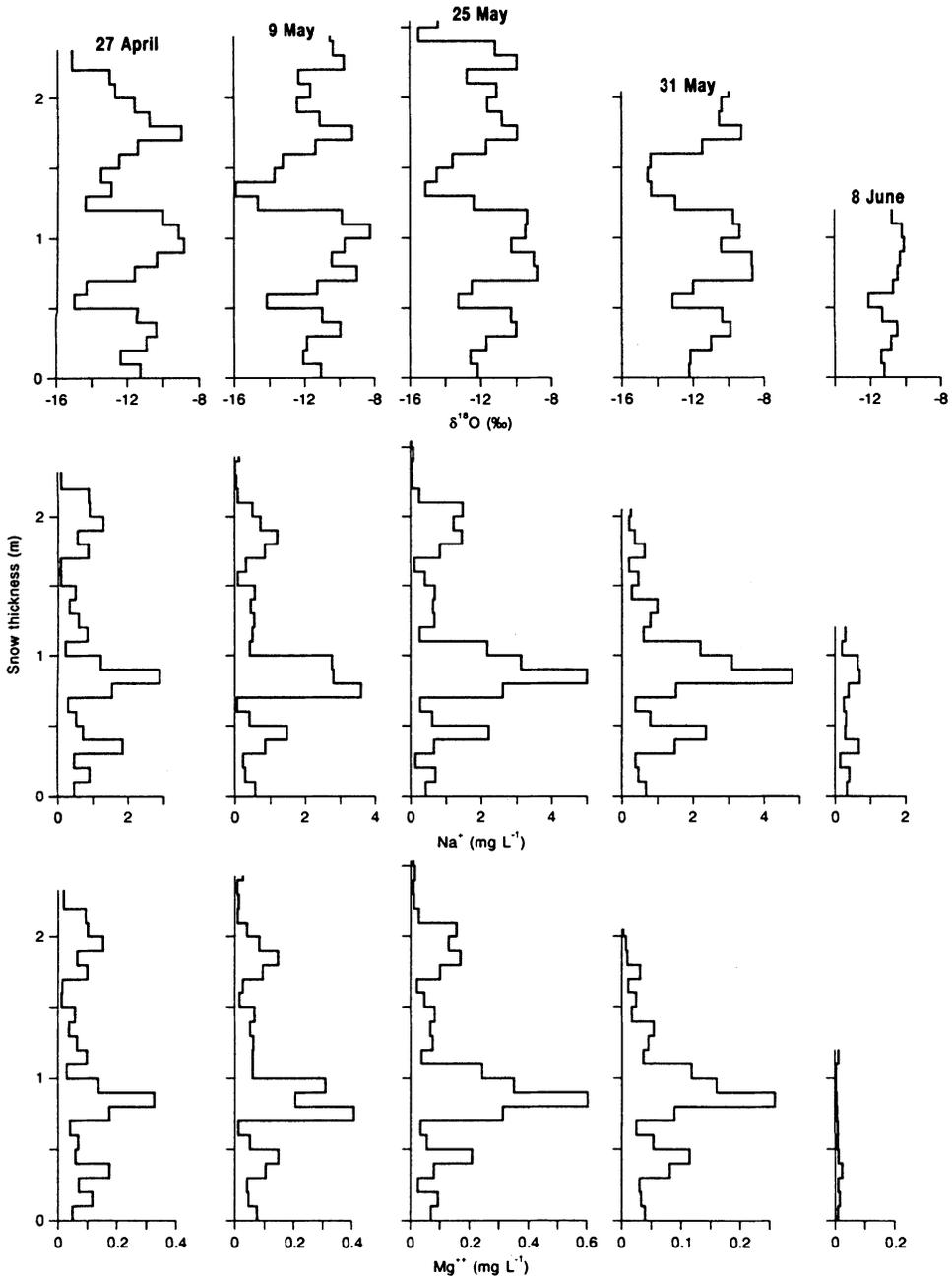


Fig. 6. Changes of snowpack thickness, ions and oxygen isotopes at 1,230 m, Austre Okstindbreen, 1995.

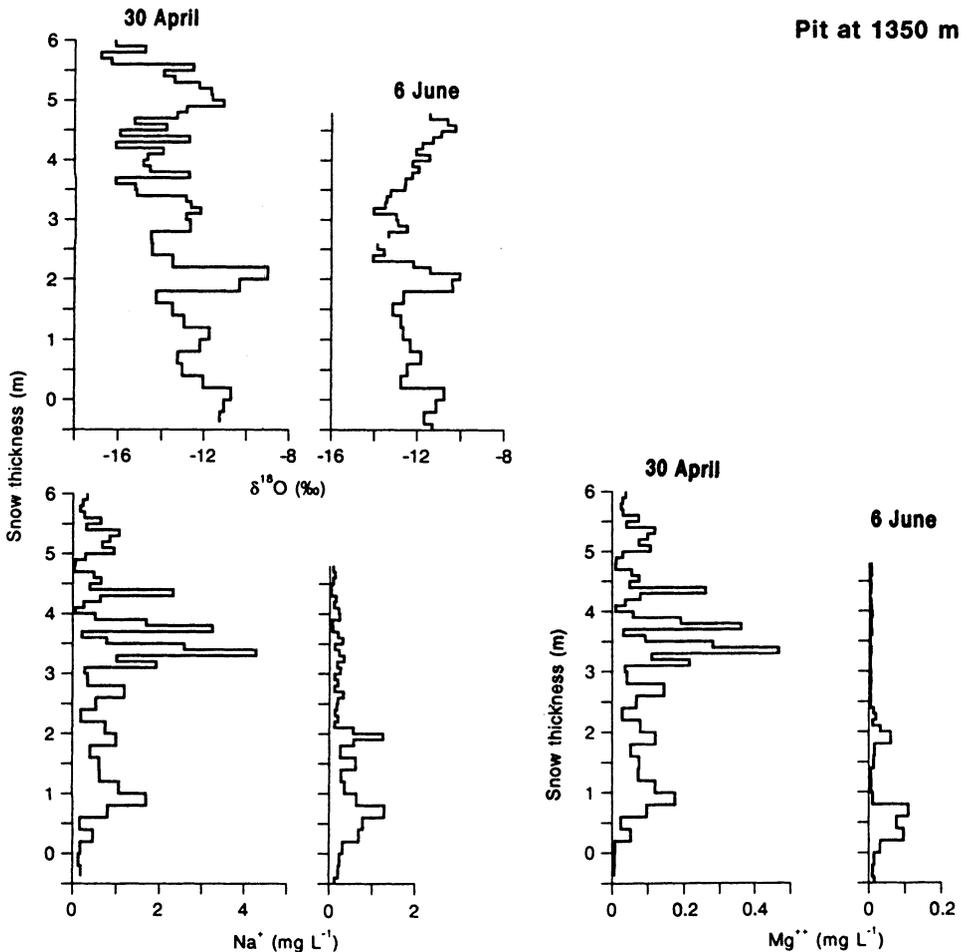


Fig. 7. Changes of snowpack thickness, ions and oxygen isotopes at 1,350 m, Austre Okstindbreen, 1995.

5). The thickness of the zone of high ionic concentrations about a metre above the glacier ice had increased and the concentrations themselves were markedly higher. Six days later, the pack was isothermal at 0°C. Its thickness had decreased by 0.50 m (0.09 m water) and the liquid water content just above the glacier ice was very high (Fig. 5). The near-horizontal surface of the underlying ice seemed to have hindered drainage of meltwater from the site, in contrast to the situation at 825 m. Elution of ions had taken place in the upper part of the pack, but the pattern of ionic variations below the high concentration layer about a metre above the glacier surface was more or less unchanged (Fig. 6).  $^{18}\text{O}$  enrichment and homogenisation had taken place in the top 0.25 m of the pack, but changes elsewhere were minor (Fig. 6). By 8 June, the pack had become still thinner (0.36 m water equivalent), most of the ions had

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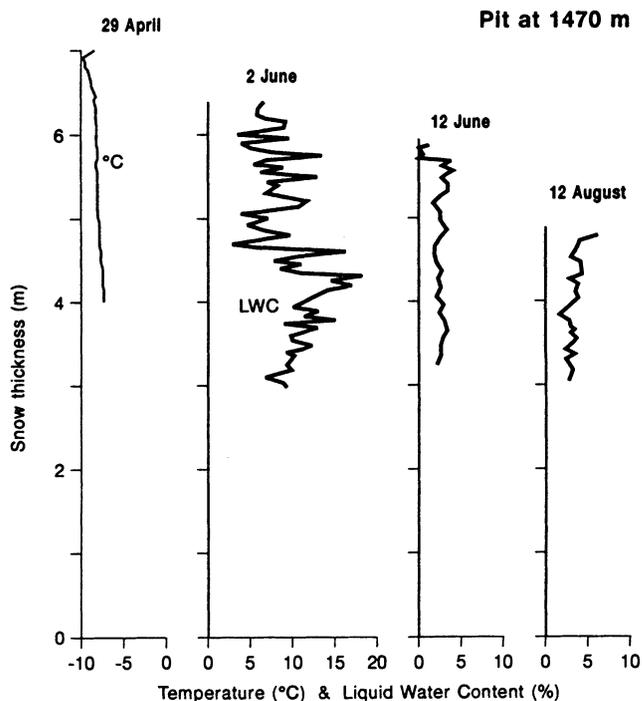


Fig. 8. Snow temperature and liquid water content at 1,470 m, Austre Okstindbreen, 1995.

been removed and no evidence of the high concentration layer remained (Fig. 6). As at the 825 m pit,  $Mg^{2+}$  was removed more rapidly than  $Na^+$ . Marked changes of the isotope stratigraphy, reflected in the lower standard deviation of the  $\delta^{18}O$  values, also occurred at this stage of melting (Table 1), although the pre-melting minimum  $\delta^{18}O$  value 0.5-0.6 m above the glacier ice remained (Fig. 6).

The pack at 1,350 m was sampled only twice, on 30 April and 6 June. Between those dates, major changes of the stratigraphy of both ions and isotopes occurred, as the thickness of the pack decreased by 1.2 m (Fig. 7). The total water content increased slightly as a result of precipitation; only a small amount of the snow present on 30 April had melted and drained into the underlying firm by 6 June, but almost all the ions had been removed from the upper part of the pack. On 6 June, there was no sign of the high ionic concentrations which had been present in the pre-melting stage, although the original stratigraphic variations still were evident in the lowest 2 m of the pack (Fig. 7).  $\delta^{18}O$  values became more homogeneous during the interval between sampling, as indicated by their lower standard deviation (Table 1) although changes in the lowermost 2 m of snow were rather slight (Fig. 7).

When the highest site, at 1,470 m, was visited for the first time, on 29 April, 7.00 m of snow covered the 1994 summer surface. The temperature increased from  $-10^{\circ}C$  near the surface to  $-7.5^{\circ}C$  at 3 m depth (Fig. 8). The concentrations of the four ma-

Table 2 - Correlation coefficient matrices for concentrations of four cations at 1,470 m, Austre Okstindbreen, April and June 1995. Cation concentrations in the 0.1 m long samples between the surface and a depth of 3.0 m were paired, to provide mean values for 0.2 m increments; this provided 35 values for the entire 7 m pack. The 99% significance level for  $n = 35$  is 0.36; for  $n = 32$  it is 0.45.

| 29 April ( $n = 35$ ) | Na   | K    | Ca   | Mg | 2 June ( $n = 32$ ) | Na   | K    | Ca   | Mg |
|-----------------------|------|------|------|----|---------------------|------|------|------|----|
| Na                    | 1    |      |      |    | Na                  | 1    |      |      |    |
| K                     | 0.97 | 1    |      |    | K                   | 0.73 | 1    |      |    |
| Ca                    | 0.93 | 0.90 | 1    |    | Ca                  | 0.14 | 0.33 | 1    |    |
| Mg                    | 0.99 | 0.96 | 0.96 | 1  | Mg                  | 0.76 | 0.80 | 0.37 | 1  |

Table 3 - Correlation coefficients between concentrations of cations and  $\delta^{18}\text{O}$  values at 1,470 m, Austre Okstindbreen, 1995. Cation concentrations in the 0.1 m long samples between the surface and a depth of 3.0 m were paired, to provide mean values for 0.2 m increments; this provided 35 values for the entire 7 m pack. Correlations which are significant at the 95% level are indicated in bold.

| $\delta^{18}\text{O}$  | Na          | K           | Ca          | Mg          |
|------------------------|-------------|-------------|-------------|-------------|
| 29 April ( $n = 35$ )  | <b>0.41</b> | <b>0.36</b> | <b>0.34</b> | <b>0.39</b> |
| 2 June ( $n = 32$ )    | 0.03        | 0.02        | 0.13        | 0.20        |
| 12 June ( $n = 30$ )   | 0.00        | 0.01        | 0.10        | 0.09        |
| 12 August ( $n = 24$ ) | 0.31        | 0.06        | 0.27        | 0.00        |

major cations were strongly correlated with each other (Table 2) and with the  $\delta^{18}\text{O}$  values of the samples (Table 3). During the four weeks of predominantly cold weather which followed, new snow accumulated, but melting occurred from 25 May; on 2 June, the snowpack was isothermal at  $0^\circ\text{C}$ . Although it was thinner than on 29 April, its water equivalent value was 0.33 m higher, suggesting that only a small fraction of the meltwater had drained into the underlying firm. An increase of ionic concentrations in the lowest 1.5 m of snow was evident (Fig. 9). As at the lower sites,  $\text{Mg}^{2+}$  concentrations had decreased more rapidly than those of  $\text{Na}^+$  (Table 1). Changes of liquid water content (Fig. 8) associated with zones of high ionic concentrations suggested that small ice layers or lenses may have slowed the drainage of water and resulted in accumulation of ions. The pre-melting stratigraphic variations of  $\delta^{18}\text{O}$  values still were evident on 2 June (Fig. 9), but there was no longer any significant correlation between  $\delta^{18}\text{O}$  values and the four major cations (Table 3). Ten days later, most of the ions had been removed, although a zone of higher concentrations remained, 1.5 m above the 1994 summer surface (Fig. 9). There was less free water in

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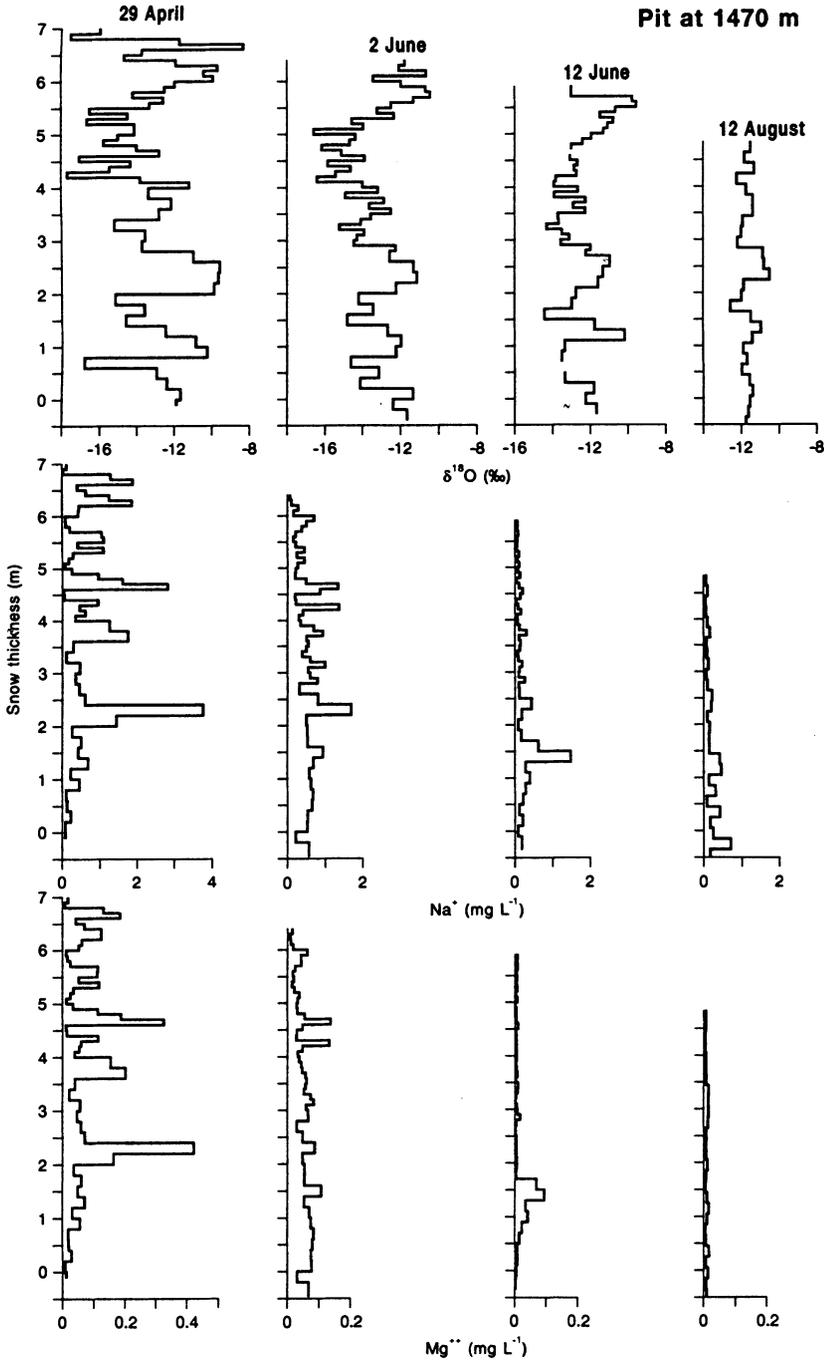


Fig. 9. Changes of snowpack thickness, ions and oxygen isotopes at 1,470 m, Austre Okstindbreen, 1995.

the pack than on 2 June, and freezing conditions immediately before the visit probably were responsible for the absence of liquid water at the top (Fig. 8). Overall, the pack had been enriched in  $^{18}\text{O}$ , but a 0.15 m thick layer of recently-deposited snow at the top was depleted in  $^{18}\text{O}$ , reflecting the relatively cold conditions during which it had fallen. On 12 August, ionic concentrations were only slightly lower than on 12 June (Fig. 9). The pack had become further enriched in  $^{18}\text{O}$  and was isotopically more homogeneous (Table 1), although the original variations of composition still were identifiable (Fig. 9).

## Discussion

The layered nature of the snowcover at Austre Okstindbreen is typical of most long-lasting packs. The strata deposited in discrete events have different physical and chemical characteristics, and the initial permeability varies from one layer to another because of differences of grain size, grain shape and density. Both the stratification and the physical characteristics influence the timing of the release of water and solutes. The times at which melting starts differ significantly with altitude, and the large altitudinal range results in spatial variations of processes affecting the pack in both the pre-melting and melting phases. The snowcover is thicker at higher sites, and meltwater there has to percolate much further to reach the base of the pack: more time is needed to disturb the original chemical stratification. In 1995, isothermal conditions were achieved at progressively later dates with increasing altitude between 825 m and 1,470 m.

Melting does not start at Austre Okstindbreen until May, or even June. However, melt/freeze cycles in both early and late winter are likely to affect the snowpack at the lowest sampling site (825 m), causing metamorphic changes as a consequence of meltwater percolation, water vapour movement and grain growth (Cragin and McGilvary 1995). Impurities may become concentrated at particular levels in the snowpack as a result of melt/freeze cycles in the early stage of melting. During metamorphism, solutes are moved to the surfaces of snow grains (Brimblecombe *et al.* 1987; Bales *et al.* 1989). Grain growth excludes impurities from crystal interiors to their surfaces. Ions on the outer side of the crystals are removed quickly by percolating water, which transfers them to lower parts of the pack.

The 1995 pack stratigraphy was very heterogeneous vertically, with pre-melt concentrations varying by a factor of 100 ( $0.05\text{--}5\text{ mg L}^{-1}$  for  $\text{Na}^+$ ). The presence of layers with different ionic concentrations results in pronounced ionic pulses in the water which leaves a snowpack (Davies *et al.* 1987). At Austre Okstindbreen, solutes moved downwards from the surface during the early phase of melting in the first week of May, but the ionic concentrations at greater depth were not affected (Figs. 4 and 6). Rapid removal of ions from the uppermost part of the pack may have

resulted from melt/freeze cycles in which both the melting period and the freezing period were rather long, allowing the melting to extend to a considerable depth before its downward progress was slowed by subsequent freezing: experimental work by Davis *et al.* (1995) indicated that, in such conditions, impurities concentrated on grain surfaces are easily removed by liquid water, and concentrations of chemical species in the first percolating meltwater are particularly high.

Ice layers tended to develop at strata boundaries within the snowpack during the melting phase. As in previous years (Raben and Theakstone 1994), both their thickness and their frequency changed as melting proceeded. At Austre Okstindbreen, as elsewhere, ice layer growth ceases when the snowpack is wet and isothermal at 0°C (Marsh and Woo 1985). Ions then can move more freely through the pack, as was seen at 1,230 m on 8 June (Fig. 5) and at 1,470 m on 12 August (Fig. 8). Whilst ice layers were present, they did block the drainage of some of the percolating meltwater: relatively-high ionic concentrations in the sample from 0.7-0.8 m above the glacier ice at 825 m on 26 April (Fig. 4) were associated with an ice layer which may have formed as a result of melting and refreezing early in the winter. Such a process did occur on the lower part of the glacier at the end of the winter: although the snow temperature at 825 m was 0°C from a below-surface depth of 0.40 m to the underlying glacier ice, percolation came to a temporary halt between 7 May and 24 May because no meltwater was supplied at the upper surface and impermeable ice layers which had formed during previous melt/freeze cycles prevented downward movement across inter-layer boundaries at 0.44 m, 0.84 m and 1.50 m above glacier ice.

There were no ice layers in the Austre Okstindbreen snowpack at 1,230 m, 1,350 m and 1,470 m in late-April 1995: the pre-melt chemical stratification at high altitude was not caused by melting and refreezing, but is likely to have resulted from variations of the impurities which were supplied by different precipitation events, as is indicated by daily analyses of snow collected at a nearby Norwegian air quality station, Tustervatnet (Statens Forurensningstilsyn 1996; Raben and Theakstone in preparation). Changes of the prevailing meteorological conditions result in the impurities supplied by some events having a marine source, whilst at other times the sources are continental (He and Theakstone 1994). The late-April snowpack at Austre Okstindbreen was somewhat enriched in  $K^+$ ,  $Ca^{2+}$  and  $SO_4^{2-}$  compared with ocean water, but was slightly depleted in  $Mg^{2+}$  (Table 4). This may reflect contributions of impurities from non-marine sources. The  $Cl^-/SO_4^{2-}$  mass ratio at 825 m, 1,230 m and 1,470 m was 70%, 59% and 45% of the  $Cl^-/SO_4^{2-}$  ratio in sea water, respectively, suggesting that 30%, 41% and 55% of the ions originated from a non-marine source. Most of the new snow which fell between late-April and mid-June 1995 had a lower solute content than that which accumulated during the winter and was similar to that which fell at Tustervatnet (Statens Forurensningstilsyn 1996).

During the early stages of melting in 1995, the liquid water content of the pack increased markedly (Figs. 3, 5 and 8), and the increasing amount of free water caused rapid changes of the physical properties of the snow cover. At this stage, percolating

Table 4- The mean composition of the snowpack (ionic ratios) at four different altitudes at Austre Okstindbreen in late-April 1995 compared with that of ocean water. (Note: Cl<sup>-</sup> and SO<sub>4</sub><sup>2+</sup> were not determined for the snowpack at 1,350 m).

|             | Na <sup>+</sup> /K <sup>+</sup> | Na <sup>+</sup> /Ca <sup>2+</sup> | Na <sup>+</sup> /Mg <sup>2+</sup> | Na <sup>+</sup> /Cl <sup>-</sup> | Na <sup>+</sup> /SO <sub>4</sub> <sup>2+</sup> |
|-------------|---------------------------------|-----------------------------------|-----------------------------------|----------------------------------|------------------------------------------------|
| 825 m       | 17.24                           | 18.18                             | 9.43                              | 0.57                             | 2.84                                           |
| 1,230 m     | 20.00                           | 16.39                             | 8.85                              | 0.55                             | 2.32                                           |
| 1,350 m     | 21.74                           | 16.95                             | 8.70                              |                                  |                                                |
| 1,470 m     | 20.00                           | 18.87                             | 8.77                              | 0.55                             | 1.78                                           |
| Ocean water | 27.78                           | 26.31                             | 8.33                              | 0.56                             | 3.97                                           |

water flows through a stratified pack in unstable vertical channels ('flow fingers'), the distribution and size of which depend on the structure of the pack and on weather conditions (Schneebeli 1995). As water penetrates along flow fingers, locally-isothermal conditions develop at depths greater than those predicted for homogeneously-infiltrating water. The rapid descent of percolating water through the pack at 1,470 m was reflected in the speed with which the thermal state changed from sub-zero to isothermal (0°C) conditions: the mean temperature of the top 3 m on 29 April was -7.9°C, yet the 7 m thick pack was isothermal on 2 June. Surface melting between 29 April and 25 May was limited by low air temperatures (Fig. 2), and much of the change to isothermal conditions is likely to have occurred between 25 May and 2 June. At both 1,470 m and 1,350 m, the high surface melt rates in late-May resulted in much liquid water penetrating into the pack and caused rapid elution of ions (Figs. 7 and 9).

Impurities remain in the snowpack on the higher parts of the glacier for some time after they have been removed at lower altitude. The mean concentration of Na<sup>+</sup> and Mg<sup>2+</sup> ions at 825 m decreased markedly in early-May 1995, although purification of the residual pack was most pronounced between 24 May and 2 June, and few ions were present after the first week of June (Fig. 4). At 1,230 m, only the upper half of the pack was subject to ionic elution before the end of May (Fig. 6) but there, too, most of the impurities had been removed by 8 June. The lowermost 2 m of the pack at 1,350 m retained marked ionic concentrations on 6 June (Fig. 7) whilst impurities remained in the lower part at 1,470 m on 12 June (Fig. 9). Ions present in the residual pack at 1,470 m on 12 August may have been added by summer precipitation.

The well-marked oxygen isotope stratigraphy observed at Austre Okstindbreen is a common feature in high-alpine snowpacks (Stichler *et al.* 1981). Broad similarities were apparent in the distribution of the pre-melt δ<sup>18</sup>O values at different altitudes (Figs. 4, 6, 7 and 9), with a double minimum in mid-pack, but there was no simple relationship between the mean δ<sup>18</sup>O value and altitude; although mean values were lower at the two higher sites than at 825 m and 1,230 m, it is evident that other factors moderated the 'altitude effect'. Despite metamorphic changes of the pack, the pre-melt pattern of isotopic variations remained evident for several weeks. Fraction-

ation leads to an increase in the proportion of heavy isotopes present and, as the ageing residual pack becomes enriched in  $^{18}\text{O}$ , stratigraphic differences decline (He and Theakstone 1994). At 825 m, the mean  $\delta^{18}\text{O}$  value increased by 1‰ between 24 May and 8 June, and there was a similar 1‰ increase at 1,470 m between 2 June and 12 June (Table 1). However, in early-June, the residual pack was substantially more depleted of  $^{18}\text{O}$  on the higher part of the glacier than at 825 m and 1,230 m, and the isotopic composition of meltwater entering the glacier above 1,300 m must have differed substantially from that entering at lower elevations.

Changes of stratigraphic variations of  $\delta^{18}\text{O}$  values as water percolated through the pack were less rapid than those of ionic concentrations: thus, the variations of  $\text{Na}^+$  and  $\text{Mg}^{2+}$  ions present at 825 m on 24 May had disappeared on 2 June whilst those of  $\delta^{18}\text{O}$  values still were evident (Fig. 4). Both preferential ion elution and preferential release of  $^{18}\text{O}$ -depleted meltwater resulting from isotopic fractionation are important in the evolution of a stratified snowpack (Shanley *et al.* 1995).

## Conclusion

In order to understand catchment-scale changes of seasonal snow covers and their potential environmental consequences, it is necessary to make repeated observations between the pre-melt stage and the end of the melt season at a range of altitudes. The results of the temporal and spatial sampling of the Austre Okstindbreen snowpack in 1995 support previous observations that preferential removal of ions and isotopically-depleted meltwater are important in the changes which occur during the melting phase at a layered snowpack (Raben and Theakstone 1994; Shanley *et al.* 1995).

The studies emphasised the important influence of altitude on the thickness, ionic composition and structural evolution of the snowpack and on the timing and duration of melting. The timing of the release of solutes and water from the snow, and the formation and disappearance of ice layers and lenses as a result of melt/freeze cycles during the melting period, are influenced by the stratified nature of the pack. Ice layers impede the elution of ions, and their partial or complete disappearance allows ions to move more quickly through the pack. Ions are moved rapidly when surface melt rates are high. The input of ions to the water leaving the catchment is affected by the large altitudinal range of the Austre Okstindbreen catchment, which results in significant differences in the time at which melting starts (Raben and Theakstone 1997).

Changes of  $\delta^{18}\text{O}$  values within the pack are delayed in relation to those of ionic concentrations. Early in the melt season, the isotopic stratigraphy is not subject to substantial change and the removal of mobile ions together with a small fraction of the meltwater is not accompanied by major isotopic exchanges between the solid and liquid phases. Isotopic homogenisation proceeds much more slowly than does ionic purification.

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