Oxygen Isotope and Ionic Concentrations in Glacier River Water: Multi-Year Observations in the Austre Okstindbreen Basin, Norway

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Austre Okstindbreen, the largest glacier of the Okstindan area, Norway, covers about 14 km^2 within a drainage basin of 22.5 km^2. Each year, about one third of the discharge of the glacier river results from snowmelt outside the glacier margins. Snow melting on the glacier contributes about twice as much water to the river as does glacier ice. Early in the melt season, the glacier river is supplied almost entirely by snow meltwater. Na^+ ion concentrations in the snow are much higher than those of Ca^{2+}; percolation of meltwater from the surface results in chemical changes. Water entering the body of the glacier from the melting snow cover is relatively depleted of ^{18}O, whilst the residual snow is more enriched. As the ablation season proceeds and the transient equilibrium line rises up-glacier, an increasing amount of ice meltwater is mixed with snow meltwater, diluting the overall concentration of ions in the river. Ice meltwater is ^{18}O-rich, and the $\delta^{18}O$ value of glacier river water rises at times of high ice ablation. Water which percolates through the snow cover above the transient equilibrium line during the melt season may maintain river discharge in late summer. Mean concentrations of the principal cations in the river water vary between years; after winters with above-average snow accumulation, Na^+ values tend to be high. Ca^{2+} concentrations are determined largely by subglacial conditions.

Introduction

Austre Okstindbreen, the largest glacier of the Okstindan area, Norway (66°00'N, 14°10'E) covers 14.0 km^2 and lies within a drainage basin of 22.5 km^2 close to the border between Norway and Sweden; the basin drains through the valley Oksfjell-
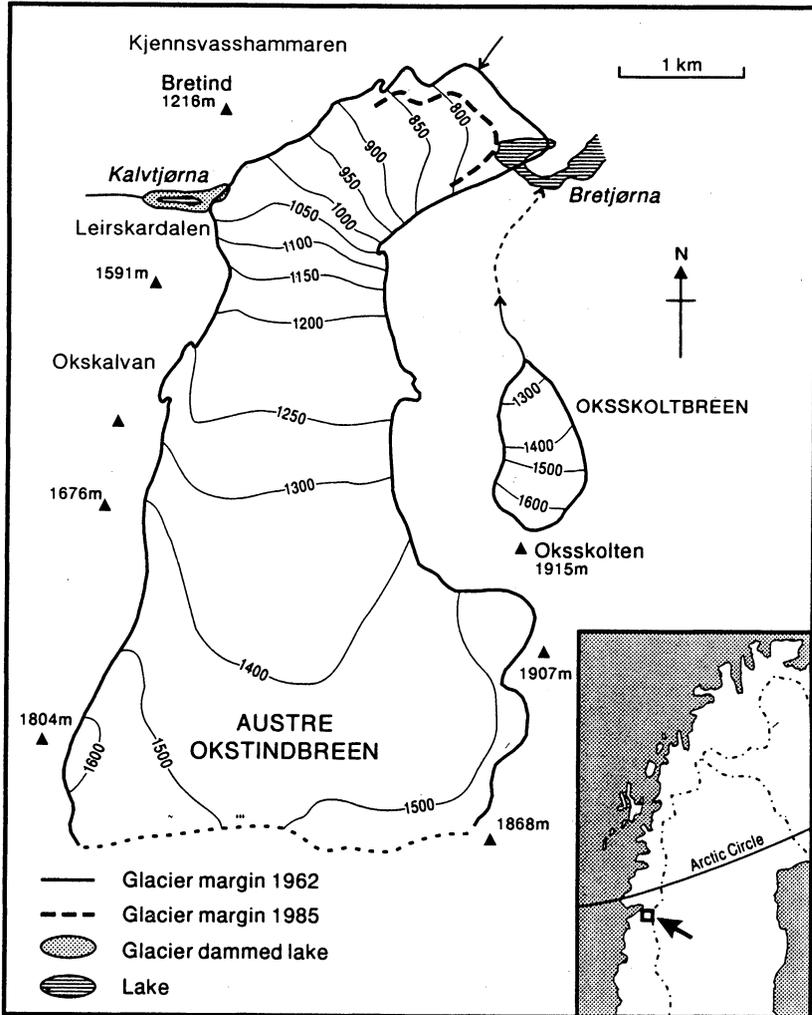
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Fig. 1. The glacier Austre Okstindbreen.

dalen to the lake Gressvatnet (Fig. 1). In 1981, a programme of hydrochemical in-vestigations was started by the Okstindan Glacier Project, a collaborative research programme undertaken by personnel from the Universities of Aarhus, Denmark, and Manchester, England. Since then, the water balance of the basin has been calculated each summer. Glacier mass-balance studies are incorporated within the Norwegian national programme (Elvehøy and Haakensen 1992). The discharge of the river which issues from Austre Okstindbreen is monitored at a station about 200 m from the glacier front (Fig. 1).

The catchment in which Austre Okstindbreen is situated includes parts of Okss-

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Table 1 – Area/altitude distribution of Austre Okstindbreen and the catchment within which it is situated.

Altitude (m)	Catchment area (km^2)	Glacier area (km^2)
> 1,600	1.43	0.21
1,600-1,500	2.55	1.91
1,500-1,400	4.92	4.14
1,400-1,300	3.63	2.56
1,300-1,200	3.69	2.56
1,200-1,100	1.30	0.64
1,100-1,000	1.49	0.61
1,000-900	1.19	0.59
900-800	1.65	0.61
<800	0.65	0.18
730-1,915	22.50	14.01

kolten (1,915 m a.s.l.), the highest mountain of northern Norway, and the glacier's highest parts are more than 1,700 m above sea level. However, most of Austre Okstindbreen is below 1,500 m (Table 1). The mean annual position of the equilibrium line is about 1,250 m, and about 70% of the glacier still is covered by the previous winter's snow at the end of the summer. The glacier ends in a lake, Bretjörna (740 m) but, as a result of retreat during the last few years, part of the front now is on land. In recent summers, the glacier river has had a short subaerial course before entering Bretjörna.

The Austre Okstindbreen Glacier River

The chemical composition of the dissolved load in water draining from a glacier differs from that of precipitation and of water generated by the melting of snow or ice at the glacier surface (Rainwater and Guy 1961; Slatt 1972). Glacier river discharge varies between years, between seasons and between days during the summer season (Collins 1978; Theakstone and Knudsen 1989). The variations are a response to differences of snow accumulation and of snow and ice ablation, to summer precipitation, and to water storage and flow routing. Recent glacier hydrochemical investigations have centred on the processes which cause enrichment of the water penetrating into the glacier, and have focused on its residence time, the availability of freshly-exposed material to interact with it, and the development of the internal drainage system within and underneath the glacier (Collins 1979; Raiswell and Thomas 1984; Thomas and Raiswell 1984; Tranter *et al.* 1993).

At Austre Okstindbreen, observations over more than a decade have shown that solute concentrations in glacier river water differ from one summer to another, and that they change during the season (Theakstone and Knudsen, in press). Both the im-

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purities in the water and its isotopic composition provide evidence about variations of water sources, flow routing and processes of solute acquisition. No water discharges from the glacier during the winter. The whole drainage basin is covered by snow until late May. As the snow starts to melt, water is stored temporarily within the pack, and some days may pass before there is any discernible river discharge. During the first stages of river discharge from the glacier, the water is supplied almost entirely by melting snow. On the lower part of the glacier tongue, water tends to move over a thin layer of superimposed ice. As the ablation season proceeds, water begins to enter the body of the glacier through crevasses, the superimposed ice at the contact between the snow cover and the glacier disappears, and the glacier ice begins to melt. Most of the ions entering the glacier are provided by the winter snow cover. After a winter with high accumulation, abundant ions are potentially available to meltwater. When ablation starts, ions are leached at a rate which exceeds that of the actual melting, and the first meltwater to leave the pack is rich in those ions which were present in the snow (Johannessen and Henricksen 1978; Raben and Theakstone 1994).

The mean isotopic composition of the winter snow pack at Austre Okstindbreen differs from year to year. Sampling of the pack in late-winter, before melting has started, has shown that, in general, the colder the winter the more pronounced is the depletion in the heavy isotope of oxygen, ^{18}O, and that less snow accumulates in cold winters than in milder ones. The isotopic composition of the snow pack generally varies with altitude (Theakstone 1991). Many days may elapse between the onset of the melt season in the lower parts of the catchment and the first melting at higher altitudes, with consequent effects on the water which maintains the baseflow of the glacier river during the summer.

As the transient equilibrium line rises up-glacier during the summer, an increasing amount of ice meltwater is mixed with snow meltwater in the river which issues from the glacier. The opening of moulins and crevasses facilitates drainage of supraglacial streams into the englacial systems. Above the transient equilibrium line, water percolates through the snow cover. Its passage may be hindered by ice layers which develop within the pack, but its entrance into the glacier is favoured by the relatively high degree of crevassing of the underlying surface, which has been observed during summers when the net mass balance was strongly negative, notably 1988.

Throughout the summer, the discharge of the glacier river is maintained by the baseflow component. This is dominated by the water which forms as snow melts above the transient equilibrium line. Some of this water is stored within or beneath the glacier for various periods. In part, this apparent storage may result simply from the slow nature of its passage through the glacier from the higher parts of the catchment. In periods of fine weather, systematic diurnal variations of discharge are superimposed on the baseflow component. These result from variations of ice melting below the transient equilibrium line: diurnal variations of melting at higher alti-

tude are smoothed out as water percolates through snow and firn. Maximum and minimum daily discharge lag behind the maximum and minimum air temperatures by about six hours (Theakstone 1988). Summer rainfall gives rise to irregular variations of river discharge.

Towards the end of the summer, as the rate of ice ablation declines, river discharge may be maintained by the release of water from temporary storage; most of this is likely to have been formed by snowmelt in the higher parts of the catchment earlier in the season. Detectable river discharge usually comes to an end in October.

The Water Balance of the Austre Okstindbreen Basin

The mean discharge of the Austre Okstindbreen glacier river during the four summer months June-September from 1989 until 1993 was about 65.0×10^6 m^3 (Knudsen 1994), equivalent to a water depth of 2,877 mm per m^2 over the 22.59 km^2 drainage basin. The discharge, Q, is supplied by melting ice and snow within the basin, M, by rainfall, R, and by the release of water from storage, S

$$Q = M + R + S$$

Water formed by late-summer melting may be stored within the glacier through the winter and released from storage, together with early summer meltwater, into the glacier river during the following summer (Knudsen 1989).

The amount of snow which melts on the glacier is determined by annual mass-balance measurements; its mean contribution to river discharge in recent years has been about 20% of the total. Ice ablation, also calculated from mass-balance measurements, contributes about 35%. 10-20% of the mean discharge is supplied by rainfall. Water balance calculations therefore indicate that about 30-35% of the discharge results from snowmelt outside the glacier margins and water released from storage. In general, the contribution of snowmelt outside the glacier margins has been high in those summers with a high rate of ablation and rather low in cooler summers.

Sampling and Analytical Methodology

Snowpack samples are collected in a continuous column from freshly-exposed pit walls, using a 1,000 cm^3 stainless steel tube. Each sample is transferred directly to a polyethylene bag. The bag is sealed, and the sample is allowed to melt. Some of the sample water is used to rinse a clean polyethylene bottle, which then is filled. Pre-cleaning of bottles involves rinsing with hydrochloric acid and distilled water. After it is bottled, the sample is kept in a snow pit at about 0°C until it can be transported to the laboratory, where it is kept in a cold room at 4°C until it is analysed.

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River water samples are collected by a 24-bottle Manning S-4050A automatic liquid sampler with a 2-hour sampling interval. The intake is kept at a depth varying between 0.3 m and 0.5 m where the water depth is 1-2 m, well away from the river banks. Each sample is transferred to a polyethylene bottle and filtered at the field station through a 0.45 µm Whatman filter, the filter paper having been cleaned with about 25 ml of the sample. Thereafter, the sample is treated and stored in the same manner as snowpack samples.

Ca^{2+}, Mg^{2+}, Na^+ and K^+ are determined by flame atomic absorption spectrometry on a Perkin Elmer 5100 PC, using an autosampler. In order to obtain results within the linear range of the calibration curve, some samples have to be diluted. The calibration is checked after ten samples have been analysed and, if a drift of >2% is observed, a new calibration is performed and the samples re-analysed. Three values are determined for each sample. Determination of divalent cations is undertaken with added 1:250 strontium chloride to prevent interference. Generally, measurements are accurate to within ±5%.

Anions (Cl^-, NO_3^-, SO_4^-) are determined by high-pressure liquid chromatography and $^{18}O/^{16}O$ ratios by mass spectrometry.

The Oxygen Isotopic Composition of Sources of Glacier River Water

The various sources which contribute water to the Austre Okstindbreen river differ in their oxygen isotope content. Glacier ice has a rather uniform composition, with a mean $\delta^{18}O$ value of around -11.6‰. The isotopic composition of ice meltwater is very similar to that of its source (Table 2). This is to be expected because, in contrast to the relatively rapid isotopic fractionation which occurs during phase changes involving the liquid and vapour phases, differences of isotopic composition which involve the compact solid phase (ice) are balanced only by molecular diffusion: in consequence, isotopic fractionation effects normally cannot be observed during melting or sublimation of ice, although they do exist if the solid phase is in the form of porous snow or firn (Moser and Stichler 1980; Souchez and De Groote 1985).

The oxygen isotopes in the snow which covers Austre Okstindbreen in winter are influenced by the temperature during snowfall. Thus, the $\delta^{18}O$ value of samples of snow collected in late-winter (May) vary considerably (Table 2). As the upper part of the snow cover melts, and water percolates through the pack and enters the underlying glacier through crevasses and moulins, isotopic exchange occurs between the phases. A tendency towards isotopic homogenisation accompanies warming of the pack, as meltwater percolates downwards from the surface (Raben and Theakstone 1994). As a result of isotopic fractionation, the water which enters the body of the glacier is relatively depleted of the heavy isotope of oxygen, ^{18}O, whilst the remaining snow is enriched. In summer, therefore, the $\delta^{18}O$ value of the snow cover is higher than at the end of the preceding winter, and the pack is isotopically more homogeneous (Table 2).

Table 2 = Range and mean $\delta^{18}O$ values (‰) of sources of glacier river water, Austre Okstindbreen

Source	Minimum	Mean	Maximum	No. of samples
Glacier ice	-12.8	-11.6	-10.8	39
Ice meltwater	-12.7	-11.9	-10.5	31
Snow (May)	-21.8	-12.8	-7.2	112
Snow (July)	-15.6	-11.5	-8.7	250
Snow meltwater	-13.8	-12.1	-10.5	16
Rain water	-15.5	-10.5	-6.5	38

Because of the original variability of the isotopic composition of the snow cover, the ratio of the heavy and light isotopes of oxygen in water which results from melting of the snow also varies considerably (Table 2). Rain which falls within the catchment in summer has a very variable stable isotope content. Because melting snow contributes about half of the water which discharges from Austre Okstindbreen in summer, the stable isotopic composition of the water in the glacier river is influenced strongly by the melting of the accumulated snow.

Elution of Ions in the Snow Cover

The winter snow at Austre Okstindbreen accumulates as a result of precipitation during discrete events. Thus, it is stratified chemically, as well as physically. The chemistry of each snow stratum is influenced by both the moisture source and the air mass trajectory between the source and Okstindan (He and Theakstone 1994). The stratigraphic variations in the pack are retained throughout the pre-melt phase, but melting-refreezing episodes result in physical changes, notably the formation of ice layers (Raben and Theakstone 1994). The winter snow is characterised by relatively-high Na^+ ion concentrations, reflecting the influence of marine aerosols. Ca^{2+} ion concentrations are much lower in winter, when the products of crustal weathering, which are sources of Ca^{2+} ions, are buried beneath the snow.

Surface melting of the snow results in downward percolation of meltwater, with consequent chemical changes. Because melting starts much earlier at lower altitudes in the catchment than at higher sites, these changes display spatial (altitudinal) variations. During snow metamorphism, grain growth occurs. This is accompanied by differential exclusion of ions (Davis 1991). Solutes become located on the outer side of snow crystals, with the result that much solute is removed during the first passage of liquid water through the pack. SO_4^{2-} is removed more quickly than is Na^+, whilst the rate of elution of Cl^- is still lower (Raben and Theakstone 1994). Observations in 1991 at 1,475 m revealed that no SO_4^{2-} was detectable after only 13% of the winter's snow cover had melted; in the same time, 88% of the Na^+ was removed from the pack.
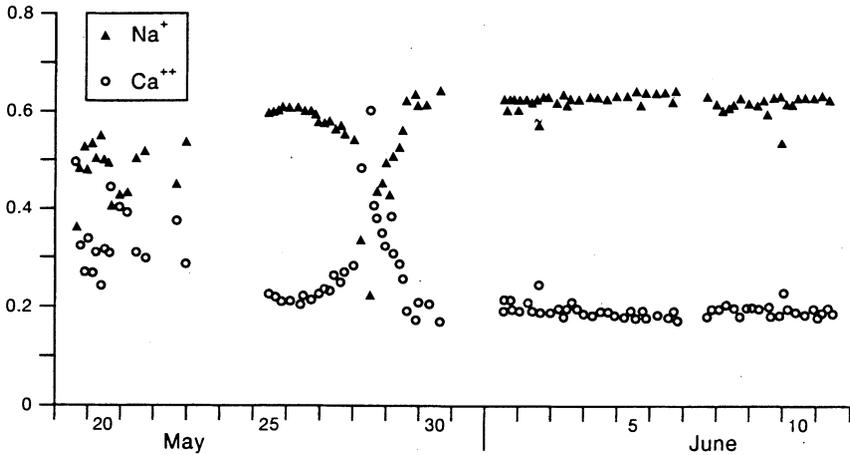
Fig. 2. Na^+ and Ca^{2+} as proportions of the total (Na^++ Ca^{2+}+ Mg^{2+}+K^+) load in water discharging from Austre Okstindbreen in May 1992.

The Chemical Composition of Water at the Start of the Melt Season

The first water to appear at Austre Okstindbreen at the end of winter results from snowmelt. In 1992, some water was flowing within the river channel in Oksfjelldalen on 19 May, when observations started. Until 28 May, the water resulted largely from the melting of snow on the lower part of the glacier and the adjacent slopes. Although some release of stored water may have been under way, it was not until early on 28 May that water began to discharge from the glacier itself. Samples collected from the channel at two-hourly intervals between 19 May and 23 May contained varying proportions of Na^+ and Ca^{2+} (Fig. 2). The dominant ions in the snow cover at Austre Okstindbreen are Na^+ and Cl^-, and the Na^+ present at the start of the melt season is likely to have been supplied principally by snowmelt. The Ca^{2+} is considered to have originated mainly from storage in 'reservoirs' which provided the water with access to the valley floor or glacier bed. There is almost no supraglacial debris at Austre Okstindbreen, and observations indicate that the principal source of Ca^{2+}, Mg^{2+} and K^+ is till and weathered bedrock.

During this early phase of the 1992 melt, Mg^{2+} and K^+ together represented a near-constant proportion of the total measured ionic load of the meltwater discharging into Oksfjelldalen (10% in parts per million). Early on 28 May, Ca^{2+} was responsible for about 20% of the total load of the four principal cations, whilst Na^+ contributed about 60%. However, as stored water was released from the glacier, there was an abrupt change: the Ca^{2+} content rose to 28%, whilst that of Na^+ fell rapidly to only 22% of the total load (Fig. 2). By 29 May, the reservoir had emptied, and a more-stable situation existed: Mg^{2+} and K^+ together contributed about 10% of

the total ion load, and Ca^{2+} between 17% and 20%, with some fluctuations out-of-phase with those of Na^+, which accounted for 60-63% of the total (Fig. 2). Thereafter, until the end of the period of sampling on 11 June, the water discharging from the glacier was dominated by the Na^+ ion.

The Chemical Composition of Water Later in the Melt Season

Mean concentrations of the four principal cations in the river water issuing from Austre Okstindbreen have varied markedly from year to year (Table 3). Na^+ ion concentrations vary between years because the depth of the glacier's snow cover differs from one year to another, and its melting depends on summer weather conditions. After winters with above-average snow accumulation, such as 1988-89 and 1989-90, Na^+ values tend to be high. Conversely, low values are likely after a winter in which snow accumulation is small; this was the case in 1988.

Observations have indicated that Ca^{2+} ion concentrations in the river water are determined largely by subglacial conditions. In 1985 and 1986, the glacier-dammed lake, Kalvtjørna, drained early in the summer; subsequently, concentrations of Ca^{2+}, Mg^{2+} and K^+ in the glacier river were high (Table 3), although they declined during the course of the season (Knudsen 1990). Ablation rates were high in both summers. The combination of a well-established subglacial route for meltwater and an abundant supply of water facilitated the acquisition of ions from the glacier bed, and resulted in the high concentrations of Ca^{2+}, Mg^{2+} and K^+ in the river water.

River flow in the Austre Okstindbreen basin is sustained by melting snow. There was a strong positive relationship between the content of Na^+ and Cl^- ions in the 80 river water samples collected between 10 and 21 July 1990, although the actual concentrations varied by a factor of 2 between the most- and least-dilute samples (Fig. 3a). The Na:Cl ratio in most samples was between 0.55 and 0.60 (Fig. 3b). This is close to the mean value for sea water.

Glacier ice has a very low solute content. As a result, when ice meltwater is mixed

Table 3 – Mean cation concentrations (ppm) and $\delta^{18}O$ values (‰) in Austre Okstindbreen river water (standard deviation in parentheses)

	Na^+	Ca^{2+}	Mg^{2+}	K^+	$\delta^{18}O$
1983	1.26 (0.25)	0.35 (0.06)	0.25 (0.06)	0.31 (0.05)	-13.01 (0.36)
1984	0.67 (0.21)	0.23 (0.08)	0.10 (0.09)	0.23 (0.46)	-13.25 (0.26)
1985	0.53 (0.18)	3.29 (1.51)	0.33 (0.13)	0.58 (0.35)	-13.36 (0.33)
1986	0.67 (0.24)	5.65 (5.84)	0.50 (0.33)	1.12 (0.59)	-12.72 (0.23)
1987	0.80 (0.23)	0.56 (0.22)	0.18 (0.08)	0.23 (0.10)	-13.80 (0.26)
1988	0.34 (0.03)	0.79 (0.35)	0.17 (0.17)	0.17 (0.10)	-13.18 (0.12)
1989	3.14 (0.35)	0.67 (0.11)	0.49 (0.07)	0.35 (0.07)	-13.05 (0.26)
1990	1.73 (0.25)	0.66 (0.24)	0.28 (0.04)	0.27 (0.04)	-13.58 (0.15)

a

Na$^+$ (p.p.m.)
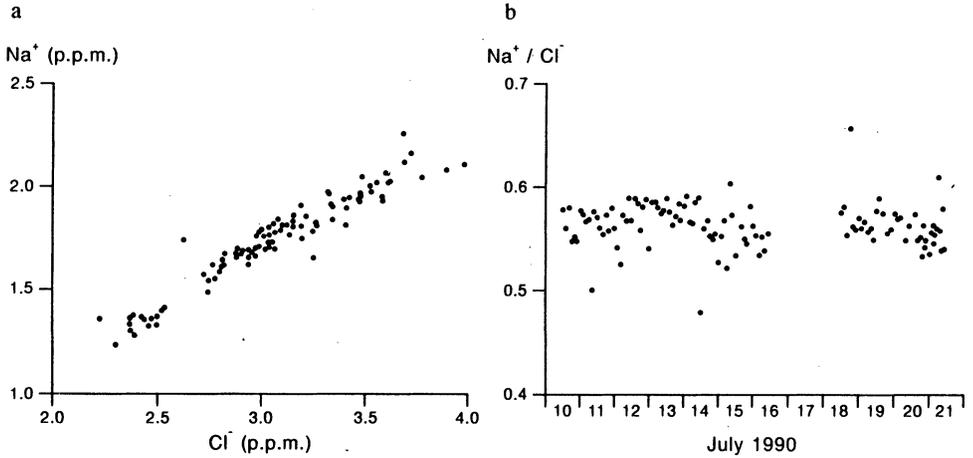
b

Na$^+$ / Cl$^-$

Cl$^-$ (p.p.m.)

July 1990

Fig. 3. a) Relationship between Na$^+$ and Cl$^-$ ion concentrations in river water samples, July 1990. b) The Na:Cl ratios of the samples.

with snow meltwater, it dilutes the overall concentration of ions. Ice meltwater is ^{18}O-rich. Thus, the δ^{18}O value of the glacier river water rises as melting ice contributes more to discharge and the proportion of snow meltwater in the river falls. During a period of fine weather between 17 July and 25 July 1993, diurnal variations characterised both the discharge and oxygen isotope records. As ablation of ice increased, diurnal variations of δ^{18}O values of the river water were superimposed on a rising trend (Fig. 4). At the same time, Cl$^-$ values declined. Cl$^-$ concentrations were determined for intervals of four hours, as against the two-hour interval used for the
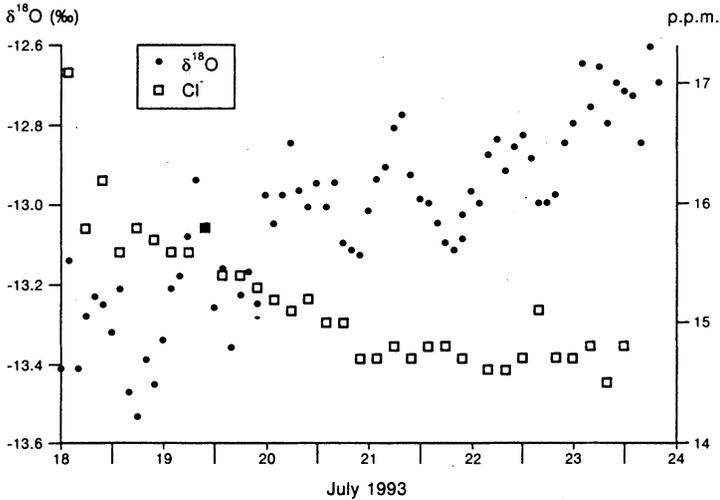
δ^{18}O (‰)

p.p.m.

July 1993

Fig. 4. Variations of δ^{18}O values and Cl$^-$ concentrations in Austre Okstindbreen river water, July 1993.
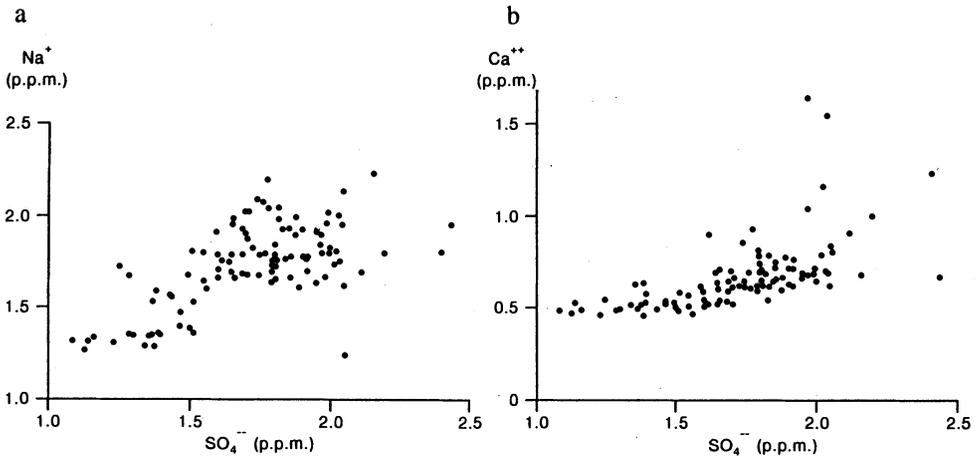
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Fig. 5. a) Relationship between Na+ and SO$_4^{2-}$ concentrations in glacier river water, July 1990. b) Ca^{2+} and SO$_4^{2-}$ concentrations.

oxygen isotope determinations, and diurnal patterns therefore are somewhat weak (Fig. 4). Nevertheless, it is apparent that the general trend of increasing δ^{18}O values was accompanied by a decreasing trend of Cl$^-$ concentrations, and that superimposed diurnal variations tended to be out of phase, with Cl$^-$ concentrations rising as δ^{18}O values fell during the night, when the dilution of snow meltwater by ice meltwater declined.

As the summer progresses, the efficiency of the glacier's drainage systems increases. The speed with which they develop influences the rate of acquisition of ions from subglacial sources. The fact that, although SO$_4^{2-}$ is removed rapidly from the snow cover at the start of the summer, it is present in the river water in the middle of the melt season suggests that some SO$_4^{2-}$ ions are incorporated subglacially. In 1990, after a winter with above-average snow accumulation, ablation started early, but river discharge was only slightly above average: apparently, much water went into storage within the glacier. The major contribution made by snow-melt to discharge during the ablation season was reflected in low δ^{18}O values, high Na+ concentrations and unusually-high SO$_4^{2-}$ concentrations in the glacier river. A positive relationship between Na+ and SO$_4^{2-}$ concentrations (Fig. 5a) suggested that much of the SO$_4^{2-}$ had originated in the snow. On 20 July, a sudden increase of discharge occurred during dry weather, and the water leaving the glacier was discoloured. Samples collected at this time had above-average Ca^{2+} concentrations, and SO$_4^{2-}$ concentrations also were relatively high. It was evident that a previously-untapped reservoir, or a conduit which had not been connected with the glacier's principal internal drainage system, had opened. The presence of rather large amounts of SO$_4^{2-}$ in those water samples which had the highest Ca^{2+} concentrations (Fig. 5b) supported the view that some SO$_4^{2-}$ was subglacially-acquired.

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Discussion

The first contribution to glacier river discharge is made by snow meltwater from the glacier tongue. Na^+ and Cl^- concentrations are likely to be high after a winter in which much snow accumulates in the catchment. Later in the summer, the thickness and stratigraphic variations of the pack and the rate of surface melting influence inputs of ions and isotopes from the snow to the glacier's drainage systems. In some years, the supply of ions from the snow is exhausted early in the summer; this is the case when a winter with low accumulation is followed by an early start to the ablation season, especially if a low frequency of melting and refreezing episodes has left the pack free of ice layers. In these years, the snow pack becomes isotopically-homogeneous rather quickly. This happened in 1988. In contrast, when the onset of ablation is delayed after a mild winter with high accumulation, as in 1989, both light isotopes and ions from the snow cover are available well into the summer.

Glacier ice is relatively pure, supplying few ions to its meltwater, and both it and its meltwater are enriched in ^{18}O compared with much of the water formed as snow melts. At times of high ice ablation, therefore, the ice meltwater dilutes the solute concentrations in the glacier river, and the $\delta^{18}O$ value rises. This may be seen in longer term trends of variation of the composition of the river water, as well as in diurnal variations during periods of fine weather.

At Austre Okstindbreen, Ca^{2+} ions are acquired principally from the glacier bed or valley sides, as water runs over weathered rock or sediment surfaces and penetrates beneath the glacier. Very heavy falls of rain may result in uplift of the glacier from its bed, permitting increased contact between water and bed material, and increased acquisition of ions by surface exchange processes and by the dissolution of very fine 'rock flour' (Tranter and Raiswell 1991). The acquisition of Ca^{2+}, K^+, Mg^{2+} and SO_4^{2-} from subglacial sources is favoured by the early establishment of a subglacial conduit for meltwater, such as occurred in 1985 and 1986, when the ice-dammed lake Kalvtjörna drained at the beginning of the summer, leaving a major routeway for water flow beneath the glacier from 1,000 m to the front (Knudsen and Theakstone 1988).

Collins (1978) introduced a simple two component mixing model of glacier river chemistry, suggesting that an englacial component was supplied principally by melting ice at the glacier surface below the transient equilibrium line and that a subglacial component acquired solutes as a consequence of rather prolonged contact with basal materials

$$Q_t C_t \equiv Q_s C_s + Q_e C_e$$

where Q represents discharge, C composition, t the total, s the subglacial component and e the englacial component. If the composition of the components is known, the contribution which each makes to the total discharge can be calculated

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$$Q_s = Q_t \frac{C_t - C_e}{C_s - C_e} \quad \text{and} \quad Q_e = Q_t \frac{C_t - C_s}{C_e - C_s}$$

However, it is clear from observations during several summers that the Austre Ok-stindbreen glacier river is not supplied by a single subglacial component of constant composition. Furthermore, the composition of the snowpack changes with time, as a result of differential elution of ions and increasing isotopic homogenisation. Consequently, the composition of the water generated by melting snow changes through the summer. It is melting snow that maintains the baseflow component of the glacier river discharge. Clearly, it is unrealistic to apply a simple two component mixing model to hydrograph separation at Austre Okstindbreen on the basis of either oxygen isotopes or ionic concentrations in the glacier river water. In order to quantify the contributions of melting ice and melting snow to glacier river discharge, it is necessary to monitor the changing ionic and isotopic composition of both the snow cover and the glacier river throughout the melt season.

Conclusions

Observations at Austre Okstindbreen, carried out over a period of many years, have shown that the dissolved load of the glacier river varies markedly from one year to another. The passage of water through the glacier, dependent on the development of its internal drainage systems, is influenced by varying conditions in both the winter and summer seasons. The amount of snow which is present at the start of the melt season, and the subsequent melting conditions, have a significant influence on the content of individual ions in the river water which issues from the glacier in summer. Snow meltwater from the lower part of the glacier and the adjacent parts of the catchment is the dominant component of the river water early in the ablation season. The Na^+ loading is higher at the end of a winter in which snow accumulation has been above average than after a winter with a low total accumulation of snow.

Later in the summer, as the transient equilibrium line moves up-glacier and the amount of melting ice increases, snow meltwater continues to be supplied from the accumulation zone, but its passage through the glacier may be relatively slow, with the water apparently going into temporary storage. Elution of ions from the residual snow generally leads to decreasing Na^+ concentrations in the glacier river water through the summer. Ionic concentrations are likely to be particularly low towards the end of summer if the preceding winter accumulation was small and the melt season began at an early date.

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Acknowledgements

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