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# SNOWFALL AND OXYGEN-ISOTOPE VARIATIONS OFF THE NORTH COAST OF ELLESMERE ISLAND, N.W.T., CANADA

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ABSTRACT. Snow-pack along the land-fast ice fringe off the north coast of Ellesmere Island was generally characterized by depth-hoar overlain by dense snow and wind slab. Mean snow depth in the study area was 0.54 m (1982–85) and the mean $\delta^{18}O$ value of the snow-pack was $-31.3^{0}/_{00}$. Isotope data were not obtained previously for this geographic region and, therefore, complement a previous study of $\delta^{18}O$ variations in High Arctic snow (Koerner, 1979). The data are consistent with an Arctic Ocean moisture source. The $\delta^{18}O$ profiles show seasonal variations, with winter snow being more depleted in $^{18}O$ than fall and spring snow. However, the $\delta^{18}O$ profiles are dominated by a trend to higher $\delta^{18}O$ values with increasing depth. This is attributed to a decrease in $\delta^{18}O$ values as condensation temperatures fall during the autumn–winter accumulation period. During this time, there is also a change from relatively open to almost complete ice cover in the Arctic Ocean. The change in evaporation conditions and consequent effect on $\delta$ values gives rise to a sharp discontinuity in the $\delta^{18}O$ profiles and a bi-modal $\delta^{18}O$ frequency distribution. The bi-modal distribution is reinforced by a secondary isotope fractionation that occurs during depth-hoar formation. This isotope effect leads to a wider $\delta^{18}O$ range but does not significantly alter the mean $\delta^{18}O$ value.

## INTRODUCTION

Each spring since 1982, a series of traverses has been made by snowmobile over the ice shelves and land-fast sea ice off northern Ellesmere Island. Objectives of the traverses included measurement of snow depths at the mass-balance networks on Ward Hunt Ice Shelf and Ice Rise, and the collection of snow samples for oxygen-isotope analyses from snow pits at 23 locations shown in Figure 1. The snowfall and $\delta^{18}O$ data are presented and discussed in this paper.

## SNOW DEPTH AND SNOW STRUCTURE

In all the snow pits dug for the study there was considerable stratification, with depth-hoar at the base overlain by layers of densely compacted snow and wind-slab. In some cases this was capped with a light, fresh snow layer. The above features are common in High Arctic snow-packs (Woo and others, 1983). In each of the pits, the deepest snow consisted of depth-hoar with "skeleton-type" crystals as described by Akitaya (1975). The size of the hoar crystals decreased towards intermediate depths where the snow was often loose and granular. This snow was overlain by dense, fine-grained snow that was, in turn, overlain by wind-slab sculpted into sastrugi. The density of the entire snow-pack ranged from 0.3 to 0.4 Mg m$^{-3}$ which compares well with the value of 0.31 Mg m$^{-3}$ obtained by Hattersley-Smith and Serson (1970).

Each of the snow pits dug for this study was sampled in April or May and, therefore, represents the accumulated snow of the previous 8 or 9 months. Table I shows that the snow pits ranged from 0.25 to 0.9 m deep, with a mean of 0.54 ± 0.28 m (2 S.D.). For the same interval (1982–85), 260

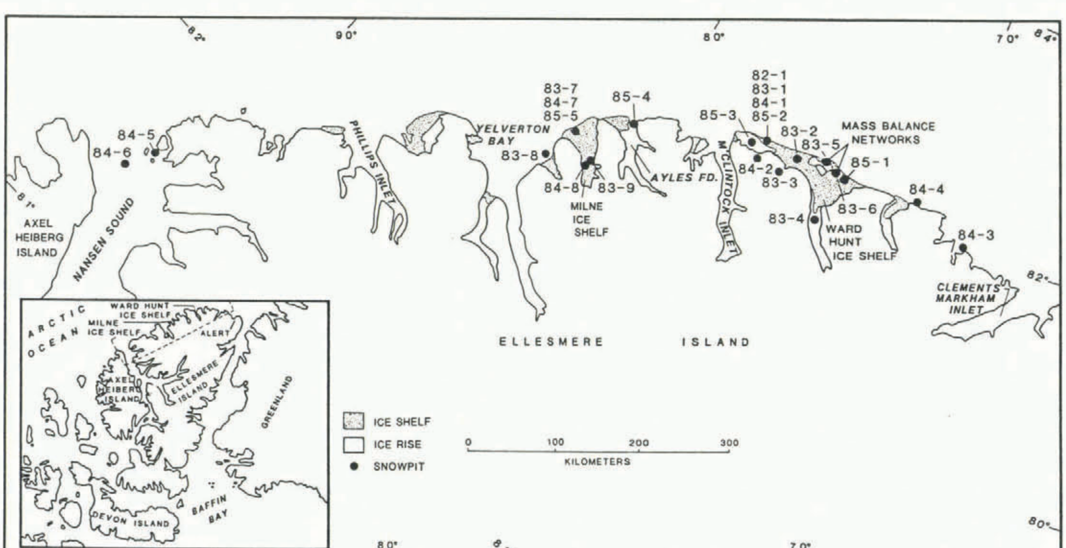


*Fig. 1. Map of the north coast of Ellesmere Island showing the location of snow pits and mass-balance networks. The insert map shows the location of the study area in relation to the Queen Elizabeth Islands, and Alert weather station.*



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TABLE I. SNOW-PIT DATA, NORTHERN ELLESMERE ISLAND, 1982–85

| *Pit number* | *Depth* | *Number of snow samples* | *Mean* $\delta^{18}O$ | $\delta^{18}O$ *range* |
|---|---|---|---|---|
| | m | | ⁰/oo | ⁰/oo |
| 82-1 | 0.35 | 5 | −30.5 | −36.7 to −25.1 |
| 83-1 | 0.25 | 5 | −30.3 | −35.5 to −24.0 |
| 83-2 | 0.63 | 6 | −31.6 | −35.2 to −29.7 |
| 83-3 | 0.45 | 5 | −34.1 | −37.8 to −26.1 |
| 83-4 | 0.60 | 7 | −33.3 | −37.0 to −24.1 |
| 83-5 | 0.55 | 6 | −30.7 | −34.4 to −22.8 |
| 83-6 | 0.33 | 6 | −30.6 | −35.8 to −23.2 |
| 83-7 | 0.90 | 5 | −29.1 | −38.6 to −21.4 |
| 83-8 | 0.60 | 7 | −30.5 | −39.5 to −19.4 |
| 83-9 | 0.52 | 6 | −30.7 | −36.8 to −23.8 |
| 84-1 | 0.70 | 10 | - | −38.2 to −21.0 |
| 84-2 | 0.51 | 9 | −32.1 | −38.6 to −21.8 |
| 84-3 | 0.44 | 7 | −31.9 | −38.2 to −19.0 |
| 84-4 | 0.40 | 7 | −32.1 | −36.0 to −22.7 |
| 84-5 | 0.74 | 6 | - | −35.4 to −20.0 |
| 84-6 | 0.70 | 5 | - | −39.8 to −21.8 |
| 84-7 | 0.50 | 5 | −29.8 | −37.2 to −21.3 |
| 84-8 | 0.58 | 6 | −31.3 | −39.0 to −23.3 |
| 85-1 | 0.58 | 8 | - | −39.1 to −22.0 |
| 85-2 | 0.62 | 8 | −32.3 | −42.0 to −24.5 |
| 85-3 | 0.37 | 3 | - | −32.2 to −21.7 |
| 85-4 | 0.54 | 4 | - | −36.1 to −18.9 |
| 85-5 | 0.58 | 4 | - | −24.4 to −23.0 |
| | Mean = 0.54 m | | Mean = −31.3⁰/oo | Total range: −42.0 to −18.9⁰/oo |

Note: Blanks in column 4 represent incomplete $\delta^{18}O$ profiles.

snow-depth measurements at the mass-balance networks (Fig. 1) ranged from 0.17 to 1.19 m, with a mean of 0.53 ± 0.32 m. A *t*-test and *F*-test were made to see if there was a significant difference between the mean and variance of the entire coast and the mass-balance networks. In each case, there was no significant difference at the <1% level which suggests that snow-depth measurements at Ward Hunt Ice Shelf and Ice Rise are representative of the land-fast ice fringe as a whole. Furthermore, recent snow-depth measurements are almost the same as those for the period 1958–76 at the mass-balance networks when mean snow depth was almost 0.53 m (Hattersley-Smith and Serson, 1970; Serson, 1979). Thus, it appears that winter snow accumulation has remained quite constant for almost 30 years in this region.

## OXYGEN-18

### *Statistical analysis*

Complete $\delta^{18}O$ profiles, represented by 100 samples, were obtained for 16 snow pits (Table I). As a result of sample losses, seven additional $\delta^{18}O$ profiles are incomplete, but are represented by 40 samples. Eleven $\delta^{18}O$ profiles are shown in Figures 2 and 3, and most show a general trend of $\delta$ values increasing (becoming less negative) as depth increases. The depth-hoar layers are the least depleted in the heavy isotope and it is noted that the top of the depth-hoar layer is often coincident with a sharp decrease of $^{18}O$. In some cases, the surface snow layer is less depleted in $^{18}O$ than the snow immediately below (Fig. 2, pit 85-2; Fig. 3, pit 84-8).

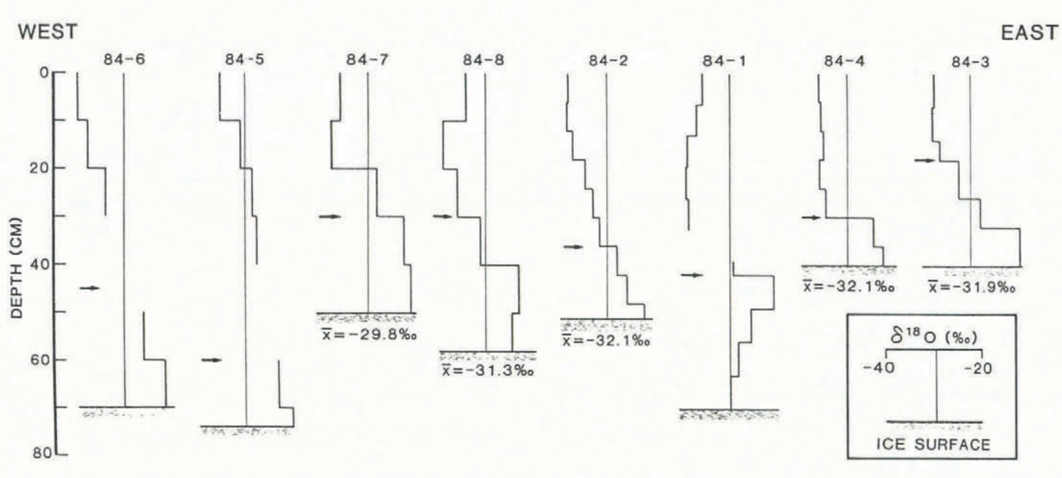


*Fig. 2. $\delta^{18}O$ profiles of snow pits on the land-fast ice fringe off northern Ellesmere Island from Nansen Sound (left) to Clements Markham Inlet (right). $\delta$ values are expressed relative to SMOW. Narrow vertical lines represent a $\delta^{18}O$ value of −30.0⁰/oo and are given as a reference. Arrows mark the top of the depth-hoar layer.*



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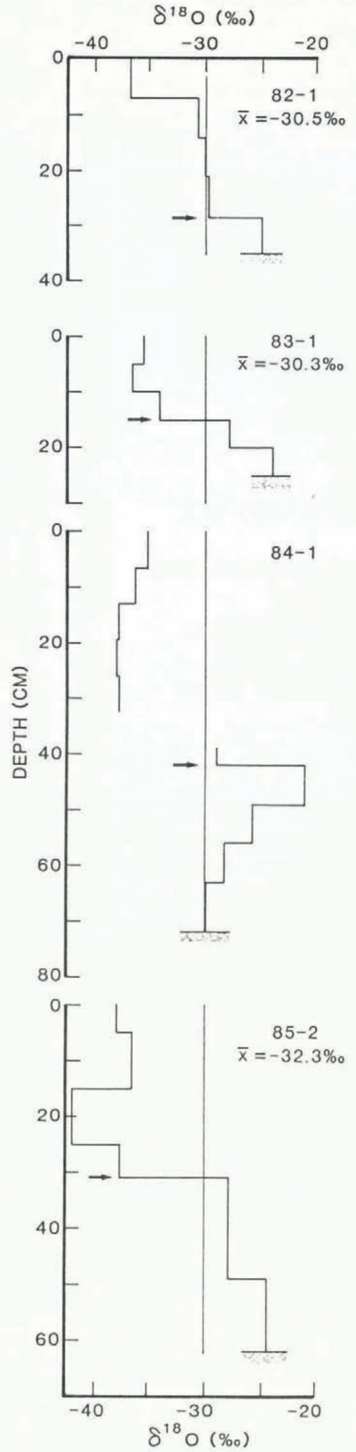


*Fig. 3. δ$^{18}$O profiles of snow pits at one location at the west end of Ward Hunt Ice Shelf, 1982–85 (see Fig. 1). Arrows mark the top of the depth-hoar layer.*

The δ$^{18}$O–depth relationship is shown in Figure 4a. It is noted that there is a distinct cluster of points corresponding to the upper snow layers and having δ values in the range −42.5 to −33.5$^0$/oo. Conversely, there is a greater scatter of δ values in deeper snow, most of which is depth-hoar.

Snow-pit isotope data are given in Table I. The overall mean δ value is −31.3 ± 5.8$^0$/oo (2 S.D.) and all but two of the values fall within two standard deviations of the mean. The mean value is not, however, the mean of a normal distribution. The frequency distribution is bi-modal and the mean falls in class 15 (−31.49 to −30.5$^0$/oo) that lies between the peaks (Fig. 4b).

The left side of the frequency distribution largely represents δ$^{18}$O values of the wind-slab and compacted fine-grained snow. The right side of the frequency distribution largely represents δ$^{18}$O values of the depth-hoar. The remaining δ values represent the intermediate snow layers and fresh snow, and are mostly found between the peaks of the frequency distribution.

*Seasonal change of $^{18}$O content*

Dansgaard (1964) has shown that the δ value of precipitation is largely dependent on the condensation temperature, i.e. the lower the condensation temperature, the greater the depletion of heavy isotopes in precipitation. Thus, snowfall exhibits temperature-dependent seasonal isotopic variations. During the accumulation period under consideration here (September–May), the same pattern of temperature and precipitation occurs at High Arctic weather stations, including Alert (Fig. 1). Mean monthly snowfall is greatest in September and October. From then until February, mean monthly temperatures and snowfall decrease, and begin to rise again in March (Maxwell, 1982). The rate of change of temperature and snowfall is greatest in September, October, and November, whereas in the period December–February, temperature and snowfall remain more constant.

The δ–depth trend in the snow pits (Fig. 4a) is evidence of increasing depletion of $^{18}$O in snow as it falls during autumn and winter. The scatter of δ values in the deeper snow (Fig. 4a) probably arises in part as a result of the rapid temperature decrease in autumn, when the greatest proportion of snowfall occurs. On the other hand, in the winter, when temperatures and snowfall are at a minimum with less variation, δ$^{18}$O values should be clustered within a smaller range. It is noted that the deep snow layers of pit 84-1 (Figs 2 and 3) do not show the same δ–depth trend as the other pits. This is attributed to the effects of drifting since the pit was dug close to a building. From March onward the rise in mean monthly temperatures should be reflected in an increase in the $^{18}$O content of snow. This is evident in the surface snow of some snow pits. The mean δ$^{18}$O values of some individual snowfall events in Table II are also evidence of the increase in $^{18}$O content with time and rising temperatures during May and June 1983.

TABLE II. MEAN DAILY TEMPERATURE AND PRECIPITATION δ$^{18}$O CHANGES, NORTHERN ELLESMERE ISLAND, SPRING 1983

| *Location* | *Date* | δ$^{18}$*O* $^0$/oo | *Mean daily temperature* °C |
|---|---|---|---|
| Ward Hunt Ice Shelf | 7 May | −31.0 | −21.5 |
| Milne Ice Shelf | 26 May | −27.2 | −3.5 |
| Ward Hunt Ice Shelf | 4 June | −24.0 | −2.5 |

*Regional significance of $^{18}$O content*

Oxygen-isotope variations in precipitation across the ice caps of the Canadian High Arctic were examined by Koerner (1979). However, Koerner's survey did not include the north coast of Ellesmere Island. Hattersley-Smith and others (1975) presented $^{18}$O data from an ice cap 220 km south-west of Ward Hunt Island, but the data represent an elevation of 1800 m a.s.l. and are not comparable with the sea-level values of this study.

In the Canadian High Arctic, mean δ$^{18}$O values of precipitation for the period August–May ranged from −21.0$^0$/oo in an isotopically "warm" zone in northern Baffin Bay to −35.0$^0$/oo in an isotopically "cold" zone in eastern Axel Heiberg Island (Koerner, 1979). This was explained as a "distance from source" effect, where an air mass originating from the south gives rise to more negative δ values in precipitation. However, on western Axel Heiberg Island (Fig. 1), mean δ$^{18}$O values (−32.0$^0$/oo) were 3.0$^0$/oo



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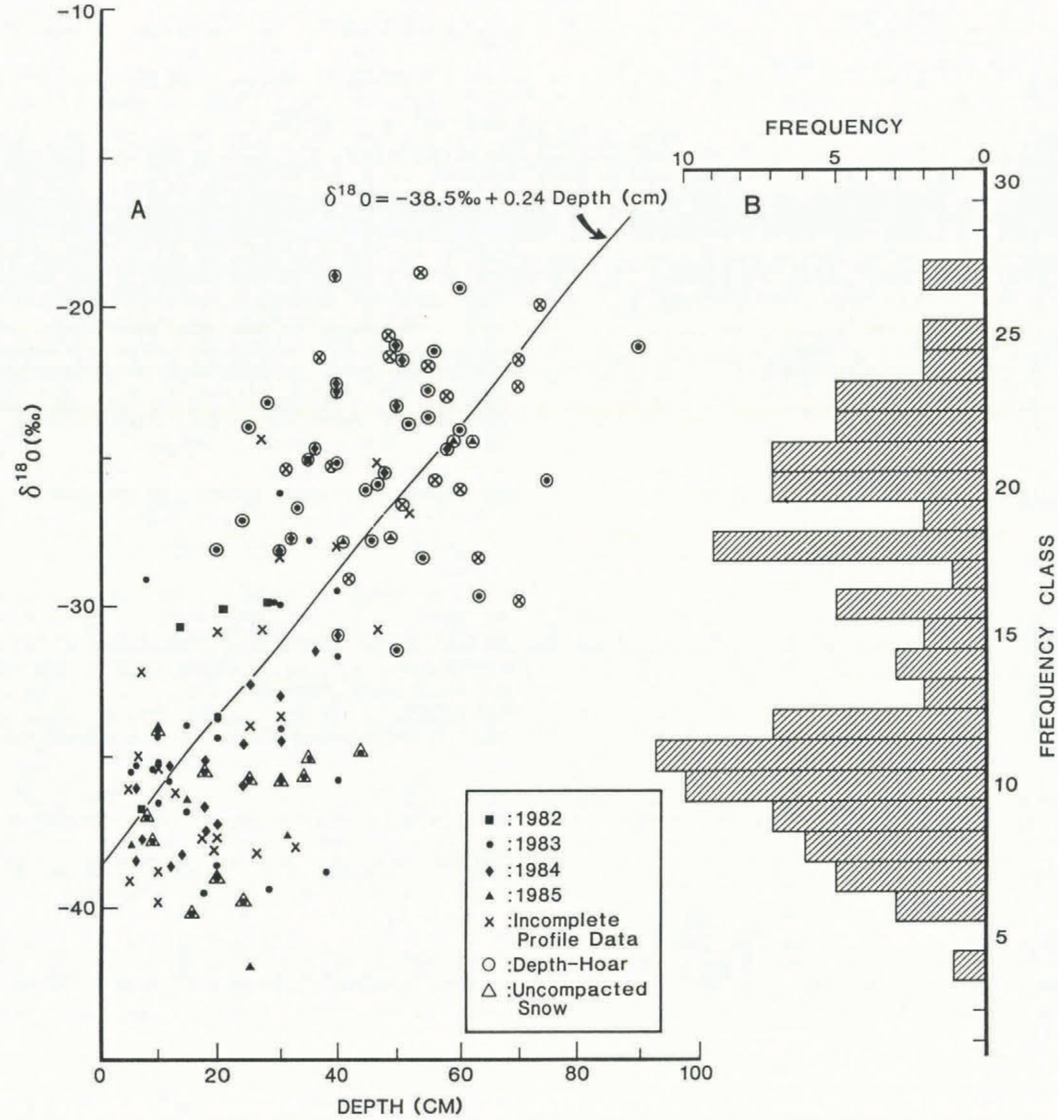


*Fig. 4. a. Relationship between snow $\delta^{18}O$ values and depth at which samples were obtained. b. Frequency distribution of $\delta^{18}O$ values. The frequency classes are at 0.99‰ intervals, e.g. class 10 represents −35.49‰ to −34.5‰, class 15 represents −31.49‰ to −30.5‰, and class 20 represents −26.49‰ to −25.5‰.*

more positive than on the eastern side. Koerner attributed this to an isotopically richer, Arctic Ocean moisture source. The mean $\delta^{18}O$ value of −31.3‰ in snow pits along the north coast of Ellesmere Island tends to support the presence of an Arctic Ocean moisture source. This gives rise to slightly more positive $\delta^{18}O$ values along the Arctic Ocean littoral than in the north-central Queen Elizabeth Islands.

Koerner(1979) considered the Arctic Ocean moisture source to be less significant than a southerly moisture source from Baffin Bay. However, it has since been shown to be inappropriate to talk in terms of two moisture sources (Fisher and Alt, 1985). Furthermore, Bradley and Eischeid (1985) showed that air masses from the south have less influence on significant precipitation events at Alert (Fig. 1) than was previously believed; westerly and northerly air masses from the Arctic Ocean are more important. This, we assume, applies to the entire north coast of Ellesmere Island.

In late summer and early autumn, the westerly and northerly flows pick up a considerable amount of moisture due to open-water conditions in the Arctic Ocean. As a result, precipitation δ values should be more positive than those when there is little or no open water. By the end of November, an almost complete ice cover is established on the Arctic Ocean (Maxwell, 1982). Therefore, the amount of moisture available to passing air masses will decrease. In consequence, the amount of precipitation decreases as does the $^{18}O$ content of precipitation.

Sea-ice extent is also an important determinant of precipitation δ values at high latitudes (Fisher and Alt, 1985). In November, the shift from relatively open to near-closed ice conditions on the Arctic Ocean changes the evaporation conditions and would account for the abrupt δ shift in the snow pits. It would also account for the bi-modal $\delta^{18}O$ frequency distribution; the scattered δ values on the right side of the distribution correspond to autumn snow and the clustered δ values on the left side correspond to winter snow.

### *Post-depositional metamorphism and $^{18}O$ content*

In this study, snow pits were dug 8 to 9 months after the first snow deposition of the previous September and in that time there had been considerable depth-hoar formation. Skeleton-type depth-hoar growth dominates when the temperature gradient is greater than −0.25 deg $cm^{-1}$ (Akitaya, 1975). Temperature gradients sufficient for depth-hoar formation must be common on the ice shelves and land-fast sea ice, and will be maintained as snow depth increases and temperatures decrease from September to February.

Epstein and others (1965) suggested that the mechanism of depth-hoar formation results in $^{16}O$ depletion in the depth-hoar due to partial recondensation. The remaining water vapour recondenses in the upper layers and leads to $^{16}O$ enrichment there. Trabant and Benson (1972) observed



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relative depletions of deuterium in the upper snow layers that only occurred in the presence of a temperature gradient. Moser and Stichler (1975) concluded that a marked increase of $\delta$ values in depth-hoar is caused by a considerable mass transport from the deepest layers to the upper layers due to steep temperature gradients. The resulting condensation in the upper layers leads to a $\delta$ value less than that of the original snow.

During sublimation, very little isotope fractionation is expected during the solid to gas transition which should proceed layer by layer under very cold conditions. On the other hand, isotopic selectivity should occur during the gas to solid transformation, favouring the heavier isotopes in the more condensed phase. Therefore, the process of depth-hoar formation is expected not only to alter the snow structure, but also the $^{18}O$ content of the admixture of hoar and snow. It can render the bottom snow layers isotopically heavy while the upper snow layers show a relative depletion in $^{18}O$ and deuterium. As a consequence, the range of $\delta^{18}O$ values probably increases during depth-hoar formation.

Water vapour in snow-pack is derived not only from the snow itself but also from the substrate. In the case of soil substrate, a considerable upward moisture flux has been found to dry the soil (Trabant and Benson, 1972). However, this appeared not to affect the mean $\delta$ value of the entire snow-pack when it was compared to snow-pack underlain by an impermeable barrier. In view of this, it is unlikely that the mean $\delta$ values of individual snow pits in this study are greatly affected by any vapour flux from the ice below the snow. Likewise, unless there are vapour losses at the surface, the mean $\delta^{18}O$ value of snow-pack should remain unchanged. The extensive wind-slabs evident at the snow-pack surface indicate that considerable amounts of vapour condense within the snow and vapour loss is minimized (cf. Benson, 1962). Thus, whereas the $^{18}O$ content of individual snow layers is altered from the original, the mean $^{18}O$ content of total snow accumulation is unaffected by depth-hoar formation.

## SUMMARY AND CONCLUSION

Depth-hoar is common in High Arctic snow-pack and isotope effects similar to those described above will occur. Since Koerner (1979) included the depth-hoar layer in a study of $\delta^{18}O$ variations in snow across High Arctic ice caps, the mean $\delta^{18}O$ value (−31.3‰) in the present study is valid for the purposes of comparison. A $\delta^{18}O$ value of −31.3‰ is consistent with moisture from the Arctic Ocean contributing to slightly lower $\delta$ values in precipitation along the coast of the Queen Elizabeth Islands. After the end of November, when a complete ice cover is established on the Arctic Ocean, the amount of precipitation and its $^{18}O$ content falls. The change in ice and evaporation conditions is manifested as a sharp discontinuity in the $\delta^{18}O$ profiles and a bi-modal $\delta^{18}O$ frequency distribution. The Arctic Ocean moisture source would appear to be greater than previously believed.

In many snow pits, the isotopic shift also coincides with the top of the depth-hoar layer. Once the snow reaches the ground, metamorphism begins and the isotopes are redistributed as a result of vapour transfers. During depth-hoar formation, the deeper snow layers are further depleted in $^{16}O$ while the upper snow layers are enriched in $^{16}O$. The combined effect is to increase the range of $\delta^{18}O$ values and reinforce the bi-modal $\delta^{18}O$ frequency distribution. The mean $\delta^{18}O$ value of the snow-pack remains unchanged.

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