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Article abstract

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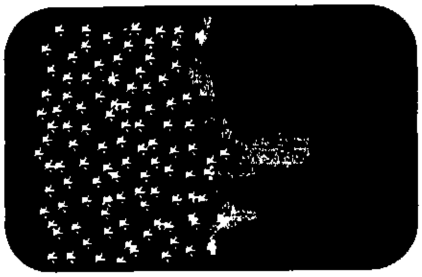

# Isotopic Variability in Arctic Precipitation as a Climatic Indicator

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## SUMMARY

Preliminary data are examined from a project in which the variability in the isotopic composition of precipitation across northern Canada and the implications for paleoclimatic reconstruction are examined. The data set shows a geographic variability of about 6‰ in isotopic composition of precipitation across the Canadian Arctic, roughly double the temporal variability seen in the ice core records from the last 10,000 years. The seasonal variability in average monthly $\delta^{18}O$ values from the arctic stations in 1991 was as much as 26‰. A snow and firn core collected on Bylot Island had a range of 14.8‰, compared to the range in average monthly precipitation of 25.6‰ covering the same time period. This difference in the observed seasonal range of values is the result of processes operating in the snow pack, such as vapor movement and molecular diffusion, and the strategy used in sampling the core.

The results indicate that a much better understanding of the geographic and seasonal variation in the $\delta^{18}O$ values of precipitation is required before a direct linkage between the isotope records in ice cores and global climate change can be determined. Using recently developed radiocarbon dating techniques, buried glacier ice that has been preserved in permafrost may be able to provide the greater spatial and temporal detail required.

## RÉSUMÉ

Dans le présent article, on étudie des données préliminaires d'un projet de la variation de la composition isotopique des précipitations dans le nord du Canada et où, on s'intéresse à l'applicabilité de telles mesures dans les reconstiutions paléoclimatiques. Le jeu de données indique qu'il existe une variabilité géographique de 6 ‰ dans la composition isotopique des précipitations à travers l'Arctique canadien, ce qui est le double environ de la variabilité temporelle observée dans le carottes de glace des derniers 10,000 ans. La variabilité saisonnière des valeurs moyennes mensuelles de $^{18}O$ mesurée en 1991 à partir de stations arctiques atteint 26 ‰. Une carotte de neige et de névé prélevée sur l'île Bylot a montré une fourchette de variation de 14,8 ‰, à comparer avec une fourchette des variations moyennes mensuelles des précipitations de 25,6 ‰ pour la même période. Les différences de fourchette de valeurs saisonnières observées dépendent des processus se déroulant au sein même de la couverture neigeuse, comme les mouvements de la phase gazeuse et la diffusion moléculaire, ainsi que des techniques de prélèvement employées.

Les résultats montrent qu'il faudra beaucoup améliorer notre compréhension des variations géographiques et saisonnières des valeurs de $^{18}O$ des précipitations avant que l'on puisse faire un lien direct entre la variation du profil isotopique des carottes de glace et un changement climatique à l'échelle du globe. L'utilisation de techniques de datation par le radiocarbon mises au point récemment sur des glaces de glacier enfouies et préservées dans le pergélisol permettra peut-être d'atteindre la précision nécessaire dans les mesures spatiales et temporelles.

## INTRODUCTION

Predicting the magnitude and character of global climate change is a daunting task. To predict future climate, an understanding of how the climatic system behaved in the past is required. One of the best ways to study the Earth's climatic history is through the study of ice cores (Johnsen *et al.*, 1995). A wealth of information can be obtained from the various physical, chemical and isotopic properties of the ice cores (see Table 1), such as past air temperatures (Dansgaard, 1964), changes in the amount of greenhouse gases in the atmosphere (Nakazawa *et al.*, 1993), and variations in precipitation rates (Fischer *et al.*, 1995). During the last 30 years dozens of ice cores have been recovered from glaciers and ice caps around the world, providing considerable insight into how the climate at these locations has changed over the last 120,000 years (Dansgaard and Tauber, 1969; Koerner and Paterson, 1974; Fujii *et al.*, 1990; Dansgaard *et al.*, 1993).

One of the main sources of information on past climates has been the $\delta^{18}O$ record preserved in ice caps. Since the $\delta^{18}O$ of precipitation is related in part to the atmospheric temperature at which the precipitation formed, the record of $\delta^{18}O$ in glacier ice can provide an estimate for paleoclimatic temperatures. The $\delta^{18}O$ records in ice cores taken from Antarctica, Greenland and several other polar glaciers have also been used to identify the timing of changes in past climates (Johnsen *et al.*, 1972). The major shift of the $\delta^{18}O$ profiles shown in Figure 1, at approximately 10 ka, indicates the transition from the colder Pleistocene to

**Table 1** Paleoclimatic information that can be extracted from ice cores.

| Information | Analysis |
|---|---|
| Atmospheric temperature | $\delta^{18}O$, melt layers, crystal size |
| Atmospheric composition | $CO_2$ and trace elements |
| Rate of accumulation | seasonal signals |
| Ice sheet stability | gas content |
| Volcanic activity | acidity, trace elements |
| Solar activity/geomagnetic field strength | $NO_3^-$ content |

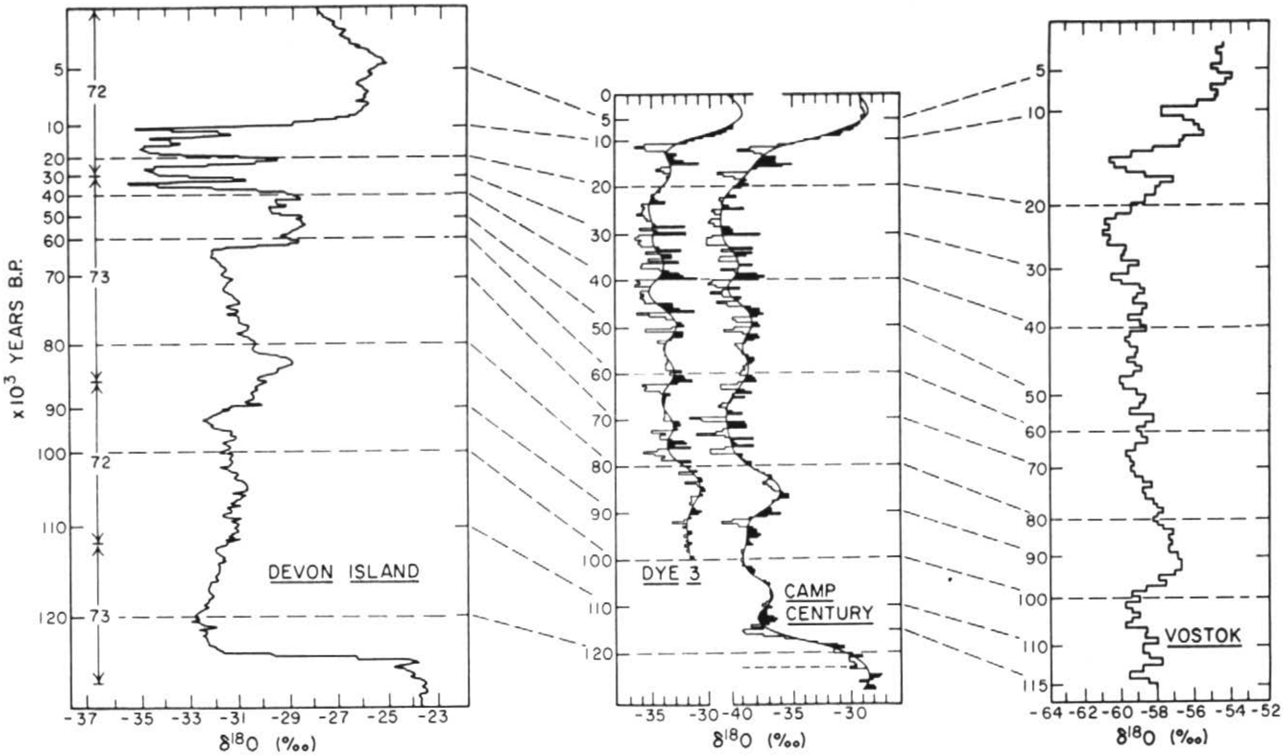


**Figure 1** *The ¹⁸O records from four long ice cores covering approximately the last 120,000 years. The accuracy of the time scales is uncertain (from Bradley, 1985). Note that the absolute δ ¹⁸O values for each core vary depending on the geographic location.*

the warmer Holocene at each coring site. These dramatic shifts in the $\delta^{18}O$ values appear frequently in the older ice records, suggesting that climate instability may be the norm for some time periods in the past (GRIP members, 1993).

Empirical relationships have been calculated to determine mean annual temperature from the $\delta^{18}O$ record derived for Greenland (Dansgaard, 1964; Johnsen *et al.*, 1989). However, it has since been determined that the relationship in Greenland could be better described by two equations (one for eastern Greenland and one for western Greenland) due to the effects of regional weather patterns (Fischer *et al.*, 1995). The linkage between $\delta^{18}O$ values and temperature on Greenland is much simpler than in most locations due to the relatively simple climatic regime of the large uniform ice cap. Fritz *et al.* (1987) showed that a unique relationship exists between temperature and $\delta^{18}O$ values for each of the weather stations they studied in southern Canada.

To reveal intricacies of how the global climate system has operated in the past, the enormous geographic variability in climate necessitates that more information on the temporal and spatial relationship between temperature and precipitation be acquired. Interpretation of ice core isotope data for paleoclimatic reconstruction is based on a number of assumptions about paleoclimatic systems which can be strengthened through the study of modern climatic patterns. Knowledge of the isotopic composition of modern precipitation throughout the

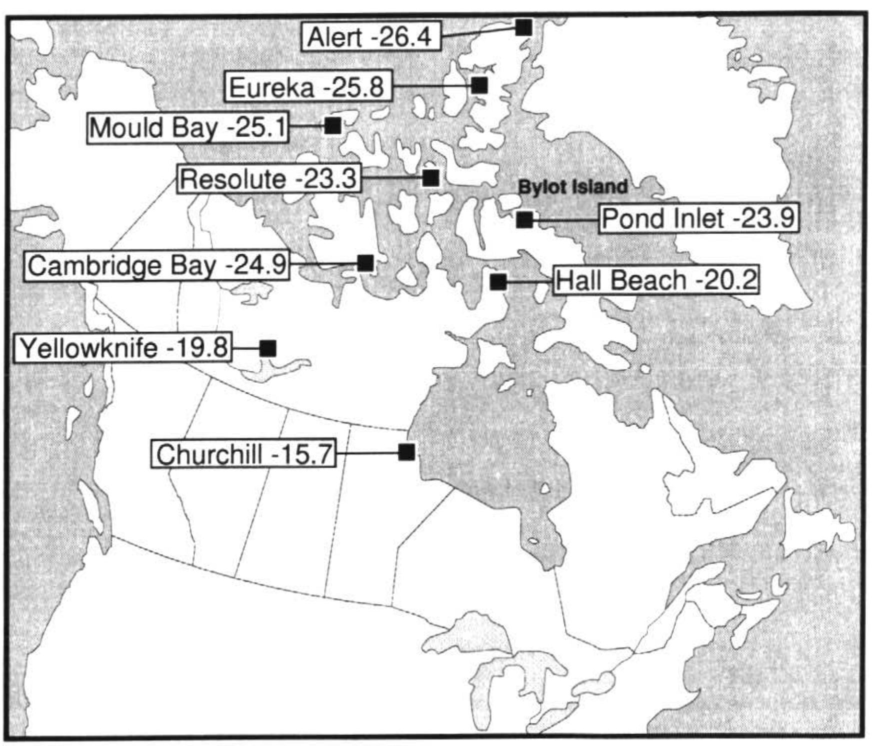


**Figure 2** *Location of weather stations collecting precipitation samples, and the weighted average δ ¹⁸O values for 1991.*

**Table 2** Total amount of precipitation in the Canadian Arctic in 1991, and the range and average oxygen isotope values in the water.

| Station | Precipitation (mm) | Range in Monthly $\delta^{18}O$ Values (‰) | Weighted Annual Average $\delta^{18}O$ Value (‰) |
|---|---|---|---|
| Alert | 172.1 | -21.9 to -38.3 | -26.4 |
| Cambridge Bay | 153.4 | -17.2 to -35.2 | -24.9 |
| Churchill | 514.0 | -10.4 to -29.1 | -15.7 |
| Eureka | 91.8 | -18.6 to -39.5 | -25.8 |
| Hall Beach | 162.8 | -15.3 to -43.0 | -20.2 |
| Mould Bay | 107.9 | -20.9 to -35.7 | -25.1 |
| Pond Inlet | 197.8 | -17.6 to -43.2 | -23.9 |
| Resolute | 139.5 | -17.9 to -35.7 | -23.3 |
| Yellowknife | 357.5 | -12.7 to -27.3 | -19.8 |

Arctic is essential to understanding current climatic patterns and the hydrologic regime of the north. Until recently, little research has been conducted on the isotopic composition of arctic precipitation (Yurtsever and Gat, 1981). A study of the variability of precipitation and its isotopic composition was initiated in 1989 for the Canadian Arctic. Detailed analysis of all available precipitation data is currently in preparation by Michel and Drimmie.

In this paper, the spatial and seasonal trends in the $\delta^{18}O$ values of modern precipitation from the Canadian Arctic are examined, with specific examples from Pond Inlet and Bylot Island. The potential for providing a better spatial distribution of paleoclimatic data by using new analysis techniques is also introduced.

## SAMPLING METHODOLOGY

Precipitation has been collected on a monthly basis since 1989 at eight Environment Canada meteorological stations in northern Canada (Fig. 2), and for a twenty-month period (July 1990 to February 1992) at Pond Inlet. The contents of the rain or snow gauge at the station were added to a master bottle after daily meteorological observations. Between additions, the bottles were tightly capped to prevent evaporation. At the end of the month, the composite sample was sent to Carleton University and submitted for isotopic analysis using standard preparation and analytical techniques at the isotope laboratory of the University of Waterloo. In addition, a snow and firn core of 5.75 m in depth was acquired from the accumulation area of the Bylot Island ice field (73°09.04'N 78°31.60'W). This core was subsampled roughly every 5 cm for oxygen isotope analysis, resulting in a record with submonthly resolution. Determinations for all analyses are within ±0.1‰ for $\delta^{18}O$, and ±1.0‰ for $\delta^{2}H$.

## GEOGRAPHIC VARIABILITY OF PRECIPITATION

Polar desert conditions exist at all of the stations in the Canadian Arctic, but not at the subarctic stations of Churchill and Yellowknife. In 1991, the range in average annual $\delta^{18}O$ values throughout the Arctic was found to be approximately 6‰ (see Fig. 2), and values generally become more negative towards the north (latitude effect). The most southerly stations (located in the subarctic) receive the greatest amount of precipitation and have the highest average annual $\delta^{18}O$ values.

Much of the variability in average annual $\delta^{18}O$ values throughout the Canadian Arctic appears to be dominantly a function of latitude; however, the spatial variability in the isotopic composition of precipitation has also been found to be a function of elevation and distance from moisture source (Dansgaard, 1961; Koerner, 1979). Since all of the meteorological stations are located close to sea level, the distribution of water bodies and the prevailing weather patterns likely are also important modifiers to the isotopic composition of precipitation.

## SEASONAL VARIABILITY OF PRECIPITATION

Unlike the geographic variability, the seasonal variability in the isotopic composition of precipitation is considerable (see Table 2). The seasonal variability in temperature, precipitation and $\delta^{18}O$ values are illustrated in Figure 3 for the weather station at Pond Inlet. Temperature and precipitation data are for the three-year period of 1990 to 1992, inclusive, while the isotope data are for the 1991 calendar year. At Pond Inlet, more than 80% of the precipitation falls during the period from May to October. The amount of precipitation in any given month of the year can vary significantly, especially in the period from April to October, whereas the range in average monthly temperatures is quite small (see Fig. 3). The relationship between temperature and isotope composition of the precipitation is also displayed in Figure 3.

The low monthly amounts of precipi-

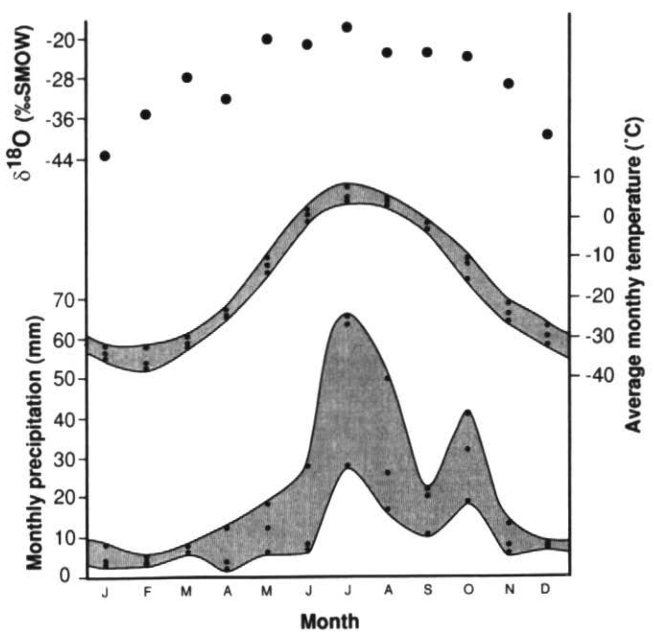


**Figure 3** *The ranges of temperature and precipitation measured at the Pond Inlet weather station for the years 1990-1992, and the δ ¹⁸O values of the precipitation during 1991.*

tation during the period from December to March reflect the lack of a moisture source, since lakes, ponds and the ocean are frozen, and the cold arctic air has a low moisture capacity. The increase in precipitation during the period from April to June reflects changes in atmospheric circulation, increasing temperatures, melting of the snow cover, and the disintegration of lake and pond ice. Removal of the ice cover from the ocean does not occur until mid-summer. Precipitation rates remain high until freeze-up of the larger water bodies in October.

The stable isotope data from Pond Inlet ($\delta^{18}O$ *versus* $\delta^2H$), shown in Figure 4, closely follow the global meteoric water line, although the summer data show some deviation. This indicates that little non-linear kinetic fractionation is occurring. The range in $\delta^{18}O$ data is nearly 26‰, with May to October values less negative than -26‰ and November to April values more negative than -26‰. The annual weighted average is -23.9‰, which is clearly within the summer range of values. The weighting process is based on the amount of precipitation, thus months with higher amounts of precipitation receive a greater weight compared to months with virtually no precipitation. The excellent relationship between weighted values and groundwater isotope data for southern Canada has been described by Fritz *et al.* (1987).

The accumulation of snow on an ice cap or glacier is not uniform throughout the year, and differential preservation of seasonal variations in the isotopic composition of the precipitation can influence the $\delta^{18}O$ signature in an ice core. The seasonal variation of $\delta^{18}O$ values for precipitation measured in the Canadian Arctic was found to be considerably larger (26‰, see Table 2) than the variability observed in the ice core records from the last 120,000 years. The total range of values reported from ice cores (comprised of precipitation from approximately the last 100,000 years) at the Vostok, Devon Island, and Camp Century sites is approximately 7‰, 12‰, and 16‰, respectively (see Fig. 1).

This phenomenon is also illustrated in a comparison of the weather station and glacier core data from the Pond Inlet area. The $\delta^{18}O$ record from a short snow and firn core taken near the center of Bylot Island in July 1992 is shown in Figure 5. The range, from -36.8‰ to -22.0‰, represents the seasonal variability in the $^{18}O$ content of precipitation. The highly negative winter values are indicated with an arrow. This is similar to firn cores of recent precipitation from Greenland, which display a variability of about 10‰ (Fischer *et al.*, 1995). The range in average monthly $\delta^{18}O$ values in the precipitation at the nearby Pond Inlet weather station during the collection period was -43.2‰ to -17.6‰, although these two ranges are not directly compatible because the resolution of the core sampling is considerably higher.

The smaller amplitude of the seasonal $\delta^{18}O$ signature in a core than found in the source precipitation is the result of three factors. In the near surface, isotopic exchange between water vapor and ice crystals in the snow pack and firn alter the $\delta^{18}O$ values. Deeper in the glacier, where the air channels have been sealed off, the signal is smoothed by molecular diffusion within the ice. This occurs at a much slower rate, but is accelerated due to thinning by plastic deformation (Johnsen *et al.*, 1972). As well, the relatively small amount of winter precipitation results in a very minor proportion of the snowpack having the most extreme winter $\delta^{18}O$ values. The magnitude of the winter peak is often reduced because a constant sampling interval (5 cm for this core) mixes snow from a longer time period when precipitation rates are low.

The difference in average $\delta^{18}O$ values between the precipitation collected at the weather station in Pond Inlet and the snow that accumulated on the Bylot Is-

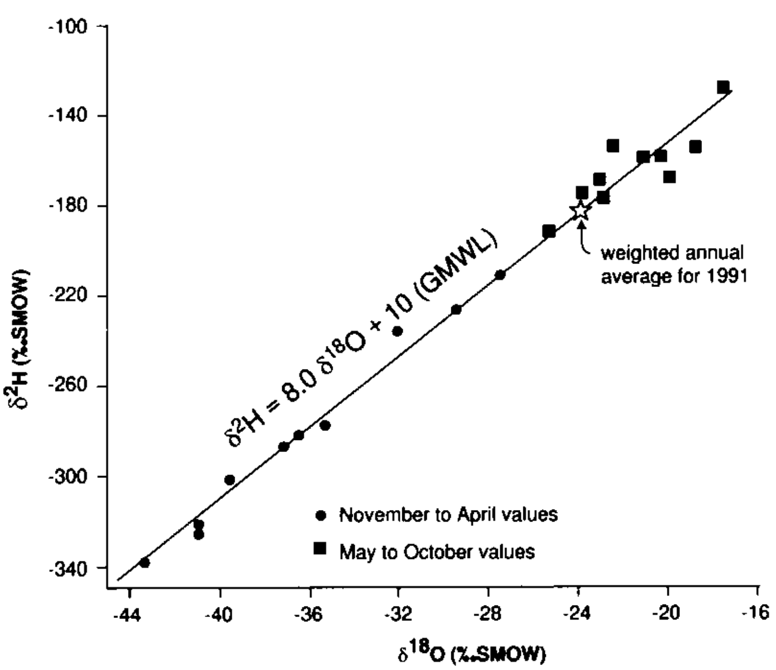


**Figure 4** *Co-isotopic plot of 20 months of precipitation data from Pond Inlet (July 1990-February 1992). Note the weighted average value of 1991 is indicated by the star. GMWL = global meteroic water line.*

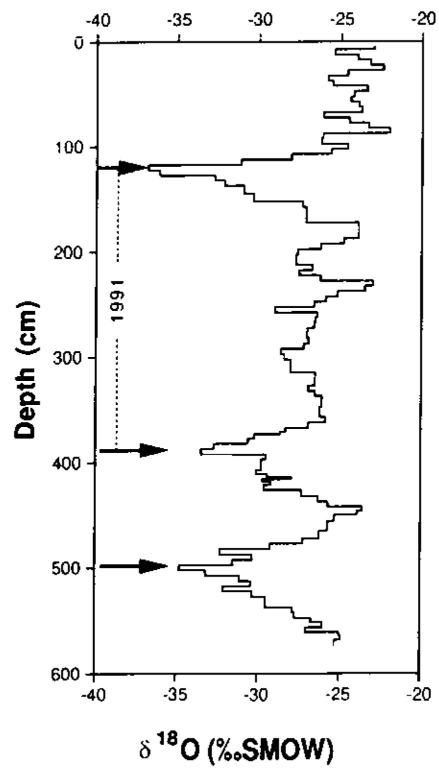


**Figure 5** *$^{18}O$ record preserved in a snow and firn core from the accumulation area on Bylot Island. The time scale of the core is roughly from July 1992 at the top to summer 1989 at the base. Winter peaks are indicated by arrows.*

land ice field may be the result of several factors. Even though the two sites are only 60 km apart it is possible that different weather patterns, with different precipitation source areas, influence the two locations.

The difference in elevation may also be partially responsible for the difference in average $\delta^{18}O$ values (Bradley, 1985). The accumulation area sampling site is at an elevation of 1600 metres above sea level (masl) while the weather station is at an elevation of 50 masl. The 1991 weighted annual average $\delta^{18}O$ value for the Pond Inlet precipitation is -23.9‰, whereas the average $\delta^{18}O$ value from the uppermost complete cycle in the core (thought to approximately represent 1991 deposition) is -27.2‰ (see Fig. 5). Therefore, the decrease in $^{18}O$ with elevation observed between Pond Inlet and the accumulation area on Bylot Island is 0.21‰ per 100 m.

## DATING PALEOCLIMATIC CHANGES

Traditionally, ice cores have been acquired in the accumulation areas of ice caps or glaciers, enabling the reconstruction of continuous records climatic proxy data, starting at the present and working backward in time with depth. Some of the most effective methods for determining the age of the ice at any given depth count: the seasonal variations in $\delta^{18}O$ values, trace element concentration, or microparticle concentration (Bradley, 1985).

While continuous cores from the accumulation areas of glaciers can offer a simple way to date young ice, acquiring information from greater than 1000 BP usually entails drilling a core several hundred metres in length. As the ice is more deeply buried, the seasonal variation is eliminated, thus limiting the use of this technique to about 10 ka (Dansgaard *et al.*, 1982). Recent advances in gas extraction and AMS radiocarbon dating techniques enable the direct dating of ice samples. By either grinding (van de Wal *et al.*, 1990) or sublimation (Wilson and Donahue, 1990, 1992) the gases trapped in bubbles within the ice can be extracted. Once the $CO_2$ is separated from the rest of the gases contained in the ice, the carbon component can be radiometrically dated. This provides an alternate method to determine the age of glacier ice. Small samples from the fringes of glaciers (where sampling is logistically much easier) can now be used to study paleoclimates, with their absolute age determined radiometrically.

Glacier ice preserved as buried ground ice also has the potential to provide paleoclimate records (Moorman *et al.*, 1996). As there is currently a much wider distribution of ground ice than glaciers, analysis of ground ice may lead to a much better spatial resolution of paleoclimate data in the future.

## DISCUSSION

Changing weather patterns at any given location may result in changes in the distribution of precipitation, freeze-up of water bodies, spring melt, evaporation rates, or wind direction and intensity. Lower temperatures and strong stable high-pressure systems over the Arctic during the Wisconsinan glaciation may have created more extreme weather conditions than currently exist.

By looking at isotope records in ice cores, information concerning climate trends through time can be obtained. Although each core has characteristics unique to its particular location, there are many similarities between ice cores collected from different ice caps which point to global-scale climate changes (Fig. 1). Throughout the Holocene, the variation in $\delta^{18}O$ within any given ice core is in the order of 3‰, about half of the 1991 spatial variability of annual weighted averages in the Canadian Arctic. Thus, an understanding of the current spatial variability in climate throughout the Canadian Arctic is required to effectively correlate the proxy data provided by $^{18}O$ records from specific locations, to regional paleoclimatic regimes.

The major shift to more negative $\delta^{18}O$ values during the Wisconsinan glaciation suggests a much more drastic climate change than estimated for the Holocene, although the magnitude of the shift is still less than present day seasonal variations. Since the average weighted values generally reflect the isotopic composition of precipitation during the period of high accumulation, the dramatic shift to lower $\delta^{18}O$ values at the Wisconsinan–Holocene boundary could either indicate a shift in seasonal precipitation patterns (*i.e.*, to a non-summer period) or a change in the condensation temperature for the precipitation (*i.e.*, cooler summer temperatures during the Wisconsinan). A component of the change in isotopic composition could also be due to elevation changes in the accumulation area relative to sea level or the distance to the source of the moisture (*e.g.*, distance to the edge of the pack ice). Thus, it is necessary to collect other independent data, and determine the geographic dependence of $\delta^{18}O$ values, to assist in the interpretation of ice core data.

A potential source of paleoclimatic data, with a much better spatial coverage than current glaciers, is buried glacier ice preserved in permafrost. Buried glacier ice has been identified throughout the Arctic, thus offering a good coverage of the geographic variability. An important consideration in using ground ice as a paleoclimatic indicator is to distinguish between buried ice and intrasedimental ice that has a ground water rather than atmospheric water source. This can be accomplished by examining the gas content, $CO_2$ content, and $^{13}C/^{12}C$ ratio of the gases trapped in the ice (Moorman *et al.*, 1996). Using radiocarbon dating techniques, buried glacier ice has the potential to provide paleoclimatic information throughout permafrost regions for at least the past 40,000 years. Thus, by analyzing ground ice from across the Arctic, a much better understanding of the geographic and temporal variability in the isotopic composition of precipitation can be gained.

## CONCLUSIONS

The $^{18}O$ records in ice cores traditionally have been an important source of paleoclimatic information. However, the limited geographic coverage offered by ice cores limits their use for regional paleoclimatic reconstruction. It was found that the spatial variability of $\delta^{18}O$ values in Canadian Arctic precipitation is greater than the temporal variation of the $^{18}O$ record preserved in ice cores throughout the entire Holocene. As well, the seasonal variability of $\delta^{18}O$ values is considerably greater than the temporal variability found in ice core records from the past 120,000 years. A comparison of the $\delta^{18}O$ values measured in precipitation and a snow and firn core shows that some of the variation in $\delta^{18}O$ values is lost almost immediately upon deposition on the snow pack.

It is suggested that quantification of the regional and seasonal variations of certain climatic parameters can be used to strengthen the correlation between arctic climate regimes and the isotopic values measured in glacier ice. By employing recently developed radiocarbon dating techniques, buried glacier ice found throughout permafrost regions may be able to provide more extensive coverage of paleoclimate proxy data than presently is available from ice cap and glacier ice cores. With more information on the spatial and temporal climatic variations in the Arctic, a better understanding can be gained of how the global climate system is changing.

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