Recent Climate and Stable Isotopes in Modern Surface Waters of Northernmost Ungava Peninsula, Canada

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Abstract

The isotope composition ($\delta^{18}O$ and δD) of surface waters were measured over a 26-month period near three localities situated along the northern coast of Ungava Peninsula (Québec, Canada). In order to caracterize the present-day local hydrological settings, the oxygen and hydrogen isotope ratios were measured from precipitation and these were compared to local and regional climate data. We show that the modern surface waters contain information on climate and that this relationship is likely to be transferred to biotic components within the lakes. These components, once sedimented, are therefore likely to form an archive of climate change. The new data presented here show the possibility of isotope paleoclimatic investigation based on lake sediments in the northern coastal region of Ungava Peninsula.

Key words Stable isotopes, $\delta^{18}O$, δD, lakes, Ungava, recent climate

Climat récent et isotopes stables des eaux de surface modernes de l'extrémité nord de la péninsule d'Ungava, Canada

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Résumé

La composition isotopique ($\delta^{18}O$ et δD) des eaux de surface a été mesurée sur une durée de 26 mois, près de trois localités situées le long de la côte septentrionale de la péninsule d'Ungava (Québec, Canada). Afin de caractériser les paramètres hydrologiques actuels, les données isotopiques ont été comparées aux données climatiques locales et régionales. Nous démontrons que les eaux de surface modernes contiennent de l'information climatique et que cette relation est susceptible d'être transférée à certaines composantes biotiques lacustres. Ces composantes, une fois sédimentées, sont donc susceptibles de constituer une archive de changements climatiques. Les nouvelles données présentées ici démontrent la possibilité de mener à bien des investigations paléoclimatiques isotopiques basées sur les sédiments lacustres dans cette région de la côte Nord de la péninsule d'Ungava.

Mots-clés Isotopes stables, $\delta^{18}O$, δD, lacs, Ungava, climat récent

Introduction

There is general interest in the Earth Science community toward the potential impacts that changing high-latitude runoff linked to climatic variability in the Canadian High Arctic and Subarctic could have on North Atlantic deep water formation. Ungava Peninsula is a vast (aproximately 350 000 km^2) and sparsley populated sector of north-eastern Canada. The northern coast of the peninsula is located along the Hudson Strait, which links the waters of the Canadian Arctic and Subarctic to the North Atlantic Ocean via the Labrador Sea. These areas play a key role in the formation of deep water and thermohaline circulation affecting climatic variability on local and global scales (Dickson 1997). However, the absence of long-term observational data in the area makes it difficult to assess the local extent of historical climatic variability and change, although recent analyses of paleolimological records suggest that certain areas of Ungava Peninsula and Labrador have not undergone environmental variations of similar extent to those recently observed in the western Subarctic and High Arctic (Pienitz et al. 2004; Smol et al. 2005). Attention needs to be focused on these areas to gain better insight into the pre-instrumental record of moisture transport to this region in order to better understand the potential impacts that changes in hydroclimatology could have on locally derived runoff.

In recent years, the use of stable isotope proxies to characterize past climate and hydrological processes has gained noticeable popularity in Quaternary paleoclimatological and paleolimnological research (summarized in Leng 2005). Isotope paleolimnology is based on the premise that the isotope composition of lake waters is related to local climate and that this signal is transferred to components that grow in the lake and form the lake sediment as they are deposited. However, the $\delta^{18}O$ and δD of lake waters do not necessarily reflect that of annual precipitation, this depends on several physical properties such as residence time of water and lake to catchment ratio (Leng et al. 2005). Thus, in order to conduct more reliable paleoclimatological studies based on stable isotope composition of lacustrine material (eg., endogenic carbonates and carbonate/silicate fossils), local present-day hydrology and climatological conditions first need to be defined and lakes identified which have the potential to accurately record different aspects of climatic and environmental variations (Leng and Anderson 2003; Leng and Marshall 2004).

There have been no investigations or systematic calibration of isotope variation in the modern environment in the Ungava region. There is sparse climatic data, and environmental isotope data are completely absent for most of northern Québec (see for example IAEA and CNIP data; http://www.science.uwaterloo.ca/~twdedwar/cnip/cniphome.html). Despite the development of models capable of estimating the modern relationships between $\delta^{18}O$ in precipitation and latitude and altitude (Bowen and Wilkinson 2002; Bowen and Revenaugh 2003; Bowen et al. 2005), the need for baseline measurements of climate data is important if we are to monitor climate change. Permanent climate monitoring facilities in northern Ungava have recently been established (between 1989 and 1992) by the Meteorological Service of Canada (Environment Canada National Climate Archive; http://www.climate.weatheroffice.ec.gc.ca/). However, to go further back in time, we must rely on inferences from various environmental data in order to understand the long-term trends in climate, especially over the last centuries to millennia. This paper provides a summary of the climatic data available for the coastal Ungava region for the last 30 years, as well as the first water isotope data from modern northern Ungava precipitation, lake waters and groundwaters contained in permafrost. The results presented here set the framework for future isotope-based paleolimnological and paleoclimatological investigations in this region, which could yield important insights into past climatic properties and dynamics that are necessary for the prediction of future environmental and climatic conditions in Ungava.

Study region

Geology, topography & vegetation

The water data presented in this study were measured from water samples collected in the vicinity of the northern villages of Salluit, Kangiqsujuaq and Quaqtaq (Fig. 1), in the northern coastal Ungava Peninsula region (between 61°-62° N and 69°-75° W). The coastal fringe of northern Ungava forms part of the Churchill geological province. The bedrock consists of granitic gneisses of Archean and Proterozoic age, overlain with thin Quaternary deposits. The northern sector of the Ungava Peninsula is a plateau (Saglouc Plateau) crossed by a mountainous corridor (Povungnituk Hills). The average altitude of the plateau is between 300 and 600 m a.s.l., and the highest elevations are found inland between Salluit and Kangiqsujuaq. In this sector, the coast is indented by fjords, but becomes lower eastward (toward Quaqtaq).

The region is covered by sparse herbaceous tundra vegetation, although protected depressions such as riparian vallies may support dense growths of *Salix* shrubs (Maycock and Matthews 1966). Grasses, mosses and lichens are dominant in the northernmost sectors (Salluit, Kangiqsujuaq), whereas sedge-moss meadows can be common closer to Ungava Bay (Quaqtaq). However, vast areas of the region remain barren of vegetation, especially at higher altitudes.

Climate

The climate of northern Ungava is cold and relatively dry (Table 1, Fig. 2) and is influenced by the extent and duration of sea-ice cover over the surrounding water bodies. In Hudson Strait, sea-ice break-up usually occurs in early July and freeze-up occurs from west to east during late October to early December. On land, snowpacks and lake ice usually disappear at the end of June for a period of 3-4 months, although snow remains present throughout the summer in sheltered, shaded areas.

Estimates of annual precipitations for Ungava Peninsula as a whole (roughly 55°- 62° N, 69°-77° W) vary between 350 and 550 mm annually, with the three warmest months (July, August, September) receiving between 150 and 200 mm (http://www.menv.gouv.qc.ca/biodiversite/aires_protegees/provinces/partie4j.htm). Temperature and precipitation data were collected sporadically in Quaqtaq between 1972 and 1988 by the Canadian Weather Office (CWO). More recently, the CWO has been recording temperatures and wind directions regularly at Salluit and Kangiqsujuaq airports (since 1992) and at Quaqtaq airport (since 1989). However, there are no precipitation records for Salluit and Kangiqsujuaq. The nearest stations where precipitation is currently measured are Kimmirut, Cape Dorset and Iqaluit, accross Hudson Strait on southern Baffin Island, where between 1971 and 2000 the mean annual total ranged from 340 to 400 mm, and more than half of annual precipitation fell as snow (88%, 64% and 52%, respectively). Most rainfall occurred during summer (between July and September), with a mean of 117 mm in Kimmirut (representing 76% of total annual rainfall), 137 mm in Cape Dorset (95% of total annual rainfall) and 180 mm in Iqaluit (91% of total annual rainfall) for those three months. The available data from Quaqtaq indicate that between 1972 and

1988, mean total annual precipitation was around 380 mm, and slightly less than half (44%) fell as snow. During July-September, a mean of 166 mm of rainfall was recorded, representing 78% of the annual total. The precipitation regime in Quaqtaq is therefore comparable, albeit with somewhat wetter summers, to that of the three previously mentioned stations on Baffin Island; consequently, we consider these values to be representative of the Hudson Strait region as a whole.

Between 1972-2005 in Quaqtaq, there was a statistically significant ($r^2 = 0.4405$; P value = 0.0008) increase in mean annual temperature (1°C), with the most notable monthly changes occurring in April, July and October. In fact, it seems all seasons have been getting warmer in Quaqtaq. However, in Salluit and Kangiqsujuaq, between 1992-2005, no significant variations in annual temperature means were recorded. But, despite the relatively short span of these two records, slight increases in autumnal seasonal means have been observed (for the months of October and November in Kangiqsujuaq and for November in Salluit).

The dominant air masses in the region shift seasonally, although Arctic air masses are predominant throughout the year. Summer air masses are important in that they bring most of the rainfall to the region. On Baffin Island during most of the year, winds blow from the west and northwest, except during the summer, when they are easterly in Cape Dorset (July-August) and south-easterly in Iqaluit (June-September) (Fig. 1) (wind directions not available for Kimmirut). In northern Ungava, the situation is slightly different. In Salluit, the dominant wind direction during the summer months (June, July and August) is from the northeast, whereas winds blow predominantly from the southwest (i.e., Hudson Bay and the interior) during the rest of the year. In Kangiqsujuaq, winds shift from a northerly direction between April and July to a westerly direction during most of the remainder of the year. This translates into a dominant influence of marine air masses in the summer (bringing precipitation) and a continental influence during the rest of the year. Finally, in Quaqtaq, the direction of the wind remains relatively constant and blows predominantly from the northwest, i.e., from Hudson Strait, throughout the year (see Fig. 1 for dominant summer wind directions). Based on the thermal amplitudes, Quaqtaq seems to have a more oceanic climate compared to the other two localities (Table 1), although all three localities receive northerly derived air masses from the Arctic.

Study sites

There are many thousands of lakes and ponds across northern Ungava but their limnology has never been studied in detail. The lakes in this study (presented in Table 2) are clear, oligotrophic and dilute ($< 90\ \mu S\ cm^{-1}$) systems with circumneutral to slightly acidic pH. Measurements of temperature, conductivity and dissolved oxygen throughout the water columns indicate that they are well mixed, year-round (continuous cold polymictic). Their depths and sizes vary, but they are all open through-flow lakes and receive the majority of their input through summer precipitation and spring surface runoff from melting snow in their catchments. Although the study region is located in a zone of continuous and widespread permafrost (Taylor and Judge 1979), lack of information on the local configuration of beneath-lake permafrost and the possible but undetected presence of taliks (unfrozen zones that occur beneath lakes) prevent us from making any assumption on the effect of groundwater seepage on the water balance of these lakes.

Methods

Water samples were collected from 8 lakes between June 2002 and September 2004. The frequency of the sampling was dictated by logistical constraints. Two of the lakes were sampled on multiple occasions during the summer of 2002, but the majority were sampled only once (4 lakes) or twice (2 lakes), with the result that these samples are both spatially and temporally specific. Water samples for isotope analysis were taken either from the center of the lake (from a small boat or through ice-cover) or, if this was not possible, from the littoral zone. Precipitation was collected five times in Salluit during the summer of 2002. Rainwater was allowed to accumulate in a pan until enough was gathered to fill a 30 ml polyethylene bottle. This usually took between 6 and 24 hours. Groundwater was extracted from 2 permafrost samples taken near Salluit. The 2 groundcore sections were allowed to melt in sealed plastic bags and were centrifuged to separate the water from the sediments. Waters were collected for $^{18}O/^{16}O$ and D/H analysis in leak-tight polyethylene bottles, additionally sealed with PVC tape. The waters were analysed at NERC Isotope Geosciences Laboratory (UK) using the equilibration method for oxygen (Epstein and Mayeda 1953), and Zn-reduction method for hydrogen (Coleman et al. 1982; Heaton and Chenery 1990). Isotopic ratios ($^{18}O/^{16}O$ and $^{2}H/^{1}H$) are expressed in delta units, $\delta^{18}O$ and δD (‰, parts per mille), and defined in relation to the international standard, V-SMOW (Vienna Standard Mean Ocean Water). Analytical precision is typically ± 0.05 ‰ for $\delta^{18}O$ and ± 2.0 ‰ for δD.

Results and discussion

Rainfall and permafrost

The $\delta^{18}O$ and δD values for rainfall collected at Salluit (Table 3 and Fig. 3) during June and July 2002 fall well below the global meteoric water line (GMWL) and are characteristically scattered, as δ values in precipitation tend to vary according to temperature, rainout history and the source of moisture (Gat 1996; Darling et al. 2005). The average $\delta^{18}O$ value of the 2002 summer precipitation samples from Salluit is −15.37‰, much higher than the value of −18.14‰ predicted by the Online Isotopes in Precipitation Calculator (OIPC; www.waterisotopes.org). The closest permanent station where isotopes in precipitation are measured is Goose Bay, in central Labrador (53°27' N 60°43' W), where the mean annual temperature between 1961 and 1990 was 0.0°C. In the 1960s (1961-1969), the mean annual $\delta^{18}O$ value measured at Goose Bay was −15.5‰. The value shifted to −14.6‰ between 1997 and 2003 (CNIP Website; http://www.science.uwaterloo.ca/~twdedwar/cnip/cniphome.html).

Two groundwater samples taken from permafrost from Salluit have similar $\delta^{18}O$ values despite originating from different depths (48-57 cm; $\delta^{18}O$ −15.81‰, in the active layer and 122-145 cm; $\delta^{18}O$ −16.92‰, in the permanently frozen layer) and from different boreholes. They have similar $\delta^{18}O$ values to some of the lakes in the region, lying on or slightly offset from the GMWL (Fig. 3), and similar to the mean $\delta^{18}O$ value of 2002 summer precipitation (−15.37‰). The values probably represent a mean of many years of accumulation.

At high latitudes, on a large geographic scale, there is generally a strong linear correlation (with a slope of 0.69‰/°C for $\delta^{18}O$) between mean annual surface air temperature and mean annual $\delta^{18}O$ in precipitation (Dansgaard 1964; Rozanski et al. 1992). The isotopic signal of nordic lake waters is therefore considered a good indicator of mean summer temperatures if a) the signal concords with the meteoric water line and there is no evaporative effect, and b) the lake is replenished by precipitation. The empirical isotope-temperature relation in precipitation for sites having a mean annual temperature (MAT) < 15°C has been described by Jouzel et al. (1994) as the following:

$$\delta^{18}O_{(p)} = 0.64MAT - 12.8 \qquad [1]$$

The MAT in Salluit in 2002 (−8.8 °C), and the mean $\delta^{18}O$ measured in local summer precipitation (−15.37‰) is 3.03‰ higher than the value (−18.43‰) predicted by Jouzel's equation, which is much closer to the aforementioned predicted value (−18.14‰) by the Online Isotopes in Precipitation Calculator (OIPC; www.waterisotopes.org). These predicted values are closer to the more isotopically depleted lake waters of Tasikutaaq and Qaanganiituuq (2002 mean −16.42‰) than to the one recorded in lac de l'Aéroport (2002 mean −14.52‰). One reason for this discrepancy might be that equation 1 demands the use of mean annual $\delta^{18}O$ of precipitation, whereas we only have measurements of summer rainfall.

Lake waters

The $\delta^{18}O$ and δD of any given lake water will depend on the hydrologic balance between inputs (direct precipitation, surface runoff, inflows, groundwater seepage) and outputs (evaporation, outflows, groundwater loss). The isotopic signals of the lake waters in this study are either similar to or fall below the GMWL (Fig. 3). The isotope signal of the groundwater and of the lakes suggest that evaporation has little effect on these components during summer. A tentative local meteoric water line is thus defined for the region, but more data is needed to confirm its trend.

The lowest lake water $\delta^{18}O$ and δD as well as the groundwater samples from Salluit lie very close to the GMWL. These lake samples come from Tasikutaaq and Qaanganiittuq, two lakes near Salluit (Table 2). The water samples from these two lakes have a deuterium excess (*d-excess* = $\delta^2H - 8\ \delta^{18}O$) similar to that of the groundwater samples (+7 to +10.5‰), whereas lac de l'Aéroport, the other lake sampled near Salluit, has *d-excess* values more similar to that of local precipitation (0 to + 5.5‰; the *d-excess* of measured local precipitation ranging from –0.6 to +4.6‰). The *d-excess* parameter gives an indication of the "humidity" of local precipitation in relation to the GMWL, which has a *d-excess* of +10‰. Many factors influence differences in *d-excess*, such as varying temperature, relative humidity and wind speed at the sea surface. Generally, local precipitation has a seasonal cycle which is marked by lower *d-excess* during the summer and higher *d-excess* in the winter (Edwards et al. 2004). The low *d-excess* values observed for the summer 2002 precipitation in Salluit are typical of precipitation derived from oceanic sources in the 60°N ±10° latitude band, in general (Bowen and Revenaugh 2003). It is worth noting here that, despite the wide scatter in the absolute $\delta^{18}O$ and δD values of our local summer precipitation, the *d-excess* values are remarkably constant (Table 3), suggesting a consistent source region effect and minimal sampling error. This leads us to considering that *d-excess* could potentially be a powerful tool for partitioning the relative contribution of moisture sources to the water budget of this area. If the right proxies can be applied (measuring both $\delta^{18}O$ and δD), past changes in precipitation seasonality or source could even be distinguished using the *d-excess* parameter.

One possible explanation for the discrepancy in the *d-excess* of the three lakes in Salluit might be that the smaller basin of lac de l'Aéroport is more responsive to summer precipitation and/or has a shorter residence time than the larger and deeper basins of Tasikutaaq and Qaanganiittuq, which have a greater storage capacity and tend to buffer seasonal variations and retain an isotopic signature closer to that of annual precipitation. Another factor which might contribute to the different isotopic signature of lac de l'Aéroport compared to the other Salluit lakes might be snowmelt bypassing, whereby the topography of the drainage basin and/or fluctuating water levels can lead to flushing of snowmelt under or around ice cover with minimal mixing, resulting in under-representation of isotopically-depleted winter precipitation in a lake's budget (Edwards and McAndrews 1989). However, this possibility was not verified in the field.

To the best of our knowledge, there are only three other lake waters for which δ^{18}O has been measured in northern Ungava. The lakes in question are located inland about 100 km west of Kangiqsujuaq, within the recently created Pingualuit Provincial Park, and were sampled in summer 1988 by Ouellet et al. (1989). Lac Rouxell (61°13'39"N, 73°47'41"W) and lac Laflamme (61°20'27"N, 73°42'48"W) are large lakes (surface area ± 20-30 km^2, max. depth 10 m), whereas Pingualuk (61°16'37"N, 73°39'38"W) is a crater lake (surface area 6.68 km^2, max. depth 265 m). The δ^{18}O values measured for these lakes (analytical precision ±0.1‰; reproducibility ±0.2‰) are significantly lower than for our study lakes; −19.1‰ (Rouxell; surface), −18.7‰ (Laflamme; surface) and −17.2‰ (Pingualuk; mean of entire water column, which is well-mixed during the ice-free season despite its great depth). Snow from the catchment of Pingualuk collected during that summer was also analysed and yielded a δ^{18}O value of −19.3‰. Unfortunately, δD was never measured, rainfall was not collected and there are no data on the provenance of the dominant air masses for the Pingualuit area. The Pingualuk crater lake has a small lake surface to basin ratio (0.7) and is replenished only by meltwater and rainwater

(Ouellet et al. 1989); it also has a very long residence time (about 330 years), which means that the isotopic signal incorporates rainfall over a long period. Interestingly, the isotopic signature of the crater lake water (−17.2‰) is equivalent to a mixture of summer rainfall which we measured at Salluit in 2002 (−15.37‰) and that of the snow from the catchment of Pingualuk (−19.3‰). This lake water data suggests that there has been no long-term shift in the average isotopic values of precipitation for the region during the last three centuries.

The lake waters from the three localities studied here have distinct isotopic signatures (Fig. 4). The three lakes from the Salluit area, the north-westernmost site, have the lowest $\delta^{18}O$ values (mean = −15.68‰, which is very close to the mean value for precipitation in this locality: −15.37‰), followed by lakes near Kangiqsujuaq (mean = −14.09‰) and finally Quaqtaq (mean = −12.91‰), which is the south-easternmost site. The values overlap somewhat, but there appears to be a geographical gradient. It is tempting to suggest that the east-west lowering of $\delta^{18}O$ in coastal summer rainfall is due to temperature as mean annual temperature for Salluit is lower than for Kangiqsujuaq and Quaqtaq (although the maximum temperature difference of 1.4°C equates to 1‰ using the aforementioned relation of 0.69‰/°C).

Interseasonal lake waters

Our data indicate some variation in the signal of the lake waters (+0.5 to +1.1‰) between spring and early fall (Table 3). Increasing $\delta^{18}O$ between spring and fall is expected because the lakes are replenished by rainfall during the summer months (the effect of the isotopically depleted winter precipitation, both snow falling onto the frozen lake and melt water during the spring thaw, is gradually countered by the input of higher $\delta^{18}O$ summer precipitation). In the two Quaqtaq lakes which were only sampled in spring under ice cover (Lakes Sunirlait and X), the $\delta^{18}O$ values were lower than those measured in Tasing, which was sampled both times in late summer. The same is true of their *d-excess* values.

Conclusion

Modern instrumental data help characterise the climate (temperature, precipitation, dominant air masses) of northern Ungava Peninsula and show that it has remained stable between 1992 and 2004 in the vicinity of the villages of Salluit and Kangiqsujuaq. In Quaqtaq, there has been a slight tendency towards warmer means throughout the year, between 1972 and 2004, but the record is of insufficient length to assess the historical representativeness of these recent observations.

The isotope composition of $\delta^{18}O$ and δD measured in precipitation and surface waters from northern Ungava fall on or slightly below the GMWL, but define a preliminary local meteoric water line for the region. There is a longitudinal gradient from west to east in the lake waters, i.e., $\delta^{18}O$ and δD are lower in Salluit than in Kangiqsujuaq and Quaqtaq. The available data, although fragmental, suggest that evaporation is negligible in some of these lakes and the isotope signal probably mostly reflects annual temperature. Our rudimentary data also suggest that some lake waters vary seasonally, possibly due to flushing of the lakes by the spring runoff of meltwater from ice and snow that accumulated during the preceding winter, before being replenished by summer rainfall. Isotope composition of winter precipitation and seasonal balance of recharge to the lakes would be needed to confirm this with more certainty. Additionnally, the possible presence of the “catchment effect” should be assessed in each lake basin before attempting paleoisotopic analysis. This process introduces waters into the lake with an isotopic composition which varies from precipitations due to the nature of the terrain and its effect on runoff to the lake. The “catchment effect” can vary in time with vegetation cover and other ecological changes and can introduce into the paleoisotopic archive a signal equivalent in size to a 2-3°C change in mean temperature (Gat and Lister 1995). Nevertheless, the lakes sampled in this study offer the potential for different types of paleoenvironmental information (annual flushing and longer term means) if their archives are to be investigated. In the Salluit area, for example, the waters of lac de l’Aéroport reflect the isotope signature of summer precipitation, whereas larger Tasikutaaq and Qaanganiittuq have values closer to the annual mean. The observations presented in this study, including the potential of *d-excess* as a powerful tool for partitioning the relative contribution of moisture sources to the water budget of this area if the right proxies can be designated, could eventually have important implications for deciphering past changes in precipitation seasonality or source in the region.

This study shows that lakes in the northern Ungava region contain water that records aspects of climate. If the $\delta^{18}O$ and δD signals of the lake waters are retained in lacustrine sedimentary components, then these could become a valuable archive of northeastern Canadian climate, a region where little paleoclimatic information is thus far available.

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Table 1. Summary of climatic data for the three studied localities.

	Salluit (1992-2004) 62°10' N 75°40' W 226.2 m altitude	Kangiqsujuaq (1992-2004) 61°35' N 71°55' W 155.8 m altitude	Quaqtaq (1972-2004) 61°05' N 69°63' W 30.4 m altitude
mean annual daily temp.	−7.7°C	−6.3°C	−6.9°C
max. annual daily temp.	+3.5°C	+4.2°C	0 °C
min. annual daily temp.	−16.9°C	−15.1°C	−13.3°C
dominant annual wind direction	SW	W	NW
mean total annual precip. (1972-1988)	No data	No data	380 mm
expected mean annual precip. isotope ratios (‰, V-SMOW) *	δD −140.1 δ^{18}O −18.14	δD −135.2 δ^{18}O −17.37	δD −130.2 δ^{18}O −16.66

Means compiled from raw data available from the National Climate Archive (Environment Canada website; http://www.climate.weatheroffice.ec.gc.ca/index.html last accessed 2006-03-17). *As calculated with the Online Isotopes in Precipitation Calculator (OIPC; www.waterisotopes.org).

Table 2. Geographic and limnological data for the 8 study lakes.

Lake name Locality *Coordinates*	Altitude (m a.s.l.)	Max.depth measured (m)	Surface area (m^2)	pH	Conductivity (mS cm^{-1})	Dissolved O_2 (mg L^{-1})	Summer Temp. (°C)
lac de l'Aéroport Salluit *62°10'N, 75°39'W*	231	8.6	38 700	6.8	0.072	12.30	8-12
Tasikutaaq Salluit *62°09'N, 75°43'W*	213	13.6	306 600	6.5	0.023	14.00	7.5
Qaanganiittuq Salluit *62°07'N 75°36'W*	426	13.9	62 200	*n.a.	n.a.	n.a.	6.7
Nipingngajulik Kangiqsujuaq *61°34'N, 71°46'W*	70	14.5	792 500	6.1	0.230	14.00	n.a.
Allagiap Tasinga Kangiqsujuaq *61°32'N, 72°00'W*	60	9.0	205 500	6.0	0.0210	12.33	n.a.
Tasing Quaqtaq *61°04'N, 69°33'W*	61	3.5	30 900	6.6	0.078	13.57	10.9
Lake X Quaqtaq *60°51'N, 70°07'W*	46	6.5	313 900	7.2	0.050	13.50	n.a.
Sunirlait Quaqtaq *60°51'N, 70°10'W*	213	18.0	158 200	6.9	0.048	n.a.	n.a.

*n.a. indicates no measurements are available

Table 3 : δ^{18}O and δD signal and *d-excess* of sampled waters with date of sampling and corresponding water or mean air temperature on the day of sampling.

Sample	**δ^{18}O(‰)/δD(‰)**	***d-excess***	**Date sampled**	**water (W) or air (A) temperature**	**observations**
Lac de l'Aéroport					
A1	−14.75 / −113.1	+4.9	02-06-26	7.0°C (A)	50% ice cover
A2	−14.69 / −112.5	+5.1	02-06-30	5.5°C (A)	40% ice cover
A3	−14.47 / −111.8	+3.9	02-07-07	12.5°C (A)	Date of ice-out
A4	−14.60 / −111.8	+4.9	02-07-08	12.5°C (A)	-
A5	−14.58 / −111.2	+5.4	02-07-10	6.0°C (A)	Sampled after rainfall
A6	−14.51 / −112.2	+3.9	02-07-14	9.3°C (W)	-
A7	−14.52 / −111.8	+4.4	02-07-15	10.1°C (W)	-
A9	−14.43 / −111.9	+3.6	02-07-20	8.7°C (W)	-
A10	−14.47 / −111.9	+3.8	02-07-27	21.8°C (A)	-
A11	−14.36 / −110.6	+4.3	02-08-03	12.3°C (W)	*
A12	−14.36 / −110.6	+4.3	04-09-15	4.5°C (W)	-
Tasikutaaq					
T1	−16.61 / −122.3	+10.6	02-07-07	15.3°C (A)	-
T2	−16.43 / −121.8	+9.6	02-07-14	7.1° (W)	-
T3	−16.43 / −121.2	+10.3	02-07-15	9.1°C (W)	-
T4	−16.47 / −121.7	+10.1	02-08-07	-	-
T5	−16.15 / −120.4	+8.8	04-09-17	6.2°C (W)	-
Qaanganiittuq					
Q1	−16.11 / −119.6	+9.3	02-07-25	6.7°C (W)	-
Allagiap Tasinga					
AT1	−14.69 / −110.8	+6.7	03-05-05	0.1°C (W)	Taken through ice
AT2	−13.62 / −102.4	+6.6	04-09-19	5.0°C (W)	-
Nipingngajulik					
N2	−14.02 / −108.2	+4.0	04-09-19	4.3°C (W)	-
Tasing					
QT1	−12.31 / −96.0	+2.5	01-08-16	10.9°C (W)	-
QT2	−11.64 / −90.4	+2.7	04-09-21	3.2°C (W)	-
Lake X					
X1	−13.35/ −102.3	+4.5	03-05-08	0.1°C (W)	Taken through ice
Sunirlait					
S1	−13.39 / −101.4	+5.8	03-05-08	0.1°C (W)	Taken through ice
Salluit precipitation					
P1	−14.00 / −110.2	+1.8	02-06-29	5.1°C (A)	Rain
P2	−10.04 / −76.6	+3.7	02-07-16	8.2°C (A)	Rain
P3	−16.81 / −129.9	+4.6	02-07-13	3.9°C (A)	Rain
P4	−16.42 / −132.0	−0.6	02-07-19	6.9°C (A)	Rain
P5	−19.57 / −153.5	+3.1	02-07-20/21	-	Rain (drizzle)
Salluit permafrost					
QW1	−16.92 / −126.2	+9.2	Summer 02	-	Permafrost
QW2	−15.81 / −119.4	+7.1	Summer 02	-	Active layer

*In early August 2002 during our last visit to lac de l'Aéroport for that year, we observed that the water level had dropped about 10 cm because of a trench that had been dug on its northern side in order to avoid eventual lake over-flow onto the airport's neighbouring landing strip.

Figure captions

Fig. 1 (a) Location map showing the study region in the context of North America (inset) and the study sites in Northern Ungava. Arrows indicate dominant summer wind directions. (b-d) Location and altitudes of villages and study lakes in their vicinities. (e) Location and altitudes of the study lakes located on the western shore of Diana Bay (Lake X and Sunirlait), ca. 30 km south-west of Quaqtaq. In b-e, the study lakes are shown in bold outline.

Fig. 2 Northern Ungava climate data (east to west) from Quaqtaq 1972-2004, Kangiqsujuaq 1992-2004 and Salluit 1992-2004. Precipitation data from Quaqtaq 1972-87 (compiled from Environment Canada's National Climate Archive).

Fig. 3 $\delta^{18}O$ versus δD from lake waters, precipitation and water extracted from permafrost from Northern Ungava collected between June 2002 and September 2004. Ungava meteoric water line established from the data presented here. Global-MWL is based on Craig's (1961) equation.

Fig. 4 Mean $\delta^{18}O$ (with standard deviation) of lake waters in each locality plotted against longitude in degrees (°) west.

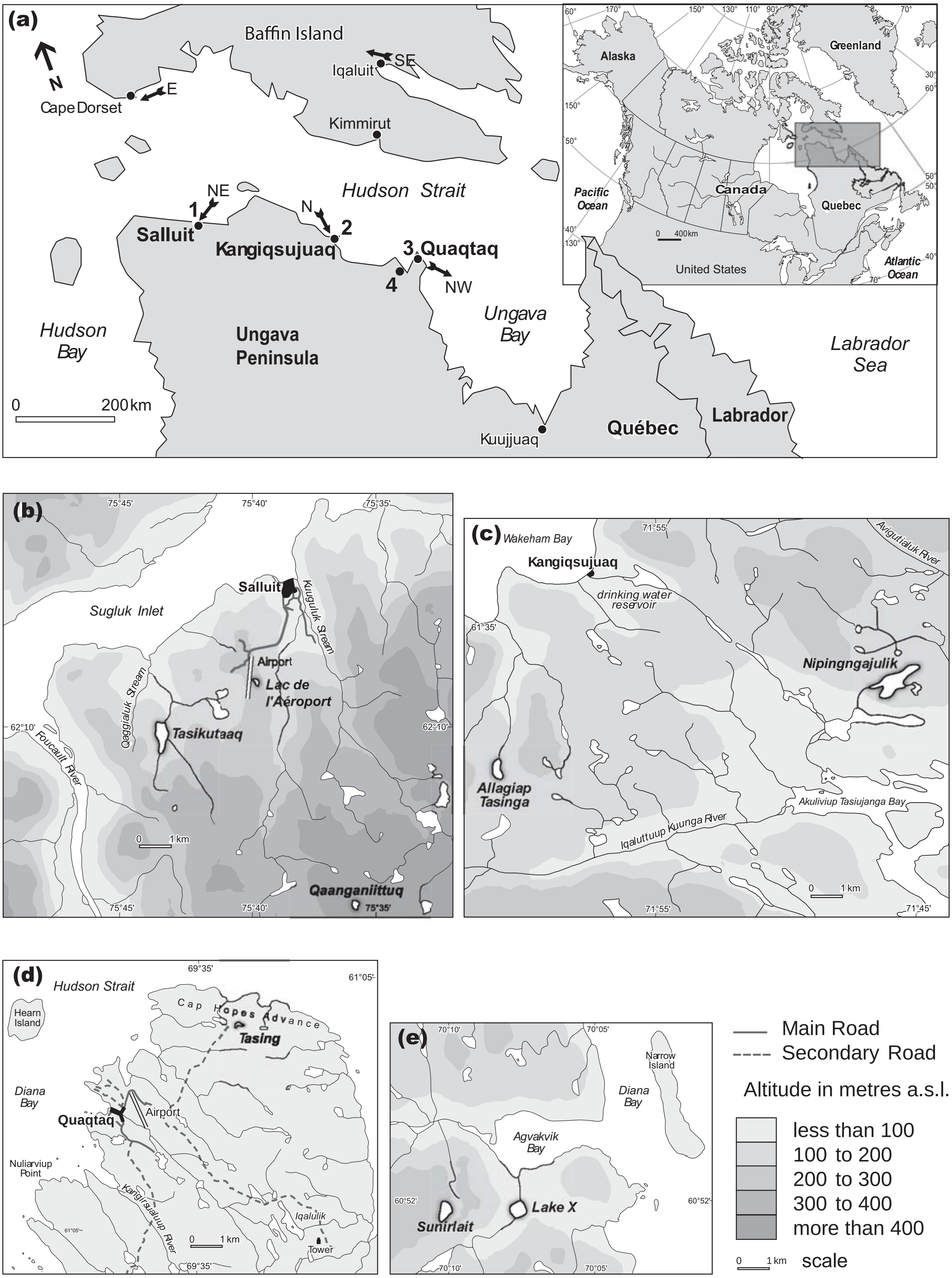
(a)
Baffin Island
N
E
Cape Dorset
SE
Iqaluit
Kimmirut
Hudson Strait
NE
1
Salluit
N
2
Kangiqsujuaq
3 Quaqtaq
4
NW
Hudson Bay
Ungava Peninsula
Ungava Bay
Labrador Sea
0 200km
Québec
Labrador
Kuujjuaq
Alaska
Greenland
Pacific Ocean
Canada
Quebec
United States
Atlantic Ocean
0 400km
(b)
75°45'
75°40'
75°35'
Salluit
Sugluk Inlet
Kuuguluk Stream
Airport
Lac de l'Aéroport
Qaggialuk Stream
Tasikutaaq
62°10'
Foucault River
0 1 km
Qaanganiittuq
(c)
Wakeham Bay
Kangiqsujuaq
71°55'
drinking water reservoir
Avigutialuk River
61°35'
Nipingngajulik
Allagiap Tasinga
Akuliviup Tasiujanga Bay
Iqaluttuup Kuunga River
0 1 km
71°45'
(d)
Hudson Strait
69°35'
61°05'
Hearn Island
Cap Hopes Advance
Tasing
Diana Bay
Quaqtaq
Airport
Nuliarviup Point
Kangirsualuup River
Iqalulik
0 1 km
Tower
(e)
70°10'
70°05'
Narrow Island
Diana Bay
Agvakvik Bay
60°52'
Sunirlait
Lake X
Main Road
Secondary Road
Altitude in metres a.s.l.
less than 100
100 to 200
200 to 300
300 to 400
more than 400
0 1 km scale

Figure 1

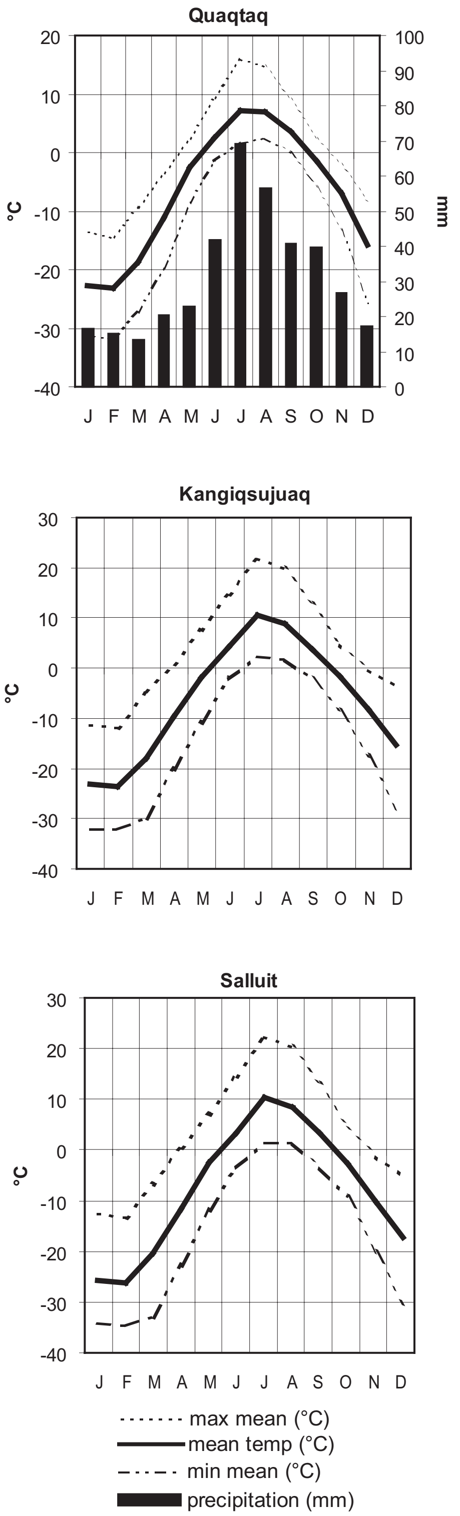
Quaqtaq
20
10
0
-10
-20
-30
-40
°C
100
90
80
70
60
50
40
30
20
10
0
mm
J F M A M J J A S O N D
Kangiqsujuaq
30
20
10
0
-10
-20
-30
-40
°C
J F M A M J J A S O N D
Salluit
30
20
10
0
-10
-20
-30
-40
°C
J F M A M J J A S O N D
max mean (°C)
mean temp (°C)
min mean (°C)
precipitation (mm)

Figure 2

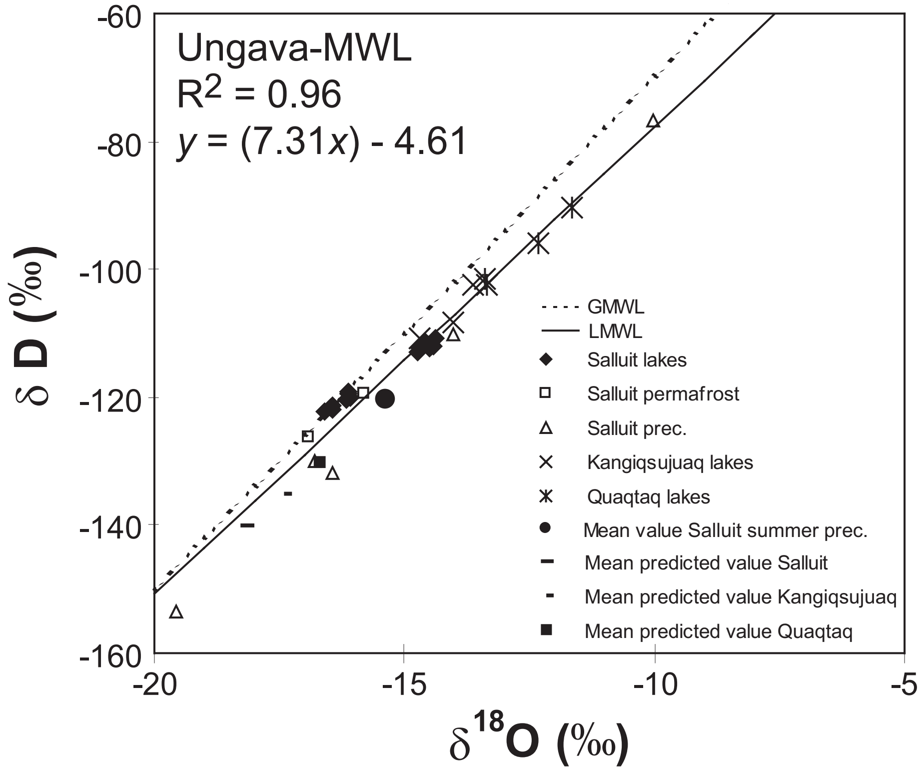
Ungava-MWL
$R^2 = 0.96$
$y = (7.31x) - 4.61$
GMWL
LMWL
Salluit lakes
Salluit permafrost
Salluit prec.
Kangiqsujuaq lakes
Quaqtaq lakes
Mean value Salluit summer prec.
Mean predicted value Salluit
Mean predicted value Kangiqsujuaq
Mean predicted value Quaqtaq
δ D (‰)
-60
-80
-100
-120
-140
-160
-20
-15
-10
-5
δ^{18}O (‰)

Figure 3

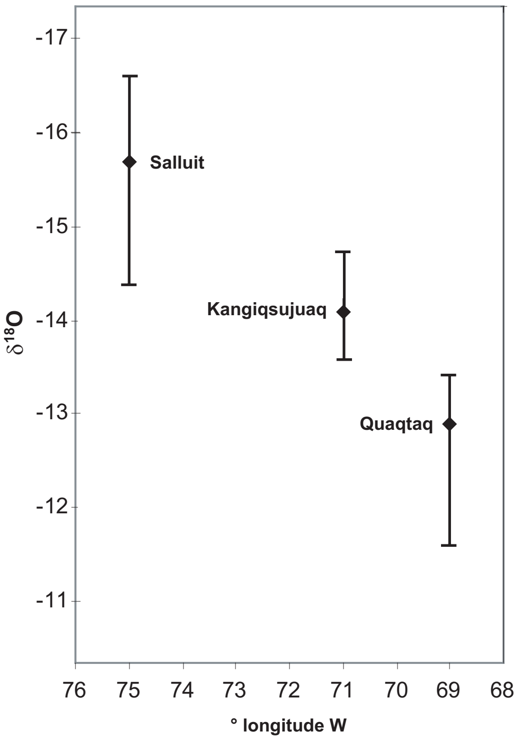
-17
-16
-15
-14
-13
-12
-11
$\delta^{18}O$
Salluit
Kangiqsujuaq
Quaqtaq
76
75
74
73
72
71
70
69
68
° longitude W

Figure 4