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Douglas R. Hardy and Raymond S. Bradley

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Article abstract

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# Climatic Change in Nunavut

Douglas R. Hardy and
Raymond S. Bradley
*Department of Geosciences*
*University of Massachusetts*
*Amherst, MA 01003 USA*

## SUMMARY

Instrumentally recorded climate records from Nunavut are too short to provide a useful perspective on climate variability in the region. Furthermore, there are only a few paleoclimate records from this large region, so that our understanding of pre-anthropogenic climatic changes is limited. The available proxy records suggest that the climate of the last few hundred years has ranged from one of the coldest episodes of the post-glacial, to one of the warmest periods. Additional high-resolution records are needed, and a case is made for obtaining well-calibrated paleoclimate data from laminated lake sediments in the region.

## RÉSUMÉ

Les registres de données climatiques instrumentales sur le Nunavut sont trop clairsemés et trop courts, et ne permettent pas d'obtenir une image utile de la variabilité climatique de la région. De plus, il n'existe que quelques registres de données paléoclimatiques sur cette grande région et donc, notre compréhension des changements pré-anthropogéniques reste fragmentaire. Les registres de données indirectes dont nous disposons semblent indiquer qu'au cours des quelques dernières centaines d'années, le climat aurait connu des fluctuations extrêmes, passant d'une des épisodes post-glaciaires les plus froides à l'une des plus chaudes. Des registres de données plus précises sont nécessaires et on présente dans le présent article, les arguments démontrant la nécessité d'obtenir des données paléoclimatiques bien étalonnées à partir des couches de sédiments lacustres laminés de la région.

## INTRODUCTION

Geologists are keenly aware that changes in global climate have occurred in the past. The magnitudes and rates of change have spanned a broad spectrum, with varying resultant effects on physical processes of the earth system. While such "natural" changes will continue in the future, considerable attention has been focussed in recent years on the evidence for, and mechanisms of, rapid climate change due to anthropogenic effects. The spectre of global warming has led to predictions of relatively rapid sea-level rise, increased storminess, changes in precipitation patterns, and other consequences, all with profound global ecological effects, and serious economic implications for human societies. High-latitude regions such as Nunavut, surrounded by sea ice and snow covered much of the year, may be particularly sensitive to global climate change, due to amplification of even small changes by feedback processes. In addition, the impacts of global change on humans may be amplified in high-latitude regions such as Nunavut, due to the dependence of resident people upon *local* climate-sensitive resources for food and subsistence.

Models used to simulate global atmospheric circulation have become increasingly sophisticated, promoting a high degree of confidence in their output. While virtually all models once predicted a relatively uniform global warming due to increased concentrations of greenhouse gases such as carbon dioxide, newer model experiments including increased sulphate aerosol loading are now predicting cooling in a few regions. To resolve: 1) whether (or when) global climate change due to anthropogenic effects has indeed begun to occur; 2) how such changes might vary regionally; and 3) the rate at which such changes will occur within a region, we must first understand both temporal and spatial patterns of *natural* climate variability. None of these issues can be adequately resolved for the Nunavut region at present.

The purpose of this paper is to provide an overview of what is known about the natural variability of climate in Nunavut through time. The time period considered encompasses the Holocene, with increasingly greater attention devoted to the recent past. The evidence is derived from numerous sources which provide proxy records, and for the past few decades, additional evidence is drawn from the instrumental record. Summer temperature is the primary climate variable considered here, because few proxies record other signals (Bradley, 1990). Fortunately, summer air temperature integrates many processes and other variables of the Arctic climate system.

Summer temperatures in Nunavut over approximately the past century have been unusual in the context of the past, as this period encompasses perhaps the warmest and coldest intervals of the past several thousand years (Bradley, 1990). To better understand climate variability through this anomalous time, and to provide a context for recent trends seen in the short instrumental record, additional high-resolution evidence must be obtained. A recommendation is made that lake sediments could significantly improve our understanding of climate variability in Nunavut through space and time.

## CLIMATIC VARIABILITY IN NUNAVUT

Nunavut is a newly designated political region of Canada that formerly was part of the Northwest Territories (see Burden, 1996). Considerable climatic variability exists within Nunavut, which spans more than 20° of latitude and ranges in physiography from coastal lowlands to ice-covered mountains. Within this large region, relatively few data have been collected documenting the spatial variability of climate. The following discussion reflects the uncertainties regarding climatic variability in the region, and our intent here is only to provide an overview of the issues and questions involved.

### Predictions of Future Climate Change: the Results of Simulation Experiments

The global climate change predicted to occur by the middle of the 21st century, based on simulation experiments using Global Circulation Models (GCMs), indicates a world warmer than today (Fig. 1). The predictions for temperature changes of between -2°C and 4°C are reduced from earlier estimates (*cf.*, Mitchell *et al.*, 1990), due to inclusion in the models of anthropogenic sulphate aerosols (Kattenberg *et al.*, 1996); nonetheless, the combined forcing (globally averaged) is positive in both winter and summer. There are two important issues illustrated by Figure 1. First, considerable spatial variability emerges in the prediction. This pattern more closely resembles the pattern of change seen in the global temperature record than did earlier predicted patterns (Santer *et al.*, 1996). Within Nunavut, both warming and cooling are predicted. Despite variability in the northern hemisphere summer response (Fig. 1), warming is clearly amplified at high latitudes during winter; this prediction has been consistent among models. Indeed, the Greenland ice core

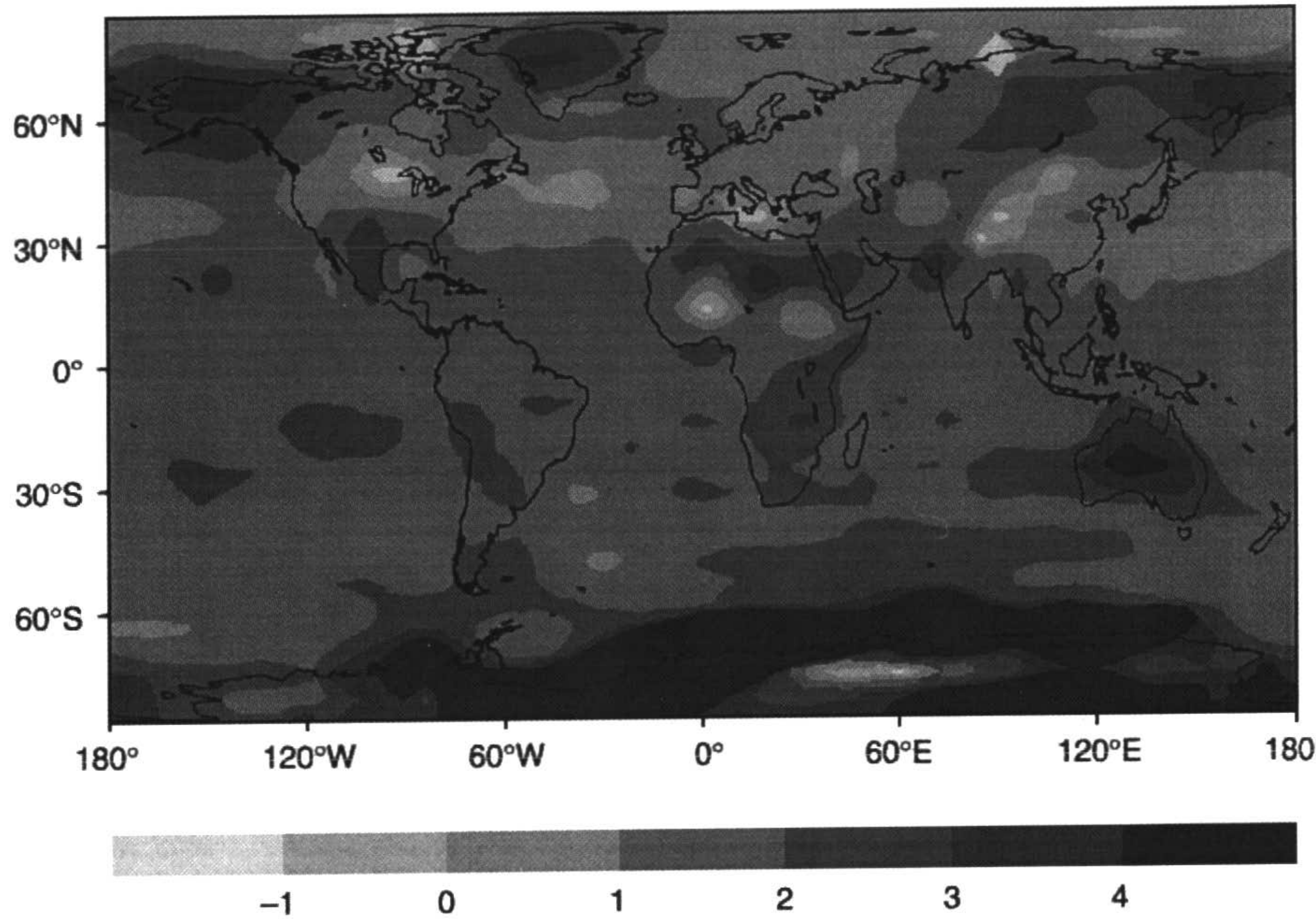

**Figure 1** *Change in surface temperature during summer months (June to August) from the period 1880-1889 to 2040-2049, as simulated by a GCM experiment including aerosol effects, and using greenhouse gas forcing from 1880 to 1990, then based on a doubling of equivalent* $CO_2$ *after 95 years (Scenario IS92A). Contour interval is 1°C. After Figure 6.10 of Kattenberg* et al., *1996.*

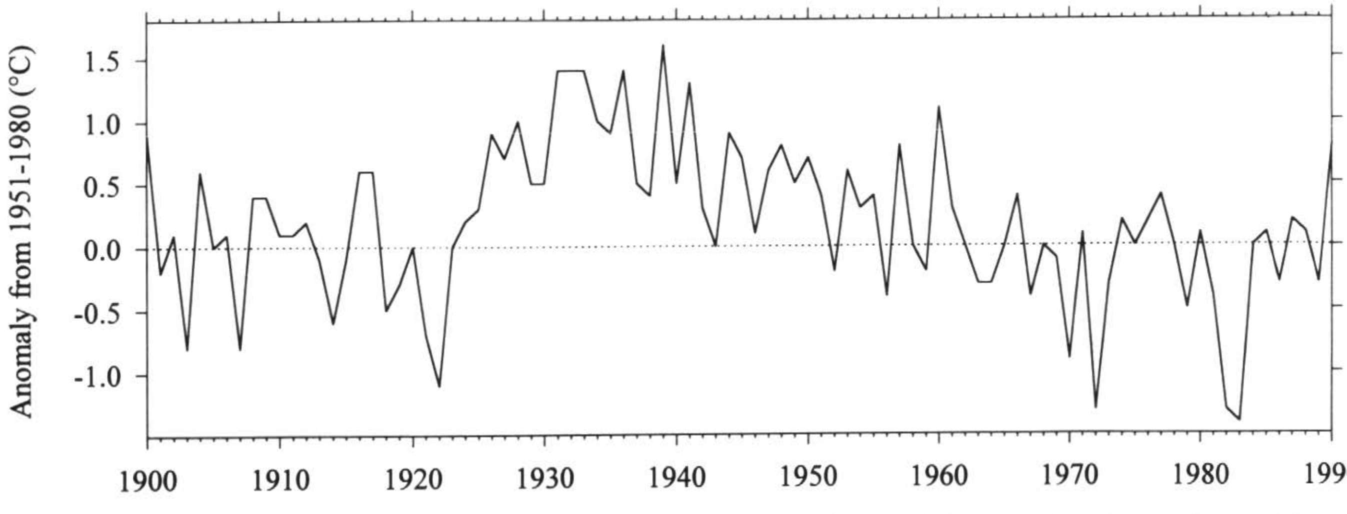

**Figure 2** *Mean summer (June to August) temperature anomaly from the 1951-1980 mean (°C), for North Atlantic weather stations with data on or before 1940 (100° to 10°W, and 60° to 90°N).*

records have recently provided some support to the idea that global climate change is amplified at high latitudes. In this case, when borehole temperatures are used to calibrate the isotopic thermometer, the temperature change from glacial to interglacial periods at high latitudes appears to have been larger than that predicted by modern isotope-temperature relationships developed at lower latitudes (Cuffey *et al.*, 1994; Peel, 1995). Second, the predictions shown in Figure 1 represent those due to anthropogenic forcing alone; in reality this forcing will be superimposed upon natural variability of the climate system. The combined effect however, cannot be known until the natural component is much better understood. Large uncertainties apply to current estimates of natural variability (Santer *et al.*, 1996).

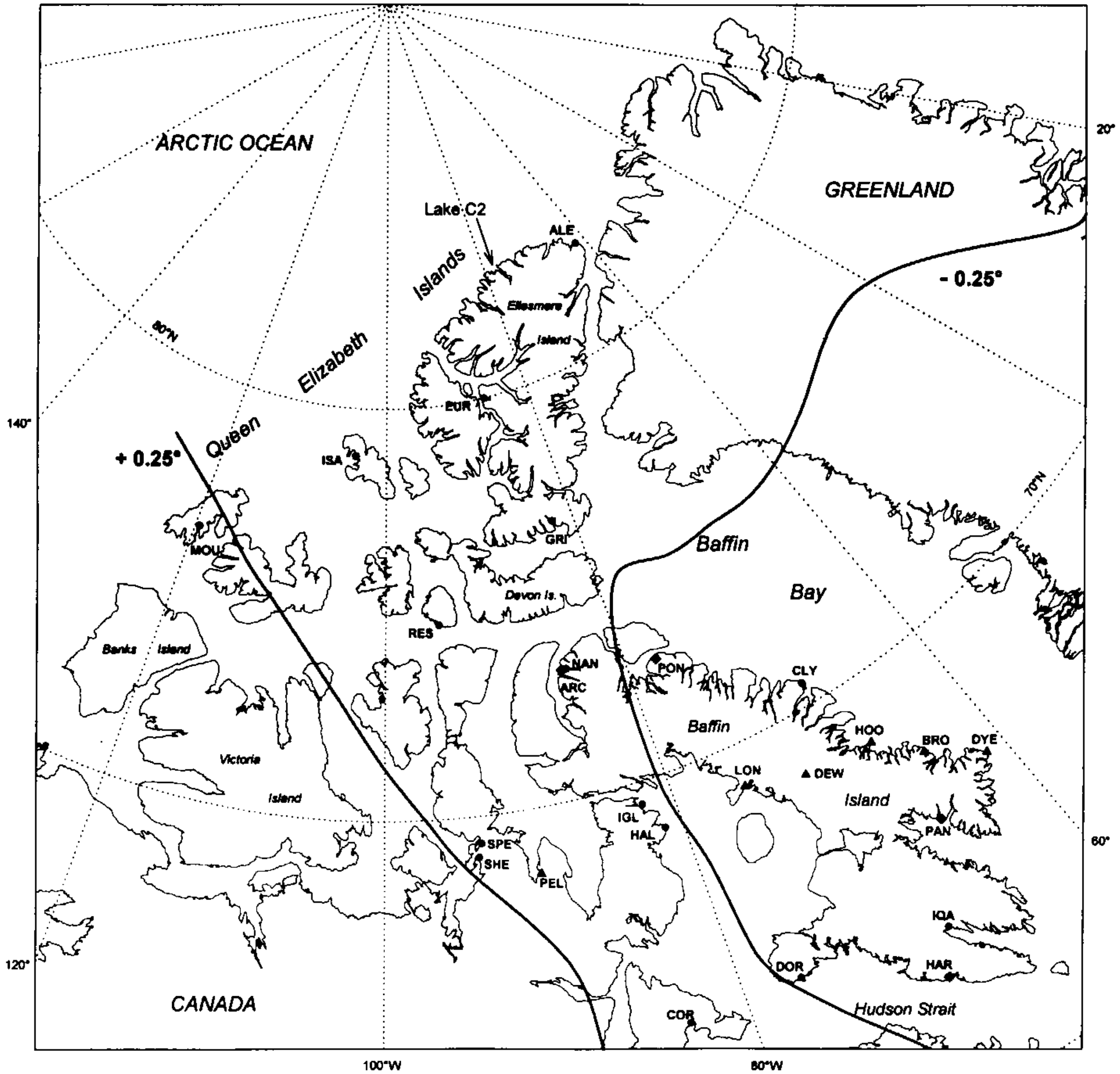

**Figure 3** *The Canadian Arctic Archipelago. Heavy lines indicate contours of annual temperature trends in C per decade (1961-1990) after Figure 1 of Chapman and Walsh (1993). Warming has occurred to the southwest of the + 0.25° contour, while there has been cooling to the southeast of the - 0.25°C line; between the lines the trend has been less than ± 0.25°C. Also shown are AES weather station locations within the Archipelago. Station names are abbreviated using the first three letters, and the symbols indicate the following:* **(diamond)** *Sea-level station where the period of record began between 1911 and 1940; all stations contain large data gaps (ARC = Arctic Bay; HAR = Lake Harbour; PAN = Pangnirtung; PON = Pond Inlet).* **(circle)** *Sea-level station where the period of record began after 1940 (ALE = Alert; COR = Coral Harbour; CLY = Clyde; DOR = Cape Dorset; EUR = Eureka; GRI = Grise Fiord; HAL = Hall Beach; IGL = Igloolik; IQA = Iqaluit (formerly Frobisher Bay); ISA = Isachsen; MOU = Mould Bay; NAN = Nanisivik; RES = Resolute; SHE = Shepherd Bay; SPE = Spence Bay).* **(triangle)** *Station located between 100 masl and 640 masl (BRO = Broughton Island; DEW = Dewer Lakes; DYE = Cape Dyer; HOO = Cape Hooper; LON = Longstaff Bluff; PEL = Pelly Bay).*

### The Instrumental Climate Record

On a global scale, the instrumental record indicates that surface land and sea temperatures have risen 0.3°C to 0.6°C (mean annual) since the mid-late 19th century (Nicholls *et al.*, 1996). The warming has not been uniform, with most of the increase being measured on the northern hemisphere continents, between 40° and 70° latitude.

When the spatial scope and seasonality of the record are restricted, important details of this global-scale warming become evident. For example, Figure 2 shows the instrumental record from North Atlantic stations inside a box 100°W to 10°W, and 60°N to 90° N (encompassing Nunavut, Greenland and Iceland). Using only stations with data on or before 1940, the annual temperature anomaly from the 1951-1980 mean ranged from -1.5°C to greater than +1.5°C. Rapid warming occurred during the decade of the 1920s, followed by three decades of gradual cooling from the late 1930s into the early 1970s. Although only six or seven stations were available for this analysis, there was very little change in the pattern when as many as 19 stations were used, which included all of those beginning operation *ca.* 1950.

Surface temperature trends for the entire Arctic have been examined by Chapman and Walsh (1993) over a shorter time interval, which allowed them to make use of a larger dataset. Monthly air and sea temperatures in this analysis were gridded into 5°x5° latitude-longitude cells. Their results indicate that the annual temperature for most of Baffin Island has decreased between 1960 and 1990 (Fig. 3), with little change through central Nunavut, and slight warming in the western portion of the archipelago. On a seasonal basis, the winter and autumn patterns are very similar to the annual pattern within the Nunavut region, while during spring and summer no trend could be resolved (less than 0.25°C change per decade). A recent re-analysis including data from the 1950s revealed little change from the 1960-1990 trends (Walsh, 1996, pers. comm.).

Arctic temperature trends in the instrumental period have also been examined using tropospheric temperature data. As with the instrumental series, these data are limited to primarily the past 40 years. Kahl *et al.* (1993) searched a comprehensive global archive of upper air soundings for temperature trends in four layers. A lack of statistical significance in the majority of the trends led them to conclude that a greenhouse-induced global warming signal was not present for the period 1958-1986. Within Nunavut, the seasonal results for autumn, winter and spring were equivocal. However, virtually all stations in the Nunavut region show cooling at all four levels during the summer, and for three stations the trends at all levels are statistically significant (*i.e.*, Eureka, Resolute and Thule).

### Shortcomings of the Nunavut Instrumental Record

There are two primary difficulties in using the instrumental record from Nunavut to assess regional climatic patterns in space or time, despite the high quality of Atmospheric Environment Service (AES) data. These are due to the location of stations and to the brevity of the record.

The geographic locations of AES weather stations within the northeastern Canadian Arctic reflect the logistical difficulties of operation in this region. As a result, there is a low density of stations (Fig. 3), all but one station is coastal, and the majority of stations are situated at an elevation of less than 100 m (including all of those within the Queen Elizabeth Islands). Indeed, all of the North Atlantic stations used in Figure 2 are also coastal, and within 100 m of sea level. The small number of higher elevation AES sites are located along the Distant Early Warning (DEW) line across south-central Baffin Island, and extend up to 640 m in elevation.

In contrast to the locations of the weather station sites, the terrain of the region is predominantly dissected plateaus or mountainous, with coastal plain found extensively only to the west. Temperature inversions are common throughout the region in all seasons (Bilello, 1966), including both surface-based and elevated structures. As a result, temperature measurements at sea level are often not representative of those at higher elevations (*e.g.*, Hardy, 1996).

Many of the AES stations in Nunavut began in conjunction with the Cold War. Only four sites illustrated in Figure 3 began continuous operation prior to 1940, and of these, all contain large data gaps (5-32 years). For the important decade of the 1930s, which appears to have been quite warm, only Lake Harbor, Pangnirtung and Pond Inlet were collecting measurements.

### Holocene Paleoclimate Overview

Widely-spaced weather stations, with climate records of only several decades, present two difficulties. The first problem, discussed above, is whether individual weather stations truly represent regional climate. The second problem is that variability is an inherent component of climate, and operates on many timescales (Mitchell, 1976). Does the warming that occurred during the 1920s, for example (Fig. 2), represent decadal timescale natural variability, or has anthropogenic forcing been superimposed upon natural variability?

Variability over time intervals equal to or longer than the instrumental period can only be assessed by using paleoclimate proxies to extend the record. Unfortunately, however, extensions based on most paleoclimate proxies are associated with a loss of temporal resolution; therefore, the utility of such records to assess variability over a broad range of timescales is decreased. Currently, the highest resolution proxy records from the Arctic are derived from ice cores. Lake sediments also offer the promise of continuous, high-resolution paleoenvironmental records, but quantitative results are only just now emerging.

Through the Holocene, the magnitude and timing of climate change has varied considerably across Nunavut. Climate in the Early Holocene was dominated by the presence of large ice masses (the Laurentide and Franklin Ice Complex) which were experiencing rapid deterioration. Nevertheless, there is considerable evidence for open-water conditions and a marine environment favorable for large marine mammals, even while there were large ice masses on the adjacent land (*e.g.*, Dyke and Morris, 1990; Evans and England, 1992). The Early Holocene warmth reflects significantly higher solar radiation receipts (+20% or more) in summer months, as a result of orbitally-forced (Milankovitch) radiation anomalies. In fact, summer radiation anomalies at 80°N, from 10,000-12,000 (calendar years) before present (BP), were higher than at any time since the previous interglacial maximum 125,000 years ago (Bradley, 1990).

During the mid-Holocene, the southeastern Canadian Arctic (southern Nunavut) appears to have experienced a warm interval at roughly 4500-7000 years BP based on a variety of proxies (Williams *et al.*, 1995), although this "climatic optimum" may reflect the final disappearance of the Laurentide ice sheet and its effect on regional temperatures. Further north, different proxies from the Queen Elizabeth Islands conflict in whether the mid-Holocene was in fact warmer than the early Holocene (Bradley, 1990).

After the mid-Holocene, at roughly 4500-2000 years BP, temperatures began to slowly decline over the entire region. Cooling was unlikely to have been continuous or spatially uniform, and some records from Baffin Island demonstrate this (*e.g.*, Williams and Bradley, 1985). Melt layers in the Agassiz Ice Cap record indicate that summer temperatures decreased from 8500 years BP to 2500 years BP, after which they remained low until the most recent century. Based on a 1°C·100m$^{-1}$ lapse rate, Koerner and Fisher (1990) estimate that summer temperatures 8500 years ago were 2.0°C cooler than today. Over a much shorter time period (since 2700 years BP), Diaz *et al.* (1989) calculated a decline of ~1.5°C, based on pollen assemblages. On northern Ellesmere, a paucity of late Holocene driftwood is probably due to the formation of continuous ice shelves along the coast by 3,200 BP. Driftwood abundance elsewhere may reflect former Arctic Ocean circulation patterns, but the climatic significance is not entirely clear (Dyke *et al.*, in press).

### *The Late Holocene Record in Nunavut*

In general terms, the gradual climatic deterioration that began several thousand years ago throughout the region continued until the mid-19th century. The Agassiz Ice Cap melt record, for example, shows that the coldest summers of the Holocene occurred only 150 years ago (Koerner and Fisher, 1990). At numerous sites in Nunavut, the maximum Late Holocene advance of glaciers has occurred within the last century, as noted by Christie (1957) on northern Ellesmere Island, and by Dowdeswell (1984) in lichenometric studies around Frobisher Bay. Douglas *et al.* (1994) have used diatom assemblages to examine environmental change in ponds on the east-central coast of Ellesmere Island (see also Smol and Douglas, 1996). Diatom assemblage shifts in these ponds began in the 19th century, following several millennia of relatively stability. Although their record lacks high-resolution chronological control, the finding provides clear evidence for recent environmental change.

Considerable proxy data indicate that a dramatic mid-19th century warming began following the prolonged cool interval. The Agassiz melt record indicates that the warmest summers in 1000 years have occurred during the past 100 years (Koerner and Fisher, 1990). An analysis of all the available paleoclimate proxy data available suggests that summer temperatures since ~1925, in the context of most of the Late Holocene, have been exceptionally high (Bradley, 1990). Indeed, evidence for recent warming extends beyond the Canadian Arctic. A composite, multiple proxy record of summer temperatures over the past 500-600 years reveals that since the 1920s, northern hemisphere summer temperatures "have been higher than for at least 500 years" (Bradley and Jones, 1993).

The Nunavut instrumental and proxy paleoclimate records together reveal an intriguing problem. Modern climate in the region appears to be atypical of conditions prevailing for much of the Late Holocene; however, the transition, from one of the cooler periods of the past millennium into the late 19th to early 20th century warming, coincides with the beginning of the instrumental record. Consequently, it is difficult to recognize how much of the temperature trend in the instrumental record is due to natural variability and how much might be due to anthropogenic effects on climate. While some interpretations of individual proxies suggest that natural variability alone can account for the warming observed (*cf.*, Koerner and Lundgaard, 1995), the body of evidence, when derived from numerous global observations and model predictions, suggests "a discernible human influence on global climate" (Santer *et al.*, 1996). However, distinguishing natural from anthropogenic climate change in Nunavut remains an unresolved problem.

## NUNAVUT PALEOCLIMATE FROM LAKE SEDIMENTS

Development of a better understanding of climate variability through the Late Holocene, especially at decadal-to-century timescales, will require well-dated, high-resolution proxy records from a dense network of sites. Additional ice core records, such as those recently obtained from the Penny Ice Cap on Baffin Island, will contribute to this knowledge, and we recommend that the current network of ice coring sites be expanded. To supplement the ice cores, annually laminated lake sediments can extend the network of sites to additional elevations and to regions within Nunavut without ice caps suitable for coring. The subannual-to-annual resolution of such sediments provides excellent age control and resolution, and provides opportunities for documenting climate variations on the decade-to-century timescale.

### Lake Sediments as a High-resolution Climate Proxy

Laminated sediments from a number of arctic lakes, in coastal and glacier-fed basins, preserve a unique record of paleoenvironmental information. The strong seasonality of clastic sediment transport into these basins results in seasonal-to-annual time resolution, which provides excellent age control. The clastic influx is intimately linked to the late spring-summer snowmelt season, yielding a proxy record of climate variables, including summer temperature and precipitation. In addition, the biogenic component of each lamina also provides important high-resolution paleo-environmental information.

Directly interpreting the structure of laminated sediments in arctic lakes, in terms of their climatic significance, can be difficult. Recognizing and discriminating between annual layers, or varves, their sub-annual components, and laminae produced by episodic sedimentation pulses, or turbidites, is central to producing a viable time series of sedimentation. Ideally, multiple cores within one basin are obtained, then independently counted and measured. A series of individual core analyses can then be correlated, allowing normalization and compilation of data from throughout a basin, and resulting in a composite chronology.

The next important issue in the production of a high-resolution proxy record of paleoclimate is calibration. Provided that allochthonous sedimentation represents a response to meteorological control of watershed sediment transfer, calibration establishes the linkage between climate and lamination thickness.

### Calibrating the Signal

Typically, an annually laminated lake sediment core contains more than one proxy of paleoclimate (for example, clastic sediment thickness and diatoms). As with all paleoclimate proxies, these must be calibrated to modern climate before a meaningful signal can be extracted. At least two approaches to calibration have been employed, depending upon which proxy is being used: 1) analysis of modern spatial patterns, or 2) modern process studies.

When pollen or diatoms from the sediments are being used, intensive spatial sampling of modern species can demonstrate how different species respond to environmental conditions across spatially defined climatic gradients (Charles and Smol, 1994). Through statistical relationships between species abundance and environmental variables, this method maps out a *species or assemblage response* to climate.

The calibration of clastic sediment thickness differs significantly from the biotic components (or analogues such as tree-ring records) in that each basin displays a unique linkage between climate and sediment discharge. This linkage is a function of multiple basin variables and processes including lithology, topographic relief, glacierization and vegetation: all of which serve to produce a *basin response* to climate. To be of optimal paleoclimatic value, the linkage must primarily reflect direct effects, and remain stable through time. For example, if the interval of greatest sediment transfer any year was associated with a streamflow response to snowmelt *or* rain-on-snow events *or* convective rainfall, the annual sediment thickness could reflect any or all of these aspects of climate. Due to the paucity of streamflow measurements in the Nunavut region, the climate-sediment discharge linkage can often only be established by intensive within-basin process measurements, including energy exchange between the atmosphere and land surface, stream discharge, and sediment transport.

## Calibrating Lake C2 Annually Laminated Sediments: An Example

The approach adopted by the Taconite Inlet Lakes Project to calibrate an annually laminated sediment record illustrates one approach to understanding a basin response to climate. Lake C2 is a 1.8 km$^2$ perennially ice-covered meromictic lake, 84 m in depth, on the north coast of Ellesmere Island (Fig. 3). Sediments deposited in the lake are primarily clastic, and are delivered by an inlet stream draining a 21 km$^2$ watershed with 1200 m of topographic relief. Further information and results of the project are reported in a special issue of the *Journal of Paleolimnology* (v. 16, 1996) or are available electronically at <http://www.geo.umass.edu/climate/climate.html>.

Streamflow, suspended sediment transport and meteorological variables at two elevations were measured through the 1990-1992 field seasons at Lake C2. The objective was to determine the extent to which suspended sediment flux responded to climatic variability. Streamflow to the lake was almost exclusively the result of snowmelt, in response to inputs of atmospheric energy as measured by air temperature at the median watershed elevation (520 m). Sea-level air temperature, global solar and net all-wave irradiance were less clearly associated with discharge. Fluctuations of discharge and suspended sediment concentration were nearly synchronous, and non-linearly related. Daily sediment discharge was therefore linked by streamflow, with a time lag, to the energy available for snowmelt. Mean daily air temperature and cumulative degree-days above 0°C, at 520 m elevation, were used successfully to predict the daily and seasonal discharge of runoff and sediment to the lake (Hardy, 1996).

The calibration process was extended through use of weather data from Alert,

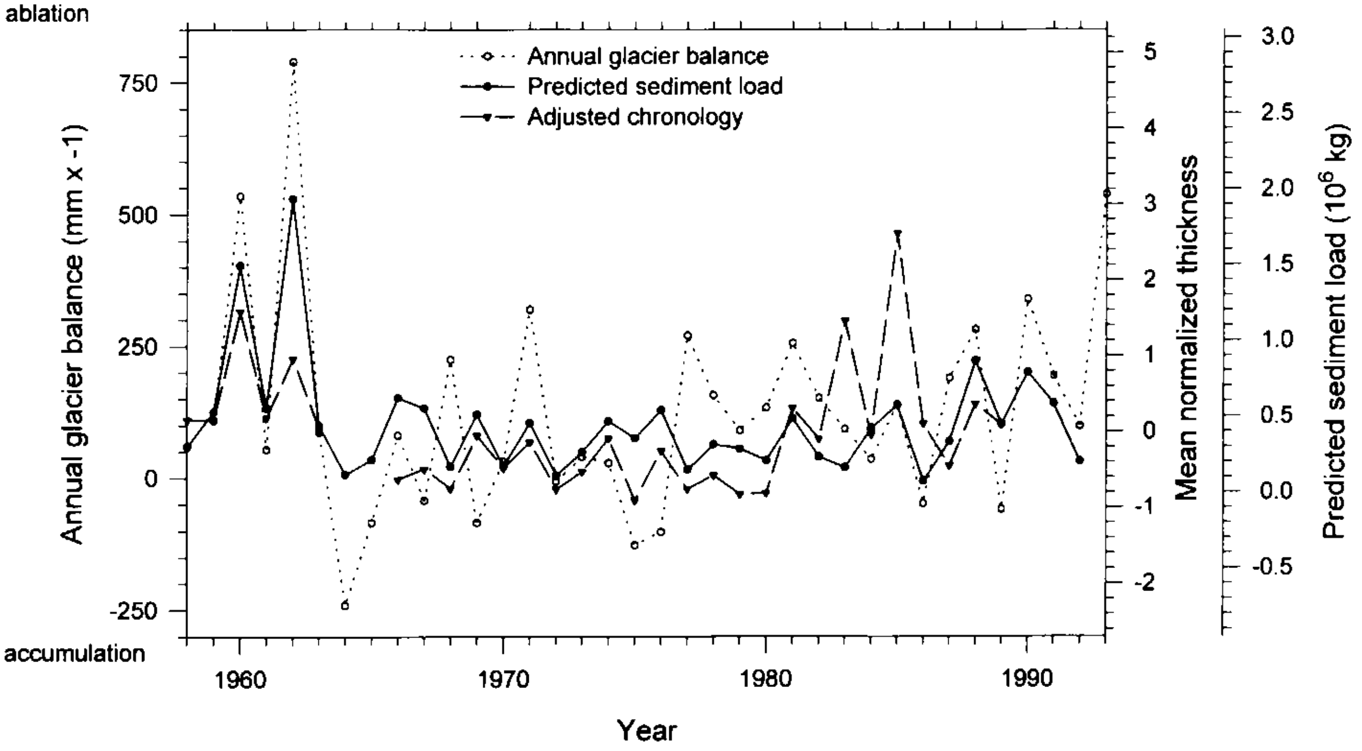

**Figure 4** *Predicted annual suspended sediment delivery ($10^6$ kg) into Lake C2, the adjusted Lake C2 varve chronology (Hardy* et al.*, 1996), and the average annual balance (mm x -1) for all available Canadian High Arctic glacier data (Koerner, 1995). Sediment flux was predicted by the 600 m sounding temperature at weather station Alert, and can account for 63 % of the varve thickness variance. Varve thickness is a mean normalized series (n = 8 cores).*

located 225 km to the east (Hardy *et al.*, 1996). Both mean daily air temperature at 520 m and daily sediment discharge from the basin were well correlated with air temperature at 600 m above Alert, as obtained from the 1200 Z (0800 LST) rawinsonde sounding. Accordingly, Alert 600 m data from 1990 and 1992 were pooled to predict the lagged daily sediment discharge into Lake C2 (adj. $r^2 = 0.43$). Daily values were predicted and then summed for each year in order to produce an annual series of predicted sediment transfer to the lake, for the period of record (1951-1990).

The original varve chronology for Lake C2 was based on eight sediment cores recovered from the deep basin of the lake (>80 m). When the last 40 years of this series were compared with the predicted annual sediment loads discussed above, there was good agreement between the low-frequency fluctuations. However, a slight tuning of the varve record optimized the correlation between them (Fig. 4). Adjustments to the chronology were based on examination of weather data for specific years, re-examination of sediment core thin sections, and by aligning fluctuations in the two series which closely matched. Although the original chronology is reasonably well correlated with 600 m temperatures at Alert (for the summer (JJA) mean, $r = 0.41$, significant at 0.01), the adjusted chronology is both better correlated and contains a more precise climate signal ($r = 0.54$ for July mean, significant at 0.01). Indeed, the detailed on-site measurements over 3 years demonstrate that sediment transfer to Lake C2 represents the local climate even better than that at Alert, as expected.

This is the first calibrated varve record produced from arctic lake sediments, and demonstrates that varves from Lake C2 contain a paleoclimatic record. We believe the *post-facto* manipulations required to produce the adjusted varve chronology are reasonable given the uncertainties inherent in varve counting, and the lack of any independent corroborating chronostratigraphic markers.

### High Arctic Lake Sediments and Glacier Mass Balance

The calibration process discussed above clearly did not account for all of the variance in the Alert climate–Lake C2 varve thickness relationship. To provide an independent test of this prediction technique, we also used data from a recent compilation by Koerner (1995) of all Canadian high arctic glacier mass balance records, dating from 1959. These data support the approach we have employed to calibrate Lake C2 varve thickness in terms of summer temperatures.

The high arctic glaciers on which mass balance studies have been conducted represent a range of ice mass types and geographic locations within the northern Nunavut region, including the 0.6 km$^2$ Baby Glacier (Axel Heiberg Island), the Ward Hunt Ice Rise, and the Devon Ice Cap (northwest side). For each year from 1959 to 1993, mean values of the winter, summer and annual balance were calculated using all available data. The number of glaciers with data any one year ranged from one to four for the winter and summer balance terms, and from one to seven for annual balance, with averages of 2.9, 2.8 and 4.7 glaciers, respectively. Correlation coefficients (r) between the three different balance terms and our predicted annual sediment loads (see section above) were 0.01 ($p = 0.94$), -0.83 ($p < 0.0001$) and -0.73 ($p < 0.0001$). Because our annual sediment load series is predicted solely from summer temperature, these relationships suggest that interannual variability of summer and annual balance is largely a response to interannual variability of ablation processes. Figure 4 illustrates the excellent agreement between average annual balance and the predicted sediment load. Examination of the annual balance series for the seven individual glaciers (not shown) revealed that the time intervals of closest agreement between annual balance and predicted sediment load (*e.g.*, 1961-1967, 1984-1987; see Fig. 4) were virtually all intervals in which four or more glaciers exhibited the same trend between years. Conversely, through several periods in which the two series disagreed (*e.g.*, 1968-1970), annual balance data exist for only three or fewer glaciers. These points suggest a general regional coherence in the climatic response by the seven monitored high arctic glaciers.

The annual mass balance series were also compared with the original and adjusted varve chronologies (Fig. 4), which provides support for the procedure discussed above of slightly shifting the varve chronology ($r = -0.04$ and $-0.39$ for the annual balance and the two chronologies, respectively). The agreement between the summer or average annual balance series, and both the predicted sediment load and the adjusted varve chronology demonstrates that Lake C2 sediments provide a regionally valid proxy for summer temperature.

## CONCLUSIONS

Because of the lack of long-term instrumentally recorded climatic data from Nunavut, proxy records of past climate must be relied upon to obtain a perspective on climate and associated environmental variability in the area. Currently, such records are limited, but those available point to a general pattern of Late Holocene cooling, following an Early to mid-Holocene warm episode. There is considerable evidence that the most recent neoglacial episode, which culminated in the mid- to late 19th century, was one of the coldest, if not the coldest period in the Holocene. The subsequent 20th century warming has been, by contrast, one of the warmest periods in the Late Holocene. In the last 200 years, therefore, Nunavut has witnessed a range of environmental change that may be representative of many thousands of years. To document these changes, and to try and resolve their causes, high-resolution proxy records of past climate are needed. Only laminated lake sediments and ice cores have the potential for providing the necessary detail and spatial coverage necessary for this task. We recommend that multi-proxy studies of laminated lake sediments be conducted throughout Nunavut, to supplement the information currently available from ice cores, and that further ice cores be recovered from appropriate sites along the mountainous interior of the eastern Canadian Arctic. In both cases, detailed studies must be carried out to fully calibrate the climate signal in the proxy record, to provide confidence in the veracity of any resulting paleoclimate reconstructions.

## ACKNOWLEDGEMENTS

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