The Holocene 11,2 (2001) pp. 243–249

A varve record of increased 'Little Ice Age' rainfall associated with volcanic activity, Arctic Archipelago, Canada*

Scott F. Lamoureux,[1] John H. England,[2] Martin J. Sharp[2] and Andrew B.G. Bush[2]

([1]Department of Geography, Queen's University, Kingston, ON K7L 3N6, Canada; [2]Department of Earth and Atmospheric Sciences, University of Alberta, Edmonton, AB T6G 2E3, Canada)

Received 6 May 1999; revised manuscript accepted 10 August 2000

A
HOLOCENE
RESEARCH
PAPER

Abstract: Varved sediments from Nicolay Lake, Canadian High Arctic, record major summer rainfall events over the last five centuries. Increased incidences of summer rainfall occurred during the coldest periods of the 'Little Ice Age' and were strongly clustered in the years immediately following major volcanic events. Comparison of the summer rainfall and proxy air temperature records thus provides a fuller understanding of the nature and causes of natural climate variability in the Arctic. Study of the synoptic conditions associated with the two most recent large summer rainfall events suggests that they are associated with the incursion of cold low-pressure systems from the Arctic Ocean Basin. Volcanic activity may produce atmospheric conditions more conducive to the formation of such low-pressure systems, which generate rainfall at low elevations and summer snowfall at higher elevations, thus explaining the correlation between rainfall and summer snow accumulation recorded in ice cores from high-elevation ice caps.

Key words: Varves, lacustrine sediments, summer rainfall, precipitation, 'Little Ice Age', volcanic activity, climatic variability, Arctic, Canada.

Introduction

Volcanism has long been considered a possible forcing mechanism for subdecadal- and decadal-scale climate variability (e.g., Lamb, 1970). A number of studies have compared instrumental (Kelly *et al.*, 1996) and proxy climate records (Briffa *et al.*, 1998) with eruption indices derived from ice cores and historical records (Hammer *et al.*, 1980; Zielinski, 1995). These studies have documented the temporal and spatial response of air temperature to eruptions, but these reveal only a single aspect of climate variability. In this report, we present the first high-resolution sedimentary record that shows a significant association between a summer precipitation signal and major volcanic events. Annually layered sediments (varves) from Nicolay Lake, in the central Canadian Arctic Archipelago (Figure 1), show that, throughout the past 500 years, the incidence of major rainfall events increased significantly in the years after major volcanic eruptions. These periods of increased storminess accompanied colder conditions during the 'Little Ice Age' (LIA). These results add a new perspective to earlier palaeoclimatic reconstructions from the region (Overpeck *et al.*, 1997).

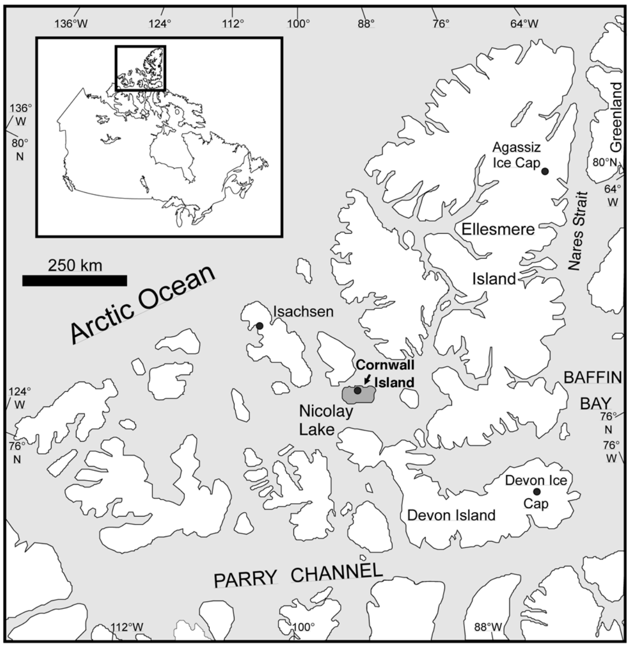

Figure 1 Location of Nicolay Lake in the Canadian High Arctic islands.

---

*Polar Continental Shelf Project contribution 01900.

Methods

Nicolay Lake is a small (21 ha), deep (31 m maximum) lake located on the north-central coast of Cornwall Island (Figure 1). Currently, the water column is entirely fresh and remains unstratified through the summer melt season due to a persistent ice cover that minimizes surface heating and mixing. The lake is fed by a river that drains a 91 km^2, unglacierized catchment underlain by poorly consolidated sedimentary bedrock and postglacial marine and fluvial sediments (Lamoureux, 1999a). Sediment is readily available and is transported in suspension by the river during the snowmelt season and runoff events resulting from major rainfall. Hydrological activity is limited to the brief melt period that typically extends from mid-June to mid-August. Winter weather between September and early June is persistently cold leading to thick (c. 2.5 m) lake ice and precluding surface runoff.

To reconstruct past hydrological activity in the catchment, eight piston-percussion and vibra-cores were collected from Nicolay Lake. All cores contain well-defined, clastic couplets that are interpreted to be varves on the basis of sedimentology, the strong seasonal rhythmicity of hydrological activity in the catchment, and ^{137}Cs and ^{210}Pb age determinations from recent sediments (Lamoureux, 1999a). The core network was used to cross-date the varves, identify the annual lakewide accumulation patterns (Lamoureux, 1999b) and to estimate interannual variations in catchment sediment yield using thickness measurements obtained from thin sections prepared with epoxy-embedded sediment (Lamoureux, 2000). Anomalously thick and localized deposits related to slump-induced subaqueous turbidites were identified and distinguished from varves deposited in years with exceptionally high catchment sediment yield (Lamoureux, 1999b). The final varve record was constructed by cross-dating the eight cores, thereby eliminating counting errors and providing a consistent record of annual sediment yield (Lamoureux, 2000). Although the error for the varve chronology cannot be directly estimated, counting errors related to thin structures or minor sediment disturbances (Lamoureux and Bradley, 1996) are rare in the Nicolay varves. Therefore, the chronology is estimated to be accurate to within 1% or better (Lamoureux, 1999b).

Results

The Nicolay Lake varve record extends from AD 1493 to 1987. Prior to *c.* AD 1500, the Nicolay lake basin lay below contemporary sea level, and suspended sediment transported from the catchment was captured in a series of shallow marine embayments further inland. Following final emergence and isolation of Nicolay Lake, these embayments were abandoned and fluvial sediment was able to enter the lake directly (Lamoureux, 1999a). The onset of varve deposition in Nicolay Lake was a consequence of these geomorphic changes and their impact on sediment delivery to the lake.

The mean sediment yield throughout the *c.* 500-year varve record was 109.8 t·km^2·a^{-1}, but several years exceeded the mean by a factor of four (Figure 2), and, in one case, by an order of magnitude (Figure 3, AD 1820). Multiple sediment cores were used to distinguish between the outliers with lakewide and localized distributions. The lakewide outliers represent fluvial inputs distributed throughout the lake by suspension flows and contrast with years with high sediment accumulation that is restricted to only one or two cores which are interpreted to be the product of turbidites or mass movement processes (Lamoureux, 1999b).

All of the lakewide, high-yielding years in the Nicolay varve record contain thick subannual rhythmites that indicate an abrupt increase in sediment delivery during the summer after the snowmelt (nival) period (Figure 2). For this study, we have examined varves from a mid-distal location in the lake, where subannual rhythmites probably represent deposition from runoff associated with large-scale weather events lasting several days or more (Smith, 1978). A comparison with the available meteorological record from the closest weather station (Isachsen, 1948–1978; Figure 1) indicates that the thickest subannual rhythmites were deposited in the same years as the two largest daily rainfall events. The largest rainfall event occurred late in the summer of 1951 (14 August, 37.5 mm total) and a thick rhythmite occurs at the top of the varve from that year (Figure 2). Conversely, a major rainfall event in 1962 (23.5 mm total) coincided with the initial snowmelt period and the thick rhythmite associated with this event occurs at the base of the 1962 varve. The 1962 rain-on-snow event is the largest early season event on record, and appears to be the only early season rainfall large enough to generate a rhythmite (Lamoureux, 2000).

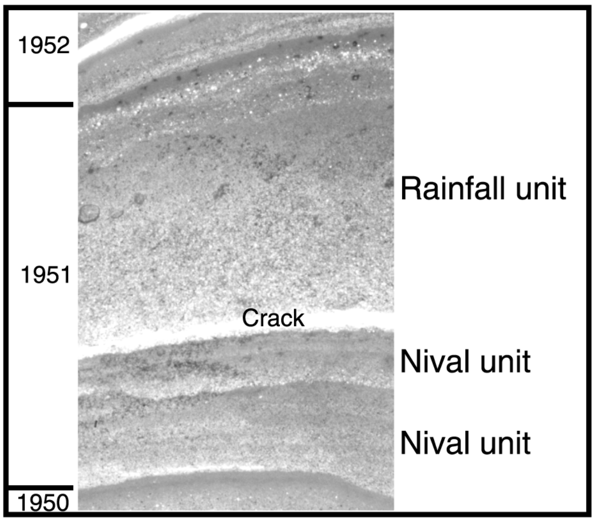

Figure 2 Photomicrograph of the 1951 varve from Nicolay Lake. Accumulation for this year was estimated to be 408 t·km^2·a^{-1}. The lower two units are interpreted as deposition resulting from two phases of snowmelt. The overlying, thick unit is related to a major rainfall event in early August, immediately prior to the cessation of streamflow.

There is also an association between the presence (or absence) of subannual rhythmites and the occurrence (or absence) of major summer rainfall events in 15 other years of the instrumental weather record. The record in the remaining years is complicated by rainfall events that occurred either during the spring snowmelt period, or following periods of prolonged summer warmth (Figure 4). In the first case, the effect of rainfall is indistinguishable from the sediment yield associated with snowmelt (except 1962, as previously noted). In the second case, warm conditions promote drainage and evaporative losses from the shallow, thawed surface layer, thereby increasing potential rainfall storage and flood peak attenuation. When early-season rainfall and the prior melting degree-days are accounted for, the record of major ($>$13 mm total) rainfall events can be explained in all but four years. In 1950, major rainfall was not recorded at Isachsen but the varve record shows a subannual rhythmite. In contrast, major rainfalls in 1954 and 1955 do not appear to have produced discernible sedimentary units in the Nicolay record. Only in 1965 does a subannual rhythmite appear to be related to a late summer snowmelt event during an otherwise cold summer (Lamoureux, 2000).

Between 1948 and 1978, rainfall events were responsible for most of the prominent subannual rhythmites, and their occurrence effectively controls the interannual variance of the sediment record (Lamoureux, 2000). Therefore, we hypothesize that throughout the entire 487-year record, prominent subannual rhythmites indicate runoff and sediment delivery associated with major rainfall events in

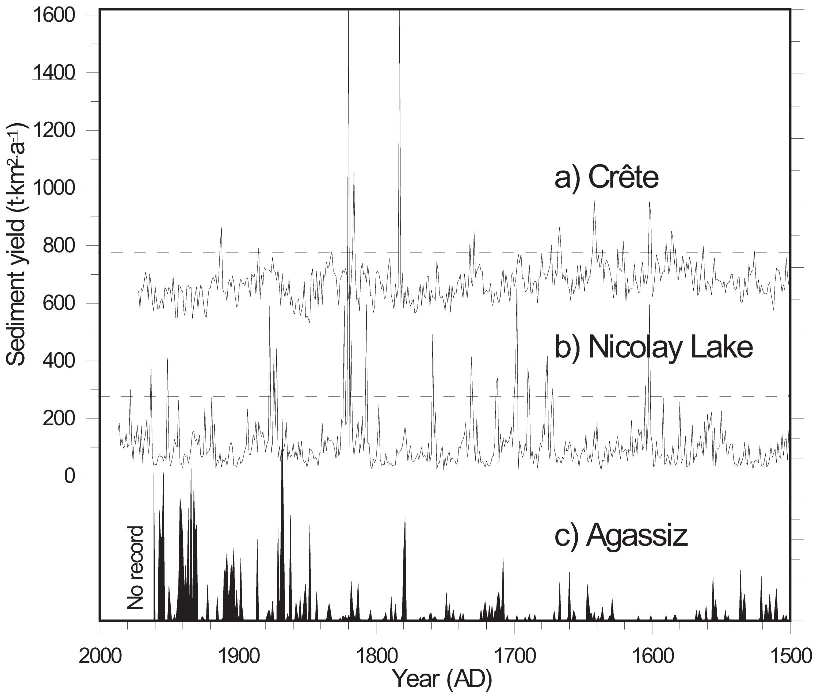

Figure 3 The Crête ice core volcanic acidity record (Hammer *et al*., 1980) (a), compared to variations in major Arctic climate proxies during the past 500 years: sediment yield estimated from Nicolay Lake varves (b) and Agassiz Ice Cap, Ellesmere Island, percentage annual melt layers (Fisher and Koerner, 1994) (c). All records have annual resolution. Dashed horizontal lines in the Crête and Nicolay Lake series indicate the 95th percentile level.

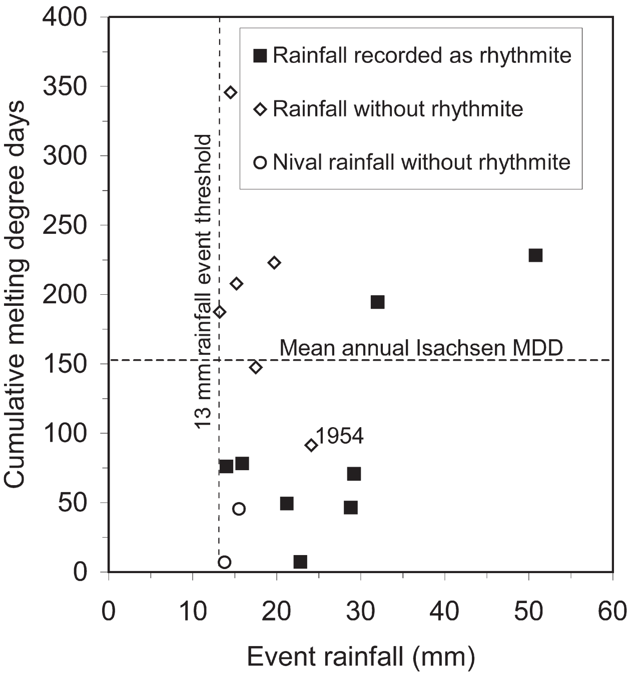

Figure 4 Major rainfall events (>13 mm total) at Isachsen compared with the occurrence of subannual rhythmites in the Nicolay Lake varve record. Rainfall events less than 20 mm were not recorded as sedimentary units if the soil was dry in warm years (open diamonds) or when the rain falls on snow cover (open circles). Meteorological data were collected at Isachsen between 1948 and 1978. Mean annual melting degree days (MDD) at Isachsen are indicated by the horizontal dashed line.

this semi-arid, permafrost environment. These events generate above-average sediment yields due to the high sediment availability in the catchment, the sparseness of protective vegetation, and the shallow depth of thawed soil. Complexities in the rainfall-runoff relationship, particularly for rainfall events <20 mm (Figure 4), indicate that similar small rainfall events may or may not have been recorded in Nicolay Lake prior to 1948 and the record should be interpreted as partially truncated. For this reason, we limit our rainfall analysis to the largest events in the sedimentary record, with magnitudes equal to or exceeding the 1951 and 1962 rainfalls.

Discussion

Palaeoclimatic comparisons

Periods in the varve record when rainfall appears to have been frequent correspond with cold periods indicated by regional palaeotemperature records (Figure 3). For example, sediment yields were persistently high during the nineteenth century, which was the coldest interval of the LIA throughout the Arctic (Overpeck *et al*., 1997). Increased occurrences of rainfall between 1670 and 1740 also correspond to more localized colder conditions during the Maunder Minimum (Overpeck *et al*., 1997), and the increased incidence of heavy rainfall between 1550 and 1610 occurred at a time of cool conditions and higher net accumulation in the nearby Devon Island ice core (Alt *et al*., 1985). Furthermore, a marked increase in rainfall after 1962 coincided with colder summers in the Canadian High Arctic recorded by more frequent positive mass balance on ice caps (Alt, 1987), increased frequency of cold, wet synoptic events in the region (Bradley and England, 1978; 1979) and overall lower summer freezing levels in the atmosphere (Bradley, 1973). In contrast, rainfall frequency was lowest during the warmer conditions of the early 1500s and 1900s, and the last half of the 1700s (Overpeck *et al*., 1997). In the Agassiz ice core, periods with more frequent melt layers (which record warmer summer temperatures) (Figure 1) (Fisher and Koerner, 1994) were broadly out of phase with periods of higher sediment yield and frequent rainfall at Nicolay Lake (Figure 3). This inverse relationship is especially clear after 1840 (Figure 5). When circum-Arctic temperatures peaked between 1935 and 1960 (Overpeck *et al*., 1997), the varves from Nicolay Lake reveal lower yield and infrequent, high-magnitude rainfall events.

Mechanism for the changing occurrence of major summer rainfall events

The timing of prominent rainfall-induced sediment yields in the Nicolay Lake record is similar to that of outliers in acidity

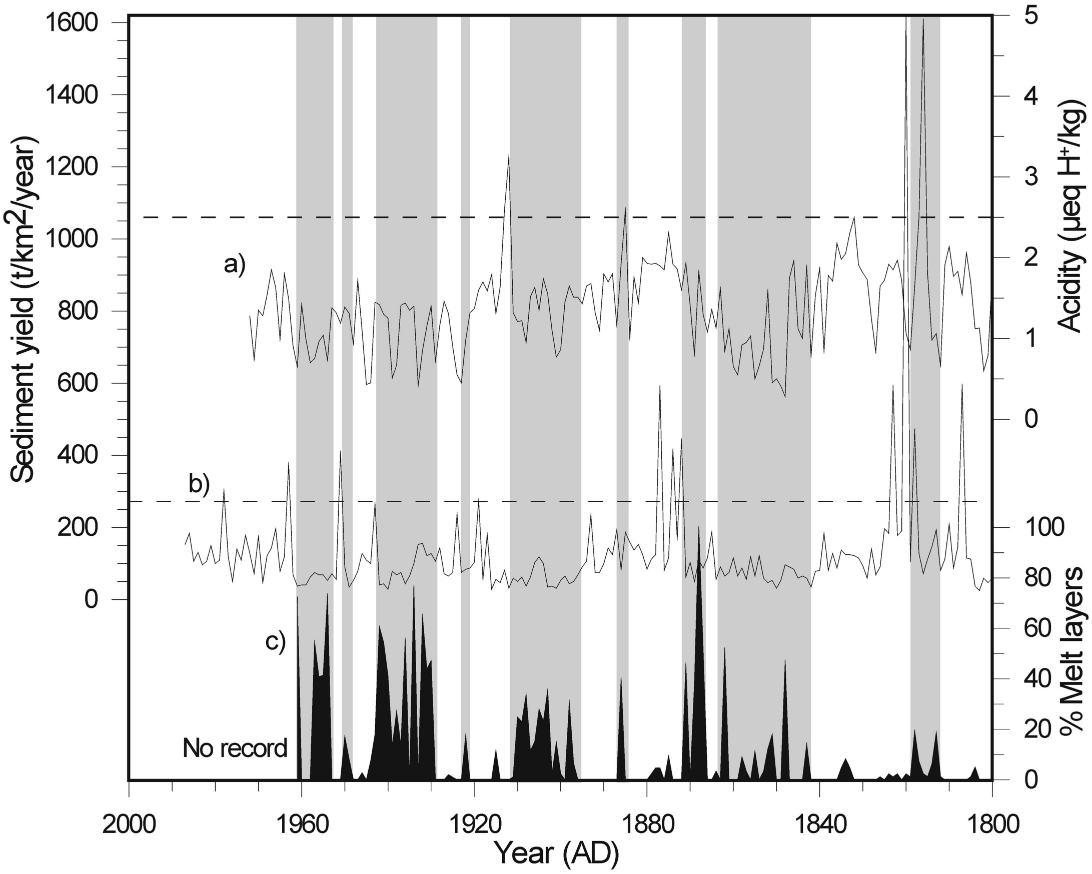

Figure 5 Comparison of the Crête (a), Nicolay Lake (b) and Agassiz % melt layer (c) acidity records since 1800. Shaded areas indicate periods of >10% melt layer occurring in the Agassiz ice core and are out of phase with rainfall events in the Nicolay Lake record. Dashed horizontal lines in the Crête and Nicolay Lake series indicate the 95th percentile level.

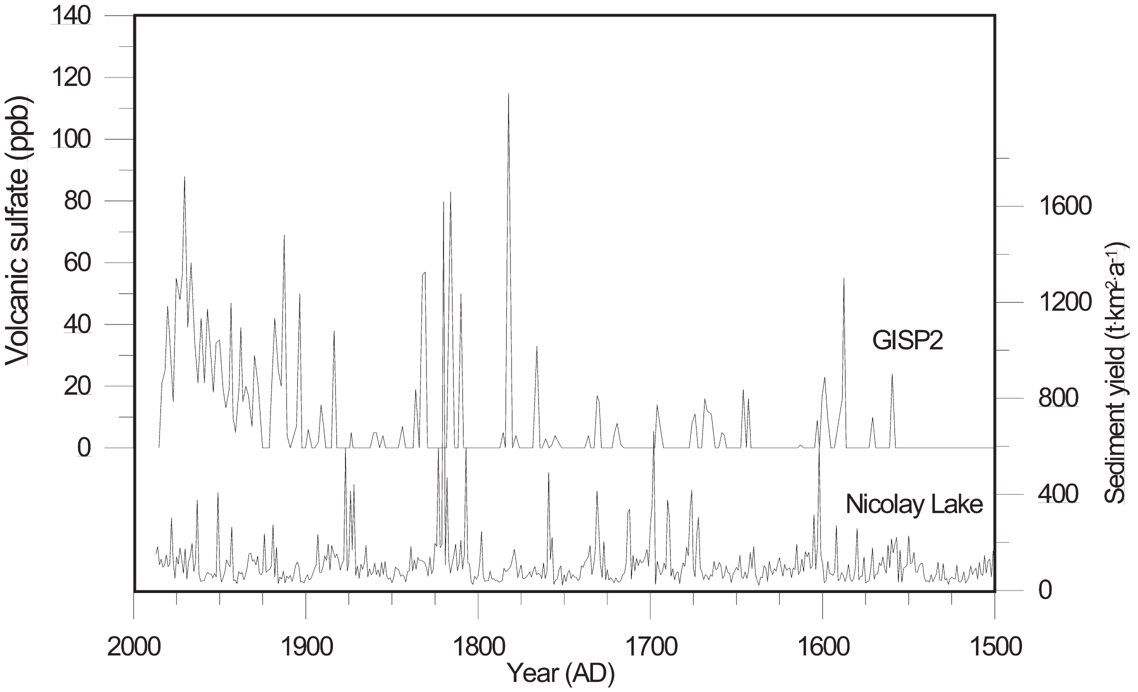

Figure 6 Comparison between the Nicolay Lake sediment yield and GISP2 volcanic sulphate record (Zielinski, 1995). Note the similarity in the occurrence of many outliers between the series as well as the anthropogenic sulphate rise after AD 1900.

measured in the Crête ice-core record (Figure 3). The latter outliers are produced by sulphate-rich deposition following major volcanic eruptions (Hammer *et al.*, 1980). Maximum correlation occurs where the varve record lags the ice-core acidity record by three years (r = 0.236, $p < 0.0001$ for 1500–1970, and r = 0.437, $p < 0.0001$ for 1800–1970). An association also occurs between sulphate outliers in the GISP2 ice-core record (Zielinski, 1995) and the major Nicolay Lake rainfall events, although the ice-core record is complicated by twentieth-century anthropogenic sulphate emissions. Prior to the twentieth century, correlation

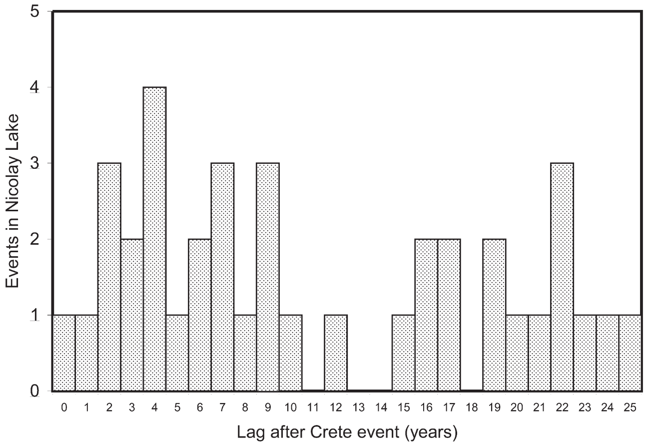

Figure 7 Histogram indicating the occurrence of major rainfall-induced sedimentation events in Nicolay Lake in the years following major acidity peaks in the Crête ice-core record (Hammer *et al.*, 1980). Major peaks were defined as the largest 5% of each series (see Figure 3).

between the two records is not statistically significant (Figure 6). Given the episodic nature of both the volcanic aerosol deposits in the ice cores and the deposition of rainfall-induced sedimentary units, the use of correlation tests is significantly limited.

We further tested the correlation between rainfall events in Nicolay Lake and acidity outliers in the Crête ice-core record by analysing the temporal associations between the records to determine whether the major outliers found in each series showed evidence of clustering together. Major outliers were defined as the largest 5% of each sample set (n = 25) and varve outliers were identified for each 25-year period following the Crête outliers. The results indicate that major events in the Nicolay Lake were more frequent in the nine years following Crête outliers (n = 21) than they were during the full 25-year lag period (n = 38) (Figure 7), suggesting a correlation between the events in each series, albeit with varying lag times. The major events in both series were synchronous in only one case (AD 1602). Because we do not know the theoretical probability relationship between the two series, we used a Monte Carlo simulation technique to determine whether the observed clustering of rainfalls following eruptions departs significantly from what might occur when compared to two random series of the same length, each containing a given number of large events. To simulate the occurrence of acidity and sediment yield outliers, our algorithm generated two 500-year time-series, each containing 25 randomly placed events (Willis *et al.*, 1996). Lag associations were calculated for 1000 paired random series to generate an empirical probability distribution to compare with the observed time series, in which 21 of the varve outliers occurred in the nine years following the acidity outliers. In the simulations, the mean number of occurrences of varve outliers within nine years after an acidity outlier was 12.4 (standard deviation 3.6). There were only 18 instances where 21 or more varve outliers occurred in the first nine years after an acidity outlier. Thus, the probability by chance that 21 or more of the 25 largest rainfall events would occur within nine years of a major acidity peak is 0.018. Therefore, we conclude that the observed correlation between the Crête and Nicolay Lake outliers is highly significant and that there is a regional mechanism that links the two records.

In general, most outliers in the Crête record lead major sedimentary events, although the magnitude of response is not linear through time. This is evident between 1560 and 1660, when large acid deposition peaks correspond to relatively small rainfall-sedimentation events (Figure 3). This discrepancy is in part probably due to higher background levels of acidity in the Crête record from non-volcanic sources (Crowley *et al.*, 1993). However, the rainfall response to the two largest eruptions during the past five centuries (Huaynaputina, Peru, in 1600 and Tambora in 1815) is especially large (Figure 3). Of the major eruptions indicated by the ice-core record, only the 1784 Laki event appears not to have generated one or more major subannual rhythmites in the varve record at Nicolay Lake. However, the Laki eruption is considered to be over-represented in the Greenland cores (Hammer *et al.*, 1980; Zielinski, 1995) and other proxy-records suggest that the late 1700s were relatively warm (Overpeck *et al.*, 1997), possibly due to increased solar irradiance (Lean *et al.*, 1995).

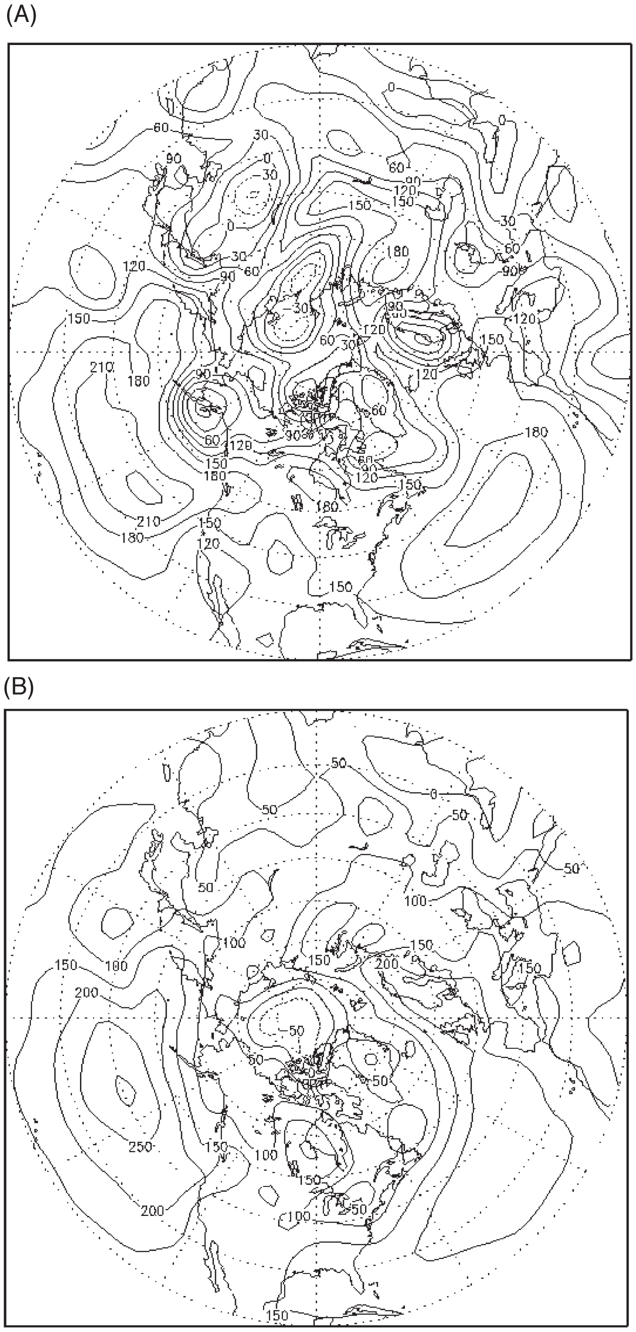

Figure 8 Surface pressure anomaly maps (1000 mb, 00Z) for rainfall events that occurred on (A) 14 August 1951 and (B) 19 July 1996. Both indicate low pressure located over the northwest Arctic Archipelago and additional low pressure anomalies migrating southeast across the Arctic Ocean. Contours are in metres and dashed contours indicate negative anomalies (source: U.S. NWS, CDAS reanalysis).

More recently, cold-wet synoptic systems were more frequent during the 1960s and early 1970s (Bradley and England, 1979) following the 1963 Mount Agung eruption – the only major volcanic eruption to occur during the early instrumental weather

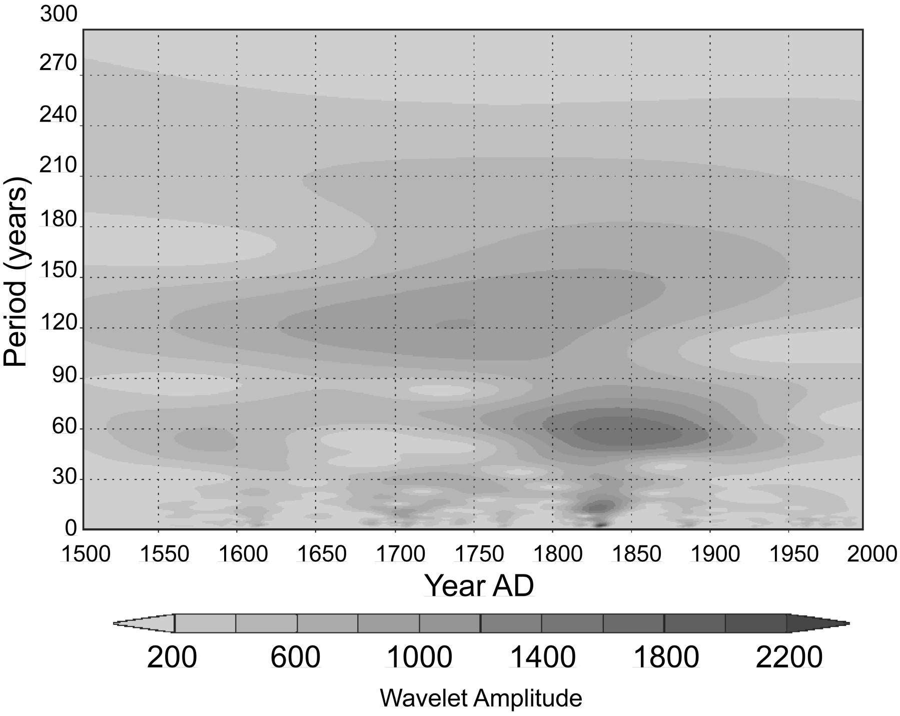

Figure 9 Time-frequency plot of wavelet amplitude for the Nicolay Lake sediment yield record.

record in the Canadian High Arctic. This coincides with increased rainfall-induced sedimentation in Nicolay Lake. Although there does not appear to be a response to every major volcanic eruption, this is hardly surprising given the localized hydrological controls that can prevent the deposition of a rainfall-induced sedimentary event (e.g., soil moisture conditions).

Synoptic conditions producing summer rainfall

Explaining the record of major summer rainfall events in Nicolay Lake requires considering the synoptic weather conditions that lead to rainfall in the region. Due to the aridity of the Canadian High Arctic, heavy summer rainfall is uncommon. At the Isachsen weather station (Figure 1), the largest daily rainfall recorded during the 30-year operation period (1948–78) was 20 mm on 14 August 1951. Analysis of synoptic weather types indicates that a variety of precipitation-bearing situations can occur in the Canadian High Arctic (Bradley and England, 1979). However, the record 1951 rainfall was produced by a surface low moving southeast across the islands from the Arctic Ocean (Figure 8). Similarly, prolonged rainfall in 1996 (estimated at >30 mm in 24 hours) at Nicolay Lake was generated by the slow passage of a low from the northwest at temperatures slightly above freezing (Figure 8). Considering glacier mass balance on the Devon Island Ice Cap (Figure 1), Alt (1987) suggested that similar weather systems resulted in summer snow accumulation, melt suppression and a lack of melt features in the ice cores. The elevation difference between the Devon ice cap (*c*. 500–2000 m) and the Nicolay Lake catchment (0–160 m) is substantial; therefore, it is reasonable to conclude that precipitation-bearing systems moving southeast through the High Arctic could produce rainfall at lower elevations and snow at higher elevations. Observations during the 1996 rainfall at Nicolay Lake showed that the freezing level was at approximately 130 m above sea level. However, the majority of the watershed was below this level and the flood response to the rainfall moved substantial amounts of sediment (Lamoureux, 2000). Therefore, our record of rainfall is consistent with the ice-core records indicating summer snow accumulation and decreased melt at the drilling sites (Figure 5). The low-pressure systems that generate the High Arctic precipitation events typically originate in the North Atlantic or Barents Sea and are diverted into the Arctic Basin by blocking in the North Atlantic and over Novaya Zemlya (Alt, 1987). Hence, our observations in Nicolay Lake indicate an increased incidence of cyclonic weather systems originating outside the Arctic Basin.

Wavelet analysis of the Nicolay Lake sediment yield record suggests further linkages with southern climate patterns during the nineteenth century through increased instances of storm penetration into the Canadian Arctic Islands. Peaks in both low (*c*. 60 years) and high frequency (2–5, 10–15 years) bands during the early 1800s correspond to the most frequent rainfall events (Figure 9). All of these frequencies have been associated with hemispheric-scale climate variability in various instrumental and proxy climate records (e.g., Schlesinger and Ramankutty, 1994; Mann *et al.*, 1995). However, because these periodicities are dominant only in the 1800s, when major rainfall was most frequent at Nicolay Lake, we suspect that the spectral signal indicates an increased influence of southern weather systems during this interval, leading to the short period of spectral coherence. During this same period, global dendroclimatic records show a reduced correlation with other climate-forcing mechanisms (solar insolation, CO_2) and a small increase in correlation with the volcanic dust veil index (Mann *et al.*, 1998). Moreover, the *c*. 60-year spectral signal in the 1800s and the weaker *c*. 120-year signal between 1650 and 1900 (Figure 9) are especially intriguing given the similar timescales for the grouping of volcanic events in GISP2 (Zielinski, 1995). Although these linkages are speculative, they do provide some additional support for our hypothesis of a volcanic forcing in the Nicolay rainfall record.

Volcanic influence on temperature and precipitation proxy-records

The rainfall proxy climate record from the Nicolay Lake varves differs from temperature records that commonly show a short-lived, immediate response to volcanic eruptions (Kelly and Sear, 1984; Rampino and Self, 1984; Sear *et al.*, 1987; Bradley, 1988). Other studies have shown that the response to individual eruptions is complicated by competing ENSO effects on temperature (Mass and Portman, 1989) and by the different location and season of each eruption (Kelly *et al.*, 1996). However, localized temperature decreases do occur between 1 and 12 months after major eruptions and may be discernible for several years (Sear *et al.*, 1987). Tree-ring records show widespread cooling in the year following documented eruptions (Briffa *et al.*, 1998), and decadal periods of growth reduction in some records suggest that the effects can last much longer (LaMarche and Hirschboeck, 1984; Scuderi, 1990; Briffa *et al.*, 1998). The record from Nicolay Lake suggests changes in synoptic conditions for up to nine years. However, the rainfall response is not necessarily immediate, as found in temperature proxies, but is subject to the vagaries associated with precipitation. The occurrence of large rainfall events during subsequent years indicates that weather conditions in the Arctic became more conducive for heavy rainfall for an extended period. Increased storminess in the years following volcanic events has been noted in other records (e.g., Dawson *et al.*, 1997), although the exact mechanisms remain poorly understood.

Conclusions

A 500-year record of varved sedimentation in Nicolay Lake indicates that increased summer rainfall during the LIA was related to volcanic activity. Broadly, these results suggest that volcanic events not only occasioned summer cooling but also increased precipitation in this part of the Arctic. In addition to substantiating previous climate-volcanic associations, our results highlight the potential for identifying major meteorological events through the use of high-resolution sedimentary records. The application of these methods to other regions may provide useful independent evidence for the linkages between external forcing mechanisms and climatic variability.

Acknowledgements

We thank C. Hammer for providing the Crête acidity data. This work was supported by an NSERC grant (A6880) to JE, the Royal Canadian Geographic Society, the Canadian Circumpolar Institute and the Northern Scientific Training Program. The Polar Continental Shelf Project (PCSP), Natural Resources Canada, provided field logistics. Field assistance by J. Barker, C. Coburn, L. Lamoureux, K. Maleski, M. Munro-Stasiuk and M. Skidmore is gratefully acknowledged. SFL acknowledges support by an NSERC postgraduate scholarship and an Alberta Heritage scholarship. Two anonymous reviewers provided helpful comments.

References

Alt, B.T. 1987: Developing synoptic analogs for extreme mass balance conditions on Queen Elizabeth Island ice caps. *Journal of Climate and Applied Meteorology* 26, 1605–23.

Alt, B.T., Koerner, R.M., Fisher, D.A. and **Bourgeois, J.C.** 1985: Arctic climate during the Franklin era, as deduced from ice cores. In Sutherland P.D., editor, *The Franklin era in Canadian Arctic history 1845–1859*, Archaeological Survey of Canada Paper no. 131, 69–92.

Bradley, R.S. 1973: Recent freezing level changes and climatic deterioration in the Canadian Arctic Archipelago. *Nature* 243, 398–400.

—— 1988: The explosive volcanic eruption signal in northern hemisphere continental temperature records. *Climatic Change* 12, 221–43.

Bradley, R.S. and **England, J.** 1978: Influence of volcanic dust on glacier mass balance at high latitudes. *Nature* 271, 736–38.

—— 1979: Synoptic climatology of the Canadian High Arctic. *Geografiska Annaler* 61A, 187–201.

Briffa, K.R., Jones, P.D., Schweingruber, F.H. and **Osborn, T.J.** 1998: Influence of volcanic eruptions on Northern Hemisphere summer temperature over the past 600 years. *Nature* 393, 450–54.

Crowley, T.J., Criste, T.A. and **Smith, N.R.** 1993: Reassessment of Crete (Greenland) ice core acidity/volcanism link to climate change. *Geophysical Research Letters* 20, 209–12.

Dawson, A.G., Hickey, K., McKenna, J. and **Foster, I.D.L.** 1997: A 200-year record of gale frequency, Edinburgh, Scotland: possible link with high-magnitude volcanic eruptions. *The Holocene* 7, 337–41.

Fisher, D.A. and **Koerner, R.M.** 1994: Signal and noise in four ice-core records from the Agassiz Ice Cap, Ellesmere Island, Canada: details of the last millennium for stable isotopes, melt and solid conductivity. *The Holocene* 4, 113–20.

Hammer, C.U., Clausen, H.B. and **Dansgaard, W.** 1980: Greenland ice sheet evidence of post-glacial volcanism and its climatic impact. *Nature* 288, 230–35.

Kelly, P.M. and **Sear, C.B.** 1984: Climatic impact of explosive volcanic eruptions. *Nature* 311, 740–43.

Kelly, P.M., Jones, P.D. and **Pengqun, J.** 1996: The spatial response of the climate system to explosive volcanic eruptions. *International Journal of Climatology* 16, 537–50.

LaMarche, V.C. Jr and **Hirschboeck, K.K.** 1984: Frost rings in trees as records of major volcanic eruptions. *Nature* 307, 121–26.

Lamb, H.H. 1970: Volcanic dust in the atmosphere; with a chronology and assessment of its meteorological significance. *Philosophical Transactions of the Royal Society of London* 226, 425–533.

Lamoureux, S.F. 1999a: Catchment and lake controls over the formation of varves in monomictic Nicolay Lake, Cornwall Island, Nunavut. *Canadian Journal of Earth Sciences* 36, 1533–46.

—— 1999b: Spatial and interannual variations in sedimentation patterns recorded in nonglacial varved sediments from the Canadian High Arctic. *Journal of Paleolimnology* 21, 73–84.

—— 2000: Five centuries of interannual sediment yield and rainfall-induced erosion in the Canadian High Arctic recorded in lacustrine varves. *Water Resources Research* 36, 309–18.

Lamoureux, S.F. and **Bradley, R.S.** 1996: A late Holocene varved sediment record of environmental change from northern Ellesmere Island, Canada. *Journal of Paleolimnology* 16, 239–55.

Lean, J., Beer, J. and **Bradley, R.** 1995: Reconstruction of solar irradiance since 1610: implications for climate change. *Geophysical Research Letters* 22, 3195–98.

Mann, M.E., Bradley, R.S. and **Hughes, M.K.** 1998: Global-scale temperature patterns and climate forcing over the past six centuries. *Nature* 392, 779–87.

Mann, M.E., Park, J. and **Bradley, R.S.** 1995: Global interdecadal and century-scale climate oscillations during the past five centuries. *Nature* 378, 266–70.

Mass, C.F. and **Portman, D.A.** 1989: Major volcanic eruptions and climate: a critical evaluation. *Journal of Climate* 2, 566–93.

Overpeck, J., Hughen, K., Hardy, D., Bradley, R., Case, R., Douglas, M., Finney, B., Gajewski, K., Jacoby, G., Jennings, A., Lamoureux, S., MacDonald, G., Moore, J., Retelle, M., Smith, S., Wolfe, A. and **Zielinski, G.** 1997: Arctic environmental change of the last four centuries. *Science* 278, 1253–56.

Rampino, M.R. and **Self, S.** 1984: Sulphur-rich volcanic eruptions and stratospheric aerosols. *Nature* 310, 677–79.

Schlesinger, M.E. and **Ramankutty, N.** 1994: An oscillation in the global climate system of period 65–70 years. *Nature* 367, 723–26.

Scuderi, L.A. 1990: Tree-ring evidence for climatically effective volcanic eruptions. *Quaternary Research* 34, 67–85.

Sear, C.B., Kelly, P.M., Jones, P.D. and **Goodess, C.M.** 1987: Global surface-temperature responses to major volcanic eruptions. *Nature* 330, 365–67.

Smith, N.D. 1978: Sedimentation processes and patterns in a glacier-fed lake with low sediment input. *Canadian Journal of Earth Sciences* 15, 741–56.

Willis, I.C., Richards, K.C. and **Sharp, M.J.** 1996: Links between proglacial stream suspended sediment dynamics, glacier hydrology and glacier motion at Midtdalsbreen, Norway. *Hydrological Processes* 10, 629–48.

Zielinski, G.A. 1995: Stratospheric loading and optical depth estimates of explosive volcanism over the last 2100 years derived from the Greenland Ice Sheet Project 2 ice core. *Journal of Geophysical Research* 100, 20937–55.