Long-term perspectives on High Arctic climate from lake sediments

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ABSTRACT

Hydrological records from High Arctic watersheds are invariably short. Records of runoff and sediment flux, and associated meteorological conditions are rarely longer than a few seasons, and commonly do not cover entire melt seasons. A longer-term perspective is needed. Lake sediments can help in assessing hydrological change on multi-decadal to centennial scales, though there are many uncertainties. Process-based studies are needed to link discharge and sediment flux to meteorological conditions, and to sediment deposition with a lake basin. Such studies provide the insight necessary to interpret changes that have occurred in the past, as observed in lake sediments. Large deep lakes in the Canadian High Arctic form end-members in the spectrum of lacustrine systems in the northern hemisphere. Lake ice cover is thick (1.5-3m) and persistent, often only melting around the margins each year. Consequently, limnological conditions are characterized by limited mixing, often leading to anoxic conditions at depth, at least seasonally. This results in minimal disturbance at the sediment-water interface, and the accumulation of annually laminated (varved) sediment. Such sediments provide an excellent chronological record. Studies of different facies in sediment cores enable the relationship between hydrological conditions in the watershed and sediment deposition in the lake to be established. We report on studies of sediment cores from South Sawtooth Lake (central Ellesmere Island, Nunavut, Canada), in which we identified sedimentary features related to summer rainfall events. These were used to assess how the frequency of summer rainfall events has changed over the last ~2700 years, thereby placing contemporary changes in a long-term perspective.

KEYWORDS

Varves, paleoclimate, lakes, rainfall, Canadian Arctic

1. INTRODUCTION

Long-term meteorological records from the Arctic are rarely more than 50 years in duration, making it difficult to place contemporary climatic conditions in a long-term perspective. Furthermore, most weather stations are located in coastal locations, close to sea-level, so they do not adequately represent upland and interior locations of the Arctic. Hydrological records are even shorter than meteorological records, so the problem of perspective is compounded when it comes to an understanding of how hydrological systems may have responded to long-term changes in climate. Lake sediments offer a possible solution to this dilemma. The type and amount of sediment transported to lakes carries with it information about meteorological and hydrological conditions in the lake watershed. For each lake basin, the amount of clastic material eroded from the watershed and carried by rivers and streams into lakes is related to the energy available for stream transport. This is a function of precipitation amount (winter snow accumulation and summer rainfall) as well as the rate of snow melt in the spring, which is related to temperature. The amount of biogenic material deposited in a lake is related to biological activity in the watershed, and in the lake itself, which is in turn related to nutrient transport via rivers and streams and the amount of ice on the lake (which affects light penetration), and these factors are again related to temperature and precipitation conditions in the watershed. That said, the relationship between sediment deposition and climate is far from simple; complications arise due to conditions within the lake (which may lead to complex depositional and erosion patterns) and to changing geomorphological conditions within the watershed (including sediment slumps due to slope failures, changes in glacial morphology, catastrophic drainage events unrelated to climate etc). Thus, what might start out as a seemingly simple relationship (snowfall-melt-runoff-sediment transport-deposition) quickly becomes a complex multivariate problem, with positive and negative feedbacks and interactions that might be quite non-linear. Nevertheless, the potential rewards for deciphering this complexity are great, and this has led to numerous studies of lake sediments from Arctic lakes aimed at reconstructing some aspect of past climate or hydrological history (e.g. Lamoureux et al., 2006; Kaufman et al., 2009).

Over the last ~20 years, we have undertaken a number of studies in the Canadian High Arctic, focused on lakes that have an annually laminated (varved) sediment record. In each of these lakes, we have made hydrological, limnological and meteorological measurements so as to better understand the processes involved in varve deposition, and the relationship between climatic conditions, runoff and sediment flux to the lake. There are clear differences between the different lake basins that we have studied, calling for "process-based studies" as an essential requirement to properly interpret the varved sedimentary record in each lake (Bradley et al., 1996). Here we illustrate some of these differences, with reference to individual years of observations at Lake C2 (northern Ellesmere Island, 82.83° N; 78.0°W), South Sawtooth Lake (central Ellesmere Island (79. 21° N, 83.54° W) and Sophia Lake (Cornwallis Island, (75.1°N, 93.55°W) Nunavut, Canada (**Figure 1**). We then focus on a specific aspect of the varved record from South Sawtooth Lake, which provides an estimate of how summer rainfall events have varied at that site over the past ~2700 years.

At each lake, a meteorological station was installed and discharge and sediment transport was measured in the main river system entering each of the lakes (for a description of field methods used, see Braun et al.,2000a, 2000b; Hardy et al, 1996; Lewis et al., 2005). **Figure 2** shows the record of temperature and rainfall (upper panels) runoff (middle panel) and suspended sediment flux (lower panel) for each set of observations.

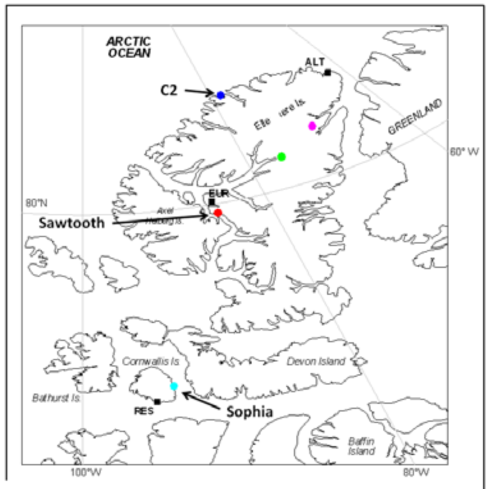

Figure 1. Map of lake study sites, Nunavut, Canada. Locations of long-term weather stations Resolute (RES), Eureka (EUR) and Alert (ALT) are also shown.

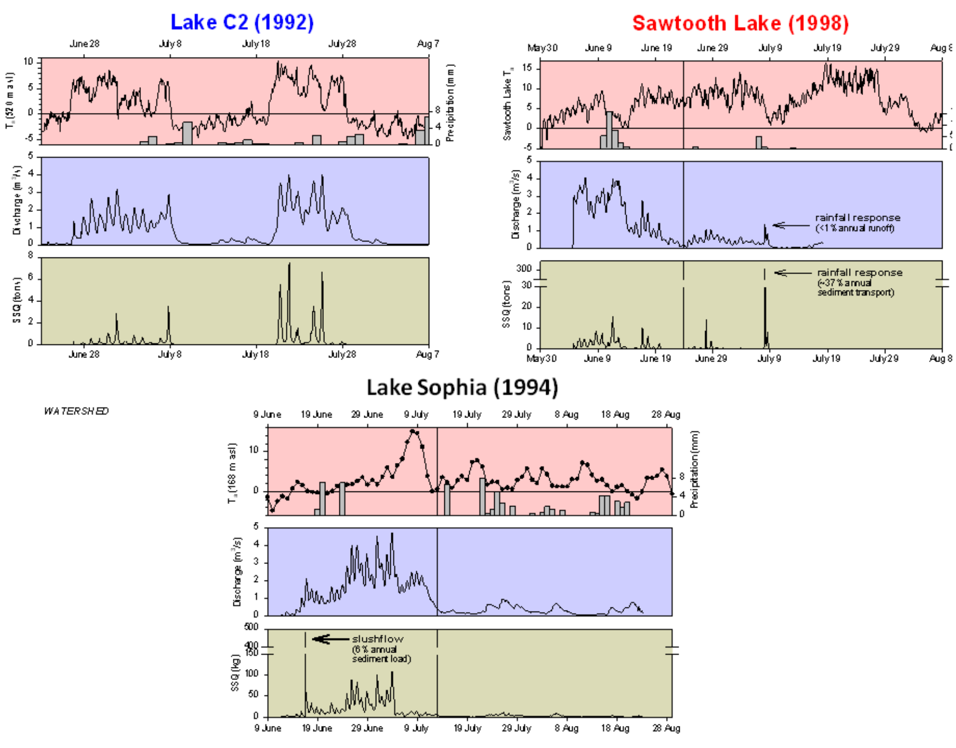

Figure 2. Daily measurements of temperature and precipitation (upper panels), discharge (middle panels) and suspended sediment flux (lower panels) at three sites in the Canadian High Arctic.

At Lake Sophia, discharge and sediment flux are closely linked to temperature, so that runoff began almost as soon as temperatures rose above the freezing point, and a great deal of sediment was transported to the lake in the initial snowmelt flood. In fact, most of the total annual suspended sediment flux to the lake had occurred within the first 2-3 weeks of the melt season beginning (Braun et al., 2000a). By that time, most of the snow on the landscape had melted and so very little energy was available for sediment transport in the remaining part of the summer. Furthermore, summer rainfall events had little effect on sediment flux to the lake. At Lake C2, discharge was also closely linked to temperature, and so was suspended sediment flux. However, as there are glaciers in the Lake C2 watershed (unlike at Sophia Lake), a continuous supply of meltwater provided the energy to transport sediment throughout the summer, so that sediment flux was closely linked to air temperatures in the upper part of the watershed (Hardy et al., 1996). Summer rainfall events had little direct effect on the volume of sediment transported to the lake. At South Sawtooth Lake, the pattern is again slightly different. Runoff and sediment flux are linked to temperature, though both decline as the season progresses (there are no glaciers in the South Sawtooth watershed, only semi-permanent snowbanks). However, discharge into the lake, and associated sediment flux both increase during summer rainfall events. This led us to undertake a detailed analysis of the South Sawtooth Lake sediments to identify the sedimentary signature of summer rainfall events, and to reconstruct a history of summer rainfall events over the last 2700 years.

South Sawtooth Lake (unofficial name) is the highest of three lakes situated in the Sawtooth Mountain range, Fosheim Peninsula, central Ellesmere Island (**Figure 3**).

Figure 3. South Sawtooth Lake in late spring.

The lake is ~2.6 km^2 in area and has a proximal and a distal basin (100 and 80 m deep, respectively) separated by a 60-m deep sill. The watershed has an area of 47 km^2 with a maximum elevation of ~915 m a.s.l. A single river feeds the lake from the southeast, otherwise runoff to the lake is via overland flow. The region is made up of sandstones (often poorly consolidated) interstratified with calcareous siltstones, and shales, with minor amounts of coal.

Till from former glaciations mantle the surface. The lake is oligotrophic, and ice-covered for most of the year. A narrow moat around the lake margin is commonly the only open water that is visible during the summer, though in some recent years, the ice has completely melted by late summer. Oxygen profiles in the lake reveal that conditions near the sediment water interface in the distal basin are disoxic, which explains why the sediments in the lake are finely laminated and undisturbed by burrowing organisms. This means that annual depositional units (varves) can be distinguished in sediment cores, providing a highly resolved chronostratigraphy for lake sediment deposition (Francus et al., 2002, 2008). By examining thin sections made from the sediment cores (see Francus and Asikainen, 2001) annual sediment thickness can be measured, and SEM images can be processed using image analysis techniques to obtain grain size characteristics for each annual layer and sublayer (Francus, 2004). This approach was used in studies of South Sawtooth Lake sediments, which revealed that the median grain size of each silt layer (see below) is related to the rate of early season snowmelt (Francus et al., 2002).

Figure 4 shows a typical varve sequence from South Sawtooth Lake. Francus et al. (2008) discussed the different sedimentary facies in South Sawtooth Lake sediments; typically, a varve consists of a coarse silt layer grading upwards into a pure clay-rich layer (a “clay cap”) which delineates each annual unit from the previous one (**Figure 5**). However, occasional sand layers are found within the “normal” summer silt layer.

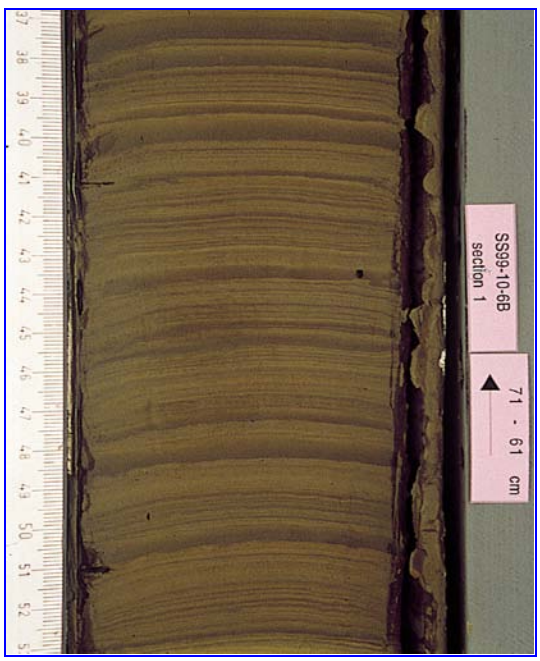

Figure 4. Core section from South Sawtooth Lake (Core SS99-10-6B), showing typical varved sediment sequence (scale in cm at left).

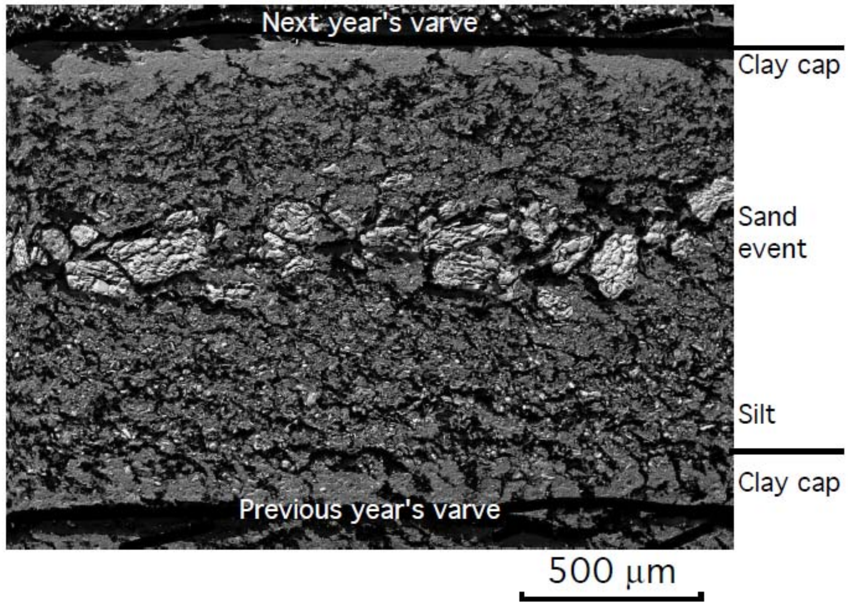

Figure 5. Photograph of an individual varve (seen with a scanning electron microscope in backscattered mode) showing a mid-summer sand deposition characteristic of summer rainfall episodes.

We interpret these facies as the result of sediment-laden density flows along the margins of the lake, resulting from rainfall events. Rain falling on a thin water-saturated active layer on the steep sides of the lake leads to sediment transport via streamlets and slope wash. Although such processes may not be universally applicable (cf. Lamoureux 2000) our observations at South Sawtooth Lake during extended rainfall episodes suggest that this is an important process in this watershed (Lewis et al., 2005). Furthermore, there are also thin graded beds that occasionally occur as sub-units within the summer silt layer. We interpret these as also related to rainfall events, but in those cases rainfall led to a significant increase in river discharge and sediment transport to the lake. This resulted in the transport of sediment via turbulent interflows across the lake basin. Thus together, the sand layers and graded beds identified within varves are indicative of summer rainfall events that were large enough to trigger sediment movement across the landscape and into the lake.

Figure 6 shows the frequency of these features and their resulting thickness in varves spanning the last ~2700 years. It is clear that the frequency of such features is not randomly distributed in time. For example, summer rainfall events were relatively uncommon from ~AD 1435-1650, and they were quite rare in the period from ~30-180B.C.

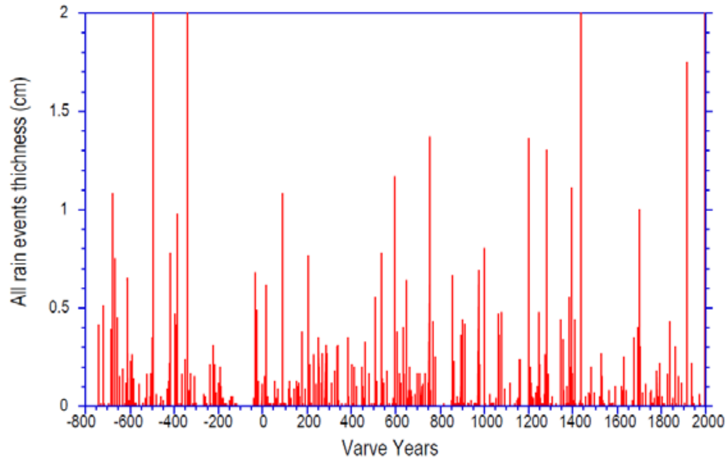

Figure 6. Time series of "intra-varve" sand layers and graded beds in sediments of South Sawtooth Lake, indicative of summer rainfall events.

To emphasise the temporal variations in summer rainfall event frequency, **Figure 7** shows the same date grouped by decade, with values ranging from 0 to 1, such that a rainfall event in every year would receive a value of 1, and no occurrences would be ranked zero. This shows that ~340-420 B.C., ~A.D. 0-200, ~A.D. 600-750, ~A.D.1000-1400, and ~A.D.1950-2000 were the periods with the most summer rainfall events. Furthermore, the most recent 50 years had the highest frequency of summer rainfall events in the entire ~2700 year period.

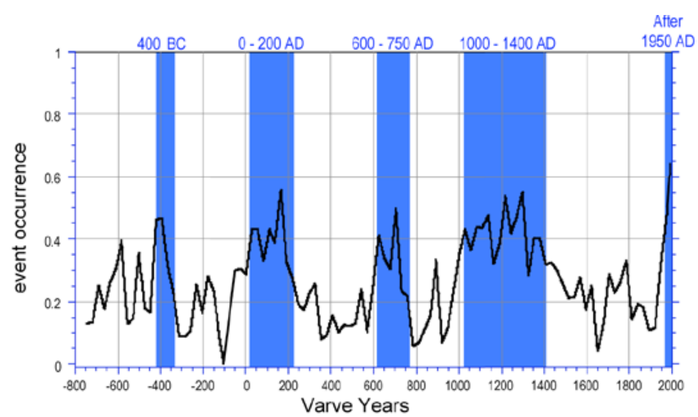

Figure 7. Frequency of rainfall events per decade (1 = all years per decade, 0= no years per decade). Periods with the highest frequency of summer rainfall events are highlighted in blue.

It is interesting that the record of summer rainfall events over the past 1000 years follows a fairly common trajectory, often seen in paleotemperature records, with a higher frequency of events in Medieval time (*sensu lato*) declining to a low frequency in the 17th and 19th centuries, followed by a sharp rise in the late 20th century. Although there are few longer-term records with which this series can be compared, there are close similarities to the nearby summer temperature reconstruction of Cook et al (2009) from Murray Lake (northeastern Ellesmere Island) for the past ~800 years, but before that the correspondence is poor. However, summer rainfall events result from relatively rare synoptic episodes which advect moist air into the High Arctic, leading to significant amounts of rainfall in this polar desert region. There is thus no strong reason to expect that such conditions are related to *overall* mean summer temperatures. Furthermore, it is clear that our identification of "summer rainfall events" is only qualitative, in that we are not able to link the thickness of each sand layer (or graded bed) to the amount of rainfall which triggered the sedimentary episode. This would be a worthy goal of future monitoring within the lake, linking sediment deposition (using sediment traps) to real-time meteorological monitoring. Given the difficulties and expense of operating a monitoring program for an extended period in the High Arctic, any work of this sort should be linked to modeling studies that can make the best use of a limited set of observational data.

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