Analysis of Varved Sediment and Weather Relationships in Lake Linnè, Svalbard

Honors Thesis for the Department of Geology
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Abstract

The recent debate involving climate change has become increasingly important in the past decade. Arctic environments are important locations for study as they are particularly sensitive to climate variations. Proglacial lake sediments, particularly varves, such as those found at Lake Linnè, on the island of Spistbergen, Svalbard, demonstrate this sensitivity as they are driven by glacial ablation. The correlation of cores from different lake locations has served to identify and discard inconsistencies in the varve record. The relationship between measured varve thickness and weather parameters is based on meteorological records for the past century, and demonstrates the responsiveness of varves to changes in climate and weather as glaciers are sensitive to these changes. The measuring and counting of varves allows the construction of a chronology which can therefore serve as a climate proxy for Svalbard for the past century. The varve analysis from this study reveals the complexity of the sedimentation in Lake Linnè, and attempts to define the other likely factors which contribute to varve deposition. Overall, the assembled climate relationships reveal varves which can be linked to changes in weather and climate patterns, and the possibility of increased sensitivity of the Lake Linnè proglacial system to climate change.

Introduction

Modern climate change has become one of the most popular topics of both scientific and political discussion during the past few decades. The questions over its occurrence, its causes and how it will ultimately affect the planet in the coming years are the topics of much debate. Scientific studies and international panels in recent years have revealed not only global anomalies in climate and temperatures as humans continue to release CO_2 and other greenhouse gases, but also how polar regions such as the high arctic are particularly sensitive to these changes. The study and observation of these climate changes in the Polar Regions is therefore important to understanding the larger global changes that are occurring today. It is also understood that glaciers act particularly sensitively to climate changes; they experience large periods of retreat and re-advance with oscillations during warm and cold periods in climate due to changes in their ablation or meltwater production (Lowell 2000). Because of this response to climate change, glaciers can provide a sensitive record in sediments eroded and washed by moving ice. The study of these sediments, specifically glacial lake sediments, realized scientific importance when DeGeer in 1910 first classified them as varves. Varves are annual layers of sediment deposited as couplets of fine sand and silt during the summer followed by a winter layer of finer clay particles. Glacial varves can provide a climate proxy record based on their measured thicknesses, as weather and climate conditions experienced by the glacier will theoretically manifest themselves in varve deposits.

This study aims to further the understanding of climate processes in the high Arctic by examining varves from the proglacial Lake Linnè, or Linnèvatnet, located on the island of Spitsbergen, Svalbard. By establishing the link between varve records and climate, it may be possible to determine past climate and weather patterns for the study region. Studying these glacial lake sediments therefore will supplement the existing knowledge on climate change in the region of Svalbard and of the high Arctic region.

The Arctic and Climate Change

Studies of late Holocene climate have shown three climatic regimes that characterize the past millennium (Mann et al 1998). The three regimes are loosely defined in time, as the Medieval Warming Period (MWP), the Little Ice Age (LIA), and the current warming period, which began during the 19^{th} and continued through the 20^{th} century to today (Figure 1). The MWP is generally defined as a period of warming beginning approximately at AD 1000 and continuing through AD 1300. A global temperature anomaly of 0.35 °C warmer (0.03 °C ooler than modern temperatures) than the following LIA indicates a possible global warming phenomenon based on Northern Hemisphere records and an overall dryer climate (Bradley 2003). Linkages between patterns in the North Atlantic Oscillation, solar radiance forcing, and even explosive volcanism (Bradley 2003) may correspond to this warming anomaly and have provided possible triggers. (Figure 1)

The LIA is loosely defined as the years AD 1400 through AD 1850, and is characterized by glacial advances and cool temperatures, and was significantly cooler than the MWP. The LIA also is defined as having a period of wet climate, and its effects are seen in the worldwide advance of glaciers throughout the northern hemisphere (Denton 1977). Reconstruction of past temperatures has shown the LIA to be the coldest interval the last 8000 years, and historical accounts record this generally cooler climate. The LIA is represented globally as well – glaciers in the southern hemisphere also responded to the cooler temperature regime (Thompson 1986).

The arctic environment is particularly susceptible to the effects of climate change. Recent studies have shown the correlation between shrinking sea ice and increasing temperatures in the arctic regions (Figure 2), as observed negative trends from the period of 1979 to 2006 (Serreze 2007). Globally, there has been an overall increase of temperatures: the years 1995 – 2006 ranked among the highest recorded in the instrumental record. The average rise of temperatures worldwide has been measured at .74 °C (IPCC 2007). Temperatures in high arctic latitudes experience changes in climate with greater displacement than the rest of the globe, and temperatures have been increasing over the past half century as well (Kaufman 2009). Additionally, the effects of anthropogenic climate change have recently become the topic of increased scientific focus, citing the increase in temperatures and its link to increased CO_2 levels over the past century (Hansen 2010).

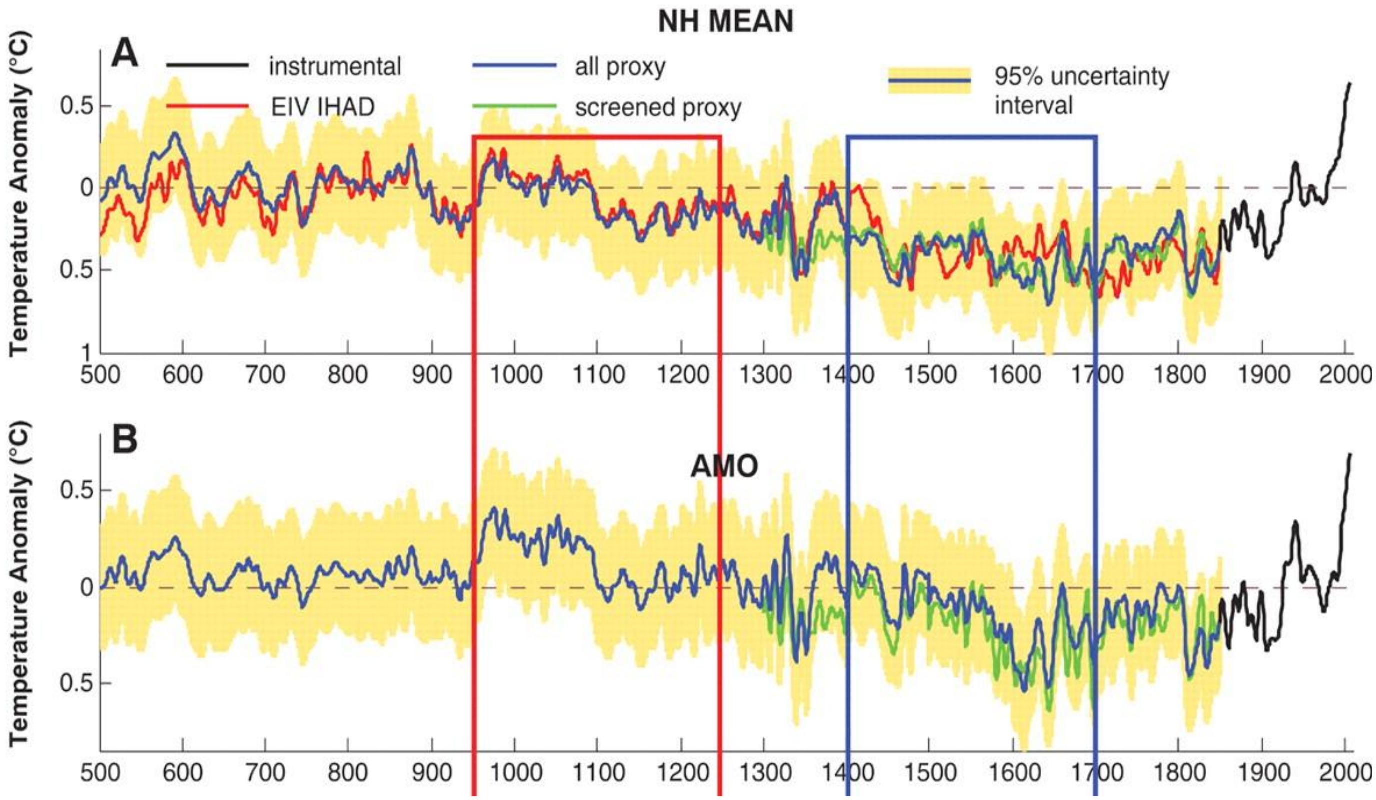

Figure 1. Surface temperature reconstructions have been averaged over (A) the entire Northern Hemisphere (NH), (B) North Atlantic AMO (Atlantic Multidecadal Oscillation) region. The blue box region indicates the LIA, and the red box indicates the MWP. Modified from Mann et al. 2009.

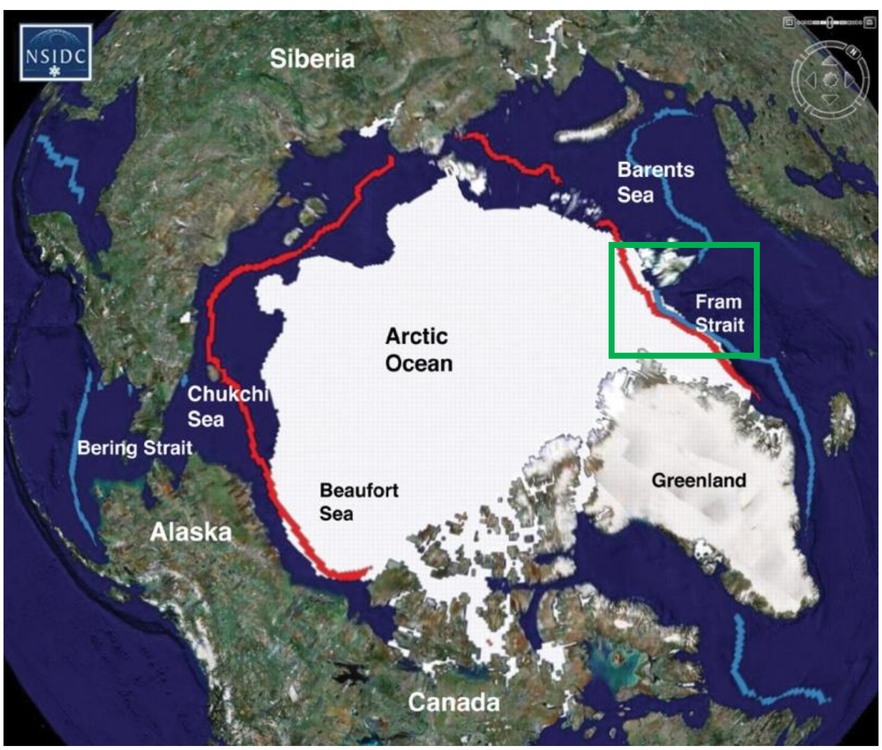

Figure 2. Arctic sea ice extent for the year 2005. Red lines are mean September extents and blue lines represent mean March extents from the period 1979-2006. The Svalbard archielego is highlighted by the green box. From Serreze et al 2007.

Study Area and Geologic Setting

In the summer of 2010, I travelled with 5 other students from the Svalbard REU program to Svalbard, Norway (Figures 3,4). Svalbard is an island archipelago chain located from 74 to 81 degrees N, and 10 to 35 degrees east, off the northern shore of Norway in the Arctic Ocean. Its total landmass is 61,020 km^2. The study area was Lake Linnè, or Linnèvatnet, and it is a proglacial lake located on the largest island of Spitsbergen. The lake is located on the western shore of the island, draining into Spitsbergen's largest fjord, Isfjorden. Lake Linnè is a proglacial lake, fed by the small glacier, Linnèbreen, to the south.

Geology of the Region

Geologically, the lake basin sits in a glacially eroded valley, between a mountain of phyllite and schist rock (the Hekla Hoek Formation) to the west and a Carboniferous carbonate/dolomite complex to the east (Figure 5). The carbonates and dolomites to the east are interbedded with basaltic lava flows. The carbonate rocks in the area show evidence of an active karst system, which potentially drains the lake Kongressvatnet in occasional discharge events that contribute to Lake Linnè (Roof and Werner, personal communication). The glacier and glacial stream erode siltstones, sandstones, and shale to the north, interbedded with tertiary coal beds. Meteoric inwash deltas and fans exist along both the east and west sides of the lake; however, few were observed to be active during the summer of 2010. On the eastern shore of the lake, carbonate red mud deposits from a paleo-marine environment were observed. These paleo-marine sediments show evidence of modern slump features and mass movement, although permafrost structures such as sorted circles and patterned ground indicate a relatively old landscape.

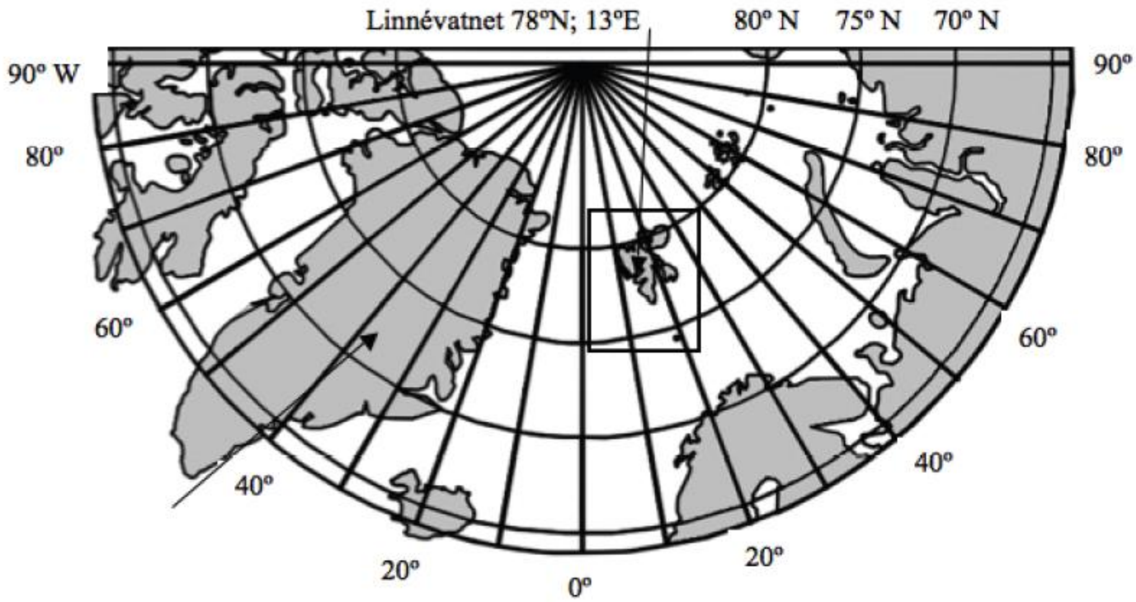

Figure 3. Map of the Arctic Circle. The boxed region represents the Svalbard archipelago. From Nelson 2009.

Figure 4. Nasa LandSAT satellite imagery of Spitsbergen. The box indicates the study area, and the L indicates the town of Longyearbyen. From Arnold 2009.

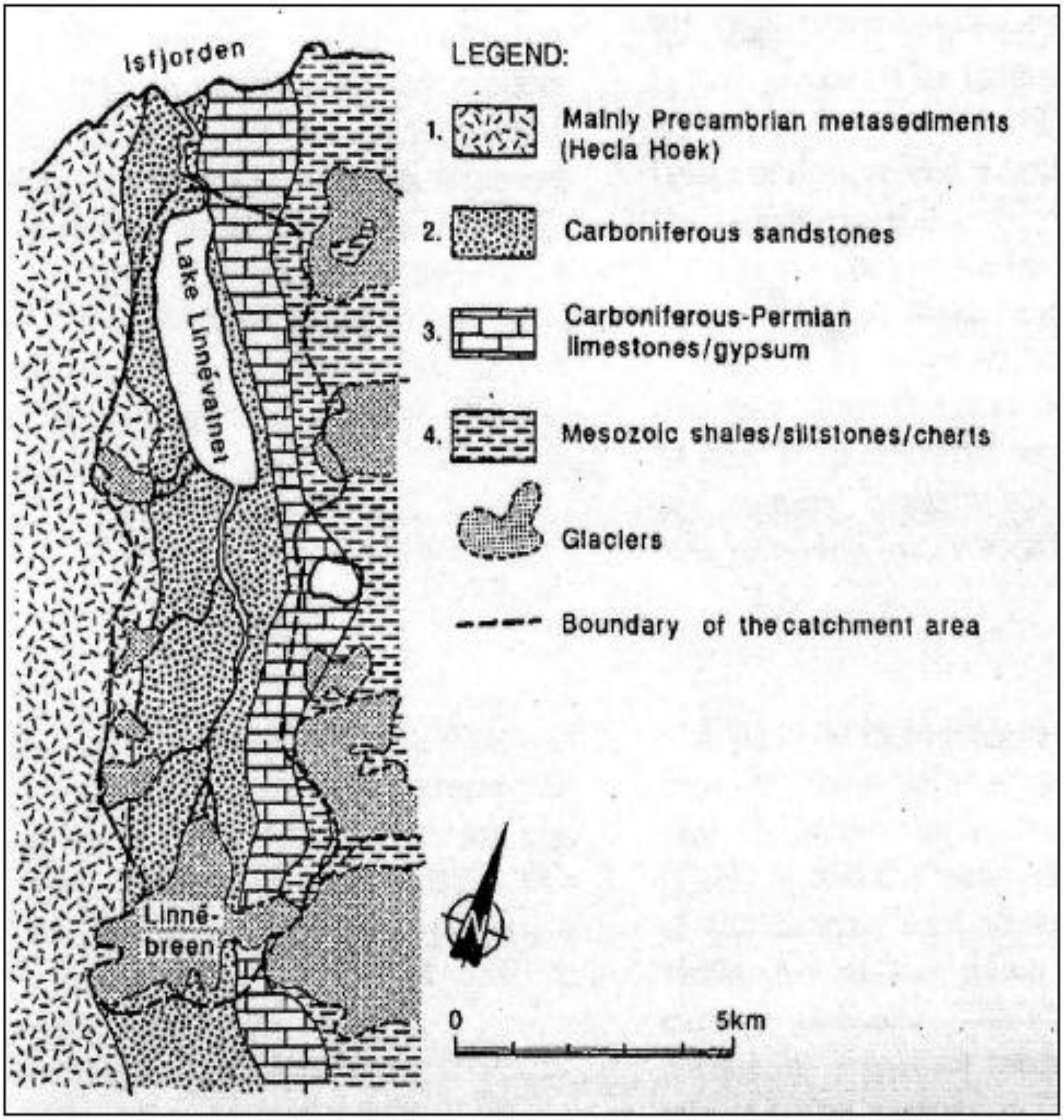

Figure 5. Geologic Map of the study area. Note the glacier Linnèbreen to the south and the Lake Linnèvatnet to the north. From Svendsen 1989.

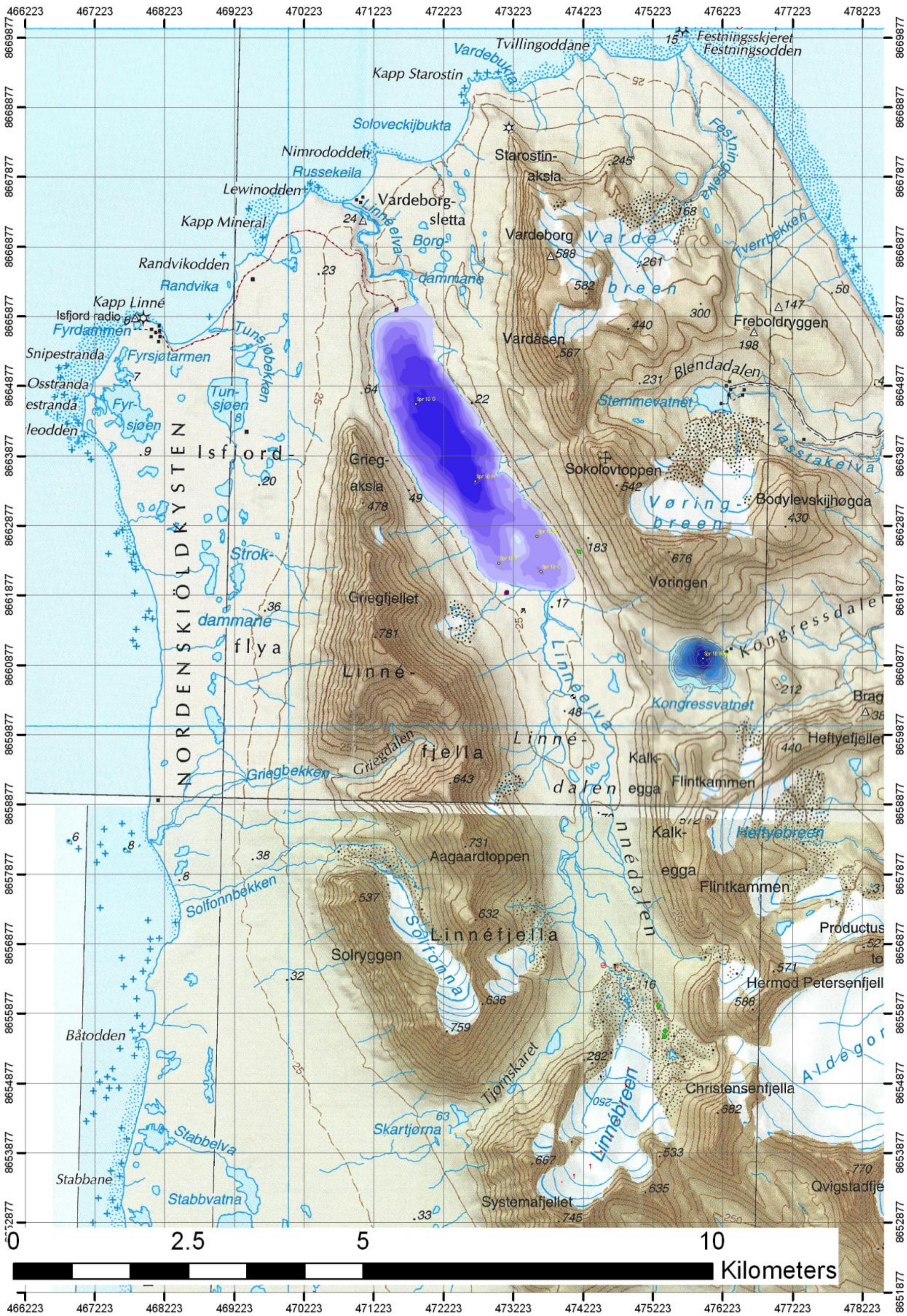

Figure 6. Topographic map of the study area, Linnè Valley or Linnèdalen. Map provided by Steve Roof and Al Werner, 2010.

Figure 7. Aerial photograph of the Linnè valley. The glacier Linnèbreen is to the south of the image and Lake Linnè is to the north.

Glacial and Geomorphic History of the Region

The island of Spitsbergen experienced multiple glacier oscillations during the last ice age. The landscape of Svalbard is dominated by ice caps, which still cover approximately 60% of the landscape (Ingolfsson 2006). In the Kapp Linnè region, Holocene glaciations first occurred between 4400-4000 years BP, with maximum glaciations occuring during the LIA. Multiple glacier oscillations are apparent in the Linnè Valley, most dominantly characterized by the LIA moraine that marks the Linnè glacier's advance (Werner 1989). Approximately 13,000 years BP, the deglaciation of Spitsbergen occurred. In the study area, Linnèdalen was a fjord serving as a tributary to the Isfjord fjord to the north at 12,500 year BP, indicating a deglaciated area. However, following ice recession and relative sea level fall due to isostatic rebound, Lake Linnè was cut off from the ocean by beach sediments deposited by longshore drift creating the lake basin evident today (Svendson 1997) Approximately 5 m of paleomarine sediments underlie 10m of the more recent freshwater sediments deposited since the fjord closure.

The proglacial lake, its glacial inlet stream, Linnèelva, and the glacier Linnèbreen, comprise the REU study region. Linnèbreen is a small alpine glacier with a polythermal glacier regime. Aerial photography from the area available from the 1930s shows the position of the glacier well behind its maximum position at an end moraine from the LIA. Rates of retreat for the glacier since the 1930s are approximately 17 meters per year (Werner and Roof, personal communication), with rates of retreat increasing to around 20 meters per year during the last decade. The modern glacier discharges its meltwater to a glacial stream, which flows northward for approximately 6 km to Linnèvatnet.

Climate of Svalbard

The climate of Svalbard is described as an Arctic polar desert. Mean annual temperatures measured from the town of Longyearbyen are -6 °C at sea level, with colder temperatures of -15.2 °C at higher elevations. Snow is the most common form of precipitation, with the region receiving approximately 400-600 millimeters of total annual precipitation in water equivalencies (Ingolfsson 2006). Measurements from the town of Longyearbyen record summer temperatures ranging from 3 °C to 6 °C , and winter temperatures ranging from -20 °C to -2 °C . Precipitation is highly variable, with the summer months being the most variable from year to year.

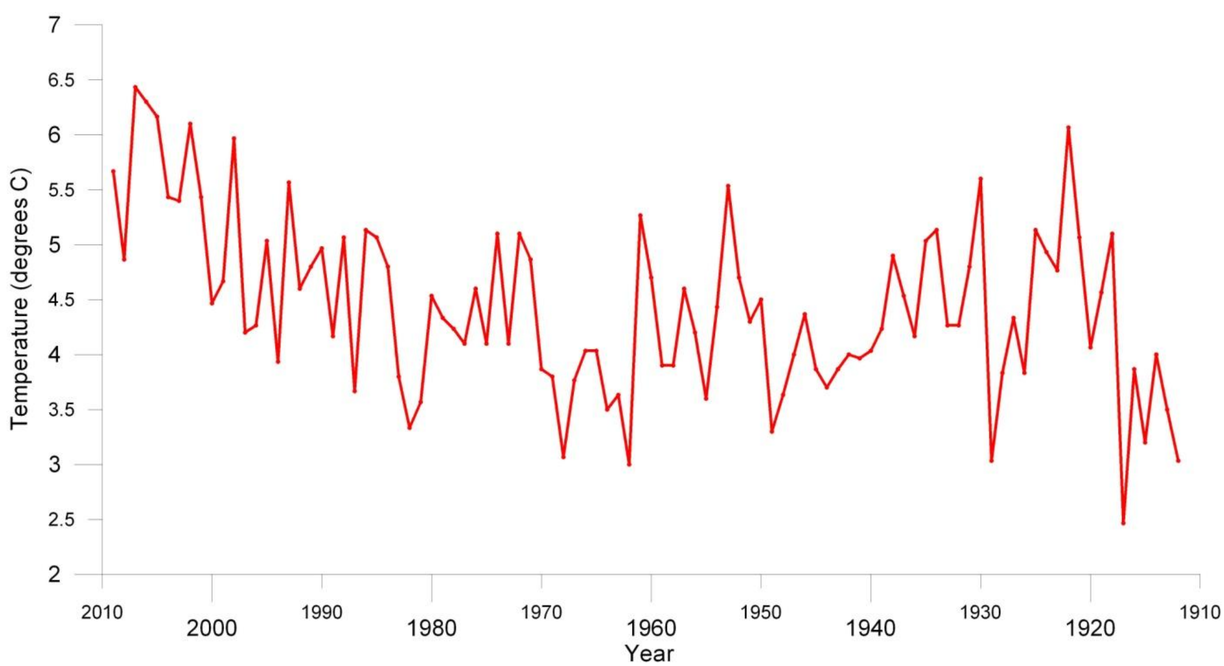

Figure 8. Summer temperature records from Longyearbyen for the period 1912 to present. Note the increasing temperatures from AD 1970 the present. Data from the Norwegian Meteorlogical Survey, assembled 2010.

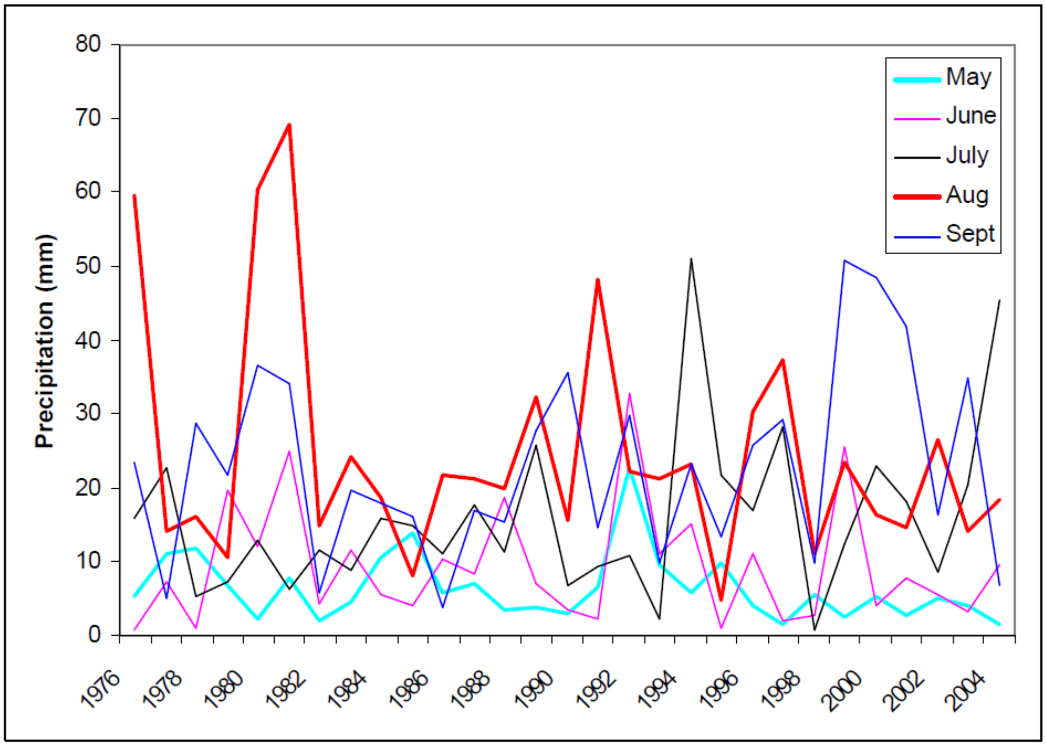

Figure 9. Graph of monthly precipitation from the period of 1976 to 2004. Note the high variability in the summer precipitation, especially August. Data from the Norwegian Meteorological Survey (2004).

Lake Linnè

Lake Linnè (Figure 10,11) covers an approximate surface area of 4.6 km^2, and experiences normal freeze/thaw cycles characteristic of Arctic freshwater lakes. A bathymetric rise splits portions of the southern lake into east and west basins. The east basin is fed by the inlet from Linnèelva, and the western basin is fed from a formerly glaciated cirque basin which is annually covered by a thin snowfield. The depth of the two basins does not exceed 15m. The deep, distal lake basin reaches depths of 30-35 m. Sediment plumes from the inlet stream Linnèelva during the summer have been shown to enter as overflows, interflows, and underflows based on observations of lake water stratigraphy and water temperatures (Zamora Reyes, personal communication). Lake temperatures for the year stay below 4 °C . It is a monomictic lake, covered by ice from November to late June/early July. Sediment traps deployed during each season show varying sedimentation rates, indicating sediment deposition in the lake varies from year to year (Arnold 2009).

The lake sediments of Lake Linnè are laminated, rhythmic couplets of very fine sand to very fine silt and clay representing annual couplets or varves. Lake ice during the winter prevents the agitation of lake water by the wind and inflows to the lake are small, allowing the deposition of winter clay. Beneath the lake floor the depth of varves is approximately 10 m and the varves overlie marine sediments (Svendson 1997).

Studies of lake sedimentation have established the accumulation rates for specific sites located throughout the lake basin. Sediment accumulation rates follow a generally lower rate of accumulation in the distal portions of the lake, and higher rates of accumulation closest to the glacial inlet stream. Grain size also shows a marked decrease distally, as the larger grains are deposited closer to the inlet stream as well (Arnold 2009). Provenance studies show that glacially eroded sediments are carried downvalley by Linnèelva and deposited into the lake (Thomas 2005). Significant mixing of glacial and inwash sediment occurs throughout the meltwater stream, and local inwash contributes sediments into localized areas of the lake basin as well.

Meltwater from glaciers controls the amount of discharge to proglacial geomorphic systems, as glacier ablation is sensitive to changes in climatic and weather conditions. The more melting a glacier experiences annually, the more meltwater a glacier produces. The varved sediment of Lake Linnè has been shown to roughly correlate with weather conditions recorded for the past century (Nelson 2009, Pompeani 2008, Leon 2006). Past studies have taken sediment samples (cores) from the proximal basin and the deep distal basins, and analyzed thickness measurements and total varve (total year) counts for the past millennium. However, these varves have proven difficult to count effectively, as the varves are very thin and clayey throughout with subtle differences between summer and winter units, (Nelson 2009, Pompeani 2008) or are interrupted by intra-annual deposits produced by precipitation or melting events (Leon 2006, Pratt 2006).

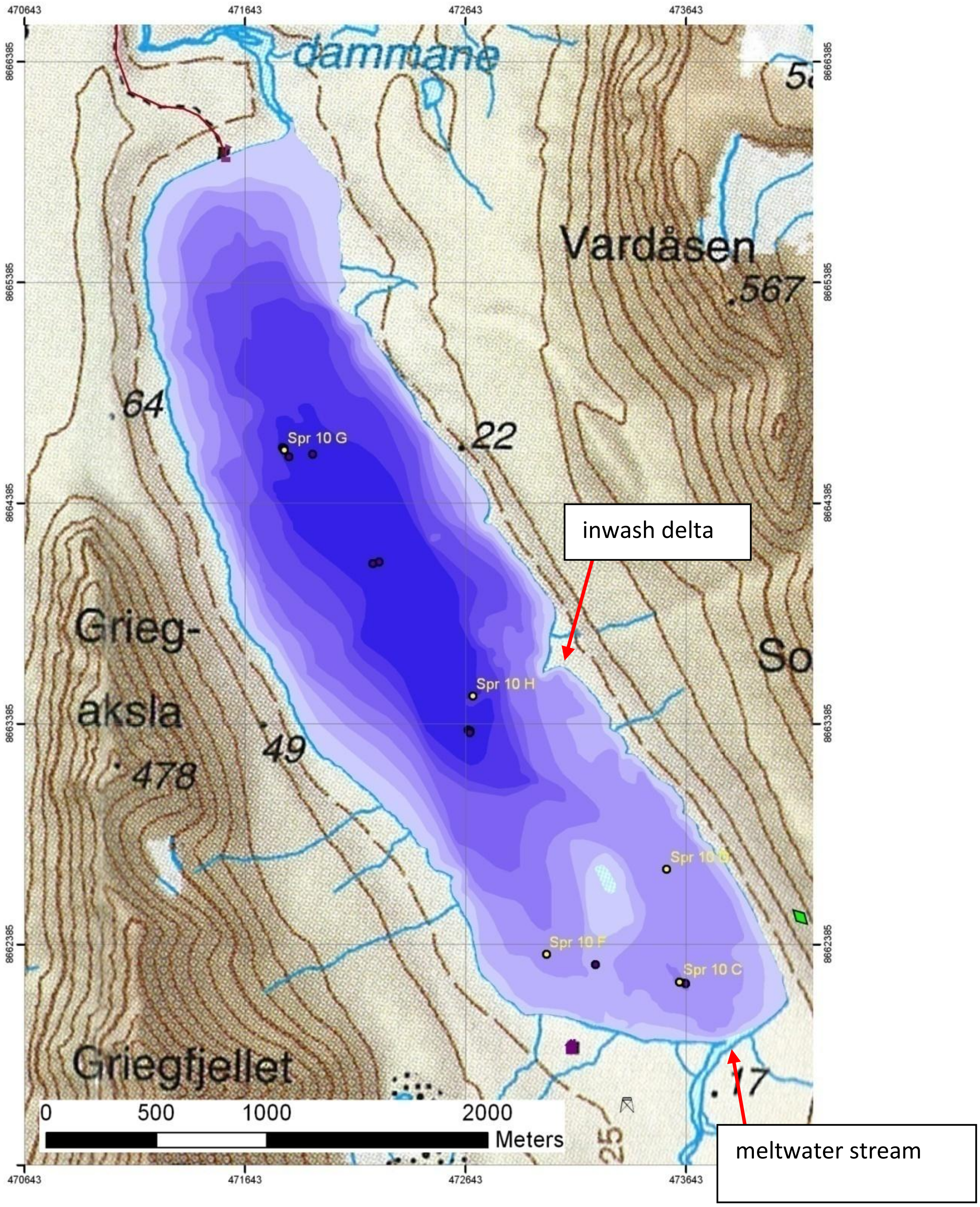

Figure 10. Map of Lake Linnè. Note the mooring sites H and D. Also of note is the delta located northeast of Site H. From Roof and Werner, 2010.

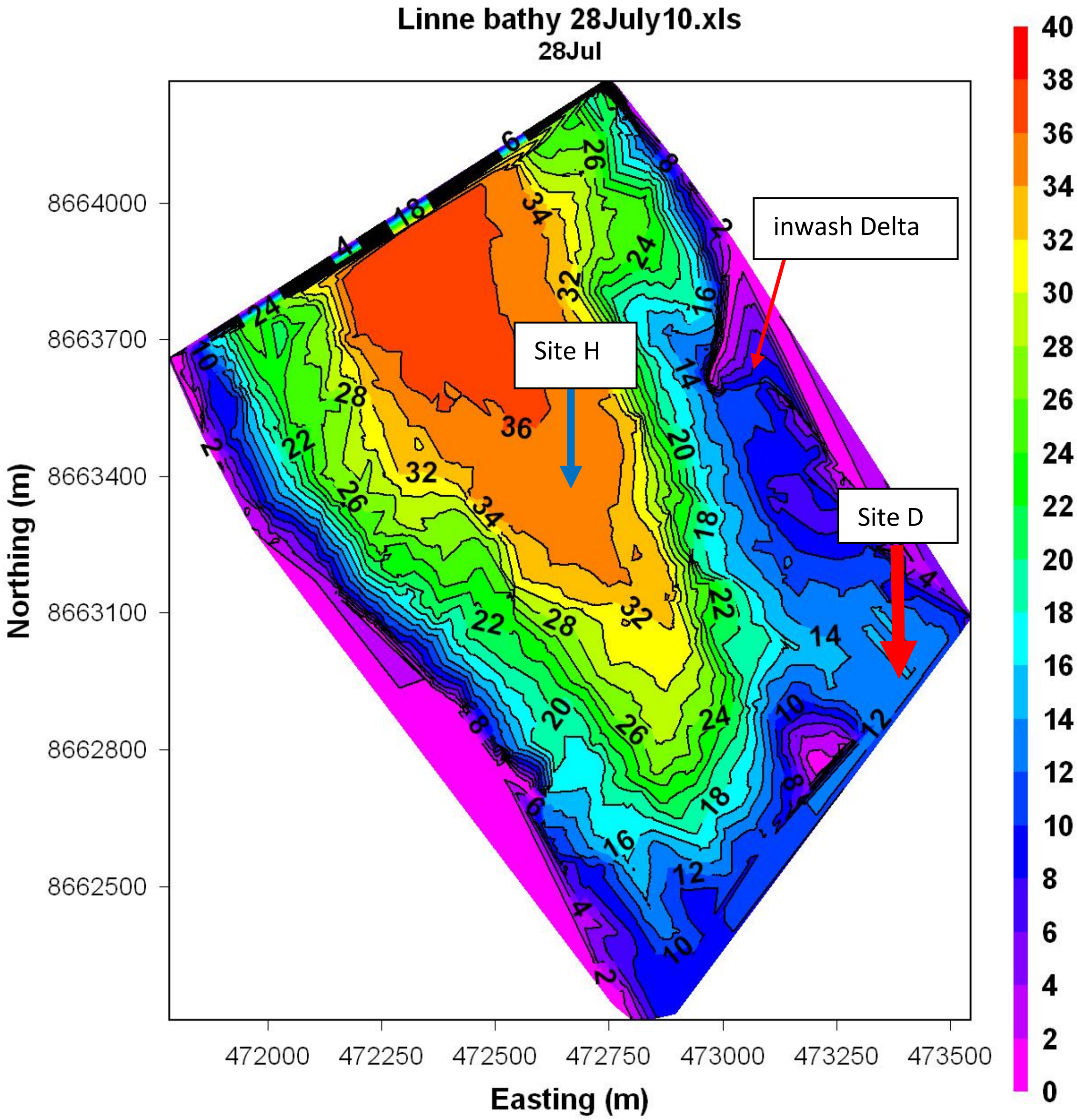

Figure 11. Bathymetric map of the floor of Lake Linnè. The map was created during the summer 2010 field season. Map contours are in meters. Provided by Roof, 2010.

Project Aims

The goal of this study is to construct an accurate varve chronology for the entire lake basin by taking advantage of the correlation of multiple cores. Using varve counts and cores from multiple sites, inconsistencies from a single core site can be found and eliminated. Additionally, a core site whose varve record proves relatively easy to interpret is also sought; varves from distal basins are often very thin and ambiguous while cored sediments from core sites located proximal to the glacial inlet stream encounter sedimentalogical noise due to storms and other event deposits, and possibly mass movement. Event deposits that may occur lake wide include possible volcanic tephra layers, large storm events, or extreme melting events. The use of magnetic susceptible readings should aid in the correlation of varves, as these fluctuations should be recorded basin wide in the lake sediment due to natural fluctuations. However, provenance and distribution of sediment may vary. With the compilation of a more complete varve record, more accurate weather comparisons can hopefully be made using historical weather data.

With an overall varve record spanning the entire lake basin, it is then possible to characterize the deposition of sediment throughout the lake and sedimentation processes. Observations of different lamination structures at certain core sites indicate the complexity and variety of depositional processes. Through correlation with other cores and weather parameters, the varved sediment potentially can offer insight into the complicated glacier system in Linnèdalen, and hopefully uncover information about the response to glacial systems to climate and weather in the Svalbard arctic.

Methods

Core Site Selection

Past sediment analysis work completed on Lake Linnè has been at the 7 mooring sites deployed in the lake. Cores have been taken from the proximal sites C and D (Leon 2006) as well as the west basin sites E and F (Pratt 2006). A strong chronology of the proximal basin has been developed by past students which capture intra-annual sedimentation. In the deep distal basin, sites G and I were sampled in 2008 and 2009 respectively (Nelson 2009 and Pompeani 2008). The varves collected distally represent annual sedimentation, however on the sub millimeter scale. In the summer of 2010, the mooring site at H was chosen for coring as it sits geographically between the deep distal sites I and G and the proximal sites C and D. Bathymetrically, the H mooring site is located at a depth of approximately 30m, placing it at the proximal portion of the distal basin. Past studies on proximal varves encountered difficulty in varve interpretation presumably due to sedimentation noise from the glacial inlet stream (Leon 2006). Distal varve interpretation also proved difficult due to the thin varve sediments. Deposition rates at site H based on sediment trap data show deposition is greater than that of the distal locations (Arnold 2009), but less sensitive to random events that occur at the proximal sites. Using the H site will potentially produce a core site where varve counts and thickness measurements correlate well to weather patterns and can be used to determine the nature of sedimentation in Lake Linnè.

To the northeast of the H site sits a meteoric inwash delta. Field observations show that this delta is active during the summer, unlike other inwash streams which appear dry or sporadically active. Located proximal to the delta is a bathymetric ridge which forms a subbasin in front of the delta. Because of the inwash delta's proximity to the H core site, this delta in addition to the glacier outwash system may contribute sediment to site H. Sampling this delta site provides a control on the varve counts obtained from the H site in the deep lake basin. If intra-annual events such as turbidites, slides, and storm inwash occur at this site and produce anomalies, then potentially these anomalies can be identified and corrected based on inter core comparisons.

The D site was also sampled, although past work on the area has shown deposition in the proximal locations is accompanied by prominent intra-annual depositional events that can confuse varve measurements. The D site deposition is characterized by numerous sand and sandy silt deposits laid down by potential intra-annual storm events that create surges to the lake. However, with the aim of creating a master varve chronology for Lake Linnè, correlation of site D and H sediments may be possible, thus linking sedimentation processes in these areas. Because the D site is located at a more proximal location, it can provide evidence and data for intra-annual glacial deposition of sediment. Correlating sites H and D may therefore result in a better identification of intra-annual events.

Coring

Coring was completed using a percussion hammer coring device, obtaining cores 40 to 50 cm in length. Core tubes with an inside diameter of 6.6 cm were used. Clear, low wind days were chosen for coring as calm conditions lend themselves to a steadier coring environment, as coring took place in a Zodiac boat with the coring device lowered to the lake floor over the boat gunwales. A total of 9 cores were obtained from the three sites, and were packed and prepared at Isfjord Radio for transportation back to Tufts University.

Figure 12. Photograph of the author with a newly recovered core sample. Summer 2010.

Thin Sections/Sub Sampling

In order to analyze lacustrine sediment cores with very thin laminae, thin sections were prepared. Thin sections were made from sub-sampled areas of each core, and vary in length depending on available thin sectioning techniques. Longer thin sections allow for easier analysis versus the standard 2.7 x 4.6 thin section size, but were more difficult to make. Following sub-sampling, the sediments underwent an acetone-epoxy replacement in order to be impregnated for thin section production.

Before sampling occurred, the cores were each scraped and cleaned. Each core was photographed with multiple pictures, and stitched together in Photoshop CS3. Sub-sampling occurred with sheet metal boxes (2.5cm by 6 cm) pushed into the surfaces of the split cores. Sub samples were taken alternating downcore, with a 1-2 cm overlap between each sub-sample. When sampling sandy and silty beds, sub sample position was moved to cover the entire sand or silt bed. To remove sub samples, a metal jig is pushed underneath the sub sample area, which lifts the sampled sediment out of the core. (Figure 13)

After the jig and sub-sample have been lifted from the core, the sediment must be removed from the sample boxes. Each box was hollow, allowing for the easy removal of sediment. A knife or razor blade is used to separate the sediment from the sides of the tray, and each sample is placed onto a plastic screen. The knife is then used to gently push the sediment onto the screen while the tray is simultaneously lifted. Placement of the samples less than 1 cm from each other in the impregnation tray minimizes acetone wastage, while also allowing for adequate acetone replacement and circulation.

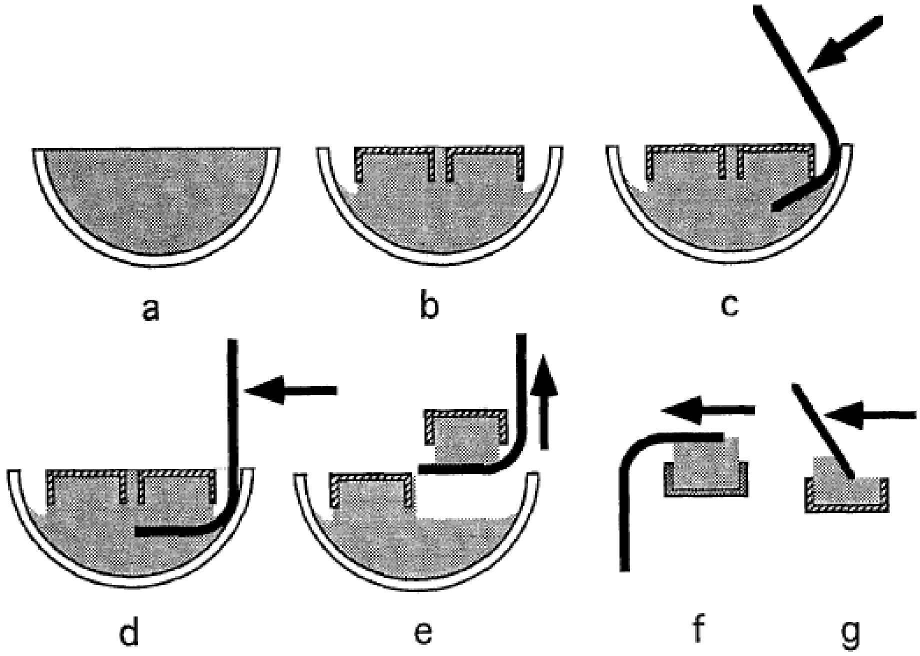

Figure 13. Demonstration of the removal of sub-sampled sediments from the core. From Lamoureux (1994).

Figure 14.
Above: the authoring sub-sampling sediment from split cores.

Right: the sub-sampled specimens ready for the acetone replacement.

Couplet Identification and Varve Classification

In order to accurately measure the thickness of varves, varve boundaries must be identified correctly. Varve definitions are based on the existence of fine, dark clay layers. The contact between the previous summer and the winter can exist as a graded sequence – as lake conditions become calm at the end of the summer clay deposition begins. This process is interrupted occasionally with an event layer due to a late season storm. The contact between a previous year's winter and the following summer is usually abrupt as the spring melt delivers a large load of sediment to the lake and commences the summer deposition season.

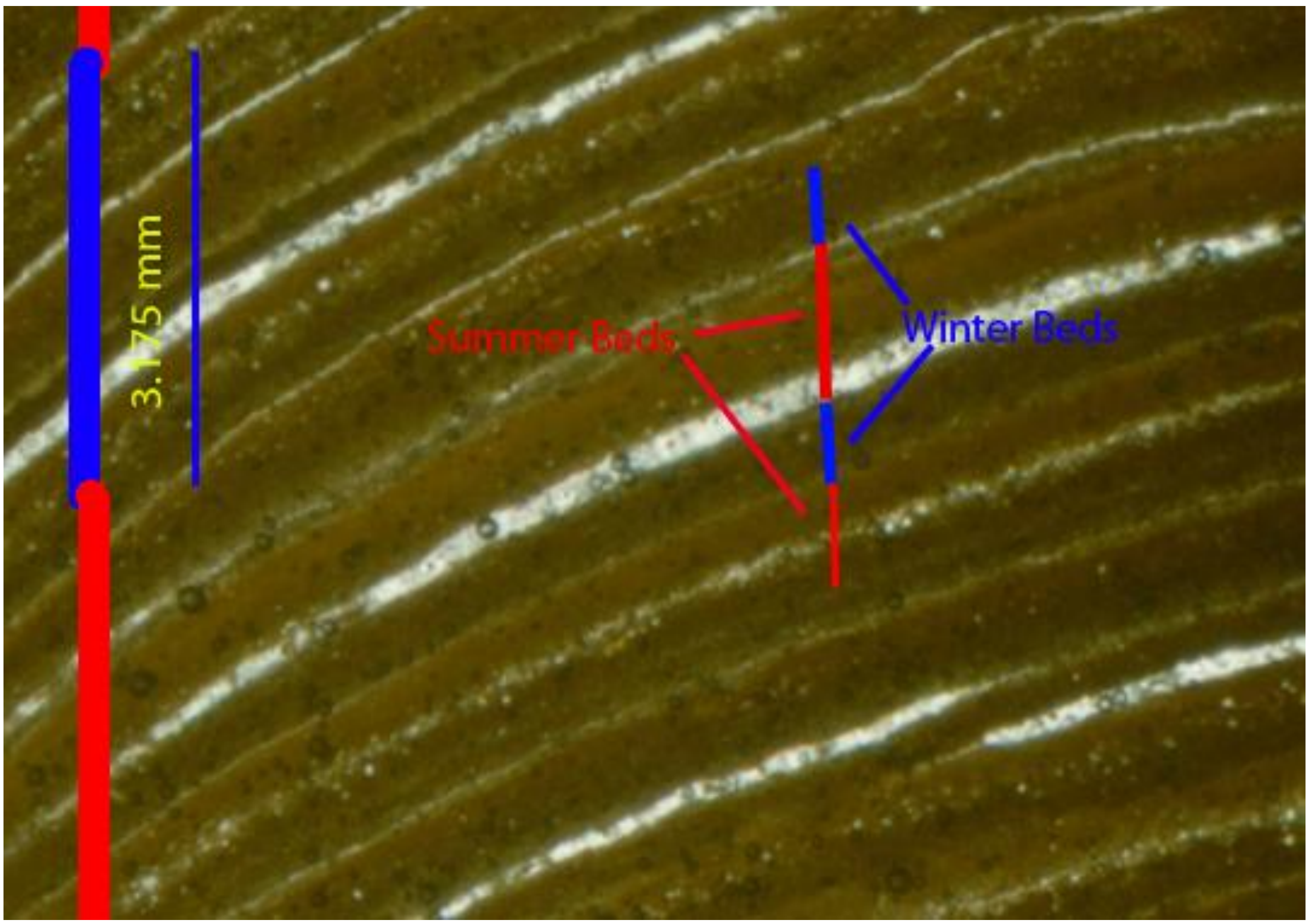

Figure 15.Image demonstrating what is classified as a summer and a winter bed. Image is from core site H4A. The white lines are cracks in the sediment.

The structures of varves are rarely simple in proglacial lakes. Complex laminations often occur within the summer layer due to variations in depositional factors driven by snowmelt, precipitation events, and varying glacier melting during the summer. In this study, four different classes of varve types are defined as complex, massive, simple and diffuse varves. *Complex* varves exist where the summer layer is composed of many different laminae, often with light silt layers, finer red layers, and coarse deposits. *Massive* varves consist of sequences defined by either a thick, graded sequence of sediment or a thick sequence of homogenous sediment. *Simple* varves are thin relative to the complex and massive varves, with no apparent bedding within the summer layer. *Diffuse* varves are varve sequences which are ambiguous due to the lack of definitive winter clay beds. (Figures 16-18)

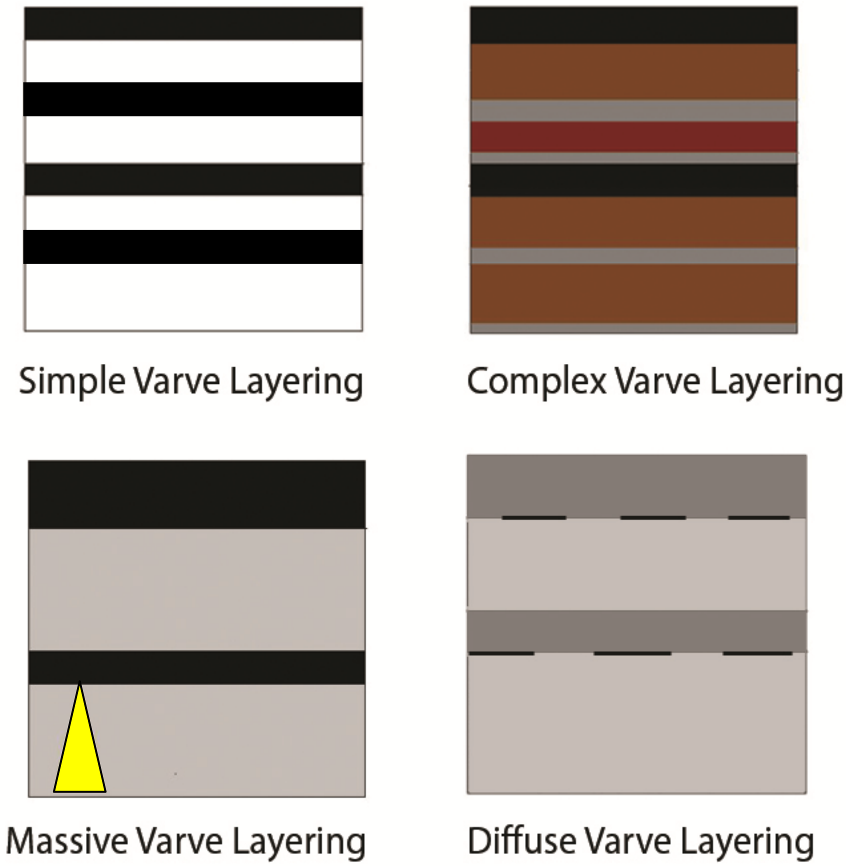

Figure 16. Idealized representations of the varying varve sediment structures evident in Lake Linnè varves. Simple varves have little variation in layering. Complex varve layers have light silt beds (gray) followed by brown or tan sediment (brown) with interspersed red fine sediment layers (red). Massive varves can be homogenous, or have fining upward sequences represented by the yellow arrow. Diffuse layers show winter and summer colors that are similar and not well defined.

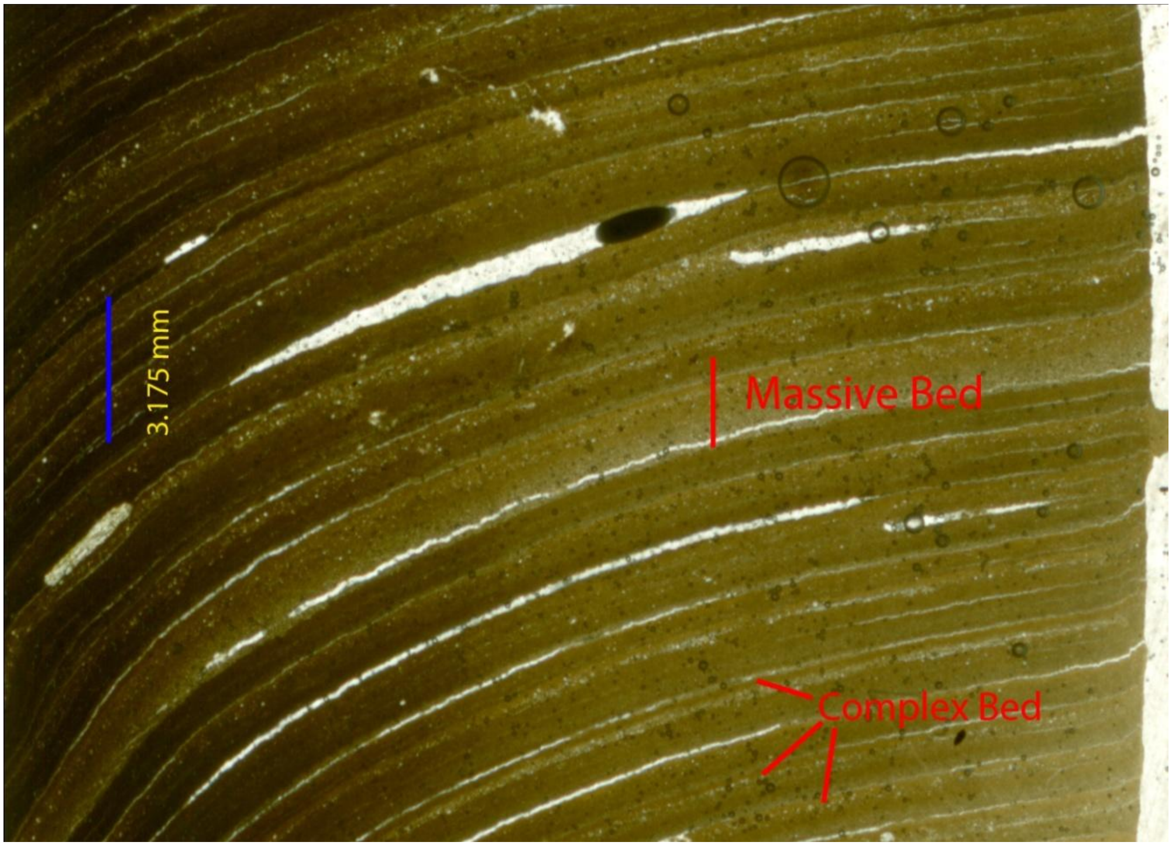

Figure 17. Image showing massive and complex laminations in the H4A core.

Figure 18. Image showing diffuse bedding in core D3A.

Counting and Correlations

In order to analyze patterns of varve deposition for their dependence on weather and climate, accurate varve counts and thickness measurements must be obtained. High resolution images of the thin sections of cores were obtained using a bed scanner, with a scanning resolution of 4800 ppi. Varve counting took place using UTHSCA Image Tool 3.0 (freeware) and a plug-in script program specifically developed for measuring varves with Image Tool 3.0 (Ridge 2010). Each thin section was counted up to four times using the computer program, with thin sections split using Adobe Photoshop CS3 into 6 separate, overlapping images for processing. Following the computer processing of varve counts, enlarged posters containing the measured counts of each slide were printed for visual analysis. Using enlarged images, visual correlations were made between cores, and inconsistencies in the varve counts were corrected manually. Corrections were incorporated into the varve count and measurements by resetting the image count with measurement corrections in Microsoft Excel. Visual correlation was done by the identification of easily recognizable marker beds in each core, and correlating varve counts and general relative thickness between cores. Graphs plotting varve thickness per year were created, and visually matched to each other. "Wiggle matches" were made by comparing two graphs from different cores, using the measured varve thicknesses along with the marker beds as indicators of identical years over time. Finally, statistical analyses of the varve correlations were made by calculating linear regression correlation coefficients (r^2) using Microsoft Excel. Varve records from core sites located distally and proximally to the inlet stream were obtained, and normalized based on the following equation:

$$\frac{Measured\ Thickness - Mean\ Thickness}{Standard\ Deviation}$$

Correlation coefficients were calculated and graphical analysis performed in order to attempt a correlation of proximal, intermediate, and distal sites with each other. One potential source of error in varve measurement was due to the deformation of sediment during the coring process. Sediment during coring was dragged downward along the edge of the core. In most cases, the centers of the cores are well preserved, and at a minimum the cores preserve relative thickness along the core axis.

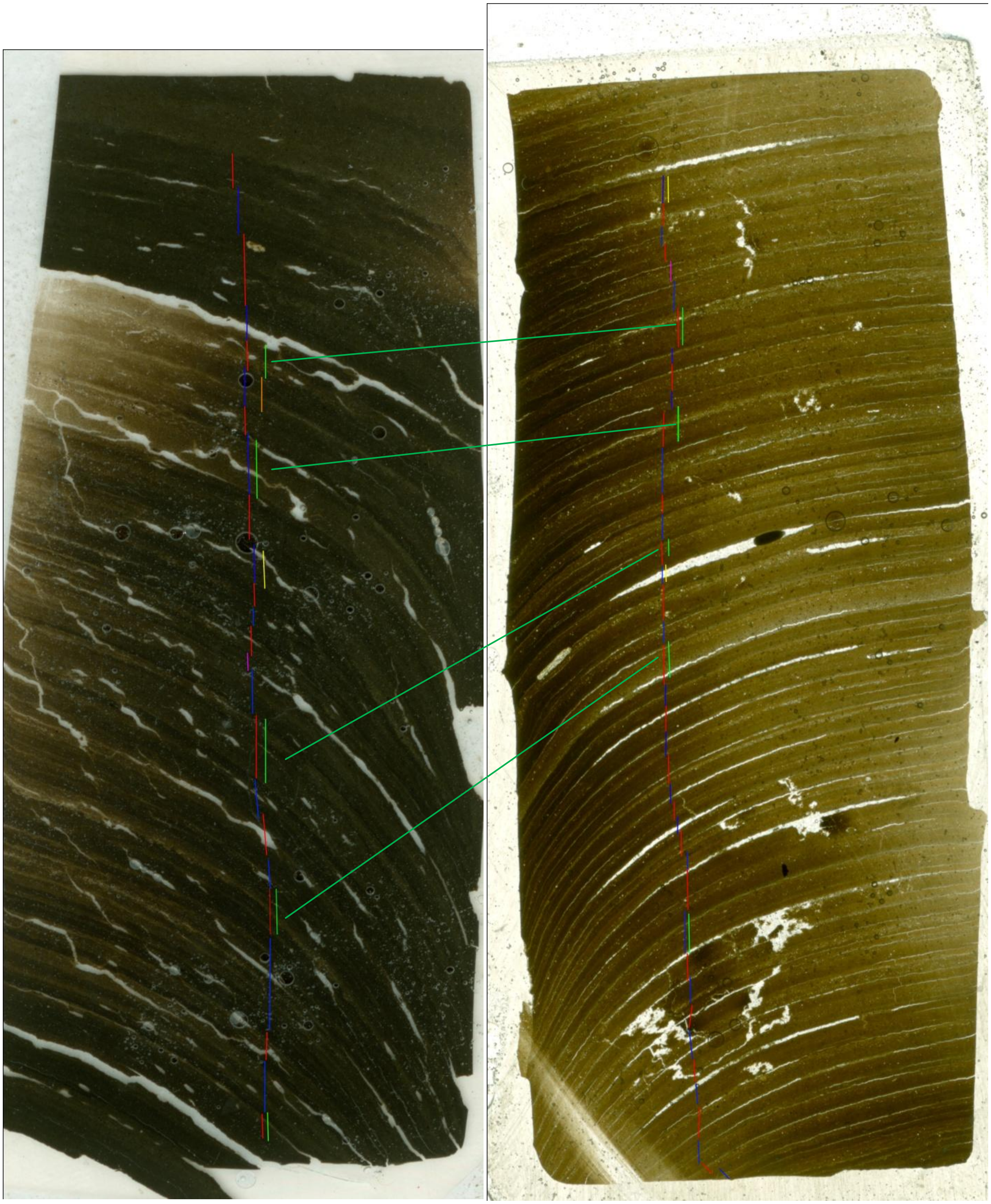

Figure 19. Two thin sectioned slides with corresponding years connected with green tie lines. Core D3A is on the left, and core H4A is on the right.

Magnetic Susceptibility Readings

Magnetic susceptibility readings were taken using a Bartington magnetic susceptibility ring sensor. Split cores were moved through the device at 1cm increments, with measurements being the average of an approximately 5 cm length of the core. Measurements were taken for 6 cores, two each from each of the core sites. Magnetic susceptibility was used as a rough guide for correlation with spikes in susceptibility matching between cores.

Weather Data

Weather data was analyzed and complied from the Longyearbyen airport Lufthavn and Isfjord Radio in order to determine the relationships between climate and varve deposition (available from the Norwegian Meteorological Service). Meteorological data was obtained from Isfjord Radio and Longyearbyen. The Isfjord Radio station is located approximately 2 to 7 km from the glacier and the field area. Daily weather measurements of precipitation were used from this site for the time period of 1956 to 1976. Precipitation data for this site was obtained through the Norwegian Meteorological Service. The Longyearbyen weather data from this site (Lufthavn domestic airport) provides weather data on daily temperatures and precipitation from 1976 to the present. For the time period of 1912 to present, a monthly average of daily temperature records is available from Longyearbyen.

An estimate of positive degree days (PDD) was also calculated. The PDD estimate is a total of all days with an average temperature above 0° C, calculated as the sum of temperatures for all days with a mean temperature above 0° C . Rain and snow estimates were also estimated with the assumption that rainfall events occur on days with an average temperature above 0° C, and with snowfall occurring on days below the freezing temperature. Snowfall was measured in water equivalents. The use of this weather data is based on the assumption that weather and climate conditions are relatively uniform at the sites and are good indicators of weather patterns at Lake Linnè. Statistical comparisons of weather and varve thicknesses were made using Microsoft Excel.

Results

General Core Stratigraphy

All cores have variations in grain size, with dark grey to tan brown colorations, and varve thickness. A tan-brown sequence of beds was observed in two of the cores, H4A and D3A. Sedimentation rates in core H6A were different, and the brown coloration potentially occurs towards the top of the core, but is not as distinctive as in the H4A and D3A cores. Below the brown band, sediment color changes to brown and tan dominated layers and continues to the bottom of each 30-40cm core.

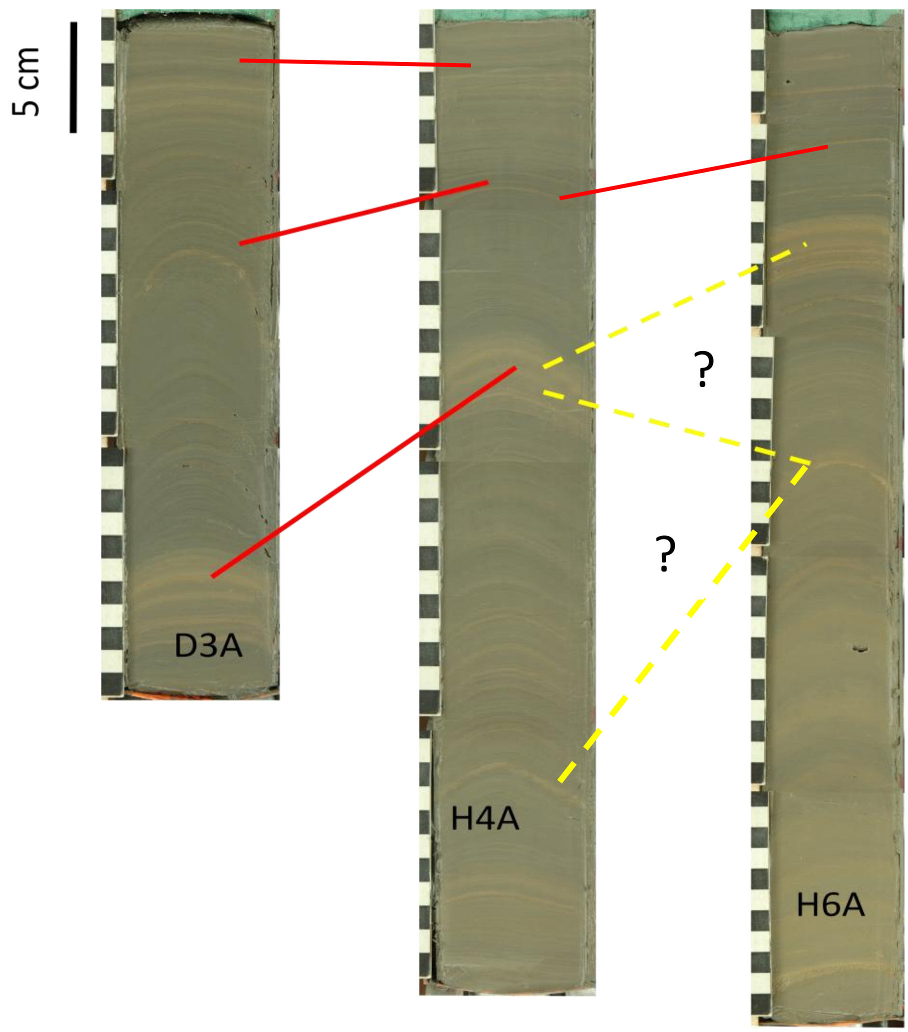

Figure 20. Core images correlated with red tie lines for definitive matches. The yellow tie lines indicate possible matches – the H6A core did not correlate well with D3A and H4A cores.

Core H4A

In thin section, general patterns are not easy to distinguish. Core H4A showed the most regular lamination patterns of the three cores, with alternating clay and silt layers throughout the core (Figure 21). Overall, sequences of varves were counted where summer silt was deposited followed by a dark fine clay cap. Summer and winter thickness did not follow any well defined ratioand instead generally following a pattern of the thicker summer years followed by thicker winter layers and thinner summers followed by thinner clay layers. Finer laminations were often visible within summer layers in H4A, with occasional fine laminations within winter layers as well. In certain summer layers, complex laminations were observed. These complex laminations consisted of alternations of light gray sand/silt layers and fine red sediments. Multiple light sand/silt bands could be seen in most years, while in others only one sand/silt layer was visible and coupled with the distinct fine grained red layer or no light sandy silt layer was evident at all. A few massive graded beds were also observed, consisting of anomalously thick sand and silt. These beds show what appears to be a fining upward sequence in the sediment, with a color change from light gray to red as well. Additionally, some varve couplets were not distinct where the differences between winter and summer layers were ambiguous. These layers were classified as diffuse layers, as it was unclear whether there was a distinct winter clay cap. Lastly, some annual couplets showed relatively simple bedding, with a sequence of lightly colored coarse sediment followed by a dark clay layer.

Core H4A showed the most regularity in varve counts. Counts were made for core H4A for approximately the last century, spanning to the year 1896. The average varve thickness was 1.214mm, with a standard deviation of .755mm and spanned a total depth of 136.63mm (13.63cm). Thickness trends also showed a marked increase through the last three decades. The average varve thickness for the years 1990 to 2009 increased to 2.1083 mm, and the average thickness for the years 1970-1989 was 1.378 mm. In the counted year 1992, a noted change in varve deposition appears to occur. Laminations in the varves prior to 1992 were notably thinner when compared to the most recent years of deposition, and better defined in thin section as well (Figures 24).

Magnetic susceptibility measurements were taken for each core. In the H4A core, two major peaks are apparent, as well as two minor peaks. The two minor peaks occur at approximately at 4 and 8 cm downcore. The two major peaks occur at 13 to 14 cm, and at 25 cm (Figure 28).

Core H4B

The stratigraphy observed in the H4B core was similar to the H4A core, as the two cores were taken from coring locations near site H (Figure 10). Core H4B was measured in order to correlate the measured varve couplets with core H4A, and only the top thin section was measured. Slight coloration differences exist between the cores due to variations in thin section thickness.

The couplet counts for H4B were similar to those reported for core H4A. There was an average varve thickness of 2.53mm with a standard deviation of 1.68mm. The total length of the counted interval was 43.09mm (4.31 cm).

Magnetic susceptibility readings for the H4B core showed similar results to the H4A core, with major peaks at 13 and 25 cm, and minor peaks at 4 and 8 cm downcore (Figure 28).

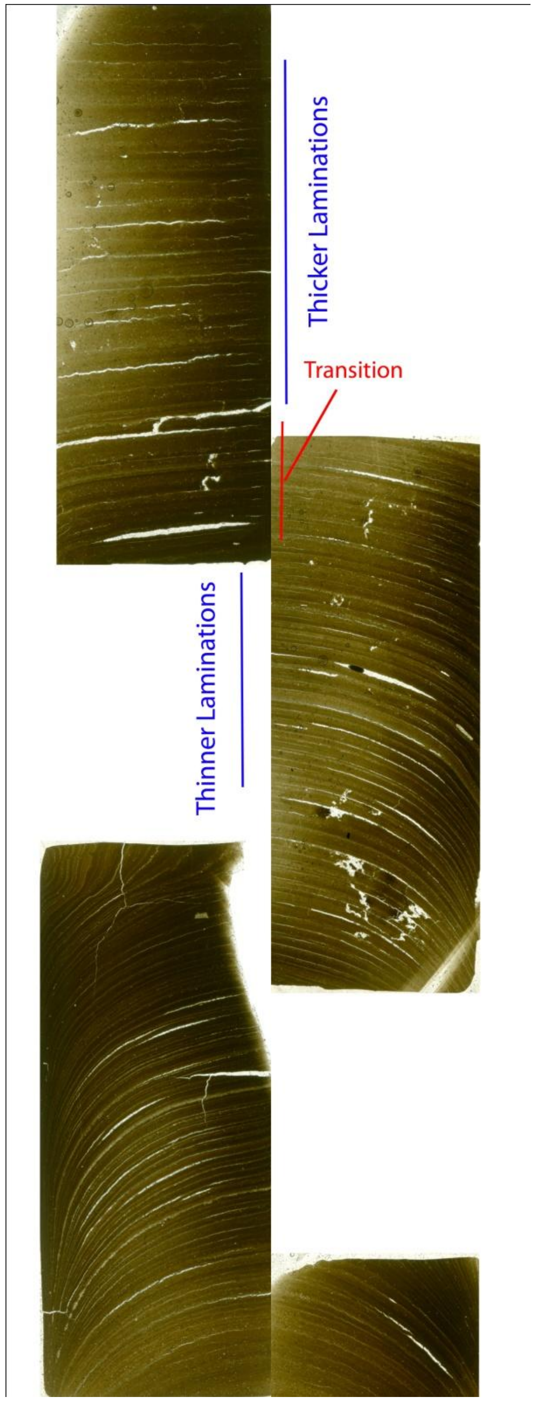

Figure 21. Image of core H4A in thin section slides. Note the transition from thinner laminations downcore to thicker laminations near the top of the core.

Core D3A

Core D3A showed generally thick lamination patterns and the most deformation due to coring (Figure 22). Cores at this site have been interpreted to represent proximal deposition of sediment near the glacial inlet stream into the lake. Therefore, the laminations represent intra-annual events interbedded with varved sediment couplets (Leon 2006, Pratt 2006). In the core, complex, massive, simple and diffuse layers were evident, as in the H core. Complex laminations of summer years involved multiple silt layers. Massive beds showed sections of thick layers, with some thick, graded beds, and some exhibiting thick beds with no gradation. Sequences of simple varve couplets also exist, with silt followed by deposition of the fine clay caps.

Measurements for core D3A were back to the year 1957. The average varve thickness was 2.276 mm, with a standard deviation of 1.706 mm. Similar to the varve counts for H4A, the youngest approximately 20 years showing increased thicknesses. For the last two decades (1990-2009) the average thickness increases to 3.56 mm, and for the interval from 1970-1989, the mean thickness measures 1.875mm. The total depth of counted varves was 100.45mm (10.04 cm). The varve years show a marked change in color at the year 1992, changing from generally dark colored sediment after 1992 to light colored and tan sediments with thinner summer beds and winter clay caps prior to 1992 (Figure 24).

The D3A core magnetic susceptibility readings showed similar magnetic patterns to the H4 core, with variations in peak depth along the length of the core. Since the D3 core is significantly shorter than the H4 cores, it only shows one major peak at approximately 25 cm. There is also a minor peak at 8cm downcore, with another minor peak occurring at 15 cm as well (Figure 28).

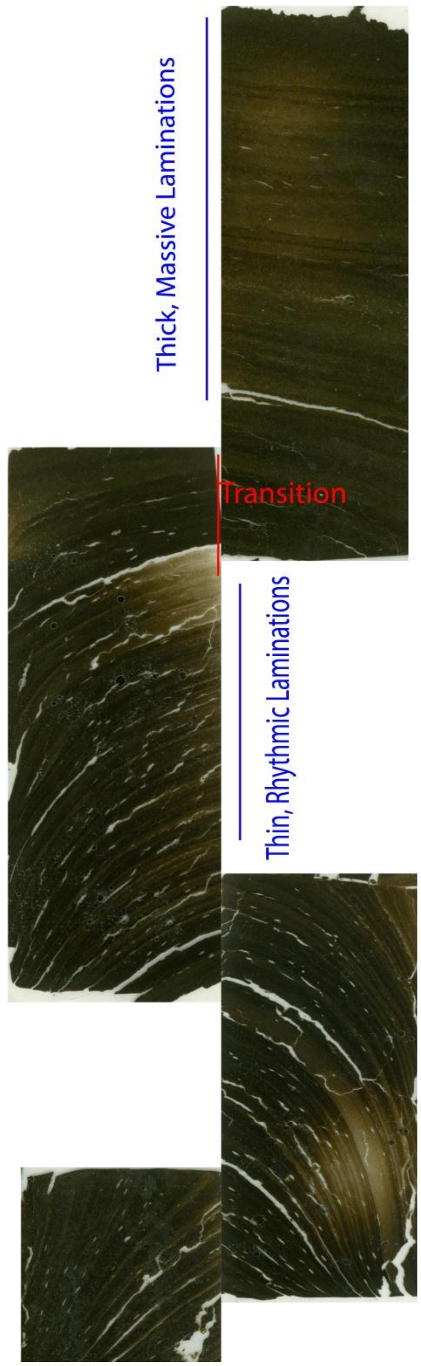

Figure 22. Core D3A in thin section images. Note the transition from more massive bedding near the top to more laminated, rhythmic bedding towards the bottom.

Core H6A

Because core H6A was sampled proximal to the meteoric inwash delta northeast of the H core site, its stratigraphy was notably different from cores H4A, H4B and D3A. The core exhibited regular lamination patterns, however large sand and silt layers were observed, with the thickest around 2.5 mm. The thickest light fine sand layers came at the top of core, whereas older fine sand layers were thinner. Similar complex laminations within possible summer layers were apparent, although not as frequently as in core H4A. Along the entire length of the core large fine sand layers were observed, seemingly interrupting the deposition of silt and clay couplets. The fine sand layers do not appear to occur annually; instead they vary in thickness and occur within summer layers. Also, the sand layers are not followed immediately by a distinct clay layer. The sand layers tend to exist between thick summer laminations in certain years. Sequences of simple and diffuse couplets were evident in the core at certain intervals. The average measured varve thickness was 2.16 mm. with a standard deviation of 1.46 mm. The total length of the counted section was 93.079 mm (9.31 cm) (Figure 24).

According to the magnetic susceptibility measurements, the H6 core showed a slightly different trend in deposition. There is one minor peak located at 8 cm downcore. There are two major peaks as well, however they occur at a different depth than the H4 core. The two major peaks occur at 25 and 42 cm downcore (Figure 28).

Figure 23. Core H6A in thin section. Note the thick fine sand units which are prominent in the stratigraphy. Sand units are generally thicker towards the top of the core.

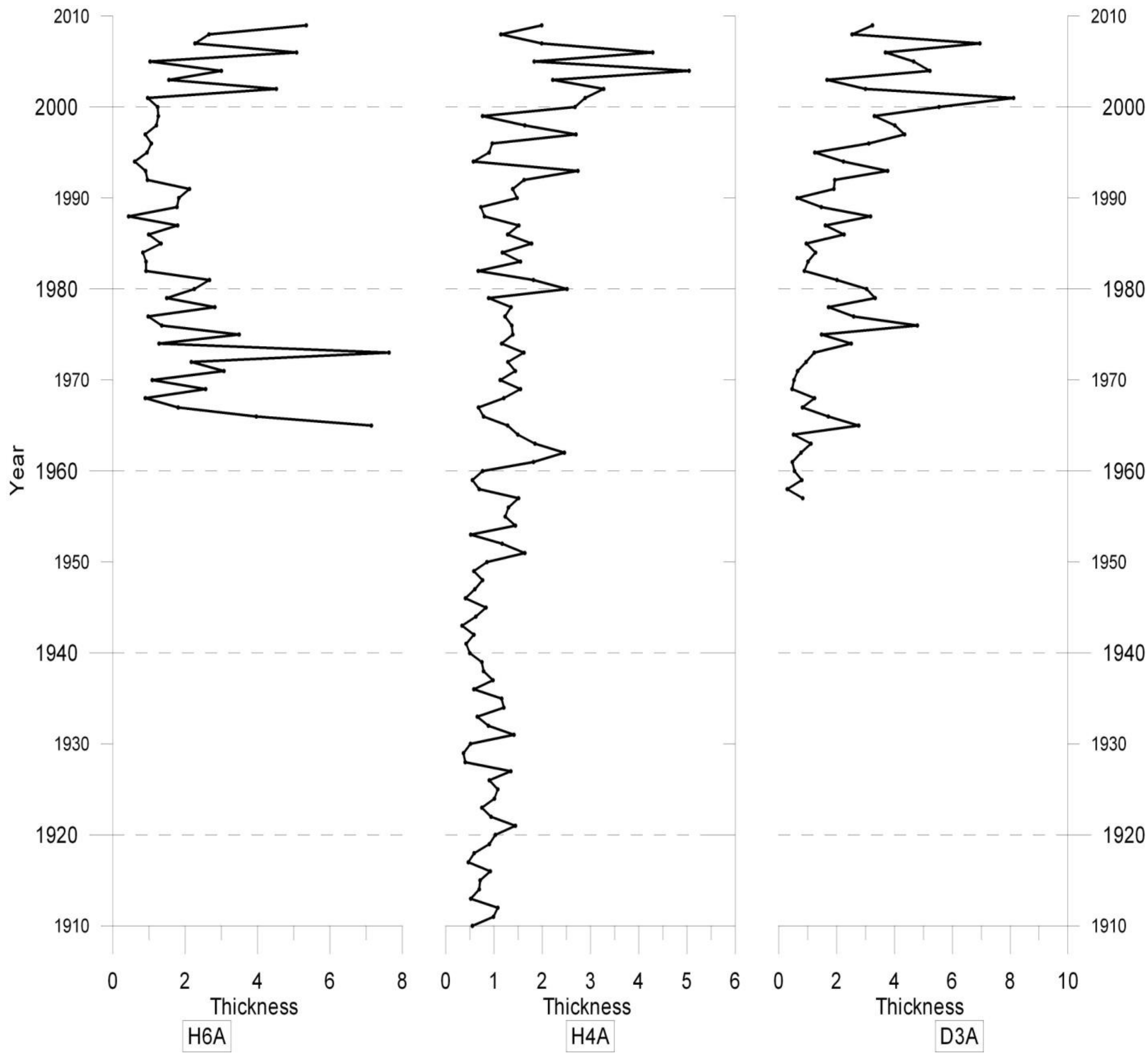

Figure 24. Annual varve thicknesses for H6A, H4A and D3A.

Basin Wide Core Correlations

Comparing the two sites H and D can be done using visual stratigraphic comparisons, as well as statistical relationships between the two cores. Graphically, both cores D3A and H4A show similar trends of increasing thickness during the past twenty years. Additionally, both experience a sediment character change in the counted year 1992. Statistically, the r^2 (linear regression correlation coefficient) value is .502.

Although the cores from H4A and D3A correlate with each other, they do not match well with core H6A from in front of the meteoric inwash delta. The large sand beds observed in the in-wash delta cores do not have correlative matches stratigraphically in either of the H4A or D3A cores, with an r^2 value of .203.

Correlating the distal sites at I and G and the proximal site D with the intermediary H site provides a basis for developing a potentially high resolution chronology that shows variations in varve thicknesses across the lake. Comparison of the measured varves from the proximal core sites shows that the rate of sedimentation at site D is less than that of the proximal sites. Leon (2006) found that varve thickness in the most distal core (core LV06-14) varied from .6mm to 7.2mm, with an average thickness of 2.3mm. Using the annual counts established by Leon (2006) and cross referencing core D3A with the 2006 core LV09-14, correlations can be drawn between the two cores. Comparison of the past 40 years shows general similarities in normalized varve thickness over time. For the D3A core, the year 1963 measures at a depth of 114.76 mm (11.4 cm). In 2006, a ^{137}Cs peak was measured at 19-20 cm downcore by Pratt in 2006 on a core taken from site C, located more proximally to the glacial inlet stream in relation to site D.

Nelson (2009) obtained $^{239+240}Pu$ readings from cores at site I and Pompeani in 2008 obtained a ^{137}Cs reading for cores at the G mooring site. Using the values reported by Nelson and Pompeani for the $^{239+240}$Pu peak, the depth of the radiation peak at the year 1963 was approximately 3.0 cm, whereas the measured depth of the year 1963 for Pompeani in 2008 was 2.9 at site G. The depth of the year 1963 in core H4A was found to be at 78.89mm (7.889 cm). Nelson reported an average varve thickness of .35mm at site I, significantly less than that measured in H4A. Comparison of approximately the last half century shows similar decadal trends in normalized varve thickness over time (Figures 25-27). Core H4A correlated best with the distal measurements from the I site but also correlated with the proximal site as well.

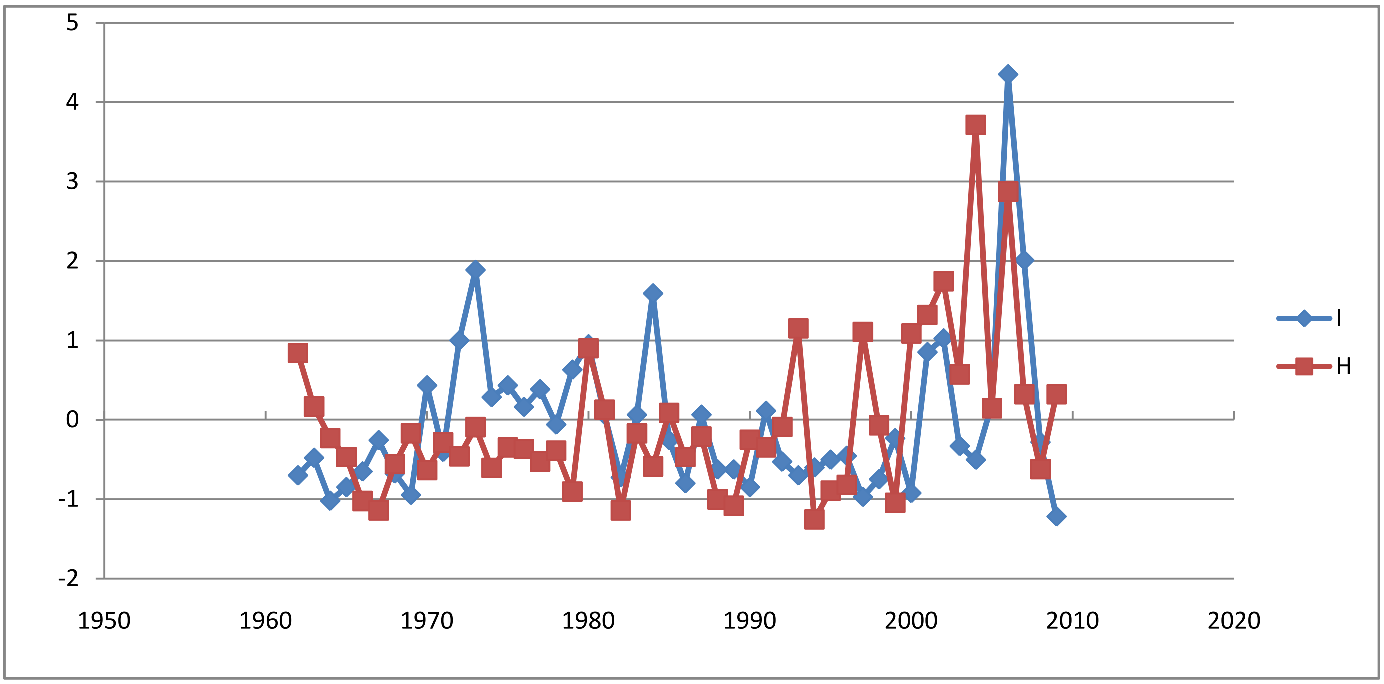

Figure 25. Graph showing normalized varve counts for sites I (data from Nelson 2009 - blue) and core H4A (red). Note the similarities in the varve thickness measurements over time.

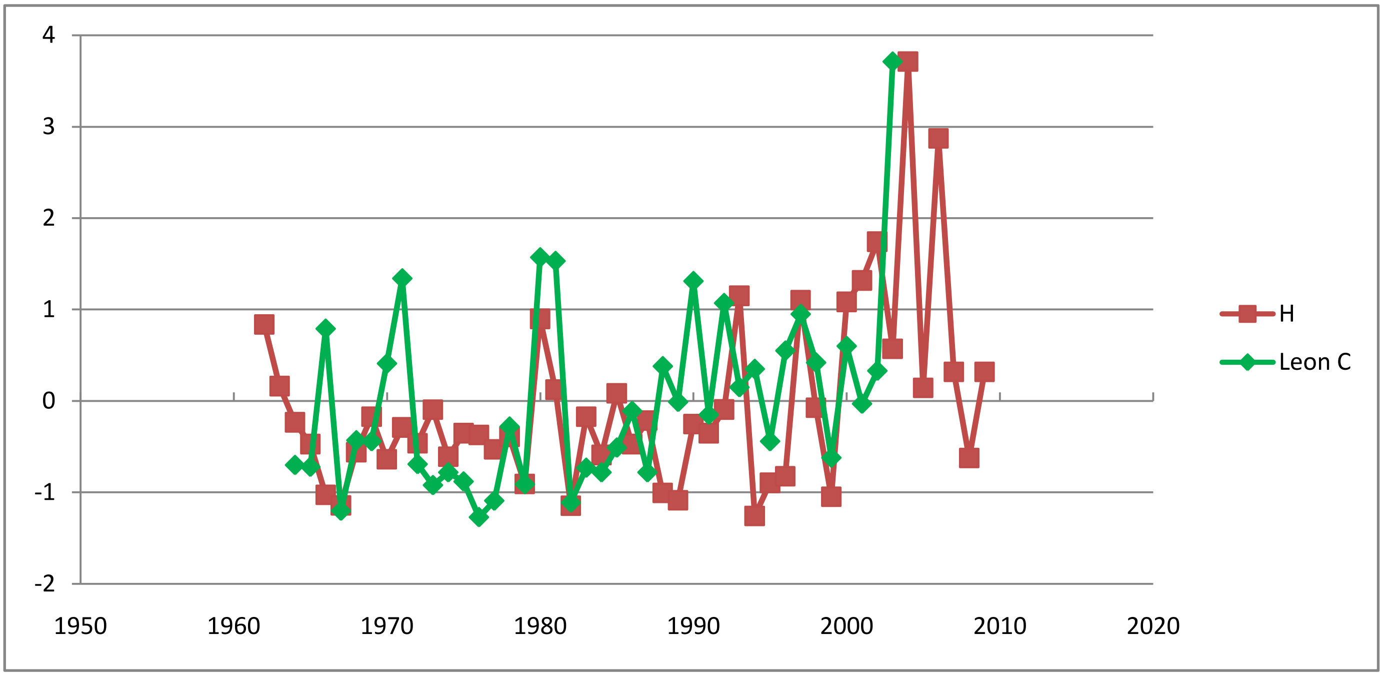

Figure 26. Graph showing the relationship between the H4A core (red) and the proximal core LV09-14 (near site C – green. From Leon, 2006).

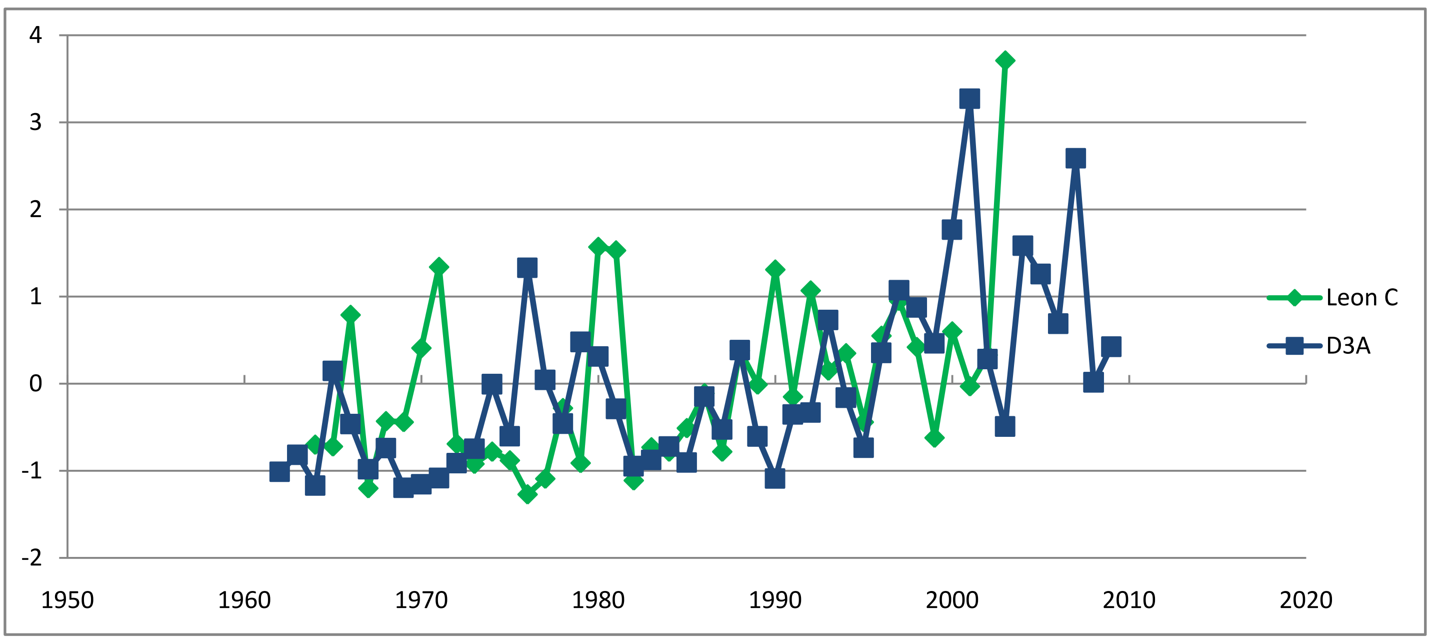

Figure 27. Graph showing the relationship between the core D3A (blue) and the proximal core LV09-14 (Leon 2006).

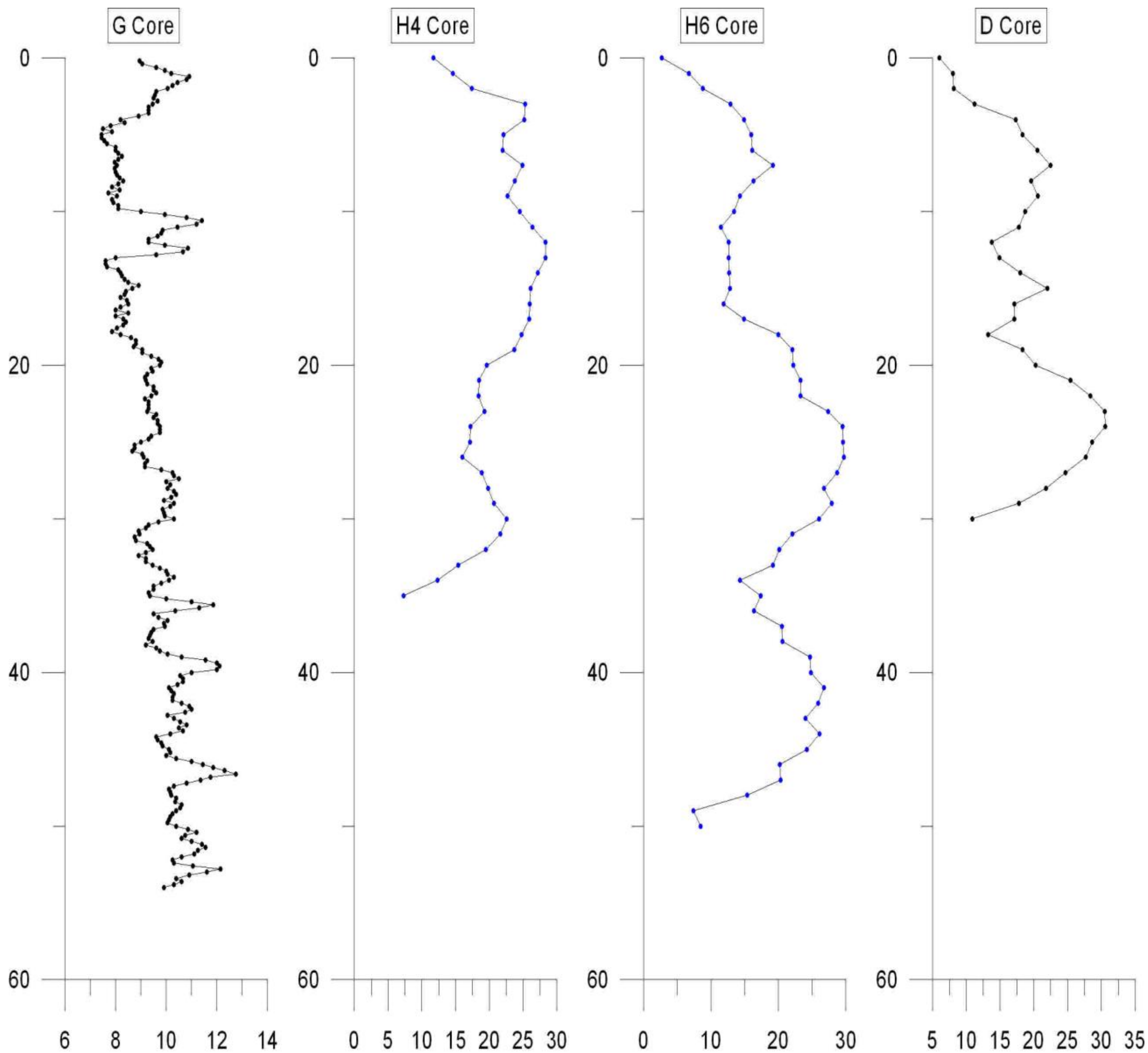

Figure 28. Magnetic susceptibility readings for cores H4, H6 and D3. The G core measurements are from Pomepani (2008), and were taken at a higher resolution.

Figure 29. Image showing the thin sections of the three measured cores. Tie lines are drawn where correlations can be easily made. Core H6A on the left cannot be tied to the cores D3A and H4A.

Weather Correlations

Weather data can be correlated with the varve counts and varve thicknesses. Correlations were attempted with mean summer temperatures for June, July and August, as well as correlations between total precipitation, total rainfall, total snowfall and total summer precipitation. The positive degree days estimate (PDD) was also correlated with varve thicknesses.

Core D3A

Correlations between weather parameters such as summer temperature and precipitation measurements were made via linear regression. The relationship between weather parameters in the D site showed a weak positive correlation between mean summer temperatures and varve thickness as well as PosDD values and varve thickness. The measured r^2 value was .203 for mean summer temperatures and varve thickness. Monthly correlations show the strongest relationship with August temperatures and thickness (r^2 = .201), with a weaker relationship between July temperatures and thickness (r^2 = .126) and even weaker for June (r^2 = .097). The measured relationship with PDD had a measured r^2 value of .322, which is stronger than the relationship between temperatures, though still weak. The relationship between precipitation (total summer precipitation r^2 = .0757) and thickness is much weaker than the temperature relationships and insignificant (Figure 30).

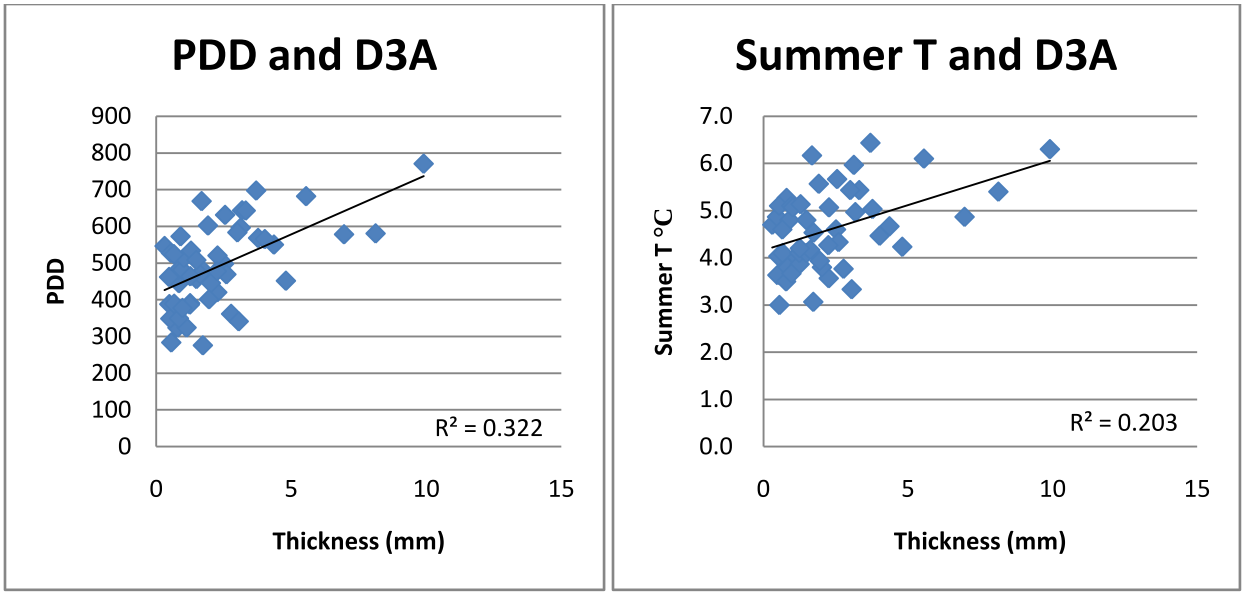

Figure 30. Linear regression of PDD and Summer Temperatures with the varve thickness measured from core D3A.

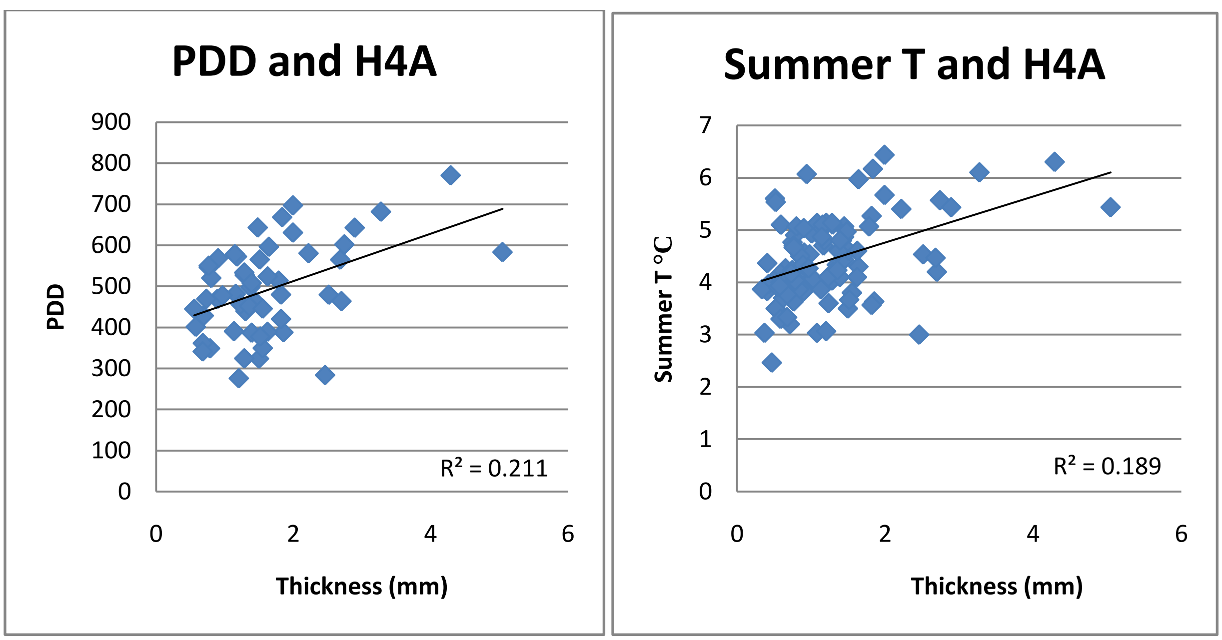

Figure 31. Linear regression of PDD and Summer Temperatures with the varve thickness measured from core H4A.

Core H4A and H4B

Comparison of summer temperatures and precipitation from each year were made for the H4A core as well. Core H4A correlates best with summer temperature, with an r^2 value of .189 (Figure 31). The relationship for the past 50 years shows a slightly stronger relationship (r^2 = .203), although similarly weak. The relationship for August temperatures and varve thickness were weak (r^2 = .239), but stronger than the relationships of July temperatures and thickness (r^2 = .096) and for June (r^2 = .064).

The measured r^2 value for PDD and varve thickness is .211, which is slightly stronger, but still weak. Correlations between precipitation weather parameters for the H site were weak as well (total summer precipitation r^2 = .0248). Comparison of the H4B measurements with summer temperature shows a similarly weak relationship as well, with an r^2 of.293.

Core H6A

Analysis of the meteoric inwash core H6A with weather parameters yielded results which differ from the comparison of weather to cores H4A and D3A. The correlation with summer temperature is very weak for the H6A core (r^2 = .007), essentially showing no correlation. Comparison of the varve thicknesses with precipitation parameters however resulted in a stronger correlation between total snowfall and varve thickness than comparisons of rainfall and summer temperatures. The measured r^2 value was .121, but it is still weak.

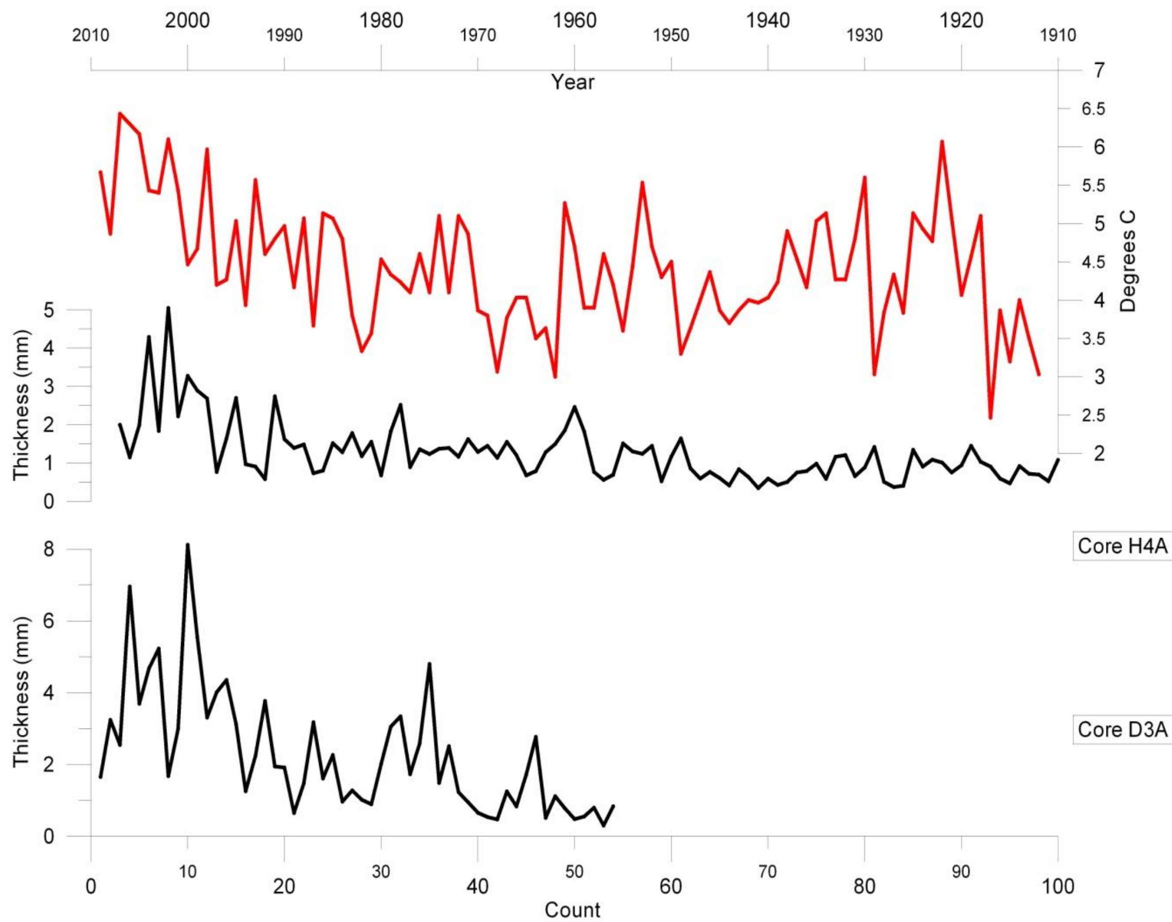

Figure 32. Plot of summer temperatures versus the annual varve thickness counts for cores D3A and H4A. Note the relationship between the increase in summer temperatures with the increase in varve thicknesses over the past twenty years.

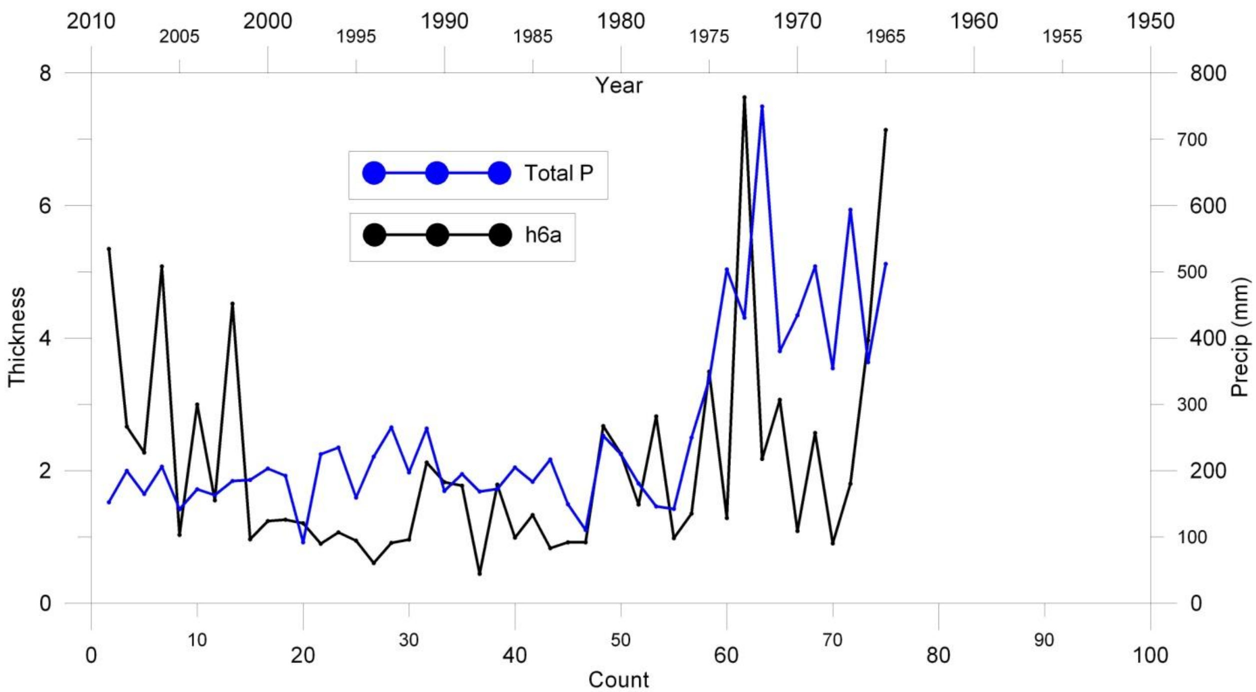

Figure 33. Plot showing the correlation between the meteoric core site (Core H6A) and total precipitation. The large values prior to the 1980s are due to high amounts of annual snowfall.

Discussion and Analysis

Varve Correlations

Based on the work of past students, the general relationships between cores can be established, and a general master chronology can be pieced together. Following the construction of an intra-basin chronology, it is apparent that deposition follows a trend of lower annual sedimentation further from the glacial inlet source, as expected with the decrease in depositional energy and diminished sediment further away from the meltwater source. When comparing varve thickness records, similar changes occur over the past three decades in all cores with a general increase in thickness in all count measurement records for this time period (Figure 24).

From analysis of the D and H cores, there is a correlation between the annual varve measurements and thickness for these two sites (Figure 24). Sequences of varves can be matched visually with similar stratigraphic characteristics; for instance the thin varve sequences from the year 1992 and older are consistent between cores, and the changes in sediment composition after 1992 offer evidence that a significant change occurs which affects deposition at both sites (Figure 19).

Additionally, the core D3A stratigraphically and graphically matches the cores taken and analyzed by Leon (2006) on core sites more proximal to D. This indicates that the intra-annual deposits in varves proximal to glacial inlet delta are consistent with site D, and that they are from fluctuations in sediment flux from the meltwater stream and not influenced by meteoric sources. Yet although the H4A and the D3A cores have been well matched and correlated, the H site does not show the same intra-annual sediment observed in the D3A core. This indicates energy of the system decreases significantly before reaching the H site, but the H site still experiences complex varve and annual couplet deposition not apparent in the more distal locations at sites I and G.

Because of the complex lamination patterns at site H, it can be inferred that the site still experiences some influence from the glacial inlet stream and the events which occur on stochastic, variable scales.

Core H6A did not match any of the other cores analyzed in this study, and counts were made based on the definitions of clay beds, as defined above. The analyzed sections therefore did not visually and stratigraphically match the other cores used in this study. Because this core site is located proximal to a meteoric inwash delta, the parameters likely driving sediment deposition at this location were not influenced by forces driving glacial meltwater and sediment production. Instead weather parameters such as snowfall and sediment from an inwash source are most likely the key driving factors and therefore result in poor correlations with other cores from the lake.

Using past work in the distal basin, correlations of core H4A can be made with cores from sites G and I. Magnetic susceptibility data from site G compared shows similar trends as observed at H. Because the G site is located distally to H, it can be expected that sedimentation would be slower further away from the glacial inlet stream. The evident trend in the magnetic susceptibility readings obtained for both G and H site cores shows similar peaks and troughs, with peaks appearing further down-core on the H site because of the higher sedimentation rate. Additionally, comparison of the varve record at site I compiled by Nelson (2009) shows a similar peak in varve thickness in the late 20th century which matches the upward trend exemplified in site H. General peak and trough trends are still similar and indicate that the intra-annual influences of glacial meltwater input do not reach the deep distal lake basin. Overall, the relationship between cores indicates that the distal locations of the lake respond to the overall flux of sediment from the glacier and the glacial meltwater stream, although with much lower sedimentation rates in the distal locations and therefore are less sensitive to individual intra-annual pulses in glacial ablation due to changing weather conditions during the summer.

Characterization of Varve Sedimentation in Linnè

The character of sediment in Lake Linnè has been shown to be due to annual seasonal changes in sediment transport and deposition between the summer and winter months that produce varves. However, deposition in the lake is spatially variable, even though the total lake area is relatively small (4.7 km^2). Past work through the REU Svalbard program has successfully cored multiple sites in the lake basin, with all of the cores ultimately covering a linear transect of the lake basin. Proximal cores show the highest deposition, with intra-annual events responsible for the deposition of intra-annual silt and sand beds within summer layers. The intra-annual complexity of the varves at sites C and D show that proximal varves capture a higher resolution image of the stochastic as well as seasonal and annual variability. At the intermediate core site H, deposition rates were notably lower than in proximal areas, being noticeably thinner on average. However, the characteristics of the summer layers were complex, implying that the forces and parameters contributing to deposition at this site are highly variable and include stochastic as well as seasonal and annual events.

Documentation of these differences in sedimentation patterns allows me to define the varve types in terms of processes. The variable complex summer layering in core sites D and H is most likely due to contributing factors such as storm events of different intensities, and/or the intensity of nival melt events which occur in the spring. Occasional large meltings events later in the summer could occur as well. A relationship between total snowfall and the number of light silty sand layers is expected, as well as the number of these layers with the number of storms.

These events likely trigger underflow currents that transport silt and fine sand across the lake floor. Chutko and Lamoureux (2008) demonstrated spring melts, and rainfall events contribute a recognizable sediment signal which can be observed in varved sediments from a lake in the Canadian Arctic. It must be noted however that the varves studied in this study were thicker than the varves from Lake Linnè, and provided a better resolution of intra-annual events.

Massive summer layers (both homogenous and graded) may occur because of anomalously large events due to spring snow melt or very large storms, or at the H site may be a result of sediment slumping or turbidities in a year when other events are absent. The thickness of the massive beds suggests that they represent large events. The H site sits at the head of the deep lake basin, relative to lake bottom current flow. It is therefore possible that a slumping event would deposit sediment in a thick, fining upward sequence.

Simple laminations may be due to years which do not meet a certain threshold for the deposition of storm events, and perhaps the generation of large underflows, as in couplets with complex or massive summer layers. An average rate of deposition may occur during these years, with very little storm activity occurring during the summer to contribute event sedimentation, as well as average temperatures with moderate to lower rates of glacial melt and glacial meltwater discharge to the lake. Simple summer layers may also occur in years where only the nival melt is recorded, with no major storm activity. Additionally, simple varve deposits may be indicative of a starved sediment system where past years of high erosion, transport and deposition of sediment leaves little sediment available for subsequent reworking beneath the glacier, as documented in other small alpine glaciers (Willis 1996)

Diffuse layering of sediments may occur during below average melting years, as diffuse varves were generally thin. There may be years or a series of years where sedimentation is low due to low summer temperatures, snowfall, and precipitation as well as storm events. Diffuse layering could also be the result of varying types of flow into the lake. Sediment is deposited most rapidly with underflow currents in the lake, but interflows and overflows have also been observed in Lake Linnè. Interflow and overflow currents deposit sediment by settling through the water column, therefore resulting in poorly defined couplets without internal laminations.

Weather Correlations

The weather data available for Svalbard provides a weather record that was utilized on the monthly scale in this study. Weather trends show highly variable summer months in terms of both precipitation as well as temperature. July and August were the two most variable months, and these variations are likely captured in the varved sediment record. Analysis of weather data from Longyearbyen and Isfjord Radio shows a general increase in average summer temperature beginning approximately in the 1980s, consistent with the general increase demonstrated in the arctic latitudes and globally (Kaufman 2009, IPCC 2007). Precipitation is generally uniform for the past three decades despite the upward trend in temperatures. Prior to the mid 1970s, there exists a period of high annual snowfall and total precipitation.

Core D3A

At core site D3Acorrelations between varve thickness and weather parameters would indicate a proximal system where deposition is driven predominantly on the seasonal scale by summer temperatures and temperatures. This would imply that summer meltwater discharge from the glacier is determined partly by the temperature changes and as a result sees the strongest relationship between temperature and annual thickness. However, the correlations between the core and weather are weak, indicating other factors must be involved that drive summer deposition. Summer precipitation is the most variable weather parameter, and in other glacier systems is a large contributor to meltwater as rainstorms add runoff to the glacier surface and may trigger the melting of significant amounts of ice during storm events. The relationship between thickness and summer precipitation is also weak, indicating that summer rains do not increase the overall sediment load to the meltwater stream.

The D site provided the strongest relationship to temperature, perhaps indicating an overall glacier system where ablation is affected most by changing temperatures. Correlations between August temperatures and thickness were the strongest, though still weak, and indicate a glacial meltwater signal that is represented more by temperatures in the late summer rather than by fluctuations earlier in the season. A positive, weak relationship with the positive degree day estimate also shows the link between the sum of degrees in days above 0° C. The varved sediments from core D3A overall contain the most complex record of the samples collected for this study, and capture a complex sediment record of potentially the magnitude of these variable events.

Core H4A

Located in the deep basin distally from Site D, the H4A core is less variable in thickness over approximately the past 100 years. Because of the less variable nature of sedimentation and the lack of intra-annual deposits, core H4A is a good candidate for overall weather parameters such as summer temperature, positive degree days, and summer precipitation correlations. The strongest relationship was demonstrated with summer temperatures; however the correlations with temperature and varve thickness were not as strong as those from the D site. The varves at the H site may therefore receive contributions from sources other than summer melting. The lack of a strong relationship between summer precipitation and varve thicknesses indicates that rainstorms during the summer do not contribute a large sediment load to the stream. Similar to site D, the H4A core has its strongest weather relationship between summer temperatures and varve thickness. August temperatures also show the strongest monthly temperature relationships, indicating that June and July temperatures have a lower impact on glacier ablation than melt temperatures during August. The positive degree estimate also showed a stronger relationship than the mean summer temperature, although these relationships are relatively weak.

It must be noted that the most recent twenty years correlates strongly with temperature records, indicating that temperature has become a larger factor in the deposition of varved sediment at site H. Compaction of sediment in the lake has been shown to be an insignificant factor in determining varve thickness at other sites in the lake (Nelson 2009), and because these sediments correlate reasonably well with other sites it can be assumed that compaction is not a factor at site H in making varves from after 1990 thinner.

Complex varves at site H indicate a highly variable intra-annual system which may experience inputs from multiple factors that vary in magnitude on an annual scale. Complex varves demonstrate certain years experience high magnitude events or years of continuous underflow current deposition. Massive varves may indicate anomalous events such as turbidity slump deposits, large storm events, or settling of large amounts of settling from interflows and overflows. Simple varve couplet sequences indicate periods of relatively low magnitude variability or muted weather factors. Spring snow melts and inwash from the neighboring meteoric delta north of the H site may contribute sediment and therefore mask the temperature signal found at site D.

Core H6A

At the meteoric inwash core site, it was found that total snowfall had the strongest relationship with measured varve thickness. Overall trends showed years with high annual snowfall during an interval prior to the mid-1970s, with the measured thicknesses in varves matching these conditions. Because the water dumped into the lake from this stream is not glacially influenced, it appears that precipitation events may drive the sedimentation proximal to the delta. The strongest relationship with total snowfall indicates that the spring melt most likely drives the sediment deposition at this site, as larger amounts of snow generate more meltwater in the spring which can therefore carry more sediment into the lake. The varves in the H6A therefore represent varves deposited periglacially rather than proglacially. It must be noted, however, that there is an increase in total varve thickness similar to the trends observed in the cores H4A and D3A, indicating that the increasing summer temperatures may also be playing a role in increased sedimentation. The increase in summer temperatures for the past few decades does not correlate to any trends in increasing precipitation, indicating the varves deposited at this site are experiencing a more complex sedimentary history. It is possible that the increased sedimentation in the lake driven by a melting glacier is affecting the varve deposition at the H6A site in the last few decades, superimposing this stronger temperature signal on top of the weak precipitation signal during the last few decades.

Note on Compaction

Bulk density measurements from site G were taken by Pratt (2006) for a core from site G. The mass accumulation rates were calculated, and for the top 5 cm of the core were .045 g/cm^3 and .033 g/cm^3 for the bottom 31 cm. There was a calculated 27% difference between the top 5 cm and bottom 31 cm, but this difference does not fully account for the thickening varves in observed in the past few decades. Therefore the thicker varves at the top of the cores D3A and H4A can be attributed in part to the relationships observed between summer temperatures and thickness.

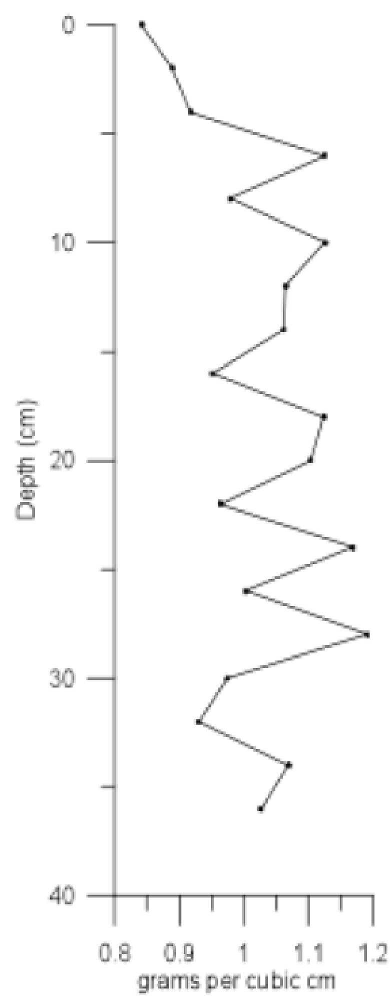

Figure 34. Bulk density measurements for a core from site G. From Pratt (2006).

Variability of the Proglacial System

The highly variably and complex varves found at site H and D demonstrated a weak correlation with summer and monthly temperatures. However, the weak relationships indicate other sources contribute to sediment flux and distribution, which can be partially explained by past studies of the proglacial environment and its relation to sediment erosion discharge. During the spring, it is possible to have a snowmelt event that percolates through existing snowpack, creating a stream carrying little sediment to the lake (Jansson 2005). A late spring snowstorm could replenish the snow cover, and later summer rainstorms could melt this snowpack, increasing the discharge of the meltwater stream significantly (figure). Additionally, meltwater streams have been documented to be sediment sinks during low discharge stages, and that high magnitude discharge events remobilize this sediment (Willis 1996). Because of its length (~6km), large amounts of sediment can be stored in the Linnè stream system, and the lack of strong precipitation correlations could indicate the storage and remobilization of transport based on these threshold limits. Field observations noted areas of the stream system where the grade of the river bed leveled off proximal to the glacier, leading to the deposition of coarser sediment on a mudflat. It is possible that large magnitude rainstorms could mobilize this trapped sediment (Rubensdotter 2003), leading to intra-annual deposits found at site D and the complex summer layers at site H. The proglacial environment directly in front of an ablating glacier also contains a large amount of newly exposed sediment, which can be eroded and transported to the lake. During a change from a cold to warm interval, (such as from the LIA to the modern) a rapidly retreating glacier can quickly expose large amounts of sediment, resulting in a large increase in sediment flux (Jansson 2005).

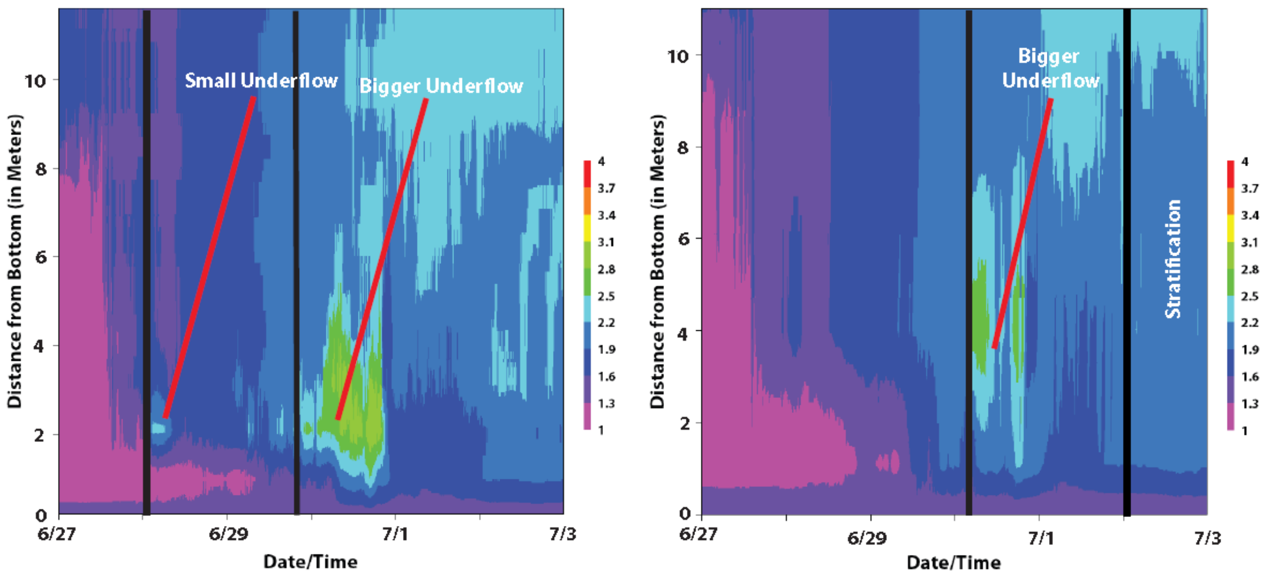

Figure 35. Temperature (color scale to the right) plots showing two underflow events at the D site during the 2010 summer. From Zamora Reyes (2010).

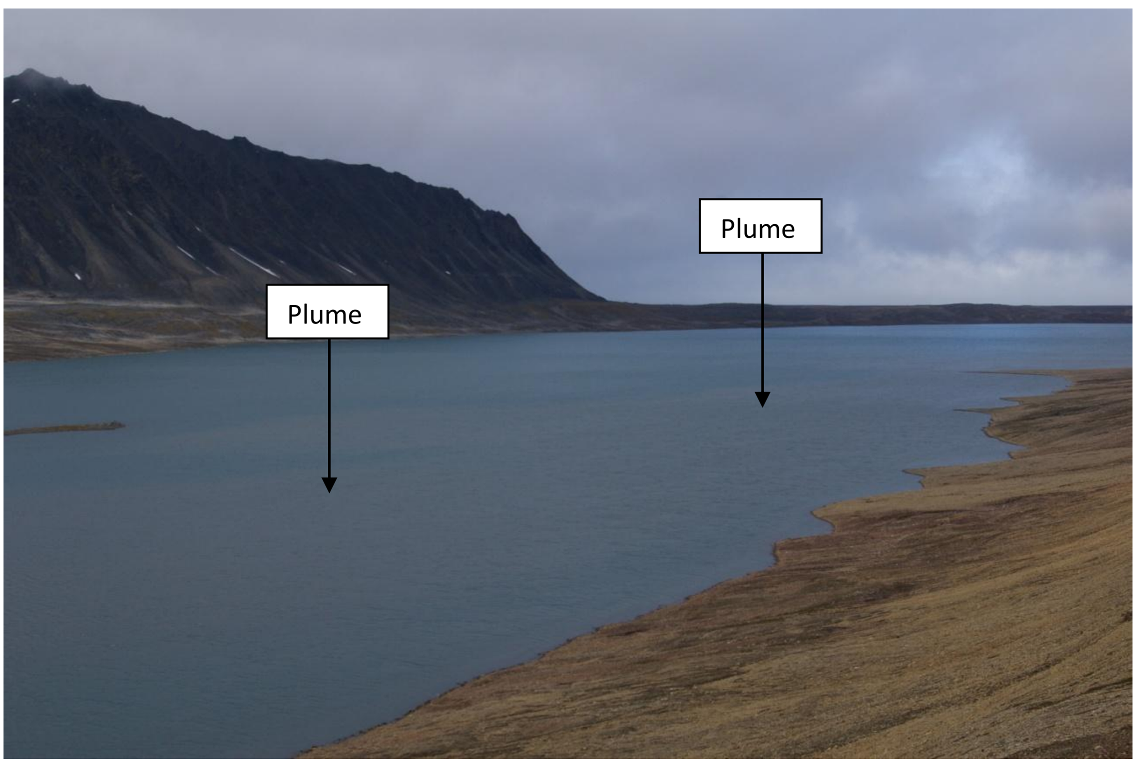

Figure 36. Photograph of Lake Linnè with a faint sediment plume moving down lake along the eastern shore (right of image). Note the color difference in sediment color (brown) and lake water.

Variability of the Subglacial System

Fluctuations in the glacier hydrology of Linnèbreen are a potential factor in determining variations in glacial sediment input to Lake Linnè. Studies have documented the variability of ablation, subglacial channels, and glacier movements with fluxes and changes in suspended sediment. The distribution of subglacial drainage systems and glacier hydrology differ annually. Drainage systems can erode previously uneroded sediments as the system shifts, producing more sediment for years where drainages encounter previously uneroded sediment (Jansson 2005). Alternatively, a drainage system may encounter little new sediment for erosion in a given year, leading to reduced sediment discharge. Therefore, the sediment amounts for a given summer are a factor of the availability of unworked sediments underneath the glacier and when this sediment is evacuated. Subglacial drainages can also become subglacial channels, exhausting the sediment supply underneath the glacier in a large magnitude event, leaving relatively little sediment available for the rest of the summer season, and potentially following years depending on the magnitude of subglacial flooding (Riihimaki 2005).

Studies of other high arctic glaciers in the Svalbard region indicate that superimposed ice has a large influence on glaciers during the early summer season. Because cold temperatures penetrate deep beneath the glacier surface in winter (Hodgkins 1997), it creates a layer of superimposed ice on the glacier. This drives supraglacial flow of water over the glacier surface in the early season, as superimposed ice does not allow water to reach subglacial channels. Therefore, subglacial channels instead do not begin to form until later in the summer when the supraglacial drainage is exhausted and surface ice and snow warm up (Hodgkins, 1997). The stronger association of August temperatures with varve thickness in cores H4A and D3A could represent the subglacial drainages opening and subsequent erosion occurs to sediment beneath the glacier, contributing more sediment to the system than supraglacial water flow.

Conclusions

Correlations of varve thicknesses with different weather parameters establish the ability of the varved sediment at Lake Linnè to act as as a complicated proxy for climate change in the region. The methods used in the counting and measuring of varves proved successful in establishing a link between past studies at distal and proximal sites with the intermediary H site and the D coring site. This link demonstrates a basin wide relationship in deposition, with the distal sites experiencing lower sedimentation rates and lack of intra-annual variations and complexities. At the D and H sites, varve sequences are difficult to interpret, but offer potential intra-annual resolution for the determination of stochastic events. Varve thicknesses at both the D and H sites show relationships between summer temperatures, but lack strong relationships between thicknesses and precipitation. Overall, temperature is the strongest force in driving sediment deposition at site D, with a lesser effect on the deposition of sediment at site H.

Summer layers that are complexly laminated indicate signals from many factors that contribute to varved deposition, but the statistical relationships with weather parameters show moderate to weak trends. Therefore, the H site may yield stronger relationships with weather parameters that may indicate climate change in the region. Its variability and sensitivity make it a candidate for future coring studies, with the correlation of other cores and use of absolute dating techniques. Analysis of the H6A core from the meteoric inwash site indicates deposition is driven weakly by precipitation, and not the melting glacier. However, there is an increase in varve thickness similar to the increasing thickness observed in cores H4A and D3A over the past few decades. This may mark a shift from an inwash dominated to glacially dominated situation at site H6A. Overall however, the lack of strong signals from summer temperatures ultimately indicates a very complex glacier, meltwater stream, and lake system, where many parameters can influence the ultimate deposition of sediment in the lake.

More significant weather and varve thickness relationships exist for the most recent decades and may indicate a system responding to a changing climate. The trends correlate with the observed global temperature anomaly (IPCC 2007) as well as the observed sensitivity of high arctic regions to climate change (Mann 1998). The cores show this general increase in varve thickness over the past decades, indicating that increased temperature appears to be having an impact on varve thickness. An abrupt transition occurring around the year 1992 in both the H and D sites indicates a rapid change in the forces driving varve deposition, also corresponding with the noted increase in temperature. This rapid response to increasing temperatures in the varve record potentially indicates that the Arctic region in Svalbard is highly sensitive to changing climatic and weather. Further development of the varve chronology at Lake Linnè may ultimately yield a highly sensitive climate proxy that is indicative of overall climate change in the region, although the complexities in the system cannot be ignored. Even though this study did not address some of the complexities mentioned above, further research is increasingly important given the modern issues of climate change and its effects on both the Arctic regions and the planet as a whole.

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References

Arnold, M.S. *Sedimentation in High-Arctic Lake, Linnèvatnet, Svalbard: A Modern Process Study Using Sediment Traps.* Bates College, 2009.

Bradley, R. et al. "Climate in Medieval Time." *Science* 302 (2003): 404-405.

Chutko, K.J. and S.F. Lamoureux. "Identification of Coherent Links Between Interannual Sedimentary Structures and Daily Meteorological Observations in Arctic Proglacil Lacustrine Varves: Potentials and Limitations." *Canadian Journal of Earth Science* 45 (2008): 1-13.

DeGeer, G. "A Geochronology of teh Last 12,000 Years." *Compte Rendu XI Session du Congres Geologique International*, 1912: 241-257.

Denton, G.H. and W. Karlen. "Holocene Glacial and Tree Line Variations in the White River Valley and Skolai Pass, Alaska and Yukon Territory." *Quaternary Research* 7 (1977): 63-111.

Hansen, J. et al. *Current GISS Global Surface Temperature Analysis.* New York, New York: NASA Goddard Institute for Space Studies, 2010.

Hodgkins, R. et al. "Suspended Sediment Fluxes in a High Arctic Glacierised Catchment: Implications for Fluvial Sediment Storage." *Sedimentary Geology* 162 (2003): 105-117.

Hodgkins, R. "Glacier Hydrology in Svalbard, Norwegian High Arctic." *Quaternary Science Reviews* 16 (1997): 957-973.

Ingolfsson, O. "Outline of the Physical Geography and Geology of Svalbard." 2006.

IPCC, International Panel on Climate Change. "Climate Change 2007: Synthesis Report." Edited by A. Reisinger R.K. Pauchari. *IPCC Fourth Assessment Report, 2007.* Geneva, Switzerland, 2007.

Jansson, P. et al. "Glacier Fluctations, Suspended Sediment Flux and Glacio-Lacustrine Sediments." *Geografiska Annaler* 87 (2005): 37-50.

Kaufman, D.S. "An Overview of Late Holocene Climate and Environmental Change Inferred from Arctic Lake Sediment." *Journal of Paleolimnology* 41 (2009): 1-6.

Lamoureux, S.F. "Embedding Unfrozen Lake Sediments for Thin Section Preparation." *Journal of Paleolimnology*, 1994: 141-146.

Leon, B.H. Undergraduate Senior Thesis, Bates College, 2006.

Lowell, T.V. "As Climate Changes, so Do Glaciers." *Proceedings of the National Academy of Sciences* 97 (2000): 1351-1354.

Mann, M. et al. "Global-Scale Temperature Patterns and Climate Forcing Over the Past Six Centuries." *Nature* 392 (1998): 779-787.

Nelson, A.H. *A Varved Sediment Analysis of 1,000 Years of Climate Change: Linnèvatnet, Svalbard.* Undergraduate Senior Thesis, Williams College, 2009.

Pompeani, D. *A 360 Year Varve-based Climate Reconstruction from Linnévatnet on Western Svalbard.* Undergraduate Senior Thesis, University of Pittsburg, 2008.

Pratt, E. *Characterization and Calibration of Lamination Stratigraphy of Cores Recovered from Lake Linné, Svalbard Norway.* Undergraduate Independent Study Report, Bates College, 2006.

Ridge, J. *North American Glacial Varve Project.* 2010. http://geology.tufts.edu/varves/nevc/nevcintro.asp (accessed April 2010).

Riihimaki, C.A. et al. "Sediment Evacuation and Glacial Erosion Rates at a Small Alpine Glacier." *Journal of Geophysical Research* 110 (2005).

Rubensdotter, L. and G. Rosqvist. "The Effect of Geomorpological Setting on Holocene Lake Sediment Variability, Northern Swedish Lapland." *Journal of Quaternary Science* 18 (2003): 757-767.

Serreze, M. et al. "Perspectives on the Arctic's Shrinking Sea Ice Cover." *Science* 315 (2007): 1533-1536.

Svendsen, J. and J. Mangerud. "Holocene Glacial and Climatic Variations on Spitsbergen, Svalbard." *The Holocene*, 1997: 45-57.

Svendsen, J. et al. "Denundation Rates in the Arctic Estimated from Lake Sediments on Spitsbergen, Svalbard." *Paleogeography, Paleoclimatology, Paleoecology* 76 (1989): 153-168.

Thomas, E. "Using Geochemical Evidence to Determine Provenance in a High Arctic Glacier-Fed Lake, Linnè Valley, Svalbard, Norway." Undergraduate Senior Thesis, 2005.

Thompson, L.G. et al. "The Little Ice Age as Recorded in the Stratigraphy of the Tropical Quelccaya Ice Cap." *Science*, 1986: 361-364.

Werner, A. "Holocene Moraine Chronology, Spitsbergen, Svalbard: Lichenometric Evidence for Multiple Neoglacial Advances in the Arctic." *The Holocene*, 1993: 128-137.

Willis, I. et al. "Links Between Proglacial Stream Suspended Sediment Dynamics, Glacier Hydrology, and Glacier Motion at Midtdalsbreen, Norway." *Hydrological Processes* 10 (1996): 629-648.