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STEVE ROOF: Hampshire College
MIKE RETELLE: Bates College

DIRECTLY-CONTROLLED LICHEN GROWTH CURVES FOR WESTERN SPITSBERGEN, SVALBARD

TRAVIS BROWN: College of Wooster
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METEOROLOGICAL AND GLACIAL ABLATION CONTROLS ON ANNUAL SEDIMENT ACCUMULATION AT LINNÉVATNET: SVALBARD, NORWAY

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Wesleyan University
Research Advisor: Suzanne O'Connell

INTRODUCTION

Today, global climate is rapidly changing, especially in the High Arctic. According to the US Arctic Research Commission, over the past decade, the Arctic has experienced unusually high melting of glaciers, sea ice, and permafrost and has seen changing patterns of both rain and snow fall (US Arctic Research Commission, 2007). One mechanism used to anticipate what climate will be like in the future is to understand how climate has changed in the past. The purpose of this study is to determine how meteorological conditions and glacier ablation influence sedimentation in Linnévatnet, a High Arctic lake in Svalbard Norway, between 2004 and 2009. Linnévatnet contains a 9,000 year record of lacustrine sediments, so understanding modern sedimentation patterns in Linnévatnet may allow for more accurate long-term interpretations of the climate record in the High Arctic. Previous studies in other proglacial lakes in the Arctic have indicated that varve thickness reflect meteorological influences in the catchment area (Leeman and Niessen, 1994; Mangerud and Svendsen, 1990; Snyder et al., 2000).

This study analyzed sediment trap data collected by four previous Svalbard REU students (Motely, 2005; Roop, 2006; Cobin, 2007; and Arnold, 2008) in combination with Jacalyn Gorczynski's data collected at mooring C in the East Basin of the lake during summer 2009. The bottom-most sediment trap at mooring C, which is approximately 0.4 km from the Linnéelva delta, was the focus of this study because it has been the focus of past projects and is considered to be more representative of sedimentation at this location. This study attempted to relate temperature degree days, glacial snow and ice ablation, and summer rainfall with total summer sediment accumulation to determine why sedimentation records in Linnévatnet differ year-to-year and season-to-season.

STUDY AREA

Svalbard, an archipelago in the Arctic Circle, is located between 74° and 81° north latitude and between 10° and 35° east longitude. The main islands are Spitsbergen, Nordaustlandet, Arentsøya, Edgeøya, Kong Karls Land, Prins Karls Forland, and Bjørnøya (Ingólfsson, 2006). The study site, Kapp Linné, is a small cape on the west coast of Spitsbergen (Fig. 1, Project Overview). Linnévatnet, a proglacial lake located just east of Kapp Linné, occupies a glacially over-deepened basin approximately 4.7 km long and 1.3 km wide (Mangerud et al., 1992; Svendsen et al., 1987; Svendsen and Mangerud, 1997). Previous studies have shown that Linnévatnet is an isochemical and isothermal monomictic lake that remains at a temperature below 4°C throughout the year (Bøyum and Kjensmo, 1978).

METHODS

Throughout Linnévatnet, moorings have been deployed, composed of sediment traps and temperature loggers. During the summer of 2009, four sediment traps were recovered at mooring C at depths of one meter, five meters, nine meters, and twelve meters above the lake bottom. However, this study only focused on the bottom-most trap. The design of each mooring consists of nylon rope which is anchored with a large rock at one end and consists of a buoy at the top of the rope. Funnels were used to collect suspended sediment. Attached to the funnel was a piece of polycarbonate tubing sealed at the bottom in which the sediment accumulates. On top of the funnel is a 1 cm^2 baffle, plastic grid, to assist the capturing of suspended sediment, as well as reintrainment of sediment.

Over the past five summers, the sediment traps have typically been deployed in late July to early August and recovered around the same time the following year. Also, over the past several years, some students (Roop, 2007) washed the sediment stuck on the funnel walls into the receiving tubes and other years, students did not, therefore the top 0.5 cm of the sediment tube may be anomalous. In this study, it was important to look at the winter and summer accumulation separately because the influence of meteorological events is dependent on the time of year. For example, when trying to understand what impacts summer sedimentation, it is important to focus on environmental controls during the summer seasons. Determining where to separate the winter and summer layer in the sediment tube was based on data from the spring Troll, an automated CTD that measured temperature, turbidity, and conductivity every two minutes. At the start of the summer melt season, turbidity levels rise indicating the initiation of sediment flux into the lake. The number of turbidity events, which vary from year-to-year, have been qualitatively correlated with sedimentation events in the lake (Arnold, 2009). Turbidity measurements were only available for the 2006-2007 and 2007-2008 sedimentation years. However, the summer and winter layers of 2004-2005, 2005-2006, and 2008-2009, were qualitatively calculated based of the 2006-2007 and 2007-2008 measurements. The sediment in each trap is defined by two unique layers. A clay (winter) layer, generally fine-grained, is deposited from the end of the summer melt season to the beginning of the melt season, whereas the summer layer is typically more coarse-grained and begins sometime in June-July.

Once the sediment traps were back on shore, visual stratigraphic measurements were recorded and the tubes were left for a few days to allow the tubes to dewater and let the remaining suspended sediment settle. The traps were then brought back to Mt. Holyoke where they were split and studied. The stratigraphic thicknesses and sample depths are based on the split trap samples.

About a kilometer south of Linnévatnet, an automated weather station records wind speed, wind direction, air temperature, ground temperature, precipitation, solar radiation upwards and solar radiation downwards. The weather station records these meteorological variables every 30 minutes year round and the average daily air temperatures are used to calculate temperature degree days. The total degree day for each sedimentation year is simply the addition of all the degree days in the winter and all of the degree days in the summer.

Temperature loggers were deployed in Linnéelva. One temperature logger was placed in the "lower-stage" which is roughly seventy-five meters south of Linnévatnet. This logger has recorded temperature at thirty-minute intervals since July, 2008. To document conditions when we cannot be in the field, an automated camera located above the eastern shore of Linnévatnet takes two daily photographs of the south end of Linnévatnet. These images provide a visual record of snow cover on the landscape, ice cover on the lake, and sediment plumes where Linnéelva flows into the lake.

To determine when the summer season started, this study looked at the average air temperatures, minimum air temperatures, river temperatures, and the plume camera. The summer season began in most sedimentation years when the average daily river temperature and minimum air temperature were greater than 0°C. When the dates that corresponded with these parameters were found, the plume camera was used to visually determine the state of Linnédalen.

To calculate the total amount of snow accumulation, summer melt, and net balance on Linnébreen, mass balance measurements were used. Mass balance measurements represent the total amount of snow or ice, either lost or gained, each year (Kohler, 2007). The winter balance is calculated by taking snow-depth soundings on the glacier and measuring ablation stake heights and snow density (Kohler, 2007).

To calculate the summer balance, one must take the stake height measurements above the ice surface made in the spring and compare them to the fall stake measurements (Kohler, 2007). Finally, these two balances are extrapolated over the entire glacier using an area of 50 meter intervals obtained from either maps or digital elevation models (DEMs) (Kohler, 2007).

RESULTS

Since 2004, the 2004-2005 sedimentation year was the warmest and 2008-2009 was the coolest (Table 1). This project however focused on the summer seasons over the past five years. During the winter season, precipitation is usually snow, so this study focused mostly on the precipitation (rain) data that occurs during the summer melt season when air temperatures were above freezing. Over the past five sedimentation years, the total amount of summer rain has ranged from 34.6 mm. to 82.2 mm, a difference of a little less than 50 mm (Table 1) Over the past five sedimentation years, the bottom-most trap at mooring C in Linnévatnet collected a cumulative total of 83.65 cm of sediment (Table 2). Because this study focused on the winter and summer seasons independently, it was important to break up the sediment data into a winter layer and a summer layer. As seen in table 2, the 2007-2008 sedimentation year was dramatically lower than the other years. Also, the 2006-2007 sedimentation year was anomalously high compared to the other years. To determine why there might be more coursed-grained sediment during one summer season than the next, this study examined how the total amount of summer degree days differ year-to-year, with 0°C as the base temperature (Table 2). The sedimentation year with the lowest amount of summer sediment accumulated was the same sedimentation year with the lowest cumulative summer degree day. Using the data collected in both the spring and the summer, Jack Kohler of the Norwegian Polar Institute calculated the total amount of snow accumulation during the winter and the total amount of snow and ice loss (ablation) in the summer (Table 3). When looking at total sediment thickness during the winter and summer seasons, it is important to look at how glacial ablation has varied year-to-year. This is because previous studies have indicated that Linnébreen is the main source of meltwater and sediment to Linnéelva, which is Linnévatnet's primary source of water and sediment (Snyder et al., 2000). The total summer rainfall per year, the number of summer degree days, and the glacial summer ablation are not significant when correlated to summer

Year Range	Mean Annual Temperature, °C	Summer Season Range	Average Summer Temperature, °C	Total Summer Rain, mm
August 3, 2004 - August 8, 2005	-3.46	June 12 - August 8	5.38	82.2
August 10, 2005 - August 10, 2006	-1.64	June 6 - August 10	5.63	81
August 13, 2006 - July 23, 2007	-3.51	June 3 - July 23	4.70	72.4
July 25, 2007 - July 23, 2008	-3.25	June 21 - July 23	5.12	67.6
August 3, 2008 - July 25, 2009	-4.28	June 15 - July 25	5.37	34.6

Table 1: The summer melt season began in June these past five sedimentation years. In 2005-2006, the mean annual temperature was the lowest and the average summer temperature was greatest.

Summer-Winter	Total Sediment Accumulation, cm	Winter Accumulation, cm	Summer Accumulation, cm	Summer Mean Grain Size	Summer Degree Days (0°C base)
2004-2005	15	5.5	9.5	17.43	318
2005-2006	15.6	5.2	10.4	15.61	371
2006-2007	21.8	5.4	16.4	20.90	239
2007-2008	8.25	3.5	4.75	17.99	170
2008-2009	23	15.5	7.5	15.41	218
AVERAGE	16.73	7.02	9.71	17.47	
TOTAL	83.65	35.1	48.55		

Table 2: The total amount of sediment accumulated in Linnévatnet has varied year-to-year, both during the winter and summer seasons. Data collected by Motely, 2006; Roop, 2007; Cobin, 2008; Arnold, 2009; Gorczynski, 2010. Similarly, the total number of summer degree days has varied year-to-year.

Summer-Winter	Winter Balance, m w. eq.	Summer Balance, m w. eq.	Net Balance, m w. eq.
2004-2005	0.64	-1.73	-1.09
2005-2006	0.74	-1.88	-1.14
2006-2007	0.72	-1.48	-0.76
2007-2008	0.79	-1.13	-0.34
2008-2009	0.60	n/a	n/a

Table 3: Over the past five sedimentation years, the winter balance was greatest in 2007-2008 and least in 2008-2009. As the summer balance increases or decreases year-to-year, the net balance increases or decreases respectively.

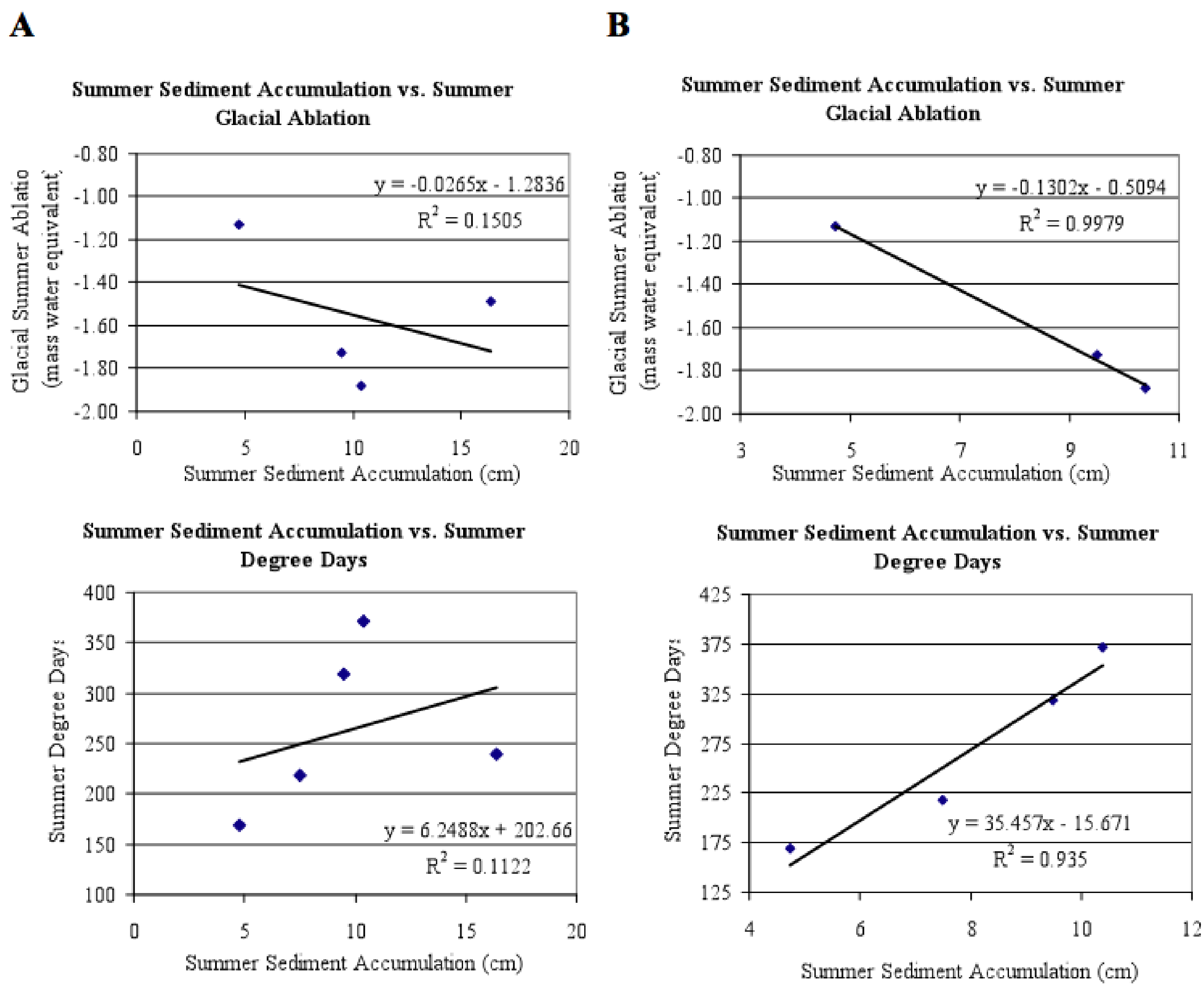

Figure 1: A) These two graphs show that there was no correlation between the total summer sediment accumulation with summer degree days and summer glacial ablation. B) Removing the 2006-2007 sedimentation year results in different r-squared values that do show significance between the total summer sediment accumulation with both summer degree days and summer glacial ablation.

sediment accumulation; the p-value was 0.586 and the r-squared value was 0.110 for total summer rainfall, 0.582 and 0.112 for the number of summer degree days, and 0.612 and 0.151 for glacial summer ablation (Figure 1). However, over the past five sedimentation years, the total summer thickness in 2006-2007 was quite different than the others. If this sedimentation year was removed, the summer glacial balance and number of summer degree day correlations were much stronger (Figure 1). Summer degree days and summer rainfall was related to summer glacial ablation. These variables

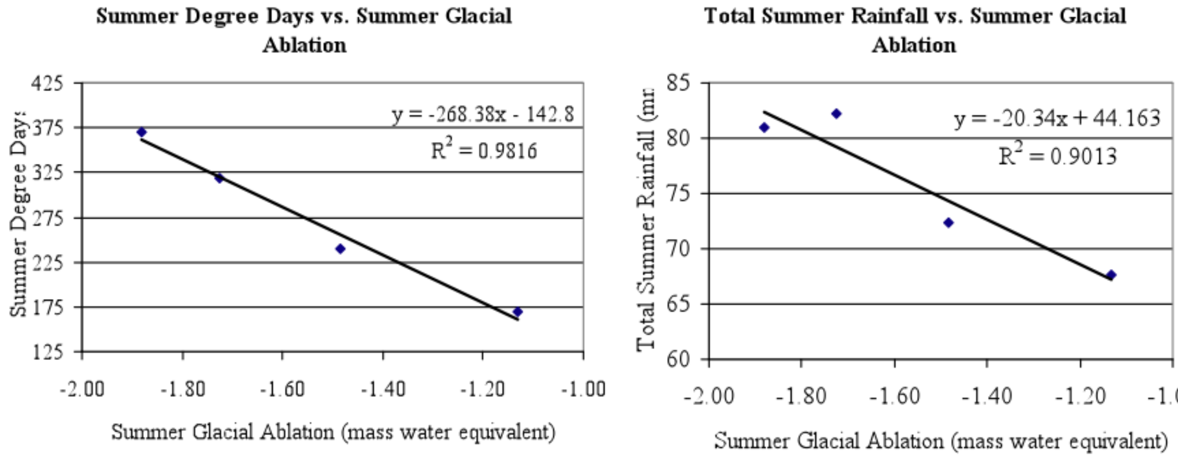

Figure 2: Both summer degree days and total summer rainfall show a strong correlation with summer glacial ablation.

both had positive correlations with summer glacial ablation (p-value = 0.009 and r-squared value = 0.982 for summer degree days and 0.050 and 0.900 for total summer rainfall) (Figure 2).

DISCUSSION

This study attempted to explain why total sediment accumulation differed year-to-year since 2004. Although the data did not initially exhibit any statistical correlations, removing the 2006-2007 sedimentation year did allow for correlations. Since the 2004-2005 sedimentation year, the 2006-2007 year had a significantly larger summer sediment accumulation. One reason why this sedimentation year had a thicker summer layer than the other years may be due to a large turbidity current flowing directly over the trap as suggested by unusually large grain-sizes. For example, the 2006-2007 sedimentation year had the largest mean summer grain-size (20.90 μm) and was greater than the overall mean grain-size for the past five sedimentation years (17.47 μm). Because 2006-2007 mean grain-size was significantly greater than the mean grain-size values recorded during the other sedimentation years, this study thought it was appropriate to run regressions both with and without this sedimentation year.

Statistical tests have shown that glacial ablation and summer rainfall since 2004 do not correlate with annual sedimentation amounts in Linnévatnet. Because of this result, this study looked at how these two variables influence one another. For example, when correlating total summer rainfall vs. summer melt, there was a r-squared value of 0.90 and a p-value of 0.05. These numbers imply that the total amount of summer rainfall impacts the total amount of glacier snow and ice melt that occurs on Linnébreen on a year-to-year basis and thus could provide clues as to how Linnédalen as system functions.

Although the data does not show a clear correlation between summer degree days and summer sediment accumulation, there is a relationship between summer degree days and summer ablation. The r-squared value was 0.982 and the p-value was 0.009. These values imply a correlation between the total amount of summer degree days and summer glacial ablation. Testing how these environmental conditions impact one another might allow for a better understanding of sedimentation in Linnévatnet.

CONCLUSION

Over the past five sedimentation years, total sediment accumulation, both during the winter and summer has varied. This study attempted to understand why these thicknesses varied through meteorological observations and glacial ablation observations.

Year-to-year analyses between meteorological observations and glacial mass balance observations with total sediment accumulation in Linnévatnet do not reveal any statistical significance. However, the anomalously large grains during the summer of 2007 justified running analysis without this sedimentation year. Disregarding the 2006-2007 sedimentation year, there is a strong relationship between weather patterns and glacial mass balance patterns with summer sediment accumulation. The total number of summer degree days has a direct relationship with the total amount of snow melt; as the total number of summer degree days increases, the greater amount of snow melt increases. Furthermore, the total amount of snowmelt is impacted by the total amount of rainfall in a given sedimentation year. Knowing how total summer rain and total value of summer degree days affect the glacial summer balance allows for a better understanding about meteorological factors that impact snow melt throughout the valley. Once we understand that factors that impact snow melt, more complete analysis might be performed to better understand how the total amount of snow melt from year-to-year impacts the total amount of sediment accumulation in Linnévatnet.

FUTURE WORK

To gain a better understanding of what factors drive sedimentation thicknesses in Linnévatnet on a year-to-year basis, a more complete analysis of meteorological and glacial ablation data should be performed. This would help determine the rate at which glacial melt impacts sediment accumulation, either on a year-to-year basis or a multi-year time period.

Deploying a second sediment trap at the bottom of mooring C would allow for a better knowledge of the winter and summer stratigraphy. This way after the two sediment traps are recovered, students could compare the two traps. If the sediment data aligns well, then the trap data will be more reliable. However, if sediment data differ significantly, then it is possible a turbidity current flowed directly over one trap and not the other. To further continue this study and produce new results, creating a multi-year sediment trap might help determine the gaps between the sediment traps from different sedimentation years.

To further understand what influences total sediment accumulation on a year-to-year basis, turbidity should be measured in Linnéelva during the melt season. This would allow us to correlate sedimentation events in Linnévatnet with those in Linnéelva and thus place a time stamp as to how long it takes for sediment to flow from Linnéelva to Linnévatnet. This would also provide a better understanding as to what meteorological factors drive sedimentation in Linnévatnet.

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