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JOHANNA EIDMANN,Williams College
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DANA REUTER, Mount Holyoke College
Research Advisor: Alan Werner

INTRODUCTION

The growing debate over climate change has created a need for understanding past climate patterns. Sediment cores from arctic lakes have been shown to be a valuable tool in paleoclimate reconstructions because of their accurate preservation of the changing climate in their seasonally deposited varved sediments (Overpeck, 1996; Bradley et al., 1996; Overpeck et al., 1997). Knowing how various environmental factors affect sediment deposition in lakes is crucial to properly interpreting past climates. Studies on inflow streams around the world have shown that they can have large effects on sediment transport into lakes (Pickrill and Irwin, 1982; Best et al., 2005; Spigel et al., 2005). The conditions and amount of melt water flowing into these lakes has also been seen to have an effect on size and composition of melt season deposits (Moore et al., 2001). The distinct event types have also been shown to result in different sediment transport and deposition in lakes (Best et al., 2005; Spigel et al., 2005; Forrest et al., 2012).

There are three main types of sediment dispersion processes that happen in lakes: overflows, interflows and underflows. They are all closely related to the density differences of the inflow water and the lake water (Spigel et al., 2005; Forrest et al 2012). The density of the inflowing water is determined by turbidity, salinity, temperature and sediment load (Simpson, 1997; Best et al., 2005; Forest et al., 2012). Overflows happen when the inflowing water is less dense than the ambient water in the lake (Forest et al., 2012) and tend to happen when the inflowing water is colder, less dense than 4 ºC (maximum density of water), than the water in the lake. They also have been seen to contain less sediment than denser flows (Best et al., 2005; Spigel et al., 2005; Forrest et al 2012). Interflows occur when the inflowing water is more dense than the lake surface water but less dense than the bottom water (Spigel et al., 2005). They often flow into the lake at some intermediate depth with slight mixing. If the water entering the lake mixes with the water column both in the vertical and horizontal dimensions it is considered a homopycnal flow (Smith and Ashley 1985, Spigel et al., 2005). Underflows are the most extensively studied because of their large effect on sedimentation; both because of large sediment load and their ability to transport sediment over long distances (Best et al., 2005; Spigel et al., 2005; Forrest et al., 2012). These occur when the inflowing water is more dense than the lake water. They usually are very dense with sediment and can be around 4 ºC.

The importance of these invents on sediment transport have prompted investigations into their timing during the melt season. This study focused on interpreting inflow stream temperature, sediment load and timing of flows, as well as the resulting types of sediment distribution as interpreted from mooring temperature data in the lake. Lake Linné is located in Spitsbergen, Svalbard and is a high arctic glacial lake that is located 4-12 meters above sea level, is 4.7 km long and 1.3 km wide and is up to 37 meters deep (Boyum and Kjensmo 1978). Lake Linné is fed by a melt-water stream that originates at the glacier Linnébreen. The lake is also fed by snow melting events in the valley and occasionally water from springs by the nearby karst Lake Kongress.

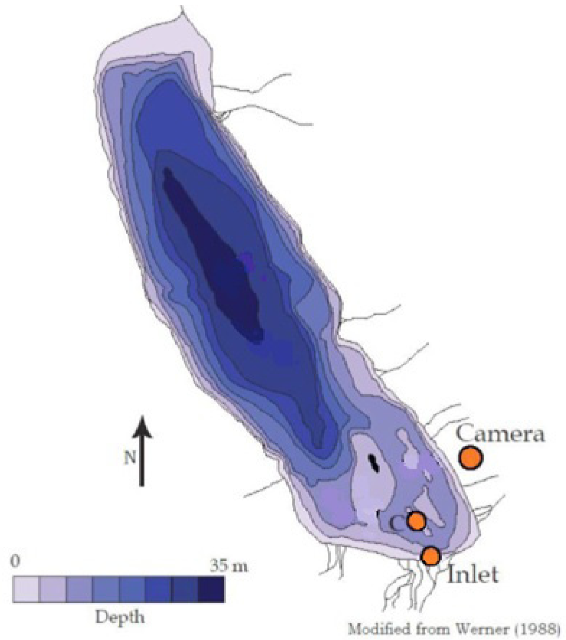

Figure 1. Bathymeteric map of Lake Linné with mooring C, plume camera and inlet locations.

METHODS

The data used in this study was collected using Onset HOBO Data Loggers. We used temperature loggers suspended in the water column by moorings to provide a clear picture of the inflow events as they entered the lake from the inlet stream. The loggers were spaced every meter for 13 meters down the water column. There was also a logger on top of the anchor rock at the base of the moorings. Data was collected every ten minutes from 4/15/13 to 7/19/13. The data used in this study was from spring mooring C located closest to the inlet river (Fig. 1). Timing of sediment deposition in the lake was also documented by an intervalometer, an automated sediment trap that records the timing and rate of sediment accumulation. Data from the intervalometer was used to help identify important depositional events and show the amount of sediment that was deposited. Inflow stream temperatures and air temperatures were also collected using temperature loggers. These were compared to lake temperatures as well as used to identify the start of the melt seasons. An automated camera (referred to as the plume cam), set up on a nearby ridge, took pictures of the inlet stream twice a day all the spring and summer season. The pictures were used to identify rain, snow, ice melt, and visible sediment plumes. All of this data was used to help compile a time line of sediment distribution events and sedimentation in Lake Linné. Sediment distribution events were identified by creating a composite graph of lake temperature stratigraphy and looking for correlations between inflow stream temperatures and temperature changes in the lake water column. Abrupt changes in temperature greater than 0.5 ºC were interpreted as significant. Smaller events were noted but were not the focus of this study. Sedimentation events recorded by the intervalometer were also studied.

RESULTS

During the time when the snow melts, around late June and early July, the lake experiences an inflow of water and sediment. In the spring and summer season a total of thirteen distinct sediment dispersal events were observed (Tbl. 1). Not all of these events, however, were seen alongside sediment deposition recorded by the intervalometer. Overflow events dominate the beginning of the melt season when inflow temperatures are close to zero and sediment content is relatively low. The middle of the melt season was dominated by interflow events as inflow temperatures warmed to 4ºC. Underflow events happened later in the season and are associated with the larger sediment depositional events recorded by the intervalometer during the 2012/2013 sedimentation year. In the spring before melting occurred patches of water were visible by the plume cam for 5/4/13. They make it to the lake's edge on 5/18/13. This event was not detected by the temperature loggers in the stream or lake. On 6/14/13 the inflow stream temperature (Lower stage data in figures) rose from freezing to 2.15ºC.

From 6/16/13 to 6/23/13 there were three distinct overflow events and 3.62mm of sediment deposited in total. The first interflow event was recorded on 6/24/13 and affected 2 meters above the bottom of the lake. It occurred after the inflow stream reached 4ºC for the first time the day before. The next important event happened on 6/28/13 and it correlates with an increase in 11.66 mm of sediment in the intervalometer data (Fig. 2). This event still did not have an effect on the bottom of the lake (TOR). On 6/30/13 there was a slight warming in all layers. The top layers were affected the most and rose from around 2 ºC to at or above 3 ºC (Fig. 3). This event was seen as an

Table 1. Inflow events with dates, layer affected, change in lake water temperature, event type based on water layers affected, air and inflow temperatures at start of event, and total sediment present in intervalometer end of event. Intervalometer data is cumulative.

Date	Logger Affected (meters above TOR)	Change water in Temperature	Event Type	Air Temperature	Inflow Temperature	Intervalometer Data
05/27/13	11 and 10 meters	0.139 drop	overflow	-2.5ºC	-0.1ºC	0.29853 volts
05/31/13	all layers except TOR	0.1 drop	Mixing of Stratified layers	2.97ºC	0ºC	0.29853 volts
06/09/13	13 meter	0.7160ºC rise	overflow	3.18ºC peak	0ºC	0.29853 volts
06/16/13	13 and 12 meters	0.656ºC rise	overflow	0.34ºC	2.155ºC peak day before	0.29915 volts
06/17/13	13 and 12 meters	0.439ºC rise	overflow	2.25ºC	1.805ºC	0.29853 volts
06/20/13	13 and 12 meters	0.655ºC rise	overflow	5.93ºC	1.940ºC	0.39499 volts
06/21/13	13 and 12 meters	0.95ºC rise	overflow	5.65ºC	3.063ºC peak	0.40720 volts
06/24/13	2 and 3 meters	0.711ºC rise	interflow	2.84ºC	4ºC before event 1.3ºC at event	0.50305 volts
06/27/13	all layers except 13, 1meter, and TOR	0.649ºC rise	Mixed interflow	4.67ºC	3.906ºC	0.51404 volts
06/28/13	1-8 meters 3 and 2 being most affected	1.339ºC being greatest rise	low interflow	5.96ºC	3.591ºC rises above 4ºC during event	0.92674 volts at end of event
06/30/13	all layers experience warming except TOR	1ºC rise	Mixing inflow	7.28ºC	5.616ºC	0.91026 volts
07/01/13	all layers affected	TOR-7 meters rise about 2ºC, 8-9 rise then drop, 10-13 drop 0.9ºC	Underflow followed by overturn	7.93ºC	4.973ºC	1.37729 volts
07/02/13	TOR	0.9 ºC rise	Underflow	8.31 ºC	5.898 ºC	1.48779 volts

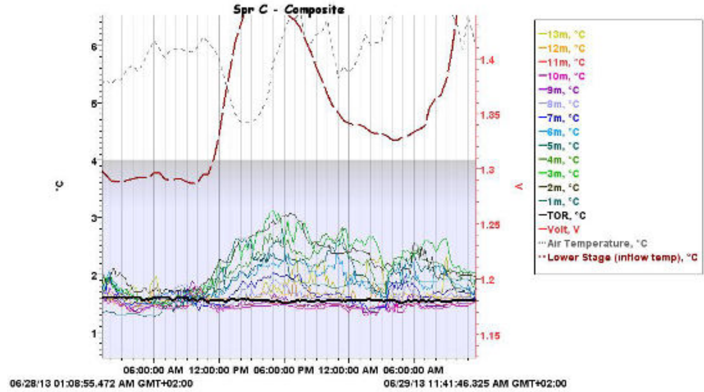

Figure 2. 6/28/13 event. Loggers most affected are 2 and 3 meters above the bottom of the lake. The logger at 1 meter above the lake is also affected but not as much. Base of the mooring (TOR) is unaffected. Inflow temperature reaches 4 ºC right as event starts but it was near 4 ºC before the event as well. Note every 0.06 volts recorded by the intervalometer represents 2mm of sediment deposited.

interflow or a homopycnal event that mixed with the water column. The first event where the bottom of the lake (TOR) saw a change in temperature, from 1.56 to 3.75ºC, happened on 7/1/13 (Fig. 4). Loggers located at 1, 2, 3, 4, 5, 6, and 7 meters above the bottom also rose in temperature. The loggers at 8, and 9 meters above the bottom of the lake experienced an initial rise in temperature but then suddenly dropped in temperature. The loggers nearest the surface of the water (10, 11, 12, and 13 meters above the bottom) drop in temperature from about 2.4 to around 1.5 ºC. This was classified to be an underflow because of the temperature of the inflow water and the rise in intervalometer data. The event also seems to have started a turning over of the water in the lake which resulted in the cooling of the top layers.

DISCUSSION

The compiled temperature data shows initial patterning in the type of event and timing in the melt season; with overflows happening in early spring, interflows happening in the middle of spring, and underflows happening in late spring and early summer. The very early inflow events seen in May before major melting and rises in air temperature could have been water from underground springs located close to Lake Kongress. The inflow temperature (below freezing) also suggests that the inflow stream was not completely melted. The dominant type of sediment dispersion being an overflow in early spring is likely related to the water temperature being around 1 to 2 ºC and not heavily sediment laden; as shown by the inactivity in the intervalometer. Therefore the inflowing water was less dense than the lake water causing it to flow over the lake surface water. Possible error in these early overflows could be that the lake surface water was warming naturally due to the increasing air temperature. The presence of ice cover during these early events could act as an insulator against the warm air temperature. This suggests that the original interpretation of the surface warming as overflows to be possible.

The later transition from overflows to interflows likely resulted from the oscillation of the inflow temperature around 4 ºC along with increases in sediment load. For two of the low interflow events there was an increase in sediment deposition recorded by the intervalometer. The amount sediment deposited by these events was much lower than the sediment deposited by the later underflow event. The small

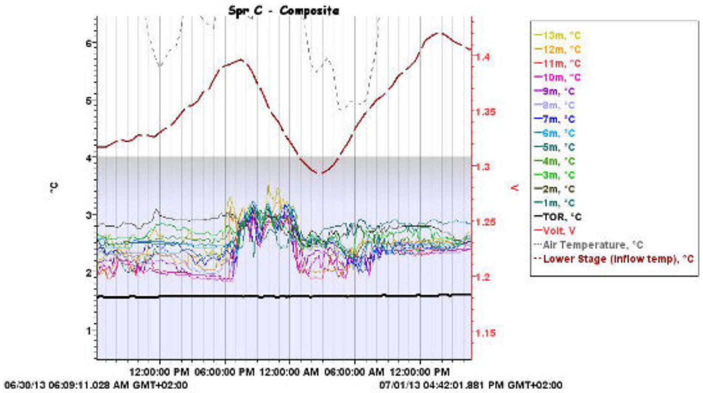

Figure 3. 6/30/13 event. Interpreted as a mixing interflow or homopycnal event. The inflow temperature was very high and above 4 ºC before the event started. Note every 0.06 volts recorded by the intervalometer represents 2mm of sediment deposited.

amount of sediment in the interflows and the water being at 4 ºC suggest that in order for underflows to be created larger amounts of sediment are needed. The bottom of the lake temperature loggers not detecting a complete underflow until the larger 0.9 volt sediment load on 7/1/13 also suggests that high sediment load is needed for underflow creation. The 7/1/13 event was very important because it is the first visible overturning in the lake. The overturning event resulted in a sudden drop in surface water temperature which could not have been caused by the warm air or the warm inflowing water. The intervalometer and temperature data shows that an underflow occurred with warm sediment dense water which caused the cold bottom water to be displaced and rise to the surface. The possibility of surface ice cooling the surface water is unsupported by the plume cam pictures because the surface ice, which drifted to the north part of the lake earlier, did not drift back to the mooring C location.

Strong and weak winds have been shown to have its effect on inflow events and upwelling in lakes (Forrest et al 2012). Persistent lake ice cover, however, would reduce these affects making them a less important factor on inflow events that occur before ice out conditions (Carmack et al 1979). Lake ice cover, even during ice break up, can prevent the wind from causing changes to the inflow events (Forrest et al., 2012). The ice is last seen by the plume cam on the surface of the lake on 7/4/13. The late persistence of ice could even shield the later underflow events from the increased mixing due to wind (Forrest et al 2012).

Another important characteristic about the events seen in Lake Linné was the isolation of most events. Rarely do events overlap and there was distinctive events a few hours apart at similar depths. Inflow events from a constant flowing source can come in pulses of varying velocities and sediment load because of shifts in plume lobes due to the deceleration as it enters the lake (Best et al 2005). Underflow plumes form when the inflowing water has enough momentum to overcome the slowing factors such as three dimensional expansion of the flow, slight mixing with upper water layers, and decreases in density because of the deposition of some sediments (Best et al 2005). Creation of these plume pulses could explain why events happen suddenly, (e.g. 7/1/13 event) instead of gradually which would be expected from a continuous source. These pulses could have large impacts on sediment deposition in the lake and suggests that sediment deposition and varve formation happens in bursts.

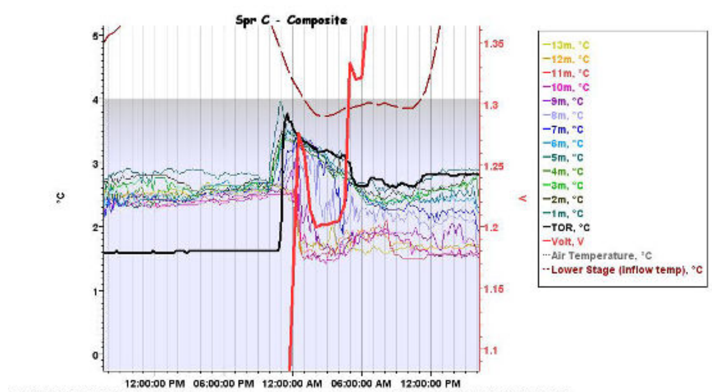

Figure 4. Interpreted as an underflow that created overturning in the lake. Note how the base of the mooring (TOR) records sudden temperature increases and loggers near the surface (9, 10, 11, 12, 13meters above the base) experience temperatures decrease. Note every 0.06 volts recorded by the intervalometer represents 2mm of sediment deposited.

CONCLUSIONS

This study found that the factors that affect temperature changes and sediment deposition in Lake Linné are many and include inflow and air temperature, inflow water turbidity, ice cover, wind, and lake turn-over. The data in this study suggests that early spring was dominated by overflows, middle spring by interflows, and late spring by underflows. Underflows were associated with high sediment loads and inflow temperatures being near 4 ºC. This suggests that sediment load plays a large role in determining what type of sediment dispersal mechanisms occur. It was also found that underflows deposit large amounts of sediment in the late spring. The suddenness and isolation of events could be attributed to pluses of flow due to an initial slowing of the plume when it enters the lake. This could have major implications for varve formation; suggesting that they happen quickly in bursts instead of slowly throughout the season. Further studies should be done on sediment load in inflow events as well as pulsing of events.

Studies like this into how lake and inflow processes can affect sediment dispersal show that our interpretation of sediment cores from glacial lakes must be made with care. Sediment dispersal in lakes could be uneven due to the suddenness of events and the occurrence of lake turn-over, wind, and ice cover. These processes show that more investigation into these sediment dispersal events could mean a better understanding of varve formation and therefore a better approach to document past climate changes.

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