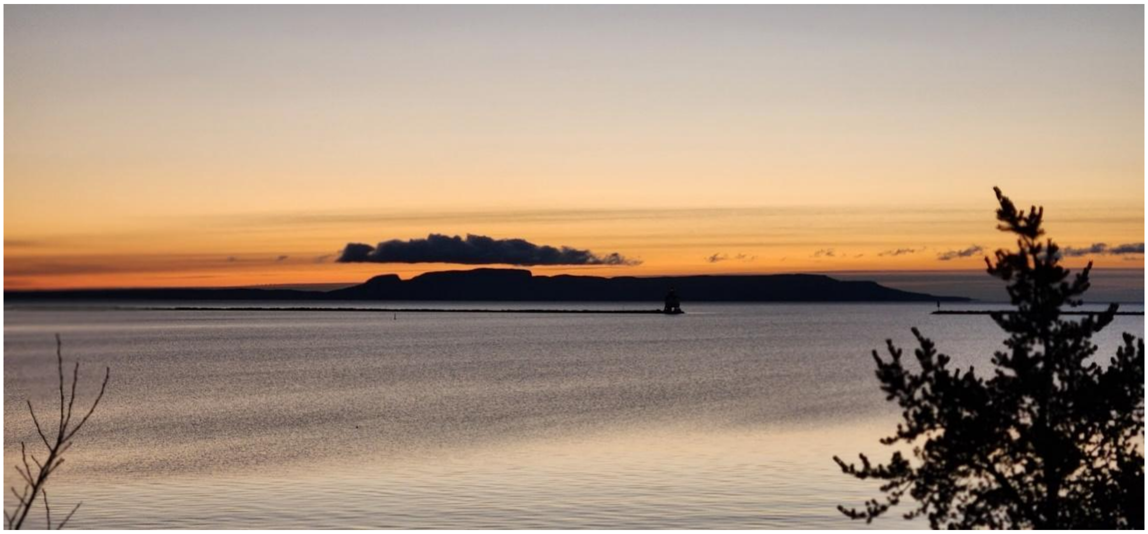
CLIMATE CHANGE EFFECTS ON THE SURFACE TEMPERATURE, ICE COVERAGE, & WATER LEVELS OF LAKE SUPERIOR

by

Martine Evans



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CLIMATE CHANGE EFFECTS ON THE SURFACE TEMPERATURE, ICE COVERAGE, & WATER LEVELS OF LAKE SUPERIOR

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ABSTRACT

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Keywords: Atmospheric Temperature, Climate Change, Ice Cover, Lake Superior, Surface Water Temperature, Water Level

Lake Superior's surface water temperature, water level, and ice cover are all suggested to be changing with increased atmospheric temperatures caused by climate change. This thesis uses data from 1995-2022 to determine if similar results can be found using a linear regression analysis. The only significant finds were of a yearly water level increase and summer atmospheric temperature increase. However, it was found that surface water temperature, ice cover, and atmospheric temperatures showed similar patterns. More research is needed to further evaluate the impacts of climate change on Lake Superior.

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ACKNOWLEDGMENTS

I would like to thank my peers, my significant other, and my family for supporting me throughout the process of this project and through my educational journey at Lakehead University. In addition, I would like to thank Dr. Jian Wang for agreeing to be my thesis advisor and guiding me through the process. Finally, I would like to thank Mr. Graham Saunders for agreeing to be my secondary reader, lending me academic material for research, and giving me access to surface water data he had previously downloaded and organized from the National Oceanic and Atmospheric Administration Great Lakes Environmental Research Laboratory. From this data I was able to create the surface water temperature graphs and excel data analysis shown within the results.

1.0 INTRODUCTION

The Great Lakes in North America, including Lake Superior, make up 21% of the world's fresh water (Withgott et al 2017) and climate change is impacting them (Anderson et al 2021). Globally, surface water has been shown to increase by 0.21°C per decade (Anderson et al 2021). Such changes are concerning because these changes will impact ecosystem function, (Anderson et al 2021, O'Beirne et al 2017), economical transportation of goods and people, drinking water, irrigation, lake-food harvest availability, and the disposal method of treated wastewater (Irbe 1992:1). The Great Lake protection binational agreement between Canada and the United States of America demonstrates how important these water resources are (GC 2022).

Studying the effects of climate change on lakes is effective because they are sensitive, react quickly, and represent information from the entire catchment area (Adrian et al 2009). Therefore, they adequately represent climate change impacts, which makes it important to continually collect and analyze the quantifiable variables such as surface temperature, ice coverage, water levels (water storage), and air temperature (Anderson et al 2021, Austin and Colman 2007). Large lakes have different characteristics to smaller lakes, like their infrequent surface thermoclines (Xenopoulos and Schindler 2001). Thus, studying the Great Lakes is necessary, but due to their size this information can also increase our understanding of oceanic systems (Austin and Colman 2007). However, the thermal structure of lakes is complex and its individual characteristics and reaction to climatic changes will depend on its location (Irbe 1992:22). Specifically, temperate climatic lakes have large changes in insolation throughout a year (Irbe 1992:22) because of the resetting ice cover (Austin and Colman 2007). So, these systems require sufficient temporal coverage in-order to accurately assess statistically significant trends (Austin and Colman 2007).

To better understand any changes happening within Lake Superior over recent times, data was collected so Microsoft regression testing could determine if there were obvious trends over time. Past studies, discussed in the literature review, have shown that surface water and atmospheric temperature has increased while ice coverage and water levels have decreased. A similar trend was expected for this study from 1995-2022. However, the analysis showed different results which were then discussed to form a conclusion.

1.1 OBJECTIVES

The objective of this undergrad thesis is to gain a better understanding of the yearly trends and relationship between water temperature, ice coverage, and water levels of Lake Superior.

1.2 HYPOTHESIS

Yearly, Lake Superiors' surface water temperature will increase with increasing atmospheric temperatures. Resulting from this it is hypothesized that the ice cover percent and water levels will decrease with yearly increases. Overall, the variables will show a dependent relationship with each other.

2.0 LITERATURE REVIEW

Most Great Lakes have shown increased temperatures, delayed and decreased ice coverage, atmospheric changes such as milder winters, and changes in water level (Anderson et al 2021, Austin and Colman 2007, Lamon and Stow 2010). Theses are all interconnected and influence each other (Adrian et al 2009) but are also affected by things such as, wind speed, cloud cover, precipitation, relative humidity (Adrian et al 2009), the heat budget of a lake, and the sub-surface circulation of the water (Irbe 1992:22). Understanding anthropogenic induced changes, like increased climate change, are important because these can decrease water quality and reduce the lakes' ability to buffer environmental changes (O'Beirne et al 2017). Such is seen with the increased primary production due to higher nutrient loading since 1900 (O'Beirne et al 2017). However, only information on surface water, ice coverage, atmospheric temperature, and water level changes were researched further.

Surface water can be an important parameter to analyze the physical and biological aspects of a lake and its changes can help estimate evaporative losses that affect water levels (Irbe 1992:1). Meanwhile, ice cover has greatly influenced the relationship between water and atmosphere temperature, thus its extent has been studied as an indicator to climate change (Austin and Colman 2007). The effects of atmospheric temperature changes on water temperature are unknown because of different geographic variability and feedback mechanisms (Hansen et al 1999). Finally, water level changes have been influenced by climate change (Lofgren et al 2002). For example, this is apparent through changing evaporation and precipitation rates (Lamon and Stow 2010). However, firstly it's important to understand how Lake Superior naturally functions.

2.1 CHARACTERISTIC REVIEW OF LAKE SUPERIOR

Large northern lakes are influenced heavily by the onset of stratification which is reliant on ice coverage and atmospheric conditions (Austin and Colman 2007). To understand changes happening within Lake Superior it is important to understand how it normally functions. Lake Superior is located 49.0 to 46.5°N, has a depth of 149.1m, a volume of $12234 km^3$, and a surface area of $82,103 km^2$ (Irbe 1992:24). Surface water temperature changes seasonally and differently based on different areas of the lake (Irbe 1992:172-209). Vertical mixing of water, called overturn, will occur when the surface water reaches its densest temperature, 3.98 to 4°C, sinking and replacing the water below it, until the lake is a uniform temperature (Anderson et al 2021, Austin and Colman 2007, Fichot et al 2019, Irbe 1992:33). Within Lake Superior, overturn happens twice a year, in the spring and fall (Irbe 1992:32-37). The exact time of overturn will differ across Lake Superior, for example in the west the overturn date occurs two weeks earlier when compared to eastern locations (Austin and Colman 2007). The density change allows the surface water to float on top creating a vertical temperature layering effect of water, known as stratification (Irbe 1992:34). The volume and depth of Lake Superior gives it a high heat index; thus, it heats and cools slowly, but this varies depending on the location point of the lake. For example, in shallow near-shore areas Lake Superior will heat quicker but temperatures will change with bay orientation. Meanwhile, the deeper and more open areas of Lake Superior will take longer to heat and cool because of wind induced turbulent mixing and the delayed convection heating with the larger water volume. For these reasons, summer and winter stratification will start and finish in the near-surface areas first and then move towards the center of Lake Superior (Irbe 1992:32,33). There will also be a horizontal gradient found within surface temperatures of a lake because of the difference in heat distribution and persistent winds, like the westerlies, which pushes the warmer water downwind. This results in an equalization effect causing subsurface currents, or upwells, of deeper colder water to happen upwind. The temperature difference from persistent winds is more prominent in the summer and fall seasons. Temperature changes are also influenced by things such as lake bottom topography (Irbe 1992:33-37).

During the summer and fall seasons the westerlies make the southeastward shores warmer, known as the Ekman effect, and the opposite northwestern side colder due to the upwelling effect. Westerly winds cause the greatest alteration of surface water temperature. If their speed decreases or the wind changes direction, there will be a more equal temperature gradient. Summer stratification is made up of a top epilimnion layer followed by the thermocline and finally the hypolimnion. The hypolimnion is the coldest and deepest layer (Irbe 1992:36, 37, 196). Lake Superior usually establishes summer stratification by the end of June and experiences the highest increase in surface temperatures in July when solar energy is the most concentrated on the epilimnion. Stratification decreases convection of heat energy because the density layers make mixing difficult. The thermocline is an area of rapid temperature change, and it prevents the hypolimnion underneath it from mixing upwards. The thermocline is closer to the surface in the mid-lake regions and slopes downward closer to the bottom in the near-shore areas (Irbe 1992:36, 196). This results in a less severe temperature difference in the thermocline in the deeper regions where the epilimnion is thinner. The epilimnion is thicker inshore because these areas are generally shallower therefore, they have a smaller heat index. These characteristics also make inshore areas prone to intense daily changes in the temperature due to quick solar absorption heating and cooling caused by radiation loss at night (Irbe 1992:34-38).

Fall overturn normally begins in September when there is a decrease in solar radiation, increased radiation loss, and evaporative cooling (Irbe 1992:37, 201). These cause surface water to cool, densify, then mix. Eventually, the lake will reach an isothermal state around mid-November. However, the introduction of Arctic air from the northwest winds in October also contribute to the cooling effect (Irbe 1992:38, 209).

Winter stratification begins in early December, with the formation of ice that floats on top of the denser warmer water underneath (Irbe 1992:30, 209). This is opposite to summer stratification when the denser water below the surface water is cooler. The water will slowly cool more throughout the winter, which forms a weak vertical stratification established around the beginning of January. During January, warmer water is slightly variable despite westerly winds because of eddies and currents. However, upwelling is found along the northwestern shore, northeastern shore, and near

Copper Harbor and Keweenawan Bay in Michigan. There will be low variation in surface water temperature except in areas with circulation patterns like in White Fish Bay (Irbe 1992:3, 36, 176, 180). A minimal water temperature will occur around mid-February to late March depending on ice coverage. The mid lake regions will be warmer in the winter whereas the near-shore areas will be below the freezing point and usually ice covered. The warm near-shore areas where there is upwelling will be just outside of the ice-covered areas in January. The horizontal surface temperature differences will be greatest in these areas during winter stratification (Irbe 1992:30-32, 176, 180).

Spring overturn happens slowly because of the distribution of broken ice, wind, and the inability for solar radiation to be absorbed into the water before ice has melted (Irbe 1992: 32). Ice melt will occur around mid-March and continue into April. The areas with open waters will have wind-driven ice fragment melting but the surface water will remain a more constant temperature. As surface waters warm, and wind helps distribute the heat downwards, a temperature front will form separating near shore from the lake's center. The shallow areas will be stratified while the deeper areas take longer to warm (Irbe 1992:32-33). This temperature difference causes the colder water from the center to circulate outward from the surface, downward along the moving front, and to the bottom of the lake. The front prevents cold and warm water from mixing and is known as an isothermal bar. As summer progresses the isothermal bar moves deeper into the center of the lake and will eventually disappear when spring overturn completes. If the topography of the lake bottom is rough, then the movement of the isothermal bar will be slow (Irbe 1992:33-34).

Ice coverage on Lake Superior is rarely close to 100% (Irbe 1992:32). The persistent surface water temperature gradient and the slow vertical heat transfer in the deep-water areas prevents this from happening (Irbe 1992:32). In January, extensive ice coverage is normally found in the northern third of the lake as well as along the southern shores and eastern basin. The northern areas of the western arm are usually ice free due to the westerly winds unless there is very cold weather (Irbe 1992:180). Even during calm and cold periods ice formation will be thin and easily broken up by wind induced turbulence. Ice that has been broken up will roam the middle regions of the lake. The surface temperature of Lake Superior is greatly affected by the tilt and Coriolis effect of Earth. These determine the intensity of incoming solar radiation and the wind direction (Irbe 1992:31, 36). In turn these affect precipitation, snow melt, runoff, evaporation, and changes in soil storage which cause normal variation in water levels (Lenters 2004). Water levels also change with the expansion and contraction of water during periods of warming and cooling. A maximum expansion of 0.7cm (210m^3/s) occurs around August when the lake is warming, and a maximum contraction of 0.9cm (280m^3/s) occurs around November (Lenters 2004).

2.2 SURFACE WATER TEMPERATURE

Surface water temperature studies can be used to determine evaporative losses from the Great Lakes as well as atmospheric temperatures of shoreline communities (Irbe 1992:3). Austin and Colman (2008) suggest that water surface temperature can exceed atmospheric temperature increase rates. Unfortunately, lakes with seasonal variation, like Lake Superior, will have climate change effects that are harder to analyze (Austin and Colman 2008). However, multiple studies have shown that all the Great Lakes' surface water has been increasing within the last few decades (Anderson et al 2021, Austin and Colman 2007). Irbe (1992:172) states, that Lake Superior's normal annual surface water temperature range is between -0.2 to 15.1°C, monthly mean temperatures range from 0 to 14.5°C, mild winters were shown to range from 0.1 to 0.5°C, and the yearly surface temperature was calculated to be 5.6 °C. This information is based on a linear regression statistical analysis of radiometric surface water temperature data collected from airborne radiation thermometers (bolometer sensors) and NOAA high resolution radiometer scanner infrared satellite surveys from 1966 to 1988 (Irbe 1992:8). It was found that within those years, February was generally the coldest month with a mean monthly temperature of 0.0°C due to high ice coverage. During the summer, Lake Superior had a normal maximum temperature range of 12.7 to 17.5, with the maximum yearly temperature reached later in August. The average maximum monthly mean temperature of August, the warmest month, is 14.5 °C (Irbe 1992:172). August and July were shown to have the largest variability in daily temperature with a standard deviation of 2.1 to 2.9 °C due to summer stratification. Small surface water temperature variations were noticed during mixing like in late November into December and during the spring (Irbe 1992:172).

Austin and Colman (2007) found that Lake Superior, from 1979 to 2006, had a yearly summer (July, August, and September) surface water temperature increase of $(11 \pm 6)\times 10^{-2}$°C and an overall increase of 2.5°C over the period (Austin and Colman

2007). This increase is caused from earlier stratification resulting from lower ice coverage creating longer periods of heating which delay fall overturn (Austin and Colman 2007, Anderson et al 2021, Piccolroaz et al 2015). Atmospheric temperatures affected the summer surface water heating but not as much as ice coverage. It was predicted that the rate of summer water temperature will start to decline because of lessened seasonal variation resulting from the increased surface water temperatures (Austin and Colman 2007).

Piccolroaz et al (2015), found differing results of summer (July, August, September) lake surface water temperatures using a volume integrated heat equation derived lumped model called “air2water”. This study used in-situ buoy data gathered from NOAAs National Data Buoy Centre and GLERL satellite imagery from 1994 to 2011. The model demonstrated surface water was found to increase by 0.107°C each year (variance of 0.08 and a probability of 0.27). They concluded that their projected warmings of atmosphere temperature (0.098°C per year) and water surface were not that different from each other (Piccolroas et al 2015).

Austin and Colman (2008), a summer data study, analysed water temperature at the outlet of Lake Superior into St. Mary’s River. The water was found to be highly correlated with open lake temperatures, but its overall representativeness of long-term open lake conditions is unknown due to the location of the St Mary’s River (Austin and Colman 2008). The study identified that the open lake stratification season is shorter, and the rate of its increase is more intense, then previously reported. Results showed that data collected from St Mary’s River from 1906- 2005 showed a summer yearly warming rate of $(2.7 \pm 0.4)\times10^{-2}$°C and data from 1980-2005 showed a summer yearly warming rate of $(11 \pm 4)\times10^{-2}$°C. This shows that there has been a rapid increase in summer surface temperatures since 1980 and a 14 day increase in the number of stratified summer days (from 145 days to 170 days). However, Austin and Colman (2008) claim that, the proxy for the last 100 years, is technically closer to 0.0357°C per year because of recent warming increases and the calculated error from the observed temperature at the buoy. The summer water temperature increased from 8°C to 11°C which is suggested to decrease ice cover. Spring warming was shown to have the weakest yearly water temperature increase (Austin and Colman 2008).

2.3 ICE COVER

Ice greatly influences the relationship between water and atmosphere temperature. For example, increased solar radiation or duration during the winter will increase ice melt and decrease ice formation. In turn, this decreases albedo causing an increased duration of solar absorption in surface water thus allowing quicker spring overturn (Ahewna et al 2016: 515, Austin and Cole 2007, Irbe 1992:8). The ice cover relationship with surface water temperature is referred to as a positive ice-albedo feedback loop. Northern hemisphere water bodies have all shown declining average winter ice coverage for the last few decades (Austin and Coleman 2007). Irbe (1992:172) found that ice cover during cold winters on Lake Superior was from January until the end of March.

Austin and Colman (2007) found, between 1979-2005, the ice-out date for Lake Superior has become 12 hours earlier each year; declining at a rate of $(0.42 \pm 0.20)\%$ per year. The decreasing ice cover has projected to be warming Lake Superior's yearly water temperature by $(6.3 \pm 4.2) \times 10^{-2}$°C (Austin and Colman 2007). This causes an increased warming rate of surface water that is more rapid than the increase of atmospheric temperatures. So, long-term change of Lake Superior's thermal regime is heavily impacted by the onset of summer stratification and thus ice melt. Austin and Colman 2007 claimed that stratification was 27 days earlier in 2006 then it had been in 1979. At this rate it was projected that Lake Superior will be ice free by 2036 which will further increase summer water temperatures (Austin and Colman 2007) because, unlike ice covered lakes, open water lakes will not reflect as much radiation and instead will absorb most of it (Irbe 1992:8). In 1998, an outlier caused a warmer than trending summer water temperature and decreased ice because of the El Nino event (Austin and Colman 2007, Piccolroaz et al 2015). This demonstrated the percentage of ice cover is determined on atmospheric conditions, which in this case created a mild winter, minimal ice cover, then a warmer than usual summer season (Austin and Colman 2007, Piccolroaz et al 2015).

Austin and Colman (2008) found that between 1906-2005 most ice decreased between 1980-2005. From 1980-2005 ice decreased by 12-23% when summer waters increased by 8-11°C.

2.4 ATMOSPHERE TEMPERATURES

Many things about the atmosphere will dictate effects on a lake such as the intensity of solar radiation, air temperature, humidity, and mixing caused by wind (Irbe 1992:5, 9). Austin and Colman (2007) claim that summer surface water temperature is increasing more rapidly than regional air temperature for Lake Superior. Their study between 1979-2005 found that the annual average atmospheric temperature increased by $(5.3 \pm 2.1)\text{x}10^{-2}$°C per year and the mean summer temperature increased by a rate of $(5.9 \pm 1.8)\text{x}10^{-2}$°C per year. Both increases were consistent with increasing surface water temperatures, but the relationship was weaker than that of surface water temperature and ice cover. The order of dependence was 1 for atmospheric temperature and surface water temperature and the correlation was weak. Thus, atmospheric temperature did not help explain the interannual variability seen in summer water temperature (Austin and Colman 2007). They claimed the surface water temperature and the above water air temperature should be proportional; however, wind changes the depth of heat distribution which affects this. They noted higher average wind speeds near the water surface from air aloft due to a decreased air density gradient. The increased wind speeds were likely to increase mixing depths which might increase the water temperature of the Great Lakes; the thermocline temperature difference was not preventing this mixing (Austin and Colman 2007). Austin and Colman (2007) claim that the temperature of surface water might be higher than projected from models because wind mixing depth is not accounted for. Additionally, they found lower wind velocities at the on land coastal marine automated network stations (STDM4) than they did at the meteorological stations (buoys) 500 km from the center of Lake Superior. The decreased wind velocity is thought to be because the monitoring stations had different heights and there were off-land winds. The disproportionality seen between surface water temperature and the above water air temperature is likely due to the increase in summer heating from decreased ice cover (Austin and Colman 2007).

Austin and Colman (2008) found that air temperature warming rate between 1906-2005 was $(0.9\pm 0.2)\times 10^{-2}$°C but this increased to $(6.0\pm 2)\times 10^{-2}$°C from 1980-2005. Water temperatures responded to the atmospheric warming trends but were not easily predictable due to geographical differences (Hansen et al 1999 from Austin and Colman 2008).

Piccolroaz et al (2015) found atmospheric temperature to increase by 0.098°C per year for the summer months. Atmospheric temperature data from the STDM4 was used, which is 35m above Lake Superior located on a lighthouse (Piccolroaz et al 2015). Their air2 model showed unusual surface water heating based on air temperature which would increase spring overturn and the onset of summer stratification. In 1998, there were uncommonly high air temperatures and warm surface water temperatures due to an El Nino event (Piccolroaz et al 2015).

2.5 WATER LEVELS

Water levels have been influenced by climate changes (Lofgren et al 2002), such as through differences with precipitation and evaporation (Lamon and Stow 2010).

Global climate, like increased carbon dioxide concentrations, could significantly impact the Great Lakes (Smith 1991). However, the Great Lakes have fluctuating water levels due to general climatic conditions as well. So, it's important to distinguish the normal cyclic water levels from new and concerning changes of water levels (Lamon and Stow 2010). Assel et al (2004) found that water levels have decreased since the 1980s. From 1997-2000 there have been prominently low levels, especially seen in 2007 (Assel et al 2004). However, studies have claimed that Lake Superior has since rebounded from these low water levels (Lean Times for Lake Superior 2007). Yet other studies like Lofgen (2002) have shown an increase in water levels due to increased precipitation.

Lamon and Stow (2010), in their dynamic linear regression model with NOAA data from 1860-2007, found an overall decline of average water levels since the 1970s. This decline was especially prominent from 1985 to 2007. The lower levels have been generally sustained in Lake Superior. Lamon and Stow (2010) claimed that ongoing low levels are concerning because they are shown to be consistent with climate change trends, like the atmospheric and water temperature increases. The mean annual decline in 2007 was about 2cm per year.

Motiee and McBean (2009) used a linear regression analysis and a non-parametric Mann-Kendall trend test, using 105-year-old data, to show that water levels in Lake Superior were affected by drought or climate change. The analysis included extra variables like runoff, river flow and precipitation data for Lake Superior. The regression between the years 1900-2005 was $y=-0.0005x+184.7$ (slope -0.005 ± 0.0009, p value 0.26, and r^2 value of 0.015). The regression between 1970-2005 was $y=-0.01x+204.3$ (slope of -0.01 ± 0.004, p value 0.0002, and r^2 value of 0.99). They found that non-linear regression worked better for studies over longer periods of time. With a quadratic equation they found that the first 70 years of the 150-year period had an increasing water trend then the 35 years afterwards had a declining trend. The water levels in the last 35 years were shown to decrease by about 1cm per year.

As mentioned before, Wang et al (2012) claimed there were lower than normal amounts of ice from 1990 to 2000s. This led to increased evaporation rates and thus a drop in water levels of 1-1.3m. Since 1998, water levels severely dropped and commercial ships were forced to lighten loads. For every inch of clearance that vessels lost equaled about 11 to 22 thousand dollars in profits per day (Wang et al 2012).

Lenters (2004) demonstrated with a linear regression that between 1948-1999 (51 years) the seasonal changes in water levels decreased by 20%. This decrease from 40cm to 32cm, caused summer and autumn water levels to remain consistent when they usually are higher than winter levels. An influx of over-land precipitation during September and October, increased evaporation losses of about 20%, and changes in the outflows through the St Mary's River are the leading influencers of this change. Water levels are also changing due to earlier snowmelt and spring runoff, overland precipitation increases, and increased evaporation in June (Lenters 2004). The annual variation difference between seasons is usually about 4cm. Over the 51 years in this study there was a monthly water decrease of 1,360m^3/s in the spring and an increase in late autumn water levels of up to 1,100m^3/s (Lenters 2004). Although there was a decreasing trend in this study, when compared to previous studies Lenters (2004) found that the changes over the period 1948-1999 are not abnormal when compared to a 140-year trend. Thus, these trends cannot be relied on for future monitoring for climate changes in Lake Superior but can be used to understand the predictability of future trends by understanding the influencers of changes. Since the 1920s, St. Mary's has been primarily responsible for dictating water levels within Lake Superior. Changes in land use will also affect the basin drainage and therefore lake levels. Despite these influences, it was concluded that the long-term trend in the lake's water level seasonality is driven by climate change (Lenters 2004).

NOAA GLERL have created a graph based on data collected of the water levels from 1860- 2020 (NOAA GLERL 2021). The mean long-term water level from 1918-2017 was 183.4m. From 1930-1950 the water levels ranged most often above this mean. Otherwise, there were fluctuations around the mean through 1860-2020. The lowest water level was recorded to be around 1927 with a water level around 182.9m. The highest water level was recorded to be in 2020 with a level a little over 183.7m. (NOAA GLERL 2021). After 1918 more water gauges were added to Lake Superior (NOAA GLERL 2022). These stations have a controlled intake pipe that reduces the water level reading from wind and wave effects (NOAA GLERL n.d.b.).

3.0 MATERIALS & METHODS

3.1 LITERATURE REVIEW SOURCES

The literature review was completed using the Lakehead University Library database available to students. Studies were found using key terms like “Great Lakes”, “climate change”, “Lake Superior", “surface water temperature”, “ice cover decline”, etc. Only peer reviewed data was used. In addition, one hard copy book written by Irbe in 1992, Government of Canada book was used.

3.2 LAKE SUPERIOR DATA

Lake Superior’s surface water temperatures, ice coverage, and water levels were analyzed using long-term data from the NOAA GLERL. Surface water temperature data is obtained by the NOAA from three different satellites, one NOAA Advanced Very High-Resolution Radar (AVHRR) and two Visible Infrared Imaging Radiometer Suites (VIIRS-NPP and VIIRS NOAA-20) (NOAA CWGL n.d.b). When imagery is unavailable, the NOAA uses a smoothing algorithm, like on cloudy days. The ice cover data was downloaded from the NOAA website but collected from the Canadian Ice Service and from the U.S. National Ice Center satellite imagery (NOAA CWGL n.d.b). Ice cover information is collected using Great Lakes Synthetic Aperture Radar and normalized Radar Cross Section Imagery (NOAA CWGL n.d.b). The surface temperature and the ice cover information are made publicly available for download on their website (NOAA CWGL n.d.a). The monthly water level data was also downloaded from the NOAA webpage (NOAA GLERL n.d.a) and was collected from representative lake-wide water level gauges from U.S. and Canadian gauges (NOAA GLERL 2022). The NOAA collects this data to support environmental science, decision making, and research to provide information to a variety of interested stakeholders (NOAA CWGL n.d.b) The atmospheric temperature was downloaded from the Thunder Bay airport meteorological station, called "Thunder Bay A" from the Government of Canada webpage (GC 2023). The available data for Lake Superior goes back to 1995 for water temperature, 1918 for the water levels, and 1773 for ice coverage. Atmospheric data from 1966-1988 was also collected for the Government of Canada webpage so atmospheric data could be compared to Irbe's (1992) surface water temperature data. As well, some observations were made from the other older data sets in order for comparisons to older studies. However, data from 1995-2022 was focused on.

3.3 DATA ANALYSIS

Data collected from NOAA and Environment Canada was inputted into Microsoft Excel so a regression data analysis could be computed. This allowed for the relationship between the variables (surface temperature, ice cover, water level, and atmospheric temperature) to be compared to the continuation of time (yearly increase). Each analysis was based on a 95% interval (alpha=0.05). The results for each variable were visually compared to each other to determine related trends. All results were used to determine if the hypothesis was true and to discuss further needs of research.

4.0 RESULTS

The results are broken up into the same sections presented within the literature review: surface water temperature, ice coverage, atmospheric temperatures, and water levels. In addition, there is a comparison between the first three variables at the end.

4.1 SURFACE WATER TEMPERATURE

The linear regression for the average surface water temperature was $y=0.0249x+6.179$. Regression testing determined the probability of surface water temperature increasing through time to be 0.30 with a coefficient of determination (r^2) value of 0.04. As well, regression testing was done for the summer month data (July, August, and September) from 1995-2022 to compare with other studies. It was determined that the summer surface water temperature increase through time was insignificant, with a probability of 0.727 and a r^2 value of 0.004. The linear regression was $y=0.0163x+13.843$.

The average surface water temperature between 1995-2022 was 6.5°C with a standard deviation of 1.0. Thus, the upper standard deviation limit is 7.5°C and the lower standard deviation limit is 5.5°C. The data points that exceeded the standard deviation limits have their temperatures labeled above them in Figure 1. The mean is shown in Figure 2 as a black line and the standard deviation limits are shown as grey lines. The data points that exceeded the upper standard deviation limit were 1998 (8.0 °C), 2006 (7.8°C), 2010 (7.7°C), 2012 (8.4°C), 2016 (8.0°C), and 2021 (8.1°C). The data points that exceeded the lower standard deviation limit were 1996 (4.4°C), 1997 (5.2°C), and 2014 (4.9°C). The highest surface water temperature, shown as red, is in 2012 (8.4°C) and lowest surface temperature, shown as a blue data point, is in 1996 (4.4°C).

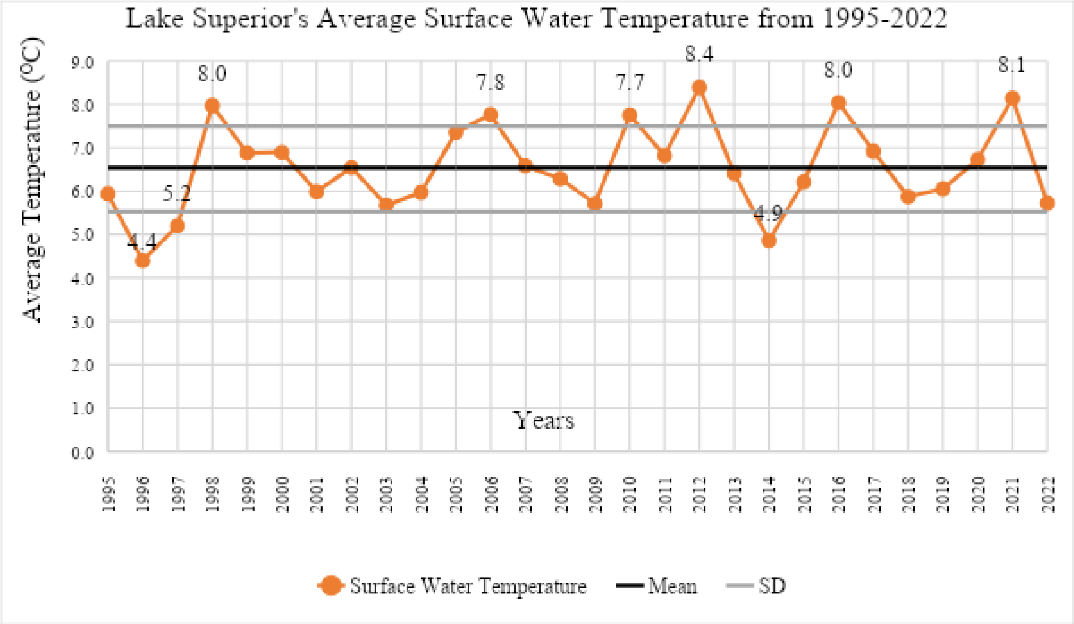

Figure 1. Lake Superior’s average surface water temperature from 1995-2022.

To compare with the data presented by Irbe (1992:172) the average temperatures for each month along with their corresponding standard deviations were graphed together, shown in Figure 2. The highest average temperature found from 1995-2022 (15.9°C) happened in August. The lowest average monthly temperature (0.9°C) was in March. The standard deviation of the average temperature data was largest in July (3.1°C).

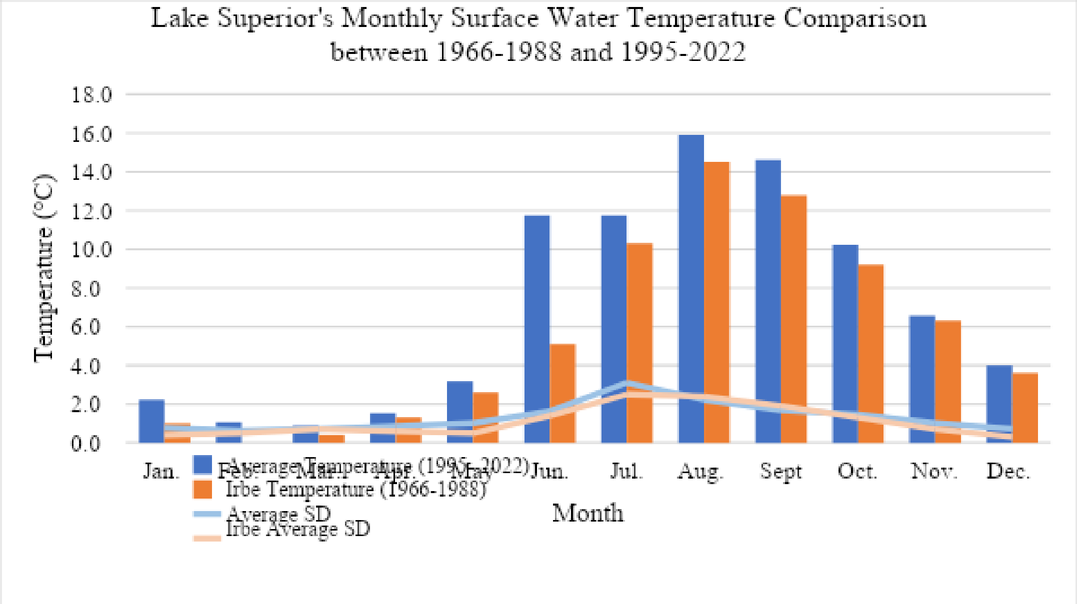

Figure 2. Lake Superior’s average monthly surface water temperatures from 1995- 2022 compared to 1966-1988 from Irbe (1992:172). Data from 1995-2022 is shown in blue and Irbe’s data is shown in orange. The lines show the standard deviation for each study with the respective colour.

4.2 ICE COVERAGE

The linear regression for the average ice cover percentage was y=0.0366x-59.439. Regression testing determined the probability of ice cover increasing through time to be 0.90 with a r^2 value of 0.01. Data from 1973-1988 was also analyzed to compare to Irbe's data. It showed that the highest ice cover was in 1979 (54.3%) and the lowest amount (0.4%) happened twice in 1978 and again in 1983. The linear regression for the average ice cover was y=-0.2125x+22.837. The regression analysis determined the probability of ice cover declining through time to be 0.84 with a r^2 value of 0.002.

The mean ice cover between 1995-2022 was calculated as 14.1% with a standard deviation of 12.5%. Thus, the lower and upper limits are 1.7% and 26.6%, respectively. The mean is shown by the black line and the standard deviation limits are shown by the grey lines in Figure 3. There were no data points that exceeded the lower standard deviation limit. The data points that exceeded the upper limit of the standard deviation were 1996 (34.5%), 1997 (29.9%), 2003 (28.7%), 2009 (33.6%), 2014 (47.6%), and 2015 (30.1%). The year with the highest ice cover percentage (2014, 47.6%) is shown as a red data point and the year with the lowest percentage (2012, 2.1%) is shown as a blue data point. All data points that exceeded the standard deviation are labeled, excluding the lowest ice cover year which is labeled in grey but does not exceed the standard deviation limit.

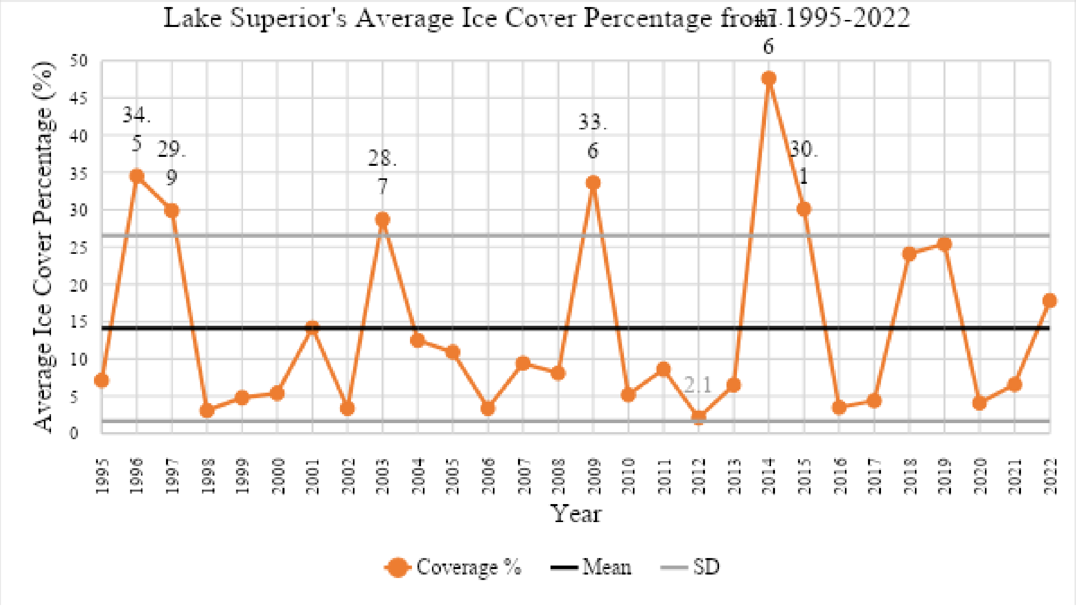

Figure 3. Lake Superior's average ice cover percentage from 1995-2022.

4.3 ATMOSPHERE TEMPERATURE

The linear regression for the average atmospheric temperature was $y=0.0261x+3.0561$. Regression testing determined the probability of atmospheric temperature increasing through time to be 0.31 with a r^2 value of 0.03. The linear regression for the average atmospheric summer (July, August, and September) temperature was $y=0.0427x+15.513$, shown in Figure 4. Regression testing determined the probability to be 0.012 with a r^2 value of 0.22. The atmospheric data collected from 1966-1988 had an average mean of 2.4°C with a standard deviation of 0.9°C. The linear regression was calculated as $y=0.0527x+1.8115$. Regression testing determined the probability of atmospheric temperature from 1966-1988 increasing yearly to have a probability of 0.06 and a r^2 value of 0.16.

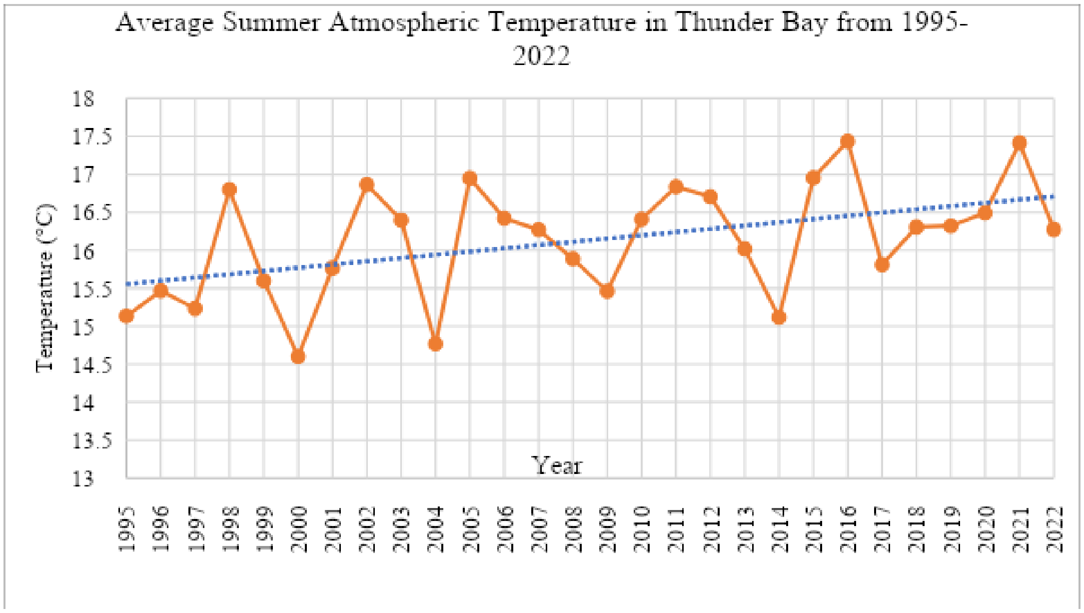

Figure 4. Thunder Bay's average summer atmospheric temperature from 1995-2022. The linear regression and its equation are shown in blue.

The mean average atmospheric temperature between 1995-2022 was 3.4°C with a standard deviation of 1.09°C. Thus, the lower and upper limits are 2.3°C and 4.5°C respectively. The mean is shown by the black line and the standard deviations are shown by the grey lines in Figure 5. The data points that exceeded the upper limit of the standard deviation were 1998 (4.8°C), 2006 (5.2°C), 2010 (4.9°C), 2012 (5.5°C), 2016 (4.7°C), and 2021 (4.9°C). The data points that exceeded the lower limit of the standard deviations are 1996 (1.4°C) and 2014 (1.5°C). The highest atmospheric temperature in 2012 (5.5°C) is shown as a red data point and the lowest atmospheric temperature in 1996 (1.4°C) is shown as a blue data point. All data points that exceeded the standard deviation are labeled.

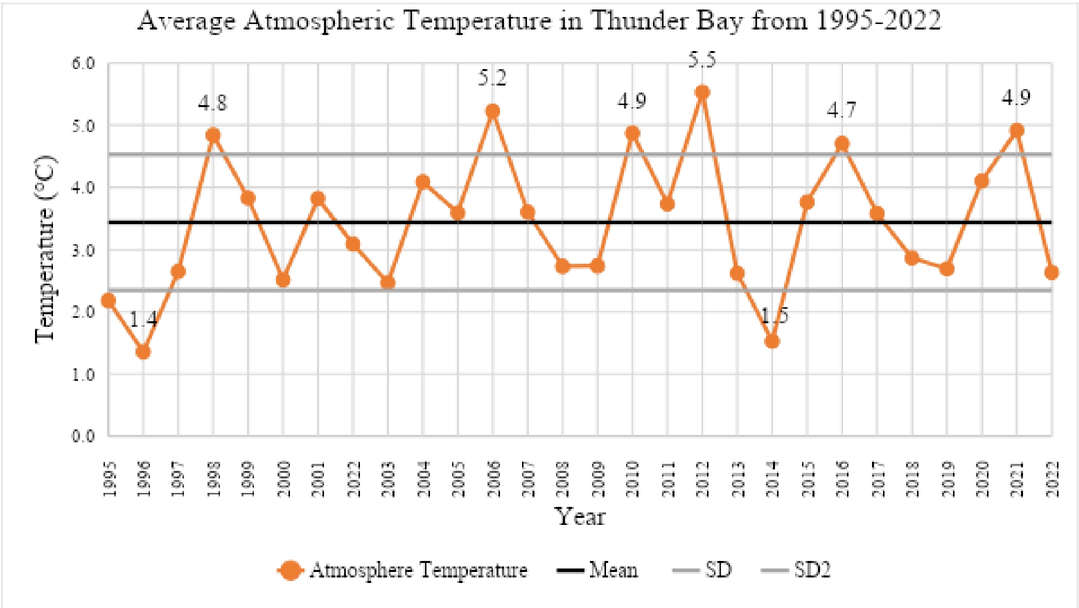

Figure 5. Thunder Bay's average atmospheric temperature from 1995-2022.

4.4 WATER LEVELS

The linear regression for the average water level was y=0.0107x+183.21, shown in Figure 6. Regression testing determined that the probability of water level increasing through time, to be 0.03 with a r^2 value of 0.17. The linear regression for the average water levels from 1995-2022 for the summer months (July, August, and September) was y=0.0106x+162.4. Data analysis testing determined that the regression probability of water level increasing through time to be 0.03 with a r^2 value of 0.17. The linear regression for the average water level from 1995- 2022 for the winter months (Jan., Feb., Mar., Apr., May, Jun., Oct., Nov., and Dec.) was y=0.0103x+162.7. Data analysis testing determined that the regression probability, of the water level increasing through time, to be 0.03 with a r^2 value of 0.16. The linear regression for the average water level from 1918- 2022 was $y=-3E^{-05}x+183.47$. Regression testing determined that the significance of the water level decreasing through time to be 0.96 with a r^2 value of $2.9E^{-05}$. The lowest water level was in 1926 (182.9m) and the highest level was 2019 (183.8m).

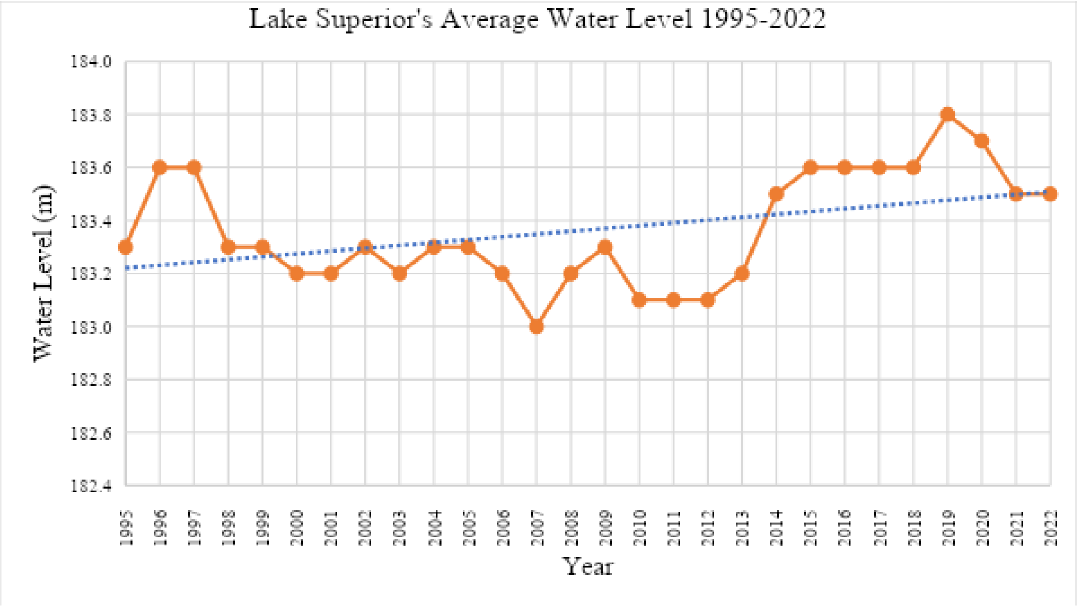

Figure 6. Lake Superior's average water levels from 1995- 2022. The linear regression and its equation are shown in blue.

The mean average water level between 1995-2022 was 183.4 m with a standard deviation of 0.2m. Thus, the upper and lower standard deviation limits were 183.5 m and 183.2 m, respectively. The mean is shown as a black line and the standard deviation limits are shown as grey lines in Figure 7. Any data point that exceeded the standard deviation limits was labeled. The years that exceeded the upper standard deviation limit were 2019 (183.8 m) and 2020 (183.7 m). The data points that exceeded the lower standard deviation limit are 2007 (183.0m), 2010 (183.1m), 2011 (183.1m), and 2012 (183.1m). The highest water level (183.8m) in 2019 is shown as a red data point and the lowest water level (183.0m) in 2007 is shown as a blue data point. All data points that exceeded the standard deviation are labeled, but there is only one label for the years 2010, 2011, and 2012 which had the same water level.

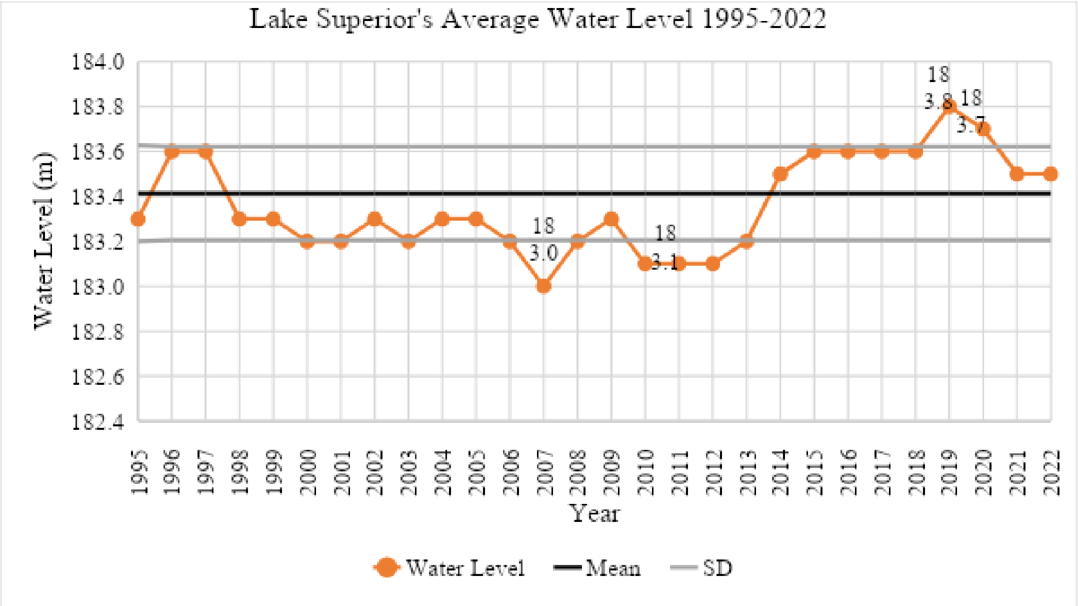

Figure 7. Lake Superior’s average water levels from 1995-2022.

4.5 COMPARISON BETWEEN VARIABLES

The average amounts for surface water temperature, atmospheric temperature, and ice cover percentage between the years 1995- 2022 were graphed and are shown in

Figure 8. The year 1996 had the lowest surface water temperature (4.4°C), the lowest atmospheric temperature (1.4°C), a relatively high ice cover (34.5%), and a high ice cover amount the following year (29.9%). The year 2014 had the second lowest surface water temperature (4.9°C), the second lowest atmospheric temperature (1.5°C), and the highest ice cover percent (47.6°C). The year 2012 was shown to have the highest surface water temperature (8.4°C) and the highest atmospheric temperature (5.5°C) with the lowest recorded ice cover (2.1%).

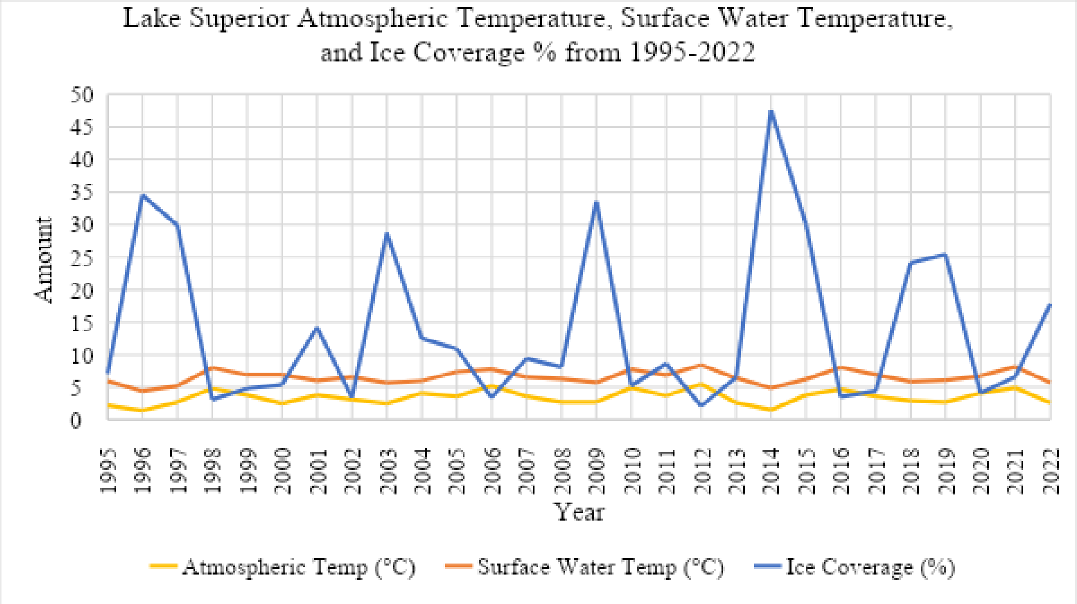

Figure 8. Lake Superior's average surface water, atmospheric temperature, and ice coverage percentage between 1995-2022.

5.0 DISCUSSION

The linear regression trend results were compared to what was found within other studies, then each variable's results are compared to each other. The coefficient determinant (r^2) for the linear regression data analysis was low for all variables assessed; 4% for surface water temperature, 1% for ice coverage, 3% for atmospheric temperature for Thunder Bay station A, and 17% for water level. This means that the variations within each of these was hardly accounted for within the regression models. The variation might not be represented in the model because the natural responses of these variables are hard to assess through regression statistics. It may also demonstrate that this model is not accurate for demonstrating the severe varying events caused from climate change. The probability of the variables being dependent on the yearly increase was considered insignificant if the p-value was higher than 0.05 and significant if it was under.

5.1 WATER SURFACE TEMPERATURE

The regression for water surface temperature was insignificant. The relationship between water surface temperature with a yearly increase had a low probability. As well, the relationship between the summer water temperature and yearly increase was insignificant. These findings were opposite to the findings from Anderson et al (2021) and Austin and Colman (2008). Within the 1995-2022 analysis it was observed that there were increased outliers after about 2010, shown in Figure 1. As well, there was an increased surface temperature in 1988, the year other studies mentioned an El Nino event. However, the variation within the data sets made this event inconspicuous because there are large variable jumps throughout 1995-2022.

Comparing my results with that of Irbe (1992:172), the average temperature from 1995- 2022 was 0.9 °C warmer than that between 1966-1988. As well, the highest and lowest temperatures from Irbe (1992: 172), 14.5°C and 0.4°C, were lower than that of this study which were 15.9°C and 0.9°C. Each month the mean surface water temperature between 1995-2022 had a higher mean temperature than between 1966-1988. The lowest temperature occurred in March for both studies but also in February for Irbe's (1992) study. The highest temperature was found to occur in July for both study periods and the warmest month was August. The temperatures between 1995-2022 kept within the normal range of summer temperatures (12.7-17.5°C) stated by Irbe (1992:172). The higher temperature in July between 1995-2022, 0.6°C higher than Irbe's (1992:172) data, understandably resulted in a higher standard deviation. This is because intensely stratified water will result in a higher temperature difference between the epilimnion and the water underneath. Thus, westerly winds would push the high temperature epilimnion downwind which would cause upwellings of cooler water and create a higher standard deviation (Irbe 1992:32,176). The standard deviations for the winter and spring remained low but have increased since those calculated by Irbe (1992), as shown in Figure 2. Rapid increases in summer temperature noted by Austin and Colman (2008), were shown to be insignificant within this study (1995-2022). However, there were large increases seen in monthly means in June, possibly suggesting an increasing spring water temperature trend like that suggested by Austin and Colman (2007). The mean June temperature more than doubled when compared to that of Irbe's (1992:172) value. Although this is the largest surface water temperature difference between the two studies, the spring surface water increasing trend was the weakest in the study by Austin and Colman (2008). Even though the increase of surface water temperatures did not significantly increase yearly, the comparisons between this study and Irbe's (1992:172), shows that surface water temperatures have increased in recent years. Increasing fall surface water trends are not noticeable between 1995-2022. In fact, the isothermal state (around 4°C) is reached in December by both Irbe (1992:172) and within this study, thus the delayed fall overturn suggested by Austin and Colman (2007) and Anderson et al (2021) cannot be proven with the analysis done here.

5.2 ICE COVERAGE

The regression analysis for ice cover was insignificant. The relationship between the ice cover percentage and the yearly increase had a low probability and a small r^2 value. Austin and Colman (2007), Piccolroaz et al (2015) and Austin and Colman (2008) have all noted that ice cover was declining, and this is influencing and being influenced by surface water temperature. However, this cannot be proven with the analysis of this study. A lower ice volume during the El Nino event in 1998, shown in Figure 3, was consistent with that shown by Austin and Colman (2008) and Piccolroaz et al (2015). However, the variation from high to low ice cover before and after the El

Nino event is not unusual because continual ice cover variation is shown throughout 1995-2022. Ice data collected from Austin and Colman (2008) showed that most ice decrease happened within the last 25 years of their data set (1906-2005). Therefore, the period of 1995-2022 might not be a long enough period to recognize changes within ice coverage. Additionally, the increase of 12 hours per year of ice melt cannot be proven within this analysis. Alternatively, most of the years had ice cover percentages within the standard deviation limits. Most of the data was between the lower standard deviation and the mean, but it was noticed the only outliers were shown above the upper standard deviation limit. Although this study found ice decrease to be insignificant, the surface water temperature increase during the summer might suggest otherwise because early ice out dates allow for more solar radiation absorption (Irbe 1992:32). Based on the insignificant trend of ice cover seen between 1995-2022, it does not seem that ice is decreasing enough to be completely absent by 2036 as suggested by Austin and Colman (2007).

Ice cover data from the NOAA, only available as far back as 1973, was downloaded in order to help examine the low surface water temperatures seen by Irbe (1992). While analyzing Figure 2, large amounts of ice during the years 1966-1988, might be responsible for the lower surface water temperatures in Irbe’s (1992:172) study when compared to this study (1995-2022). It was found that between 1973-1988, the overall average ice cover was higher and had a lower standard deviation. The highest ice cover percentage was in 1979 (54.34%) and a total of six years had ice cover above 30%. Meanwhile between 1995-2022 the highest cover was 47.6% (2014) and there were only four data points above 30%. Therefore between 1973-1988, the later part of Irbe’s study, there seems to be more ice present than there was between 1995-2022, despite this being a longer period. This would contribute to the lower surface temperature values seen by Irbe. Although this might be worth mentioning, ice cover data was not available during the entire period of 1966-1988 thus it is hard to make accurate comparisons. However, the relationship between surface water temperatures increasing with decreasing ice cover is suggested in other studies like Austin and Coleman (2007), Austin and Colman (2008), Piccolroaz et al (2015). Additionally, the large increase in surface water temperature in June, shown in Figure 2, might indicate that there are lower ice amounts or quicker ice melt within the more recent years. It seems that lower ice cover percentages are causing earlier stratification dates, as suggested by Austin and Colman (2007).

5.3 ATMOSPHERIC TEMPERATURE

The regression analysis for the atmospheric data for Thunder Bay station A compared to yearly increase was shown to be insignificant. The relationship had a low probability and a small r^2 value. It was noticed that there were more years with temperature above the upper standard deviation than below the standard deviation, but there was continued variation throughout the period 1995-2022. Piccolroaz et al (2015) claims to have higher yearly temperature increases than other studies, like Austin and Colman (2007), because their study used inland meteorological stations (i.e., lighthouse not buoy). The results in this study (1995-2022) also used inshore meteorological data however the results are not like that of Piccolroaz et al (2015). Both studies have shown that the El Nino event in 1998 caused warmer atmospheric temperatures, which was shown as an outlier above the standard deviation within this study for both the overall and summer atmospheric temperature data sets. The regression analysis for the summer atmospheric data increasing yearly was significant with a probability of 0.012, but it still had a low r^2 value. These findings therefore agree that there are increased atmospheric summer temperatures as shown by Austin and Colman (2007), Austin and Colman (2008) and Piccolroaz et al (2015). The slope of increase for the summer months between 1995-2022 (0.0427) was similar to the summer trend calculated by Austin and Colman (2007) and Austin and Colman (2008) from 1980-2005. Unfortunately, the probabilities and coefficient determinants were either unavailable or the other studies used different methods of calculating their trends.

The average atmospheric temperature between 1966-1988 was also analyzed to further assess Irbe's data shown in Figure 2. The mean and standard deviation between 1966-1988 is lower than that from 1995-2022, by 1°C. Thus, so far this study has determined that there are lower surface water temperatures, more ice coverage, and lower atmospheric temperatures during Irbe's (1992) study period when compared to the period 1995-2022. This demonstrates the interconnected relations between surface water temperature, ice coverage, and atmospheric temperature. The surface water temperature was shown to have no significant relationship with increasing yearly trends, which is opposite to findings from Austin and Colman (2007). However, this study does show that there were increased surface water temperatures with the significant yearly summer atmospheric temperature increase.

For a better comparison of atmospheric temperature to lake changes, multiple stations located closely around the lake should be used. The station used in this paper is about 8km away from the shoreline which will have variables impacting atmospheric temperature that are incomparable to variables affecting the surface water temperatures, ice cover, or water levels. Differences in atmospheric analysis, as discussed by Piccolroaz et al (2015) in reference to Austin and Colman (2008), are a result of differences in meteorological station heights, location, and wind speeds.

5.4 WATER LEVELS

The water level for Lake Superior between 1995-2022 showed an obvious increase in Figure 7. The regression analysis for water level compared to yearly increase was significant but still had a low r^2 value. There were more years with water levels below the lower standard deviation than there were above the upper standard deviation limit. Despite there being an increasing linear regression trend, most of the study period (1998-2013) had low water levels. Lenters (2004) and Mortiee and McBean (2009) both show a decreasing water level within Lake Superior over time. However, Lenters (2004) notes that the changes between 1948-1999 were consistent with long-term trends (i.e., 140 years). Thus, claims of carbon emissions decreasing water levels (Smith 1991) might not be easily proven without studies over extensive time lengths. Further data from 1860-2022 from the NOAA GLERL hydrograph (NOAA GLERL 2021) did not show any obvious trend. Within the graph it was shown that the same mean value was found from between 1918-2017, as there was in this study from 1995-2022.

Lofgen (2002) suggested that precipitation increases could be a factor of increased water levels, which could potentially explain the jump in 2019 (Figure 7). In contrast, Mortiee and McBean (2009) show decreasing precipitation. Based on the linear regression analysis of the winter and summer water levels, there was not a clear indication of which might have increasing water levels because similar significant increases and yearly water level increases were found in both winter and summer. Wang et al (2012) found that there were lower winter water levels due to decreased ice cover percentages and increased evaporation. The ice cover percentages were mostly below the mean (Figure 3), however still within the standard deviation limits. So, this does not help explain the increasing winter water levels yearly. The study by Lenters (2004), between 1948-1999, found that there were decreased summer and autumn water levels. This might explain the even seasonal water level increase in this study. The normal seasonal water level change from summer to winter was shown to decrease by 20%, due to things like increased spring runoff evaporation (Lenters 2004). The significantly decreasing linear regression results from Motiee and McBean (2009), between 1990-2005, had a higher probability and higher variance of ice coverage than this study found. This might suggest that variance from the mean water level is increasing with climate changes throughout time, especially because this paper analyzes a more recent time period. More research would be needed to prove this.

Further water level data was downloaded to analyze similarities and differences to other studies. Data from 1918-2022 showed no significant linear regression relationship between water level and yearly increase. Lamon and Stow (2010) claimed that there were decreasing water levels since 1970, however, here it was found that water levels from 1927 to 1988 seemed constantly around the mean of 183.5m. Additionally, from 1918-2022 it was found that water levels were more frequently above the mean than below it. The variation between 1918-2022 does not seem more prominent at any point, not even in more recent years. The lowest water level was in 1926 (182.9m) although 2007 was also low (183.0m). The yearly decrease noted in 2007 from Lamon and Stow (2010) was 2cm but later in 2009 Motiee and McBean showed a 1cm per year decline. This could represent a fluctuation in water level or a difference between models used.

Lamon and Stow (2010) said that low water levels were consistent with water temperature increase. However, 2003 and 2007 had opposite trending atmospheric and surface water temperatures yet had similar water levels. It is important to note that the fluctuations of water level should be considered with the water levels of the other Great Lakes due to the controlled drainage system through the St. Mary's dam since the 1920's (Lenters 2004). Additionally, things such as land use and land coverage will affect drainage basins and thus lake levels (Lenters 2004). In 1998, the El Nino event (Piccolroaz et al 2015, Austin and Colman 2008) did show a lower than mean water level, however this was within normal limits. The low water levels continued until 2007, despite varying atmospheric conditions. Thus, atmospheric conditions as well as other watershed characteristics should also be considered when analyzing water levels.

5.5 COMPARISON BETWEEN VARIABLES

There was an opposite trend for ice cover percentage shown with similar trends of surface water and atmospheric temperatures. During the period of lower water level 1998-2012, there were lower than mean atmospheric and surface water temperatures, thus low evaporation levels. These lower temperatures are shown more prominently within Figure 8 with increased ice cover percentages for years 2003 and 2009. The years 2010, 2012, 2014, 2016, and 2021 show outliers for surface water temperature, ice coverage, and atmospheric temperature in Figures 1, 3, and 5. The years above the upper standard deviation mean for surface water temperature show a similar pattern for atmospheric temperature and the opposite pattern for ice cover percentage. Decreased ice cover and warmer surface water due to increased atmospheric temperatures was also found by Austin and Colman (2007) and Piccolroaz et al (2015). Therefore, it seems obvious that these variables influence one another but changes caused from climate change were not proven. The water levels do not follow the same pattern except for lower water levels (Figure 6) seen with the warm years of 2010 and 2012 (Figure 5).

The claim that surface summer water temperatures are increasing more rapidly than air temperatures for Lake Superior (Austin and Colman 2007) was not shown in this paper. The summer surface water temperatures were considered insignificant with yearly increases and the linear regression has a slope 0.03 less than that of the significant summer atmospheric temperature.

The air2water model from Piccolroaz et al (2015) showed an increase in surface water heating during the spring due to increased atmospheric temperatures. As discussed above, the increased monthly temperature averages compared to the previous study by Irbe (1992:172), especially seen in June, could suggest something similar.

5.6 CONSIDERATIONS

Comparing the changes with Lake Superior's characteristics is a challenge because the data should be from a reputable source that has continual measurements taken throughout time. However, with increasing knowledge and technology the measurements of some parameters were shown to change. For example, the change from vessel in-situ surface water temperature data to the measuring surface water temperature data from satellite imagery (Irbe 1991:8). Another example includes the water level data being measured from one station to many stations around Lake Superior after 1918 (NOAA GLERL 2022). Additionally, even if measured properly, the comparisons of studies on the characteristics of Lake Superior in relation to a changing climate is difficult because of the different methods used and the different time periods studied. As well, there are different opinions about measuring methods. Irbe (1992) found there was a 0.3°C temperature difference between satellite radiation thermometer data and buoy temperature. However, Piccolroaz et al (2015) claimed that there was not a significant difference between the buoy data and satellite data based on their modeled outputs. For this reason, it would be beneficial to have a continuing study using the same analyzation methods or comparable methods to determine if lake changes are abnormal or are a part of Lake Superior’s natural cycle as Irbe (1992) and

Lamon and Stow (2010) mention. Suggestions, like that of Irbe (1992:172), claiming range and water temperature variability is within acceptable bounds despite adequate winter temperature data, may quickly become unacceptable while trying to maintain the resilience of Lake Superior in the face of climate change. Normal atmospheric changes such as El Nino events must also be considered when analysing trends caused from anthropogenically caused changes. The continuing effects of these events need to be noted, for example the decrease of surface water temperature was slow two years after the 1998 El Nino event despite the much lower atmospheric temperatures. Additionally, there was decreased ice coverage for three years after. Most likely these changes are due to the high heat capacity of water (Irbe 1992:34). This high heat capacity could potentially allow water to heat faster than atmospheric temperature because it will not cool fast during mild winters so it will not remain within normal limits as spring heating begins again. The faster increase in water surface temperature compared to atmospheric temperature is suggested by Piccolorz et al (2015).

The period of the study will also have an impact on the relationships seen and the trends calculated. For example, if this study did not include the El Nino event of 1998 one might not realize its potential effects the next few years without further research. Also, variables such as precipitation, snow melt, runoff, and evaporation, etc. might increase differences between studies (Lenters 2004, Austin and Colman 2007). This study spans over 27 years, Irbe's (1992) study spans over 22 years, Austin and Colman (2007) spans over 99 years, etc. Despite the differences, continual studies of Lake Superior are beneficial to monitoring climate change impacts.

6.0 CONCLUSION

This study showed that the only significant yearly linear relationship between 1995-2022 was the summer atmospheric temperature for Thunder Bay station A and the yearly water levels. The hypothesis that Lake Superior's surface water temperature will increase yearly and ice cover will decline yearly, cannot be proven. The hypothesis that yearly atmospheric temperatures will increase cannot be proven either. However, the summer atmospheric temperatures were shown to have a significant yearly increasing relationship. Also, water levels were shown to have a significant yearly increasing relationship. Other than increasing atmospheric data the results in this study differed from other studies which could be due to various reasons such as time length of study and measurement tools. It was noted that there seems to be dependent relationships between surface water temperature, atmospheric temperature, and ice cover percentages. However, water levels are different, and this is thought to be from anthropogenic control over water withdrawal. Measuring changes in Lake Superior would be hard due to its size and depth, because it has multiple provinces/states on its shorelines, and climate change and ecosystems are complex. This is concerning due to multiple uses of the Great Lakes and their economic importance. It is important to understand the mechanisms that drive lake changes so that data can be accurately compared to long-term trends, to claim that changes are in fact due to climate change. This project reinnervates the need for further research into the mechanisms of climate change that are changing this system, so suggestions can be made to mitigate the degradation of Lake Superior.

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