Limnology of a Large Northern Lake (Lhù’ààn Mân’ [Kluane Lake], Yukon) in an Era of Reconciliation and Rapid Climate Change

By

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ABSTRACT

Almost 60% of Canada’s freshwater drains North, where air temperatures are increasing at twice the global rate. Despite the exposure of northern lakes to higher rates of change and their ecological, hydrological, and cultural importance, baseline knowledge and monitoring of their water properties and dynamics remains limited. However, impacts to physical, biological, and chemical lake water properties have been documented and are likely to continue, with consequences for ecological and human communities. As such, understanding how northern lakes are changing is critical for implementing adaptation, mitigation, and protection measures to help ensure their long-term health. Lhù’ààn Mân’ (Kluane Lake) is Yukon’s largest lake, is important to local communities, and provides habitat to keystone species. In 2016, Lhù’ààn Mân’ lost its primary inflow — comprised mostly of glacial meltwater — to glacier recession, offering a unique opportunity to investigate how glacier recession (and eventual disappearance) can impact downstream lakes. For these reasons, Lhù’ààn Mân’ is a good case study to better understand how large northern lakes are impacted by climate change. In 2015, a baseline study to characterize physical, biological, and chemical lake water properties was conducted with Kluane First Nation, Dän Keyi Renewable Resources Council, academic and community colleagues (Chapter 2). This baseline revealed that Lhù’ààn Mân’ was comprised of four distinct regions influenced by depth and proximity to glacial inflow: a cold, turbid, and poorly stratified southern basin, a mid basin and northeastern arm with relatively clear and consistently stratified waters, and a warm, nutrient-rich, productive northwestern arm. Spatial variability between lake regions and seasonal variability within sites was significant, emphasizing the need for sufficient spatial and temporal resolution in limnological studies. The baseline study led to the design and implementation of a long-term monitoring program for Lhù’ààn Mân’ (Chapter 3). While the initial research interest focused on how gradual climate change was impacting the lake, after 2016 it evolved to include how more abrupt climatic changes (i.e., sudden loss of glacial inflow) could impact lake thermal dynamics. Four moorings equipped with continuously recording temperature data loggers were deployed in spring 2017 across the lake's different regions. Water temperature was selected because it is a key indicator of general freshwater conditions, and is reliable and cost-effective to measure. The first three years of Lhù'ààn Mân' thermal monitoring confirmed that each region of the lake has distinct thermal dynamics, but also different temporal patterns in thermal dynamics: warming occurred in the south end of the lake between 2017 and 2019 (but not in other regions of the lake), possibly impacted by the loss of significant glacial inflow in 2016. Continued monitoring will be critical to determine whether the south-end warming pattern continues, if warming will occur elsewhere in the lake, and how fish habitat will be impacted. Since thermal monitoring of large northern lakes is scarce, other available data was explored to investigate how these systems are changing. MODIS satellite imagery between 2000 and 2019 was used to examine whether lake ice break-up was occurring earlier at Lhù'ààn Mân' and nine other large lakes in southwest Yukon/northeast British Columbia (Chapter 4). All lakes revealed negative slopes indicating trends towards earlier spring ice break-up (and possibly longer ice-free periods), with mean start/end of break-up of all lakes occurring 0.72/0.46 days per year earlier. Three lakes exhibited significant trends ($p<0.05$) and two exhibited marginally significant trends ($0.05<p<0.10$). These results reinforce the need for monitoring lake water properties, which can be impacted by longer ice-free periods. While knowledge about changing ecosystems is a key component to ensuring their long-term health, how this knowledge is gathered and shared is equally — if not more — important in this era of reconciliation. The field of environmental sciences is in a paradigm shift moving towards practicing reconciliation and respect and equality for Indigenous ways of knowing, being, and doing. Current challenges to — and recommendations for — reconciliation in research were identified via personal experiences and conversations (Chapter 5). Challenges are rooted in individual bias, lack of resources, and western academic structures. Recommendations include a need for systemic level changes regarding the use, respect, and understanding of Indigenous ways of knowing, being, and doing, fostering safe and respectful spaces for reflection and conversation, and identifying strategies for practicing and supporting reconciliation.

PREFACE

Each thesis chapter represents a publication and is structured for the journal to which it has been/will be submitted. While the study design of all chapters were led by Ellorie McKnight, this thesis would not be possible without collaboration. Kluane First Nation, Dän Keyi Renewable Resources Council, David Hik and Suzanne Tank provided input and guidance for each chapter design and structure. Contributions to fieldwork, data analysis, writing, and editing are acknowledged by co-authorship of publications and in the separate acknowledgement section of each publication.

Chapter 2: McKnight, E., Swanson, H., Brahney, J. & Hik, D. 2021. The physical and chemical limnology of Yukon’s largest lake, Lhù’ààn Mân’ (Kluane Lake), prior to the 2016 ‘A’ą̈y Chù’ diversion. Arctic Science.7(3): 655-678. Doi: 10.1139/as-2020-0012.

Chapter 3: McKnight, E., Tank, S., Swanson, H., Brahney, J., Giroux-Bougard, X., Korver, M., Hik, D., Dän Keyi Renewable Resources Council & Kluane First Nation. Lhù’ààn Mân’ (Kluane Lake) thermal dynamics between 2017 and 2019 suggest influence from sudden loss of glacial inflow in 2016. In preparation for submission to *Freshwater Science*.

Chapter 4: McKnight, E, Hik, D., Williamson, S., Varney, J. Analysis of spring ice phenology for ten large lakes in southwest Yukon/northern British Columbia, Canada, between 2000 and 2019. In preparation for submission to *Limnology and Oceanography*.

Chapter 5: McKnight, E. Identifying challenges to — and recommendations for — reconciliation in (northern) environmental science research. In preparation for submission to *Northern Review*.
As per the acknowledgement section of this publication, many colleagues and friends contributed in various ways to this chapter. Carmen Wong, Pauly Sias, Bronwyn Hancock, and Suzanne Tank provided edits and suggestions during the multiple written iterations of this chapter. Additionally, conversations with Kate van Ballegooyen, Mathieya Alatini, Peter Upton, Cecile Sias, Grace Southwick, Marissa Mills, Sam White, Sophia Lavergne, Meagan Grabowski, Gwenn Flowers, Ally Menzies, Heidi Swanson, and David Hik contributed to shaping the ideas and content of this chapter.

DEDICATION

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Water ceremonies are an Indigenous practice which give thanks and respect to water. These ceremonies also remind us of our deep interconnection with water and our duty to care for it.

In the absence of a physical water ceremony, I invite everyone who is about to read these pages to take a moment to hold gratitude for water and reflect on their responsibilities to care for it.

~

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Most importantly, thank you to the land, water, and people of Kluane. I cannot adequately express the gratitude I feel to have lived and worked in this part of the world for a period of time. The learning, personal growth, reflection, conversations, and connections I experienced with the land, water, and especially people of Kluane were immense. Thank you especially to Pauly Sias, Kate Ballegooyen, Peter Upton, Lance, Sian and Bronwyn Goodwin, Mathieya Alatini and family, and the youth and elders of Kluane First Nation.

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CHAPTER 1 . General Introduction

Arctic climate change

In 2017, mean global air temperatures were 1°C warmer than pre-industrial (1850-1900) levels, and increasing at a rate of 0.2°C per decade. This warming has been caused by anthropogenic processes and land use changes from the last century, which have increased the atmospheric concentration of greenhouse gases (IPCC 2014; IPCC 2018). Over the last two decades, warming in the Arctic has occurred at more than double the global average (Meredith et al. 2019). This phenomenon is known as Arctic amplification, attributed primarily to feedback loops from loss of sea ice and snow cover (Serreze & Barry 2011). The impacts of both increased atmospheric greenhouse gases and warming on the Arctic Ocean and terrestrial environments are numerous and include: ocean acidification, permafrost degradation, glacier recession, expansion of shrubs, changes in wildlife migration patterns and health, increased wildfire activity, and changes to the quantity and quality of freshwater ecosystems (Meredith et al. 2019). Impacts of climate change on northern freshwaters are of particular concern due to their importance to both ecosystems and communities (Prowse et al. 2006).

Large northern lakes and climate change

Northern Canada holds a vast amount of the world's freshwater, much of it in large ($>500km^2$) lakes (Cott et al. 2016). Many of these lakes are influenced by glaciers and snowmelt and are a result of historical ice sheet advances and retreats. High latitude lakes are typically ice-covered either year-round or only experience brief periods free of ice and are considered to be monomictic (Vincent et al. 2008). Sub-Arctic lakes typically experience periods of ice-off long enough for the water column to mix in the spring, stratify in the summer, and mix again in the fall (i.e., dimictic) (Lewis 1983; Vincent et al. 2008; Woolway & Merchant 2019). Many of the large northern lakes in Canada are remote and relatively pristine compared to southern lakes located in high density population regions with more exposure to agricultural and industrial activity. The large lakes of northern Canada act as sentinels of change, play important roles in regulating ecological processes, storing water, providing key habitat for fish and other species, providing travel corridors both in summer and winter, and hold significant traditional, cultural, and recreational value for communities (Adrian et al. 2009; Mueller et al. 2009).

Through gradual and abrupt, as well as direct and indirect impacts, climate change is impacting large northern lakes (Woolway et al. 2020). Direct impacts of warmer air temperatures and Arctic amplification on lakes include shifts in lake ice phenology (Livingstone et al. 2010), warmer lake surface water temperatures (O'Reilly et al. 2015), and shifts in mixing regimes (e.g., stronger stratification in dimictic lakes) (Woolway & Merchant 2019). Indirect impacts of climate change to lakes are a result of changes within the watershed which subsequently affect the quantity and or quality of lake water, such as glacier recession (e.g., Shugar et al. 2017), permafrost degradation (Mao et al. 2018; Smith et al. 2005), shifts in precipitation which affect nutrient transport, ions and dissolved organic carbon to lakes (Collins et al. 2019), and vegetation change (Larsen et al. 2011). While some of these changes are more gradual (i.e., increasing water temperature trends over time), others can be more abrupt (i.e., glaciers disappearing or receding and resulting in large scale and rapid changes to downstream physicochemical water properties and quantities) (Figure 1-1).

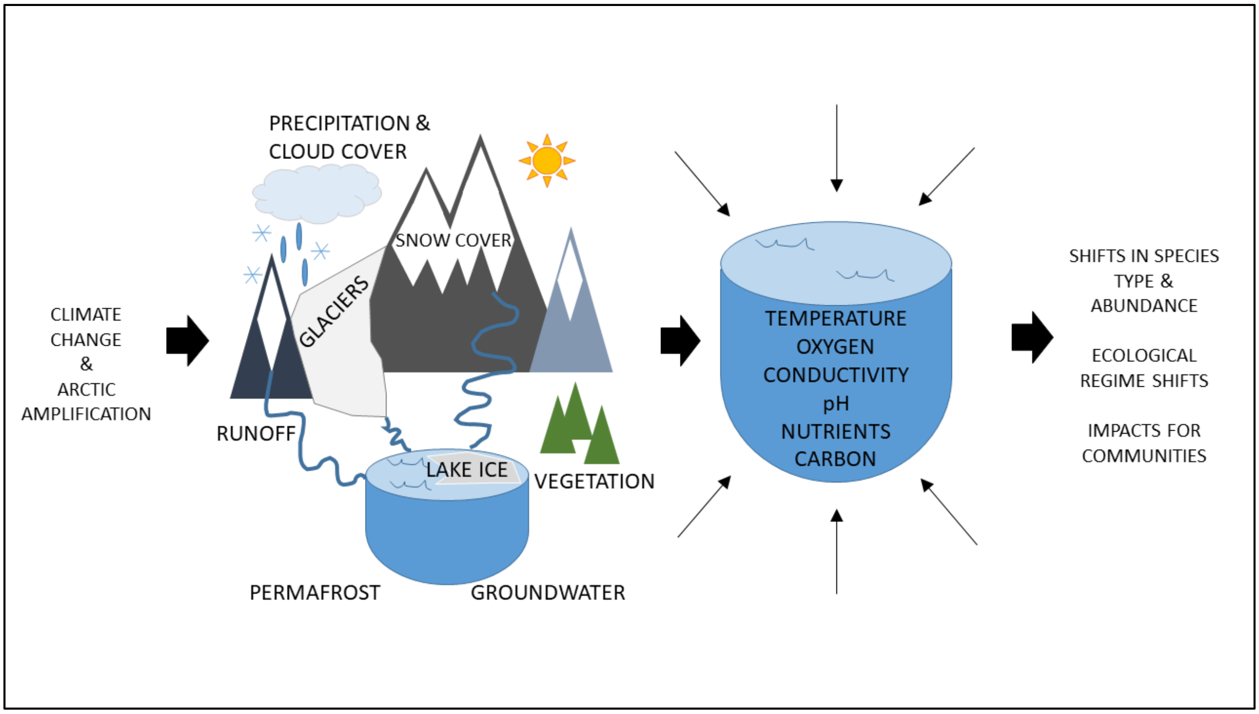

Figure 1-1. Conceptual framework of the direct and indirect impacts of climate change on the physical, chemical and biological properties of northern lakes.

Gradual, abrupt, direct and indirect impacts of climate change can all cause changes in the physical, chemical, and biological properties of lake water. Small shifts in these properties can cascade into significant consequences (Adrian et al. 2009; Schindler 2009; Williamson et al. 2009). Changes in water temperature and thermal dynamics are especially of concern, since temperature is largely tied to other water properties and ecological processes (Magnuson et al. 1979). For example, small increases in water temperatures can cause fish optimal physiology limits to be exceeded, leading to declines in habitat and populations (Sharma et al. 2007). Not only would this have ecological consequences, it would also greatly impact communities that rely on subsistence (Sharma et al. 2007).

However, despite the importance of northern Canada's large lakes, there are significant knowledge gaps about both how these systems may be impacted by climate change, as well as baseline limnological knowledge which is required to understand change (Woolway et al. 2020). Baseline knowledge and monitoring of large northern lakes in the face of climate change is a critical and needed step towards predicting future conditions, adapting and mitigating to change, and conserving key freshwater ecosystems.

Reconciliation and research

In Canada, Indigenous ways of knowing, being and doing guided and informed people until settlers arrived and imposed western values, practices, and views — including science as a way of understanding the world. In the early-mid 1900s, access to northern Canada was facilitated by the construction of roadways and air travel, resulting in an influx of settlers and visitors, residential schools, and colonialism which had significant and devastating impacts for Indigenous communities and ways of life (Castillo et al. 2020). National and global recognition of the wrongs and damages of colonization has occurred in recent history: in 2007, both the United Nations Declaration on the Rights of Indigenous Peoples was adopted by the United Nations (United Nations General Assembly 2007), and the Indian Residential Schools Settlement Agreement was implemented in Canada, resulting in the establishment of the Truth and Reconciliation Commission of Canada (Truth and Reconciliation Commission of Canada 2015). In 2015 the TRCC published 94 Calls-to-Action to provide guidance and direction towards reconciliation between Aboriginal and non-Aboriginal Canadians. These Calls-to-Action apply to all Canadians as treaty people, including scientific researchers.

While science has largely dominated our global understanding of climate change, the recognition, respect, and need for Indigenous ways of knowing, being and doing – within this field and others – is increasing (Alexander et al. 2011; Chapman & Schott 2020; Ford et al. 2016; Wheeler et al. 2020; Wong et al. 2020). The way knowledge is collected, shared and understood is intertwined with the reconciliation process, and science can no longer be conducted without a reconciliatory lens. “Helicopter research” is a term sometimes used to describe “western” researchers travelling to study sites – often in northern or remote regions - to conduct research that is typically not led, prioritized or conducted by local communities and with limited, no, or tokenistic engagement. While the knowledge gained from the research may be valuable on a global scale (for example, a project investigating a component of climate change to better understand a larger picture), the way this kind of research is conducted is effectively colonial. Research and academia are currently navigating a paradigm shift in which there is growing focus on the need for reconciliation, including respect for Indigenous ways of knowing, being and doing, and working with and for local communities. Despite a growing number of resources, guidelines, and expectations regarding how to do research in a reconciliatory way, scientists are still very much navigating the process of reconciliation within research (Wheeler et al. 2020). While this thesis attempts to better understand the impacts of climate change on northern lakes, it also identifies some of the current challenges regarding research and reconciliation, encourages honest and respectful conversations about the topic, and identifies positive ways in which to move forward.

Lhù’ààn Mân’ (Kluane Lake)

Lhù’ààn Mân’[1] is the largest lake entirely within the Yukon (Figure 1-2). Within the Kluane watershed, air temperatures are rising at twice the global average (Chapter 3) with

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[1] Lhù’ààn Mân’ is the Southern Tutchone name for Kluane Lake. Southern Tutchone is one of seven Athapaskan languages in the Yukon and is spoken by Kluane First Nation people (Kluane Lake is located within Kluane First Nation Traditional Territory – see next section). With Kluane First Nation’s encouragement, and in accordance with Canada’s Truth and Reconciliation Commission’s Call to Action regarding Indigenous language respect and use, I have used Southern Tutchone place names whenever possible throughout this thesis. While I have done my best to use the most recent spelling of these place names, it is possible that some spellings may not be up-to-date as the written language continues to be updated.

numerous impacts on the local environment and for communities (see Chapters 2 and 3). Understanding the impacts of climate change on Lhù'ààn Mân' is of interest for local communities because of the possible consequences to traditional customs, travel, and subsistence. Understanding impacts of climate change on northern lakes is also of global interest because of the importance of northern freshwaters in the global hydrological cycle. Because of its importance, the rate at which climate change is impacting the watershed, and lack of proximal industrial development, and its complex history regarding colonization and self-government, Lhù'ààn Mân' is a good model system for better understanding impacts of climate change on large northern lakes and working towards reconciliation.

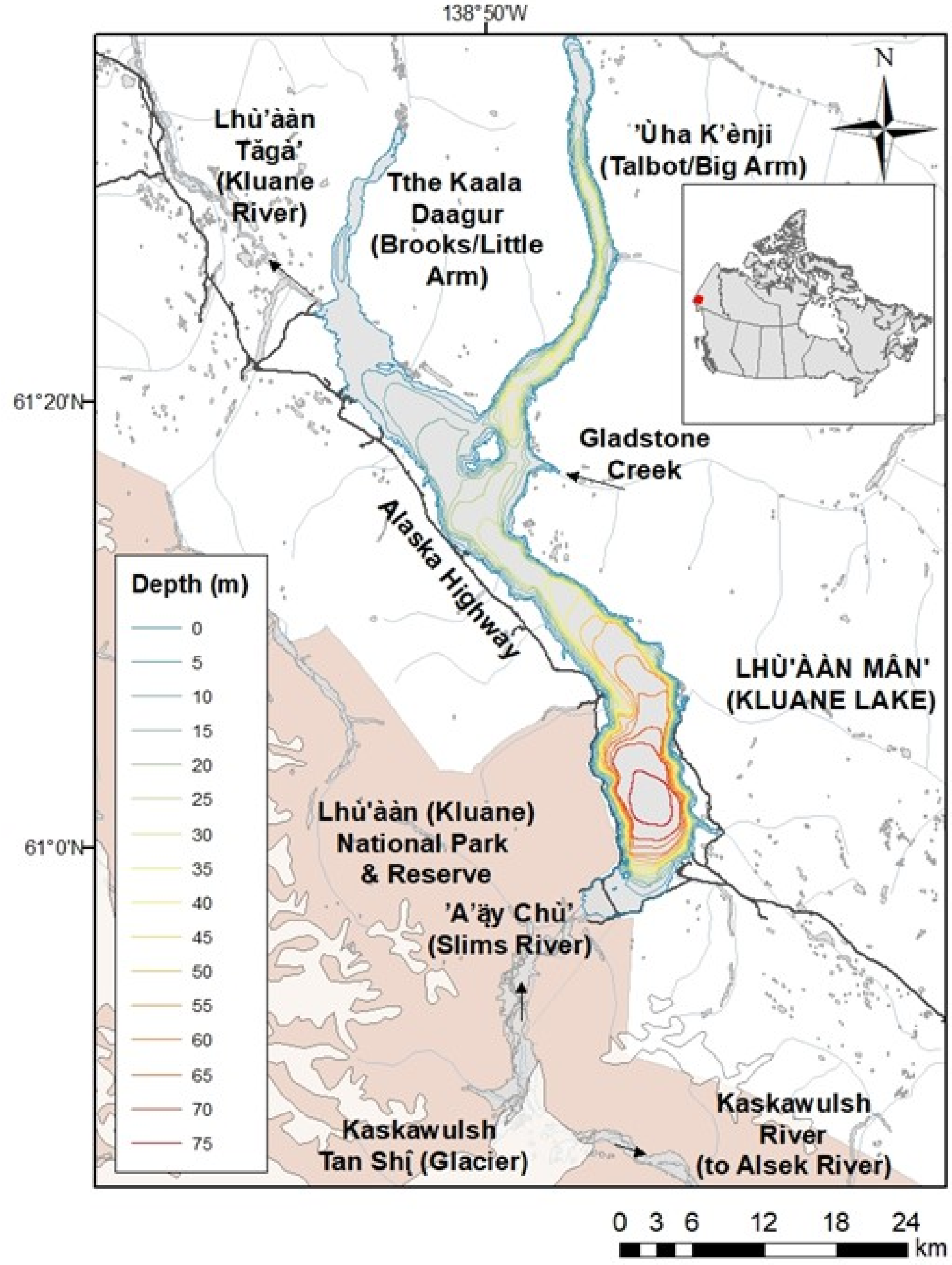

Figure 1-2. Map of Lhù'ààn Mân' (Kluane Lake), Yukon, lake bathymetry and surrounding area. Bathymetry from Yukon Environment (1980s source map) and Clague et al. (2006 source map of southern basin) were merged and corrected with 2013 and 2015 bottom depths measured from approximately 150 Castaway CTD casts. Produced in Esri ArcMap 10.7.1 with open-access basemaps from Natural Resources Canada and Yukon Government.

Kluane people and history

Lhù'ààn Mân' is located on Kluane First Nation and White River First Nation traditional territories. The Kluane region has been inhabited for over 10 000 years by primarily Southern Tutchone speaking Lhù'ààn Mân' Ku Dän (Kluane Lake people) who lived nomadically and travelled throughout the area to hunt, fish, and gather food. Contact with settlers, and subsequent establishment of residential schools, became prominent shortly after the Gold Rush which occurred at the end of the 1800s. The settlement of Burwash Landing was established in 1904 when a trading post was opened there, but still no major roads reached the area. In 1942, the Alaska Highway was built, connecting Alaska with the lower 48 states. The highway, which runs along the western shores of Lhù'ààn Mân', resulted in the first influx of travellers, visitors and settlers to the area (Council of Yukon First Nations 2010). In 1943, the Kluane Game Sanctuary (which became Kluane National Park and Reserve in 1972) was established to conserve wildlife and landscapes, which effectively denied access to important hunting, fishing, and trapping areas. Kluane and Champagne Aishihik First Nations have since reasserted their rights to carry out traditional activities within the park boundaries (Council of Yukon First Nations 2010). In 1960, The Arctic Institute of North America established the Kluane Lake Research Station, located 70 km south of the communities of Destruction Bay and Burwash Landing and attracting a seasonal summer influx of researchers studying human physiology and glaciology in the nearby high elevation mountains and boreal forest ecology (Danby et al. 2014). All of this history has had significant impacts for the Lhù'ààn Mân' Ku Dän.

The Kluane region was not the only part of the Yukon to be impacted by colonialism. In 1973, Indigenous leaders throughout Yukon presented Together Today for our Children Tomorrow (Council of Yukon First Nations 1977) to the federal government, initiating a process for modern-day treaties in the Yukon. This lead to the Yukon Umbrella Final Agreement (finalized in 1990), an agreement between the Canadian government, Yukon government, and Yukon First Nations which provided a framework for final claim settlement agreements of Yukon First Nations (including compensation, self-government, and creation of boards), followed by the Kluane First Nation Final Agreement in 2003. White River First Nation initially participated in negotiations but have not reached an agreement with the Canadian and Yukon territorial governments[2]. The Kluane First Nation Final Agreement resulted in what is known today as the Kluane First Nation government, as well as a subset of important councils including the Dän Keyi Renewable Resources Council, which acts in the public interest and was established "as a primary instrument for local renewable resources management as set out in the Kluane First Nation Final Agreement" (Kluane First Nation Final Agreement, 2003).

Today, Kluane First Nation has approximately 230 citizens, about half of whom live in Kluane (Kluane First Nation, unpublished). Citizens travel on Lhù'ààn Mân' in both summer and winter to access traplines, hunting areas, cabins, heritage sites, and fishing sites. The lake holds significant cultural and traditional value for the people of Kluane. As previously noted, researchers, visitors, travellers and local people use the Alaska Highway to access the area. The number of researchers, visitors and travellers to Kluane each year far exceeds the number of people that reside in the local communities. Historically, researchers working in the region and out of the Arctic Institute of North America have had limited interaction with the local

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[2] Throughout my thesis, I had regular contact with Kluane First Nation, but not with White River First Nation. This occurred naturally, and from my point-of view, resulted primarily from Kluane Lake being more central to Kluane First Nation than to White River First Nation, as well as the existing relationships established between certain researchers and Kluane First Nation. Throughout my thesis and time spent living and working in Yukon, I have learned more (and am still learning) about Indigenous land claims processes. As Kluane Lake is also within White River First Nation, I should have also had contact and communication with White River First Nation, regardless of their Agreement status with the Government of Canada. I wish to acknowledge this error and commit to continued learning and future actions which contribute to reconciliation.

communities, although the need for change has been recognized in recent years and has resulted in increased communication and relationship building between researchers and local community members (e.g., Kluane Research Summits 2018 and 2019).

Lhù'ààn Mân' and climate change

Lhù'ààn Mân' has a dynamic history, having reversed flow directions several times and fluctuating drastically in both size and depth over time due to glacier advancement and recession affecting hydrologic flow (Clague et al. 2006, Brahney et al. 2010) (Figure 1-3, reproduced from Clague et al. 2006).

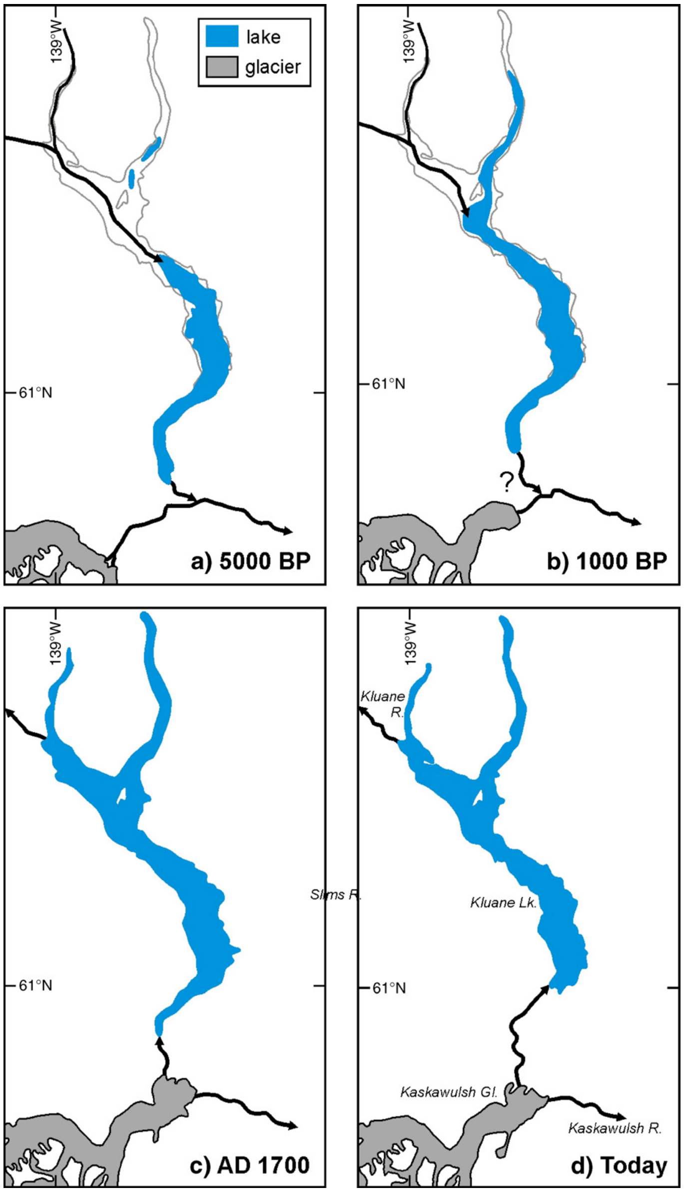

Figure 1-3. Reproduced from Clague et al. 2006. Approximately 5 000 years before present, Lhù'ààn Mân' drained to the North Pacific and was 35m lower than present. Approximately 1000 before present, the Kaskawulsh advanced early during the Little Ice Age, aggrading the Slims valley bottom and causing the lake to expand and rise to about 12m below present levels. During the late seventeenth century, the Kaskawulsh blocked the Slims valley and caused the lake to rise about 10m above present level and overflow north into Yukon drainage system, where it continues to drain today.

In recent history and until 2017, the primary inflow to Lhù'ààn Mân' was the 'A'ą̈y Chù' (i.e., Slims) River, which was mostly composed of Kaskawulsh Glacier meltwater (Figure 1-2). The 'A'ą̈y Chù' flowed into the lake's southern end and the water flowed out Lhù'ààn Tăgà' (i.e., Kluane River) in the lake's northwest arm, into the Yukon River watershed and eventually the Bering Sea. The lake is approximately 80 km long and is in the shape of a 'Y'. The physicochemical properties of the lake change throughout its length, resulting in different ecoregions hosting a variety of habitat and species (Chapter 2).

In Yukon, air temperatures have increased at twice the global rate over the last 50 years, (at 2°C yearly and 4°C in winter) (Government of Yukon 2020). Scientific research and Indigenous knowledge have described a changing environment within the Kluane watershed, with observations that include glacier recession (Flowers et al. 2014), shrubification (Myers-Smith & Hik 2018), and structural changes in boreal ecosystems (Boonstra et al. 2017). In addition to these gradual changes, in 2016 the Kluane watershed experienced a more abrupt impact of climate change that directly impacted Lhù'ààn Mân' and its shorelines. The Kaskawulsh Glacier receded to a critical point which caused its meltwaters to be diverted into the neighboring Kaskawulsh-Alsek watershed (Shugar et al. 2017). This caused a drier 'A'ą̈y Chù' riverbed composed only of snow meltwater and secondary creeks, resulting in a sudden reduction of water flowing into Lhù'ààn Mân'. Lake levels, which previously had fluctuated seasonally by about 2 m over the course of the melt season, now only fluctuate ~0.5-1 m per year, and the winter lake level is approximately 0.25 m lower (Chapter 3). Impacts of the 2016 diversion are also captured when comparing pre- and post- diversion peak summer discharges from the lake's primary outflow (Lhù'ààn Tăgà'): peak mean discharge before the diversion (using data between 1975 and 1995, which is the most recent pre-diversion data available from

Environment and Climate Change Canada) was 296.0 m^3/s. In 2020 and 2021 (the discharge gauge for Lhù’ààn Tăgà’ was re-established in late 2019 after being discontinued in 1995), peak discharges were recorded at182 m^3/s and 124 m^3/s respectively. These changes in lake level and outflow discharges are an indication that lake residence time has likely become longer.

The drier ‘A’ą̈y Chù’ riverbed is now exposed to katabatic winds from the St Elias mountains, resulting in massive dust storms impacting the communities of Destruction Bay and Burwash Landing (Bachelder et al. 2020). The dust storms may also directly impact the physical limnology and thus water quality of Lhù’ààn Mân’ in fundamental ways which have yet to be investigated.

The impact of this abrupt change on the lake itself, as well as the impacts to the lake of more gradual changes within the watershed, are not well known. Baseline limnological conditions of the lake – against which to compare future change – are also not well understood. The limited limnological knowledge of Lhù’ààn Mân’ includes historical information on flow direction and lake levels (Bostock 1969; Brahney 2007; Brahney et al. 2008a, 2008b, 2010; Clague et al. 2006); sedimentary processes at the south end of Lhù’ààn Mân’ (Bryan 1970; Crookshanks 2008; Crookshanks & Gilbert 2008); fish stock assessments, angler surveys, and salmon spawning investigations (Barker et al. 2014; de Graff 1992; Department of Fisheries and Oceans 2018; Foos 2004; Wilson 2006); and limited measurements of physical limnology which include select point measurements or column profiles of temperature, conductivity, pH, total dissolved solids, ions, and chlorophyll-*a* (Carmack et al. 2014; Geological Survey of Canada 1978; Lindsey et al. 1981) as well as two roughly year-long, full column thermal datasets from the southern end of Lhù’ààn Mân’: one is from a mooring deployed in early June 1985 and retrieved mid June 1986 (Carmack et al. 2014) and the other is from a mooring deployed in

August 2013 and retrieved in July 2014 (unpublished data from Carol Janzen, Eddy Carmack, and David Hik).

Objectives

The overarching goal of my thesis is to better understand how large northern lakes are impacted by climate change in a way that is committed to reconciliation. Since water temperature is a key driver of lake conditions and processes, it is a critical indicator of overall lake change. Water temperature also integrates direct, indirect, gradual and abrupt climatic change and is relatively easy, affordable, and reliable to measure. As such, I have focused specifically on better understanding the thermal dynamics of large northern lakes in the face of climate change.

Despite significant warming of air temperature occurring in Yukon, the number of large lakes in the territory, and the potential for thermal changes and associated consequences, both baseline and monitoring of large lakes in this region are very limited, especially at the high spatial and temporal resolution which is needed for identifying change. The need to address this knowledge gap, and existing relationships with Kluane First Nation and community members through academic and personal contacts, led me to focus on Lhù'ààn Mân' as a model system to begin exploring the above research interests. This research addresses local interests, and results will simultaneously contribute to a more global understanding of climate change impacts on the thermal dynamics of lakes. The objectives of this thesis are to:

a) Address the limnology knowledge gap for Lhù'ààn Mân' by conducting a multi-seasonal baseline study of its physical, chemical, and biological properties (2015) with which to characterize the system and against which future research can be compared in order to identify change (Chapter 2)

b) Use the information collected from the baseline study to co-design and establish a cost-effective, valuable, and sustainable long-term monitoring program for Lhù’ààn Mân’ (2017-present). Lake temperature was identified as the most reliable, valuable, and informative parameter for the program. The objective of the long-term monitoring program is to identify possible thermal changes over time which can then be used to inform future adaptation, mitigation, conservation and management (Chapter 3)

c) Conduct an updated ice phenology assessment for ten large lakes in southwest Yukon/northern British Columbia (including Lhù’ààn Mân’). Such an assessment has not been completed for this region despite the number of large lakes and their overall importance. Since lake ice phenology is associated with lake thermal dynamics, this assessment will provide an indication of how lakes – and their thermal dynamics – may be changing in this area (Chapter 4)

d) Navigate and commit to reconciliation throughout the thesis process and identify challenges to – and recommendations for – reconciliation in (northern) environmental research. While this objective has a less quantifiable end goal, it is perhaps the most important – both ethically and for the success of the research – and is woven into all aspects of this thesis (Chapter 5)

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CHAPTER 2 . The physical and chemical limnology of Yukon’s largest lake, Lhù’ààn Mân’ (Kluane Lake), prior to the 2016 ‘A’ą̈y Chù’ diversion

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Abstract

Despite increasing evidence that large northern lakes are rapidly changing due to climate change, descriptive baseline studies of their physicochemical properties are largely lacking, limiting our ability to detect or predict change. This study represents a comprehensive scientific assessment of the limnology of Yukon’s largest lake: Lhù’ààn Mân’ (Kluane Lake), an important waterbody for local and First Nation communities, and key habitat for trout and salmon. Water sample and instrument data generated throughout 2015 describe distinct regions within the lake and their respective seasonal variability. A deep, glacially-influenced southern basin was characterized by cold, turbid, poorly stratified, unproductive and nutrient-poor conditions; a shallower northwestern region (Tthe Kaala Daagur [Brooks/Little Arm]) was warmer, fully mixed, and more productive; a northeast region (’Ùha K’ènji [Talbot/Big Arm]) was clear and stratified with intermediate depth, temperature, productivity, and nutrient concentrations; a central region had intermediate physicochemical conditions relative to the other three. This variability demonstrates the need for adequate spatial (within lake) and temporal (between seasons) monitoring of large northern lakes. In 2016, glacier recession within the watershed resulted in diversion of the lake’s primary inflow (‘A’ą̈y Chù’ [Slims River]). Our results, when used together with Indigenous Knowledge, form a historical reference that enables assessments of the potential ecological consequences to Lhù’ààn Mân’.

Introduction

Over 60% of Canada's freshwater flows north into Arctic and Sub-Arctic watersheds, much of it through large lakes (Cott et al. 2016; Sprague 2007). Large northern lakes provide habitat and travel corridors for many species, regulate hydrological processes and local climate, and have significant cultural value (Cott et al. 2016; Reist et al. 2016; Rouse et al. 2005; Vincent et al. 2011). However, the integrity of these ecosystems and the services they provide are being affected by accelerating Arctic warming (Drake et al. 2018; Heino et al. 2009; Lehnherr et al. 2018; Magnuson et al. 2000; Rosenzweig et al. 2007; Vincent 2020; Woelders et al. 2018). This warming may result in reorganization of Arctic landscape and hydrology, including the loss or creation of rivers, and in some cases significant (>30 m) changes in lake levels (Brahney et al. 2008; Clague & Rampton 1982; Shugar et al. 2017).

Large lakes are sensitive to incremental and cumulative effects of changes in climate, which manifest in changes to physical, chemical, and biological water properties that have consequences for surrounding ecosystems and human communities (Adrian et al. 2009; Mueller et al. 2009; Smol et al. 2005). Direct effects include warming lake surface temperatures (O'Reilly et al. 2015) and intensified thermal stratification (Kraemer et al. 2015) that results from warmer air temperatures and longer ice-free seasons. Indirect effects, which are often mediated through watersheds, can also be significant; receding and disappearing glaciers can result in lower lake water levels (Cruikshank 1981) and alterations to downstream hydrological conditions, including changes in temperature, turbidity, and chemistry of lake outflow waters (Milner et al. 2017; Slemmons et al. 2013). Degrading permafrost in lake watersheds can also cause changes in lake water chemistry, including increases in ionic concentrations and clarity (Kokelj et al. 2009). These alterations to physicochemistry can impact lake ecology, including the health, habitat, and physiology of fish (Ficke et al. 2007). Lower lake levels reduce shoreline and availability of shallow water spawning habitat (Gaeta et al. 2014). Shifts in the timing of ice-on and ice-off also affect timing of algal blooms, overall lake productivity, and species' phenology (Prowse et al. 2011a). Human communities who rely on these ecosystems for transportation and provision of food (through commercial and subsistence fisheries) and drinking water are also impacted. Despite the vulnerability, ecological value, and importance of large northern lakes to remote communities, scientific knowledge and long-term data about their dynamics and physicochemical structure remains scarce. Together with Indigenous knowledge, baseline research and sustained monitoring are needed, particularly in northern Canada (Cott et al. 2016; Evans 2000; Prowse et al. 2015), if we are to accurately forecast and adapt to effects of a changing climate on large aquatic ecosystems.

Lhù'ààn Mân' (Kluane Lake) is located within Kluane First Nation and White River Traditional Territories, and is the largest lake entirely within the Yukon Territory (Figure 1-2). It provides a unique opportunity for assessing impacts of climate change on large northern lake systems for several reasons. Within the last few hundred years, climatic changes have led to notable shifts in the physical limnology of the lake, including lake size, flow direction, mixing regime, productivity, chemistry, and ecology. Prior to the Little Ice Age (late 17th and early 18th centuries), the lake was approximately 25m below current level, drained south through the Dhal T'à' (Slims River Valley) (Brahney 2007; Brahney et al. 2008a; Reyes et al. 2006), and was meromictic (Brahney et al. 2008b) and more productive (Zabel 2017). During the Little Ice Age, the Kaskawulsh Glacier advanced and blocked the main outflow of the lake, which caused lake levels to rise to 12m above present. The Lhù'ààn Tăgà' (Kluane River) outlet at the northwest end of the lake (Figure 1-2) was created shortly thereafter. This resulted in a reversal in the direction of lake flow, allowing migrating salmon to enter the lake from the Yukon River system and establish spawning and rearing grounds (Brahney et al. 2008a; Kluane First Nation 2005; and Local knowledge). From approximately AD 1800 until 2016, the primary source of water to the lake was the ‘A’ą̈y Chù’ (Slims River), which was comprised mostly of meltwater from the Kaskawulsh Glacier. There have also been several documented changes in the Lhù’ààn Mân’ watershed that reflect warming and altered precipitation regimes in recent decades, including permafrost degradation (James et al. 2013), tree and shrubline advance (Danby & Hik 2007; Myers-Smith & Hik 2018), and glacier recession (Barrand & Sharp 2010; Flowers et al. 2014; Streicker 2016).

In spring 2016, the ‘A’ą̈y Chù’ dramatically decreased in volume after the Kaskawulsh Glacier receded to a critical point and meltwaters were diverted south to the Kaskawulsh and Alsek Rivers (Shugar et al. 2017). Since the reduction of this important inflow, seasonal annual fluctuations in lake levels have decreased from approximately 2m to 0.5m, and minimum (winter) lake levels are approximately 0.25m lower (Environment and Climate Change Canada, online data). Lake levels and fluctuations are not expected to return to pre-2016 levels because meltwaters of the Kaskawulsh Glacier are unlikely to return flowing down the Dhal T’à’ (Slims River Valley) (Shugar et al. 2017). Lower lake levels have created significant challenges for boat access and travel for local and First Nation lakeshore communities, and have also resulted in growing air quality concerns due to increased frequency and intensity of airborne dust from the drier Dhal T’à’ bed (Bachelder et al. 2020). Decreased lake levels have also exposed lacustrine salmon spawning habitat to air, and in the event that the lake continues to recede below the level of the lake outlet, salmon access to Lhù’ààn Mân’ could effectively end (Brahney et al. 2010; Department of Fisheries and Oceans 2018).

Lhù’ààn Mân’ is culturally and ecologically important to surrounding local and First Nation communities. The lake supports subsistence and commercial fishing, and summer and winter travel routes to traplines, cabins, businesses and mines within the watershed that are not road accessible. The cultural value, stories, and ecological value of the lake, as well as its provision of recreational opportunities, cannot be overstated. Despite this, and the fact that effects of climate change are anecdotally well understood, descriptive scientific limnological data for Lhù’ààn Mân’ are scarce: full-column temperature data were collected in the southern basin of Lhù’ààn Mân’ over one annual cycle in the mid-1980s (Carmack et al. 2014) and over another annual cycle in 2013-2014 (unpublished data by Eddy Carmack, Carol Janzen and David Hik), turbidity currents were studied in the southern basin (Crookshanks & Gilbert 2008), and only scattered point surface data and profiles (water temperature, oxygen, nutrients) exist (Barker et al. 2014; de Graff 1992; Foos 2007).

To address this knowledge gap, ensure appropriate design of long-term monitoring, and complement local and Indigenous knowledge, we established a benchmark of physicochemical lake properties. With guidance from Kluane First Nation, the Dän Keyi Renewable Resources Council, and local communities regarding safe lake travel and navigation, geographical knowledge, community context, community priorities and interests, and how to engage respectfully and effectively with local communities, we conducted a comprehensive limnological baseline study of Lhù’ààn Mân’ between February and November 2015, with particular attention paid to within-system variability in this large and morphologically diverse lake. Given the sudden shift of ‘A’ą̈y Chù’ headwaters into a different watershed in 2016, this dataset provides a particularly important reference point from which to evaluate change in coming years and decades: the reduction of glacial waters to downstream aquatic systems can result in significant changes, including loss of endemic species and highly adapted biota (Khamis et al. 2014; Milner et al. 2017; Slemmons et al. 2013). As glaciers continue to recede and disappear, and the loss of cold, silty glacial waters to northern lakes is likely to be a more common feature in northern aquatic ecosystems (Shugar & Clague 2018), this study, when combined with post-2016 physicochemical work, will provide valuable insight into how downstream lakes could be influenced by glacier disappearance.

Methods

Study area

Lhù'ààn Mân' is located along the Shakwak Fault, with its western shores flanked by the steep and tall St. Elias Range (up to 2600m) and its eastern shores by the Kluane and Ruby Ranges (up to 1600m). The Kluane area was entirely glaciated around 14 000 years ago, followed by deglaciation and an ice-free valley 12 500 years ago (Krebs & Boonstra 2001). As new sediment was exposed and became airborne due to katabatic winds, it was deposited as loess on moraines and remains the primary soil component of the Kluane area. Since the last deglaciation, vegetation established and ecosystem succession has occurred, with boreal forest now primarily characterizing the below-treeline landscape (white spruce, balsam poplar, aspen, willow and birch shrubs). Higher elevations are characterized as alpine tundra. Discontinuous permafrost underlies the valley with most prominence on north facing slopes (Krebs & Boonstra 2001). The tall and glaciated St. Elias range acts as a rainshadow to the Kluane area, creating a semi arid ecoregion with low annual precipitation in both summer (1981-2007 mean annual rainfall of 196.2mm) and winter (1981-2007 mean annual snowfall of 105.7mm) (Canadian Climate Normals, Government of Canada). The proximity of the mountains and icefields results in often windy conditions. Strong summer wind events are often dominated by katabatics from the Kaskawulsh Glacier (Crookshanks 2008), whereas Arctic winter wind tends to come from the north. The combination of proximity to two mountain ranges and high latitude of Lhù’ààn Mân’ results in a cool climate (Krebs & Boonstra 2001), with an average frost-free period of 20 days per year (Canadian Climate Normals, Government of Canada). The mean annual air temperature (1981-2007) in Burwash Landing is -3.2°C (Canadian Climate Normals, Government of Canada).

In 2015, the Lhù’ààn Mân’ watershed was approximately 5 400 km^2 (1 100 km^2 of which was glaciated), and the lake surface area was approximately 400 km^2 with a maximum depth of 80±5 m and an approximate volume of 11.4 km^3 (calculated using the area of each 10m bathymetry data). Lhù’ààn Mân’ is in the shape of a “Y”, with a deep, cold, and turbid southern basin, a central (mid) region, a warm and shallow arm to the northwest (Tthe Kaala Daagur [Brooks/Little Arm)]), and a cooler and deeper arm to the northeast (’Ùha K’ènji [Talbot/Big Arm]) (Barker et al. 2014) (Figures 1-2 & 2-1). Using the last 20 years of available Lhù’ààn Tăgà’ discharge data before the ‘A’ą̈y Chù’ diversion (1975-1995; Environment and Climate Change Canada), we calculated annual mean residence time, summer peak discharge mean residence time, and winter low discharge mean residence time for Lhù’ààn Mân’. Annual mean discharge between 1975 and 1995 was 80.7 m^3/s, resulting in an annual mean residence time of 4.48 years. Summer peak discharge mean between 1975 and 1995 was 296.0 m^3/s, resulting in a summer peak discharge mean residence time of 1.22 years. Winter low discharge mean between 1975 and 1995 was 11.6 m^3/s, resulting in a winter low discharge mean residence time of 31.14 years. The seasonal discrepancy between residence times could be an indication of summertime underflowing density current in the lake with implications for residence time of different lake strata.

Sampling Design

Sampling sites were selected to represent spatial variability (four to five centrally situated sites per basin/region of the lake) (Figure 2-1; see Appendix 1. Supplementary Data File S1 for geographic coordinates of sites). To represent temporal variability, the lake was surveyed at most sites six times during 2015 (mid-late February; early April; early June; early July; early August; and mid-late October; each of these events may be herein referred to as a sampling “snapshot”). Ice break-up began on April 19 2015, and the lake was ice-free by May 21 2015; as such, data obtained before April 19 were collected through the ice whereas data obtained after May 21 were collected from boats on open-water. Our October data were collected before ice-on, which began in mid November. The lake was entirely ice-covered by early December. Some data gaps exist due to logistically impossible and/or unsafe sampling conditions including, high winds, large waves, unavailability of boats, and very cold winter temperatures.

Temperature, conductivity, oxygen, and turbidity measurements were taken throughout the water column at each site. Temperature, conductivity and depth were measured using a Castaway CTD. The Castaway CTD uses a pressure sensor to determine depth. A temperature sensor and conductivity electrodes are used to measure temperature (±0.05°C) and conductivity (±5µS/cm), respectively. The Castaway CTD uses a standard method for applying temperature correction to conductivity measurements, using a temperature coefficient of 0.02 [SpC= C/(1+0.020*(T-25)), where SpC=Specific conductance (µS/cm), C=conductivity (µS/cm) and T=temperature (°C)). We report specific conductance values in this manuscript.

Turbidity was quantified optically using an RBR XR-620 Ltd. Multi-channel sonde mounted with a Seabird turbidity meter (±2 % 0-1250 FTU). Additional and irregular point secchi disk data was also collected (Appendix 1. Supplementary Data File S3). The Seabird turbidity meter measures turbidity by detecting scattered light from suspended particles in water and is factory-adjusted for consistent response to Formazin Turbidity Standard (measured in Formazin Turbidity Units (FTU)). Oxygen (mg/L) was measured using a Hydrolab DS5 (± 0.01 mg/L for 0-8 mg/L; ± 0.02 mg/L for greater than 8 mg/L) at 0.5-1m intervals.

Near-surface water samples were collected in new, sterile amber Nalgene bottles in early June, early August, and October at sites SL1 (southern basin), TA3 ('Ùha K'ènji) and BR3 (Tthe Kaala Daagur) – that is, at one representative site for each of three regions known to be distinct. Samples were refrigerated at 4°C, shipped to the University of Alberta Biogeochemical Analytical Service Laboratory (BASL) within 7-10 days of sampling, and analyzed for total dissolved solids (TDS) (gravity filtered residue then dried at 180°C, detection limit 0.04 ppm), dissolved organic carbon (DOC) (Shimadzu TOC-5000A Total Organic Carbon Analyzer, detection limit 0.1 ppm), total phosphorus (TP) and total nitrogen (TN) (Lachat QuickChem QC8500 FIA Automated ion Analyzer, TP detection limit 1.4ppb and TN detection limit 7 ppb). All samples were processed under the BASL Quality Assurance protocol.

Near-surface water samples were collected for photosynthetic pigment analysis (chlorophyll-*a*, fucoxanthin, diadinoxanthin, lutein, and zeaxanthin) at most sites once or twice between June and August, and then again in October. These samples were prepared in the field following the University of Alberta BASL protocol of filtering water samples through ethanol rinsed GF/F filters. Filters were stored in a freezer at -20°C until analysis. High-performance-liquid chromatography (HPLC) analysis using an Agilent Series 1100 (detection limit of 1.5 nanograms) was conducted on these filters following the protocol outlined in Millie et al. (1993) to determine concentrations of carotenoid and chlorophyll pigments.

Near-surface lake water samples, as well as select samples from other water sources within the watershed, were collected during the open-water season for water isotope analyses (deuterium H^2 and oxygen O^{18}) in 25mL Nalgene bottles, filled to the brim and capped tightly. Samples were analyzed using ring-down spectroscopy (L2120-*i*®, Picarro, Inc.) at the Western University BIOTRON Institute for Experimental Climate Change Research and processed by Dr. Brian Branfireun and Dr. Heidi Swanson. Values are expressed as standard δ notation (in permil (‰)), relative to the Vienna Standard Mean Ocean Water (VSNOW) on a scale normalized to Standard Light Antarctic Precipitation ($\delta^{18}O$ = -55.5%, δ^2H= -428) (Coplen 1996). Analytical precision of the $\delta^{18}O$ and δ^2H measurements was 0.1‰ (permil) and 0.5‰, respectively.

Data Analysis

Mean epilimnetic temperature (unless the column was well mixed [i.e., Tthe Kaala Daagur] in which case full-column mean was used) and mean full-column specific conductance, turbidity and oxygen concentrations were calculated for each sampling “snapshot” within each region/basin using data from all sampling sites indicated in Figure 2-1 unless otherwise noted. We chose full-column mean comparisons with specific conductance, turbidity and oxygen because these properties did not display significant stratification. We chose epilimnetic mean temperature (full-column mean if column was well mixed) because this value more accurately allows for comparisons between sites of varying depths and stratifications. We defined the epilimnion as the upper column layer that was fully mixed. The lower limit of the epilimnion was determined as the depth at which a thermocline was visually observed on a plot of temperature vs. depth, and was defined as the point in the water column where the temperature began a clear and evident decline. In instances when more than one thermocline was present, this depth was determined for the top (first) thermocline. A temperature threshold could not be used to quantitatively define a fully mixed layer due to the variability of thermal dynamics of Lhù’ààn

Mân’. The metalimnion of the profiles was often composed of several smaller thermoclines separated by sections of thermally mixed water (see Figure 2-S1 for higher resolution examples of profiles displaying this phenomenon). Spatial and temporal comparisons of select lake physicochemical characteristics were achieved using these means and two one-way analyses of variance (ANOVA) with post-hoc Tukey tests. Additionally, mean whole-lake specific conductance was compared between the ice-on and ice-free seasons using a two-sample t-test. Surface water temperatures were interpolated between sites using ArcGIS (ArcMap) and the Inverse Distance Weighted (IDW) interpolation method, which estimates cell values by averaging the values of sample data points in the neighborhood of each processing cell. Turbidity (FTU) was also interpolated for the southern end of the lake (using data from sites SL01, SL02, SL03 and SL1) using Kriging methodology with Surfer (Golden) software.

Mean, near-surface summer (July-August) and autumn (October) photosynthetic pigment concentrations were compared spatially between lake regions (as above) using analysis of variance (ANOVA) with post-hoc Tukey tests. Mean, near-surface, open-water period nutrient (TN & TP), TDS and DOC concentrations were also compared spatially, but only between three sites due to data availability (SL1 [southern basin], TA3 [’Ùha K’ènji] and BR3 [Tthe Kaala Daagur]) using analysis of variance (ANOVA) with post-hoc Tukey test; temporal comparisons were not possible for these analyses.

Isotope data were analyzed within the hydrologic isotope framework previously determined for Lhù’ààn Mân’ and its environs in Brahney et al. (2010). The Local Meteoric Water Line (LMWL) represents seasonal variation in the isotopic composition of precipitation: it was found to closely approximate the Global Meteoric Water Line (GMWL) at $\delta^2H = 6.8\delta^{18}O - 22.5$, and is similar to the LMWL reported in the Global Network of Isotopes in Precipitation

(GNIP) station at Whitehorse. The Local Evaporation Line (LEL) reflects enrichment of heavy isotopes in an evaporating body of water. Slopes of LELs typically range from 4-6, and are dependent on relative humidity and air temperatures during the open-water season. In the region of Lhù’ààn Mân’, the LEL is $\delta^2H=4.3\delta^{18}O- 76.7$. The intersection of the GMWL and the LEL represent the flux-weighted average composition of local runoff, whereas displacement along the line indicates degree of evaporative enrichment experienced by the water body (Gibson & Edwards 2002).

Results

Temperature

In winter, inverse stratification was observed in all areas of the lake (Figure 2-2), with the water column warming slightly between February and end of March/early April. Ice break-up first occurred in Tthe Kaala Daagur, followed by the mid and south basins. ’Ùha K’ènji was the last region to become ice-free. During the open-water season, the lake exhibited a temperature gradient from cooler in the south to warmer in the north, due to the effect of the cold, glacially derived ‘A’ą̈y Chù’ inflow at the south end (Appendix 1. Supplementary Figure 2-S2). The shallow Tthe Kaala Daagur warmed in spring and cooled in autumn more rapidly than the other regions within Lhù’ààn Mân’ (Figure 2-2; Figure 2-3; Appendix 1. Supplementary Figure 2-S2).

In June, Tthe Kaala Daagur was significantly warmer than all other regions (ANOVA; $F_{(3,8)}=37.9$; $p<0.001$; post-hoc Tukey; $p<0.003$) whereas in October, Tthe Kaala Daagur was significantly cooler than both ’Ùha K’ènji and the southern basin (ANOVA; $F_{(2,7)}=50.1$, $p<0.001$; post-hoc Tukey; $p<0.001$) (no data were available for the mid region in October due to sampling conditions) (Figure 2-3). Surface temperatures in Tthe Kaala Daagur reached up to 17°C during the open-water season, whereas maximum surface temperatures for ’Ùha K’ènji and the southern basin were 16°C and 12°C, respectively (Appendix 1. Supplementary Figure 2-S2). In July and August, Tthe Kaala Daagur and ’Ù̀ha K’ènji were significantly warmer than the mid region and southern basin (ANOVAs; $F_{(3,15)}>17.3$; p<0.001; post-hoc Tukey: p≤0.02) (Figure 2-3).

The shallow and warm Tthe Kaala Daagur did not thermally stratify (warming rapidly and consistently to bottom), whereas all three other regions of the lake exhibited stratification of varying depth, timing, and strength throughout the open-water season (Figure 2-2 shows examples of profiles from BR2 (Tthe Kaala Daagur), TA0 (’Ù̀ha K’ènji) and the southern basin (SL1)).

Specific conductance

Full-column mean *s*pecific conductance during all open-water season snapshots was lowest near the distal ends of both arms (Tthe Kaala Daagur [229-251 µS/cm] and ’Ù̀ha K’ènji [237-251 µS/cm], with a gradient of increasing conductance towards the central region [254-270 µS/cm] and southern basin [228-279 µS/cm] (Appendix 1. Supplementary Data File S2). Specific conductance was relatively consistent throughout the water column except for in the southern basin (Figure 2-4c): during ice-on conditions, specific conductance decreased gradually from surface to a depth of approximately 20m, after which specific conductance increased, and was more variable until a depth of approximately 40m (blue and light blue lines in Figure 2-4c). While specific conductance was consistent throughout the water column in spring and early summer (yellow and light orange lines in Figure 2-4c) as well as in fall (purple line in Figure 2-4c), during mid-summer (dark orange and red lines in Figure 2-4c) specific conductance decreased/became more variable at depths 20-40m (Figure 2-4c).

Mean full-column specific conductance was only significantly different between regions in June, and only between Tthe Kaala Daagur and ’Ù̀ha K’ènji (ANOVA; $F_{(3,11)}=4.92$; $p=0.02$; post-hoc Tukey; $p=0.02$). However, mean lake-wide, full-column, specific conductance was significantly higher during the ice-on period (February and March) (279 µS/cm) than during the open-water period (June-October) mean (256 µS/cm) (2 samples t-test; $p<0.0001$) (Appendix 1. Supplementary Figure 2-S3).

Turbidity

Turbidity in Lhù’ààn Mân’ in 2015 varied between seasons and some regions (Appendix 1. Supplementary Figure 2-S4). During winter, ice cover eliminated wind-driven mixing and the ‘A’ą̈y Chù’ was at baseflow, which resulted in very low turbidity (<1 FTU) throughout the water column and at all sites sampled (Appendix 1. Supplementary Data File S3). With ice break-up, effects of wind and spring freshet from the ‘A’ą̈y Chù’ (an influx of silty glacial meltwater), as well as increased algal growth in the water column, resulted in higher lake turbidity (i.e., >1 FTU), although the seasonal increases in turbidity varied among regions. In ’Ù̀ha K’ènji, Tthe Kaala Daagur, and the central/mid region, turbidity values were consistently low throughout the open-water season (column averages below 6 FTU and secchi depths between 6.25-14.5m; Appendix 1. Supplementary Data File S3). In July, turbidity in ’Ù̀ha K’ènji and the mid region were equivalent to values observed under-ice throughout the lake during the previous winter (<1 FTU). Increased turbidity during the open-water period was most distinct in the southern basin where the ‘A’ą̈y Chù’ and Silver Creek (both primarily glacier-fed water sources) entered the lake (Appendix 1. Supplementary Figure 2-S5).

Mean full-column turbidity values differed significantly among regions in August and October only (Figure 2-5). In August, the southern basin was significantly more turbid than the other three basins (ANOVA; $F_{(3,17)}=5.509$, $p=0.008$; post hoc Tukey; $p<0.038$) and in October, Tthe Kaala Daagur was significantly more turbid (ANOVA; $F_{(2,9)}=28.412$, $p<0.0001$; post hoc Tukey; $p<0.0001$) than the other basins.

Turbidity values in the glacially influenced southern basin varied both throughout the water column and through time, and were driven by the depth and location of the 'A'ą̈y Chù' plume entering the lake. For example, in early June the plume was most evident near site SL01, and turbidity was relatively high (30-60 FTU) throughout the water column (Figure 2-6). In July, the plume had migrated toward site SL02, with very turbid waters (>40 up to 85 FTU) present only in the bottom half of the water column (Figure 2-6). By August, the plume had moved further northwest toward site SL03 and turbidity was highest near lake bottom (Figure 2-6). With the lake water flowing north and eventually out of Lhù'ààn Tăgà', a progressive settling of glacial silt and sediments appeared to occur throughout the southern basin. At the most northerly site in the southern basin, site SL1, maximum turbidity values reached a maximum of 40 FTU and only between the end of June and August and between ~20-40m depth.

Oxygen

In 2015, Lhù'ààn Mân' was oxygen saturated or near-saturated year-round and throughout the water column in all parts of the lake (Appendix 1. Supplementary Figure 2-S6). Under-ice full-column mean oxygen concentrations ranged between 10.6-13.3 mg/L (percent dissolved oxygen ranged between 80-95%) whereas open-water period full-column means were lower and ranged between 8.7-11.9 mg/L (percent dissolved oxygen ranged between 95-110%). Full-column mean oxygen concentrations differed among regions only in July and August (July ANOVA; $F_{(3,10)}=26.552$, $p<0.0001$; August ANOVA $F_{(3,12)}=14.673$, $p<0.0001$), with significantly lower concentrations in Tthe Kaala Daagur (July post-hoc Tukey; $p<0.014$; August post-hoc Tukey; $p<0.005$) (Figure 2-7). Not enough data were available to compare the October snapshot data among regions, although the few available October profiles show a higher concentration of dissolved oxygen in Tthe Kaala Daagur (BR2) compared to the rest of the lake (sites SL1, TA0 and TA3) (Appendix 1. Supplementary Data File S4).

Concentrations of nutrients, dissolved organic carbon, and total dissolved solids

Concentrations of nutrients and dissolved organic carbon indicated higher nutrient availability and organic matter in Tthe Kaala Daagur than in other regions. Near-surface, open-water season mean total nitrogen (TN) concentrations differed significantly among regions (ANOVA; $F_{(2,7)}=69$, $p<0.0001$), with significantly higher TN in Tthe Kaala Daagur (BR3) (190.3 μg/L) than in the southern basin (SL1) (49.4 μg/L) (Tukey's test; $p<0.0001$) or 'Ùha K'ènji (TA3) (65.5 μg/L) (Tukey's test; $p<0.0001$) (Figure 2-8). Near-surface, open-water season mean total phosphorus (TP) concentrations also differed significantly among lake regions (ANOVA; $F_{(2,5)}=40$, $p=0.001$), and similar to TN, TP was significantly higher in Tthe Kaala Daagur (BR3) (8.3 μg/L) than in the southern basin (SL1) (2.5 μg/L) (Tukey's test; $p=0.001$) or 'Ùha K'ènji (TA3) (4 μg/L) (Tukey's test; $p=0.016$) (Figure 2-8). Ratios of TN:TP (in μg/μg) during the open-water season were 49:3 at SL1, 71:4 at TA3, and 190:8 at BR3. Concentrations of dissolved organic carbon (DOC) were highest in Tthe Kaala Daagur (BR3); DOC ranged from 0.5-0.9 mg/L at SL1, 0.7-1.3 mg/L at TA3, and 2.8-5.2 mg/L at BR3 (Appendix 1. Supplementary Data File S5). Near-surface, open-water season mean DOC in Tthe Kaala Daagur (BR3) was significantly higher (ANOVA; $F_{(2,7)}=17$, $p=0.002$) than in 'Ùha K'ènji (TA3) (Tukey's test; $p=0.002$) or in the southern basin (SL1) (Tukey's test; $p=0.012$) (Figure 2-8). In all regions, concentrations of nutrients and dissolved organic carbon were highest during the latter part of the open-water season (autumn) (Appendix 1. Supplementary Data File S5). Total dissolved solids (TDS) concentrations ranged between 117-170 mg/L throughout the lake, with no significant differences between regions.

Photosynthetic pigments

Near-surface, lake-wide mean total photosynthetic pigment concentration in summer (July-August) was 0.24 µg/L (range 0.1-0.72 µg/L), which was approximately three times lower than in autumn (October; mean 0.91 µg/L, range 0.32-2.65 µg/L) (Appendix 1. Supplementary Data File S6). This seasonal difference was largely driven by an approximately 5-fold increase in total photosynthetic pigments in Tthe Kaala Daagur between summer and autumn (Figure 2-9). Total pigment concentrations in autumn were significantly higher in Tthe Kaala Daagur (ANOVA; F($_{2,5}$)=23, p=0.003) than in ’Ùha K’ènji (Tukey’s test; p=0.005) and the southern basin (Tukey’s test; p=0.003). Mean chlorophyll-*a* concentrations were significantly higher in Tthe Kaala Daagur in both summer (0.43 µg/L) (ANOVA: F($_{2,10}$)=12.8, p=0.002) and autumn (1.17 µg/L) (ANOVA: F($_{2,5}$)=56.7, p=0.01) compared to the other two regions (’Ùha K’ènji: summer mean of 0.07 µg/L and autumn mean of 0.30 µg/L; southern basin: summer mean of 0.05 µg/L and autumn mean of 0.19 µg/L) (Tukey’s tests; p<0.005) (Figure 2-9). There were no significant differences among regions in concentrations of total combined secondary pigments (fucoxanthin, diadinoxanthin, lutein, and zeaxanthin) in either summer (ANOVA: F($_{2,10}$)=0.334, p=0.724) or autumn (ANOVA: F($_{2,5}$)=3.219, p=0.126) (Figure 2-9).

Isotope ratios of water

Isotope ratios (deuterium H^{2} and oxygen O^{18}) in water samples within Lhù’ààn Mân’ indicated hydrological differences among regions, and varied overall by approximately 3‰ between the ‘A’ą̈y Chù’ source and the annual flux-weighted mean composition of precipitation at the intersection of the LEL and LMWL (Figure 2-10). All samples were plotted on the LMWL throughout the 2015 sampling season, and did not reflect isotopic enrichment from evaporation but rather were closely aligned with water source contributions. Isotopic values near the south end of the lake were more similar to the 'A'ą̈y Chù' source (-24 ‰), and became progressively more reflective of other water sources that enter the lake toward the northern (particularly Tthe Kaala Daagur) arms (Appendix 1. Supplementary Data File S7). As expected, the isotope composition of rivers that drain the high-elevation Kluane Ranges were isotopically depleted (-22.3 ‰) compared to mean precipitation (-21.5 ‰), while rivers that drain the Shakwak Trench and the lower elevation Ruby Range (-21.1 ‰ and -21.2 ‰, respectively) more closely approximated mean precipitation.

Discussion

Analyses of physicochemical conditions in Lhù'ààn Mân' in 2015 reflect a complex, large lake system that had distinct regions defined by unique properties and seasonal dynamics. In 2015, the physicochemistry of the southern basin was especially distinct; this basin had the coldest open-water season temperatures, highest and most variable turbidity and specific conductance, and lowest concentration of photosynthetic pigments, conditions that reflected the inflow of cold, turbid waters from the 'A'ą̈y Chù' (which until 2016 provided 40% of total inflow to Lhù'ààn Mân' (Brahney 2007)). The thermal profiles of the southern basin did exhibit some stratification, but the metalimnion was typically divided into several smaller thermoclines (with each thermocline separated by short sections of vertical or near-vertical mixing instead of a single strong thermocline). This weak stratification is likely influenced by turbidity under- and through- flows (Crookshanks 2008), as well as wind. In summer, strong katabatic winds originating from the icefields travel down the 'A'ą̈y Chù' valley and onto Lhù'ààn Mân'. The strength of these winds combined with lake fetch likely impacts stratification in at least the top section of the water column, and possibly to greater depths, by turbulent mixing. At the time of sampling, the ‘A’ą̈y Chù’ ‘plume’ was visually and chemically distinct, particularly in mid-late summer, between the pro-delta island and the lake’s eastern shore, and its silty, lower specific conductance waters disrupted stratification and the stability of the water column in the southern basin. Crookshanks & Gilbert (2008, pp.1132-1143) confirm that “because turbidity currents in Kluane Lake are typically formed by relatively fresh glacial meltwater, they can normally be identified by their lower conductivity” which is consistent with our mid-late summer findings. Similar to Crookshanks & Gilbert (2008), we also a) observed higher turbidity closest to the river inflow with a gradual reduction and near disappearance of turbidity currents at approximately the same location in the lake (site SL1 in this study) and b) decreased turbidity at lake bottom further from the inflow (as the turbidity current slows and thickens throughout the vertical column). The seasonal variation that we observed in the location of the underflow turbidity current (movement from the east to the west side of the lake just beyond the delta at sites SL01-03 as summer progressed in 2015) is likely caused by changes in river morphology at the river outflow, as well as shifts in turbidity current strength, as suggested by Crookshanks (2008). The turbidity ranges reported in the southern basin are within the range reported for other pro-glacial lakes (Sugiyama et al. 2016).

The higher turbidity and colder water temperatures that we observed in the southern basin in 2015 likely support a unique biological community: high turbidity associated with glacial meltwaters is often restrictive to many taxa (Milner & Petts 2004). Glacierized systems are often host to endemic specialized species that are at risk of extinctions (Milner et al. 2017). For example, several studies have shown that diatom diversity is higher in glacierized systems than in non-glacierized systems (Fell et al. 2018). Additionally, the cold southern basin waters and rocky shorelines provided ideal spawning habitat for fall-spawning chum salmon (*Oncorhynchus keta*). There is concern among many local residents and agencies that lower lake levels will reduce access to and quality of chum salmon spawning habitat. The southern basin was also known by local fishers and managers to support lake trout (*Salvelinus namaycush*), whose optimal temperature range is between 2-12°C (Barker et al. 2014). The loss of inflow waters from the ‘A’ą̈y Chù’ will likely lead to physical and chemical changes in fish habitat through decreased turbidity and increased lake water temperature in this basin.

A progressive settling of glacial silt and sediments occurred as lake water flowed northward toward Lhù’ààn Tăgà’, creating natural gradients in temperature, turbidity, and productivity from the south to the north end of the lake. Tthe Kaala Daagur did not exhibit thermal stratification (likely due to its shallowness), and had higher nutrient concentrations and warmer temperatures, which supported a larger and more diverse algal community as indicated by the pigment analysis results. Although fucoxanthin was present in most samples throughout the lake, diadinoxanthin, lutein, and zeaxanthin only consistently occurred in Tthe Kaala Daagur. In contrast to fucoxanthin, which is indicative of chrysophyte and diatom algal groups (Leavitt & Hodgson 2001) that are well adapted to low nutrient conditions (Kalff 2001), lutein is derived from chlorophytes and euglenoids (Leavitt & Hodgson 2001), both of which are more dominant in mesotrophic to eutrophic systems (Kalff 2001). The higher organic matter concentrations and warmer waters in Tthe Kaala Daagur may also have contributed to the lower concentrations of dissolved oxygen observed in spring and summer in this region, although concentrations of dissolved oxygen were still well above thresholds for supporting biota. Turbidity values in this part of the lake reflected higher productivity as opposed to glacial silt. In combination, these characteristics are highly suitable for the documented population of lake whitefish (*Coregonus* *clupeaformis*) in Tthe Kaala Daagur (Barker et al. 2014). Local knowledge also indicates that this is the only region of the lake where the warm water fish species northern pike (*Esox lucius*) is found.

Overall, the concentrations of photosynthetic pigments found throughout Lhù'ààn Mân' were low and consistent with values typical of oligotrophic sub-Arctic lakes (Kling 2009). Higher whole-lake mean specific conductance in Lhù'ààn Mân' during the ice-on period reflects a common phenomenon observed in other lakes, resulting from the release of ions from lake ice into water during ice formation (Adams & Lassenby 1985). Our reported open-water season specific conductance values align with those previously reported for Lhù'ààn Mân' (Crookshanks & Gilbert 2008). These values are slightly higher than other glacially influenced lakes, and are "likely caused by solute-enriched groundwater that enters the lake from the south and the west (Harris 1990)" (Crookshanks & Gilbert 2008, pp. 1132). Loess and till deposits, combined with a large watershed, may also contribute to the higher conductivity values observed. While evaporation could play a role in elevated conductivity values - particularly in Tthe Kaala Daagur where temperatures profiles were warm and uniform - our isotope data does not show evaporative enrichment.

Priorities for future monitoring of Lhù'ààn Mân'

By examining spatial and temporal variability of select physical, chemical, and biological characteristics of Lhù'ààn Mân', it is obvious that the lake is comprised of several unique regions and would not be adequately represented by a single monitoring site nor infrequent sampling. Additionally, and with the increasing influence of climate change, parts of the lake may change differently and at varying paces. Our observations underline the importance of comprehensive and continuous monitoring of these large lakes, and the insufficiency of surface samples, single sampling locations, and infrequent sampling. Of particular importance is monitoring that captures seasonal variability in water properties to ensure a more comprehensive and accurate analysis of interannual variability for the entire lake. This is particularly true for glacier-influenced lakes which experience large seasonal fluxes in turbidity and temperature.

By replicating the detailed observations of our study, future researchers may investigate how this and other large, glacier-influenced lake systems react as glacial inflows eventually decrease and disappear in response to glacial recession and headwater diversion. Because many lake systems are fed by glaciers that will continue producing meltwater for several decades, the circumstance in Lhù'ààn Mân' presents a unique opportunity to study impacts of climate-induced loss of glacial inflow well before these changes become commonplace (e.g. Prowse et al. 2015; Shugar & Clague 2018).

Summary

Many previous studies have shown that lakes are responding to climate change with surface warming, altered thermal stratification, and a suite of direct and indirect effects that involve nutrients, plankton, and fish assemblages (e.g., Havens & Jeppesen 2018; O'Reilly et al. 2015; Peter & Sommaruga 2017), but robust and frequent field data collection remains limited, especially for larger and higher latitude lakes, which are comparatively understudied in the literature. The data that do exist for large lakes is often low resolution (spatially and temporally) and often cannot be used to adequately assess temporal (seasonal, diurnal, interannual) or spatial variability. Additionally, the majority of field research is conducted during the open-water season, resulting in particularly limited scientific knowledge of seasonal dynamics in spring, winter and autumn, despite recent studies indicating that under-ice ecology contributes to the overall productivity of these systems (Hampton et al. 2015). Although modelling, satellite data, and latitudinal/elevational comparative studies have all been used in recent years to predict future scenarios, infer information, and detect trends (Arp et al. 2010; Carmack et al. 2014; O'Reilly et al. 2015; Sharma et al. 2008), baseline field data are critical to furthering our general understanding of the limnology of large northern lakes, and how they may be affected by change.

The paucity of limnological surveys and scientific long-term observations is particularly evident in the North, and is heavily influenced by unique resource constraints, logistical challenges, and severe weather conditions. Nevertheless, the need for adequate baseline knowledge, monitoring, local and Indigenous knowledge of these systems is urgent, given their heightened vulnerability to Arctic amplification (Heino et al. 2020; Prowse et al. 2011a; Prowse et al. 2015) and the presence of permafrost and/or glaciers in these watersheds. Some exceptions exist, such as Lake Hazen, the world's largest High Arctic lake located on Ellesmere Island, Nunavut (Lehnherr et al. 2018; St. Pierre et al. 2019), which has a rich history of scientific research and monitoring. Generally, however, large northern lakes remain scientifically understudied and poorly understood, and the situation is not improving: since the 1990's, the number of lake-ice and river-ice observation sites have declined by 50-90% globally (Prowse et al. 2011b). Given that large northern lakes play a large mediating role in high latitude hydrology and that cumulative effects of any changes in their dynamics are poorly constrained in future scenarios, it is crucial that their basic physical, chemical, and biological water property dynamics receive more attention.

Conclusion

This foundation of descriptive scientific study will contribute to the collective (scientific & Indigenous) knowledge of Lhù'ààn Mân' and our broader understanding of the spatial and seasonal variability of large northern lakes. This dataset also represents a unique and invaluable historical reference for Lhù’ààn Mân’ by capturing its state prior to the ‘A’ą̈y Chù’ decrease in flow in 2016, thereby providing a platform for future investigations into impacts of this climate change-induced event on the lake. Comparisons with data collected after 2016 will serve as a valuable asset to gaining a broader understanding of how loss of glacier inputs may influence the physicochemical characteristics of previously glacier-fed lakes.

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Figures

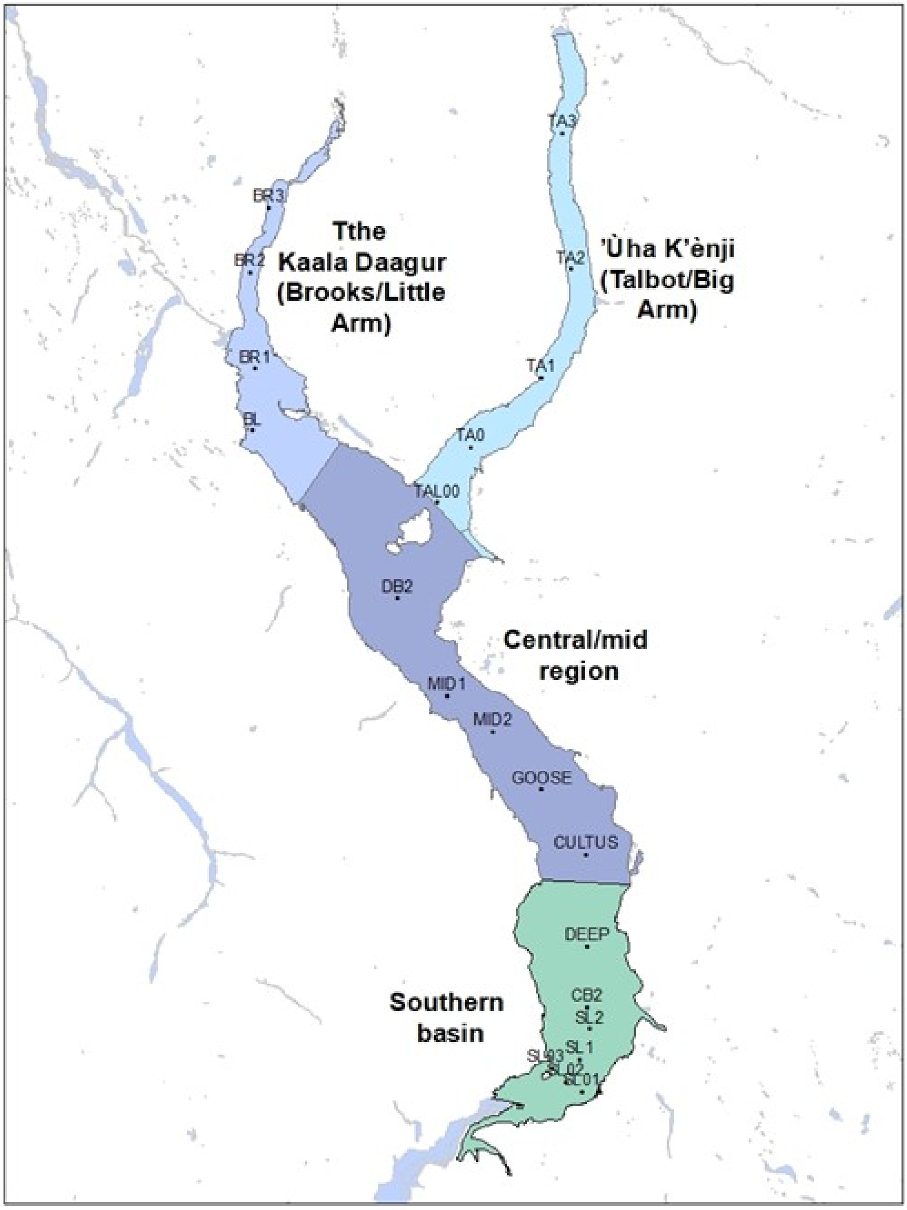

Figure 2-1. Lake regions and sampling locations (n=21) for 2015 baseline data collection at Lhù'ààn Mân'. Map produced in Esri ArcMap 10.7.1 with open-access basemaps from Natural Resources Canada and Yukon Government.

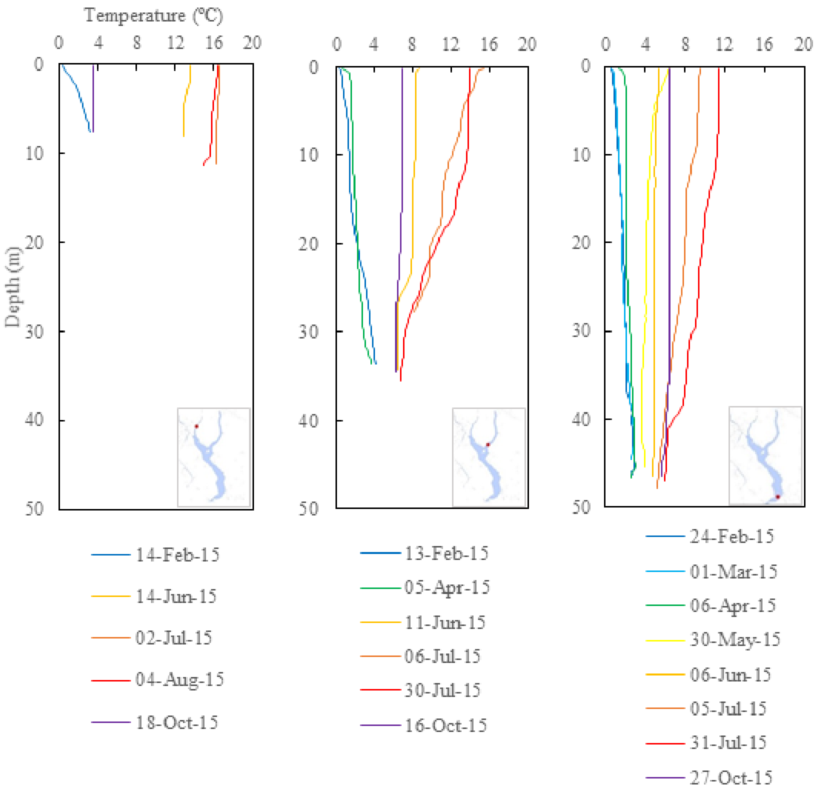

Figure 2-2. Water temperature profiles during select sampling events in 2015 in Tthe Kaala Daagur (BR2), ’Ùha K’ènji (TA0), and the southern basin of Lhù’ààn Mân’ (SL1). Insert map produced in Esri ArcMap 10.7.1 with open-access basemaps from Natural Resources Canada and Yukon Government.

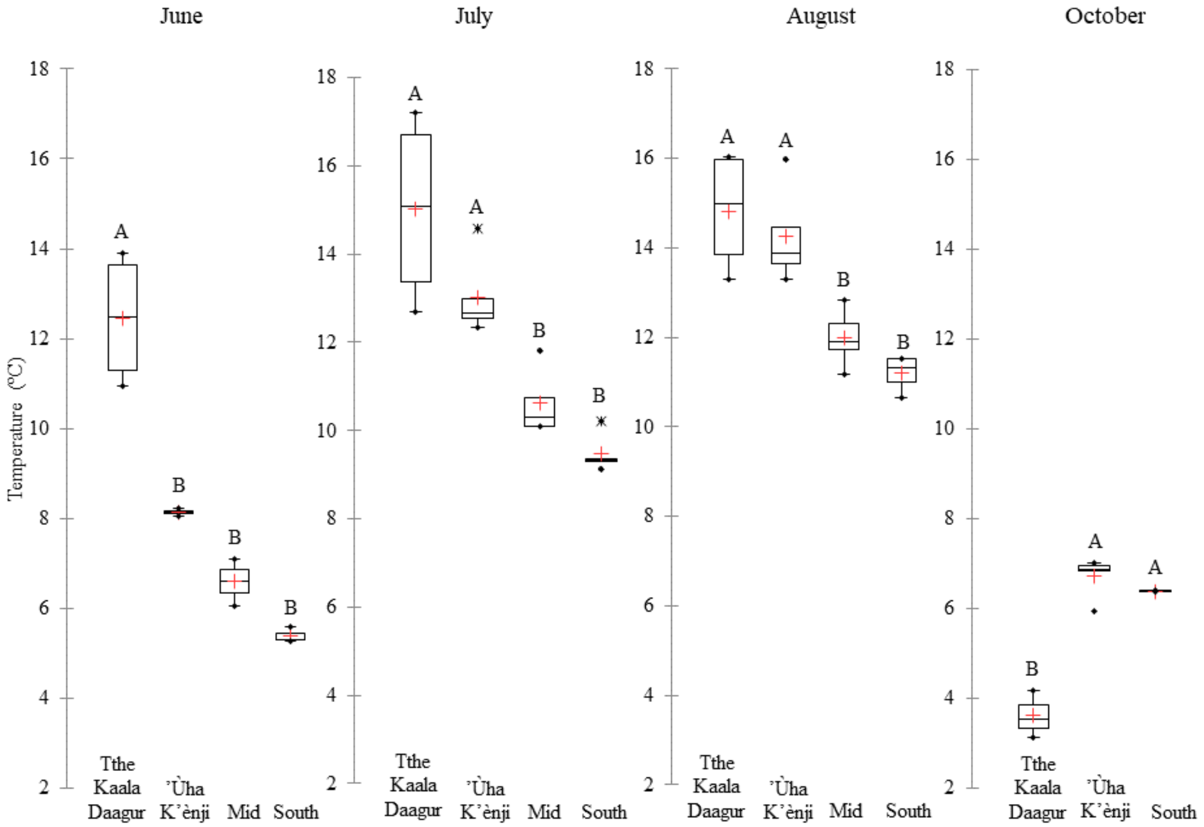

Figure 2-3. Box plots showing mean epilimnion (and mean through-column when well mixed) water temperatures (°C) in each lake region for June, July, August, and October. Letters indicate significant differences between basins (Tukey's test, p<0.05). The dots indicate maximum and minimum values, red crosses represent means, boxplots show the median as well as the first and third quartiles, and whiskers indicate Tukey limits.

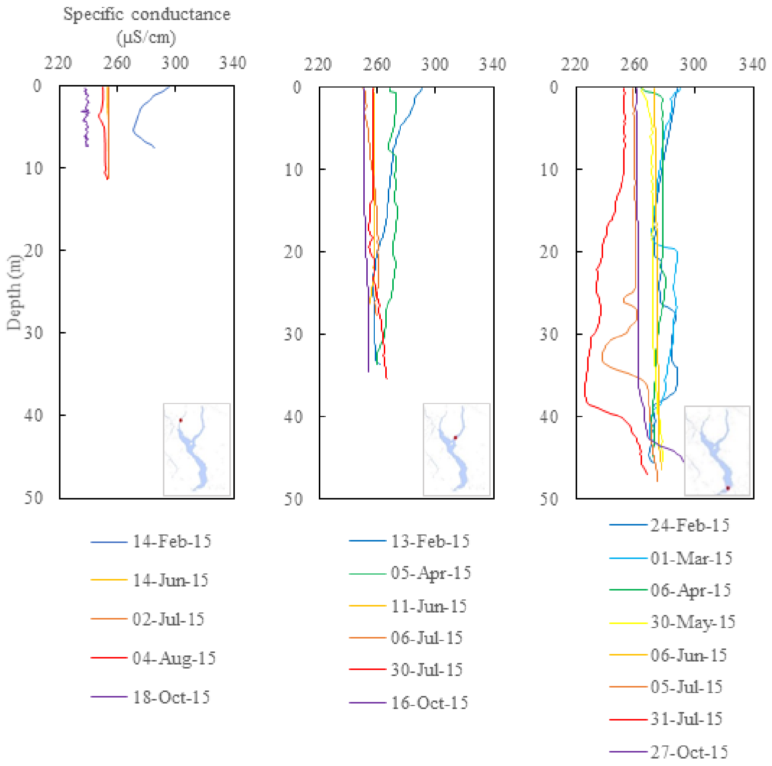

Figure 2-4. Specific conductance (µS/cm) profiles during select sampling events in 2015 in Tthe Kaala Daagur (BR2), ’Ùha K’ènji (TA0), and the southern basin of Lhù’ààn Mân’ (SL1). Insert map produced in Esri ArcMap 10.7.1 with open-access basemaps from Natural Resources Canada and Yukon Government.

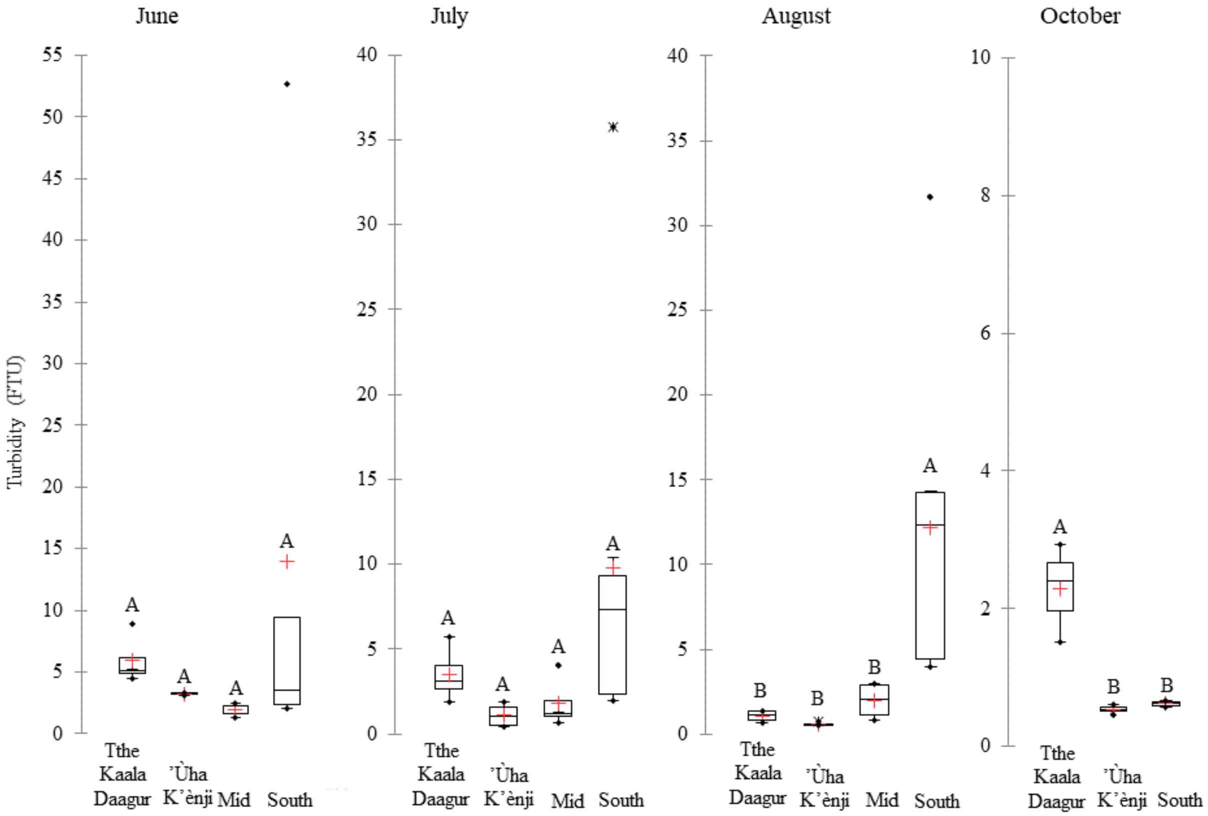

Figure 2-5. Box plots showing mean through-column turbidity (FTU) in each lake region for June & July (no significant differences) and August &October (significant differences). Letters indicate significant differences between regions ($p<0.05$) from results of ANOVA and post-hoc Tukey tests. Note: different Y-axis values between panels to show outliers; no data were available for Mid region in October. The dots indicate maximum and minimum values, red crosses represent means, boxplots show the median as well as the first and third quartiles, and whiskers indicate Tukey limits.

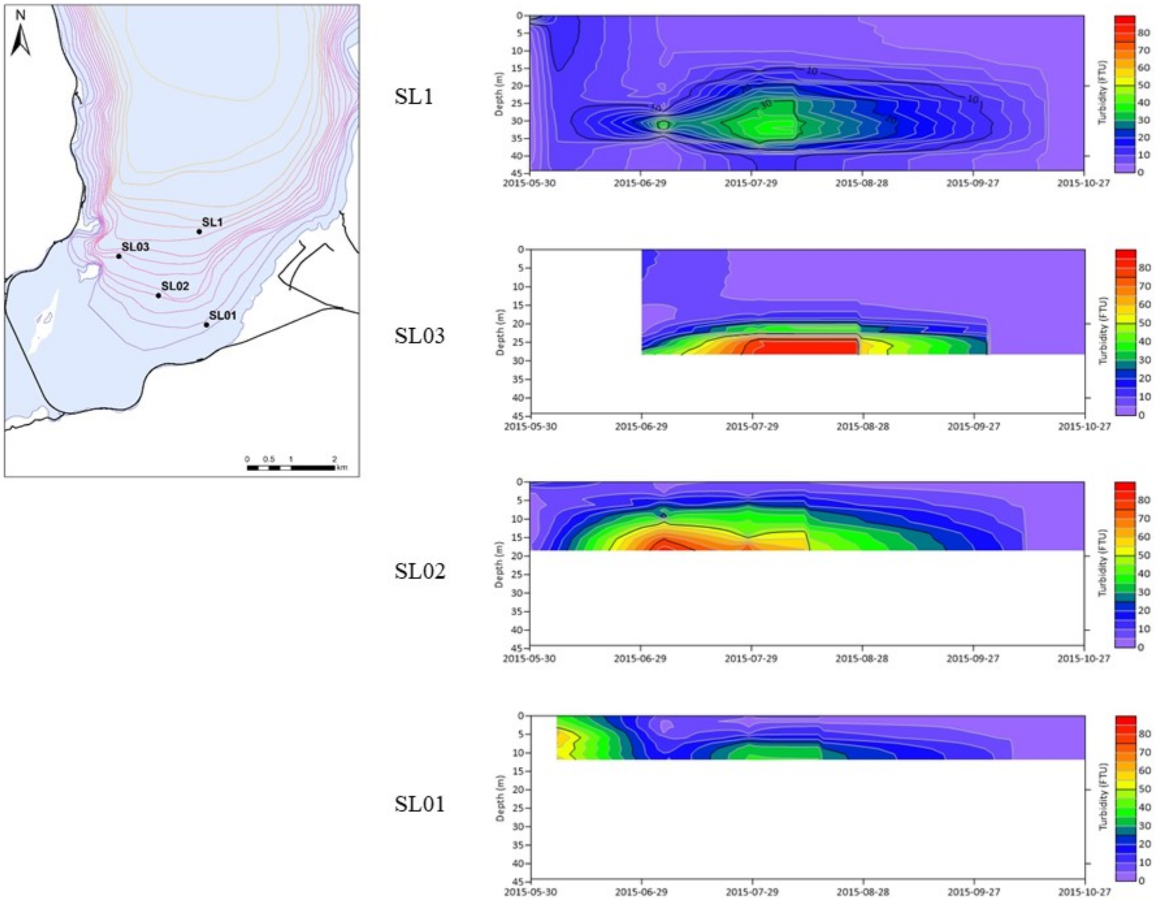

Figure 2-6. Turbidity (FTU) (Z axis) profiles (to lake bottom) interpolated over time (X axis) for four sites (SL03, SL02, SL01 and SL1) in the southern basin during the open-water period of 2015. Interpolation was conducted using Kriging and Surfer (Golden) software. Blank spaces indicate data gaps and/or differences in site depths as indicated on the Y-axis. Insert map produced in Esri ArcMap 10.7.1 with open-access basemaps from Natural Resources Canada and Yukon Government.

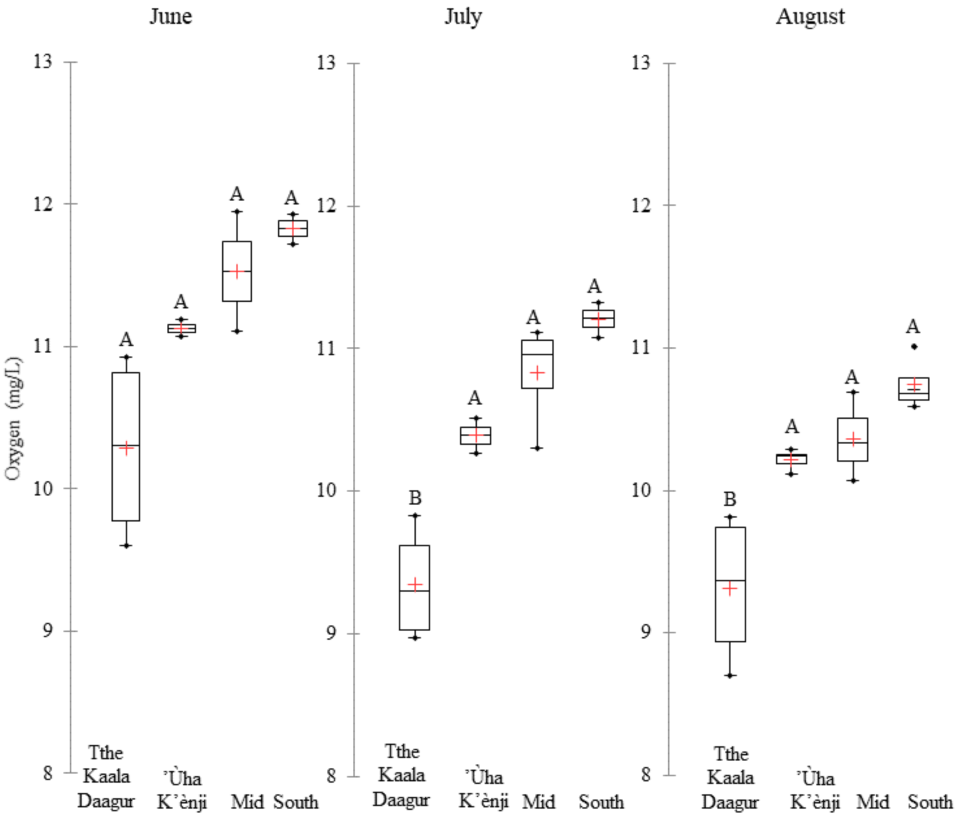

Figure 2-7. Box plots showing mean through-column oxygen (mg/L) in each lake region for June, July and August (no data available for October). Letters indicate significant differences between basins ($p<0.05$) from results of ANOVA and post-hoc Tukey tests. The dots indicate maximum and minimum values, red crosses represent means, boxplots show the median as well as the first and third quartiles, and whiskers indicate Tukey limits.

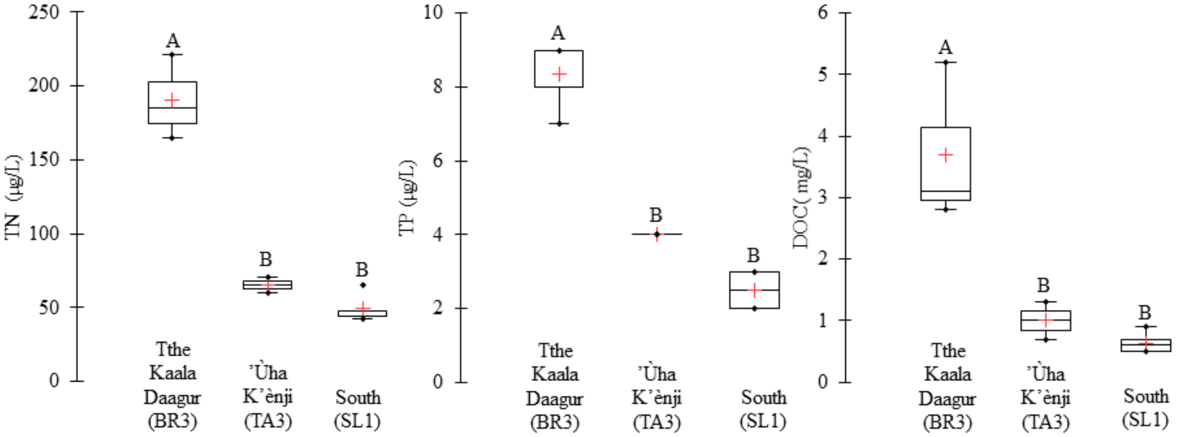

Figure 2-8. Box plots showing mean open-water season (near-surface) TN (µg/L), TP (µg/L), and DOC (mg/L) at sites BR3 in Tthe Kaala Daagur, TA3 in ’Ùha K’ènji, and SL1 in the southern basin. Letters indicate significant differences between basins ($p<0.05$) from results of ANOVA and post-hoc Tukey tests. The dots indicate maximum and minimum values, red crosses represent means, boxplots show the median as well as the first and third quartiles, and whiskers indicate Tukey limits.

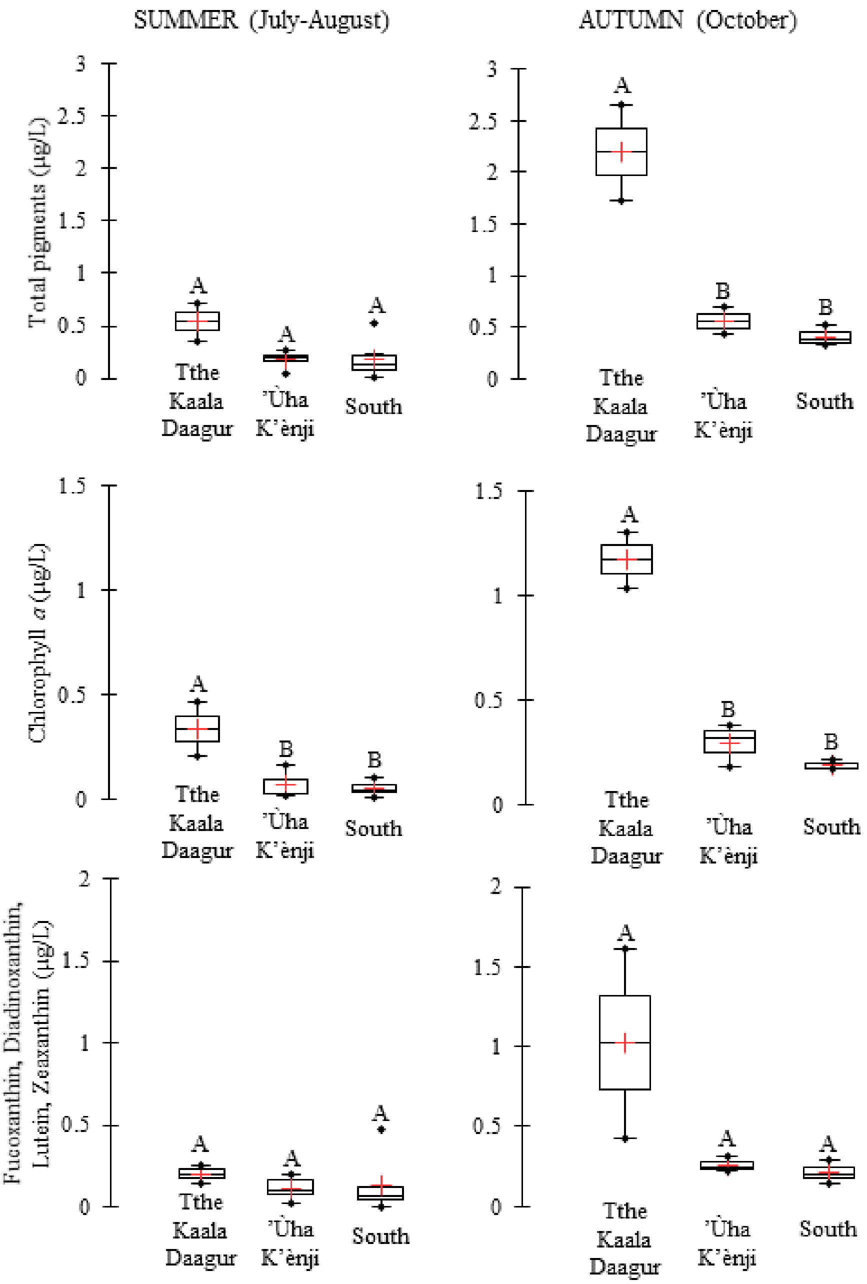

Figure 2-9. Box plots showing total pigment concentration (µg/L), further divided into chlorophyll-*a* concentration (µg/L), and combined fucoxanthin, diadinoxanthin, lutein and zeaxanthin concentrations (µg/L), in each lake region during the summer and autumn seasons. Letters indicate significant differences between lake regions ($p<0.05$) from results of ANOVA and post-hoc Tukey tests. The dots indicate maximum and minimum values, red crosses represent means, boxplots show the median as well as the first and third quartiles, and whiskers indicate Tukey limits.

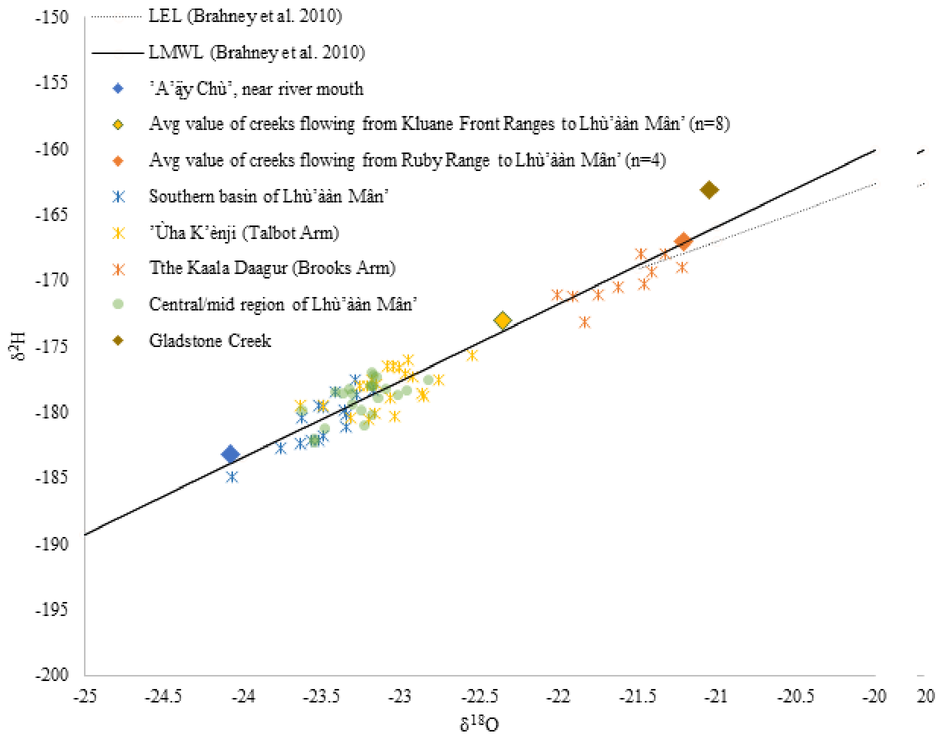

Figure 2-10. Isotopic values of water (deuterium H^2 and oxygen O^{18}) for Lhù'ààn Mân' plotted against the Local Evaporation Line (LEL) and Local Meteoric Water Line (LMWL), as determined by Brahney et al. (2010).

CHAPTER 3 . Lhù’ààn Mân’ (Kluane Lake) thermal dynamics between 2017 and 2019 suggest influence from sudden loss of glacial inflow in 2016

Abstract

Climate change is impacting the physical, biological, and chemical properties of large northern lakes with consequences for water quality and quantity, ecosystem health, and human communities. Water temperature is a key indicator of change since it is closely linked with other water properties and physiological thresholds of fish. Understanding and monitoring lake thermal dynamics is critical to ensuring the long-term health of large northern lake ecosystems, yet adequate spatial and temporal resolution of both baseline and monitoring thermal data is limited. To address this knowledge gap and local interests, we worked with local communities to establish a long-term thermal monitoring program for Yukon’s largest lake, Lhù’ààn Mân’ (Kluane Lake). In 2016, sourcewater for the lake’s primary inflow (cold and turbid glacial meltwater) was abruptly diverted to a neighboring watershed due to glacier recession. The impacts to lake water properties and dynamics are largely unknown but could have significant consequences. Beginning in spring 2017, hourly temperature data was collected throughout the water column at four sites in the lake. Thermal dynamics were compared between sites and over time using water column heat content (MJm^2) and generalized additive models. Each site exhibited unique thermal dynamics, and the temporal patterns of thermal dynamics were also different for each site. Of particular interest was that the lake’s southern basin displayed an increase in water column heat storage over the three years, but this increase was not observed in other regions of the lake. To investigate possible causes of this, and in the absence of pre-2016 mooring data against which to compare pre- and post- diversion thermal dynamics, we used historical lake ice phenology, satellite-derived lake surface temperature, and historical air temperature to investigate the relationships of these variables with the observed temporal patterns of the lake’s thermal dynamics. Air temperature and days of open water increased at all sites between 2017 and 2019. Since only the south basin of the lake exhibited significant warming during this timeframe, this suggests that other factors other than air temperature and days of open water may be influencing the lake’s thermal dynamics. A significant difference in south basin lake surface temperatures before and after 2016 suggests that the sudden loss of glacial inflow may be impacting south basin thermal dynamics. Continued long-term monitoring to account for interannual variability and to accurately identify trends is needed in order to further study this hypothesis and understand any long-term changes in Lhù’ààn Mân’ thermal dynamics. This work is particularly timely given that glacier recession and eventual loss of glacial inflow to lakes will only become increasingly common. We also present a robust and cost-effective design for thermal monitoring of large and seasonally ice-covered lakes.

Introduction

Approximately 60% of Canada’s freshwater drains north, where air temperatures are rising at twice the average global rate (Bush & Lemmen 2019; Environment and Climate Change Canada 2013). These rising temperatures are increasingly impacting northern freshwater lakes and rivers through both direct and indirect mechanisms (Box et al. 2019; Serreze & Barry 2011; Vincent 2020). For example, degrading permafrost and receding glaciers are changing the chemistry of freshwater lakes and rivers (Brahney et al. 2020; Colombo et al. 2018; Frey & McClelland 2008) and altering hydrological regimes (Huss & Hock 2018; Milner et al. 2017). Changing precipitation patterns are predicted to shift the timing of freshet as well as the quantity and chemistry of meltwater inputs (Schnorbus et al. 2012), while shifting ice phenology is directly causing changes in the thermal dynamics of lakes (Duguay et al. 2006; Prowse et al. 2006).

Water temperature is a primary ecological driver in freshwater systems, and changes in thermal dynamics can have significant consequences for the organization and function of entire freshwater ecosystems. Shifts in primary productivity, species composition, oxygen levels, nutrient cycling, fish physiology, and habitat availability have all been documented or are predicted to occur in response to warming waters (Caissie 2006; Cline et al. 2013; Farrell et al. 2020; Jeppesen et al. 2010; Knouft & Ficklin 2017; Northington et al. 2019; Prowse et al. 2006; Weckström et al. 2018; Woodward et al. 2010). While there is an increasing body of knowledge developing around warming water temperatures in lakes, most of this research is biased to more southerly latitudes (e.g., Blaen et al. 2013; Butcher et al. 2015; Nickus et al. 2010; Schneider & Hook 2010; van Vliet et al. 2013), and knowledge regarding impacts on northern lakes (including baselines and long-term monitoring) remains limited.

At lower latitudes, general trends in the thermal properties of lakes include warming surface temperatures, altered mixing regimes, and shifting epilimnion and thermocline depths, which are occurring primarily as a result of increasing air temperature and longer ice-free seasons but also influenced by lake morphology, precipitation, and wind patterns (Adrian et al. 2009; Drake et al. 2019; Kraemer et al. 2015; Niedrest et al. 2018; O'Reilly et al. 2015; Shimoda et al. 2011; Vincent et al. 2008; Woolway & Merchant 2019). With amplified climate change in northern environments, northern lakes are likely to exhibit similar trends (Carmack et al. 2014; Vincent et al. 2012). Lakes that had previously remained ice-covered even in summer periods are beginning to experience more frequent and longer periods of ice-off, enabling stratification and mixing which can have ecological consequences (e.g., Bégin et al. 2021; Lehnherr et al. 2018).

Given the cultural, recreational, hydrological, and ecological importance of northern lakes, the amount of freshwater they hold, and the critical role that thermal dynamics have on their ecological function (Cott et al. 2016; Reist et al. 2016; Vincent et al. 2011; Williamson et al. 2009), the lack of baseline thermal data and continued monitoring to understand change is a significant knowledge gap (Arp et al. 2010; Heino et al. 2020). Fundamental understanding of the thermal dynamics of northern lakes and how they may be shifting is a critical component of preparing for a different future by shaping adaption and mitigation measures and helping to ensure the health of these systems. This is particularly relevant for glacier-influenced lakes where hydro ecological changes are occurring more quickly and suddenly (Milner et al. 2017; Shugar et al. 2017).

Lhù'ààn Mân' (Kluane Lake) (Figure 1-2) is Yukon's largest lake. Recent baseline and long term monitoring limnological studies as well as the sudden loss of significant glacial inflow in 2016 due to glacier recession makes Lhù'ààn Mân' an excellent case study for examining the possible thermal consequences of glacier recession and climate change on large northern lakes. In 2015, a collaborative baseline limnology study of Lhù'ààn Mân' was conducted based on common interests between academic partners, Kluane First Nation, the Dän Keyi Renewable Resources Council, and Kluane community members (Chapter 2). These interests focused on developing a better understanding of the general impacts of climate change on the lake and were prompted by concern over observed changes in lake conditions and potential impacts on lake trout (*Salvelinus namaycush*) and chum salmon (*Oncorhynchus keta*) habitat. Lake trout are sensitive to increasing water temperatures, are known to be experiencing loss of preferred thermal habitats with climate change (e.g., Guzzo & Blanchfield 2016; Jansen & Hesslein 2004), and are an important element of subsistence fishing at Lhù'ààn Mân'. The baseline data allowed for a characterization of the physical, chemical, and biological water properties of the lake, which was necessary for designing a long-term monitoring program with sufficient temporal and spatial resolution to capture change. Monitoring the thermal dynamics of the lake's various regions became the focus of the program based on a combination of logistical and fiscal constraints as well as local interests and value of information. The monitoring program was established in the spring of 2017, consisting of four year-round moorings collecting hourly temperature data throughout the water column in each of the lake's regions as identified by the 2015 baseline study.

In addition to concerns over longer-term incremental warming of lake water, a single larger scale event with relevance to lake thermal dynamics occurred in 2016. Meltwaters of the Kaskawulsh Glacier, which prior to 2016 mainly composed the primary inflow to Lhù'ààn Mân' (the 'A'ą̈y Chù' [Slims River]), were diverted to a neighboring watershed due to glacier recession, causing Lhù'ààn Mân' to lose nearly all its glacial inflow over a single season (Shugar et al. 2017). This event provided a unique and serendipitous opportunity to study how thermal properties of glacially influenced lakes may be affected by loss of glacial inflow. This is particularly relevant as glaciers across the globe are receding rapidly: their eventual disappearance will have physical, chemical, and biological impacts on downstream freshwater ecosystems and communities (Jacobsen et al. 2012; Milner et al. 2017).

Here, the first three years of the Lhù'ààn Mân' thermal monitoring data (2017-2019)[3] are presented and analyzed to provide a high resolution characterization of the lake's thermal

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[3] At the time of thesis submission (December 2021), the mooring program at Lhù'ààn Mân' was still operational with the intention of collecting data into the foreseeable future, pending logistical and financial support. However, only the first three years of data from the program were available at the time of analysis and as such the 2020 and 2021 data are omitted here. An updated analysis including 2020 and 2021 data would be valuable and may be undertaken for future publications.

dynamics. This data was also used to conduct a preliminary investigation into whether lake thermal dynamics may be changing. While recognizing that a three-year time series does not account for interannual variability and is insufficient for confidently identifying trends, we did observe that while the south basin exhibited warming between 2017 and 2019, the lake's northern arms did not. We wondered which factors could be impacting this observation, and whether the preliminary warming pattern in the south basin could be influenced by the 2016 diversion event. In the absence of pre-2016 high resolution and continuous lake temperature data[4], a direct comparison of lake thermal dynamics before and after 2016 was not possible. However, satellite-derived lake surface temperature in the south basin between 2010 and 2020 was available and analyzed for differences before and after 2016. We also analyzed available data with relevance to lake thermal dynamics, including historical air temperature and lake ice phenology, to explore the relationship between these variables and the first three years of thermal lake data. While continued monitoring is required to truly understand any changes over time in thermal dynamics of Lhù'ààn Mân', this study provides a valuable preliminary investigation into the possible impacts of loss of glacial inflow to large northern lakes. This work also serves as a robust and economical example for how to successfully monitor the spatial and temporal thermal dynamics of large, ice-covered lakes.

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[4] The only other continuous thermal data that exists for Lhù'ààn Mân' prior to 2016 (to the best of my knowledge) is thermistor data from the deep southern basin of the lake between late June 1985 and late June 1986 (Carmack et al. 2014) and again between early August 2013 and July 2014 (unpublished data from Carol Janzen, Eddy Carmack, and David Hik). While the instrumentation resolution may be acceptable for compararison with the 2017-present mooring data, both of these datasets do not cover a full ice-off period, which is when thermal dynamics are especially interesting and relevant for fish habitat thresholds. Without data from a full ice-off period, these datasets cannot be used to accurately compare possible differences between lake thermal dynamics before and after 2016. Because these datasets are also over a single (incomplete) year, they also do not account for interannual thermal dynamics of the lake prior to the diversion, further limiting possible comparisons of lake thermal dynamics before and after 2016. Despite this, it is possible that comparison between these records and the current mooring data could present interesting information which could be investigated in future studies.

Methods

Study Area

The surface area of Lhù'ààn Mân' is approximately 400 km^2, with a maximum depth of 80±5 m and an approximate volume of 11.4 km^3 (Chapter 2). Lhù'ààn Mân' is in the shape of a "Y", with a deep southern basin, a central (mid) region, a warm and shallow arm to the northwest (Tthe Kaala Daagur, commonly referred to as Brooks Arm or Little Arm), and a cooler and deeper arm to the northeast ('Ùha K'ènji, commonly referred to as Talbot Arm or Big Arm) (Chapter 2) (Figure 1-2). To the west is the glaciated St. Elias Range (up to 2600m) and to the east are the Kluane and Ruby Ranges (up to 1600m). The St. Elias Range produces a rainshadow in the area causing low annual precipitation (less than 30cm) (Krebs & Boonstra 2001). The mountains also cause strong summer wind events that are dominated by katabatics from the Kaskawulsh Glacier (Crookshanks 2008), whereas arctic winter winds tend to come from the north. The average frost-free period is only 30 days per year at Kluane (Krebs & Boonstra 2001). The area is underlain with discontinuous permafrost, with valley bottoms dominated by boreal forest and higher elevations characterized as alpine tundra (Krebs & Boonstra 2001).

The lake has experienced a dynamic hydrologic history in response to climatic changes within the last few hundred years, including shifts in lake size, flow direction, mixing regime, productivity, chemistry, and ecology (Chapter 2; Brahney 2007; Brahney et al. 2008a; Brahney et al. 2008b; Reyes et al. 2006; Zabel 2017). Until 2016, the primary source of water to the lake was the 'A'ą̈y Chù', which was comprised mostly of meltwater from the Kaskawulsh Glacier (Brahney 2007). In spring 2016, the 'A'ą̈y Chù' dramatically decreased in volume after the Kaskawulsh Glacier receded to a critical point, causing its meltwaters to be diverted south to the Kaskawulsh and Alsek rivers (Shugar et al. 2017). Meltwaters of the Kaskawulsh Glacier are unlikely to return flowing down the Dhal T’à’ (Slims River Valley) (Shugar et al. 2017). Post 2016, flow within the ‘A’ą̈y Chù’ was composed primarily of snowmelt, rainwater, and groundwater, with some inflow from other small glacially-influenced creeks.

Study approach and mooring design

The 2015 baseline study at Lhù’ààn Mân’ evidenced the need for high spatial and temporal resolution monitoring in order to understand seasonal dynamics and differences between basins. Year-round, through-column data collection in lakes can be challenging during the spring and fall ice formation and break-up periods, although the value of these datasets is increasingly recognized. As such, new technologies and robust designs are allowing for increased deployment of continuous moorings in lakes. However, many existing pre-fabricated options are expensive and highly specialized. We worked with the Department of Fisheries and Oceans Canada (Mike Dempsey and Eddy Carmack) to design and build moorings for Lhù’ààn Mân’ which adhered to logistical, fiscal, and physical project limitations.

The Lhù’ààn Mân’ temperature monitoring program consists of four moorings equipped with dataloggers. Each mooring is located in a basin or area of Lhù’ààn Mân’ with unique depth and physicochemical limnological properties, as identified from 2015 baseline data (Chapter 2) (Figure 3-1). The moorings and sites are referred to as Brooks (depth 10.5m), Talbot (depth 39m), Deep (depth 75.6m) and South (depth 26.5m). No mooring was deployed in the center of the lake due to logistical impossibilities and risk of drift due to the consistent presence of high winds at this location. The moorings consist of Amsteel line attached to subsurface buoys and steel chain anchors: the weights of the anchors and buoyancy of the buoys were carefully measured to ensure the moorings were light enough to be pulled out of the water by hand, but heavy enough to remain stationary in the lake, with enough buoyancy to keep the line as straight as possible in the water column. The moorings were designed to sit just under lake ice in winter (to avoid being caught in ice), which translates to roughly 2-3m below water surface during maximum spring lake levels. This allows moorings to collect data year-round, including during the ice-on and ice-off periods.

Prior to the diversion of Kaskawulsh Glacier meltwater, lake levels fluctuated ~1.5-2.5m during the open water season in response to snowmelt and glacier meltwater, with water levels peaking in August-September before decreasing again in advance of ice formation in autumn (Figure 3-2). Since 2016, Lhù'ààn Mân' levels have shown a more modest fluctuation of ~0.5-1.0m during the open-water season[5] and a winter lake level that is approximately 25cm lower than pre diversion levels.

The moorings were equipped with data loggers (HOBO Tidbit v2 Temperature Data Logger; accuracy ±0.21°C from 0° to 50°C; resolution 0.02°C at 25°C; stability (drift) < 0.1°C per year), mounted to plastic blocks fixed to the Amsteel at select intervals (every 1m at Brooks, and every 5 m at the deeper South, Deep, and Talbot sites). The Tidbit dataloggers recorded continuous (hourly) temperature data. A SubSea Sonic AR-60-E Accoustic Release Unit transponder was attached to each mooring to facilitate retrieval. A conductivity logger was also mounted near the top of each mooring (Figure 3-3) but since some of these loggers experienced failure and/or drift, this data was unusable for comparative purposes and not presented here. The moorings are relocated and visited once per year (as soon after ice-off as possible for ease of retrieval due to proximity to water surface in early season) for data download and redeployment.

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[5] The higher lake level observed in 2020 (compared to 2016-2019) is due to high precipitation in winter 2019-2020 and a rainy summer in 2020, contributing increased snowmelt and runoff to the lake. It does not indicate return of Kaskawulsh Glacier melt inflow to the lake.

They are relocated using a combination of GPS coordinates, depth finder signals, and transponder signals. During these yearly field visits the moorings are pulled out of the water and cleaned, loggers are downloaded and redeployed, and the moorings are returned to their specified locations in the lake.

Temperature data and heat storage calculation

Temperature data (°C) from each mooring's Tidbit dataloggers between April 1 2017 and July 1 2020 was downloaded into CSV file format using HOBO software (Appendix 2. Supplementary Data Files). Data were imported into Golden Surfer Software and interpolated using Kriging interpolation technique to produce hourly temperature data at each mooring site, for every meter depth.

Given that several basins of Lhù'ààn Mân' exhibit ephemeral and weak stratification (Chapter 2), comparing temperature changes (over time and between sites) by thermal layers (e.g., epilimnion, metalimnion, hypolimnion) was not feasible. To compare thermal dynamics over time at each site and between sites, we used an integrated approach that estimated the heat content of the entire water column. First, the interpolated temperature dataset (i.e., hourly temperature values in degrees Celsius (°C) at every meter in the water column) was used to calculate hourly heat capacity for each cubic meter in the water column at each site. The heat capacity in each cubic meter was calculated by multiplying degrees Celsius (°C) by volume (x 10^6 cm^3) resulting in units of calories per m^3 (Wetzel & Likens 2000). The hourly heat storage of the entire water column was then calculated by summing the heat capacity of each cubic meter in the water column at each site from the surface to the bottom (different total depths at each site) and then multiplying by 4.184 x 10^6 to obtain values in SI units of MJm^{-2}. Only heat storage values between April 1 and December 31 were calculated and used in analysis since heat storage during this timeframe is most relevant to fish habitat and health, and winter values were relatively consistent across sites. The result was hourly water column heat storage (MJm^{-2}) at each site, between April 1 and December 31 for 2017, 2018 and 2019.

Comparing water column heat storage and temporal patterns of heat storage between sites

Water column heat storage was compared between sites and between years during the April 1 to December 31 period. To model seasonal patterns in water column heat storage over the three-year time series at each site, we used generalized additive models (GAMs) which are ideal for fitting nonlinear relationships between response and predictor variables as they use smooth curves and splines (Pederson et al. 2019). We used the 'mgcv' package (Wood 2020) implemented in R (R Core Team 2014) to build GAMs using the 'bam' function designed for large datasets. We modelled water column heat storage using three explanatory variables, including: 1) the variable 'year' to account for long-term trends; 2) the variable 'site' to account for differences between sites; and 3) the variable 'month' to account for recurring seasonal patterns. We allowed the seasonal patterns of total-column heat storage to vary as a function of year by including an interaction between the 'month' and 'year' variables using a tensor smooth. The 'month' component of the tensor smooth was modelled using a cyclic cubic spline to account for recurring annual patterns, while the 'year' component was modelled using a cubic regression spline. For both 'month' and 'year' we used the maximum allowable basis dimensions, k=12 and k=3 respectively, and let the complexity penalties implement in the 'mgcv' package determine the best wiggliness for each spline. To allow for difference between sites, we included an interaction between the tensor smooth and the variable 'site'. This resulted in the tensor smooth being fit separately for each site with a separate intercept term. Lastly, we included an AR(1) error term to remove the temporal autocorrelation of residuals arising due to repeated observations nested within 'month', within 'year', and within 'site' (see Appendix 2. Supplementary File – Generalized Additive Model R code).

Historical air temperature, lake ice phenology, and satellite-derived lake surface temperature

Air temperature and lake ice phenology have strong effects on lake thermal dynamics; secondary effects include lake morphometry, wind, precipitation, groundwater influence, and water clarity (O'Reilly et al. 2015; Rose et al. 2016; Smits et al. 2020; Woolway & Merchant 2018). While data for wind, precipitation, groundwater influence and water clarity for Lhù'ààn Mân' was either unavailable or insufficient for analysis (i.e., significant data gaps), historical air temperature records from Burwash Landing and lake ice phenology determined via satellite imagery were available and analyzed. First, we conducted trend analysis on these data to identify trends over time. We then examined whether 2017, 2018, and 2019 were anomalous years and how closely their three-year pattern related to the three-year lake thermal patterns.

Air temperature data between 1953 and 2021 were obtained from Environment and Climate Change Canada Historical Weather Data web site (https://climate.weather.gc.ca/historical_data/search_historic_data_e.html) for weather station Burwash A (61°22'00.000" N, 139°02'00.000" W; elevation: 806.9m; ClimateID: 2100179). Yearly and monthly temperature anomalies for the time series were calculated using the 1970-1990 mean. Linear regression analysis was performed on the yearly and monthly anomaly time series to determine whether there was an increasing trend over time.

Ice-on and ice-off dates between 2000 and 2020 for the Talbot, Brooks, and Deep/South sites were determined visually using NASA Worldview application from the Earth Observing System Data Information System (EOSDIS) (https://worldview.earthdata.nasa.gov). EODIS presents daily satellite imagery from the MODIS Aqua and Terra Sensors (2000 - present), which are commonly used to determine lake ice phenology. South and Deep sites were analyzed as one site due to their proximity resulting in identical ice phenology. We did not automate the process using MODIS snow and ice products since we could visually verify – and more accurately identify – precise ice phenology dates using the Worldview application. Ice-off is defined as the day of year when all ice was entirely off each of the individual regions that surround the three sites (i.e., Tthe Kaala Daagur, ’Ù̀ha K’ènji, and the Deep/South basin), and ice-on was defined as the day of year when ice entirely covered each basin. Because of the large size of Lhù’ààn Mân’, usually enough of each area was visible to determine true ice phenology dates. However, when cloud cover obscured an entire area during the break-up or freeze-up periods for a day or more at a time, the day of ice-on or ice-off was determined as the midpoint between the last unobscured day of observable transition and the first day of unobscured water or ice. For example, if Tthe Kaala Daagur (Brooks Arm) had ice in it on May 10, then was obscured by clouds for the next three days, and on May 14 the Arm was composed entirely of open water, then the date of ice-off was determined as May 12. Clouds obscured true dates approximately half the time, but only on average for a span of 1.8 days (up to a maximum of 7).

Time series of ice-off dates, ice-on dates, and days of open water for each area were analyzed with Mann Kendall trend tests and Sen’s slope tests (both non-parametric tests) using the ‘trend’ package (Pohlert 2020) in R statistical software, with year as the independent variable. These two tests are commonly used in hydrological research and for ice phenology trend analysis (Duguay et al. 2006; Latifovic & Pouliot 2007; Yue et al. 2002). We report the Mann Kendall Z and p-values, and the Sen’s slope. Z-values show the direction of trend, p-values determine the significance of the trend, and the Sen’s slope determines the magnitude of the trend.

While it does not represent the thermal dynamics of the entire water column, lake surface temperature during the open water season typically represents the maximum temperature found in a lake and can have an important role in lake thermal dynamics. We used MODIS Land Surface Temperature (LST) imagery products (downloaded from Google Earth Engine) from both the Terra (MOD11A1.006) and the Aqua satellites (MYD11A1.006) to compare lake surface temperature at the Deep mooring site between the pre-diversion (2010-2015) and post-diversion (2016-2020) periods. Since the LST MODIS products have a spatial resolution of ~1km, surface water temperatures for Brooks, Talbot and South mooring sites could not be determined because these sites are located less than 1km from the shoreline. The LST MODIS product is calculated from longwave thermal radiation emitted at the Earth's surface (10.78-12.27 µm) using a split-window algorithm (Wan & Dozier 1996) and surface emissivity values (assuming a constant emissivity for water. MOD11A1.006 and MYD11A1.006 provide once daily and once nightly surface temperature data, up to four data points per 24 hr period. However, cloud cover contamination resulted in the removal of data points, resulting in 28% of days between 2010 and 2020 having between 1 and 3 LST data points per day instead of four.

An independent sample, one-tailed t-test was used to compare lake surface temperatures at the Deep site between pre- (2010-2015) and post- (2016-2020) ’A’ą̈y Chù’ diversion. Yearly means (using all data >0°C) were used in the t-test (n=6 for 2010-2015 and n=5 for 2016-2020).

Results

Characterizing Lhù'ààn Mân' thermal dynamics

The mooring data is consistent with the findings in Chapter 2; Tthe Kaala Daagur (Brooks Arm) effectively does not stratify, and is the area of the lake that exhibits the warmest temperatures (Figure 3-4). Despite this, this area has relatively low water column heat storage values compared to the rest of the lake due to its shallow depth (Figure 3-5). 'Ù̀ha K'ènji (Talbot Arm) displays gradual warming through spring and summer, clear summertime stratification, and a deepening of the epilimnion throughout the open-water season (Figure 3-4). The Deep and South sites are colder overall, during both open-water and ice-on seasons (Figure 3-4). Whereas the Deep site displays gradual warming throughout the open-water season, the South site is characterized by more erratic thermal dynamics, with some warming periods affecting the entire water column (Figures 3-4 & 3-5).

Comparing 2017-2019 patterns of water column heat storage between sites

Hourly, interpolated (1m resolution) temperature data (Figure 3-4) allows an initial visual exploration of differences between sites over the three-year time series. The most striking observations are found at the South and Deep sites, where both surface and through-column temperatures appear to be increasing between 2017 and 2019. Through-column temperatures also appear to possibly warm very slightly over time in Tthe Kaala Daagur (Brooks Arm). These patterns are also visually observed when plotting the water column heat storage data (Figure 3-5). Water column heat storage data allowed for a more precise identification of differences in seasonal patterns (i.e., the height, width, and location along the x axis of the plotted heat storage curves) and timing of peak water column heat storage among sites. For example, water column heat storage in Tthe Kaala Daagur (Brooks Arm) increased in spring before any other site, but also declined before other sites in autumn, suggesting that ice phenology patterns may be different in this part of the lake (this was confirmed by our ice phenology analysis (see below)). Peak water column heat storage also occurred earliest at the Brooks site. Variability in day-to-day water column heat storage was greatest at the South and Deep sites (Figure 3-5).

Our generalized additive model performed well by capturing changes in seasonal cycles at each site over the three years and explaining 96.9% of the deviance in our dataset. The model confirmed that both the seasonal patterns and the three-year patterns of water column heat storage were different for each site as indicated by the 95% confidence intervals of site-specific model predictions (Figures 3-6 & 3-8) and significant tensor smooths for each site (Table 3-1). The mean water column heat storage also differed between sites as indicated by significant intercepts (parametric terms) (Figure 3-6 and Table 3-1). Across all sites, the South site displayed the most significant (and near linear) increase in water column heat storage over the three years (of approximately 400 MJm^{-2}); the Deep site displayed an increase of approximately 450 MJm^{-2} between 2017 and 2018 followed by a slight increase of approximately 50 MJm^{-2} between 2018 and 2019; the Brooks site displayed no discernable increase or decrease; and the Talbot site displayed a slight decrease in water column heat storage (of approximately 150 MJm^{-2}) between 2017 and 2019 (Figure 3-7).

Historical air temperature, lake ice phenology and satellite-derived lake surface temperature

Analyses of historical air temperature data from Burwash Landing (Yukon) revealed that yearly mean air temperature in the Lhù'ààn Mân' region has increased by ~2°C between 1967 and present (Figure 3-8). 2017, 2018, and 2019 were all above the 1970-1990 yearly mean, by

0.80°C, 1.56°C, and 2.51°C, with Z-scores (i.e., standard deviations above the mean) of 0.65, 1.24, and 1.99, respectively (Table 3-2). Monthly means were also above the 1970-1990 means for each month of 2017, 2018 and 2019 except for March and November 2017, February, April and September 2018, and February and August 2019 (Table 3-3).

Ice phenology patterns were different across Lhù'ààn Mân' basins: lake ice always came off Tthe Kaala Daagur (Brooks Arm) first, followed by the main lake basin (and South/Deep mooring sites), and finally 'Ùha K'ènji (Talbot Arm) (Figure 3-9). Ice formed first in the fall on Tthe Kaala Daagur (Brooks Arm) followed by 'Ùha K'ènji (Talbot Arm), with the main lake basin freezing last (Figure 3-9). Consequently, there were more days of open water in the main and southern lake basins (and Deep/South mooring sites, 189 ± 3.1 (SE) days; 2000-2020 mean), with less days of open water at the Talbot (174 ± 2.1) and finally Brooks mooring site (165 ± 1.7) (Figure 3-9).

Ice-off trends for all three areas of the lake had negative Mann-Kendall Z factors and Sen's slopes between 2000 and 2020, indicating that ice-off is occurring earlier over time; these were significant at the 90% confidence level (Table 3-4). There were no significant temporal trends for timing of ice-on (Table 3-4). Mann-Kendall Z factors and Sen's slopes days of open water trends were positive for all three basins (indicating trends towards increased days of open water), though only Tthe Kaala Daagur (Brooks Arm) was significant at the 90% confidence level (Table 3-4).

Days of open water were below the 2000-2020 mean for 2017, but higher in both 2018 and 2019 (Table 3-2). Days of open water increased over the three-year period at all sites.

Mean open-water surface lake temperature between 2016 and 2020 at the Deep site was significantly (p=0.02) warmer (mean of 6.596°C ± 0.18 (SE)) than mean surface lake temperature between 2010 and 2015 (6.039 ± 0.13 (SE)) (Figure 3-10).

Discussion

We found that each basin within Lhù'ààn Mân' had unique thermal dynamics, especially with regards to strength and timing of water column heat storage patterns. The lack of defined stratification at the South site was particularly interesting. Before 2016, the large volume of cold and silty glacial meltwaters flowing into this end of the lake disrupted the water column with strong turbidity currents, causing weak stratification and more frequent mixing between layers (Chapter 2). With the 'A'ą̈y Chù' having significantly reduced volume and likely warmer river water, we expected reduced turbidity currents and a more stable water column to develop. However, between 2017 and 2019, we did not observe strong stratification at the South site, which instead displayed erratic temperature profiles and events of mixing to depth (Figure 3-4). Although the volume of the 'A'ą̈y Chù' decreased substantially after 2016, snowmelt and other, minimal glacier meltwaters from sources other than the Kaskawulsh Glacier (e.g., Vulcan Creek, Canada Creek) contributed to its continued but drastically reduced flow. It is possible that these combined sources had enough volume, turbidity, and density differences to continue disrupting the stability of the water column at the South mooring site. Alternatively, the thermal dynamics observed could be explained by possible groundwater sources to the lake at this site. While groundwater seeps have been identified on the southern lakeshore, groundwater contribution to the lake has not been calculated (Department of Fisheries and Oceans 2018; Wilson 2006).

Air temperature, ice phenology, and water column heat storage data for Lhù'ààn Mân' between 2017 and 2019, as well as lake surface temperature at the Deep site between 2010 and 2020, were used to investigate possible preliminary impacts of the loss of Kaskawulsh Glacier meltwaters to the thermal dynamics of Lhù'ààn Mân'. Most prominently, the three-year water column heat storage patterns over time were different for each of the four mooring sites at Lhù'ààn Mân'. While differences in strength and timing of seasonal heat storage patterns between basins are expected due to differences in days of open water and basin morphology, the reasons behind differing three-year patterns in total-column heat storage across sites are less evident (Figure 3-7). If air temperature was a dominant factor in water column heat storage patterns over time, and because 2017, 2018 and 2019 had consecutively increasing yearly mean air temperatures, we would expect all sites to exhibit similar three-year patterns in water column heat storage since air temperature is similar for all areas of the lake.

Unlike air temperature, ice phenology differs for each basin of Lhù'ààn Mân'. We observed a pattern of increasing days of open water between 2017 and 2019 in all basins, which likely corresponds to the increasing air temperature anomalies over this time. Since water column heat storage patterns didn't increase at all sites between 2017 and 2019, this suggests that ice phenology was not a dominant factor influencing the observed heat storage patterns.

Given that neither air temperature nor ice phenology fully explain the three-year water column heat storage patterns across sites, and that satellite-derived lake surface temperature analysis shows lake surface in the Southern basin was significantly warmer after 2016, this suggests that the preliminary warming pattern observed at the South site between 2017 and 2019 is impacted by other variables, including possibly the loss of glacial inflow in 2016. Because the influence of the 'A'ą̈y Chù' on the Brooks and Talbot Arms was minimal in 2015 (Chapter 2) this also suggest that the south end of Lhù'ààn Mân' is likely the region of the lake that is most sensitive to the loss of the Kaskawulsh Glacier meltwater.

Since both lake trout and chum salmon can be found in the south end of the lake (Barker et al. 2014), we explore the possible impacts on these species' habitat suitability. The optimal thermal range for lake trout is typically between 8-12°C, however, some Yukon lake trout have a much lower thermal range (Mackenzie-Grieve & Post 2006). Chum salmon spawning, fry development, and adult optimal range is roughly 7-12.8°C (Richter & Kolmes 2006). Within Lhù'ààn Mân', these optimal ranges are mostly limited to the 'Ùha K'ènji (Talbot Arm), central and southern basins of the lake, with Tthe Kaala Daagur (Brooks Arm) waters exceeding optimal thermal range throughout much of the open water season, even prior to the diversion of Kaskawulsh Glacier meltwater (Chapter 2). The impacts of warming as a result of the loss of significant glacier inflow on optimal thermal ranges of fish will depend on whether the observed, preliminary heat storage patterns continue: if the southern basin continues to display warming but the other basins remain thermally stable, effects on habitat availability would be relatively minor. However, if the other basins begin to exhibit warming over time, the impacts on habitat availability could be more significant. Sustained thermal monitoring of all basins at Lhù'ààn Mân' will provide critical information regarding spatial variability of thermal changes and trends. While this work focuses on thermal dynamics of Lhù'ààn Mân', shifts in chemistry are also anticipated: the loss of significant glacier meltwater inflow has also resulted in a significant decrease of turbidity input to the lake. The potential impacts of chemical changes (e.g., turbidity) to Lhù'ààn Mân' as a direct result of the Kaskawulsh Glacier meltwater diversion will also impact fish habitat and should be considered for future studies.

Continued, high spatial and temporal resolution monitoring of the lake’s thermal dynamics is critical. While this study indicates that the southern basin of Lhù’ààn Mân’ may be warming, trends typically require at least ten years of data in order to be identified with confidence and to account for interannual variability. Year-round, hourly datasets of lake water temperature throughout the column are incredibly valuable for monitoring fish habitat changes, yet these datasets are rare - especially across the circumpolar north. In order to understand how climate change may be impacting the thermal dynamics of lakes, this kind of monitoring is critical. This study serves as a robust and economical example for how to successfully monitor the spatial and temporal thermal dynamics of large, ice-covered lakes.

Additionally, the importance of meaningful collaboration with local partners cannot be overstated. The impacts of climate change in the north will be most felt by northerners, and understanding change and its consequences on ecosystems and species (particularly food sources) is critical for adaptation. While many existing monitoring programs utilize scientific methodology and instruments, founding collaborative projects based on community needs, principles of respect and reciprocity, and understanding for other ways of knowledge gathering and sharing is key to successful monitoring.

Conclusion

Both incremental (i.e., air temperature warming over time) and more abrupt (i.e., sudden loss of glacial inflow due to glacier recession) impacts of climate change can have thermal consequences on northern lakes, particularly in glacierized catchments. In larger lakes, these impacts may be more pronounced in certain basins. For Lhù’ààn Mân’, preliminary (3-year) and high resolution (spatial and temporal) thermal monitoring data suggests that the loss of the lake’s primary, glacially-influenced inflow in 2016 may be contributing to warming (using total-column heat storage as an indicator of warming) observed in the lake’s southern basin. Continued high resolution monitoring will be needed to confirm this hypothesis and investigate consequences on fish habitat suitability and availability at Lhù’ààn Mân’. As air temperatures continue to increase, impacts on lake thermal dynamics are likely to amplify, emphasizing the need for continuous and high resolution lake thermal monitoring for both adaptation and mitigation.

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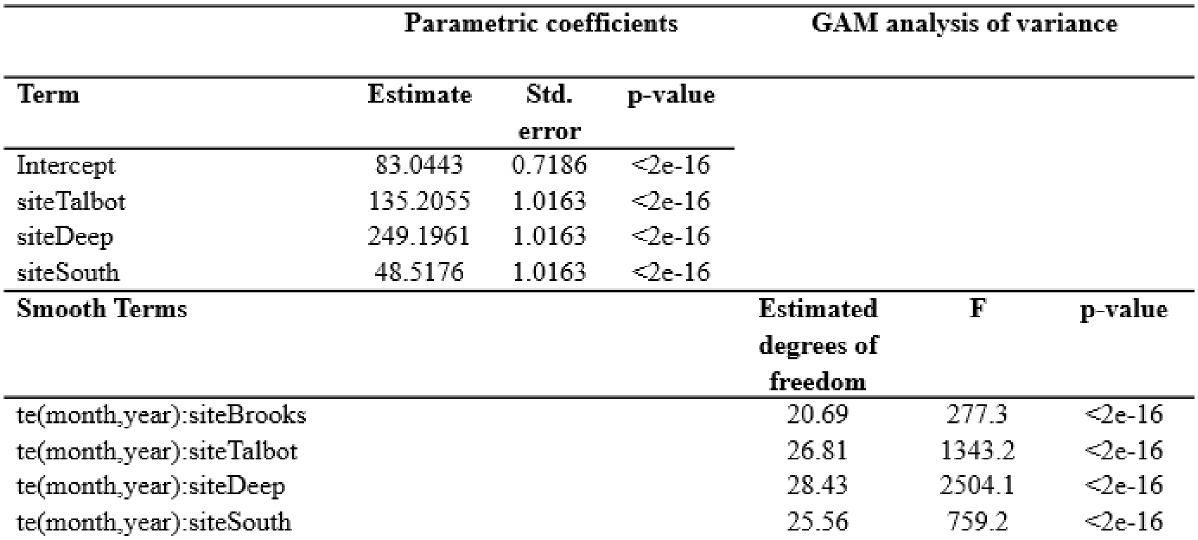
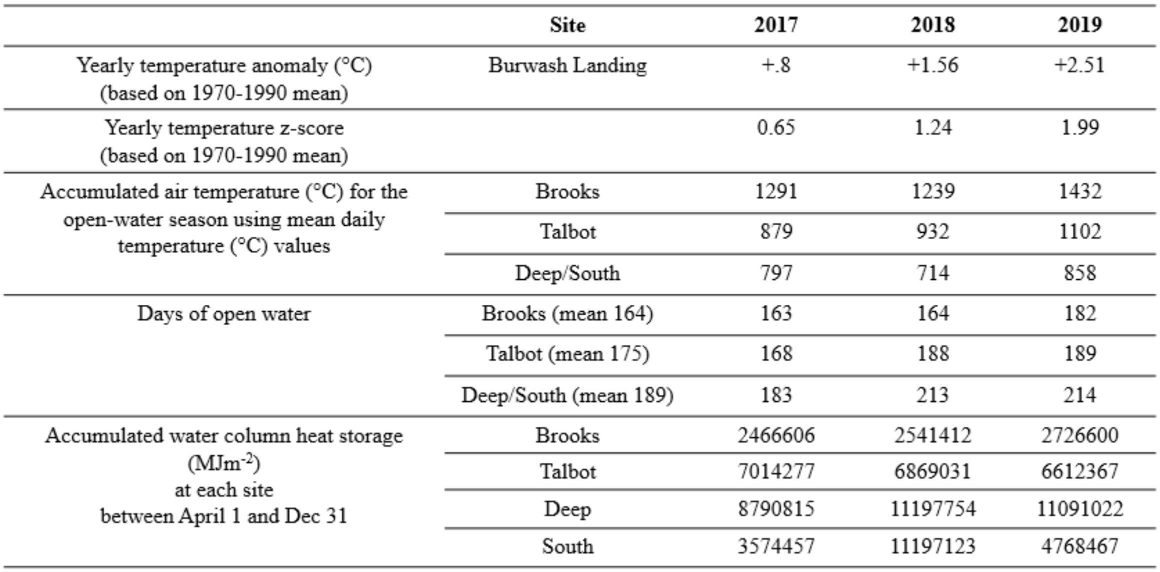
Tables

Table 3-1. Lhù'ààn Mân' water column heat storage generalized additive model results for parametric coefficients and analysis of variance of the model's smooth terms.



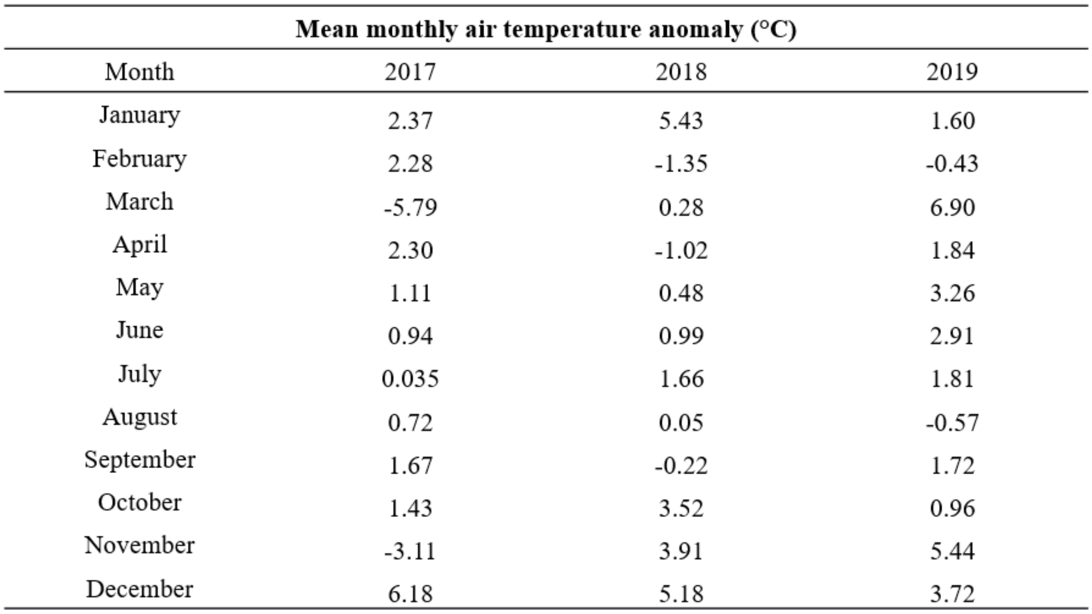
	Parametric coefficients			**GAM analysis of variance**		
Term	**Estimate**	**Std. error**	**p-value**			
Intercept	83.0443	0.7186	<2e-16			
siteTalbot	135.2055	1.0163	<2e-16			
siteDeep	249.1961	1.0163	<2e-16			
siteSouth	48.5176	1.0163	<2e-16			
Smooth Terms				**Estimated degrees of freedom**	**F**	**p-value**
te(month,year):siteBrooks				20.69	277.3	<2e-16
te(month,year):siteTalbot				26.81	1343.2	<2e-16
te(month,year):siteDeep				28.43	2504.1	<2e-16
te(month,year):siteSouth				25.56	759.2	<2e-16

Table 3-2. Mean annual air temperature anomalies (°C) at Burwash Landing (Yukon) based on the 1970-1990 mean; accumulated air temperature (°C) at Burwash landing (Yukon) for the open-water season; days of open water for each mooring site (Brooks, Talbot, Deep/South); and accumulated water column heat storage (MJm^{-2}) for each mooring site.



	Site	2017	2018	2019
Yearly temperature anomaly (°C) (based on 1970-1990 mean)	Burwash Landing	+.8	+1.56	+2.51
Yearly temperature z-score (based on 1970-1990 mean)		0.65	1.24	1.99
Accumulated air temperature (°C) for the open-water season using mean daily temperature (°C) values	Brooks	1291	1239	1432
	Talbot	879	932	1102
	Deep/South	797	714	858
Days of open water	Brooks (mean 164)	163	164	182
	Talbot (mean 175)	168	188	189
	Deep/South (mean 189)	183	213	214
Accumulated water column heat storage (MJm^{-2}) at each site between April 1 and Dec 31	Brooks	2466606	2541412	2726600
	Talbot	7014277	6869031	6612367
	Deep	8790815	11197754	11091022
	South	3574457	11197123	4768467

Table 3-3. Mean monthly air temperature anomalies (°C) based on the 1970-1990 monthly means at Burwash Landing (Yukon). Historical air temperature data obtained from Environment and Climate Change Canada, retrieved from https://climate.weather.gc.ca/historical_data/search_historic_data_e.html.



Mean monthly air temperature anomaly (°C)			
Month	2017	2018	2019
January	2.37	5.43	1.60
February	2.28	-1.35	-0.43
March	-5.79	0.28	6.90
April	2.30	-1.02	1.84
May	1.11	0.48	3.26
June	0.94	0.99	2.91
July	0.035	1.66	1.81
August	0.72	0.05	-0.57
September	1.67	-0.22	1.72
October	1.43	3.52	0.96
November	-3.11	3.91	5.44
December	6.18	5.18	3.72

Table 3-4. Mann-Kendall Z factors, Mann-Kendall p-values, and Sen's slope values for ice-off, ice-on, and days of open water trends for Brooks site, Talbot site, and South/Deep (sites combined due to proximity) at Lhù'ààn Mân'.

	Mann-Kendall Z factor	Mann-Kendall p-value	Sen's Slope
Brooks ice-off	**-1.79**	**0.07**	**-0.44**
Brooks ice-on	0.15	0.88	0.03
Talbot ice-off	**-1.97**	**0.05**	**-0.50**
Talbot ice-on	0.15	0.88	-0.03
Deep/South ice-off	**-1.75**	**0.08**	**-0.55**
Deep/South ice-on	0.06	0.95	0.00
Brooks days of open water	**1.81**	**0.07**	**0.50**
Talbot days of open water	0.88	0.38	0.26
Deep/South days of open water	0.91	0.36	0.50

Figures

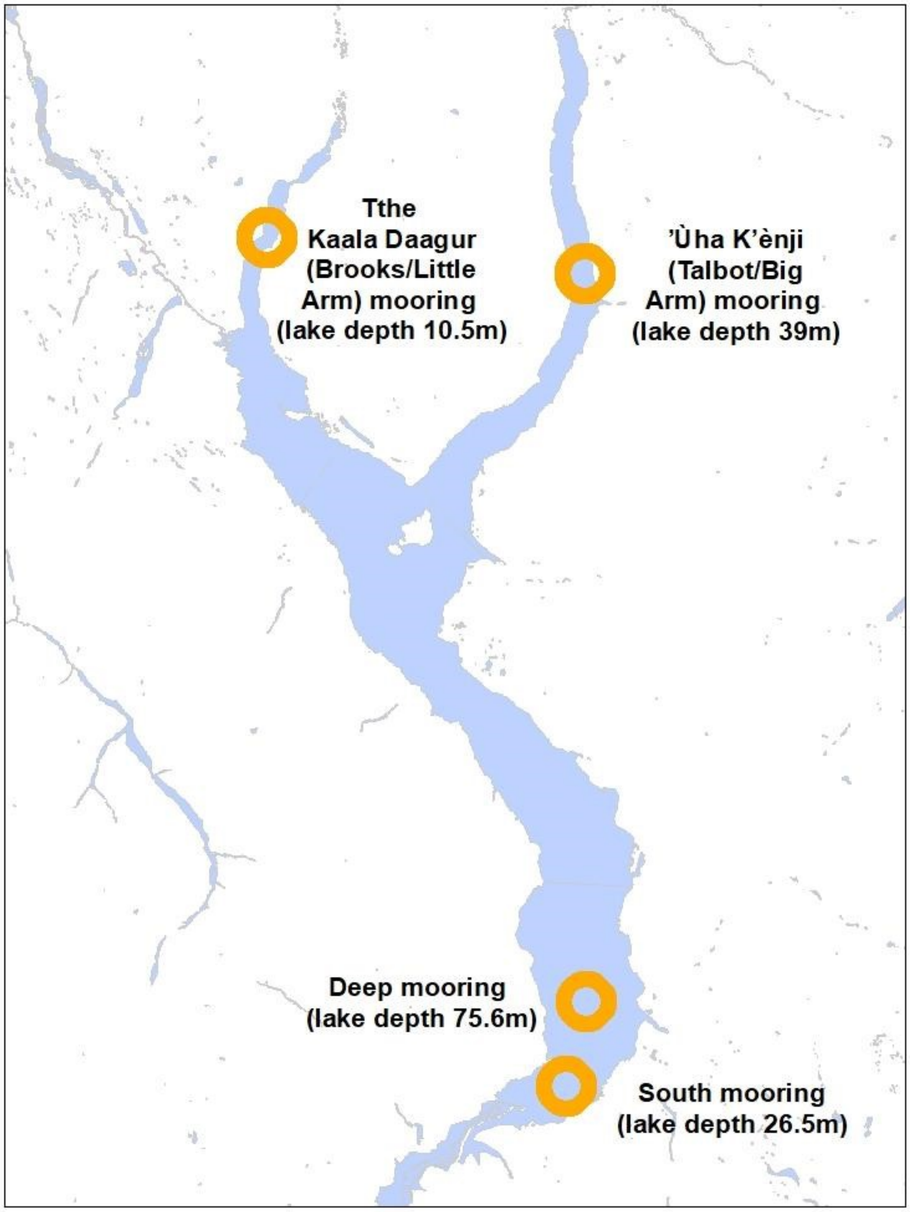


Figure 3-1. Location of the four moorings (and lake depth at each site) in Lhù'ààn Mân', represented by orange circles. Produced in Esri ArcMap 10.7.1 with open-access basemaps from Natural Resources Canada and Yukon Government.

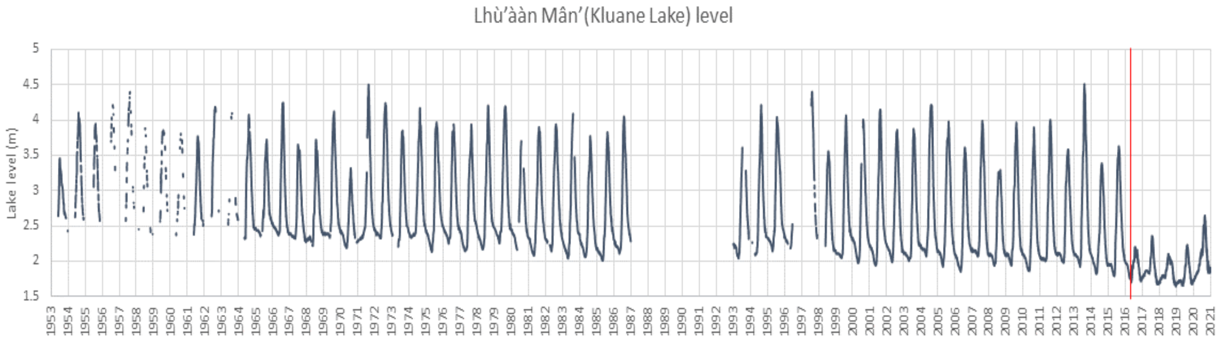


Figure 3-2. Lhù'ààn Mân' levels between 1962 and 2020, as measured by station number 09CA001, station name: Kluane Lake, near Burwash Landing (Yukon), located at 61°03'16'' N, 138°30'21" W. Data obtained from the Environment and Climate Change Canada Historical Hydrometric Data web site (https://wateroffice.ec.gc.ca/mainmenu/historical_data_index_e.html). The red line indicates the diversion of the Kaskawulsh Glacier meltwater in spring 2016.

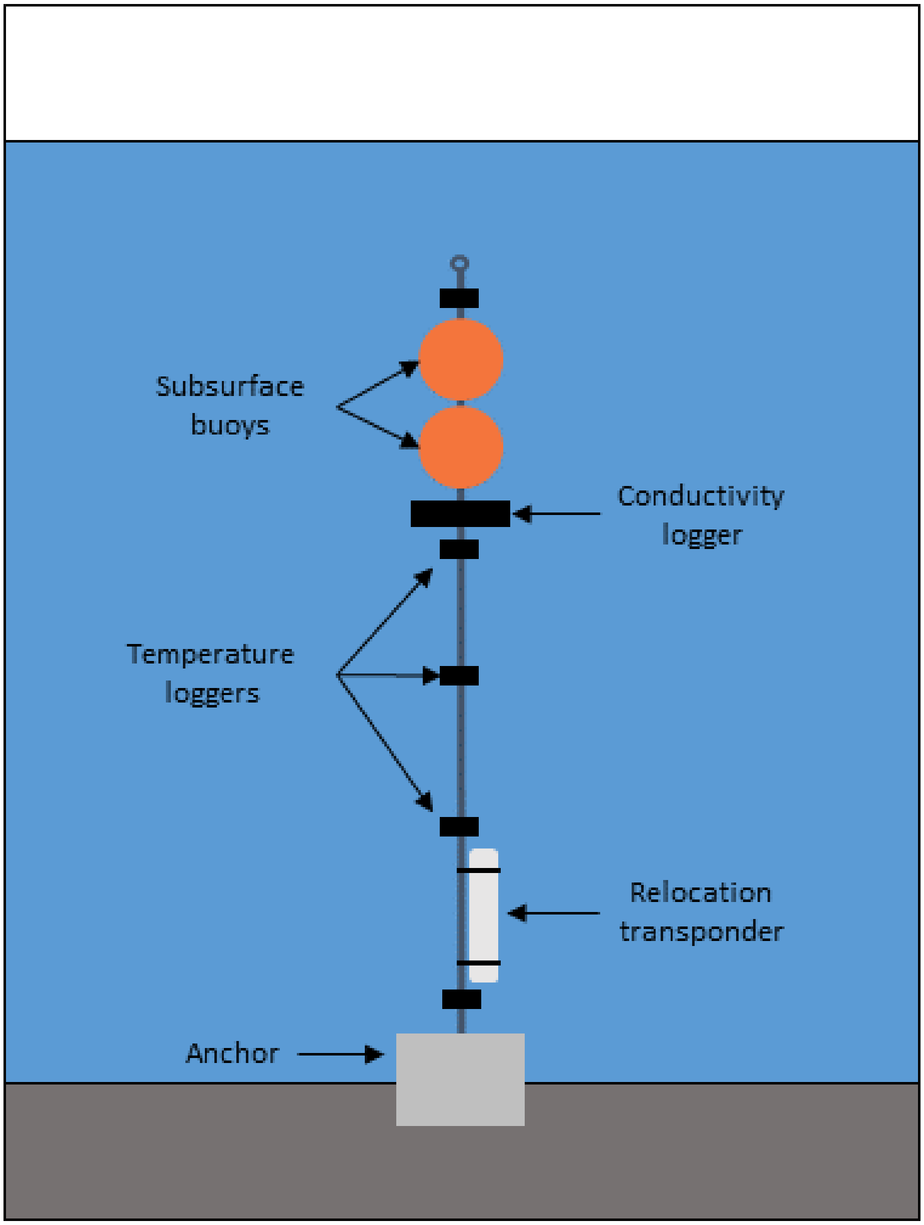


Figure 3-3. Lhù’ààn Mân’ mooring design as seen through the water column. Mooring length is dependent on lake depth at each site. Temperature logger interval is every 1m for the Brooks mooring, and every 5m for the Talbot, Deep, and South moorings.

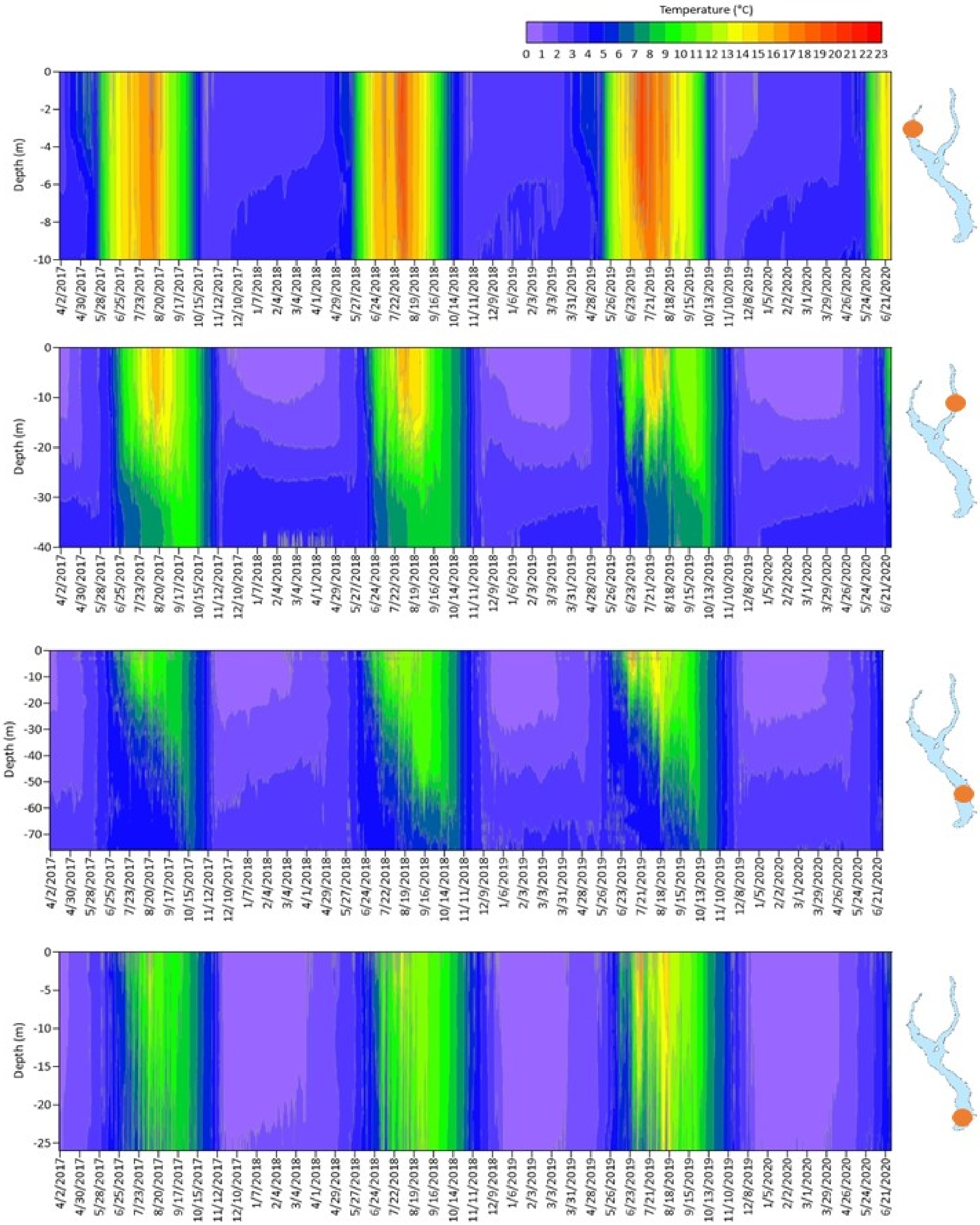


Figure 3-4. Temperature data (°C) from Lhù’ààn Mân’ moorings (identified by inlaid maps), between April 1 2017 and early summer 2020, interpolated to every meter depth using Kriging method in Golden Surfer software. Note different y-axis scales, representing the varying depths at each site. Produced in Golden Surfer software.

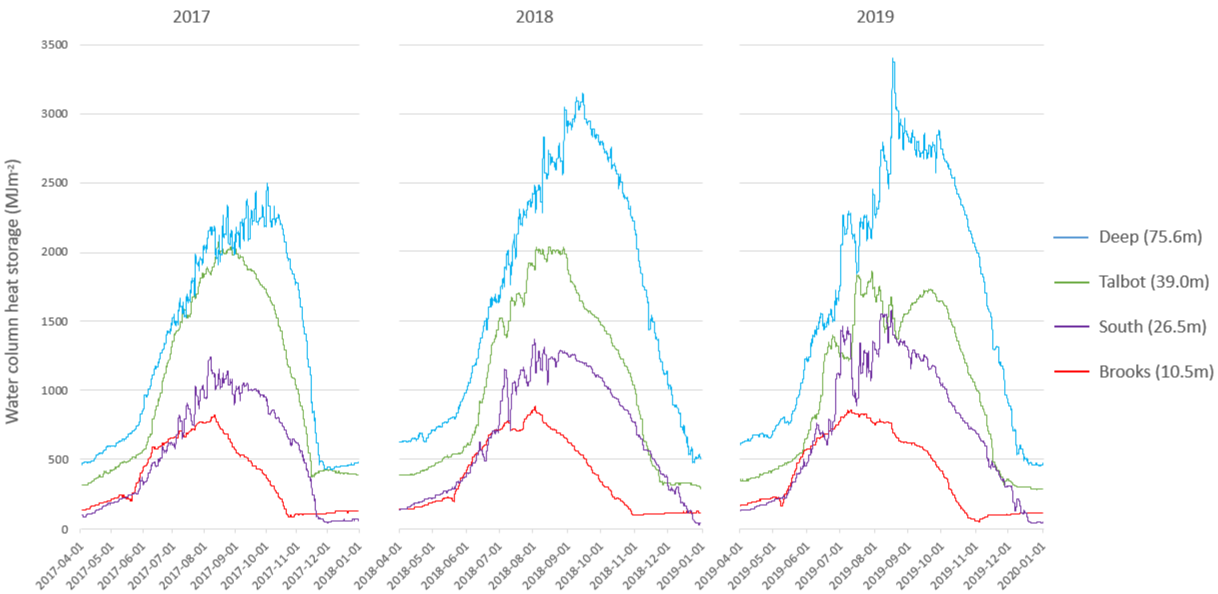


Figure 3-5. Hourly water column heat storage (MJm^{-2}) for each mooring site (each with different depth identified in legend) at Lhù'ààn Mân' between April 1 and December 31 for years 2017, 2018 and 2019.

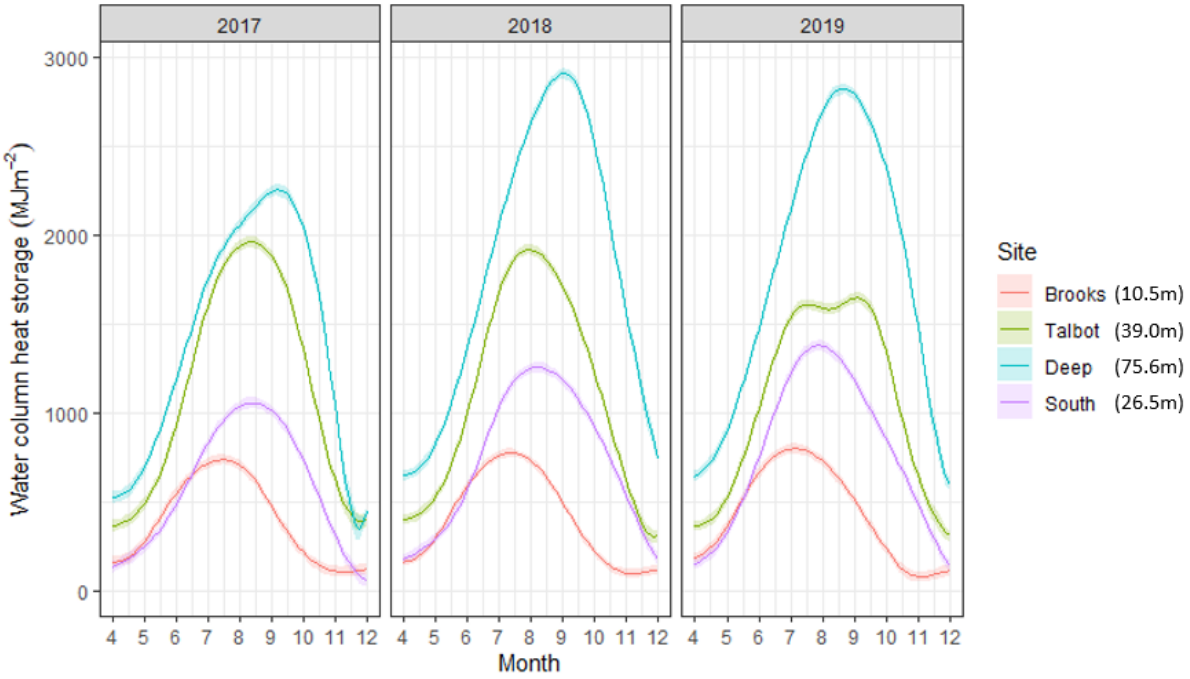


Figure 3-6. Modelled water column heat storage (MJm^{-2}) for each mooring site at Lhù’ààn Mân’ between April 1 and December 31 for years 2017, 2018 and 2019.

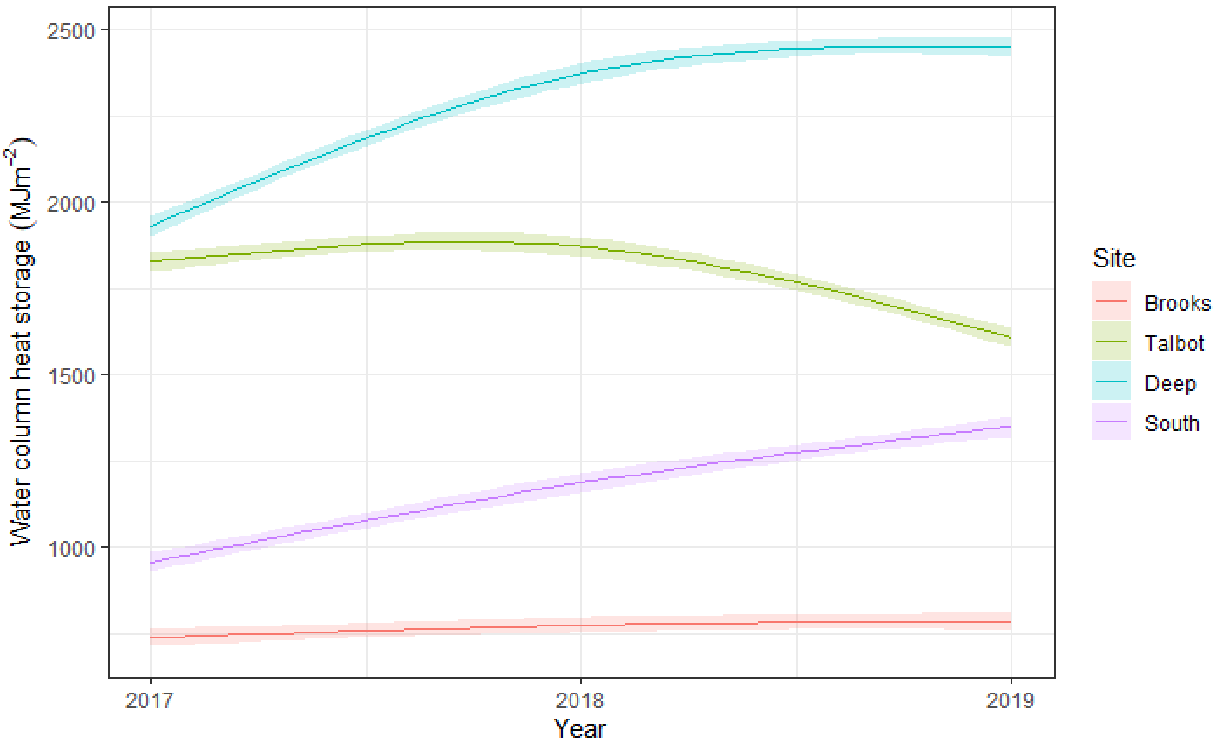


Figure 3-7. Water column heat storage (MJm^{-2}) trend between 2017 and 2019 for each mooring site at Lhù'ààn Mân'.

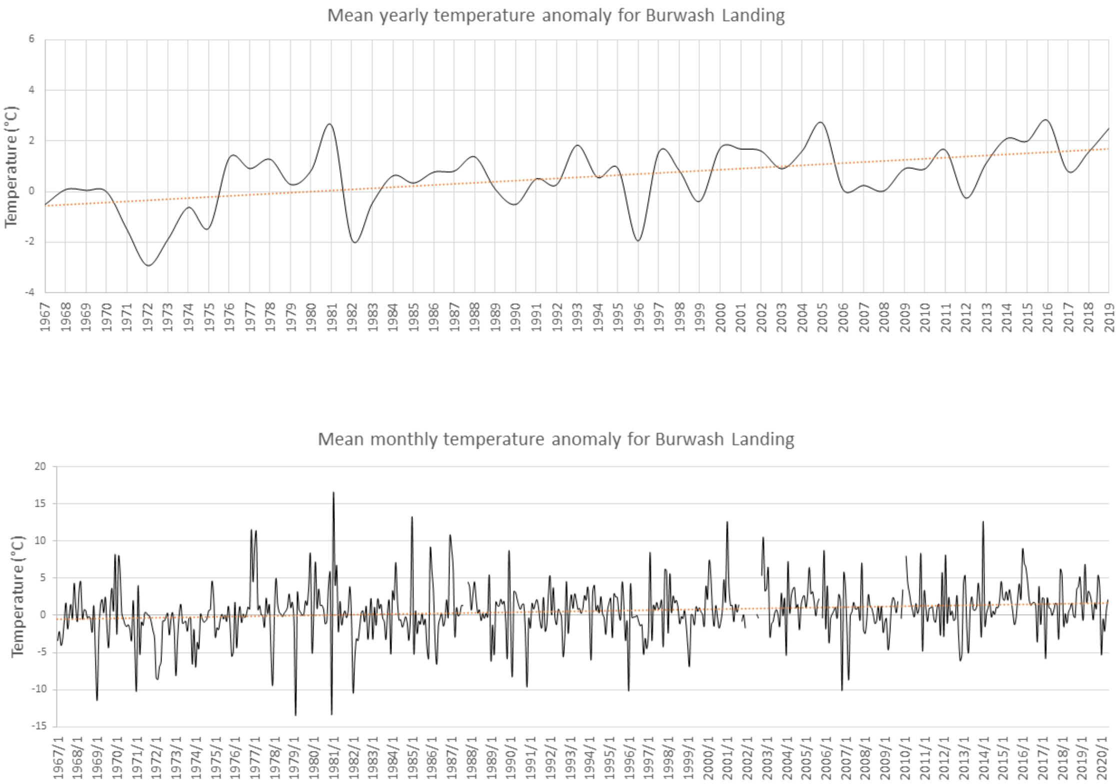


Figure 3-8. Yearly and monthly mean temperature anomalies (based on 1970-1990 mean) from 1967-2020 for Burwash A station, located at 61°22'00.000" N, 139°02'00.000" W, elevation: 806.9m. Data obtained from the Environment an Climate Change Canada Historical Weather Data web site (https://climate.weather.gc.ca/historical_data/search_historic_data_e.html). Red dotted lines represent linear regression slopes.

Figure 3-9. Ice-on dates, ice-off dates, and total days of open water, between 2000 and 2020, for Brooks, Talbot and Deep/South mooring sites at Lhù'ààn Mân'.

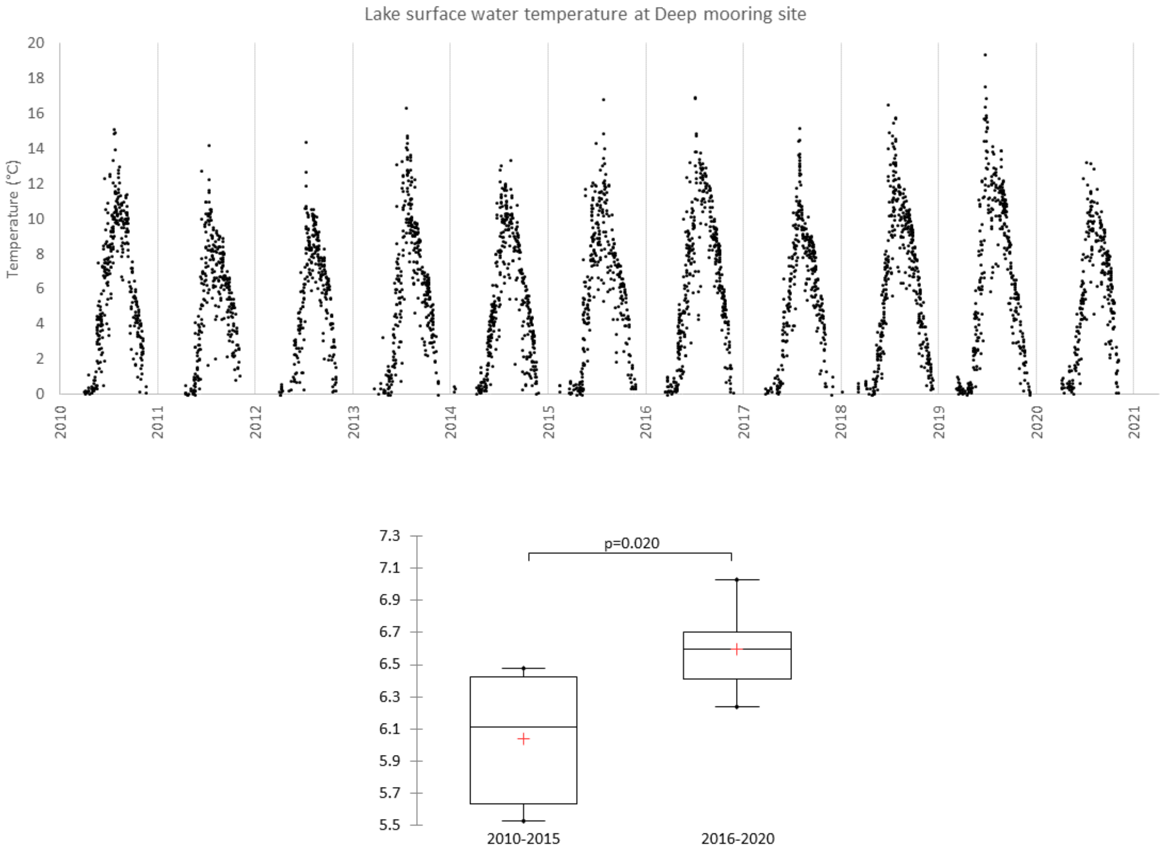


Figure 3-10. (a) MODIS-derived lake surface water temperatures for the Deep mooring site at Lhù’ààn Mân’ between 2010 and 2020; (b) Box plots comparing 2010-2015 (n=5) vs. 2015-2019 (n=4) yearly mean lake surface temperature at the Deep mooring site.

CHAPTER 4 . Analysis of spring ice phenology for ten large lakes in southwest Yukon/northern British Columbia, Canada, between 2000 and 2019

Abstract

Lake ice phenology is a strong climate change indicator and changes in the length of lake ice can have significant impacts on lake ecology. Despite amplified climate change and a large number of lakes in southwestern Yukon and northern British Columbia, an updated lake ice phenology analysis for this area is lacking. Spring lake ice phenology (including the start of break-up (SBU) and end of break-up (EBU) dates) were determined for ten large lakes in southwestern Yukon and northern British Columbia between 2000 and 2019 using MODIS satellite imagery. Mean SBU for all lakes for all years was between day of year (DOY) 125-136, and mean EBU for all lakes for all years was between DOY 141 and 154. Mean length of break-up period was between 9 and 23 days. All lakes exhibited earlier ice break up over time (negative Sen's slopes); four of which had significant trends ($p<0.05$). Mean SBU and EBU of all lakes are becoming earlier at a rate of 0.72 days year^{-1} and 0.46 days year^{-1} respectively, which is comparable to regional and global average spring lake ice phenology trends. Spring ice phenology time series were also compared to the time series of spring 0°C isotherm (i.e., when the 31-day running average of daily air temperature data [obtained from proximal weather stations] reaches 0°C each spring). Air temperature was highly and significantly correlated ($p<0.01$) with SBU for seven of the lakes, and with EBU for nine of the lakes. We encountered challenges specific to identifying ice phenology for large lakes, including long periods of break-up and moving ice pans, which affect the accuracy of phenology dates. We propose a methodology to ensure consistent identification of SBU and EBU in large northern lakes, facilitating accurate comparisons with other studies.

Introduction

Northern watersheds hold approximately 60% of Canada's freshwater (Cott et al. 2016), and most of this is contained within large (400 – 31,000 km^2 surface area) and deep (90 – 415 m) lakes (Reist et al. 2016). These large waterbodies also provide diverse and unique habitats for wildlife and cold adapted fish species; recreational, commercial and subsistence harvesting opportunities for local communities; and act to modulate local microclimates (Brown & Duguay 2010; Long et al. 2007; Prowse et al. 2009; Vincent et al. 2008). As headwaters for many Arctic rivers, large lakes also play an important role in the pan-Arctic hydrological cycle (Prowse et al. 2015).

Rates of warming in the Arctic and sub-Arctic are at least twice those occurring at more southern latitudes (Serreze & Barry 2011; Streicker 2016), with impacts on large northern lakes (Adrian et al. 2009; Carmack et al. 2014; Prowse & Brown 2010). One of the most evident and easily measurable impacts of warming on large lakes is a longer ice-free period (Duguay et al. 2006; Latifovic & Pouliot 2007). Since water absorbs more solar radiation than ice, longer ice-free periods can increase surface water temperatures (O'Reilly et al. 2015) and fundamentally alter mixing and stratification regimes (Woolway & Merchant 2019). These physical changes, in turn, can have pronounced impacts on chemical and biological limnological properties, and subsequent cascading effects at all trophic levels (Bokhorst et al. 2016; Dibike et al. 2011; Prowse & Brown 2010; Prowse et al. 2011; Vincent et al. 2008; Woolway et al. 2020). Lake ice phenology (i.e., the timing of ice formation (freeze-up) and ice break-up), is thus an important indicator for quantifying the effects of climate change on lakes (Brown et al. 2002; Magnuson et al. 2000; Robertson et al. 1992). While freeze-up is most closely tied to lake volume and heat storage capacity, several factors influence spring lake ice phenology, including air temperature, lake morphometry, wind conditions and lake elevation (Brown & Duguay 2010; Jensen et al. 2007; Livingstone et al. 2009; Vavrus et al. 1996; Walsh et al. 1998). However, air temperature has been shown to be the primary driver of ice break-up (Livingstone et al. 2009; Robertson et al. 1992; Schindler et al. 1990; Šmejkalová et al. 2016), and is thus a critical factor for understanding current and future lake ice phenology change.

While lake ice phenology studies are relatively common, few have included the large lakes of southwest Yukon and northern British Columbia, which is surprising given the size of these lakes, their cultural and ecological importance, and the rapid rates of warming and associated impacts being observed in this region (Streicker 2016). To our knowledge there are only two assessments of historical lake ice phenology which include lakes within this region (Kluane and Teslin Lakes). These assessments used in situ observations (1951-2000; Duguay et al. 2006) and Advanced Very High Resolution Radiometer (AVHRR) satellite data (1985-2004; Latifovic & Pouliot 2007). Since baseline and long-term limnological data and monitoring for large lakes of this regions is limited, an updated trend analysis of spring ice phenology is valuable for determining how these lakes may be changing over the last two decades in response to climate change, consequently informing needs for future research priorities and monitoring.

Here, we provide an updated spring ice phenology analysis for ten large lakes in southwestern Yukon and northern British Columbia using imagery from the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor on board the Terra satellite. Recent lake ice phenology studies have been facilitated by the use of MODIS, which can detect and differentiate between snow and snow-free terrain, water, ice and cloud at a 500 m resolution using a daily fractional snow cover product (Arp et al. 2013; Duguay et al. 2015; Kropáček et al. 2013). Our objectives were to: (1) examine spring lake ice phenology trends between 2000-2019 for these ten lakes; (2) determine the relationships between ice break-up trends and air temperatures; and (3) compare 2000-2019 ice break-up trends in our study area with historical regional and global trends; in order to understand the degree of recent change, and understand its relationship with the key driver of air temperature.

Methods

Study area

The terrain of southwestern Yukon and northern British Columbia is dominated by sub-Arctic boreal forest and some of the highest mountains in the northern hemisphere. The area is water- and ice-rich, with an abundance of creeks, rivers, lakes and glaciers, and is underlain by large areas of discontinuous permafrost. Large lakes are abundant in this region and hold significant recreational, cultural and traditional value (Environment Yukon 2011). These large lakes also host large populations of fish including trout, salmon, pike and grayling (Environment Yukon 2010) and represent significant sources of subsistence for local communities.

The lakes analyzed in this study are Aishihik, Atlin, Dezadeash, Kluane, Kusawa, Laberge, Little Salmon, Marsh, Tagish and Teslin. All of these lakes are either entirely within Yukon or cross over the British Columbia border (Figure 4-1). Lakes in this region were initially formed by historical ice advances and retreats, the most recent retreat being that of the Cordilleran Ice Sheet 11 000 years ago (Lindsey et al. 1981). Aishihik and Dezadeash Lakes are part of the Alsek River watershed, which drains towards the Pacific, and the remaining lakes are part of the Yukon River watershed, draining towards the Bering Sea (Scudder 1996; Lindsey et al. 1981). Marsh, Tagish, and Laberge Lakes are influenced by the Lewes and Whitehorse hydrostations and control structures, constructed in 1922 and 1958, respectively. Marsh and Tagish Lakes (and Bennett Lake, which is not included in our study) are all hydrologically connected and located upstream of the control structures which effectively control water storage in these lakes (Yukon Energy 2012). Lake Laberge is located downstream of the stations and also influenced by water storage and controlled flow in the Yukon River. A hydrostation at Aishihik Lake was built in 1975 and a dam at the outlet of Aishihik Lake controls water storage (Yukon Energy 2012).

All of these lakes have a surface area greater than 60 km^2 and meet the guidelines established by Arp et al. (2013), where ice phenology studies using the MODIS Terra gridded snow cover product should only consider lakes that have at least one full grid cell (500 m resolution) located entirely within open water. The lakes in this study all have more than 100 grid cells located completely within open water.

Satellite data

Spring lake ice phenology trends were determined using the MODIS Terra Version 5 gridded snow cover product (MOD10A1), derived from radiance data acquired by MODIS. Fractional snow cover is produced using a regression method that incorporates Normalized Difference Snow Index (NDSI), Normalized Difference Vegetation Index (NDVI) for forested areas, a thermal mask, and a cloud mask to produce daily data at 500m resolution. Each surface type is assigned a value according to MOD10A1, with lake ice represented as fractional snow (0-100) and open water classified as 237 (Table 4-1). Overall accuracy for the MOD10A1 product is 93% (Hall & Riggs 2007). MODIS swath data (vertical tiles 2 and 3, horizontal tile 11) for each spring (days of year 100-190) between 2000 and 2019 were downloaded from the Land Processes Distributed Active Archive Centre (U.S. Geological Survey (USGS) and the National Aeronautics and Space Administration (NASA)). The data were imported into ArcMap 10.6 software and projected to Albers Equal Area Conic projection using the WGS84 datum.

Determining lake ice phenology

The Atlas of Canada National Scale Data (1:5,000,000) Waterbodies shapefile was imported into ArcMap and masked with a 500m negative buffer. Since each MODIS grid cell is 500m, applying this buffer eliminates all shoreline grid cells, ensuring that all analyzed grid cells are located completely within open water. This mask was then applied to the MOD10A1 data, and MOD10A1 values for each grid cell were extracted for the previously mentioned dates. Consistent with Arp et al. (2013), we define the start of break-up (SBU) as the day of year when 10% of the lake surface (i.e., 10% of the grid cells) are categorized as open water, and the end of ice break-up (EBU) as the day of year when 90% of a lake's surface is categorized as open water.

Challenges specific to large lakes

Large lakes pose several problems for determining lake ice phenology. Warm winter or spring temperatures may result in either very saturated ice or pooling of water on ice, which we found can cause the Terra snow cover product to miscategorise grid cells as water. Since water-on-ice events can occur weeks before the start of ice break-up, SBU can therefore be prematurely misclassified. Additionally, ice on large lakes can break-up but continue to move on the lake for several days before completely melting. These windblown ice pans can shift across grid cells several times before eventually melting, also causing SBU to be misinterpreted. To address both of these issues, we began by identifying the first instance of water, and the last instance of ice detected within each cell. If ice was detected less than 10% of the time between these two instances, the cell was categorized as open water on the date of the first detection of water. If ice was detected more than 10% of the time between these two instances, the cell was categorized as open water on the date of the last instance of ice. Using this methodology for all cells, we then define lake SBU as the day when 10% of all lake cells reached open water classification, and

EBU when 90% of these cells were achieved. This analysis was repeated for each year for each lake resulting in a time series for SBU and EBU for each lake between 2000 and 2019.

Since the duration of ice break-up can last several days, the presence of clouds over consecutive days can also obscure exact SBU and EBU dates because MODIS is a passive sensor (Ackerman et al. 2008). However, due to the large size of our study lakes, daytime clouds rarely covered the entire extent of any one lake and not for more than three days at a time. On the rare occasion when clouds obscured either the entire lake surface or specific grid cells for several days during the ice break-up period, we classified cells using the following method: during periods of cloud cover that were less than 3 days, the value from the previous cloud-free day was used in classification. For cloud cover of 3 days or greater, the value from the previous cloud-free day was only used if the value from the next cloud-free day was the same.

SBU and EBU trend analysis

The Mann-Kendall test (non-parametric) and Sen's slope (Kendall, 1975; Mann, 1945; Sen, 1968) were used to determine the presence, direction, magnitude, and significance of trends. These tests are frequently used in hydrological sciences and ice phenology studies (Duguay et al. 2006; Hewitt et al. 2018; Latifovic & Pouliot 2007; Nõges & Nõges 2014). Mann-Kendall is suitable for non-normally distributed data which are common in hydrological time series and the Sen's slope is calculated using the median of the time series to reduce the impact of outliers (Ruan et al 2020). A positive trend is identified by a positive Mann-Kendall Z value, and the statistical significance of the trend is described using a p-value (Duguay et al. 2006). Both the Mann-Kendall and the Sen's tests are non-parametric. Unlike linear regression tests, these methods assume data that are not normally distributed. We tested our data for distribution and confirmed that it was not normally distributed using R statistical software. The 'trend' R package

(Pohlert 2020) was used to find the slope values (Sen's method) and significance (Mann-Kendall test) of trends at the 95% confidence level.

Air temperature

Historical air temperature data were downloaded for select Environment Canada meteorological stations from http://climate.weather.gc.ca/historical_data/search_historic_data_e.html (Table 4-2). Stations were identified based on their proximity to individual lakes, their elevation in comparison to the lake, and the completeness of dataset. All stations were <80km from the lake with which data was compared. A 0ºC isotherm was identified for each station, for each year, defined as the day of year when daily average temperatures rise above 0ºC as calculated from a 31-day running average (Bonsal & Prowse 2003; Duguay et al. 2006). The relationship between ice break-up (both SBU and EBU) and air temperature (using the 0ºC isotherm DOY) was established for each paired lake and meteorological station using the Pearson correlation coefficient (Duguay et al. 2006). The Pearson correlation coefficient assumes linear relationships between variables as well as a normal distribution, and is a common correlation coefficient used in ice phenology studies (e.g., Šmejkalová et al. 2016).

Results and Discussion

SBU and EBU trends for southwest Yukon/northern British Columbia lakes

The 2000-2019 mean SBU for all lakes ranged from DOY 125 to 136, and mean 2000-2019 EBU ranged from 141 to 154 (Table 4-3). Duration of break-up varied between nine and twenty-three days, depending on the lake and year (Figure 4-2). Sen's slopes were negative for all SBU and EBU time series for all lakes, indicating a tendency towards earlier ice break-up dates (Table 4-3). Mean SBU for all lakes was 0.72 days year^{-1} earlier, while mean EBU for all lakes was 0.46 days year^{-1} earlier. Aishihik, Kluane, and Marsh Lakes displayed significantly ($p<0.05$) earlier SBU trends, and Dezadeash and Tagish displayed marginally significant ($0.05<p<0.10$) results. Aishihik, Kluane, and Little Salmon displayed significant ($p<0.05$) earlier EBU trends, and Marsh displayed marginally significant ($0.05<p<0.10$) results. Of note is that three out of the four lakes displaying significantly earlier ice-off trends (i.e., Aishihik, Kluane, and Little Salmon) were located in the northernmost latitudes of our study area. Only one of the lakes that is regulated (Marsh) displayed a significant trend (SBU with $p<0.05$), suggesting that the effect of regulation may reduce the impacts of climatic factors on ice break-up trends. The lack of more than four significant trends is most likely explained by the short time series (<30 years) available for this study (Latifovic & Pouliot 2007; Šmejkalová et al. 2016).

The winter of 2015-2016 was anomalously warm in southwest Yukon/northern British Columbia, resulting in a very early and mild spring and for the first time in available historical records, a lack of complete ice cover on Atlin Lake. While the lake did not completely freeze, our analysis showed that ice pans did form and move on the lake throughout the end of winter and early spring, allowing us to still identify an EBU date (Figure 4-2). However, we note that our methods using 100-190 DOY as the analysis period for spring lake ice break-up would not be adequate for identifying the instance when a lake might not freeze at all. As air temperatures continue to rise and early springs occur more regularly, instances where lakes do not freeze over and earlier dates of break-up will become more frequent, and trend analyses will have to extend observation dates accordingly.

While Atlin Lake not freezing over during the winter of 2015-2016 was an anomaly, ice phenology shifts of this magnitude are being observed in other northern lakes (Lopez et al. 2019). Particularly, some lakes at higher latitudes, which typically exhibit either no, or only partial, ice break-up during the short summer period are now experiencing partial break-up and/or longer ice-free periods, allowing for mixing and/or more developed stratification of the water column (Bégin et al. 2021; Lehnherr et al. 2018). The physicochemical and ecological impacts of lakes transitioning from having full winter ice coverage, to partial or no winter ice coverage, are significant, and include changes in oxygen, chlorophyll, turbidity and temperature (Bégin et al. 2021) leading to shifts in the physiology and behavior of fish (Shuter et al. 2012).

The influence of air temperature on ice break-up

Nearly all Pearson correlation coefficients comparing SBU and EBU with 0ºC isotherms were significant (<0.01). Only Aishihik Lake (SBU and EBU), and Dezadeash and Kluane Lakes (SBU only) were not significantly correlated to air temperature (Table 4-4). Significant Pearson correlation coefficients for SBU ranged from 0.68 to 0.83 ($p<0.09$), and from 0.60 to 0.78 for EBU ($p<0.02$). These findings align with those of other studies that have confirmed air temperature as a key predictor of ice break up. Due to lack of data records, the impact of other climatic variables such as precipitation and snow cover on lake ice phenology in southwest Yukon/northern British Columbia could not be determined. While also secondary to the impact of air temperature (Jakkila et al. 2009), the impact of cloud cover on lake ice phenology of this area could be investigated in future studies using satellite imagery. The high correlation between air temperature and spring lake ice phenology is valuable for estimating future conditions, as future warming air temperatures are very likely to correspond with earlier ice break-up trends. Any rates of change in air temperature increases could also indicate rates of change in spring lake ice phenology.

Comparing historical spring ice phenology trends for Kluane and Teslin lakes

Latifovic & Pouliot (2007) used AVHRR and *in situ* observations, and Mann-

Kendall/Sen's statistical tests, to determine the ice phenology trends of select Canadian lakes between 1970 and 2004, including Kluane and Teslin Lakes. We have compared our results with theirs (Table 4-5) even though there are differences in the data used for analysis (e.g. AVHRR vs MODIS), and the period of record. The Mann-Kendall Z values and Sen's slopes for Kluane and Teslin Lakes determined in both Latifovic & Pouliot (2007) and here, were negative. In Latifovic & Pouliot (2007), only Teslin was significant at the 90% confidence level. Here, we report a significant (at the 95% confidence level) trend towards earlier ice break-up for Kluane Lake only, with Teslin lake showing marginal trends for SBU (EBU) of p=0.13 (p=0.11) only. These findings could suggest that the trend rate of ice break-up at Kluane may be increasing in recent years. However, comparing trends which use different data collection methods (*in situ*, AVHRR, and MODIS) should be done cautiously, as results may differ significantly due simply to the resolution of data collection method.

Comparing Canadian and global lake ice phenology trends

To examine whether our rates of earlier ice break-up were comparable to Canadian and global trends, we compared our results with other studies. Duguay et al. (2006) used *in situ* data from the Canadian Ice Database to analyze ice phenology of Canadian lakes between 1951 and 2000. Most lakes (>75%) in this study exhibited trends towards earlier break-up dates, several of which were significant at the 90 % confidence level, with western Canada showing the most consistent trends towards earlier break-up dates. Latifovic & Pouliot (2007) had similar results, with thirty-one of the thirty-six Canadian lakes in their study exhibiting a trend toward earlier break-up (0.23 days year^{-1}) between 1970 and 2004, eight of these statistically significant at the 90% confidence level, analyzed using *in situ* and AVHRR data. The six far northern lakes (primarily on the Canadian Archipelago) in their study also showed trends towards earlier break up (0.99 days year^{-1}), but only one was significant at the 90% confidence level. Jensen et al. (2007) found that a suite of lakes in southern Ontario and northern USA were breaking up earlier (0.21 days year^{-1}) between 1975 and 2004, also using *in situ* data records.

Benson et al. (2012) analyzed seventy-five Northern Hemisphere lakes using data from the National Snow and Ice Data Center and found these lakes to be breaking up earlier at 0.03-0.07 days year^{-1} between ~1900 and 2005, but 0.16-0.43 days year^{-1} between 1975 and 2005. Weyhenmeyer et al. (2005) found that southern latitude Swedish lakes displayed a trend of earlier break at a rate of 0.92 days year^{-1} (vs. 0.25 days year^{-1} for Arctic lakes) between 1961 and 1990. Šmejkalová et al. (2016) analyzed lakes across the circumpolar Arctic which exhibited rates of earlier SBU ranging from 0.10 to 1.05 days year^{-1}, and rates of earlier SBU ranging from 0.14 to 0.72 days year^{-1}. Our mean lake ice break-up trends and rates for ten large lakes in southwest Yukon/northeast British Columbia (i.e., SBU occurring earlier at a rate of 0.72 days year^{-1} and EBU occurring earlier at a rate of 0.46 days year^{-1}) are within the range of both Canadian and global spring lake ice phenology trend rates.

Significance

For the large lakes of southwestern Yukon and northern British Columbia, earlier ice break-up trends will lengthen periods of open-water, resulting in a shift towards earlier and stratification of the water column, particularly in the deeper lakes where stratification is stronger. Earlier stratification could lead to an increase in maximum surface temperatures (Austin & Colman 2007) and increased column stability, resulting in less mixing between epilimnetic and hypolimnetic waters, limiting oxygen replenishment at depth and nutrient resupply to surface waters. These changes could affect the quantity of nutrients and amount of primary production near the surface (Yankova et al. 2017), as well as habitat availability for fish requiring cold, well oxygenated hypolimetic waters (Kraemer et al. 2015). In shallower lakes such as Dezadeash Lake, or shallow parts of lakes such as the northwestern arm of Kluane Lake, the water column currently warms to bottom instead of stratifying (Chapter 2). Thus, longer open-water seasons could result in warmer temperatures throughout the water column, and severely limit habitat for certain fish species (Chapter 2; Mackenzie-Grieve & Post 2006).

Since earlier lake ice break-up can ultimately lead to ecosystem-scale consequences, monitoring ice phenology trends is critical for understanding how these large lake ecosystems may be changing, and is required for taking appropriate adaptation, mitigation and conservation measures. Because changes in lake ice phenology are directly associated to changes in lake water physicochemical properties, earlier break-up trends also reinforce the need for consistent and rigorous monitoring of both baseline and long-term changes of the physical, chemical, and biological properties of lakes.

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Tables

Table 4-1. MODIS Terra Snow Cover product (MOD10A1) values for determining surface topography of each grid cell, reproduced from the National Snow and Ice Data Centre (Hall et al. 2006).

Fractional snow cover field coded integer values	
Value	**Description**
0-100	fractional snow
200	missing data
201	no decision
211	night
225	land
237	inland water
239	ocean
250	cloud
254	detector saturated
255	fill

Table 4-2. Lake names/elevations, and corresponding meteorological station names/elevations used to determine air temperature correlation with lake ice break-up phenology (elevations of lakes from Lindsey et al. 1981).

Lake	Lake elevation (m)	Environment Canada Meteorological station name	Distance from lake (km)	Elevation of station (m)	Location of station (decimal degrees)
Aishihik	915	Haines Junction	79	596	60.773º;-137.580º
Atlin	668	Atlin	0	673	59.567º;-133.700º
Dezadeash	702	Haines Junction	42	596	60.773º;-137.580º
Kluane	781	Burwash Landing	0	806	61.367º;-139.050º
Kusawa	671	Whitehorse A	79	706	60.000º;-136.767º
Laberge	628	Whitehorse A	50	706	60.710º;-135.069º
Little Salmon	608	Carmacks	80	543	60.710º,-135.069º
		Faro	65	716	62.210º,-133.380º
Marsh	656	Whitehorse A	49	706	60.710º;-135.069º
Tagish	656	Atlin	38	673	59.567º;-133.700º
Teslin	683	Teslin	0	705	60.167º;-132.733º

Table 4-3. Name, location, surface area and depth of each lake, followed by spring ice phenology trend statistics (including Mann-Kendall Z factors and p-values, and Sens slopes of start and end of break up trends), mean day of year of SBU and EBU, and mean length or duration of ice break-up period for each lake. Bolded values indicate significant trends towards earlier ice break-up (p<0.05). SBU and EBU are defined as the start of break-up and end of break-up, respectively (further details in-text). NA=data not available.

Lake	Location (decimal degrees)	Surface area (km^2)	Depth (m) (mean/max)	Mann-Kendall Z factor (SBU /EBU)	Mann-Kendall p value (SBU /EBU)	Sens slope (SBU /EBU)	Mean day of year SBU±SE	Mean day of year EBU±SE	Mean length of break-up±SE
Aishihik	61.509° -137.277°	140	30/120	-2.83/-2.15	**0.01/0.03**	-1.03/-0.56	136±2.7	154±1.5	18±1.8
Atlin	59.602° -133.777°	791	86/289	-0.91/-1.50	0.36/0.13	-0.65/-0.52	127±3.1	141±2.2	15±1.6
Dezadeash	60.478° -136.98°	80	4.1/6.0	-1.72/-0.75	0.09/0.45	-0.85/-0.29	134±2.8	143±1.9	9±1.6
Kluane	61.302° -138.774°	411	31/91	-2.05/-2.45	**0.04/0.01**	-1.00/-0.63	136±2.6	151±1.8	15±1.6
Kusawa	60.369° -136.334°	140	54/140	-0.62/-0.94	0.54/0.35	-0.41/-0.33	125±2.7	148±1.8	23±1.8
Laberge	61.190° -135.215°	201	54/146	-0.88-1.43	0.38/0.15	-0.48/-0.46	125±2.7	144±1.6	19±1.8
Little Salmon	62.188° -134.718°	63	NA/140	-1.27/-2.25	0.20/**0.02**	-0.55/-0.50	129±2.9	147±1.4	18±2.3
Marsh	60.181° -137.112°	94	13/50	-2.05/-1.72	**0.04/**0.08	-0.89/-0.52	128± 2.7	145±1.8	17±1.6
Tagish	59.848° -134.287°	349	-/300	-1.79/-1.34	0.07/0.17	-0.73/-0.46	126±2.5	143±2.4	17±1.6
Teslin	60.098° -132.635°	354	59/214	-1.53/-1.60	0.13/0.11	-0.59/-0.37	129±2.5	145±1.6	16±1.4

Table 4-4. Pearson correlation coefficient and p-values (bolded if significant at <0.05) between the 2000-2019 SBU (start of break up)/EBU (end of break up) of each lake and air temperature (0ºC isotherm calculated using a 31-day running average from nearby meteorological stations as identified in Table 4-2).

Lake	Pearson correlation coefficient (and p value) comparing 0ºC and SBU	Pearson correlation coefficient (and p value) comparing 0ºC and EBU
Aishihik	0.39(0.08)	**0.50(0.02)**
Atlin	**0.75(<0.01)**	**0.75(<0.01)**
Dezadeash	0.40(0.08)	**0.60(<0.01)**
Kluane	0.39(0.09)	**0.73(<0.01)**
Kusawa	**0.68(<0.01)**	**0.74(<0.01)**
Laberge	**0.80(<0.01)**	**0.66(<0.01)**
Little Salmon (Carmacks)	**0.81(<0.01)**	**0.61(<0.01)**
Little Salmon (Faro)	**0.78(<0.01)**	**0.61(<0.01)**
Marsh	**0.81(<0.01)**	**0.64(<0.01)**
Teslin	**0.83(<0.01)**	**0.69(<0.01)**
Tagish	**0.79(<0.01)**	**0.78(<0.01)**

Table 4-5. Mann-Kendall Z values and Sens slopes for Kluane and Teslin lakes from Latifovic & Pouliot (2007) and this study. Bolded values are significant at $p<0.05$.

Lake	Latifovic & Pouliot (1970-2004) AVHRR & in situ Z value	Latifovic & Pouliot (1970-2004) AVHRR & in situ Slope	McKnight et al. (Chapter 2) (2000-2019) MODIS Z value (SBU/EBU)	McKnight et al. (Chapter 2) (2000-2019) MODIS Slope (SBU/EBU)
Kluane	-1.440	-0.267	**-2.05/-2.45**	**-1.00/-0.63**
Teslin	**-1.807**	**-0.333**	-1.5/-1.60	-0.59/-0.37

Figures

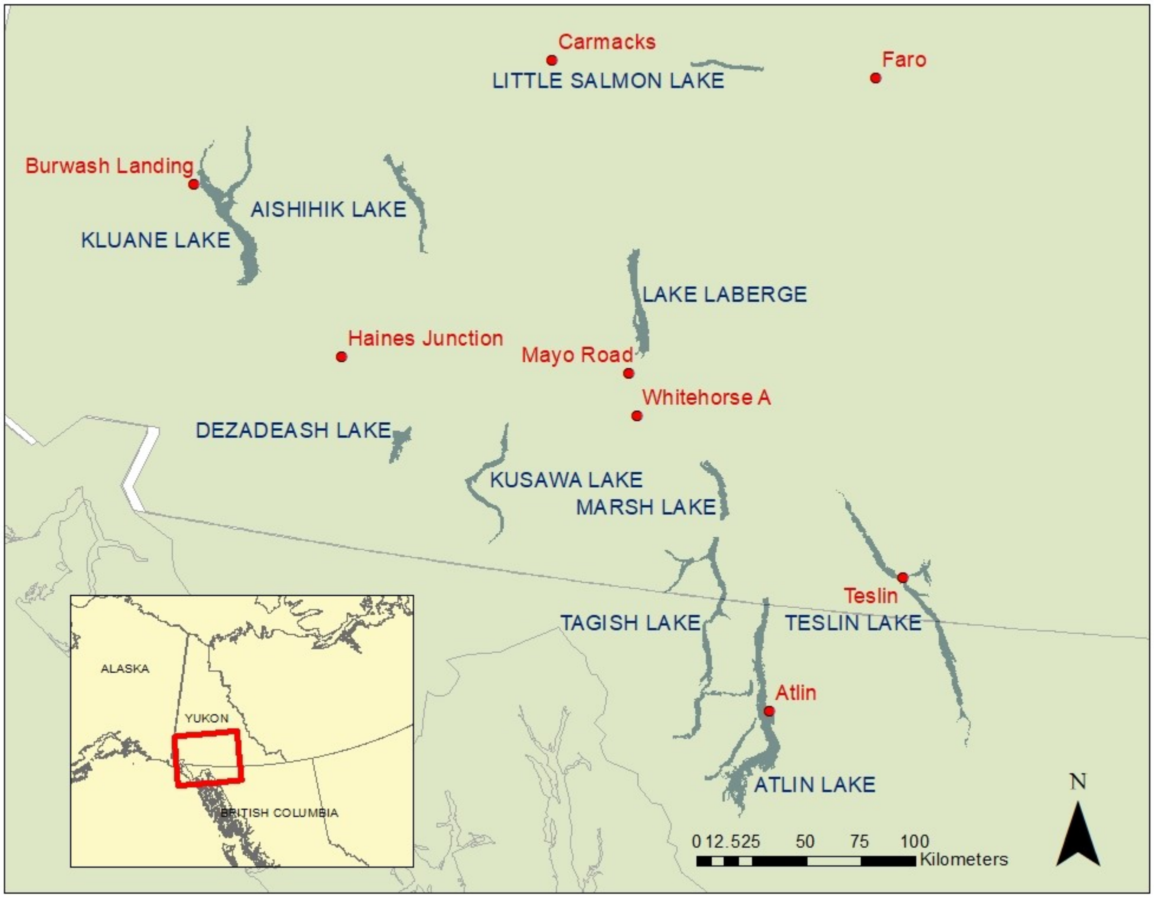

Figure 4-1. Names and locations of lakes analyzed for spring ice phenology (blue) and paired Environment Canada meteorological stations (red) from which historical air temperature records were retrieved and compared with ice break-up dates.

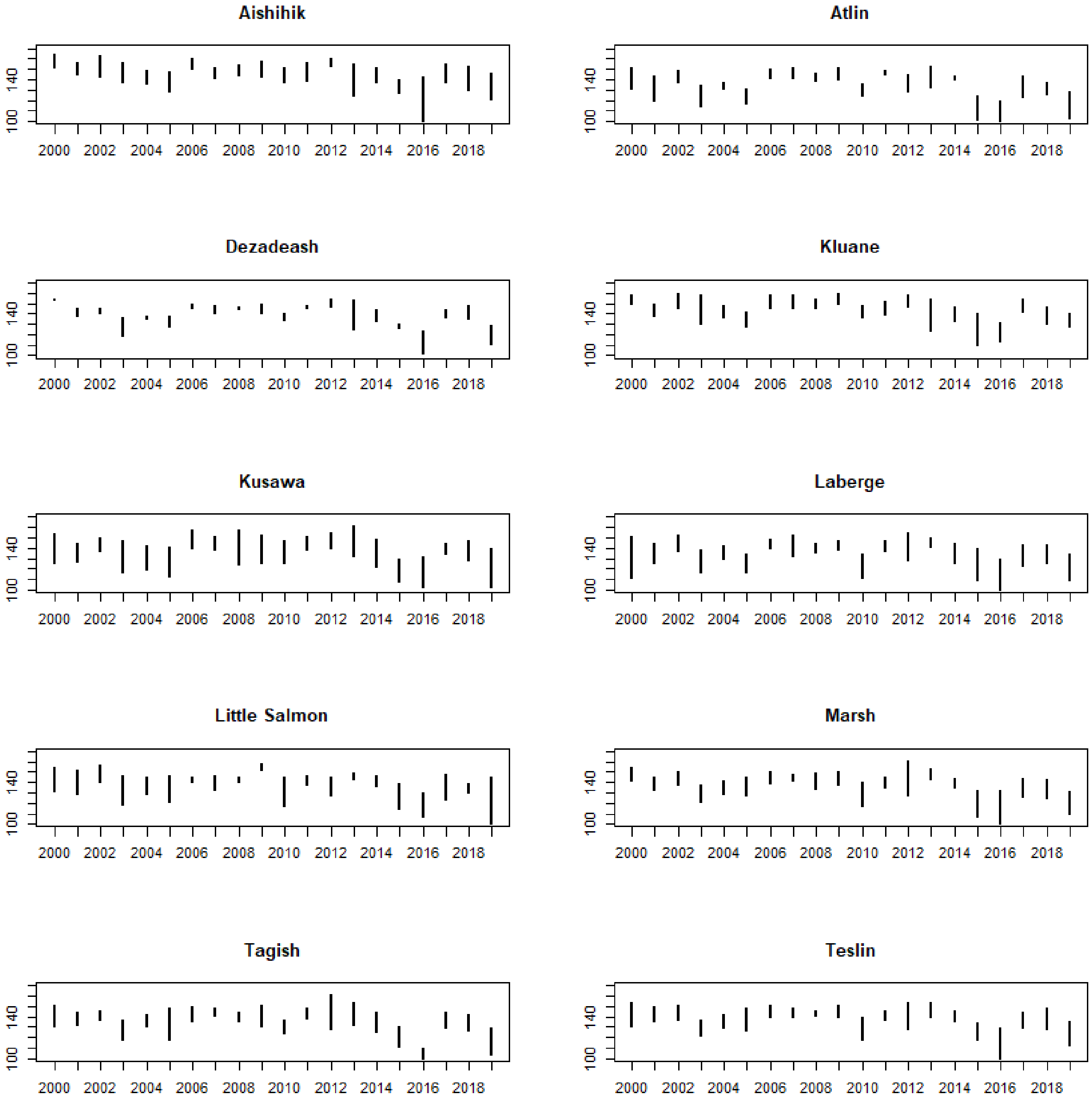

Figure 4-2. Start of break-up (SBU) and end of break-up (EBU) dates (y axis is in DOY of days of year) for each year, for each lake, between 2000 and 2019. The lower limit of each vertical dash in each plot indicates SBU, the upper limit indicates EBU, and the duration of ice break-up is indicated by the length of the line.

CHAPTER 5 . Identifying challenges to – and recommendations for – reconciliation in (northern) environmental science research

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Abstract

Awareness surrounding the need for reconciliation in environmental science research is increasing, as are expectations to practice reconciliation within this field. However, there remains a general lack of knowledge among – and guidance for – researchers with regards to how to "do research in a good way". Respectful and sensitive reflection is critical to identifying both existing challenges and constructive strategies for moving forward. Here, challenges to, and recommendations for, reconciliation in environmental science research (with a focus on northern environments) are explored based on personal experience, reflection and observations. The challenges to reconciliation include: environmental science being perceived as less relevant to reconciliation because it does not directly involve people as subjects; lack of understanding of Indigenous ways of knowing, being, and doing among environmental scientists; emphasis on quantitative results and publications as indicators of success as opposed to qualitative processes such as relationship building; continued permeation of colonial approaches and western science bias particularly in the environmental science field of academia; and lack of knowledge, education and experience among environmental scientists regarding how to respect and bring together different worldviews. Recommendations are founded on respect, creativity, and patience and include education and equality of Indigenous ways of knowing, being, and doing; fostering structural change within the western science academic agenda to prioritize relationships, flexibility, and support for reconciliation; and increased emphasis on environmental scientists identifying and holding awareness of individual bias.

Introduction

Northern lands and waters are rapidly changing due to climate change-induced Arctic amplification, with significant impacts on communities, flora and fauna, and infrastructure (Box et al. 2019; Serreze & Barry 2011). Understanding how these systems are changing and how we interact with them is key to adaptation, mitigation, survival, and well-being (Vincent 2020, Arctic Council 2016). Indigenous peoples and ways of knowing, being, and doing have guided populations' understanding of — and interaction with — existing and changing lands and waters prior to the arrival of settlers in Canada in the 1800s (Castillo et al. 2020). Following contact with European settlers, Western worldviews and science subsequently collided with Indigenous ways of knowing, being, and doing for the first time, and settlers used and imposed western worldviews to document, study, and colonize the country's political, social, economic, educational, historical, and environmental spheres (Bocking 2005; Castillo et al. 2020). Consequently, the primary education and governing systems in Canada became rooted in western worldviews and science (Aikenhead 2006; Marker 2004). However, in the last several decades, many actions have contributed to increased awareness, and clearer expectations and responsibilities, for all non-Indigenous Canadians (including researchers) towards reconciliation with Indigenous peoples, These include the globalization of human rights, the adoption the United Declaration on the Rights of Indigenous Peoples (UNDRIP), the creation of the First Nations principles of Ownership Control Access and Possession (OCAP), Indigenous self-governing agreements and land claim settlements in (northern) Canada, the closure of residential schools and the exposure of First Nations history and colonization in Canada, and the work of the Truth and Reconciliation Commission of Canada.

Environmental science[6] in northern Canada has traditionally been driven by Western knowledge approaches, and characterized by southern researchers travelling to northern environments to conduct research based on questions/interests largely originating outside of the North. Environmental science research has often been characterized as “helicopter research”, defined as research conducted by non-northerners who may travel quickly through communities to reach field sites, work on a project using scientific methodology with little or no relevance to local communities, and leave with limited interaction/communication with local communities contributing to damaging and negative relationships between researchers and communities (Gearhead & Shirley 2007; Korsmo & Graham 2002; Minasny et al. 2020; Peltier 2018). More recently, however, there has been a growing recognition of the need to end this approach and shift towards reconciliatory practices and research involving both science and Indigenous ways of knowing, being and doing, with a focus on prioritizing trusting and respective relationships, working with and for communities, supporting and encouraging Indigenous research methodologies, and executing clear two-way communication (Adams et al. 2014; Bocking 2005; Bocking 2011; Johnson et al. 2015; Kouril et al. 2015; Pfeifer 2018). This is evidenced by a growing body of written work on the topic, including entire journal special issues dedicated to the topic (e.g., Northern Public Affairs July 2018; Arctic Science September 2020; The International Indigenous Policy Journal Special Issue on Reconciling Research 2017 (Wingert & White 2017)), the dedication of new monetary resources (e.g., Canada’s Indigenous Research Capacity and Reconciliation Connection Grants (2019)), and increasing value and respect for

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[6] Environmental science is defined as science which integrates physical, biological, natural (combined biological and physical sciences) and information (mathematics and logistics) science to study the environment, including how it is impacted by climate change. See definitions in Table 5-1 for more information.

Indigenous ways of knowing, being, and doing both inside and outside of academia (Wong et al. 2020).

Despite the shift in approaches described above, the increasing number of projects and researchers that are "doing research in a good way", and the many good examples of reconciliation within environmental science, the ideas, conversations, and actions surrounding reconciliation in environmental science research are relatively new and still developing (Brunet et al. 2014a; Castleden et al. 2016; Mantifel 2020; Wong et al. 2020). Generally, reconciliation remains under-discussed in the environmental sciences and often sits as the elephant in the room as researchers explore how to move towards reconciliation within existing academic structures. Yet the importance of reconciliation within this field is only increasing: in addition to the self-explanatory need for reconciliation, as impacts of climate change on people and the environment intensify and result in an increase of knowledge production (Ford et al. 2012) more frequent interactions between ways of knowing are likely to occur.

The intent of this manuscript is to provide a much-needed space to foster continued reflection and conversation about reconciliation as it applies to (northern) environmental science research, including recognizing individual bias. To do this, I first identify and discuss current challenges to reconciliation within the field of environmental science based largely on personal experiences. I then provide some general recommendations as a response to these challenges. It is my hope that both space for respectful discussion about the topic, and the outlined recommendations, may contribute to the development of approaches and strategies that will advance reconciliation in environmental science research.

Positionality and background

This manuscript and the ideas it contains stem from a decade of working as a non-Indigenous, settler environmental scientist in the roles of research assistant and graduate student in northern environments in Yukon, Alaska and Greenland, often living and working in the sometimes dichotomous space between the academic research community and small Indigenous communities. With an education and upbringing rooted in western society and science, I recognize that I inherently hold a personal bias in ways of thinking, analyzing, and understanding, and that my understanding of Indigenous ways of knowing, being and doing is limited but growing, and impacted by my past.

The challenges and recommendations in this manuscript have been identified as a result of my direct observations, conversations, and experiences within both academic and community environments including gatherings with academic peers, community events and presentations, my time living in the North for the duration of my graduate degree, and time spent with northerners (Indigenous and non-Indigenous) both within and outside of the context of research. Although this manuscript stems from my experience as a northern environmental scientist primarily working out of Yukon, the concepts and ideas herein likely also hold relevance to researchers in other realms of science and social science, and across northern environments.

By identifying and discussing these challenges, as well as strategies and recommendations for moving forward, it is my hope that researchers can foster awareness and action towards reconciliation within their field of study. It is important to note that while I believe identifying issues and strategies for reconciliation within research can foster positive change, this is not a stand alone solution. The work of reconciliation is deep and complex and while doing research in a way that respects reconciliation needs is critical, it is but one small piece. I have taken care to present and discuss the ideas herein in a way that does not support the colonization of the reconciliation process. As such, this chapter is not intended to serve as a how-to guide, but rather as a space for respectful conversation, growth and idea sharing as we navigate a path forward. The challenges and recommendations identified are not listed in an order of importance, but are generally presented from most to less common and/or large to small scale.

Many important terms used throughout this paper merit definition often absent in the literature in order to elucidate their connotation within the context of which they are being described. To enable a clear understanding of the challenges and recommendations outlined in this manuscript, detailed definitions of each of these terms are presented in Table 5-1. Additionally, although this paper specifically refers to environmental scientists, I believe many of the concepts apply to other scientific researchers.

Current challenges for reconciliation in environmental science research

Challenge 1: There remains a perception held in the environmental sciences that since environmental science typically does not directly involve people as subjects, it is less relevant to reconciliation.

While it is important to note that this perception is not held by all environmental scientists, it is a perception that is encountered in this field and cannot be dismissed. The origins and nuances of this perception are complex. Primary contributing factors include the historical lack of ethical obligations for research that does not include people, a general lack of education, training, requirements and resources for reconciliation specific to environmental scientists, and the inherent existence of projects within this field that aren’t necessarily local priorities. These factors are explored in further detail below.

To better understand how the perception that environmental science is less relevant to reconciliation relates to ethical reviews, a review of historical and current ethical requirements within the Canadian research sphere is needed. Currently in Canada, research projects "involving Indigenous peoples" are subject to federal and academic ethical expectations and regulatory processes including ethics reviews, permits, and training (for example, the Tri-Council Policy of Ethical Conduct for Research Involving Humans 2nd edition (TCPS-2)). These processes are intended to ensure ethical conduct and clarify use and ownership of data, as well as roles and responsibilities. The definition of "involving" [Indigenous peoples] is absent from the TCPS-2, leaving room for interpretation with regards to which projects require an ethics review. In my experience, the word "involving Indigenous people" has been widely interpreted as "Indigenous people as subjects in research". As a result, research about climate, landscapes, water and animals (i.e., environmental sciences not directly involving people as subjects) is almost never subject to academic ethical scrutiny and review (Baker et al. 2019; Bozhkov et al. 2020; David-Chavez et al. 2019; Kershaw et al. 2014), despite occurring on Indigenous lands and often resulting in some level of interaction with Indigenous communities.

When I began graduate school, working with local First Nation communities was a personal priority, and my thesis subject was determined by combining both my, and the local community's, interests. Despite my thesis topic focusing on the impacts of climate change on the thermal dynamics of a large northern lake, I would be collaborating and interacting regularly and substantially with the local community throughout my degree. I questioned whether I should submit an ethics review via my university, knowing that the TCPS-2 required ethics submissions for any research involving First Nations, Inuit, and Metis peoples of Canada. In my context, although Indigenous peoples were not the topic of my thesis, they were inherently "involved" as co-creators and on-going collaborators of the research. However, the possibility of needing to submit an ethics review to my institution was not brought up by my department, my supervisor or my committee, nor was it mentioned in any of my graduate courses. Conversations with peers led me to conclude that the TCPS-2 requirements were generally understood to be applicable only when First Nations, Inuit, or Metis peoples were the subjects of the research, as opposed to partners in research, leaving most science-focused projects out of the ethics review process. In conclusion, while I was personally committed to ethical and respectful relationships with the community members I worked closely with over the course of my PhD, I did not submit an ethics review to my institution for my PhD project, despite my relationship and continuous communication with First Nation communities.

In 2017, the Canadian Research Coordinating Committee brought together Canada's Tri-council granting agencies to reaffirm their commitments to the Truth and Reconciliation Commission of Canada's Calls to Action, resulting in a document (Setting New Directions 2019) which states that "research by and/or with Indigenous peoples, in their communities and on their lands" applies to and requires ethical conduct of research as well as to the Truth and Reconciliation Commission's principles and Calls to Action. This is some of the first federal/academic recognition and documentation where the subtle language choice of "research in/on Indigenous lands" as opposed to "research involving Indigenous peoples" confirms the inclusion of environmental scientists' responsibilities to reconciliation. However, this effort did not result in wording changes within the TCPS-2, and still leaves "research in/on Indigenous lands" without a designated ethical review process, despite the CRCC's statement requiring ethical conduct. Aside from federal/academic institution ethics requirements, many local governments, communities, councils, and groups in Canada have or are developing their own ethical review processes, which may or may not apply to environmental science researchers working "in/on Indigenous lands". Most of these are voluntary (i.e., guidelines) though some may be mandated or required.

Despite these efforts, the general lack of ethical obligations in environmental science research continues to be prominent and contributes to the perception that reconciliatory/ethical conduct may not be as relevant in this field. However, an important note to make here is that while ethics reviews acknowledge the sensitivity of connections between humans (thus encouraging — and sometimes enforcing — ethical reflection, planning, and action), undertaking a more formalized ethics review doesn't necessarily equate reconciliation and present a solution. In fact, some even argue that western academic ethics processes actually inhibit reconciliation because of the western institution and structure under which they operate (Glass & Kaufert 2007). However, the existence or lack of ethical review processes can impact perceptions and action as it relates to reconciliation, since reconciliation necessarily involves ethical reflection and moral conduct. Whether a formal ethics process for the environmental sciences is the right way forward is debatable and could be the subject of many theses in and of itself (e.g., Is reconciliatory action within this field most likely to be undertaken when an ethics review is required? Are there other ways to encourage ethical reconciliatory conduct?). The point here is simply to note that the existing ethics review landscape, which focuses on research with humans, prioritizes ethical conduct of research with humans over research involving the environment and therefore can contribute to the perception that the environmental sciences are less relevant to reconciliation.

The lack of ethical obligations within environmental sciences also implies that non-human components of the environment hold less importance than human components, effectively failing to recognize and support relationality[7] (Darling et al. 2020) and also fuelling the perception that reconciliation is less relevant to environmental science. In part to address some of these issues, some permitting and ethics processes in Yukon and other northern jurisdictions are considering using an Indigenous approach which supports and/or requires ethical considerations of land, water, and animals in addition to humans (Darling et al. 2020).

In addition to lack of ethical requirements for environmental scientists, a general lack of direction, education, training, requirements and resources specifically for environmental scientists and reconciliation supports the perception that reconciliation is less relevant in this field. For example, in the 94 Calls to Action of the Truth and Reconciliation Commission of Canada, there are no calls to action specific to environmental scientists. Where specific guidance or direction for researchers does exist (e.g., in Yukon's Together Today for Our Children Tomorrow (1973)), it is typically directed towards health and social science researchers.

Finally, many environmental scientists are working on projects that study one component of a much larger, often global problem, which may be abstract and not relatable for local communities. Climate change studies are typically a good example of this. For example, a single PhD project might investigate the physics of snow transport, which could be used to improve mathematical models that will ultimately lead to more accurate predications of future environmental conditions. Since they are working towards a global gain, researchers may not see the need or relevance to practice reconciliatory research because the research has little to not relevance at a local scale and for local people. The issue of working on more abstract and/or

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[7] Relationality is an Indigenous epistemology which describes the concept that "people are all related to each other, the natural environment, and to the spiritual world, and these relationships can bring interdependencies" (Antoine et al. 2018).

globally rather than locally relevant research projects and how this ties into challenges for reconciliation is explained in further detail in Challenge 9.

Challenge 2: Despite growing awareness and acceptance of Indigenous ways of knowing, being, and doing, there remains a lack of understanding about —and equal respect for— this worldview among environmental scientists.

Although post-secondary education systems in Canada are beginning to acknowledge and respect Indigenous methodologies through action plans and new curriculum, western science approaches remain the foundation for science education and research in Canadian colleges and universities. While history and epistemology of science courses are usually mandatory within science-based university-level programs, courses about Indigenous ways of knowing, being, and doing are only now becoming available (and are usually optional) for students enrolled in science-based programs. For example, new undergraduate courses at McMaster University and University of Saskatchewan have both introduced courses related to Indigenous research methodologies and ethics to their undergraduate programs. In my undergraduate and graduate school experience, mandatory research methods courses did not mention Indigenous ways of knowing, being and doing, and courses specifically about Indigenous ways of knowing, being, and doing were either not yet available, or not accessible (i.e., they were optional courses within faculties other than Science with reserved seating for students enrolled in related/relevant programs).

For western researchers and scientists who have known only western governance, education, and culture, and who have had limited education and experience with Indigenous worldviews, the result is often an “unconscious” bias towards science, in turn presenting a challenge in their work towards reconciliation (von der Porten et al. 2016). An example of this bias is expressed via language choice: for example, the “integration” or “incorporation” of

Indigenous knowledge into science, management, and decision-making is often used in reference to merging worldviews. This language choice implies a power imbalance which favors science (Bohensky & Maru 2011; Reid et al. 2020): it is uncommon to hear of science being "incorporated" or "integrated" into Indigenous ways of knowing, being, and doing (see Challenge 3 for further conversation on bringing worldviews together).

The above concept outlines the issues associated with a more general lack of understanding regarding Indigenous worldviews, but an absence of understanding at a more localized level is also problematic and can result in lack of awareness and respect. This includes more localized knowledge of Indigenous history, norms, culture and language where a researcher may be working. In my experience conducting northern environmental science as an early career researcher, and through conversations with peers, learning about an area's cultural, colonial, and Indigenous history is typically not a priority — I found this to be rarely encouraged, and generally categorized as voluntary. In other words, researchers are not encouraged (and often are also not supported) to learn about the history of a people and place. While it might benefit them personally to do so (in terms of understanding context and building relationships), this often has no direct professional reward. Furthermore, reliable and detailed information about local history and culture is often difficult to find and access. A better understanding of both generalized Indigenous worldviews and localized Indigenous context is critical for reconciliation: it can encourage awareness of personal bias, encourage comprehension of historical context and damage, and foster empathy, respect, and a desire to practice reconciliation.

Challenge 3: There is a general lack of knowledge and consensus among environmental scientists regarding how to effectively respect and bring together various worldviews (i.e., science and Indigenous ways of knowing, being and doing), despite increasing literature on this topic.

It is only within the last few decades that environmental management, monitoring, governance, Indigenous and scientific literature explores the concepts of integration, incorporation, bridging, interweaving, linking, braiding, and blending science and Indigenous ways of knowing, being, doing (e.g., Bohensky & Maru 2011; Falardeau & Bennett 2019; Ford et al. 2016; Latulippe & Klenk 2020; Makondo & Thomas 2018; Peacock et al. 2020; Weiss et al. 2013; Wilson et al. 2020). The existing literature is a mix of: a) descriptions of the two worldviews and knowledge types; b) case studies that have attempted to bridge them; and c) suggested methods and frameworks for how to do so - though many of these methods and frameworks remain fairly generalized (Bohensky & Maru 2011; Ford et al. 2016; Parsons et al. 2016).

This increase in literature has been accompanied by growing expectations and/or requirements for the bridging of knowledge types. While some governments, entities, and groups have released general guidelines and expectations on how to respect and bridge knowledge types, this concept is relatively new and very much still evolving: only a decade ago, co-production of knowledge and research projects in environmental sciences was deemed novel (Levac et al. 2018). Furthermore, although broad or general guidelines may be useful in some contexts (e.g. ‘Ethical Principles for conduct of research in the North (ACUNS 2003) and ‘First nations Ethics Guide on Research and Aboriginal Traditional Knowledge’ (Assembly of First Nations n.d.), cultural, local, and contextual differences need to be accounted for between communities.

As the expectation of communication and co-knowledge production increases, and without clear education, training, and mentorship on how to do this properly, Indigenous

Knowledge has been used primarily in ways that are complimentary, convenient, and/or relevant to environmental science research, such as filling gaps or datasets (Cruikshank 1984; Latulippe & Klenk 2020; Pfeifer 2018; Whyte 2013). Not only does this falsely imply Indigenous ways of knowing, being and doing are only valuable when they are complementary (Pfeifer 2018), it also implies that Indigenous ways of knowing, being and doing can be documented as data or observations, and can be understood universally and accommodated by/integrated into western science, rather than treated as an entirely separate knowledge system (Ford et al. 2016; Latulippe & Klenk 2020).

In recent years, the term and concept “Two-Eyed Seeing” has seen an increase in use (Abu et al. 2018; Bartlett et al. 2012; Institute on Governance 2019; Peltier 2018; Reid et al. 2020; Tyance Hassell 2019). This term is defined by Mi’kmaw Elder Albert Marshall as “learning to see from one eye with the strengths of Indigenous knowledges and ways of knowing, and from the other eye with the strengths of mainstream knowledges and ways of knowing, and to use both these eyes together, for the benefit of all” (Bartlett et al. 2012). Unlike integration or incorporation, the terminology “Two-Eyed Seeing” supports equality instead of power imbalance and assimilation of Indigenous ways of knowing, being, and doing into science (more on this in the Recommendations section).

Challenge 4: Western academic structures remain colonial and biased towards western science approaches.

Although there is a growing trend towards research projects that are relevant to, identified by, and led by communities using Indigenous methodologies and principles, many environmental science projects are still ultimately guided by non-Indigenous academic researchers and conducted within a scientific framework (Bohzkov et al. 2020; Held 2019; Pfeifer 2018). This framework imposes agendas and practices such as ways of thinking, gathering information, and communicating, ultimately reinforcing power imbalances (Baker et al. 2019; CRCC 2017; Latulippe & Klenk 2020).

Despite pressure for Canadian universities and colleges to indigenize education and research in response to the Truth and Reconciliation Commission's Calls to Action, current academic structures still are not readily or easily supporting research conducted outside of the western framework (Gaudry & Lorenz, 2018). Examples include the lack of flexibility of institutions for doing things "outside the box" (Ninomiya & Pollock 2017). Challenges I personally encountered included a lack of institutional support and funding for relationship building and spending time in communities to identify research topics prior to defining projects, or justifying expenses such as food and costs associated with hosting community events. Research funding models and an emphasis on peer-reviewed publications and results (see Challenge 5 for more discussion on this topic) also contribute to the colonial academic structure under which research is conducted (Pfeifer 2018). Additionally, instead of tackling fundamental transformation of western academy's conception of knowledge, many universities focus instead on Indigenous enrolment and hires (Gaudry & Lorenz 2018).

Challenge 5: There is greater valuation of, and emphasis on, quantifiable results (e.g. publications) over relationship building in environmental science research.

The post-secondary, environmental science environment in Canada values measurable and quantifiable results, with success measured using quantifiable metrics that include frequency and quality of publications. Though these metrics have merit, such as contributing knowledge and increasing transparency of, and accessibility to, research results, this system fails to emphasize and reward the value of more qualitative success, particularly relationship building and sustained relationships between researchers and communities. For example, a researcher who takes the time to nurture relationships, and focus on community-oriented communication products (such as newsletters, or easily understandable reports as opposed to academic publications) may subsequently be penalized by not having the time to produce as many publications.

Relationships are a key component of reconciliation: “All Canadians, as Treaty peoples, share responsibility for establishing and maintaining mutually respectful relationships” (Truth and Reconciliation Commission Final Report 2015). The central theme of respectful and meaningful relationships is trust, built by understanding perspectives and community history, open communication, equal respect, honesty, and reciprocity (Gordon 2017). Getting to know people as people first and as researchers second is critical for both reconciliation efforts and successful research (Brunet et al. 2014b; Feir & Hancock 2016).

Despite the importance of building and maintaining good relationships in environmental science research, there remains limited tangible support for this process, and emphasis on its importance. Within the current timeline and structural confines of academic programs, it is still very challenging for students to visit and build relationships with communities they have never previously visited or spent time in, but wish to work with. Spending time in these communities both before and during research is challenging because of teaching and course requirements as well as academic calendars and timelines. Additionally, time spent visiting local community members and attending local events (if not for research purposes) is often difficult to justify to research funders. For example, as a new graduate student, living near the community where I wanted to work was important to me so that I could establish and build relationships with community members. However, because of university residence requirements, in addition to increased costs of sustained living in a remote northern community, living in the community where I conducted my research was challenging, and in the end required supervisor support, creativity on my behalf, and a willingness to confront difficult and frustrating bureaucratic hurdles. Without emphasis on successful and effective relationship building within current western academic structures, this key component of reconciliation is not adequately supported (Feir & Hancock 2016; Gordon 2017; Ninomiya & Pollock 2017).

In addition to lack of emphasis on, and support for relationship building between researchers and Indigenous communities, there is also a lack of training and education regarding how to build such relationships. Throughout my post-secondary experience, mentorship and formal training regarding relationship building and working with Indigenous communities was limited and not readily available. While I found support in personal conversations with peers and colleagues, these conversations were sometimes challenging to initiate, mostly out of discomfort or lack of prioritization. Additionally, many graduate students in the field have limited soft skills training because the skills emphasized in environmental science are often hard skills (including field or lab work, writing, and project design). This lack of soft skills may result in discomfort with regards to navigating community dynamics and relationship building, or simply an uncertainty around appropriate actions or conversations.

Because of the valuation of publications within the western academic system, throughout my graduate program I have also felt pressure to write about and publish personal accounts of relationships and experiences of knowledge co-production (in addition to quantitative scientific publications). While publications which describe a researcher's experience of trying to advance reconciliation in the environmental sciences may contribute to collective progress by sharing lessons learned, I have found that these kinds of accounts often feel challenging and conflicting to share. Despite being personal observations, accounts, opinions and perspectives, experiences inherently involve other people and are often collective, sometimes emotional experiences which do not always feel like they should be shared in an academic journal, even despite collective permission and participation in the writing of these accounts. Sharing personal and shared experiences in this realm is sensitive and often uncomfortable, with the discomfort lying in the fact that reconciliation experiences are emotional and sensitive. Academic journals don't always reflect this sensitivity nor feel like the appropriate "home" for such accounts.

Challenge 6: Environmental scientists can be nervous or anxious about "doing it wrong" when it comes to working and reconciling with Indigenous communities, which can prevent them from taking action.

In northern Canada, a history of colonialism and poorly conducted research resulting in difficult relationships between researchers and communities underlies the nervousness or anxiety that many researchers feel about the possibility of "doing it wrong" when it comes to conducting research in a reconciliatory way with Indigenous communities. The mistrust, trauma, frustration, and anger resulting from these relationships cannot be ignored. This history, combined with a lack of training, mentorship, and understanding of Indigenous ways of knowing, being and doing, creates a sensitive environment that can be challenging to navigate — for both Indigenous communities and environmental scientists. Additionally, and as previously mentioned, environmental scientists are trained in hard skills such as fieldwork, statistics and writing, but often lack experience and training in soft skills including relationship building and communication.

As a consequence of a fraught history, a general lack of agreement regarding how best to conduct reconciliation, and lack of training and experience with relationship building, environmental scientists are often left to determine their own approaches when it comes to identifying the best path forward and unsure of what the right actions or words might be. In my experience, researchers are often afraid of saying or doing the wrong thing which could cause more harm than good. In this new era of reconciliatory research, relationships are often newly mended and sensitive, with trust actively being re-established. If mistakes are made, the hard fought progress in relationship building can be quickly dismantled. Additionally, because of a difficult history and the possibility of triggering trauma and/or challenging emotional situations, the stakes of making mistakes can be significant.

As a graduate student, information on how to do research "in a good way" or how to "do reconciliation within environmental science research" was often challenging to find, not readily available, and/or sought voluntarily. Any guides that were referenced to were often high-level, lacking context or examples (e.g., the Ethical Principles for the Conduct of Research in the North (2003)) and as a result were sometimes difficult to apply in practice. I chose to use the principles of respect, reciprocity, honesty, and flexibility to guide my general decision making and interactions with others, but with limited guidance and direction, I often found myself nervously questioning whether or not I was doing things the right way. I was also anxious about causing offence without knowing, either by referencing or wrongly addressing an issue that could harmfully trigger someone or a community, or via lack of awareness of cultural norms and respect. The handling of wild animals for environmental research is an example of this, outlined by Wong et al. (2020).

Challenge 7: There is a lack of resources, time, and support (fiscal and otherwise) for reconciliation in environmental sciences.

Since the Truth and Reconciliation Commission's Calls to Action were published, resources and support for reconciliation within academia has increased, from individual to institutional levels. This increase in resources has taken the form of increased conversation (such as increased informal conversations amongst academic peers and colleagues); curriculum development and availability (for example, since 2015 the University of Winnipeg requires all undergraduate students to fulfill mandatory Indigenous course requirements); strategic visions and Indigenization plans (summarized in Universities Canada document (2016)); new course or training requirements within academia (for example, Nipissing University's Office of Indigenous Initiatives requesting that researchers who engage with Indigenous peoples and communities submit a "Community Engagement Plan"); funding specific to reconciliatory action (for example, University of Alberta North Community Reporting Award); and training/awareness development workshops (for example, Sentinel North Indigenous Engagement Workshop available to graduate students, postdoctoral fellows and professionals). While these initiatives demonstrate momentum towards change and merit celebration, there remains a general lack of support and resources specific to the environmental sciences, which currently presents a challenge for reconciliation within this field. While the lack of support and resources is woven into many of the challenges identified throughout this paper, it merits distinction and identification as a challenge in and of itself. The lacking resources and supports include widely available funding for reconciliatory actions, education regarding Indigenous worldviews and history, mentorship and training in relationship building and sensitive conversation, and support for 'outside the box' events or expenses that support reconciliation. Development of these resources will need to be undertaken with care and sensitivity, with careful thought regarding where the information is obtained, how it is presented, and who it is presented by.

Challenge 8: As expectations increase for scientists to work alongside communities, these communities can become overburdened by communication and workload increases.

As the importance of relationship building and communication with communities is increasingly recognized and undertaken by environmental scientists, time communicating and working with each other also increases. While working together is beneficial and critical to reconciliation, the increased communication and demands can also overwhelm a small community, either at an individual level or at a community scale. For example, many First Nation governments in Yukon are seeing an increase in researchers reaching out and requesting community input and/or collaboration on projects. Most of these governments are small, with branches often being composed of one or two employees. For example, an environmental officer might be responsible for research applications, fieldwork, mining, forestry, and hydrology projects, essentially trying to conduct a workload that would be undertaken collaboratively by many employees within a larger government, such as Yukon Government. With limited capacity and increased demand for communication, the contact person within the First Nation government who is responsible for communication with researchers (if there is one) inevitably experiences an increased workload. While some First Nations in Yukon are establishing processes to review research requests (e.g., both Kluane First Nation and Vuntut Gwitchin First Nation are developing and refining a process for handling communication with researchers), many simply rely on the contact person handling the increased requests. Often, that employee becomes the main contact person, sometimes also referred to as the "community champion" for researchers. If for any reason that employee moves on (health, burnout, change in position, etc.), momentum and communication about the project can be delayed or lost.

Although the "community champion" contact is key, working with communities can also means connecting with the community as a whole. It is important for researchers to discuss with First Nation and communities and determine what their preferred method of communication is, and default to that method. While in one community, having conversation solely with a community champion who then relays information back and forth may be completely acceptable, in another community it may be important for the researcher to connect with other community members directly. In some communities, information sessions are preferred, whereas others who may be inundated with such sessions can experience “research fatigue”, which can contribute to unhealthy relationships between researchers and community members.

Finally, as funders shift to prioritizing projects that support community priorities, as well as outputs other than academic publications such as community workshops or engagement sessions, communities may experience added pressures and workloads. While there may not be an immediate solution, acknowledging this tension is critical to the conversation.

Challenge 9: Navigating the interaction between community research priorities, global research priorities, and reconciliation is complex.

Early career researchers in the environmental sciences (particularly climate change related) are currently faced with increasing and conflicting expectations of working on global research questions as well as community priorities, and the path forward is not always clear, and often context dependent. While the goal of adapting to changing climatic conditions is ultimately one that is shared globally, specialized climate change and environmental science research projects are often required in order to understand larger scale issues. These specialized projects are not always directly relevant to local communities, particularly in a northern context, and are usually secondary to community priorities. The number of critical issues in northern communities is high, and while communities may be interested in, and support environmental science research, interest and resources are often being dedicated to more pressing concerns such as health, social welfare, housing, localized impacts of climate change, etc.

This begs reflection on what is appropriate with regards to research topics and community priorities in the context of reconciliation: Is it possible to pursue (northern) environmental science research and practice reconciliation if the research topic is not a community priority? If so, what does this look like (is simply community approval enough)? If not, how are community priorities identified and communicated? How can these conversations occur without putting extra pressure and work on communities? With situations that are context-dependent, the question of whether it is appropriate to conduct research that is not a community priority (but is relevant to global wellbeing) whilst practicing reconciliation is complex and merits reflection, conversation, and consideration, both between researchers and between researchers and communities.

Summary of challenges

While it is important to reinforce that many environmental scientists have tackled the challenges identified herein with grace and aptitude and identified solutions and recommendations that have succeeded in their contexts, overall there remains much work to be done regarding reconciliation in environmental sciences. The challenges to reconciliation identified in this paper have been presented independently to explore their intricacies and complexities more deeply. However, whether they are large or small scale, systemic or local, or rooted in perceptive or logistical challenges, they are all very much intertwined (Figure 5-1). For example, a lack of understanding among environmental scientists of Indigenous ways of knowing, being and doing (both at local and broader scales) may contribute to a lack of awareness of the role natural scientists have in reconciliation, a lack of described approaches on how to interweave worldviews, hesitation by environmental scientists for fear of “doing it wrong”, and an emphasis on quantitative results. Alternatively, the lack of resources to support action towards reconciliation, emphasis on quantitative results, lack of guidelines on how to bring together different worldviews, and a lack of understanding of Indigenous ways of knowing, being and doing among environmental scientists may contribute to the lack of awareness/acceptance of the role that environmental scientists have in reconciliation. These interactions portray the complexity of some of the challenges, and the importance of understanding their impacts on each other.

Discussion and recommendations for reconciliation in environmental science research

The dialogues I have been engaged in, my observations of challenges to reconciliation in environmental sciences, and reflection on how to move forward have led me to identify and propose the following recommendations. Although these recommendations do not equate to full solutions, my hope is that they may provide guidance, and foster productive discussions and brainstorming on ways to move forward positively.

Recommendation 1: Researchers and institutions must work towards increased awareness, acceptance, and understanding of Indigenous ways of knowing, being and doing to foster equality of knowledge systems.

At an individual level, this may include taking the initiative and responsibility to learn about a place, its people and culture, its lands, and its history. It can also include working to recognize and articulate inherent bias (individual, institutional, cultural, etc.) and taking steps to acknowledge and overcome it, such as challenging one's concept of knowledge and relationality. Identifying, recognizing, and managing individual bias will require encouragement and the creation of safe environments from both researchers and institutions. To meet this recommendation, a shift in language use and language awareness will also be needed, particularly when referring to the interaction of knowledge systems (e.g., using terms such as bridging, bringing together, "two-eyed seeing" as opposed to terms such as integration and incorporation).

At an institutional level, this may include mandatory curriculum which focuses on knowledge systems and recognition of individual bias, and curriculum on the history, cultures, languages, traditions, and colonialism of Indigenous people, co-developed with Indigenous communities. The Yukon First Nations 101 course offered through Yukon University is a good example, having been designed in partnership with Yukon First Nations and built by the University's First Nations Initiatives. This model aims to bring people to a baseline level of knowledge regarding Indigenous history and culture to more easily facilitate mutual conversations and understanding, with the ultimate goal of increasing sensitivity, respect, and curiosity amongst researchers. It is important to note that training, education, and mentorship are not all-encompassing solutions, and care should be taken to develop and implement them respectfully. The responsibility of researchers to seek out learning opportunities is also emphasized here, to alleviate the sometimes overwhelming task of expecting communities to provide educational experiences or resources.

Recommendation 2: It is critical for researchers, academic entities, and communities to foster respectful and sensitive conversations about reconciliation.

Especially within the academy and amongst colleagues, an increase in respectful and sensitive conversations about reconciliation is much needed. These conversations could focus on discussing challenges and recommendations, addressing history and emotional trauma, sharing resources, etc. To increase this dialogue, a tangible suggestion for individual researchers and research teams might be to create and follow through with reconciliation plans, including articulating – and committing to – values associated with reconciliatory actions. Such plans could take the shape of verbal conversations or written documents, and would outline reconciliation goals and actions as they pertain to the research. This would not only encourage academic colleagues to discuss how they might conduct reconciliatory research, it would also create and foster awareness and accountability. Examples of commitments outlined in such plans could include budgeting time (particularly unexpected time) to have discussions amongst peers and others to discuss progress, challenges, opportunities, and successes related to reconciliation;

and identifying and sharing reconciliation related resources/learning opportunities such as readings, workshops, and mentorship opportunities.

Recommendation 3: Individuals, institutions, and communities need to apply pressure to western academic and government structures to encourage systemic change which prioritizes relationships, flexibility, and support for reconciliation efforts.

Applying pressure to encourage systemic change could include submitting/accepting only project proposals and funding applications that build-in time and resources to prioritize spending meaningful time in communities and building relationships and/or submit reconciliation plans. The valuation of relationships will need to come from all realms of academia and funding, and including this in applications could emphasize this. At an institutional level, this could include re-examining metrics that recognize success, such as the rank and tenure process, or metrics reported to oversight bodies like boards of governors. Tangibly, this could mean prioritizing the hiring of employees who have strong track records in relationship building and knowledge co-production over those with strong publications records, as well as developing and mandating training such as effective relationship building.

Recommendation 4: Researchers and academic institutions need to embrace, encourage, and support creativity when it comes to identifying context-specific reconciliatory actions.

Although broad reconciliation guidelines spanning the environmental sciences may certainly be useful, they are not by themselves a solution, and researchers need to recognize that every challenge will be circumstantial, with each project having different considerations influencing the approaches needed to move forward. As such, embracing creativity to identify context specific reconciliatory actions is critical. Creative solutions may not always fit within the boundaries and options of existing academic structures, but they may pave pathways to new and effective reconciliatory actions. For example, to address the real possibility of creating community research fatigue by having individual researchers present and consult individually, communities and researchers could instead come together at yearly gatherings, at a time that is convenient for the community, to discuss all matters related to research (e.g., the Kluane Research Summits in 2018 and 2019 in Burwash Landing, Yukon — see references for summary documents of these events). This would reduce the pressure and commitment of citizens without compromising the importance or value of their input and feedback. It would also allow for more interdisciplinary and holistic conversation and collaboration between researchers, as well as between community members and researchers. This example also outlines the need for researchers to make efforts to work together and coordinate their communication efforts, in addition to being creative.

Conclusion

Growing expectations of reconciliation within environmental science, combined with reconciliation resources, guidance and education that are very much still developing, are resulting in a dynamic time for this field. However, despite some of these challenges being systemic, many (especially early career) researchers are recognizing that, as treaty people, reconciliation is not optional in Canada. This community of researchers is identifying creative ways to conduct northern environmental science research that is rooted in shared human values and abides by the principles of reconciliation. These include the identification, acknowledgement, and reflection of current issues and perceptions that may pose challenges to reconciliation within this field, and consciously taking subsequent action that directly address these challenges. It is my hope that continued, respectful, and open conversation about the process can foster awareness, reflection, respect, sensitivity, and creativity, ultimately resulting in solutions and ideas for practicing reconciliation within this field.

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Tables

Table 5-1. Relevant terminology and definitions.

Reconciliation	Reconciliation is “ensuring that everything we do today is aimed at a high standard of restoring the balance to the relationships between Aboriginal and non-aboriginal peoples in this country”. - Honourable Justice Murray Sinclair (Chair of the Truth and Reconciliation Commission of Canada) Reconciliation is “about coming to terms with events of the past in a manner that overcomes conflict and establishes a respectful and healthy relationship among people going forward […]. It is about establishing and maintaining mutually respectful relationships between Aboriginal and non-aboriginal peoples in this country. For that to happen, there has to be awareness of the past, acknowledgement of the harm that has been inflicted, atonement for the causes, and action to change behavior. […]. Whether one is First Nations, Inuit, Metis, a descendant of European settlers, a member of a minority group that suffered historical discrimination in Canada, or a new Canadian, we all inherit both the benefits and obligations of Canada: We are all treaty people who share responsibility for taking action on reconciliation […] and reconciliation must happen across all sectors of Canadian society”. - Truth and Reconciliation Commission of Canada Final Report
Research	Although research is generally described as a means to collect knowledge, some definitions of research imply the use of science (whereby research and science are interconnected and not separate entities; e.g. Kothari 2004), whereas others consider non-scientific definitions of research (e.g. Wilson 2008). For the purposes of this paper, research is defined “the systematic investigation or inquiry aimed at contributing to knowledge of a theory, topic, etc. by careful consideration, observation, or study of a subject” (Oxford English Dictionary, 2020).
Science (sometimes also referred to as western science, especially when used alongside terms such as Indigenous knowledge)	The term science is used here to refer to a way of knowing embedded within the western worldview. Science involves the scientific method, which is defined as “principles and procedures for the systematic pursuit of knowledge involving the recognition and formulation of a problem, the collection of data through observation and experiment, and the formulation and testing of hypothesis” (Merriam-Webster Dictionary, n.d.). “Science assumes nature is knowable through the eradication of mystery, and is characterized by its predictive validity, a validation process, uniformitarianism, assumption of rectilinear time, anthropocentrism, Cartesian dualism, reductionism and quantification. It is a rational, empirically based way of knowing nature that yields, in part, descriptions and explanations of nature” (Aikenhead & Ogawa 2007). Types of science include physical science (astronomy, physics, chemistry, Earth sciences), biological science (biology, medicine), and social science (anthropology, economics, human behavior) (Encyclopedia Britannica, 2020).

	Natural science typically refers to combined biological and physical sciences and for purposes of this manuscript, environmental science is defined as integrating physical and biological sciences to study and better understand the environment.
Indigenous ways of knowing, being, and doing	The terms Indigenous knowledge, traditional knowledge, traditional ecological knowledge, and Indigenous science are often used to describe Indigenous ways of knowing, being and doing (Latulippe & Klenk 2020, Whyte 2013). The definitions of this term differ significantly in the literature and elsewhere, often depending on the authors and context (Whyte 2013, Mazzocchi 2006, Berkes 1993). Importantly, Mazzocchi (2006) states that "our difficulty in approaching the knowledge from Indigenous cultures is already reflected in the way in which we describe and name it". As a white settler raised in a western worldview, I find it challenging to define Indigenous Knowledge because I am less familiar with it and do not wish to portray it inadequately. However, I also think there is value in providing context and some definition, in order to reach a baseline of common understanding which is required for reconciliation and moving forward together. The following quotes capture what I would consider as key concepts to Indigenous ways of knowing, being and doing. Indigenous ways of knowing, being and doing "cannot be uncoupled from people, the land, or from ways it is generated, understood, enacted or shared" (Latulippe & Klenk 2020) "Traditional ecological knowledge refers to the knowledge, practice, and belief concerning the relationships of living beings to one another and the physical environment and is born of long intimacy and attentiveness to a homeland, arising where people are materially and spiritually integrated within their landscape. It has been developed through generations of intimate contact by native peoples and their lands." (Kimmerer 2002). Rather than Indigenous knowledge, *Indigenous ways knowing, being, and doing* are used in this paper to reflect the interconnected nature of Indigenous knowledge with culture and ways of life.
Indigenous	The term Indigenous encompasses First Nations, Inuit and Métis peoples in Canada. The United Nations defines Indigenous peoples as "inheritors and practitioners of unique cultures and ways of relating to people and the environment, and who have retained social, cultural, economic and political characteristics that are distinct from those of the dominant societies in which they live" (United Nations, n.d.).

Figures

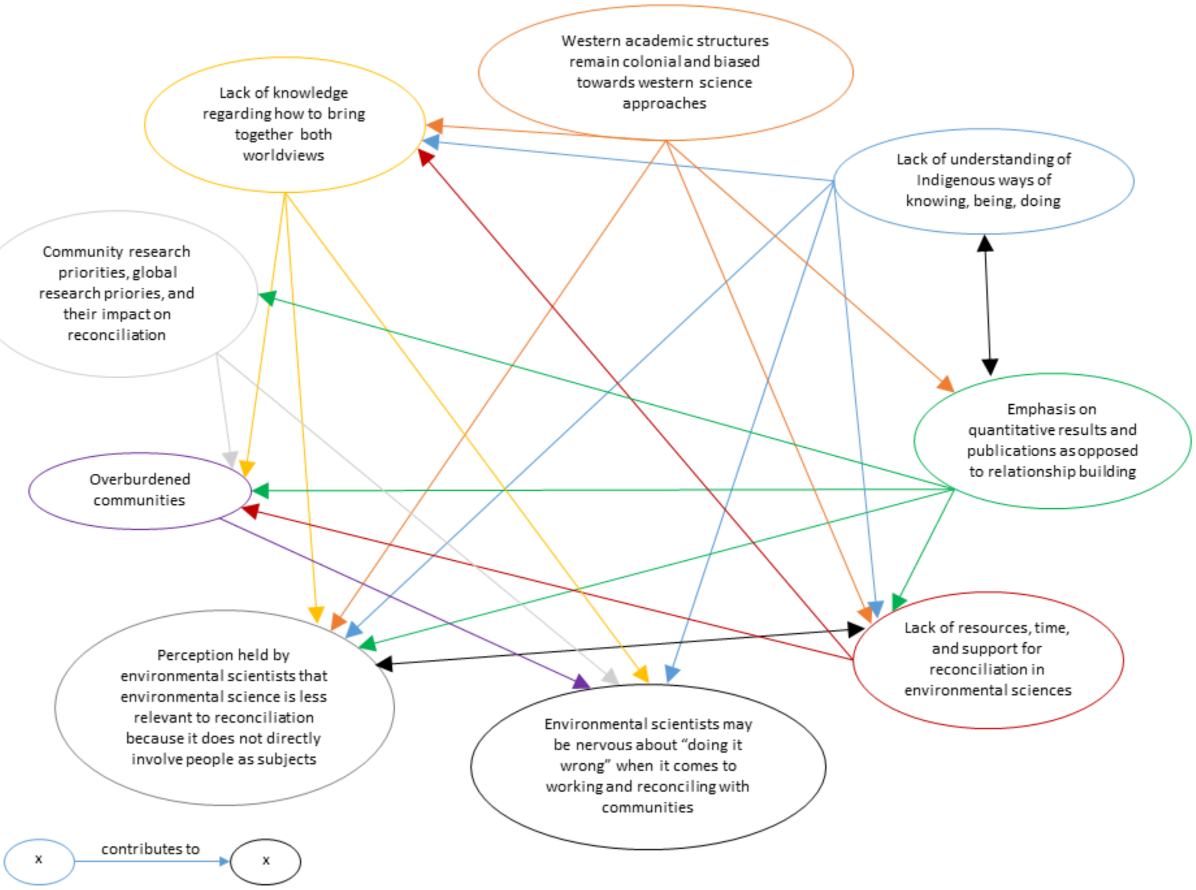

Figure 5-1. Challenges for reconciliation in (northern) environmental sciences and how they relate to one another.

CHAPTER 6 . General conclusions

Summary of findings

Climate change is affecting ecosystems around the globe, with Arctic amplification causing pronounced impacts in northern environments (Serreze & Barry 2011; Vincent 2020). The impacts on northern freshwater ecosystems are especially concerning. Physical, biological, and chemical changes are occurring in northern lakes and rivers, with consequences for water quality and quantity, fish population and distributions, ecosystem function, and human communities (Prowse et al. 2006; Prowse et al. 2015; Reist et al. 2006; White et al. 2007; Wrona et al. 2016). Knowledge about how northern lakes and rivers are changing is critical for informing how they can be protected, as well as how we can adapt to and mitigate impacts of change.

In order to understand how aquatic systems are changing, a basic understanding of their current structure and function is required against which to compare future conditions. Working with Kluane First Nation and the Dän Keyi Renewable Resources Council, a high resolution baseline of physicochemical water properties of Lhù’ààn Mân’ (Kluane Lake) was conducted in 2015 (Chapter 2), serving as a case study and first step towards better understanding how climate change is impacting large northern lakes. This baseline study revealed a lake composed of multiple regions each with distinct properties and dynamics, influenced largely by proximity to glacial inflow and lake depth. The regions varied from cold, turbid, unproductive waters with weak stratification in the lake’s southern basin, to clear, well-oxygenated waters with strong stratification in the mid basin and northeast arm, to waters that were productive, shallow, and warmed to bottom in the lake’s northwest arm. In addition to spatial differences, the seasonal differences in physicochemical properties at each site were also significant. The seasonal and spatial differences in physicochemical properties and dynamics identified at Lhù’ààn Mân’ underline the need for, and importance of, high resolution limnological monitoring in order to accurately understand, monitor, and predict changes in large lake systems. For example, monitoring a lake at a single site, or only during the summer months, or only at lake surface, may not adequately capture the spatial or temporal variability of a system and could potentially lead to misidentification of changes over time. To accurately identify change, baseline studies and monitoring must adequately represent the variability of the system.

The 2015 Lhù’ààn Mân’ baseline data was used to design and implement a long-term monitoring program (beginning in April 2017) of lake thermal dynamics with sufficient spatial and temporal resolution to capture the variability within the lake (Chapter 3). As a key indicator of general freshwater conditions (Carr & Neary 2006), and because it is relatively reliable and cost-effective to measure, water temperature was chosen by project partners (including Kluane First Nation and the Dän Keyi Renewable Resources Council) as the main parameter of the monitoring program. The monitoring was initially established to investigate the long-term and gradual impact of climate change on lake temperature. However, after the diversion of Kaskawulsh Glacier meltwater in 2016, the response of lake thermal dynamics to sudden loss of glacier inflow increased in importance and interest. Impacts to lake thermal dynamics are locally relevant because of the potential consequences to fish habitat and health, and local communities practicing subsistence fishing. A better understanding of how lake thermal dynamics are impacted by climate change and loss of glacial inflow is also globally relevant as glaciers continue to recede and eventually disappear, resulting in loss of glacial inflow to downstream lakes and rivers (Milner et al. 2017).

The first three years of thermal monitoring data from Lhù'ààn Mân' confirmed that each region of the lake has unique thermal dynamics. The data also revealed a preliminary warming pattern occurring in the southern end of the lake (the region previously most directly influenced by the 2016 diversion of Kaskawulsh Glacier meltwater) between 2017 and 2019, but not in the northern basins of the lake. Between 2017 and 2019, mean yearly air temperatures at Kluane (using data from Burwash Landing) increased, as did days of open water in each basin. If air temperature and days of open water were primary causes of lake warming, all parts of the lake would be expected to exhibit warming over the three years. Since this wasn't the case, other possible factors could be influencing this observed pattern, including the loss of Kaskawulsh Glacier meltwater flowing into the lake after 2016. A comparison of satellite-derived lake surface temperature before and after the 2016 diversion event confirmed significantly warmer temperatures at lake surface in the South basin after 2016, supporting the hypothesis that the south basin may be exhibiting impacts of the diversion. However, continued long-term monitoring will be required to account for interannual variability and to identify trends with confidence.

While changes in thermal dynamics can be a good indication of ecosystem change, continuous historical records of lake water temperature are generally scarce, especially in northern lakes. As such, other available tools to better understand the general impacts of change on northern lakes were explored, including using satellite imagery to assess spring lake ice phenology trends of Lhù'ààn Mân' and nine other large lakes in southwest Yukon/northern British Columbia between 2000 and 2019 (Chapter 4). Although using satellite imagery to determine lake ice phenology trends is increasingly common (Duguay et al. 2015), a recent assessment for the lakes of interest had not been completed. An updated assessment revealed that all of the study lakes displayed tendencies towards earlier ice break-up, with three of the lakes displaying significant trends ($p<0.05$) and two additional lakes with marginally significant trends ($0.10<p<0.05$). Rates of earlier ice break up (0.72 days year^{-1} for start of break up and 0.46 days year^{-1} for end of break up) were highly correlated with air temperature, and are within the range of rates reported for spring lake ice break up trends of other Canadian and global lakes for similar timeframes. Because ice phenology is closely linked with the physicochemical properties of lake water, trends towards earlier ice-off indicate potential physicochemical changes occurring within these lakes (Caldwell et al. 2020; Sharma et al. 2019), further reinforcing the need for monitoring of their water properties.

While gathering knowledge about changing ecosystems is a key component to ensuring their long-term health, the way knowledge is gathered, and the type of knowledge that is gathered, is equally if not more important in this era of reconciliation. While a primarily western scientific approach was used to explore the research interests of this thesis, deep reflection about reconciliation occurred, including the role of Indigenous ways of knowing, being and doing in research. Environmental scientists — especially early career researchers – are currently navigating a paradigm shift which is defined by growing recognition and need for reconciliation in all fields of research (Adams et al. 2014; Bocking 2005; Kouril et al. 2015). And yet, mentorship, guidance, resources, and accountability for “how to do research in a good way” are generally still lacking, leaving researchers largely to their own motivations, strategies, and creativity with regards to reconciliation within the field of environmental science (Brunet et al. 2014; Wong et al. 2020). Personal experiences and conversations held throughout this thesis allowed for identification of current key challenges to reconciliation and recommendations for supporting reconciliation moving forward. Some of the key challenges included an existing perception that environmental science is less relevant to reconciliation largely influenced by a general lack of encouraged or required ethical review process for this field, academic emphasis on quantitative results (such as publications) over qualitative results (such as relationship building), lack of support (fiscal, logistical, practical, etc.) for reconciliatory practices within the field, and overburdened Indigenous communities. Recommendations were rooted in a need for systemic level changes regarding the use, respect, and understanding of knowledge systems especially western educational and government structures, increased support (fiscal, logistical, training, etc.) for reconciliation, and fostering safe and respectful spaces for reflection and conversation about individual and cultural biases and strategies for practicing and supporting reconciliation.

Reflections and future research

While three years of continuous thermal monitoring at Lhù’ààn Mân’ allowed for a preliminary assessment of how the lake’s thermal dynamics may be impacted by climate change, this timeframe does not account for interannual variability and therefore does not provide a definitive trend. Continued, long-term monitoring is needed to confirm whether the three-year warming pattern observed to date in the south end of the lake will continue over time, and if so, whether the trend will remain linear, fluctuate, or plateau over time. Continued monitoring would also determine whether other parts of the lake eventually begin to warm over time, which would be critical to understanding general ecosystem health and any significant habitat changes. While thermal dynamics are a key indicator of ecosystem change, other important properties of water could be added to the monitoring program in the future, and provide additional knowledge on system change. For example, monitoring oxygen and nutrients could provide additional and complementary information on how fish habitat may be changing.

Finally, while great care was taken throughout this research to practice reconciliation and work closely and meaningfully with local communities, ultimately this research was still largely conducted using western knowledge and practices. Furthermore, while the health of Lhù'ààn Mân' was identified as a local community priority which largely guided the motives for this research, contributing to a more global understanding of climate change also motivated this work. This has been cause for reflection regarding what is appropriate when it comes to the role of research topics/interests and reconciliation, particularly as it applies to climate change. Is it possible to fully practice reconciliation while conducting research that is not a community priority? While climate change does have local manifestations, research towards better understanding climate change is often nested under a global motive with little or no direct relevant to local communities. As these issues continue to be explored, respect, humility, open mindedness, and commitment to reconciliation should be prioritized and used to guide research practices in this era of reconciliation.

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APPENDIX 1. Supplementary Material for Chapter 2

Supplementary Figures

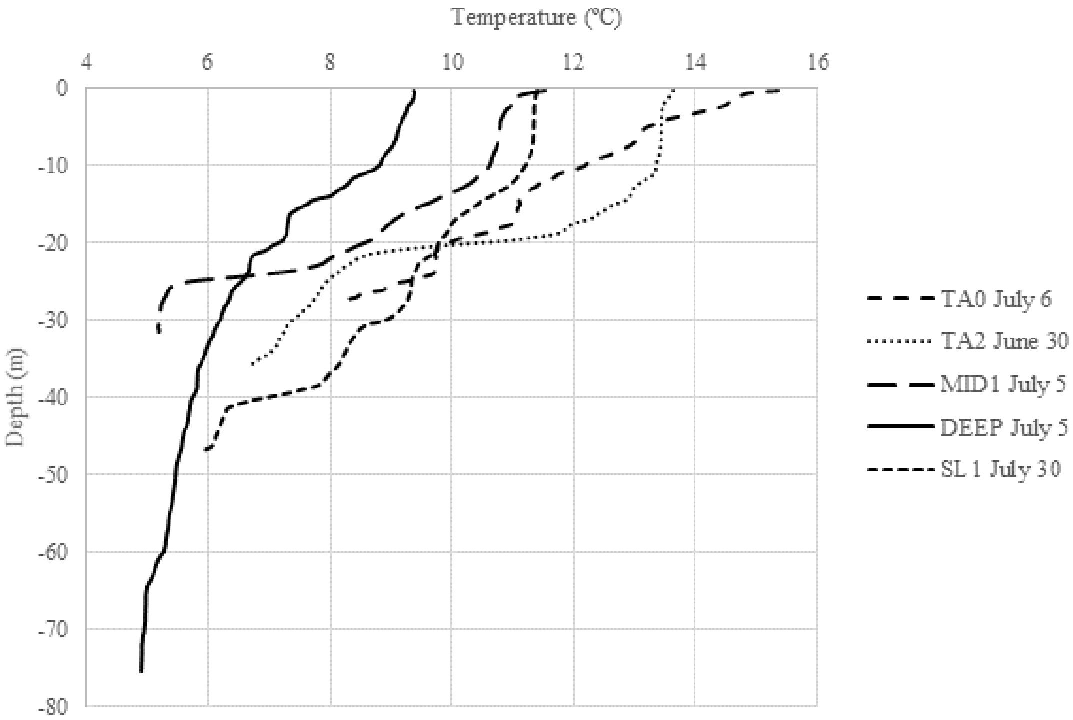


Figure 2-S1. Temperature profile examples from ’Ùha K’ènji, mid, and south regions of the lake showing metalimnions composed of several smaller thermoclines of varying strengths.

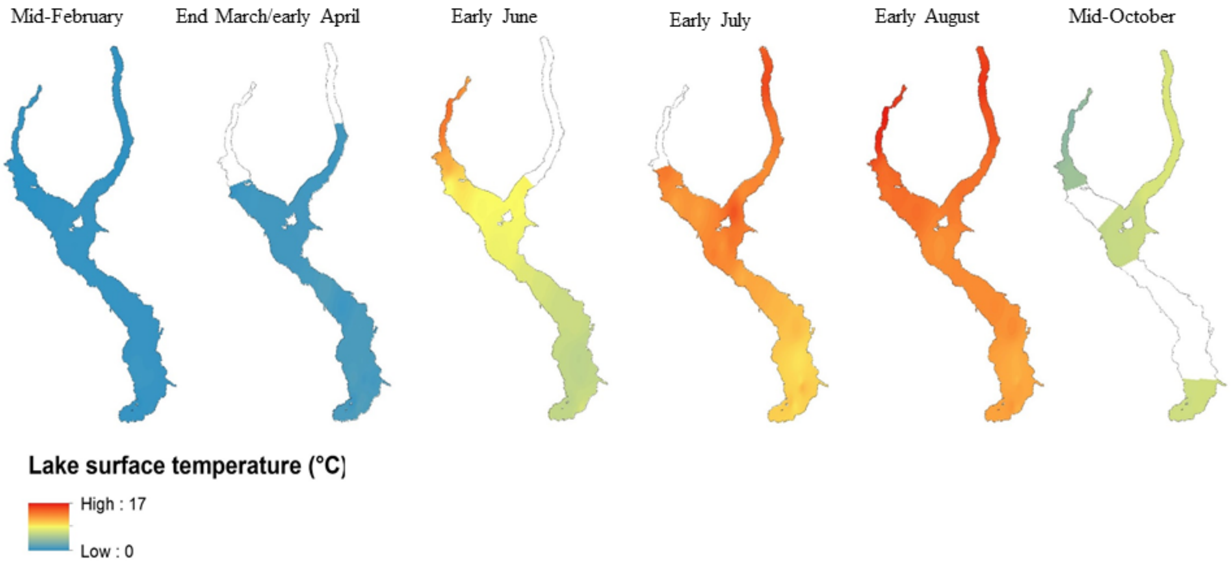


Figure 2-S2. Interpolated lake surface temperature, created using ArcGIS (ArcMap) and Inverse Distance Weighting (IDW). White areas represent unavailable data.

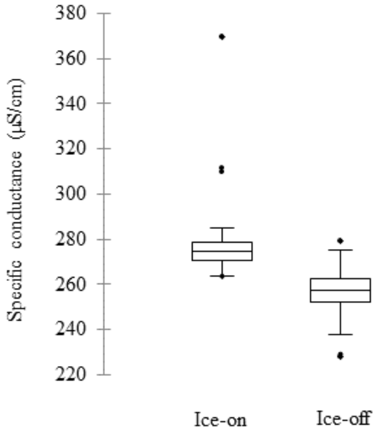


Figure 2-S3. Box plots showing lake-wide mean specific conductance (µS/cm) during the ice-on and ice-off periods. Box plots show median values as well as first and third quartiles, dots indicate maximum and minimum values.

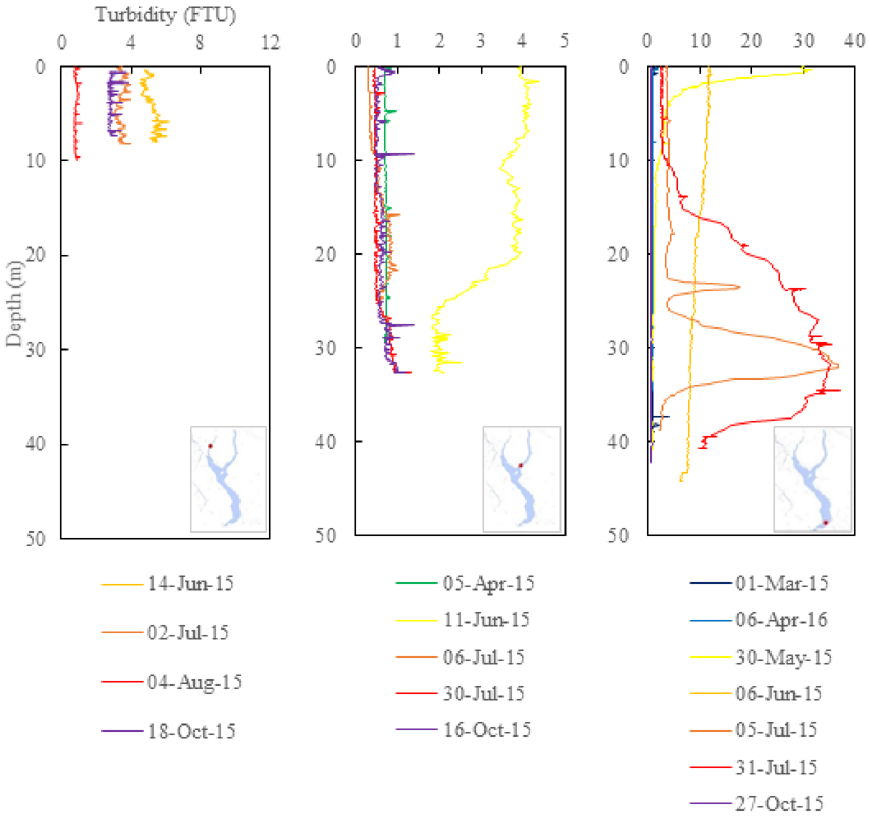


Figure 2-S4.Turbidity (FTU) profiles during select sampling events in 2015 in Tthe Kaala Daagur (BR2), ’Ùha K’ènji (TA0), and the southern basin of Lhù’ààn Mân (SL1).

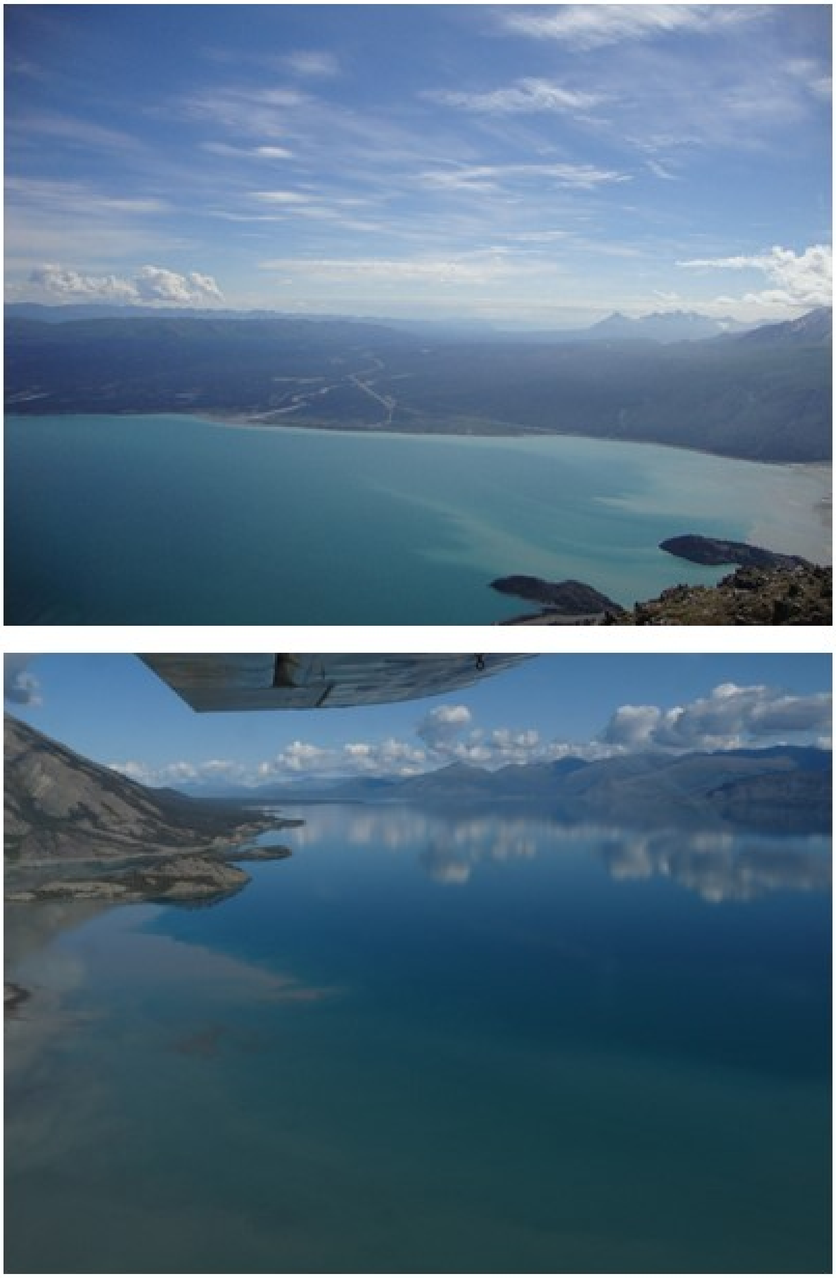


Figure 2-S5. Top photo taken from Thechàl Dhâl’ (Sheep Mountain) looking south across the southern basin of Lhù’ààn Mân and down the Alaska Highway. Bottom photo taken from the air looking north and up the Alaska Highway.

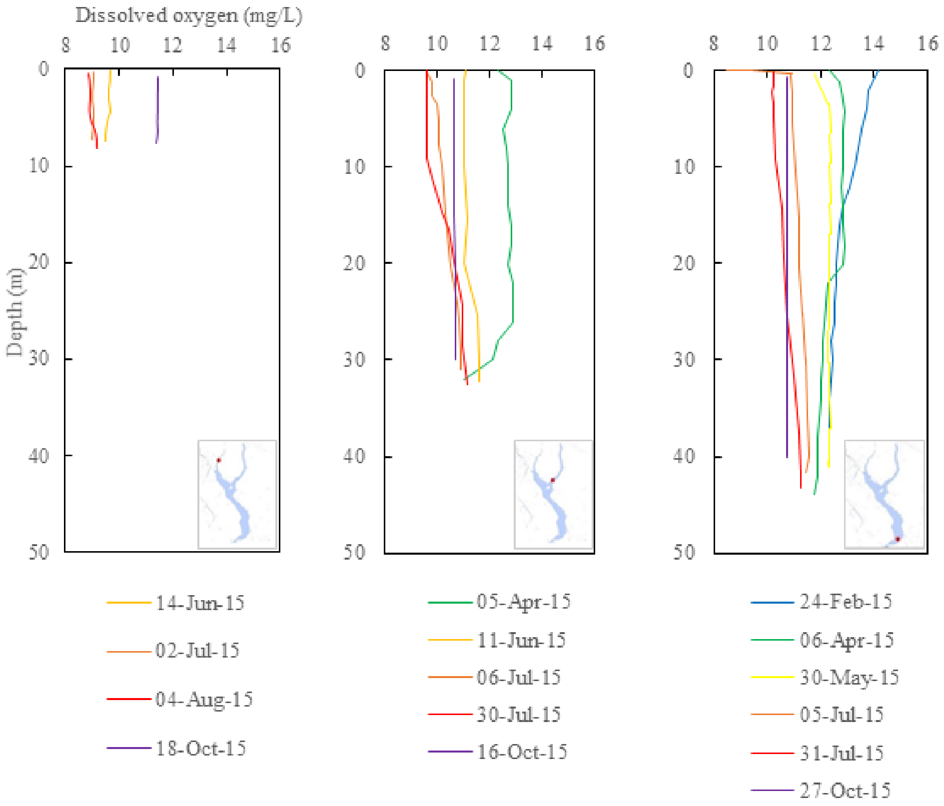


Figure 2-S6. Dissolved oxygen (mg/L) profiles during select sampling events in 2015 in Tthe Kaala Daagur (BR2), ’Ùha K’ènji (TA0), and the southern basin of Lhù’ààn Mân (SL1).

Supplementary Data Files

The data files cited in this chapter can be found in the following Dataverse repository:

McKnight, Ellorie, 2021, "Kluane Lake 2015 Data Files", https://doi.org/10.7939/DVN/Q8YUUN , Scholars Portal Dataverse, V1, UNF:6:2r+6qC5G+GtjFe/FyyMT4w== [fileUNF]

APPENDIX 2. Supplementary Material for Chapter 3

Supplementary File – Generalized Additive Model R code

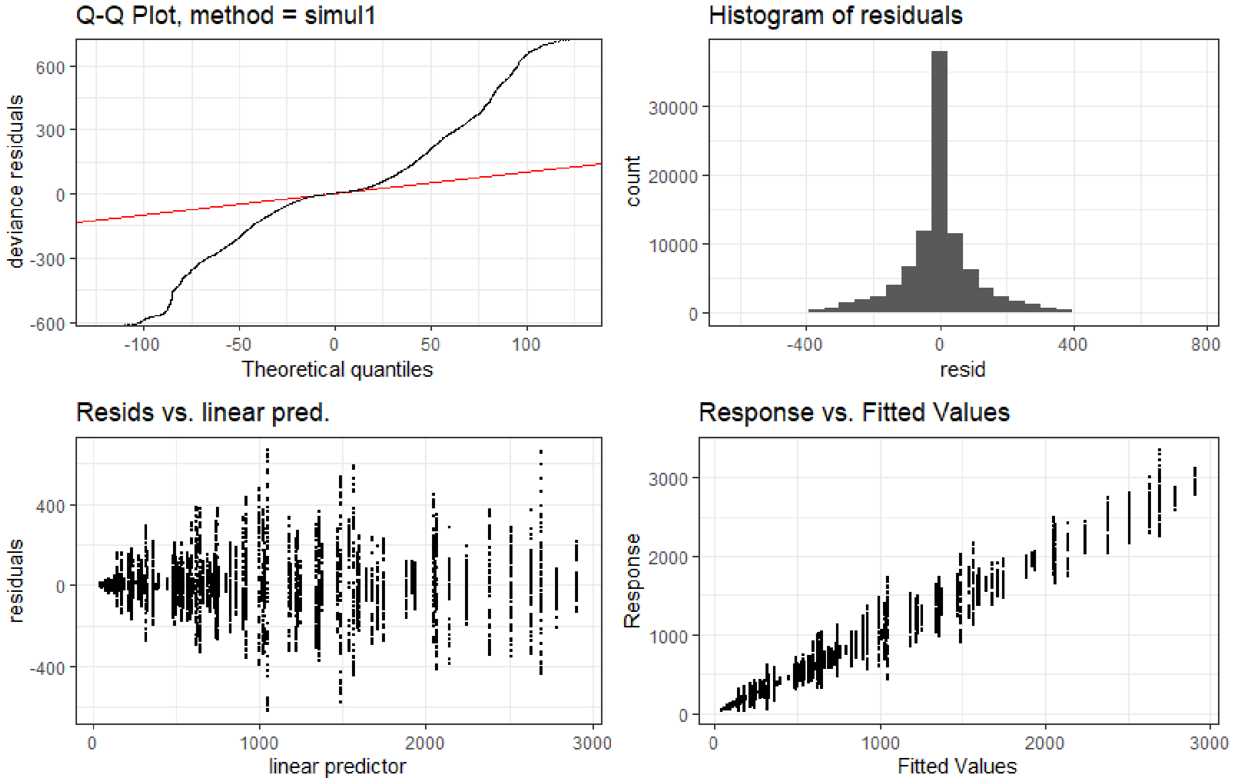
```
# 0. Load packages and functions ####

# Data manipulation and modelling tools
library(tidyr)
library(readr)
library(dplyr)
library(forcats)
library(lubridate)
library(mgcv)

# Visualization and inspection tools
library(mgcViz)
library(itsadug)
library(ggplot2)

# 1. Read and wrangle data ####
data <- readr::read_csv("./data/kluane_heatstor_joules.csv") %>%
  # Forge time variables
  dplyr::mutate(
    # Year variable
    year = lubridate::year(DateTime),
    # Month variable (just in case we need it)
    month = lubridate::month(DateTime),
  ) %>%
  # Prep model factors
  dplyr::mutate(site = forcats::as_factor(Site)) %>%
  # Add logical column for AR(1) to define start of nested time series
  # (repeated observations nested within month, within year, within site)
  dplyr::group_by(site, year, month) %>%
  dplyr::mutate(
    start_event = dplyr::if_else(
      condition = dplyr::row_number() == 1,
      true = TRUE,
      false = FALSE
    )
  ) %>%
  dplyr::ungroup() %>%
```

```
  # Clean up, remove 2020 and select required columns
  dplyr::filter(year < 2020) %>%
  dplyr::select(heat_storage = Heatstor, month, year, site, start_event) %>%
  # Testing
  glimpse() %>%
  {.}

# 2. Fit gam model with tensor smooth for month/year ####
tensor_month_year <- mgcv::bam(
  formula = heat_storage ~
    # Tensor smooth for 'month' and 'year', interaction with site
    te(
      month, # Cubic cyclic smooth (0.5 and 12.5 connect), k = 12
      year, # Cubic regression smooth, k = 3
      by = site,
      k = c(12, 3),
      bs = c("cc", "cr")
    ) +
    # Intercepts for 'site' factor
    site,
  # Knots for cyclic smooth (month 1 and 12 connect at 0.5 and 12.5)
  knots = list(month = c(0.5, seq(1, 12, length = 10), 12.5)),
  # Data
  data = data
)

# Inspect model summary
mgcv::summary.gam(tensor_month_year)

# Inspect residuals, test if complexity parameters (k) are appropriate
mgcViz::check.gamViz(mgcViz::getViz(tensor_month_year))

# Inspect autocorrelation in residuals
acf(resid(tensor_month_year))
pacf(resid(tensor_month_year))

# 3. Fit gam model with tensor smooth for month/year and AR(1) term ####

# Quick rho based on first lag of model with no AR(1)
(rho_val <- acf(resid(tensor_month_year), plot = FALSE)$acf[2])

# Model with AR(1), rho = 0.9939287
tensor_month_year_ar1 <- mgcv::bam(
```

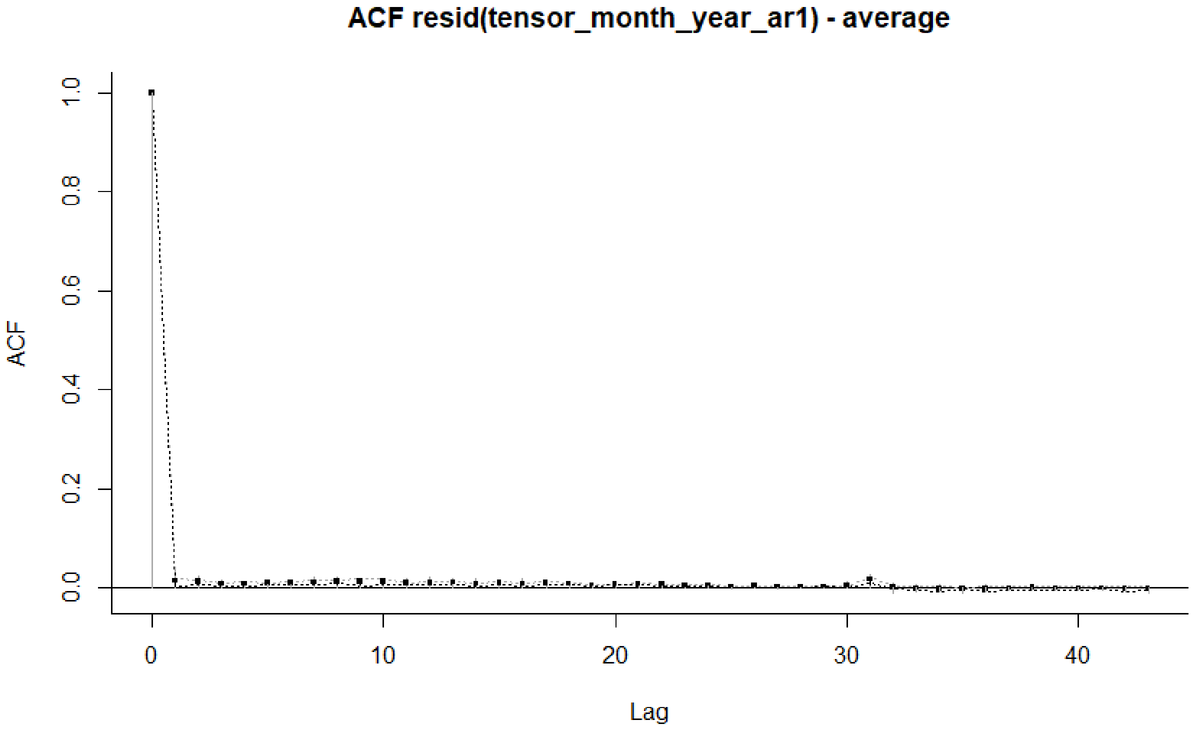
```
  formula = heat_storage ~
    # Tensor smooth for 'month' and 'year', interaction with site
    te(
      month, # Cubic cyclic smooth (0.5 and 12.5 connect), k = 12
      year, # Cubic regression smooth, k = 3
      by = site,
      k = c(12, 3),
      bs = c("cc", "cr")
    ) +
    # Intercepts for 'site' factor
    site,
  # Knots for cyclic smooth (month 1 and 12 connect at 0.5 and 12.5)
  knots = list(month = c(0.5, seq(1, 12, length = 10), 12.5)),
  # Auto-regression model
  AR.start = data$start_event,
  rho = rho_val,
  # Data
  data = data
)

# Inspect model summary
mgcv::summary.gam(tensor_month_year_ar1)
```

```
Family: gaussian 
Link function: identity 

Formula:
heat_storage ~ te(month, year, by = site, k = c(12, 3), bs = c("cc", 
    "cr")) + site

Parametric coefficients:
            Estimate Std. Error t value Pr(>|t|)    
(Intercept)  347.457      3.007  115.56   <2e-16 ***
siteTalbot   565.700      4.252  133.04   <2e-16 ***
siteDeep    1042.637      4.252  245.19   <2e-16 ***
siteSouth    202.998      4.252   47.74   <2e-16 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Approximate significance of smooth terms:
                             edf Ref.df      F p-value    
te(month,year):siteBrooks 20.69  23.84  277.3  <2e-16 ***
te(month,year):siteTalbot 26.81  28.06 1343.2  <2e-16 ***
te(month,year):siteDeep   28.43  29.32 2504.1  <2e-16 ***
te(month,year):siteSouth  25.56  27.22  759.2  <2e-16 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

R-sq.(adj) =  0.969   Deviance explained = 96.9%
fREML = 2.5572e+05  Scale est. = 960.01    n = 96480
```

```
# Inspect residuals, test if complexity parameters (k) are appropriate
mgcViz::check.gamViz(mgcViz::getViz(tensor_month_year_ar1))
```

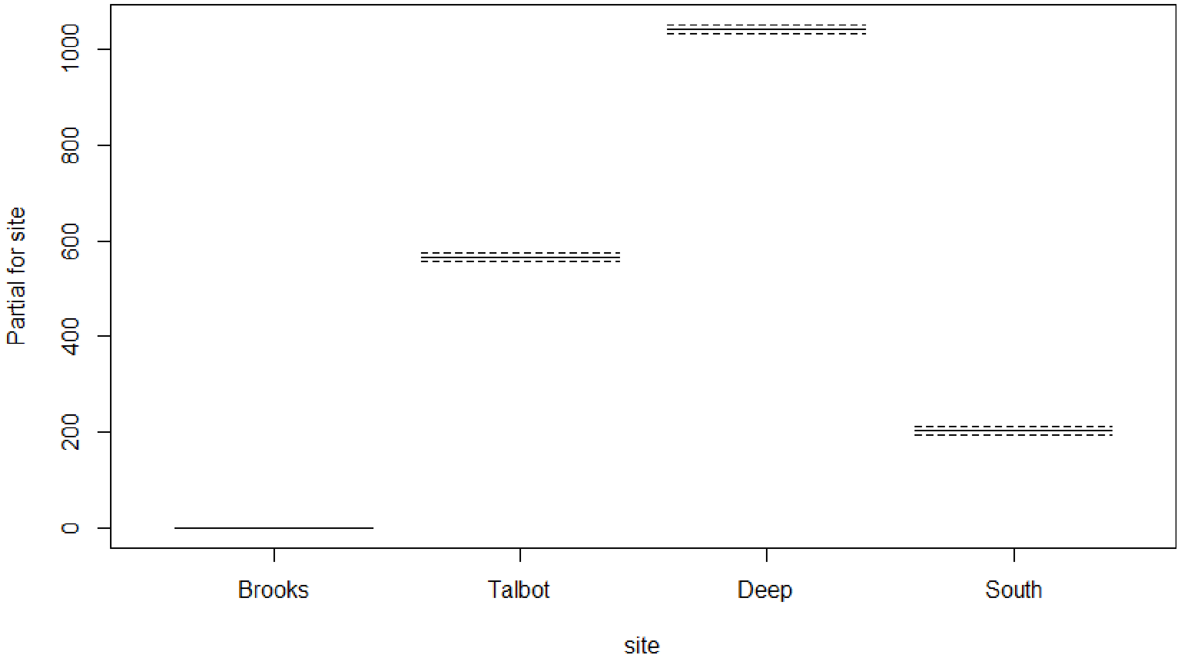


```
# Check autocorrelation in residuals and other diagnostics
itsadug::check_resid(tensor_month_year_ar1, split_pred = c("site"), ask = FALSE)
# NOTE: Density plot shows light tails compared to normal distribution
#       ACF plot shows complete removal of autocorrelation in residuals
```



```
# Compare AIC to model without AR(1)
AIC(tensor_month_year)
1199274

AIC(tensor_month_year_ar1)
511146.6


# Visualize patterns across years within each site
mgcv::vis.gam(
  x = tensor_month_year_ar1,
  view = c("month", "year"),
  plot.type = "contour",
  color = "topo",
  cond = list(site = "Brooks"),
  main = "Brooks"
)
mgcv::vis.gam(
  x = tensor_month_year_ar1,
  view = c("month", "year"),
  plot.type = "contour",
  color = "topo",
  cond = list(site = "Talbot"),
```

```
  main = "Talbot"
)
mgcv::vis.gam(
  x = tensor_month_year_ar1,
  view = c("month", "year"),
  plot.type = "contour",
  color = "topo",
  cond = list(site = "Deep"),
  main = "Deep"
)
mgcv::vis.gam(
  x = tensor_month_year_ar1,
  view = c("month", "year"),
  plot.type = "contour",
  color = "topo",
  cond = list(site = "South"),
  main = "South"
)

# Check intercept differences between sites
plot(tensor_month_year_ar1, select = 5, all.terms = TRUE)
```



```
# Visualize 3D tensor smooths
```

```r
tensor_month_year_ar1_viz <- mgcViz::getViz(tensor_month_year_ar1)
plotRGL(mgcViz::sm(tensor_month_year_ar1_viz, 1))
plotRGL(mgcViz::sm(tensor_month_year_ar1_viz, 2))
plotRGL(mgcViz::sm(tensor_month_year_ar1_viz, 3))
plotRGL(mgcViz::sm(tensor_month_year_ar1_viz, 4))

# 4. Visualize model predictions ####

# Create new data for prediction
pdata <- tidyr::expand_grid(
  site = unique(data$site),
  month = seq(1, 12, length.out = 100),
  year = 2017:2019,
)

# Predict based on new data
pred <- predict(tensor_month_year_ar1, newdata = pdata, se.fit = TRUE)

# Compute and add SE
crit <- qt(0.975, df = df.residual(tensor_month_year_ar1)) # ~95% interval critical t
pdata <- pdata %>%
  mutate(
    fitted = pred$fit,
    se = pred$se.fit,
    upper = fitted + (crit * se),
    lower = fitted - (crit * se)
  ) %>%
  # Remove observations before the start of the time series
  filter(!(year == 2017 & month < 4)) %>%
  # Testing
  glimpse() %>%
  {.}

# Plot 4 sites per year
ggplot(pdata, aes(x = month, y = fitted)) +
  geom_ribbon(mapping = aes(ymin = lower, ymax = upper,
                            fill = site), alpha = 0.2) + # confidence band
  geom_line(aes(colour = site)) +    # predicted temperatures
  theme_bw() +                       # minimal theme
  labs(y = bquote('Water column heat storage'~(MJm^-2)), x = "Month", fill = "Site", colour =
"Site") +
  scale_x_continuous(breaks = seq(1,12,1), limits = c(4,12)) +
  facet_grid(.~year) +
```

```
  NULL


# Predict effect of year (keeping month constant at 7.5, near peak)
pdata_year <- tidyr::expand_grid(
  site = unique(data$site),
  month = 7.5,
  year = seq(2017, 2019, length.out = 40),
)


# Predict based on new year data
pred_year <- predict(tensor_month_year_ar1, newdata = pdata_year, se.fit = TRUE)

# Compute and add SE
crit_year <- qt(0.975, df = df.residual(tensor_month_year_ar1)) # ~95% interval critical t
pdata_year <- pdata_year %>%
  mutate(
    fitted = pred_year$fit,
    se = pred_year$se.fit,
    upper = fitted + (crit_year * se),
    lower = fitted - (crit_year * se)
  ) %>%
  # Testing
  glimpse() %>%
  {.}

# Plot 3 year pattern for each site
ggplot(pdata_year, aes(x = year, y = fitted)) +
  geom_ribbon(mapping = aes(ymin = lower, ymax = upper,
                    fill = site), alpha = 0.2) + # confidence band
  geom_line(aes(colour = site)) +   # predicted temperatures
  theme_bw() +                   # minimal theme
  labs(y = bquote('Water column heat storage'~(MJm^-2)), x = "Year", fill = "Site", colour =
"Site") +
  scale_x_continuous(breaks = seq(2017, 2019, 1)) +
  NULL
```

Supplementary Data Files

Water temperature (°C) data from the Kluane moorings is available in the following Dataverse repository:

McKnight, Ellorie, 2021, "Kluane Lake Moorings Temperature Data", https://doi.org/10.7939/DVN/RTJMIF , Scholars Portal Dataverse, V1, UNF:6:YS6xIq5b6BUaPfHFYPmwDg== [fileUNF]