Quantifying the vulnerability of Arctic water supply lakes to environmental change through paleolimnological assessment

Thesis submitted in partial fulfillment of the requirements for the degree of
Master of Science in Geography

Paige Cincio

Co-supervisors:
Dr. Sonia Wesche
Dr. Andrew Medeiros

Committee Members:
Dr. Konrad Gajewski
Dr. André Viau

Department of Geography, Environment, and Geomatics
Faculty of Arts
University of Ottawa

ACKNOWLEDGEMENTS

I am especially grateful for my co-supervisors, Dr. Andrew Medeiros and Dr. Sonia Wesche, for their expertise, support, and patience. Andrew, thank you for guiding me through my undergraduate and master's theses over the past three years and for our many Arctic adventures. Sonia, thank you for your efforts towards developing my project, and for always ensuring I was managing inside and outside the lab. It has been an honour learning from you both.

To my committee members, Dr. Konrad Gajewski and Dr. André Viau. Konrad, you were the backbone of this project for offering your lab and office space to me, and for treating me as one of your own students. I cannot thank you enough for your unending support and generosity, and I'll never forget how to run the "clam" package in R. André, thank you for stepping in last minute as an examiner and for your valuable insight.

For two seasons of field work, I must thank Alannah Niemeyer, Sevrenne Sheppard, Andy Williams, and Sherry Wu. Fieldwork would not have been possible without your hard work and friendship, especially on the "Sole Circuit". Thank you to Simon Qamanirq for being our field guide in Igloolik. Thank you to the Northern Scientific Training Program for funding my field research. Thank you to all the lab personnel at uOttawa, including Chronos Scientific Inc. and the André E. Lalonde AMS Lab for helping me analyze my samples. Thank you to Cara MacKenzie for processing core IG8, and to Freddy Liu for GIS assistance.

To my girls at the Laboratory for Paleoclimatology and Climatology – Michelle Briere, Amanda Lagacé, Mercedes Liedtke, Karen Neil, Camille Tamo, and Charlene Williams – thank you for welcoming me into your group and molding me into a true "DH". Your friendship and academic advice were integral to my time at uOttawa. Special shout out to Camille Tamo and Michelle Briere for their technical support in R.

Writing this thesis during a global pandemic was interesting to say the least, and I'd like to thank my friends and family for saving me from going completely "chirono-mad". You all were the driving forces keeping this Pangaea together. A final dziękuję ci to my biggest supporters, Chris and Alina Cincio.

ABSTRACT

Anthropogenic stressors to freshwater environments have perpetuated water quality and quantity challenges for northern communities across Arctic Canada, making drinking water resources a primary concern for Arctic populations. To understand the ecological trajectory of freshwater supply sources, we conducted a paleolimnological assessment on two supplemental sources of freshwater in Igloolik, Nunavut, Canada. A stratigraphic examination of bioindicators (Insecta: Diptera: Chironomidae) allowed for paleotemperature reconstructions with decadal and centennial resolution over the past 2000 years. Between 200 and 1900 CE, the sub-fossil chironomid community was comprised of cold-water taxa, such as *Abiskomyia, Micropsectra radialis*-type, and *Paracladius*. Reconstructed temperatures were consistent with known climate anomalies during this period. A rapid shift in the composition of the chironomid community to warm-water adapted taxa (*Chironomus anthracinus*-type*, Dicrotendipes,* and *Tanytarsus lugens*-type) in the late 20th century was observed in both systems. Our results demonstrate that these lake ecosystems are undergoing marked transformations to warmer, more nutrient-rich environments, and suggest water sustainability pressures on freshwater and human systems will likely continue in tandem with ongoing climate change. To contextualize the influence of recent warming and elucidate the status of water resource vulnerability over the longer term, paleolimnological methods can be usefully applied as components of vulnerability assessments.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1:

Introduction

Freshwater sustainability in Arctic regions is increasingly uncertain amid ongoing climate change through the 21st century. Pronounced warming in high latitude regions has altered hydrological cycles that govern freshwater distribution and availability, resulting in enhanced evaporative stress to Arctic lakes (Ahmed et al., 2013; Bouchard et al., 2013; Linderholm et al., 2018). Increased evaporative stress in the summer months, coupled with decreased winter precipitation inherently destabilizes the water balances of drinking water resources (Woo, 2010; Bakaic & Medeiros, 2017). This presents challenges for Arctic communities that often rely on a single, shallow source for their municipal supply (Medeiros et al., 2017). The water quality and quantity pressures to drinking water sources impact both environmental and human well-being, raising water security concerns for Arctic communities in Canada (Medeiros et al., 2017; Harper et al., 2020).

Approaches to address water security concerns through vulnerability assessments have gained momentum throughout recent decades (Raskin et al., 1997; Ford & Smit, 2004; PRI, 2007; Alessa et al., 2008; Dunn & Bakker, 2011), utilizing a variety of biophysical and social indicators to characterize freshwater vulnerability. Here, we define water resource vulnerability as the susceptibility of a system to damage caused by external forces, the sensitivity of the system, and the ability of the system to respond (Kelly & Adger, 2000; Luers, 2005; Plummer et al., 2012). While it is generally agreed that freshwater vulnerability persists amongst Arctic communities, these conclusions are based on temporally limited observations (Plummer et al., 2012). It is therefore necessary to examine aquatic ecosystem functioning beyond annual and decadal measures to adequately capture environmental variability (Alessa et al., 2008; Wu et al., 2013).

Using subfossil biological indicators known to respond to environmental disturbances (Walker et al., 1999, Brooks et al., 2001), paleoclimate reconstructions offer long-term records of environmental change to elucidate current ecological patterns through a contextual lens. Over the past 2000 years, Arctic climate reconstructions have identified climate oscillations and associated biological changes coincident with the Medieval Climate Anomaly (Porinchu et al., 2009a), Little Ice Age (Fortin & Gajewski, 2016), and 20th century (Quinlan et al., 2005; Medeiros et al., 2012).

In a vulnerability context, paleolimnological analysis can provide a basis for evaluating current and future ecological trends to inform sustainable freshwater use. To date, paleolimnology has not yet been explored as a measurement of water resource vulnerability.

1.2 Central thesis objectives

This thesis is guided by three objectives: (1) reconstruct the climate of Igloolik over the past 2000 years, (2) relate the temperature reconstruction to past lake productivity, and (3) use the paleoenvironment to quantify the ecological trajectory of the system. A paleolimnological analysis was conducted to quantitatively assess the vulnerability of two supplemental drinking water lakes in Igloolik, Nunavut, Canada to environmental change over the period 200 – 2018 CE. Past July air temperatures and biological productivity reconstructed using chironomids was used to contextualize recent climate warming and estimate ecological trajectories. This study aims to address the research gaps regarding climate change and measurements of drinking water vulnerability, and results from this study will contribute to the understanding of freshwater sustainability in Arctic communities.

CHAPTER 2:

Literature Review

2.1 Arctic Climate

Multi-proxy paleoclimate records indicate spatial and temporal patterns of climate change though the Holocene in the Canadian Arctic (Kaufman et al., 2009; Briner et al. 2016). Oscillations in average temperatures over the past ~11,600 years BP (before present) indicate warming in the early Holocene (Holocene Climate Optimum), a transition period of broad warmth in the middle Holocene, followed by cooling in the late Holocene (Briner et al., 2016). Fortin & Gajewski (2016) reconstructed mean July air temperatures on the Boothia Peninsula in the Central Canadian Arctic over the last 7000 years BP, noting several trends. Prior to 5000 years BP, temperatures were highest and reached 7.5 °C. This was followed by cooling over the mid- to late-Holocene, with the coolest temperatures coinciding with the Little Ice Age between 460 years BP and 360 years BP. The Neoglacial cooling trend through the late Holocene is attributed to an orbitally driven reduction in summer insolation in northern latitudes (Kaufman et al., 2009).

Over the last 2000 years, Arctic climate was defined by a long-term cooling, with periods of decadal to centennial variability. Although the timing of the major climate variations may vary spatially, periods identified within the Common Era (CE) include the Roman Warm Period (RWP; ~1-300 CE; Ljungqvist, 2010), Dark Ages Cold Period (DACP; ~300-800 CE; Ljungqvist, 2010), Medieval Climate Anomaly (MCA; ~950-1250 CE; Lamb, 2002), and Little Ice Age (LIA; ~1300-1900 CE; Lamb, 2002). Within these major climate periods, regional environmental influences dominated rather than uniform warming or cooling (Hunt, 2006; Graham et al., 2011). For example, the onset of the LIA occurred earlier in the Arctic, Europe, and Asia than other parts of the globe (Stocker et al., 2013). Common Era paleoclimate reconstructions often lack data from the western and central Canadian Arctic Archipelago (Nicolle et al., 2018), where the entire Canadian Arctic may not be adequately represented (Tamo & Gajewski, 2019).

Unlike the spatial variability of climate changes, climate patterns across the Arctic during the Common Era are more defined (Kaufman et al., 2009). The DACP from ~300-800 CE was cooler, with a cold spike around 675 CE possibly from volcanic activity (Nicolle et al., 2018). The MCA from ~ 950 – 1250 CE was characterized by peak warming and a drier climate (Werner et al., 2018). The LIA from ~ 1300 – 1900 CE was the coolest period over the past 2000 years, and associated with wetter conditions (Linderholm et al., 2018). Since the 20th century, Arctic regions continue to warm at a rapid rate as a result of anthropogenic disturbances (Stocker et al., 2013).

2.2 Arctic Environmental Change

Arctic environments are considered to be highly sensitive to changes in temperature and seasonality (Schindler & Smol, 2006), and are currently warming at double the global rate as a consequence of anthropogenic influence (Stocker et al., 2013). The polar amplification of warming on Arctic lakes results from positive feedback mechanisms such as increased energy absorption, and increased surface and atmospheric temperatures (ACIA, 2004). Altered thermodynamic relationships impair seasonal regimes to promote earlier onset of snow melt (Stone et al., 2002), shorter ice-cover duration (Brown & Duguay, 2011), permafrost degradation (Osterkamp, 2005), and changes in precipitation and evaporation regimes (Kattsov & Walsh, 2002; Derksen & Brown, 2012). These changes have been prominent since the end of the Little Ice Age ~ 1900 CE, however, anthropogenic forcing characteristic of recent decades has likely accelerated these processes (Solomon, et al., 2007). This change is significant compared to temperatures reconstructed from Arctic lakes over the last two centuries (Quinlan et al., 2005).

Arctic landscapes contain a multitude of lakes as a result of depressions shaped by receding glaciers, however, naturally low precipitation input yields water renewal times of 100+ years (Schindler & Smol, 2006). In addition, large, shallow lakes have a broad interface for atmospheric interactions, making them highly susceptible to environmental stressors (Hinzman et al., 2005). Rising air temperatures exert evaporative stress on Arctic lakes (Carroll et al., 2011), coupled with low precipitation reducing snow and ice melt contributions (Lantz & Turner, 2015, Bakaic & Medeiros, 2017). Historically permanent lakes are transitioning to ephemeral systems (Smol, 2007), and recent observations of Arctic lakes temporarily drying out (Antoniades et al., 2005) and desiccating completely (Macdonald et al., 2012; Bouchard et al., 2013, Lewis et al., 2015) are becoming more common. The already limited supply of available freshwater in Arctic regions is being exacerbated by increased drawdown and decreased replenishment, enhanced through complex relationships that emerge from climate change.

2.3 Water Security in Arctic Canada

For Indigenous communities in Arctic Canada, water security in a warming climate is increasingly becoming a cause of concern, with implications for future freshwater supplies (McCarthy et al., 2005). For example, Bakaic & Medeiros (2017) modelled the water supply under climate and demand scenarios for Iqaluit and Rankin Inlet, Nunavut, identifying end-of-winter shortages as early as 2018 and 2020, respectively. In both 2018 and 2019, the City of Iqaluit declared a water emergency. For most communities, however, a lack of proper baseline data presents challenges for mitigation and adaption efforts (Bring et al., 2015). Vulnerabilities of freshwater systems emerging from biophysical and social origins function simultaneously to exacerbate pressures on freshwater supply (Medeiros et al., 2017), emphasizing the importance of anticipating upcoming challenges for Indigenous communities in the Arctic from multiple perspectives.

A lack of planning, as well as overuse of the freshwater supply in Arctic Canada, has jeopardized the sustained access to freshwater of adequate quantity and quality. For example, in the vast Inuit territory of Nunavut, while municipal governments are responsible for water infrastructure and treatment systems, the Government of Nunavut has not allocated efforts towards freshwater policy development or planning for territory-wide adaptation to climate change (Medeiros et al., 2017). Weaknesses in governance have resulted in poor planning, improper resource development, inadequate infrastructure, and loss of Indigenous knowledge (Ford et al., 2007), ultimately increasing local vulnerability to environmental change. Increased incidences of boil and drinking water advisories and large-scale water outages have raised concerns about looming water security crises (GN, 2015). In response, Medeiros et al. (2017) proposed a freshwater management framework for Nunavut, incorporating human, infrastructure, and environmental elements to address water security for northern peoples.

Water security measures generally follow a human-centred focus; however, freshwater systems are significantly affected by biophysical components which should be incorporated into governance and adaptation strategies (Medeiros et al., 2017). Recent climate warming in Arctic regions has destabilized water balances by shifting seasonal transitions, reducing winter precipitation input, and increasing evaporative stress on aquatic ecosystems (Woo, 2010). Permafrost degradation can also redirect water into an increasing active layer rather than remaining in lakes and ponds (Wrona et al., 2016), resulting in reduced surface water availability. Low precipitation during dry summer months already constrains the water supply in Arctic regions, limiting the natural reservoir recharge capacity to support human populations (Schindler & Smol, 2006; Bakaic & Medeiros, 2017). Arctic communities therefore face natural and anthropogenic pressures that impact water quantity. This is coupled with water quality issues that arise from ageing municipal water infrastructure, population growth and expansion of communities, and leeching contamination from industrial and resource development (Instanes et al., 2016). For example, biological impairment and elevated concentrations of nutrients and metals from local pollution were identified in two urbanized streams in Iqaluit (Medeiros et al., 2011).

Biophysical changes, in conjunction with societal changes, have recently placed increased pressure on the susceptibility of Inuit to climate-related risks (Ford et al., 2006). For example, Goldhar et al. (2014) documented the experiences of Inuit residents in Rigolet, Nunatsiavut, Labrador, to changes in freshwater, where residents noted decreased summer water levels affecting their ability to obtain drinking water. Evaporative stress in drier summer months has impacted access to drinking water and food sources, threatening water security despite Inuit adapting accordingly. To successfully cope with climate change, Ford et al. (2006) demonstrated that Inuit rely on traditional knowledge, flexible and diverse use of resources, and social networks. Additional efforts are required, however, to address and characterize biophysical changes to climate and drinking water-related risks for Arctic populations.

2.4 The Vulnerability Approach

Addressing water security challenges often begins by assessing a system's vulnerability, defined by Ford & Smit (2004) as "*the susceptibility to harm in a system relative to a stimulus or stimuli*". From a biophysical perspective, social (or human) vulnerability is determined by the nature of the physical event to which the human system is exposed, the likelihood or frequency of occurrence of the event, the extent of human exposure, and the system's sensitivity to the impacts of a particular event (Brooks, 2003). The research framework for vulnerability analysis is a two-stage process; first assessing the current vulnerability, then defining and projecting future vulnerability. The current vulnerability of a community to climate-related risks is a function of the physical exposure itself, and its adaptive capacity to address the risks (Ford & Smit, 2004; Smit et al., 2008). Projected future vulnerability is characterised by future exposure and future adaptive capacity; this stage relies on examining past climate responses to climate change to characterize the trajectory of future climate scenarios.

While Ford & Smit (2004) first developed a (social) vulnerability approach for Arctic communities, water resource vulnerability refers to the exposure, sensitivity, and adaptive capacity of water resources to climate change (Wu et al., 2013). Relevant indices have been developed to assess water resource vulnerability at different scales; globally (Water Resources Vulnerability Index; Raskin et al. 1997) regionally (Water Availability Index; Meigh et al., 2004) and locally (Canadian Water Sustainability Index; PRI, 2007). Operationally, these indices quantify water availability using various indicators, where an indicator is defined as any variable used to determine the vulnerability to a drinking water system in a watershed. The indicators from the respective indices are suitable for quantifying water availability/vulnerability for mid-latitude regions, however, they may not be adequate for assessing the hydrologically sensitive and isolated nature of Arctic watersheds (Alessa et al., 2008). Thus, the Arctic Water Resource Vulnerability Index (AWRVI) was developed by Alessa et al., (2008).

The AWRVI framework expands on existing water indices (Water Resources Vulnerability Index, Raskin et al., 1997, Water Poverty Index; Lawrence et al. 2002, Water Availability Index; Meigh et al., 2004), and assumes that communities lacking data are more vulnerable than communities with extensive data. The AWRVI is based on social and physical sub-indexes, allowing for initial water security assessments to be made for communities and knowledge transfer to community members. The physical subindex contains five constituent subindices of biophysical drivers, including the natural supply, municipal supply, water quality, permafrost, and habitat. The physical subindex as follows:

$$\text{AWRVIphysical} = [\text{AWRVI}_{\text{natural\_supply}} + \text{AWRVI}_{\text{municipal\_supply}} + \text{AWRVI}_{\text{water\_quality}} + \text{AWRVI}_{\text{permafrost}} + \text{AWRVI}_{\text{subsistence\_habitat}}]/5$$

The equation presents limitations, as the indicators do not consider the quantitative data of source productivity, availability, or climate trajectory to effectively define future vulnerability. Thus, the AWRVI may be insufficient in characterizing the influences of climate variability on aquatic ecosystem functioning. Moreover, while the described indices (Raskin et al., 1997; Meigh et al., 2004; PRI, 2007; Alessa et al., 2008) assess vulnerability at one specific time or over short (decades) time scales, environmental variability cannot be effectively evaluated over limited temporal scales (Wu et al., 2013). For water vulnerability assessments, Alessa et al. (2008) highlight the potential importance of a timescale longer than 30 years to account for the interannual and interdecadal effects of climate variability on freshwater ecosystems.

2.5 Paleolimnology

In the absence of a long-term instrumental temperature record, proxy data are used to reconstruct past temperatures. Paleolimnology extracts the proxy data archived in sediment profiles of inland aquatic systems to reconstruct past environmental conditions (Smol & Douglas, 1996). The foundation of paleolimnological studies relies on sediment cores, which represent the chronological deposition of organic materials over short (decades) and long (centuries) time scales. Sediments continuously accumulate materials over time, such that deeper deposits are older material, progressively overlain by younger material. The result is a depositional sequence containing fossilized biota, among other components to provide a record of environmental change through time (Quinlan et al., 2005).

Proxy data include physical and biological parameters, each functioning as different expressions of productivity. Common proxies employed in climate reconstruction studies include diatoms, pollen, and chironomids (non-biting midges). Multi-proxy approaches are often conducted to maximize the array of information contained in the sample and provide a more holistic overview of past limnological conditions (Birks & Birks, 2006). For example, Kaufman et al. (2009) compiled lake sediment, tree ring, and ice core records to produce a 2000-year Arctic-wide climate reconstruction through multi-proxy analysis. In lake sediment archives, chironomid subfossils are a reliable biological proxy for developing quantitative estimates of the past.

2.6 Chironomids as Indicators

Chironomids (Insecta: Diptera: Chironomidae) are one of the most abundant and diversified animal remains in Arctic lake sediments (Oliver & Dillon, 1997). At least 10,000 species exist globally (Armitage et al., 2012), which undergo holometabolism; a life cycle that follows four stages of development: egg, larva, pupa, and adult. The adult terrestrial stage of chironomids is limited to a few days, dedicated to reproduction. The majority of the lifecycle develops in the aquatic environment, where the larval stage may take several years to complete (Walker, 2001). The larval stages are most relevant to paleolimnological studies, as the chitinized head capsules shed by third- and fourth-instar larvae during ecdysis are best preserved in the fossil record. The head capsules contain structural features that can be identified to genus, species-type, or species level, depending on the taxon. The distribution of larvae within lake sediments can be correlated to a variety of environmental factors, including temperature, dissolved oxygen, and nutrients, and thus are indicative of regional ecological conditions (Walker, 2001).

Temperature has been demonstrated to be a primary variable governing chironomid abundance and distribution (Walker et al., 1991; Medeiros and Quinlan, 2011; Heiri et al., 2014; Fortin et al., 2015), and directly affects chironomid lifecycle development (Eggermont & Heiri, 2012). For example, Medeiros & Quinlan (2011) sampled surficial lake sediments and found that deep lakes in cold regions of the Arctic are dominated by cold-water adapted taxa such as *Abiskoymia* and *Heterotrissocladius*, and shallow lakes and ponds in warmer regions of the Arctic are represented by warm-water adapted taxa such as *Microtendipes* and *Dicrotendipes.* Porinchu et al. (2009a) sampled a lake sediment core and noted shifts in chironomid community composition from cold- to warm-stenothermic species that corresponded to higher chironomid-inferred summer air temperatures post-1600 CE. Changes in chironomid community stratigraphy provide valuable linkages between climate change and biotic responses, thus, chironomids are highly useful for detecting and inferring past environmental conditions.

Trophic status (Brooks et al., 2001) and food availability (Walker & Cwynar, 2006) have been demonstrated to influence chironomid taxa distribution. Medeiros et al. (2014) noted that some stenothermic taxa form a positive relationship with allochthonous nutrient input, and Medeiros & Quinlan (2011) identified nitrogen as a significant secondary variable governing chironomid assemblages across the eastern Canadian Arctic. As such, employing a multi-proxy approach by examining the organic matter and carbonate content are useful for interpreting chironomid community dynamics and reinforcing climate reconstructions. Fortin & Gajewski (2010a) examined primary production and food availability in conjunction with chironomid concentrations in a sediment core from northern Victoria Island, Nunavut Territory, finding that changes through time aligned for all proxies to produce a coherent climate record for the Holocene.

It is therefore necessary to consider secondary environmental gradients when developing chironomid-inferred paleotemperature reconstructions as multiple variables can significantly influence trophic activity (Medeiros et al., 2015).

Chironomids are used widely in temperature reconstruction studies (Quinlan et al., 2005; Larocque-Tobler et al., 2009; Axford et al., 2019; Porinchu et al., 2019). Medeiros et al. (2012) reconstructed recent environmental changes at Baker Lake, Nunavut, where chironomid community shifts determined that summer surface water temperatures increased by 2 °C over the past 60 years. Fortin & Gajewski (2010b) reconstructed the temperature history of western Victoria Island over 10.5 ka, where the sediment and chironomid archives produced climate reconstructions similar to others across the Arctic. Fortin & Gajewski (2016) also demonstrated that during periods of climate transitions through the Holocene, chironomid production increased on the Boothia Peninsula, irrespective of it was a cooling or a warming. The chironomid assemblages could be explained by the intermediate disturbance hypothesis (Connell, 1978), where environmental conditions enabled the increase of new species, as well as the persistence of older assemblages.

2.7 Calibration Data

Quantifying the chironomid-temperature relationship in paleolimnological studies relies on modern calibration datasets (Birks & Birks, 1980). These modern calibration sets are composed of biotic assemblages from the uppermost sediments of a series of lakes that correspond to modern environmental conditions (Webb & Bryson, 1972). Necessarily, calibration sets need to cover large geographical ranges so that environmental and climate gradients, and modern distributions of a particular bioindicator are adequately captured (Porinchu et al., 2009b; Fortin et al., 2015). Interpretations of past conditions can be made with greater confidence with a calibration dataset that maximizes the number of modern analogues in the environment to effectively represent a bioindicator's tolerances (Birks, 1998). The modern analogues within an expansive dataset can then be applied to characterize all biotic assemblages archived down-core to reconstruct past environmental conditions.

Regionally-based chironomid training sets representing northern North American lakes include Wilson et al. (2004) from the Yukon/BC, Gajewski et al. (2005) from the Canadian Arctic Islands, Barley et al. (2006) from western Canada, Larocque et al. (2006) from northwestern

Québec, Porinchu et al. (2009b) from the central Arctic, Fortin & Gajewski (2011) from the Canadian Arctic, and Medeiros & Quinlan (2011) from eastern Canada. A compilation of seven regional training sets from the Canadian Arctic and sub-Arctic merged as one pan-northern North American calibration set was produced to encompass modern analogues and enable transfer function computation (Fortin et al., 2015). This dataset contains 435 lakes and 78 chironomid taxa. This study demonstrates that larger datasets covering greater environmental gradients are better equipped to detect significant correlations between chironomid assemblages and environmental variables, differentiate outliers from errors in a limited sample population, and accurately reconstruct regional summer temperatures.

CHAPTER 3:

Detailed Methodology

This study analysed sediment cores from two lakes in Igloolik, Nunavut, Canada: Small Fish Lake (core SFL), and lake IG8 (core IG8). Small Fish Lake is the deepest freshwater lake on the island and used as a supplemental freshwater supply for the municipality, as well as for recreational fishing. Lake IG8 is located on the east end of the island near a local whaling camp and used to support seasonal subsistence activities. The paleoenvironmental methods applied to the two cores included age-depth modelling, loss-on-ignition, and chemical and biological processing of the fossil assemblages. As studies involving lake sediment cores from the Arctic often present data processing challenges (Peros & Gajewski, 2009), alternative methods for developing a reliable age-depth model for core SFL were used, as detailed below. Multivariate data analysis methods were then used to identify the timing and magnitude of the chironomid assemblage changes, and inference models were developed to reconstruct historic July air temperatures for both cores.

3.1 Field Methods

Two sediment cores were collected from Small Fish Lake and Lake IG8 on July 17 and July 19, 2018, respectively (Figure 3.1). Core SFL, totalling 40.5 cm in length, was extracted from the western basin of Small Fish Lake at a depth of 5.3 m. Core IG8, totalling 12.5 cm in length, was extracted from the centre basin of Lake IG8 at a depth of 1.9 m. Both cores were sampled using a Uwitec gravity corer (8.4 cm diameter) deployed from a boat, extruded on site at 0.5 cm intervals, and stored in Whirl- Pak® bags. The samples were transported back to the University of Ottawa in Ottawa, Ontario and refrigerated at 4 °C. In situ measurements of GPS coordinates, epilimnetic (0.5 cm) water temperature and depth were recorded for each lake.

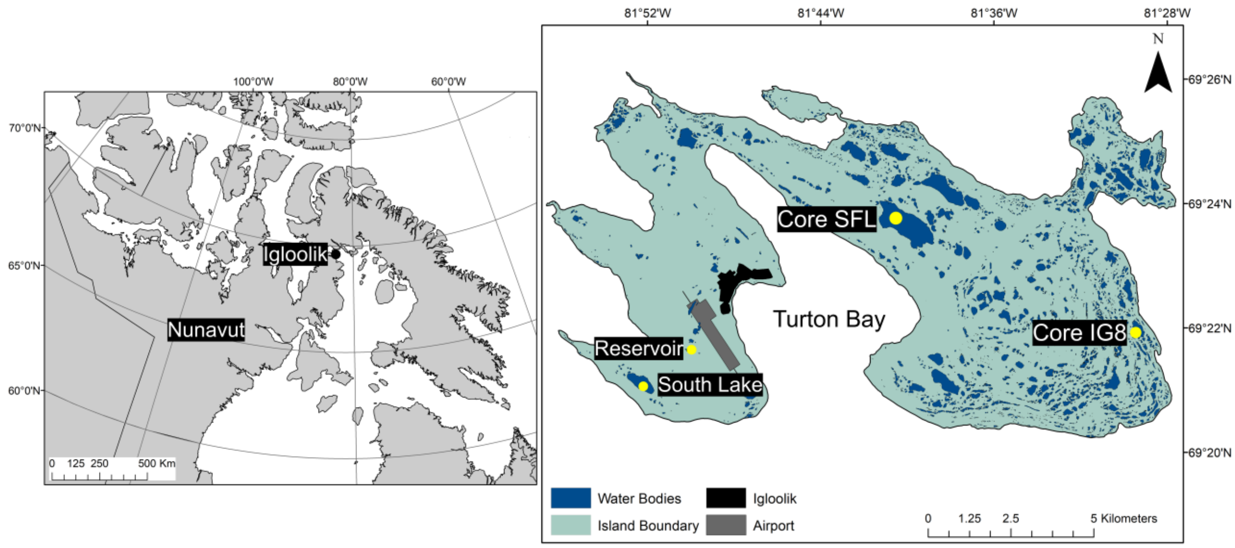

Figure 3.1. Location of the Small Fish Lake and Lake IG8 coring sites in Igloolik, Nunavut, Canada.

3.2 Laboratory Methods

To maintain standard methods throughout the laboratory components of this study, protocols were followed as outlined on the Laboratory for Paleoclimatology and Climatology website (www.lpc.uottawa.ca). The sediment cores were first measured for percent organic matter and carbonates using loss-on-ignition (LOI). Chronologies were then developed using ^{210}Pb and ^{14}C dating techniques. Finally, the biological assemblages were processed as described below.

3.2.1 Loss-On-Ignition

Organic matter and carbonate content (expressed as % dry weight) for the length of the sediment cores were determined by measuring the weight loss-on-ignition (LOI) following Heiri et al. (2001). At 0.5 cm intervals, ~0.5cm^3 of wet sediment were taken, heated to 105°C to remove any moisture, ignited at 550°C for 4 hours to remove organic matter, then ignited at 950°C for 2 hours to remove carbonates using a LECO TGA701 Thermogravimetric Analyzer. Calcium oxalate was used as a standard with each batch to ensure analytical uncertainty no greater than

0.1%. The following formulas were used to express the weight percent organic matter and carbonate:

$$\text{weight \% organic matter} = \frac{100(dry\ weight_{150} - ignited\ weight_{550})}{dry\ weight_{105}}$$

$$\text{weight \% carbonate} = \frac{100(dry\ weight_{550} - carbonate\ weight_{950})}{dry\ weight_{105}}$$

3.2.2 Chronology

For the uppermost horizons of core SFL and the entire length of core IG8, Lead-210 (^{210}Pb) dating was employed. Seventeen subsamples from core SFL and nine subsamples from core IG8 were extracted at 0.5 cm intervals, dried in an oven at 75°C for 24 hours, and ground with a mortar and pestle. Samples weighing between 100 – 300 mg dry weight were sent to be analyzed by Chronos Scientific Inc. (formerly MyCore Scientific Inc.) at the University of Ottawa. ^{210}Pb activity was measured using alpha spectroscopy and converted to age using a constant-rate-of-supply model (CRS; Appleby & Oldfield, 1978).

For the lower sedimentary horizons of core SFL, Radiocarbon (^{14}C) dating was used. While picking organic matter from the sediments was attempted, sufficient amounts of aquatic plant material required for radiocarbon dating could not be obtained from the core. Instead, four bulk sediment samples were used, where subsamples were dried at 60 °C for 24 hours, and ground with a pestle and mortar. The dried subsamples weighed between 300 – 500 mg and were sent to the André E. LaLonde Accelerated Mass Spectrometry Laboratory at the University of Ottawa to be further processed and analyzed. The radiocarbon carbon results were expressed as the fraction modern carbon ($F^{14}C$), and the ages were calculated as -8033ln($F^{14}C$). The samples were calibrated using OxCal v4.3 (Bronk Ramsey, 2009) and the IntCal13 calibration curve (Reimer et al., 2013).

3.2.3 Chironomids

Chironomid analyses followed Walker (2001). The subfossil head-capsule remains of chironomids were analyzed at 0.5 cm resolution between 0 and 10 cm, then at 2 cm intervals between 12 and 40 cm with 2 additional samples from 11 and 39 cm depth for core SFL. For core

IG8, 12 samples were analyzed at 1 cm intervals between 1 and 12 cm, as well as 2 additional samples at 0.5 and 12.5 cm depth. 1 – 2 grams wet weight of untreated sediment were digested in a 5% KOH solution for ~20 minutes over a hotplate, then rinsed with deionized water through a 90µm mesh sieve to collect the head capsules. In a Bogorov tray under a dissection microscope at 3x magnification, the individual specimens were picked and enumerated with forceps, where a minimum of 50 head capsules for each interval were collected; additional sample was weighed and sorted for intervals containing below 50 head capsules (Heiri & Lotter, 2001; Larocque, 2001; Quinlan & Smol, 2001). The head capsules were then collected and oriented onto glass coverslips and affixed to permanent slides using Entellen Mounting Medium over a warmed surface. Identifications were performed at 400x magnification under a compound light microscope to the best taxonomic resolution possible following Oliver & Roussel (1983) and Brooks et al. (2007), and Medeiros & Quinlan (2011) identification keys.

3.3 Data Analyses

3.3.1 Age-Depth Modeling

Developing reliable age-depth models based on the radiocarbon dating of Arctic sediments has proven to be difficult for several reasons. Local reservoir effects operating within lacustrine environments create ^{14}C-deficient carbon within the sediments, resulting in age offsets up to 2000 years too old (Macdonald et al., 1991). Low inputs of allochthonous and autochthonous organic matter within the lake catchment often yield inadequate amounts of material to extract from the sedimentary archives, where aquatic plants additionally absorb carbon from ^{14}C-deficient water. Likewise, the dissolution of calcareous bedrock and permafrost terrains can contaminate water with old carbon (Macdonald et al., 1991). With bulk sediment analysis, further ambiguity surrounds geochronology constructions due to uncertain carbon source pathways. These circumstances were no exception for core SFL, therefore, the methods to deal with a reservoir effect and/or old carbon for this study follow Peros & Gajewski (2009) and Tamo & Gajewski (2019).

The age-depth model for core SFL was built in the “clam” package v.2.3.2 (Blaauw, 2020) in R v.3.6.0 (R Core Team, 2019) using eight ^{210}Pb and four ^{14}C dates. The uppermost calibrated ^{14}C date at 11.25 cm and the lowermost ^{210}Pb date at 10.25 cm indicated an unusually high sedimentation rate, and thus a reservoir correction was estimated to establish a reliable chronology for core SFL (Peros & Gajewski, 2009). To correct for reservoir effects, the difference between the oldest ^{210}Pb date and youngest ^{14}C date was calculated and subtracted from the remaining radiocarbon dates, following Peros & Gajewski (2009) and Tamo & Gajewski (2019). The oldest radiocarbon date was unusually old and was discarded. To estimate the ages of samples deeper than 32.5 cm, 50 years were added to the third hardwater-corrected radiocarbon date for every 2 cm intervals. A new age-depth model was fit with a linear interpolation to the corrected ages with an estimated hardwater correction of 731 years (Figure 3.2).

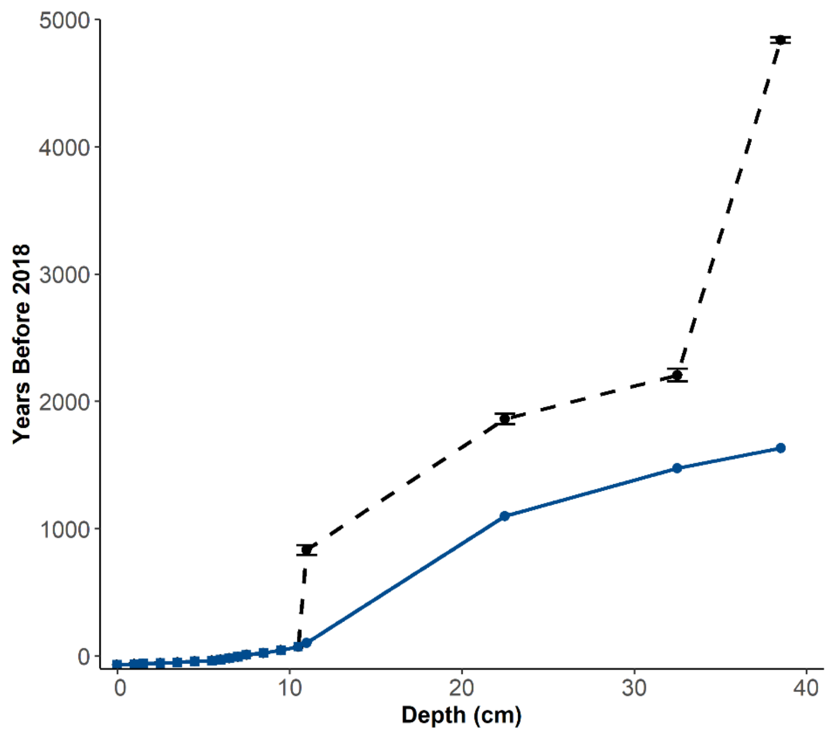

Figure 3.2. Age-depth model for core SFL. Black circles are ^{14}C median calibrated dates with age range; squares are ^{210}Pb dates; blue circles are hardwater-corrected ^{14}C dates. Dashed line represents the age-depth model without hardwater correction; solid line represents the corrected age-depth model. See text for details.

3.3.2 Numerical analyses and climate reconstructions

All data analyses were completed in R v.3.6.0 (R Core Team, 2019). Rare taxa were removed from analysis, and taxa that were retained comprised of at least > 2 % of the chironomid sum per sample. The diagrams were divided into zones using a constrained cluster analysis with incremental sum of squares partitioning (CONISS) and a squared chord distance dissimilarity coefficient (Gordon & Birks, 1972). Significance of the zones was identified using a broken stick model (Bennett, 1996). Species richness was estimated through rarefaction using the "vegan" package v.2.5-6 (Oksansen et al., 2019). The chironomid assemblages were Hellinger-transformed and summarized using Principal Components Analysis (PCA) using the "FactoMineR" package v.2.0 (Lê et al., 2008) and visualized using the "factoextra" package v.3.6.3 (Kassambara & Mundt, 2020).

A chironomid-inferred paleotemperature model (Fortin et al., 2015) was applied to the relative abundance of chironomids from both lakes to estimate July air temperatures for the past two millennia. This was based on a weighted-averaging partial-least squares (WA-PLS) transfer function and validated with goodness-of-fit tests using the "palaeoSig" package v.2.0-3 (Telford, 2019). The root-mean square error of prediction (RMSEP) indicated a 2-component model was most appropriate for the temperature reconstructions for both cores. The overall trends in the WA-PLS2-derived temperature profiles were then summarized using Gaussian smoothing Generalized Additive Modelling (GAM) in the "mgcv" package v.1.8-34 (Wood, 2011). Finally, the rate of change for temperature from 1950 CE to present was calculated for each lake.

CHAPTER 4:

Quantifying the vulnerability of Arctic water supply lakes to environmental change through paleolimnological assessment

Key words: Climate change, Arctic, Paleolimnology, Chironomidae, Freshwater supply, Vulnerability

4.1 Introduction

The long-term sustainability of Arctic freshwater resources is uncertain in regions undergoing large-scale transformations in response to 20^{th} century climate warming (Wrona et al., 2006). Greenhouse gas radiative forcing and positive feedback mechanisms, such as reduced ice-albedo and altered hydrological cycles (Müller et al., 2012; Linderholm et al., 2018), have increased heat transport to high-latitude regions (Ahmed et al., 2013). One manifestation of modern warming is increased evaporative stress on Arctic lakes during lengthening summer seasons (Serreze & Barry, 2011; Bouchard et al., 2013), which can affect the recharge capacity of freshwater basins (Bakaic et al., 2018). Hydroclimate varies both spatially and temporally; this arises from strong seasonal controls during ice-free periods, and on permafrost thaw, snowmelt, and evapotranspiration, which can alter the distribution and availability of water (Bring et al., 2016). The cascading effects of climate warming are depreciating the naturally low storage capacities of Arctic watersheds, making water security an increasingly important component of community sustainability (Medeiros et al., 2017).

Water security is achieved through sustainable access to adequate quantities of acceptable quality water to support drinking water needs, human well-being, ecosystem integrity, and socio-economic development, as well as protect against water-related hazards and climate change (U.N. Water, 2013). Across the North American Arctic, water security challenges have been reported in Nunavik, Quebec (Martin et al., 2007), Rigolet, Labrador (Goldhar et al., 2014), Coral Harbour, Nunavut (Daley et al., 2015), and much of rural Alaska (Penn et al., 2017), and remain largely unaddressed. Vulnerability assessments (Ford & Smit, 2004) are often conducted to address climate related impacts within a water security framework, where water resource vulnerability refers to the susceptibility of a system to damage caused by external forces, the sensitivity of the system, and the ability of the system to respond (Kelly & Adger, 2000; Luers, 2005; Plummer et al., 2012). While water resource indices tend to assess vulnerability at one specific time or over short (decades) time scales (Raskin et al., 1997; PRI, 2007; Dunn & Bakker, 2011), environmental variability is not effectively captured over limited temporal scales (Wu et al., 2013). Alessa et al. (2008) highlight the potential importance of using a timescale longer than 30 years for water vulnerability assessments to account for the interannual and interdecadal effects of climate variability on freshwater ecosystems. In the Arctic, with few long climate records, paleoclimate methods are needed to provide the required data.

Proxy-based paleoclimate reconstructions have documented long-term Arctic climate variability during the Common Era (last 2000 years) (e.g., Kaufman et al., 2009; Briner et al., 2016; Werner et al., 2018), and indicate that the rate of recent warming is anomalous. Arctic lakes are an important source of information about these past climates as their basins contain sedimentary sequences of subfossil biological indicators. Chironomids (Insecta: Diptera: Chironomidae) are well preserved in lake sediments and are indicators of paleoclimate due to their associations with environmental variables, such as temperature, dissolved oxygen, and nutrients (Walker et al., 1991; Brooks et al., 2001). At the scale of importance to this study, chironomid-inferred paleotemperature reconstructions conducted across the Arctic have detected climate variability during the Medieval Climate Anomaly (Porinchu et al., 2009a), Little Ice Age (Fortin and Gajewski, 2016), and 19th century (Quinlan et al., 2005; Medeiros et al., 2012). This suggests that a paleolimnological analysis can provide an understanding of climate history and associated ecological changes, which are useful for assessing current and future trends in a vulnerability context.

In this study, we apply a paleolimnological approach to establish the local water resource vulnerability of two supplemental water sources for the community of Igloolik, Nunavut, Canada. Through stratigraphic examination of bioindicators that respond to environmental stress (chironomids), we characterize the relationship between climate change and aquatic ecosystem functioning by (1) reconstructing the climate of Igloolik over the past 2000 years, (2) relating the temperature reconstruction to past lake productivity, and (3) using the paleoenvironment to quantify the ecological trajectory of the system. Our quantitative estimates of temperature and biological productivity are motivated by freshwater sustainability challenges, and we aim to address the research gaps that currently exist regarding climate change and indicators of drinking water resource vulnerability in the Canadian Arctic. This study can also serve as a template for freshwater sustainability strategies for other northern peoples and contributes to our understanding of water vulnerability in remote Arctic communities.

4.1.1 Site Description

The hamlet of Igloolik (69° 22’ 34” N, 81° 47’ 58” W, 53 m.a.s.l) is located on Igloolik Island in Foxe Basin, Qiqiktaaluk (Baffin) Region of Nunavut Territory, in Arctic Canada (Figure 3.1). The island is 103 km^2 in size, and the hamlet (population ~1700, 95% Inuit) lies adjacent to Turton Bay (Ford et al., 2006). Igloolik is located within a continuous permafrost zone, and the geology consists of Precambrian rocks flanked by Paleozoic sediments (Schau, 1984). The vegetation is mid to high Arctic, including grasses (*Dupontia* sp), mosses (*Bryum* sp., *Plagiomnium medium*), dwarf shrubs (*Salix* sp.), and flowering plants (*Dryas integrifolia*, *Saxifraga* sp.) (Derry et al., 1999). The region has a polar climate with a mean July air temperature of 7.4 °C and a total annual precipitation of ~222.4 mm (Station 2402541, Environment Canada).

Currently, the hamlet of Igloolik receives its drinking water from an un-named reservoir, which is recharged from South Lake (Figure 3.1). Small Fish Lake (SFL) (69 23’35” N, 81° 41’2” W) is the largest freshwater lake on the island, with a maximum depth of 5.6 m and has a known lake trout population, which local residents use for recreational fishing. In 2015, SFL was designated as a supplemental drinking water source for Igloolik after an over-winter shortage of reservoir water, and the exhaustion of the available end-of-winter supply from South Lake, which is not sufficiently deep for winter resupply purposes. Lake IG8 (69° 21’41” N, 81° 29’4” W) is situated in the eastern sector of the island with a maximum depth of 3.8 m and used seasonally by whalers during subsistence activities. The nearest mainland freshwater source in Melville Peninsula is approximately 10 km from the hamlet.

At the local level, additional risks to drinking water result from a multitude of socioeconomic factors. In the majority of Arctic communities, freshwater undergoes basic primary treatment through chlorination before being transported and deposited into the water storage tanks of individual buildings (Medeiros et al., 2017). As such, boil and drinking water advisories, and reports of residents running out of water and waiting for water refills (for hours or days) are not uncommon in Arctic communities (Daley et al., 2015). Population growth is also expected to impact water availability and increase short-term vulnerability (Bakaic & Medeiros, 2017). Cultural and personal preferences of Inuit also include drinking untreated water from its source (Daley et al., 2015), especially when travelling out on the land during camping and subsistence activities (Goldhar et al., 2013; 2014).

4.2 Methods

4.2.1 Field Methods

Two sediment cores were collected from SFL and Lake IG8 on 17 July and 19 July, 2018 respectively. The first, totalling 40.5 cm in length, was from the mid-basin (5.3 m depth) of Small Fish Lake (core SFL). The second, totalling 12.5 cm in length, was from the mid-basin (1.9 m depth) from Lake IG8 (core IG8). Both cores were collected using an Uwitec gravity corer (8.4 cm diameter) deployed from a boat, extruded on site at 0.5 cm intervals into Whirl-Pak® bags, then transported, stored, and refrigerated at 4 °C at the University of Ottawa in Ottawa, Ontario. In situ measurements of GPS coordinates, epilimnetic (0.5 cm) water temperature and depth were recorded for each lake.

4.2.2 Laboratory Methods

Organic matter and carbonate content (expressed as % dry weight) were determined by measuring the weight loss-on-ignition (LOI), where the sediment cores were analyzed at 0.5 cm intervals by sequentially igniting at 550 °C for 4 hours and 950 °C for 2 hours (Heiri et al., 2001) using a LECO TGA701 Thermogravimetric Analyzer. Core chronologies were established using ^{210}Pb for core IG8 and the uppermost horizons of core SFL, and ^{14}C for the remainder of core SFL. Nine subsamples from core IG8 and seventeen subsamples from core SFL were measured for levels of ^{210}Pb activity using alpha spectroscopy and converted to age using a constant rate of supply model (CRS) (Appleby & Oldfield, 1978), performed by Chronos Scientific Inc., in Ottawa, Ontario; formerly MyCore Scientific Inc. Four bulk sediment samples weighing between 300 – 500 mg dry weight were analyzed for ^{14}C at the André E. LaLonde Accelerated Mass Spectrometry Laboratory at the University of Ottawa. The samples were calibrated using OxCal v4.3 (Bronk

Ramsey, 2009) and the IntCal13 calibration curve (Reimer et al., 2013). The age-depth model was built in the "clam" package (Blaauw, 2020) in R v.3.6.0 (R Core Team, 2019).

Standard methods for chironomid processing followed Walker (2001). The subfossil head-capsule remains of chironomids were analyzed at 0.5 cm intervals between 0 and 10 cm, then at 2 cm resolution between 12 and 40 cm with 2 additional samples from 11 and 39 cm depth for core SFL. For core IG8, 12 samples were analyzed at 1 cm intervals between 1 and 12 cm, as well as 2 additional samples at 0.5 and 12.5 cm depth. For each interval, a minimum of 50 head capsules were enumerated (Heiri & Lotter, 2001; Larocque, 2001; Quinlan & Smol, 2001) from 1-2 grams (wet weight) of sediments washed through a 90 µm mesh sieve. The head capsules were individually picked from the sediment remaining on the sieve, oriented onto glass coverslips and affixed to permanent slides. Remains were identified at 400x magnification under a compound light microscope to the best taxonomic resolution possible following Oliver & Roussel (1983), Brooks et al., (2007), and Medeiros & Quinlan (2011).

4.2.3 Numerical analyses and climate reconstructions

All data analyses were completed in R v.3.6.0 (R Core Team, 2019). Rare taxa were removed from analysis, and taxa that were retained comprised of at least > 2 % of the chironomid sum per sample. The diagrams were divided into zones using a constrained cluster analysis with incremental sum of squares partitioning (CONISS) and a squared chord distance dissimilarity coefficient (Gordon & Birks, 1972). Significance of the zones was identified using a broken stick model (Bennett, 1996). Species richness was estimated through rarefaction using the "vegan" package v.2.5-6 (Oksansen et al., 2019). The chironomid assemblages were Hellinger-transformed and summarized using Principal Components Analysis (PCA) using the "FactoMineR" package v.2.0 (Lê et al., 2008) and visualized using the "factoextra" package v.3.6.3 (Kassambara & Mundt, 2020).

A chironomid-inferred paleotemperature model (Fortin et al., 2015) was applied to the relative abundance of chironomids from both lakes to estimate July air temperatures for the past two millennia. This was based on a weighted-averaging partial-least squares (WA-PLS) transfer function and validated with goodness-of-fit tests using the "palaeoSig" package v.2.0-3 (Telford, 2019). The root-mean square error of prediction (RMSEP) indicated a 2-component model was most appropriate for the temperature reconstructions for both cores. The overall trends in the WA-PLS2-derived temperature profiles were then summarized using Gaussian smoothing Generalized Additive Modelling (GAM) (Wood, 2017). Finally, the rate of change for temperature from 1950 CE to present was calculated for each lake.

4.3 Results

4.3.1 Chronology

The chronology for SFL was based on eight ^{210}Pb (Table 5.1) and four ^{14}C dates (Table 4.1). The level of unsupported ^{210}Pb activity in core SFL was 0.528 Bq/g in the uppermost sediment horizon and reached the supported level of 0.0326 Bq/g by 10.25 cm (Figure 4.1A). The lowermost three samples were below background, with activity <0.046 Bq/g and a CRS model was used to estimate the ages. Four radiocarbon dates had no reversals and the upper three dates increase linearly with depth. However, the uppermost calibrated ^{14}C date at 11.25 cm was dated at 870 – 800 cal BP (1080 – 1150 CE; median 834 cal yr BP), whereas the lowermost ^{210}Pb age at 10.25 cm was dated at 1876 CE, inferring an unusually high sedimentation rate between the last ^{210}Pb date and first ^{14}C date. It is likely that a reservoir effect was observed, which is common in Arctic sediments (Gajewski et al., 2000; MacDonald et al., 1991; Peros & Gajewski, 2009; Tamo & Gajewksi, 2019). Thus, we corrected for reservoir effects by calculating the difference between the oldest ^{210}Pb date (75 cal BP) and youngest ^{14}C date (834 cal BP) then subtracted this value from the remaining radiocarbon dates following Peros & Gajewski (2009) and Tamo & Gajewski (2019). Similarly, the lowermost ^{14}C date was unusually old, and was discarded. To compute the ages of samples deeper than 32.5 cm, 50 years were added to the third hardwater-corrected radiocarbon date for every 2-cm intervals. A new age-depth model was established by linear interpolation between the hardwater corrected calibrated ages, where the estimated hardwater correction is 731 years (Figure 3.2).

The chronology for core IG8 was established using eight ^{210}Pb dates (Table 5.2). The level of unsupported ^{210}Pb was 0.156 Bq/g in the uppermost horizon (2018 CE) and reached background at 0.0106 Bq/g at 11.75 cm. The 12.25 cm sample was below background (<0.011 Bq/g) and a CRS model was used to estimate the ages. Using the CRS model and linear extrapolation, a basal date of 1843 CE was determined (Figure 4.1B).

Table 4.1. Radiocarbon dating results for core SFL. Calibrations performed using OxCal v4.3 (Bronk Ramsay, 2009) and the IntCal13 calibration curve (Reimer et al., 2013). See text for details.

Lab ID	Depth (cm)	^{14}C yr BP	cal BP range	Median cal BP	Corrected median cal BP
UOC-12221	11-11.5	973 ± 22	872-797 (52.5%), 934-896 (42.9%)	834	105
UOC-12222	22-22.5	1922 ± 22	1903-1821 (89.1%), 1924-1909 (6.3%)	1862	1130
UOC-12223	32-32.5	2248 ± 23	2257-2158 (64.2%), 2339-2299(31.2%)	2207	1475
UOC-12224	38-38.5	4248 ± 24	4860-4816 (88.2%), 4753-4725 (6.4%), 4718-4713 (0.8%)	4838	1630

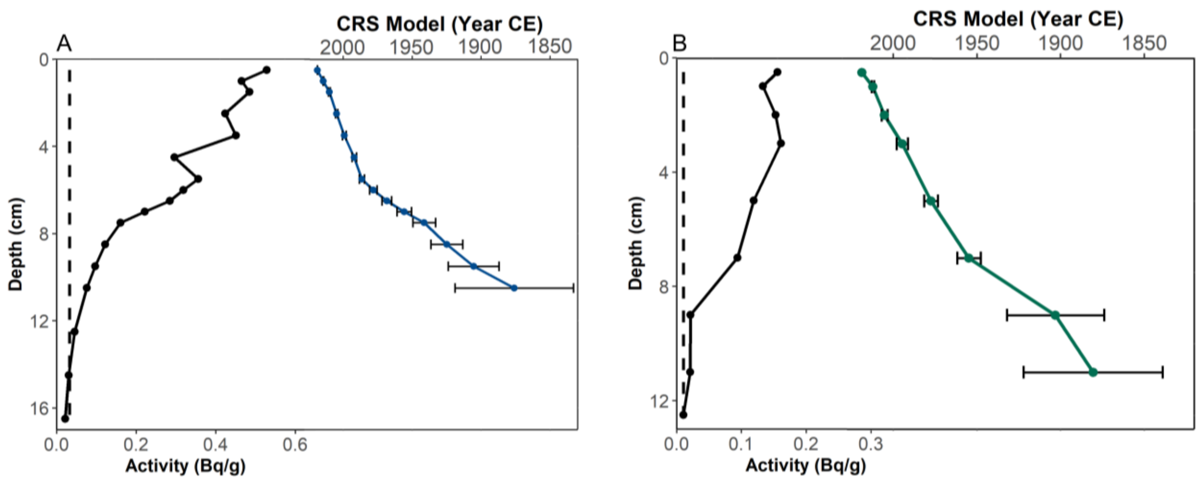

Figure 4.1. Age-depth models for cores (A) SFL and (B) IG8 based on a constant-rate-of-supply (CRS) model. Black lines represent unsupported ^{210}Pb activity; coloured lines represent CRS dates; error bars represent standard deviation; vertical dashed line represents supported ^{210}Pb activity, respectively.

4.3.2 Sedimentary stratigraphy

In core SFL %Organic matter based on loss-on-ignition at 550 °C (%OM) ranged from 6 – 60 % dry mass. %OM was greatest (48 – 60 %) in the uppermost 5.5 cm (2018 – 1990 CE) (Figure 5.1A), and gradually decreased with depth to 7 % dry mass at 40.5 cm (240 CE). From 7.5 – 9 cm (1915 – 1940 CE), there was a slight decrease in organic matter that spanned 4 samples. Carbonate content ranged from 2.5 to 11 % dry mass from 0 – 30.5 cm (570 – 2018 CE), then increased to 28 % in the remaining 10 cm of the core. In core IG8 %OM ranged from 22 – 39 %, with the lower percentages occurring in the middle horizons of the core (Figure 5.1B). Carbonate percentages were high and remained relatively uniform throughout the core.

4.3.3 Chironomid Stratigraphy

The dominant taxa in core SFL were *Abiskomyia*, *Micropsectra radialis*-type, *Paracladius*, *Sergentia*, and *Tanytarsus lugens*-type (Figure 4.2A). A stratigraphically constrained cluster analysis (CONISS) was used to divide the chironomid assemblages into four zones, where the number of zones was determined by comparing the results to a broken stick model (Figures 5.2, 5.3). Zone 1 (240 – 650 CE; 28 – 40 cm) was comprised of samples with high values of *Abiskomyia*, *M. radialis*-type, and *Sergentia*, which reached maximum abundances of 45, 25, and 20 %, respectively. An abrupt decrease in these taxa and an emergence of *Corynocera oliveri*-type and *T. lugens*-type, as well as *Corynoneura arctica*-type and *Psectrocladius sordidellus*-type was observed from 290 – 440 CE. Species richness increased from 12 to 16, then decreased to 13 during this time period.

A gradual compositional shift was observed that characterized Zone 2 (650 – 1990 CE; 5.5 – 26 cm). *Abiskomyia*, *M. radialis*-type, and *Paracladius* dominated between the years 720 – 1850 CE and reached maximum abundances of 40, 20, and 20 %, respectively. Between the years 1850 – 1990 CE, *Abiskomyia* decreased from 40 - 20 %, *M. radialis*-type from 10 - 3 %, and *Paracladius* from 15 - 9 %. During the period 1850 – 1990 CE *C. oliveri*-type, *P. sordidellus*-type, and *T. lugens*-type increased in abundance. Species richness remained relatively stable throughout Zone 2 and increased from 12 – 18 between 1850 – 1990 CE.

Zones 3 (1990 – 2005 CE; 2.5 – 5.5 cm) and 4 (2005 – 2018 CE; 0 – 2.5 cm) were the most dissimilar periods as identified by the cluster analysis. *Abiskomyia* represented 15 – 20 % of species abundances in Zone 3, then decreased to 4 % in Zone 4. Zone 4 was also marked by the disappearance of *Paracladius*. During the years 2000 – 2018 CE, *P. sordidellus*-type and *T. lugens*-type dominated the chironomid assemblages and reached maximum abundances of 25 % and 32 %, respectively. Species richness decreased throughout Zones 3 and 4 from 18 – 12.5.

The dominant taxa in core IG8 were *Chironomus anthracinus*-type, *Dicrotendipes*, *Paratanytarsus,* and *P. sordidellus*-type (Figure 4.2B), and chironomid assemblages were divided into two significant zones by the constrained cluster analysis and broken stick model (Figures 5.4, 5.5). Zone 1 (1840 – 1970 CE; 6 – 12.5 cm) was comprised of samples with high values of *Cricotopus intersectus*-type, *Paratanytarsus*, and *P. sordidellus*-type, which reached maximum abundances of 15, 20, and 15 % respectively. Zone 2 (1970 – 2018 CE; 0 – 5 cm) marked the increase of *C. anthracinus*-type from 12 – 21 % and *Dicrotendipes* from 17 – 32 %. *Cladotanytarsus mancus*-type appeared in 1980 CE, and *C. intersectus*-type and *Paratanytarsus* reached minimum abundances of 2 and 5 %, respectively. Species richness was highest in 2012 CE at 27, and lowest in 1980 CE at 16.

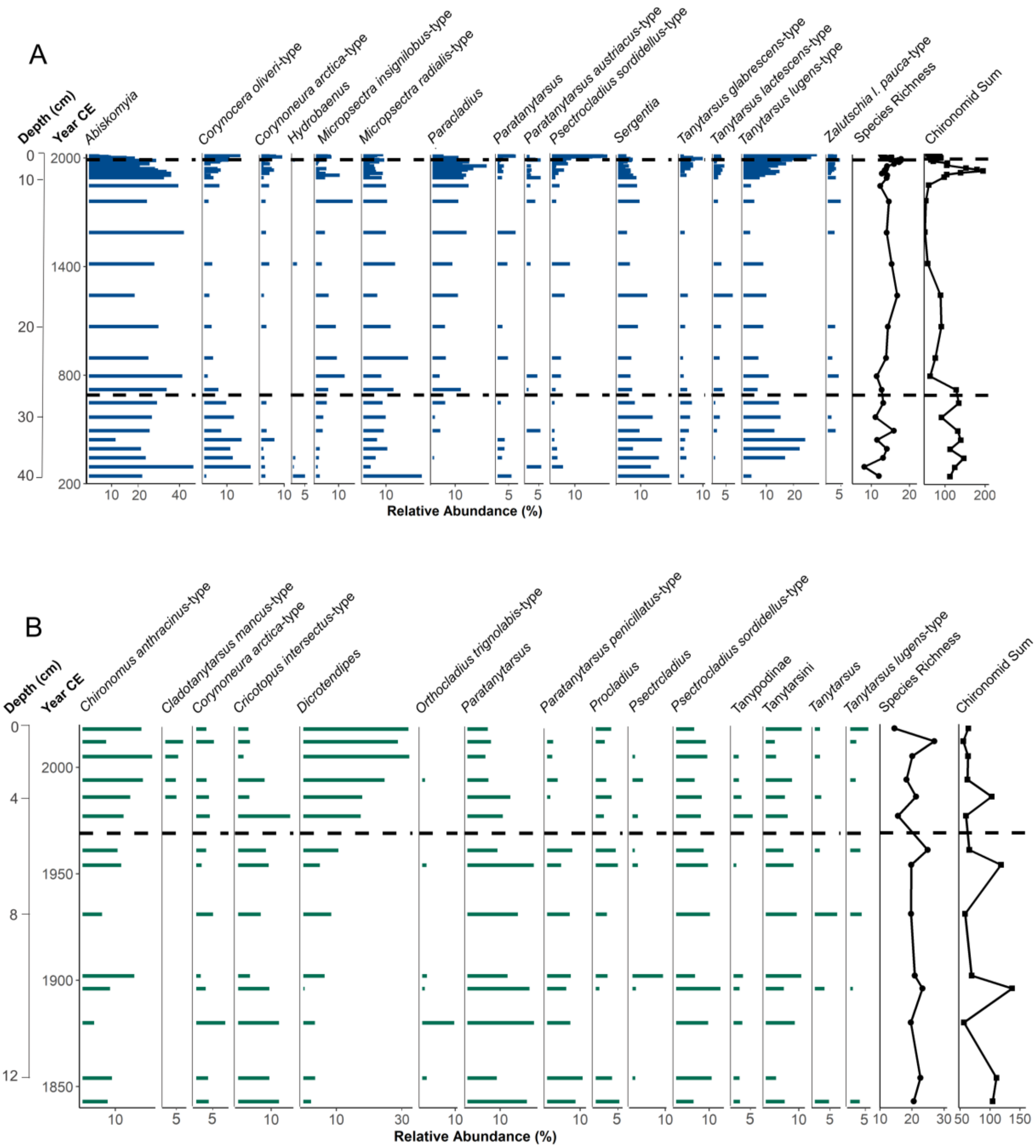

Figure 4.2. Percentages of major chironomid taxa in cores (A) SFL and (B) IG8. Species richness calculated through rarefaction analysis using all taxa from the respective depth interval. Chironomid sum is all individuals counted from each depth interval. Horizontal dashed lines denote the three time zones within the respective cores based on a constrained cluster analysis. Note the delineation of Zones 3 and 4 in core SFL is indistinguishable.

4.3.4 Ordinations of chironomid assemblages

A principal component analysis (PCA) was used to evaluate temporal trends in the chironomid taxa through time. For core SFL, component 1 explained 22.9 % of the variance, with taxa such as *Abiskomyia*, *Hydrobaenus*, *M. radialis*-type, *Sergentia*, and *Paracladius* positively correlated, and *C. oliveri*-type, *T. lugens*-type, and *P. sordidellus*-type negatively correlated (Figure 4.3A). The scores of the first component were generally positive, except between the years 390 – 430 CE, and again from 1990 – 2018 CE (Figure 4.3B). The scores also highlight an abrupt change after 1990 CE, when taxa negatively correlated with this axis increased in abundance. Component 2 of the PCA explained 18.8 % of the variance, with *C. oliveri*-type, *Hydrobaenus*, *M. radialis*-type, and *Sergentia* negatively correlated, and *T. glabrescens*-type*, T. lugens*-type, and *Paracladius* positively correlated. The second component showed negative loadings between 240 and 440 CE, and high values between 1890 and 2018 CE (Figure 4.3C).

The first two components of the PCA of the chironomid assemblages from core IG8 explained 52.2 % of the total variance. The first component explained 32.1 % of the variance, where *C. mancus*-type, *Chironomus anthracinus*-type*, Dicrotendipes*, and *T. lugens*-type were negatively loaded, and *Corynoneura arctica*-type, *Cricotopus intersectus*-type, and *Paratanytarsus* positively loaded (Figure 4.5D). The scores of the first component revealed a long-term decline (Figure 4.3E). The second principal component explained 20.1 % of the variance, with *C. arctica*-type, Tanytarsus (undifferentiated without spur), and *T. lugens*-type positively loaded, and *C. anthracinus*-type, *Orthocladius trignolabis*-type, *Psectrocladius*, and undifferentiated Tanypodinae negatively loaded. The scores of the second component oscillate around zero (Figure 4.3F).

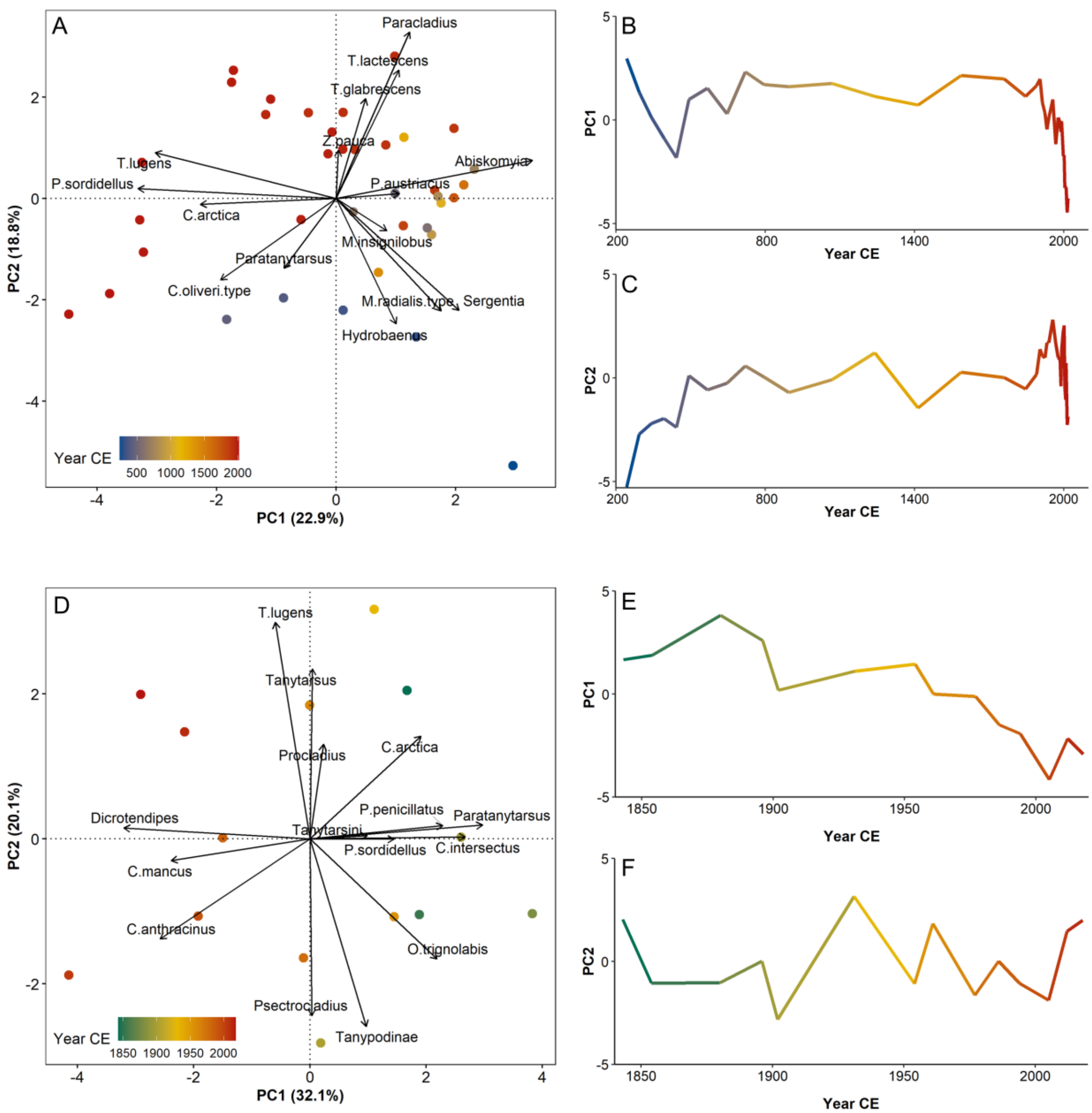

Figure 4.3. Principal components analysis of cores (A, B, C) SFL and (D, E, F) IG8. (A, D) Biplot of the loadings (arrows) and scores (dots); (B, E) scores of the first principal component through time; and (C, F) scores of the second principal component through time. The percent variance of the axis is listed on the respective biplot labels.

4.3.5 Climate Reconstructions

Reconstructed July air temperatures for core SFL ranged from 4.8 – 7.9 °C and showed warmer temperatures in Zone 1, a cool period during Zone 2, and rapid warming through Zones 3 and 4 (Figure 4.4). The lowest reconstructed temperature in the record (4.8 °C) occurred at 720 CE in Zone 2 (650 – 1990 CE), where temperatures ranged from 4.8 – 6.1 °C. The most recent 30 years of the record (Zones 3 and 4; 1990 – 2018 CE) revealed a 1.9 °C increase in temperature and the highest reconstructed temperature in the record occurred in 2014 CE. During the period 1850 CE to the present, core SFL showed little change from 1850 – 1970 CE, followed by an increase in temperature (Figure 4.5A), while core IG8 showed a relatively continuous increase in temperature (Figure 4.5B). Between the years ~1950 – 2018 CE, temperatures in core SFL rose from 5.1 – 7.8 °C, and from 6.2 – 8.9 °C in core IG8. The linear trends for SFL and IG8 over the last ~175 years were +0.36 °C and +0.16 °C per decade, respectively.

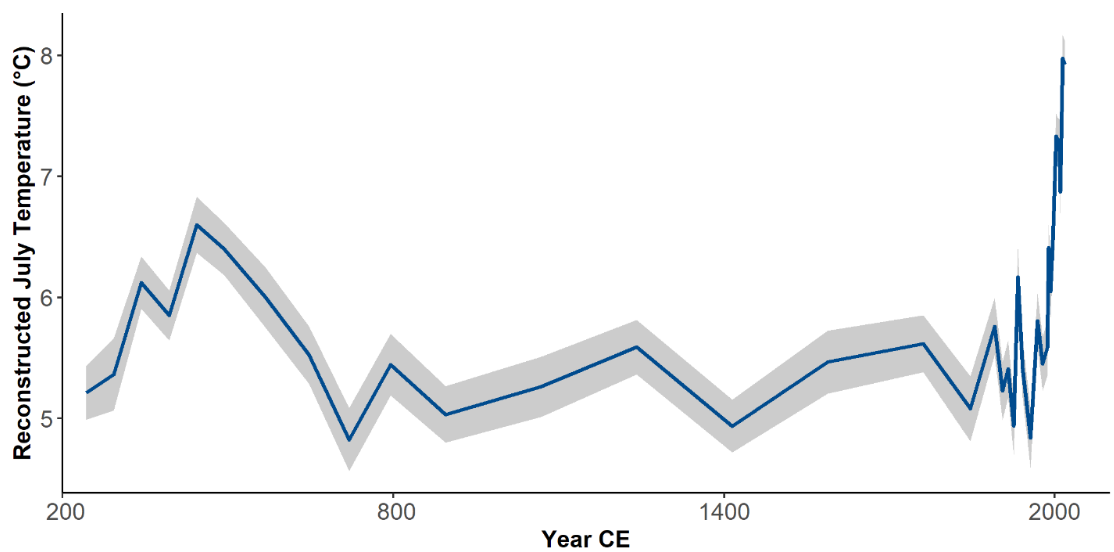

Figure 4.4. Reconstructed July air temperatures for core SFL using the Fortin et al. (2015) modern training set and the WA-PLS2 transfer function. Grey shaded area represents the standard error of the model.

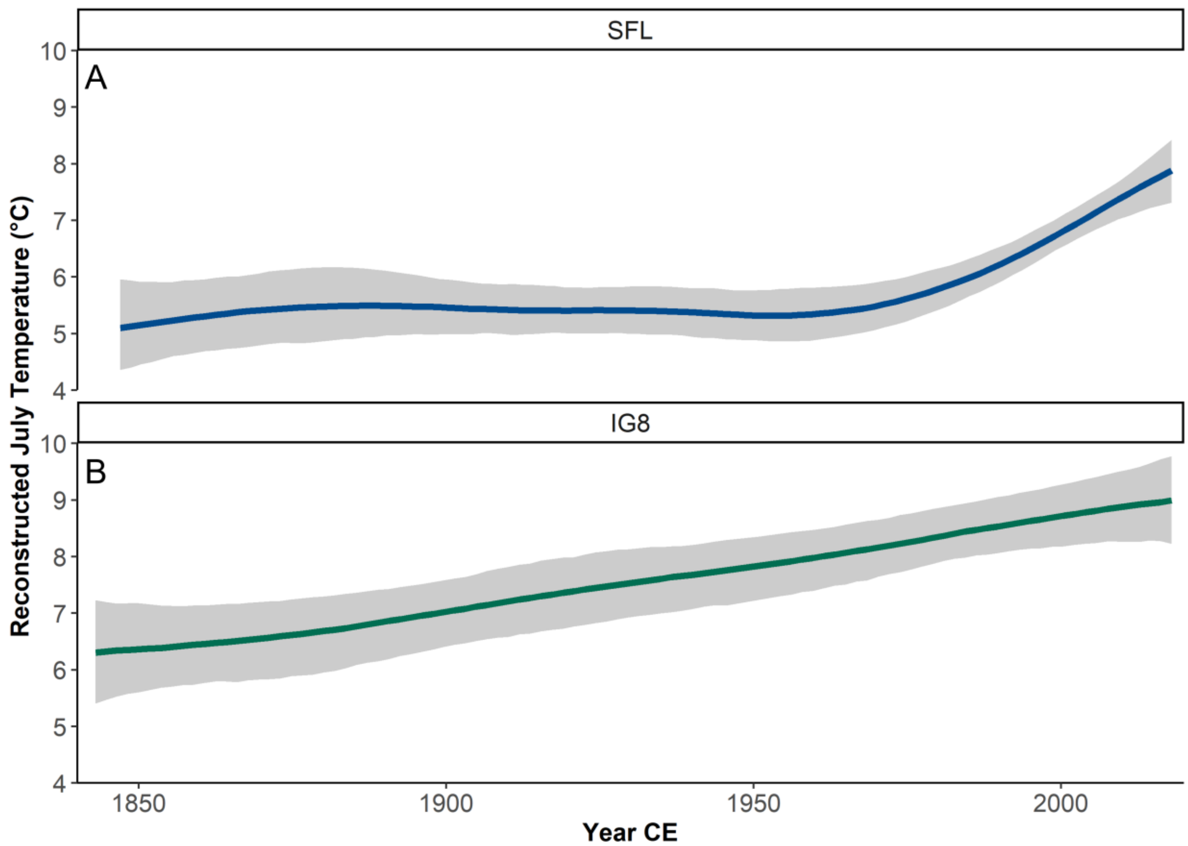

Figure 4.5. Comparison of trends in the July air temperature reconstruction over the last ~175 years for lakes (A) SFL and (B) IG8 as fit using GAM; see text for details. Grey shaded areas represent the standard error of the respective models.

4.4 Discussion

The examination of two supplemental water supply lakes for the hamlet of Igloolik, Nunavut demonstrated synchronous shifts in chironomid community structure in response to climate variability over the past 2000 years. The increase in abundance of indicator taxa associated with warmer temperatures around 1980 CE in both archives suggests SFL (Figure 4.2A) and Lake IG8 (Figure 4.2B) are in the process of transitioning to warmer, more productive systems. The consequences of climate warming may impact water quality and quantity, thus increasing the vulnerability of these drinking water sources.

4.4.1 Context of the Late Holocene

The chironomid taxa in core SFL (Figure 4.2A) were similar to those identified in other paleolimnological records of the late Holocene from Victoria Island (Fortin & Gajewski, 2010), Baffin Island (Thomas et al., 2011), Baker Lake (Medeiros et al., 2012), and Boothia Peninsula (Fortin & Gajewski, 2016). Temperature is an important factor in determining the composition of chironomid assemblages in this region (Medeiros & Quinlan, 2011). Previous work has identified several climate oscillations over the past 2000 years, as well as an overall cooling during this period (Kaufman et al., 2009; Ahmed et al., 2013; Werner et al., 2018; Kaufman et al., 2020). The coolest reconstructed temperature (4.8 °C) in this study (Figure 4.4) occurred in ~720 CE, consistent with chironomid-based temperature reconstructions in the central Canadian Arctic (Porinchu et al., 2009a) and Victoria Island (Fortin & Gajewski, 2010b), as well as a circum-Arctic multi-proxy reconstruction (Shi et al., 2012). Other studies have reported cooling at various times in the late Holocene, such as during the onset of the Little Ice Age on Baffin Island (Thomas et al., 2011), or the Boothia Peninsula (Fortin & Gajewski, 2016). These observations suggest spatio-temporal heterogeneity in temperature regimes across Arctic environments (Kaufman et al., 2009; Shi et al., 2012; Werner et al., 2018), especially during the Medieval Warm Period and Little Ice Age (Ahmed et al., 2013; Nicolle et al., 2018). However, low temporal resolution of many records and dating issues suggest it is not possible to make conclusions about the spatio-temporal climate variability across the region at this time. The most recent decades in the SFL record exhibited a reversal of the long-term cooling trend, which have been attributed to anthropogenic disturbance, and highlight that modern temperatures are anomalously warm compared to the past two millennia (Ahmed et al., 2013; Stocker et al., 2013; Briner et al., 2016).

Productivity in core SFL was highest during Zone 2 (650 – 1990 CE), a period where temperatures enabled the co-existence of cold- and warm-tolerant taxa such as *Abiskomyia* and *T. lugens*-type, respectively (Fortin et al., 2015). High productivity was accompanied by maximum species richness between 650 and 1990 CE, which resulted from the coexistence of a variety of temperature-optimized taxa as predicted by the intermediate disturbance hypothesis (Connell, 1978; Finkelstein & Gajewski, 2007). This suggests that productivity was most active during periods of climate transition, consistent with observations by Fortin & Gajewski (2016). Recent years exhibited decreases in abundance of cold-water taxa (*Abiskomyia, M. radialis*-type, *Paracladius*) and suggests a transition away from oligotrophic conditions and towards increased productivity (Gajewski et al., 2005).

4.4.2 Recent Environmental Change

Over the last few decades, shifts in chironomid assemblages in both lakes are interpreted as a progression to warmer, more nutrient-rich systems. SFL was characterized by large declines around 1980 CE of several cold-tolerant taxa (e.g. *Abiskomyia*, *M. radialis*-type, *Paracladius*) and appearance of taxa that are typically found in lakes with higher dissolved organic carbon (*T. lugens*-type*)* and generalist taxa (*P. sordidellus*-type) (Figure 4.2A). These assemblage changes indicate reduced lake water levels and/or warmer temperatures (Francis, 2006; Brooks et al., 2007). Lake IG8 resembled contemporary warm, shallow lakes (Gajewski et al., 2005; Medeiros & Quinlan, 2011; Fortin et al., 2015), where biological responses appeared to be more pronounced and inferred the evolution to more mesotrophic conditions (Figure 4.2B). This was reflected in the compositional transition from warm water-taxa (*C. intersectus*-type, *Paratanytarsus*) in Zone 1 (1840 – 1970 CE) to taxa associated with higher thermal optima and total nitrogen (*C. anthracinus*-type, *C. mancus*-type*, Dicrotendipes*) in Zone 2 (1970 - 2018 CE) (Porinchu et al., 2009b; Medeiros & Quinlan, 2011). The higher production and presence of taxa known to respond to increased nutrient availability (*C. anthracinus*-type, *C. mancus*-type*, Dicrotendipes)* (Gajewski et al., 2005) in Lake IG8 suggests this lake may not be a potable source of freshwater unless first subjected to standard treatment.

Both paleoclimate reconstructions (Figure 4.5) displayed a strong response to recent warming (Kaufman et al., 2009; Ahmed et al., 2013; Nicolle et al., 2018). The decadal rates of change for Lakes SFL and IG8, respectively, were +0.36 °C and +0.16 °C since 1950 CE, similar to the IPCC (2013) CMIP5 projections of a 0.10 – 0.23 °C per decade increase in global mean surface air temperatures for the period 2016-2035 (Stocker et al., 2013). Whereas small Arctic lakes like IG8 are more sensitive to increased air temperatures through evaporative stress (Rautio et al., 2011), SFL may be responding faster to atmospheric temperature due to thermal stratification (Rühland & Smol, 2005; Medeiros et al., 2012). Temperature and evaporative stress nonetheless affect lakes of varying sizes, where recent observations of ponds evaporating (Abnizova & Young, 2010; Andresen & Lougheed, 2015), thermally stratifying (Rühland & Smol, 2005; Medeiros et al., 2012), experiencing regime shifts (Randsalu-Wendrup et al., 2016) and decreasing in size (Muster et al., 2019) have been made throughout the Canadian Arctic. Such catchment characteristics, when subjected to climatic-induced changes, have the potential to modify natural ontogenic processes and ecological successions in lacustrine environments (Law et al., 2015; Luoto et al., 2017; Kivilia et al., 2019).

4.4.3 Consequences for Freshwater Vulnerability

For water resource vulnerability assessments, a fundamental problem stems from the lack of long-term measures of change based on the data sources used for quantitative estimates. Plummer et al.'s (2012) review of 710 indicators across 50 water vulnerability assessment tools showed that the plethora of resources used to characterize water vulnerability across different geographical scales and environmental considerations generally rely on annual and decadal data. This raises concerns, as current and future climate impacts cannot be adequately contextualized without considering past ecosystem dynamics from a centennial and millennial perspective. Our quantitative analysis of the paleoenvironment demonstrates that Small Fish Lake and Lake IG8, respectively, warmed by 2.5 and 1.1 °C since 1950 CE (Figure 4.5), and the temperature trajectories in both systems infer higher productivity, and accelerated rates of change when placed in the context of reconstructed temperatures over the last two millennia (Figure 4.4). Inuit have long demonstrated adaptive capacity in the face of environmental disturbances (Briere & Gajewski, 2020), however, recent biophysical changes have inherently increased the vulnerability of Igloolik's residents to climate change (Ford et al., 2006).

To facilitate future water resource assessments, we propose including paleolimnology as a method for measuring water resource vulnerability. Paleolimnology provides a meaningful long-term perspective of climate variability to evaluate the extent of recent environmental changes. With this temporal dimension of vulnerability, uncertainty regarding natural processes and future trajectories can be reduced (Saulnier-Talbot, 2016). Informing sustainable freshwater use for community and regional planning is essential for Arctic water security (Medeiros et al., 2017), especially with the prevalence of population expansion and limited water infrastructure (Instanes et al., 2016). Addressing Arctic water security in relation to climate change ultimately requires a contextual approach (Ingram, 2008) to reduce water vulnerability and increase sustainability for human and environmental well-being (Bunch et al., 2011).

4.5 Conclusions

A paleolimnological assessment applied to two supplemental drinking water sources in Igloolik, Nunavut, analyzed biological responses to climate change over the late Holocene and indicated water resource vulnerability. Reconstructed July air temperatures showed an overall cooling that preceded significant warming from 5.4 to 7.9 °C after 1980 CE, and stratigraphic changes from cold- to warm-water taxa after 1980 CE were observed in both lakes. Historical biological responses to climate perturbations demonstrated that recent environmental changes are anomalous in the archives, and increased lake productivity in Lake IG8 may impact potable usage. Utilising biological indicators from centennial and millennial archives expands upon current water resource assessments that operate on annual and decadal scales to better contextualize aquatic ecosystem functioning. As well, paleolimnology allows for improved quantifications of water resource vulnerability, which can inform community and regional planning in the context of evolving, dynamic socioeconomic and environmental pressures.

Acknowledgements

This project was funded by the Climate Change Preparedness in the North Program awarded to ASM and SW by Crown-Indigenous Relations and Northern Affairs Canada, the Northern Scientific Training Program awarded to PC, and Dalhousie University. We are grateful to Michael Bakaic, Andy Williams, Sherry Wu, and Simon Qamanirq field sampling assistance, and the staff at the Nunavut Research Institute for providing fieldwork support. We thank Cara MacKenzie for assistance in processing and identification of chironomids, and Freddy Liu for GIS assistance. We also thank Igloolik SAO Brian Fleming, Mayor Merlyn Recinos, and Council for their guidance and support. Samples were collected under a Land and Water Scientific Research License (02-046-18N-M) from the Nunavut Research Institute and a Nunavut Water Board approval for the use of water without a license (8WLC-WRA1819).

CHAPTER 5:

Supplementary Information

5.1 Introduction

A paleolimnological study of two sediment cores from Igloolik, Nunavut was used to quantify the ecological trajectory of lakes that were potential supplemental freshwater sources for the Hamlet, as part of a water resource vulnerability assessment. Contained in this chapter is additional information on ^{210}Pb results, sedimentary and biotic diagrams, diagnostic tests for the temperature inference models, and Generalized Additive Modelling (GAM) methods. To validate the paleotemperature reconstructions, analogue-matching techniques and goodness-of-fit tests were applied and are shown below. Rationale and implementation of the GAM are described as well.

5.2 Methods

Chironomid assemblages were plotted stratigraphically and divided into zones using a constrained cluster analysis with incremental sum of squares partitioning (CONISS) and a squared chord distance dissimilarity coefficient (Gordon & Birks, 1972) using the “rioja” package v.0.9-21 (Juggins, 2017). A broken stick model was used to assess the statistical significance of the cluster zones using the “vegan” package v.2.5-6 (Bennett, 1996; Okansen et al., 2019). Biotic assemblages were summarized using a constrained cluster analysis using the “factoextra” package v.1.0.7 (Kassambara & Mundt, 2020) and visualized using the “dendextend” package v.1.13.4 (Galili, 2015). To determine the suitability of the modern calibration set, modern analogues were assessed by plotting the data passively on top of the Fortin et al. (2015) chironomid training set using the “analogue” package v.0.17-4 (Simpson & Oksanen, 2020) and by calculating the analogue distances using the “ggpalaeo” package v.0.0.0.9005 (Telford, 2020). Significance tests of the reconstruction were conducted using the “palaeoSig” package v.2.0-3 (Telford, 2019) and “ggpalaeo” package v.0.0.0.9005 (Telford, 2020). The WA-PLS transfer function was cross-validated and the components were verified using the “rioja” package v.0.9-21 (Juggins, 2017) and “analogue” package. A generalized additive model (GAM) was fitted to the July temperature reconstructions of cores SFL and IG8 and values were interpolated to regularly spaced intervals using the "brms" package v.2.12.0 (Bürkner, 2018) and "mgcv" package v.1.8-31 (Wood, 2011).

5.3 Results

5.3.1 Chronology

Table 5.1. ^{210}Pb activity and dates estimated using a constant-rate-of-supply (CRS) model for core SFL.

Midpoint Depth (cm)	Unsupported Activity (Bq/g)	Year CE	CRS Error (Years)
0.25	0.528	2018	0.00
0.75	0.465	2014	0.26
1.25	0.485	2010	0.71
2.25	0.424	2005	0.86
3.25	0.451	1999	1.39
4.25	0.296	1992	1.65
5.25	0.356	1986	1.86
5.75	0.319	1978	2.68
6.25	0.285	1968	3.52
6.75	0.222	1956	5.25
7.25	0.161	1941	8.28
8.25	0.122	1925	11.53
9.25	0.097	1905	18.42
10.25	0.076	1876	42.92
12.25	0.046	NA	NA
14.25	0.031	NA	NA
16.25	0.022	NA	NA

Table 5.2. ^{210}Pb activity and dates estimated using a constant-rate-of-supply (CRS) model for core IG8.

Midpoint Depth (cm)	Unsupported Activity (Bq/g)	Year CE	CRS Error (Years)
0.25	0.156	2018	0.00
0.75	0.133	2012	0.73
1.75	0.153	2005	1.70
2.75	0.161	1995	3.33
4.75	0.119	1977	4.09
6.75	0.094	1955	7.02
8.75	0.021	1903	29.03
10.75	0.021	1881	41.60
12.25	0.011	NA	NA

5.3.2 Sedimentary stratigraphy

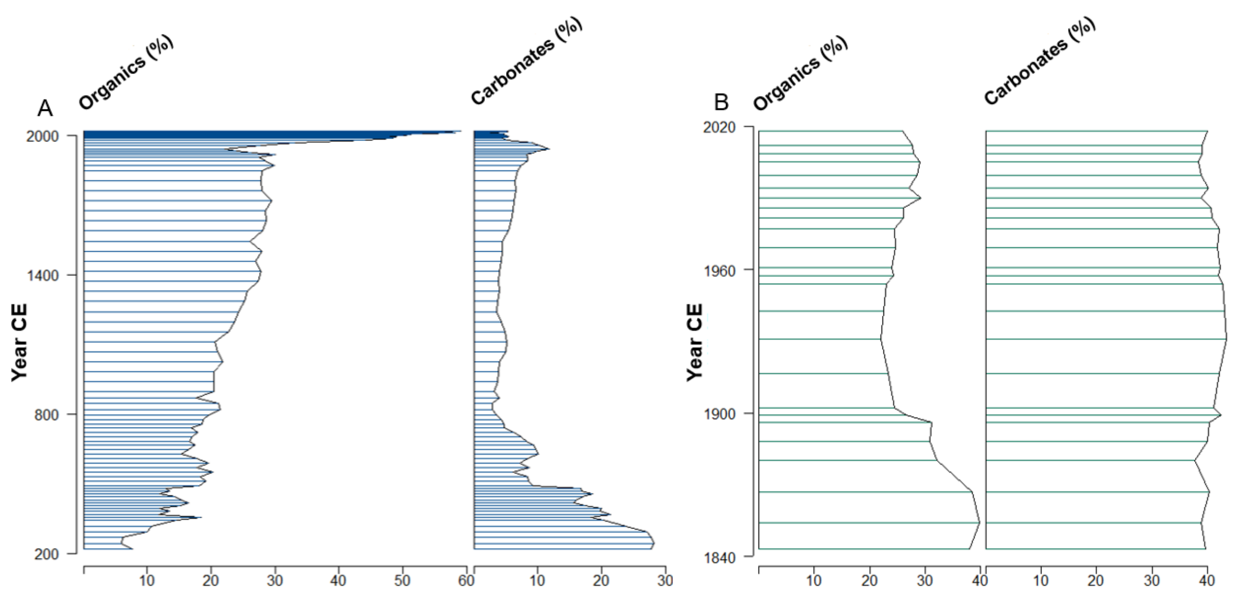

Figure 5.1. Loss-on-ignition at 550 °C (organic matter content) and 950 °C (carbonate content) for cores SFL (A) and IG8 (B) plotted against time.

5.3.3 Zoning of the chironomid records

A stratigraphically-constrained cluster analysis with incremental sum of squares partitioning (CONISS) of chironomid assemblages from core SFL indicated four zones (Figure 5.2), where the significant zones were determined by a comparison with a broken stick model (Figure 5.3). A constrained cluster analysis with CONISS for core IG8 indicated two zones of chironomid assemblages (Figure 5.4), where a broken stick model indicated these zones were statistically significant (Figure 5.5).

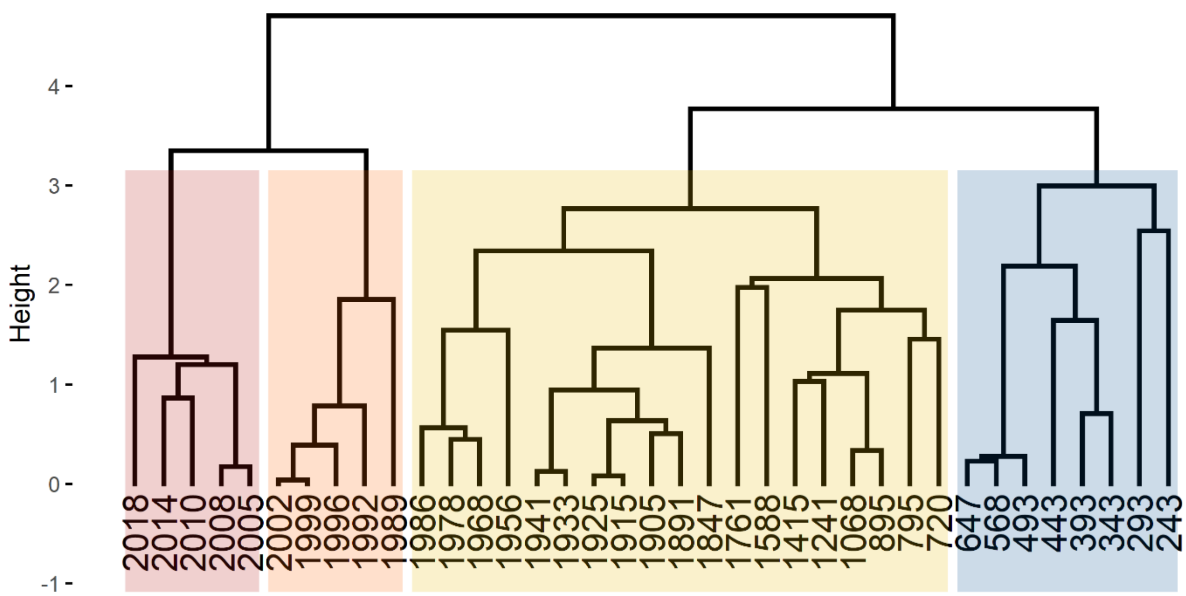

Figure 5.2. Stratigraphically-constrained cluster analysis of chironomid assemblages of core SFL.

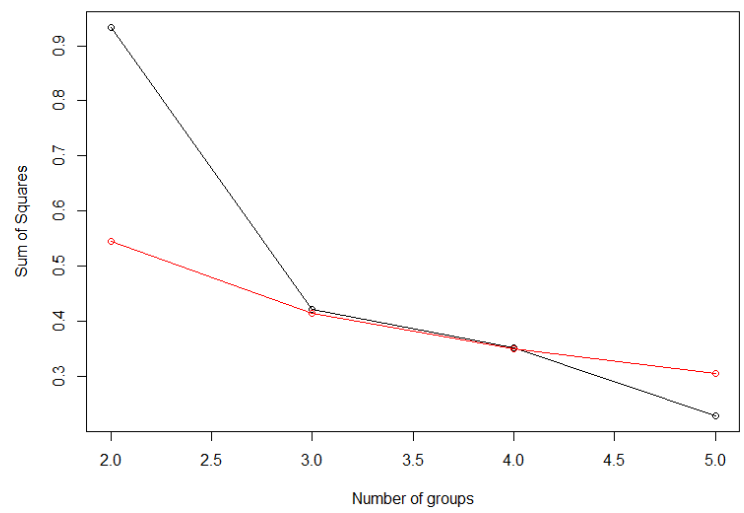

Figure 5.3. Sum of squares of the chironomid data (black) compared to that from a broken stick model (red) for core SFL.

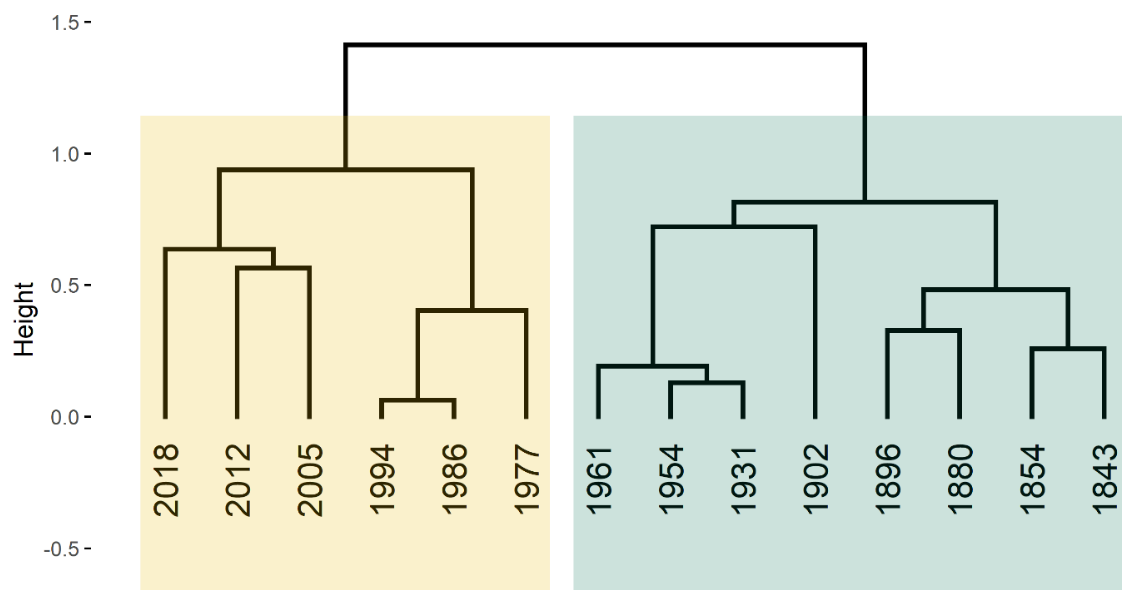

Figure 5.4. Stratigraphically-constrained cluster analysis of chironomid assemblages of core IG8.

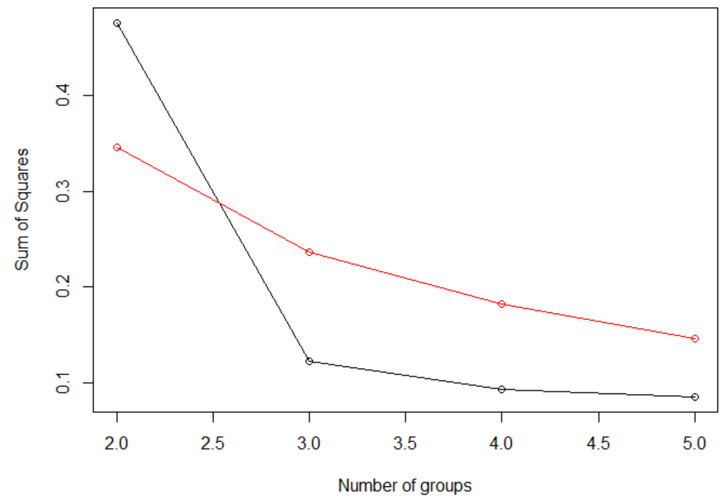

Figure 5.5. Sum of squares of the chironomid data (black) compared to that from a broken stick model (red) for core IG8.

The squared chord distance of the nearest analogue from the modern dataset (Fortin et al., 2015) to each fossil sample was plotted against time for lakes SFL (Figure 5.6) and IG8 (Figure 5.7). In both lakes, "good" analogues could be identified among the modern samples for the fossil assemblages.

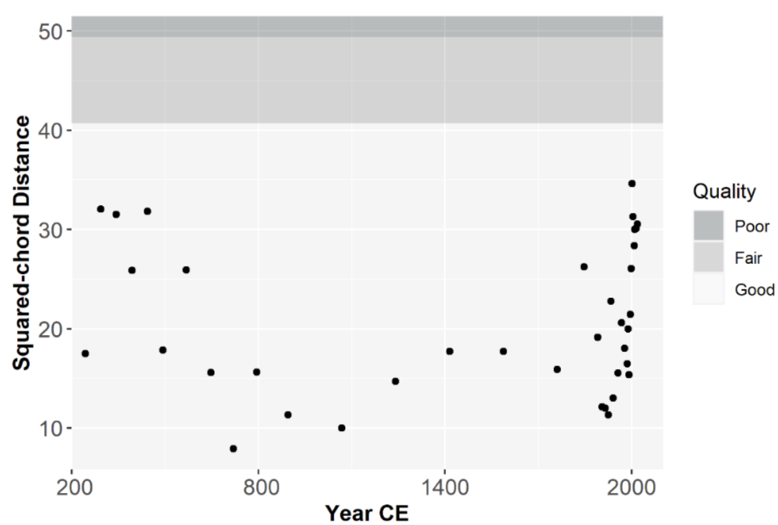

Figure 5.6. Squared-chord distance between the fossil assemblages of core SFL with the modern analogue through time.

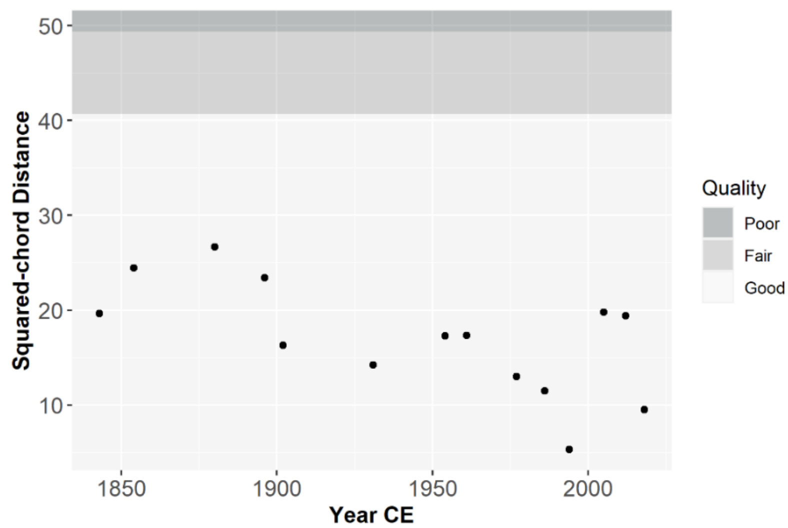

Figure 5.7. Squared-chord distance between the fossil assemblages of core IG8 with the best modern analogue through time.

The squared residual lengths between the chironomid assemblages in cores SFL and IG8 and the modern dataset (Fortin et al., 2015) were plotted against time for lakes SFL (Figure 5.8) and IG8 (Figure 5.9).

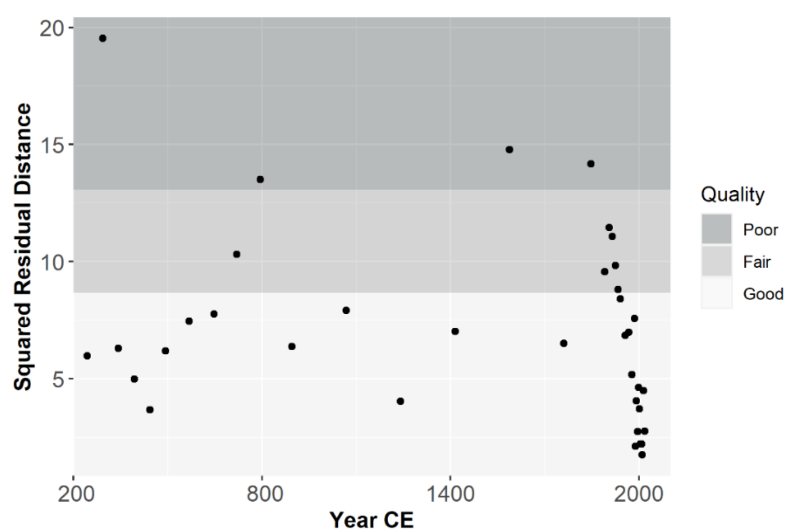

Figure 5.8. Squared residual lengths between core SFL chironomid assemblages and the Fortin et al. (2015) training set through time.

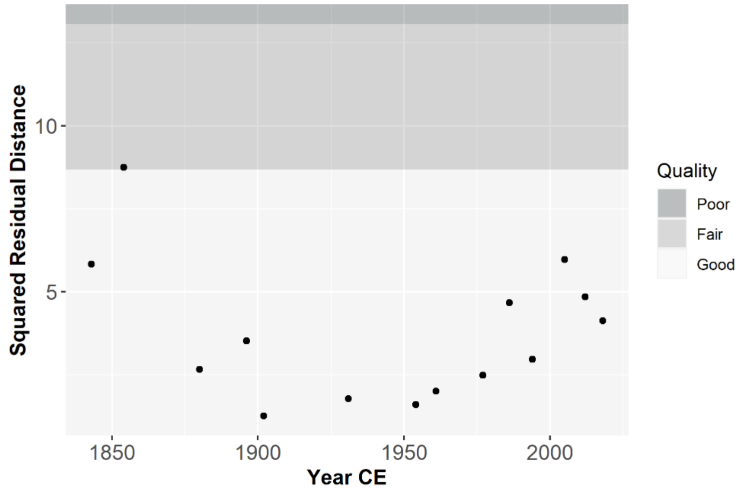

Figure 5.9. Squared residual lengths between core IG8 chironomid assemblages and the Fortin et al. (2015) training set through time.

The fossil assemblages from lakes SFL (Figure 5.10) and IG8 (Figure 5.11) were projected onto a redundancy analysis (RDA) of the modern dataset (Fortin et al., 2015). The temperatures of the chironomid assemblages in core SFL ranged from 5 – 10 °C between 243 and 2018 CE when passively plotted onto the training set ordination. Chironomid assemblages from core IG8 ranged from 10 – 11 °C in the modern training set.

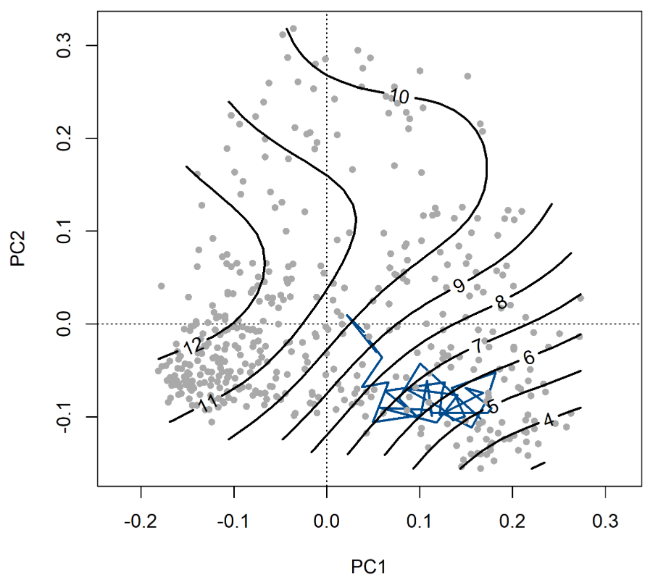

Figure 5.10. Changes in chironomid composition of core SFL through time projected into the Fortin et al. (2015) training set. Contours represent temperature.

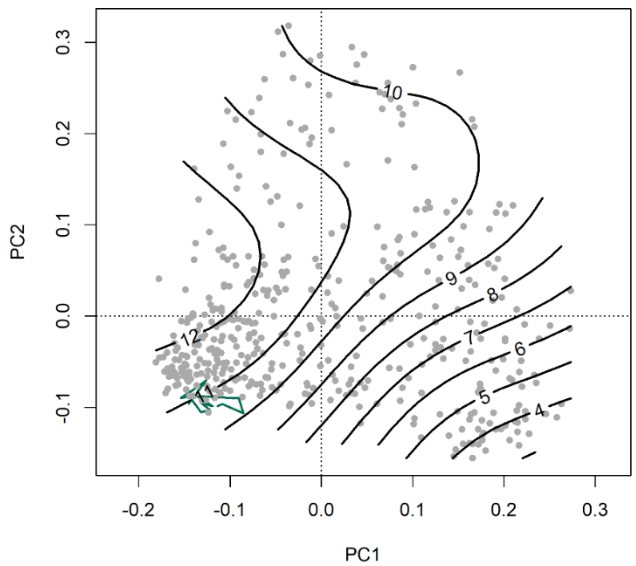

Figure 5.11. Changes in chironomid composition of core IG8 through time projected into the Fortin et al. (2015) training set. Contours represent temperature.

5.3.4 Climate reconstructions

The WA-PLS2 reconstruction of July temperatures from core SFL were smoothed using GAM (Figure 5.12). Temperatures were warm between the years 240 and 700 CE and were cool between the years 800 and 1900 CE. After 1900 CE, temperatures warmed continuously.

Reconstructed July temperatures of the period of 1850 CE to the present were compared from core SFL and core IG8 (Figure 5.13). Core IG8 reconstructed significantly warmer July air temperatures after an abrupt increase at the end of the 19th century compared to core SFL, and both cores show an increase in temperatures since the mid 20th century.

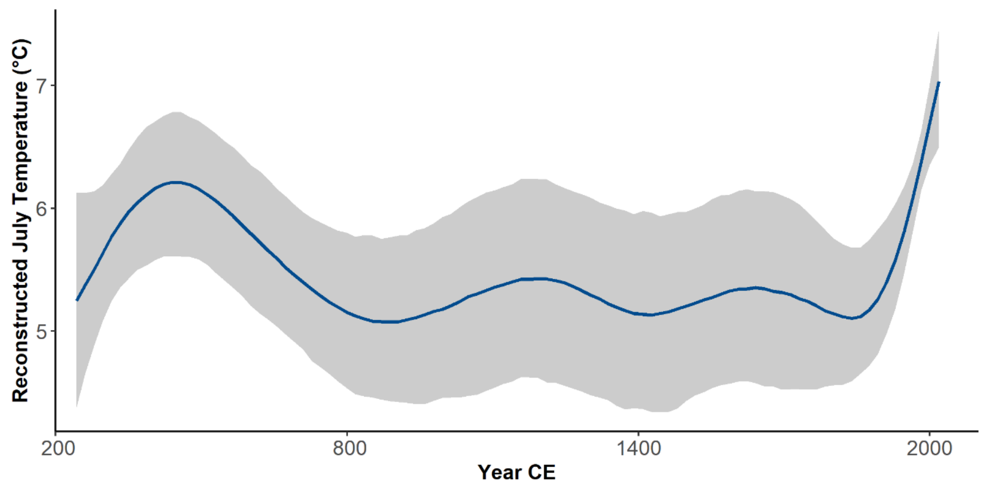

Figure 5.12. WA-PLS2 reconstructed July temperatures for core SFL, smoothed using a generalized additive model (GAM). Grey shaded area represents the standard error of the model.

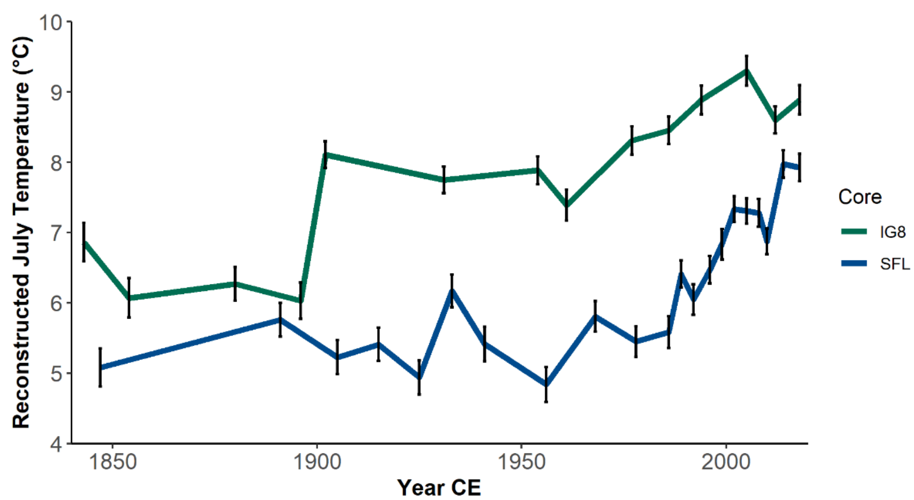

Figure 5.13. Reconstructed July air temperatures of the past ~175 years from cores IG8 and SFL using the WA-PLS2 transfer function and the Fortin et al. (2015) modern training set. Error bars represent the standard errors of the models.

CHAPTER 6:

Conclusions

Over the past 2000 years, the Arctic has experienced several climate oscillations, including a long-term cooling period and abrupt warming period in the late 20th century (Kaufman et al., 2009). Arctic lakes are highly sensitive to thermodynamic changes (Quinlan et al., 2005), which are reflected in the biological community composition and stability over time (Walker, 2001; Mayfield et al., 2020). Paleoclimate reconstructions indicate recent warming is anomalous in most archives (Stocker et al., 2013), impacting freshwater quality and quantity for environmental and human health (Instanes et al., 2016; Wright et al., 2018). Furthermore, ongoing and future climate warming presents freshwater sustainability challenges for Arctic communities, putting drinking water security at the forefront of concerns for Arctic populations (Medeiros et al., 2017; Harper et al., 2020). Vulnerability assessments on freshwater resources have indicated increased vulnerability to climate change, despite utilizing short term measures of environmental variables to characterize the long-term effects of warming (Ford et al., 2006; Plummer et al., 2012; Goldhar et al., 2014).

In this study, we examined the climate variability and associated biological responses over the past 2000 years in two supplemental drinking water sources in Igloolik, Nunavut, Canada to quantify water resource vulnerability. Using a chironomid-inferred paleotemperature model, past July air temperatures were reconstructed using data from sediment cores from lakes SFL and IG8 for the period of 200 to 2018 CE. Prior to 1980 CE, chironomid assemblages were dominated by cold-water indicators such as *Abiskomyia, Micropsectra radialis*-type, and *Paracladius*, and the reconstructed climate showed an overall cooling period. After 1980 CE, reconstructed temperatures rapidly warmed with synchronous shifts to warm-water taxa such as *Chironomus anthracinus*-type*, Dicrotendipes,* and *Tanytarsus lugens*-type. The increase in temperature and abundance of thermophilic taxa suggest lakes SFL and IG8 are both experiencing transitions to warmer, more productive environments.

The onset of intensified warming and biological changes in the late 20th century indicate two key findings. First, recent warming is anomalous in an archive that was generally characterized by a cooling trend and cold-water taxa. Second, the rate of recent warming will impact water resource vulnerability and have consequences for Arctic community sustainability. Our results emphasize the importance of long-term environmental measures in vulnerability assessments to contextualize the influence of recent warming. The 2.5 °C increase in temperature since 1980 CE is unprecedented for the 2000-year temperature history of SFL; a paleolimnological analysis enables this perspective.

Often, assessment tools rate vulnerability based on a standardized scale, where vulnerability is categorized and not fully quantified. Here, we demonstrated that the decadal rate of change in temperature since 1950 CE (+0.36 °C for SFL and +0.16 °C for IG8) is much greater relative to the 1850-1950 CE period and is expected to continue on this trajectory. Likewise, our estimates of temperature change can also be compared to those at a global scale (+0.10 – 0.23 °C; Stocker et al., 2013) to understand the lower and upper limits of temperature change in SFL and IG8. This allows for site specific conditions to be evaluated against a broader context to determine the significance of the documented changes. Future research could usefully build on this study by incorporating paleolimnology into vulnerability assessment tools to improve calculations of water resource vulnerability and evaluate temperature change within the context of long-term timescales.

As water security challenges are persistent in Arctic communities, our research focused on climate change impacts on drinking water at the local level to examine water resource vulnerability in Arctic watersheds. Human populations are situated near freshwater resources to support everyday needs, thus, paleolimnological assessments may be usefully conducted in proximity to human settlements to improve understandings of local trajectories of change and contribute to evidence-based sustainability planning. Paleolimnology, however, is not limited to Arctic environments and can also be usefully applied in other water insecure regions to reconstruct past climates and biological successions.

REFERENCES

Abnizova, A., & Young, K. L. (2010). Sustainability of High Arctic ponds in a polar desert environment. *Arctic*, 67-84.

Ahmed, M., Anchukaitis, K. J., Asrat, A., Borgaonkar, H. P., Braida, M., Buckley, B. M., ... & Curran, M. A. (2013). Continental-scale temperature variability during the past two millennia. *Nature Geoscience*, *6*(5), 339-346.

Alessa, L., Kliskey, A., Lammers, R., Arp, C., White, D., Hinzman, L., & Busey, R. (2008). The arctic water resource vulnerability index: an integrated assessment tool for community resilience and vulnerability with respect to freshwater. *Environmental Management*, *42*(3), 523.

Andresen, C. G., & Lougheed, V. L. (2015). Disappearing Arctic tundra ponds: Fine-scale analysis of surface hydrology in drained thaw lake basins over a 65 year period (1948–2013). *Journal of Geophysical Research: Biogeosciences*, *120*(3), 466-479.

Antoniades, D., Douglas, M. S., & Smol, J. P. (2005). Quantitative estimates of recent environmental changes in the Canadian High Arctic inferred from diatoms in lake and pond sediments. *Journal of Paleolimnology*, *33*(3), 349-360.

Appleby, P. G., & Oldfield, F. (1978). The calculation of lead-210 dates assuming a constant rate of supply of unsupported 210Pb to the sediment. *Catena*, *5*(1), 1-8.

Armitage, P. D., Pinder, L. C., & Cranston, P. S. (Eds.). (2012). *The Chironomidae: biology and ecology of non-biting midges*. Springer Science & Business Media.

Assessment, A. C. I. (2004). Impacts of a Warming Arctic-Arctic Climate Impact Assessment. *Impacts of a Warming Arctic-Arctic Climate Impact Assessment, by Arctic Climate Impact Assessment, pp. 144. ISBN 0521617782. Cambridge, UK: Cambridge University Press, December 2004.*, 144.

Axford, Y., Lasher, G. E., Kelly, M. A., Osterberg, E. C., Landis, J., Schellinger, G. C., ... & Francis, D. R. (2019). Holocene temperature history of northwest Greenland–With new ice cap constraints and chironomid assemblages from Deltasø. *Quaternary Science Reviews*, *215*, 160-172.

Bailey, R.C., Kennedy, M.G., Dervish, M.Z., and Taylor, R.M. (1998). Biological assessment of freshwater ecosystems using a reference condition approach: comparing predicted and actual benthic invertebrate communities in Yukon streams. *Freshwater Biology, 39*, 765-774.

Bakaic, M., & Medeiros, A. S. (2017). Vulnerability of northern water supply lakes to changing climate and demand. *Arctic Science*, *3*(1), 1-16.

Bakaic, M., Medeiros, A. S., Peters, J. F., & Wolfe, B. B. (2018). Hydrologic monitoring tools for freshwater municipal planning in the Arctic: the case of Iqaluit, Nunavut, Canada. *Environmental Science and Pollution Research*, *25*(33), 32913-32925.

Balasubramaniam, A.M., Medeiros, A.S., Turner, K.W., Hall, R.I., and Wolfe, B.B. (2017). Biotic responses to multiple aquatic and terrestrial gradients in shallow subarctic lakes (Old Crow Flats, Yukon, Canada). *Arctic Science*, *3*, 277–300.

Barley, E. M., Walker, I. R., Kurek, J., Cwynar, L. C., Mathewes, R. W., Gajewski, K., & Finney, B. P. (2006). A northwest North American training set: distribution of freshwater midges in relation to air temperature and lake depth. *Journal of Paleolimnology*, *36*(3), 295.

Bennett, K. D. (1996). Determination of the number of zones in a biostratigraphical sequence. *New Phytologist*, *132*(1), 155-170.

Birks, H.J.B., 1998. Numerical tools in paleolimnology- progress, potentialities, and problems. *Journal of Paleolimnology, 20*, 307-322.

Birks, H. H., & Birks, H. J. B. (2006). Multi-proxy studies in palaeolimnology. *Vegetation History and Archaeobotany*, *15*(4), 235–251.

Birks, H.J.B., and Birks, H.H. (1980). Quaternary Paleoecology. Edwards Arnold, London.

Blaauw, M. (2020). clam: Classical Age-Depth Modelling of Cores from Deposits. R package version 2.3.4. Available at: https://CRAN.R-project.org/package=clam.

Borisko, J. P., Kilgour, B. W., Stanfield, L. W., & Jones, F. C. (2007). An evaluation of rapid bioassessment protocols for stream benthic invertebrates in Southern Ontario, Canada. *Water Quality Research Journal*, *42*(3), 184-193.

Bouchard, F., K. W. Turner, L. A. MacDonald, C. Deakin, H. White, N. Farquharson, A. S. Medeiros, B. B. Wolfe, R. Hall, R. Pienitz & T.W. D. Edwards. (2013). Vulnerability of shallow subarctic lakes to evaporate and desiccate when snowmelt runoff is low. *Geophysical Research Letters*, *40*(23), 6112–6117.

Briere, M. D., & Gajewski, K. (2020). Human population dynamics in relation to Holocene climate variability in the North American Arctic and Subarctic. *Quaternary Science Reviews*, *240*, 106370.

Briner, J. P., McKay, N. P., Axford, Y., Bennike, O., Bradley, R. S., de Vernal, A., ... & Jennings, A. (2016). Holocene climate change in Arctic Canada and Greenland. *Quaternary Science Reviews*, *147*, 340-364.

Bring, A., Fedorova, I., Dibike, Y., Hinzman, L., Mård, J., Mernild, S. H., ... & Woo, M. K. (2016). Arctic terrestrial hydrology: A synthesis of processes, regional effects, and research challenges. *Journal of Geophysical Research: Biogeosciences*, *121*(3), 621-649.

Bring, A., Jarsjö, J., & Destouni, G. (2015). Water information and water security in the Arctic. In *The New Arctic* (pp. 225-238). Springer, Cham.

Bronk Ramsey, C. (2009). Bayesian analysis of radiocarbon dates. *Radiocarbon*, *51*(1), 337–360.

Brooks, N. (2003). Vulnerability, risk and adaptation: A conceptual framework. *Tyndall Centre for Climate Change Research Working Paper*, *38*(38), 1-16.

Brooks, S. J., Bennion, H., & Birks, H. J. B. (2001). Tracing lake trophic history with a chironomid–total phosphorus inference model. *Freshwater Biology*, *46*(4), 513-533.

Brooks, S. J., Langdon, P. G., & Heiri, O. (2007). *The identification and use of Palaearctic Chironomidae larvae in palaeoecology*. Quaternary Research Association.

Brown, L.C., and Duguay, C.R. (2011). The fate of lake ice in the North American Arctic. *Cryosphere*, 5, 869–892.

Bunch, M. J., Morrison, K. E., Parkes, M. W., & Venema, H. D. (2011). Promoting health and well-being by managing for social–ecological resilience: the potential of integrating ecohealth and water resources management approaches. *Ecology and Society*, *16*(1).

Bürkner, P. C. (2018). Advanced Bayesian multilevel modeling with the R package brms. *The R Journal* 10(1): 395-411. Available at: https://cran.r-project.org/web/packages/brms/

Carroll, M. L., Townshend, J. R. G., DiMiceli, C. M., Loboda, T., & Sohlberg, R. A. (2011). Shrinking lakes of the Arctic: Spatial relationships and trajectory of change. *Geophysical Research Letters*, *38*(20).

Christiansen, B., & Ljungqvist, F. C. (2017). Challenges and perspectives for large-scale temperature reconstructions of the past two millennia. *Reviews of Geophysics*, *55*(1), 40–96.

Connell, J. H. (1978). Diversity in tropical rain forests and coral reefs. *Science*, *199*(4335), 1302-1310.

Daley, K., Castleden, H., Jamieson, R., Furgal, C., & Ell, L. (2015). Water systems, sanitation, and public health risks in remote communities: Inuit resident perspectives from the Canadian Arctic. *Social Science & Medicine*, *135*, 124-132.

Danks, H.V. (1992). Arctic insects as indicators of environmental change. *Arctic, 45*, 159-166.

Dean, W. E. (1974). Determination of carbonate and organic matter in calcareous sediments and sedimentary rocks by loss on ignition; comparison with other methods. *Journal of Sedimentary Research*, *44*(1), 242-248.

Derksen, C., and Brown, R. (2012). Spring snow cover extent reductions in the 2008–2012 period exceeding climate model projections. *Geophysical Research Letters*, *39*, 1–6.

Derry, A. M., Kevan, P. G., & Rowley, S. D. (1999). Soil nutrients and vegetation characteristics of a Dorset/Thule site in the Canadian Arctic. *Arctic*, 204-213.

Dranga, S. A., Hayles, S., & Gajewski, K. (2017). Synthesis of limnological data from lakes and ponds across Arctic and Boreal Canada. *Arctic Science*, *4*(2), 167-185.

Dunn, G., & Bakker, K. (2011). Fresh water-related indicators in Canada: An inventory and analysis. *Canadian Water Resources Journal*, *36*(2), 135-148.

Edwardson, K. J., Bowden, W. B., Dahm, C., & Morrice, J. (2003). The hydraulic characteristics and geochemistry of hyporheic and parafluvial zones in Arctic tundra streams, north slope, Alaska. *Advances in Water Resources*, *26*(9), 907-923.

Eggermont, H., & Heiri, O. (2012). The chironomid-temperature relationship: expression in nature and palaeoenvironmental implications. *Biological Reviews*, *87*(2), 430-456.

Finkelstein, S. A., & Gajewski, K. (2007). A palaeolimnological record of diatom-community dynamics and late-Holocene climatic changes from Prescott Island, Nunavut, central Canadian Arctic. *The Holocene*, *17*(6), 803-812.

Ford, J. D., & Smit, B. (2004). A framework for assessing the vulnerability of communities in the Canadian Arctic to risks associated with climate change. *Arctic*, *57*(4).

Ford, J. D., Smit, B., Wandel, J., & MacDonald, J. (2006). Vulnerability to climate change in Igloolik, Nunavut: what we can learn from the past and present. *Polar Record*, *42*(2), 127-138.

Ford, J., Pearce, T., Smit, B., Wandel, J., Allurut, M., Shappa, K., ... & Qrunnut, K. (2007). Reducing vulnerability to climate change in the Arctic: the case of Nunavut, Canada. *Arctic*, *60*, 150-166.

Fortin, M. C., & Gajewski, K. (2010a). Holocene climate change and its effect on lake ecosystem production on Northern Victoria Island, Canadian Arctic. *Journal of Paleolimnology, 43*(2), 219-234.

Fortin, M. C., & Gajewski, K. (2010b). Postglacial environmental history of western Victoria Island, Canadian Arctic. *Quaternary Science Reviews*, *29*(17-18), 2099-2110.

Fortin, M. C., & Gajewski, K. (2011). Modern chironomid assemblages from the Canadian Arctic. *Chironomus*, *1*, 5.

Fortin, M. C., & Gajewski, K. (2016). Multiproxy paleoecological evidence of Holocene climatic changes on the Boothia Peninsula, Canadian Arctic. *Quaternary Research*, *85*(3), 347-357.

Fortin, M.C., Medeiros, A.S., Gajewski, K., Barley, E.M., Larocque-Tobler, I., Porinchu, D.F., and Wilson, S.E. (2015). Chironomid–environment relations in northern North America. *Journal of Paleolimnology, 54*, 223–237.

Francis, D. R., Wolfe, A. P., Walker, I. R., & Miller, G. H. (2006). Interglacial and Holocene temperature reconstructions based on midge remains in sediments of two lakes from

Baffin Island, Nunavut, Arctic Canada. *Palaeogeography, Palaeoclimatology, Palaeoecology*, *236*(1-2), 107-124.

Fritz, S. C., & Anderson, N. J. (2013). The relative influences of climate and catchment processes on Holocene lake development in glaciated regions. *Journal of Paleolimnology*, *49*(3), 349-362.

Gajewski, K., Mott, R. J., Ritchie, J. C., & Hadden, K. (2000). Holocene vegetation history of Banks Island, Northwest Territories, Canada. *Canadian Journal of Botany*, *78*(4), 430-436.

Gajewski, K., Bouchard, G., Wilson, S. E., Kurek, J., & Cwynar, L. C. (2005). Distribution of Chironomidae (Insecta: Diptera) head capsules in recent sediments of Canadian Arctic lakes. *Hydrobiologia*, *549*(1), 131-143.

Galili, T. (2015). dendextend: an R package for visualizing, adjusting, and comparing trees of hierarchial clustering. *Bioinformatics*. DOI: 10.1093/bioinformatics/btv428.

Goldhar, C., Bell, T., & Wolf, J. (2013). Rethinking existing approaches to water security in remote communities: an analysis of two drinking water systems in Nunatsiavut, Labrador, Canada. *Water Alternatives*, *6*(3), 462.

Goldhar, C., Bell, T., & Wolf, J. (2014). Vulnerability to freshwater changes in the Inuit settlement region of Nunatsiavut, Labrador: A case study from Rigolet. *Arctic*, *67*, 71-83.

Gordon, A. D., & Birks, H. J. B. (1972). Numerical methods in Quaternary palaeoecology I. Zonation of pollen diagrams. *New Phytologist*, *71*(5), 961-979.

Government of Nunavut (2015) Government of Nunavut, Department of Health. http://www.gov.nu.ca/health.

Graham, N. E., Ammann, C. M., Fleitmann, D., Cobb, K. M., & Luterbacher, J. (2011). Support for global climate reorganization during the “Medieval Climate Anomaly’’. *Climate Dynamics*, *37*(5), 1217–1245.

Harper, S. L., Edge, V. L., Ford, J., Thomas, M. K., Pearl, D. L., Shirley, J., & McEwen, S. A. (2015). Acute gastrointestinal illness in two Inuit communities: burden of illness in Rigolet and Iqaluit, Canada. *Epidemiology & Infection*, *143*(14), 3048-3063.

Harper, S. L., Edge, V. L., Schuster-Wallace, C. J., Berke, O., & McEwen, S. A. (2011). Weather, water quality and infectious gastrointestinal illness in two Inuit communities in Nunatsiavut, Canada: potential implications for climate change. *EcoHealth*, *8*(1), 93-108.

Harper, S. L., Wright, C., Masina, S., & Coggins, S. (2020). Climate change, water, and human health research in the Arctic. *Water Security*, *10*, 100062.

Heiri, O., Brooks, S. J., Renssen, H., Bedford, A., Hazekamp, M., Ilyashuk, B., ... & Millet, L. (2014). Validation of climate model-inferred regional temperature change for late-glacial Europe. *Nature Communications*, *5*, 4914.

Heiri, O., & Lotter, A. F. (2001). Effect of low count sums on quantitative environmental reconstructions: an example using subfossil chironomids. *Journal of Paleolimnology*, *26*(3), 343-350.

Heiri, O., Lotter, A. F., & Lemcke, G. (2001). Loss on ignition as a method for estimating organic and carbonate content in sediments: reproducibility and comparability of results. *Journal of Paleolimnology*, *25*(1), 101-110.

Hinzman, L. D., Bettez, N. D., Bolton, W. R., Chapin, F. S., Dyurgerov, M. B., Fastie, C. L., ... & Jensen, A. M. (2005). Evidence and implications of recent climate change in northern Alaska and other arctic regions. *Climatic Change*, *72*(3), 251-298.

Hunt, B. G. (2006). The medieval warm period, the little ice age and simulated climatic variability. *Climate Dynamics*, *27*(7–8), 677–694.

Huntington, H., Fox, S., Berkes, F., Krupnik, I., Whiting, A., Zacharof, M., ... & Brubaker, M. (2005). The changing Arctic: indigenous perspectives. *Arctic climate impact assessment*, *64*.

Huntington, T. G. (2006). Evidence for intensification of the global water cycle: review and synthesis. *Journal of Hydrology*, *319*(1-4), 83-95.

Ingram, H. (2008). Beyond universal remedies for good water governance: a political and contextual approach. In: 6th Rosenberg water policy forum. *Available at: http://rosenberg. ucanr. org/documents/V Ingram. pdf*.

Instanes, A., Kokorev, V., Janowicz, R., Bruland, O., Sand, K., & Prowse, T. (2016). Changes to freshwater systems affecting Arctic infrastructure and natural resources. *Journal of Geophysical Research: Biogeosciences*, *121*(3), 567-585.

IPCC: Climate change 2013: The physical science basis. *Contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change*, *1535*.

Juggins, S. (2017). Rioja: analysis of quaternary science data, R package version 0.9–21. *URL http://cran. r-project. org/package= rioja*.

Kassambara, A., & Mundt, F. (2020). factoextra: Extract and Visualize the Results of Multivariate Data Analyses. R package version 1.0.7. Available at: https://CRAN.R-project.org/package=factoextra.

Kattsov, V.M., and Walsh, J.E. (2000). Twentieth-century trends of Arctic precipitation from observational data and a climate model simulation. *Journal of Climatology*, *13*, 1362–1370.

Kaufman, D., McKay, N., Routson, C., Erb, M., Davis, B., Heiri, O., ... & Brussel, T. (2020). A global database of Holocene paleotemperature records. *Scientific Data*, *7*(1), 1-34.

Kaufman, D. S., Schneider, D. P., McKay, N. P., Ammann, C. M., Bradley, R. S., Briffa, K. R., ... & Lakes, A. (2009). Recent warming reverses long-term Arctic cooling. *Science*, *325*(5945), 1236-1239.

Kelly, P. M., & Adger, W. N. (2000). Theory and practice in assessing vulnerability to climate change and Facilitating adaptation. *Climatic Change*, *47*(4), 325-352.

Kivilä, E. H., Luoto, T. P., Rantala, M. V., & Nevalainen, L. (2019). Late-Holocene variability in chironomid functional assemblages and carbon utilization in a tundra lake food web. *Hydrobiologia*, *847*(3), 895-911.

Lamb, H. H. (2002). *Climate, history and the modern world*. Routledge.

Lantz, T. C., & Turner, K. W. (2015). Changes in lake area in response to thermokarst processes and climate in Old Crow Flats, Yukon. *Journal of Geophysical Research: Biogeosciences*, *120*(3), 513-524.

Larocque, I. (2001). How many chironomid head capsules are enough? A statistical approach to determine sample size for palaeoclimatic reconstructions. *Palaeogeography, Palaeoclimatology, Palaeoecology*, *172*(1-2), 133-142.

Larocque, I., Pienitz, R., & Rolland, N. (2006). Factors influencing the distribution of chironomids in lakes distributed along a latitudinal gradient in northwestern Quebec, Canada. *Canadian Journal of Fisheries and Aquatic Sciences*, *63*(6), 1286-1297.

Larocque-Tobler, I., Grosjean, M., Heiri, O., & Trachsel, M. (2009). High-resolution chironomid-inferred temperature history since AD 1580 from varved Lake Silvaplana, Switzerland: comparison with local and regional reconstructions. *The Holocene*, *19*(8), 1201-1212.

Law, A. C., Anderson, N. J., & McGowan, S. (2015). Spatial and temporal variability of lake ontogeny in south-western Greenland. *Quaternary Science Reviews*, *126*, 1-16.

Lawrence, P. R., Meigh, J., & Sullivan, C. (2002). *The water poverty index: an international comparison*. Keele, Straffordshire, UK: Department of Economics, Keele University.

Lê, S., Josse, J., & Husson, F. (2008). FactoMinR: An R package for multivariate analysis. *Journal of Statistical Software* 25(1): 1-18. Available at: https://doi.org/10.18637/jss.v025.i01.

Lewis, T. L., M. S. Lindberg, J. A. Schmutz, P. J. Heglund, J. Rover, J. C. Koch & M. R. Bertram, 2015. Pronounced chemical response of Subarctic lakes to climate-driven losses in surface area. *Global Change Biology, 21*, 1140–1152.

Linderholm, H. W., Nicolle, M., Francus, P., Gajewski, K., Helama, S., Korhola, A., ... & Debret, M. (2018). Arctic hydroclimate variability during the last 2000 years: current understanding and research challenges. *Climate of the Past*.

Ljungqvist, F. C. (2010). A new reconstruction of temperature variability in the extra-tropical northern hemisphere during the last two millennia. *Geografiska Annaler: Series A, Physical Geography*, *92*(3), 339–351.

Luers, A. L. (2005). The surface of vulnerability: an analytical framework for examining environmental change. *Global Environmental Change*, *15*(3), 214-223.

Luoto, T. P., Kuhry, P., Holzkämper, S., Solovieva, N., & Self, A. E. (2017). A 2000-year record of lake ontogeny and climate variability from the north-eastern European Russian Arctic. *The Holocene*, *27*(3), 339-348.

MacDonald, G. M., Beukens, R. P., & Kieser, W. E. (1991). Radiocarbon dating of limnic sediments: a comparative analysis and discussion. *Ecology*, *72*(3), 1150–1155.

MacDonald, L. A., K. W. Turner, A. M. Balasubramaniam, B. B. Wolfe, R. I. Hall & J. N. Sweetman, 2012. Tracking hydrological responses of a thermokarst lake in the Old Crow Flats (Yukon Territory, Canada) to recent climate variability using aerial photographs and paleolimnological methods. *Hydrological Processes*, *26*, 117–129.

Martin, D., Bélanger, D., Gosselin, P., Brazeau, J., Furgal, C., & Déry, S. (2007). Drinking water and potential threats to human health in Nunavik: adaptation strategies under climate change conditions. *Arctic*, 195-202.

Mayfield, R. J., Langdon, P. G., Doncaster, C. P., Dearing, J. A., Wang, R., Nazarova, L. B., ... & Brooks, S. J. (2020). Metrics of structural change as indicators of chironomid community stability in high latitude lakes. *Quaternary Science Reviews*, *249*, 106594.

McCarthy, J. J., Martello, M. L., Symon, C., Arris, L., & Hill, B. (2005). Climate change in the context of multiple stressors and resilience. In: Arctic climate impact assessment scientific report, Cambridge: Cambridge University Press: 945-988.

Medeiros, A.S., Friel, C.E., Finkelstein, S.A., and Quinlan, R. (2012). A high resolution multi-proxy record of pronounced recent environmental change at Baker Lake, Nunavut. *Journal of Paleolimnology, 47*, 661-676.

Medeiros, A. S., Gajewski, K., Porinchu, D. F., Vermaire, J. C., & Wolfe, B. B. (2015). Detecting the influence of secondary environmental gradients on chironomid-inferred paleotemperature reconstructions in northern North America. *Quaternary Science Reviews*, *124*, 265-274.

Medeiros, A. S., Luszczek, C. E., Shirley, J., & Quinlan, R. (2011). Benthic biomonitoring in arctic tundra streams: A community-based approach in Iqaluit, Nunavut, Canada. *Arctic*, *64*(1), 59-72.

Medeiros, A.S., and Quinlan, R. (2011). The distribution of the Chironomidae (Insecta: Diptera) along multiple environmental gradients in lakes and ponds of the eastern Canadian Arctic. *Canadian Journal of Fisheries and Aquatic Sciences, 68*, 1511–1527.

Medeiros, A.S., Taylor, D.J., Couse, M., Hall, R.I., Quinlan, R., and Wolfe, B.B. (2014). Biological and nutrient responses to catchment disturbance and warming in small lakes near the Alaskan tundra-taiga boundary. *The Holocene, 24*, 1308-1319.

Medeiros, A. S., Wood, P., Wesche, S. D., Bakaic, M., & Peters, J. F. (2017). Water security for northern peoples: review of threats to Arctic freshwater systems in Nunavut, Canada. *Regional Environmental Change*, *17*(3), 635-647.

Meigh, J. R., McKenzie, A. A., & Sene, K. J. (2004). A grid-based approach to water scarcity estimates for eastern and southern Africa. *Water Resources Management*, *13*(2), 85-115.

Müller, J., Werner, K., Stein, R., Fahl, K., Moros, M., & Jansen, E. (2012). Holocene cooling culminates in sea ice oscillations in Fram Strait. *Quaternary Science Reviews*, *47*, 1-14.

Muster, S., Riley, W. J., Roth, K., Langer, M., Cresto Aleina, F., Koven, C. D., ... & Jones, B. M. (2019). Size distributions of Arctic waterbodies reveal consistent relations in their statistical moments in space and time. *Frontiers in Earth Science*, *7*, 5.

Nicolle, M., Debret, M., Massei, N., Christophe, C., Divine, D., Werner, J. P., … Linderholm, H. W. (2018). Climate variability in the subarctic area for the last 2 millennia. *Climate of the Past*, *14*(1), 101.

Oksanen, J., Blanchet, F. G., Friendly, M., Kindt, R., Legendre, P., McGlinn, D., ... & Solymos, P. (2019). vegan: Community Ecology Package. R package version 2.5-6. Available at: https://CRAN.R-project.org/package=vegan.

Oliver, D. R., & Dillon, M. E. (1997). Chironomids (Diptera: Chironomidae) of the Yukon Arctic North Slope and Herschel Island. *Insects of the Yukon. Biological Survey of Canada (Terrestrial Arthropods), Ottawa*, 615-635.

Oliver, D. R., & Roussel, M. E. (1983). *The insects and arachnids of Canada. Part 11. The genera of larval midges of Canada. Diptera: Chironomidae*. Minister of Supply and Services. Agriculture Canada, Ottawa.

Osterkamp, T.E. (2005). The recent warming of permafrost in Alaska. *Global and Planetary Change*. *49*, 187–202.

Penn, H. J., Loring, P. A., & Schnabel, W. E. (2017). Diagnosing water security in the rural North with an environmental security framework. *Journal of Environmental Management*, *199*, 91-98.

Peros, M. C., & Gajewski, K. (2009). Pollen-based reconstructions of late Holocene climate from the central and western Canadian Arctic. *Journal of Paleolimnology*, *41*(1), 161-175.

Plummer, R., de Loë, R., & Armitage, D. (2012). A systematic review of water vulnerability assessment tools. *Water Resources Management*, *26*(15), 4327-4346.

Porinchu, D.F., and MacDonald, G.M. (2003). The use and application of freshwater midges (Chironomidae: Insecta: Diptera) in geographical research. *Progress in Physical Geography,* 27, 378-422.

Porinchu, D. F., MacDonald, G. M., & Rolland, N. (2009a). A 2000 year midge-based paleotemperature reconstruction from the Canadian Arctic archipelago. *Journal of Paleolimnology*, *41*(1), 177-188.

Porinchu, D., Rolland, N., & Moser, K. (2009b). Development of a chironomid-based air temperature inference model for the central Canadian Arctic. *Journal of Paleolimnology, 41*(2), 349-368.

Porinchu, D. F., MacDonald, G. M., Moser, K. A., Rolland, N., Kremenetski, K., Seppä, H., & Rühland, K. M. (2019). Evidence of abrupt climate change at 9.3 ka and 8.2 ka in the central Canadian Arctic: Connection to the North Atlantic and Atlantic Meridional Overturning Circulation. *Quaternary Science Reviews*, *219*, 204-217.

PRI. (2007). Canadian Water Sustainability Index (CWSI) Policy Resaearch Initiative. Government of Canada.

Quinlan, R., Douglas, M.S.V., and Smol, J.P. (2005). Food web changes in arctic ecosystems related to climate warming. *Global Change Biology, 11*, 1381-1386.

Quinlan, R., & Smol, J. P. (2001). Setting minimum head capsule abundance and taxa deletion criteria in chironomid-based inference models. *Journal of Paleolimnology*, *26*(3), 327-342.

Randsalu-Wendrup, L., Conley, D. J., Carstensen, J., & Fritz, S. C. (2016). Paleolimnological records of regime shifts in lakes in response to climate change and anthropogenic activities. *Journal of Paleolimnology*, *56*(1), 1-14.

Raskin, P., Gleick, P., Kirshen, P., Pontius, G., & Strzepek, K. (1997). Comprehensive assessment of the freshwater resources of the world. Water futures: assessment of long-range patterns and problems. Stockholm Environmental Institute, Stockholm, Sweden.

Rautio, M., Dufresne, F., Laurion, I., Bonilla, S., Vincent, W. F., & Christoffersen, K. S. (2011). Shallow freshwater ecosystems of the circumpolar Arctic. *Ecoscience*, *18*(3), 204-222.

Reimer, P. J., Bard, E., Bayliss, A., Beck, J. W., Blackwell, P. G., Ramsey, C. B., ... & Grootes, P. M. (2013). IntCal13 and Marine13 radiocarbon age calibration curves 0–50,000 years cal BP. *Radiocarbon*, *55*(4), 1869-1887.

Rühland, K., & Smol, J. P. (2005). Diatom shifts as evidence for recent Subarctic warming in a remote tundra lake, NWT, Canada. *Palaeogeography, Palaeoclimatology, Palaeoecology*, *226*(1-2), 1-16.

Saulnier-Talbot, É. (2016). Paleolimnology as a tool to achieve environmental sustainability in the Anthropocene: An overview. *Geosciences*, *6*(2), 26.

Schau, M., 1984. Northern Melville Peninsula. Geological Survey of Canada, Ottawa, Map 1046, Scale 1:500 000.

Schindler, D. W., & Smol, J. P. (2006). Cumulative effects of climate warming and other human activities on freshwaters of Arctic and subarctic North America. *AMBIO: a Journal of the Human Environment*, *35*(4), 160-169.

Serreze, M. C., Walsh, J. E., Chapin, F. S., Osterkamp, T., Dyurgerov, M., Romanovsky, V., ... & Barry, R. G. (2000). Observational evidence of recent change in the northern high-latitude environment. *Climatic change*, *46*(1-2), 159-207.

Shi, F., Yang, B., Ljungqvist, F. C., & Yang, F. (2012). Multi-proxy reconstruction of Arctic summer temperatures over the past 1400 years. *Climate Research*, *54*(2), 113-128.

Simpson, G. L., & Oksanen, J. (2020). analogue: analogue matching and Modern Analogue Technique transfer function models (R package version 0.17–4). Available at: https://cran.r-project.org/package=analogue.

Smit, B., Hovelsrud, G., and Wandel, J. (2008). CAVIAR: Community adaptation and vulnerability in Arctic regions. Occasional Paper No. 28. Guelph: University of Guelph Department of Geography.

Smol, J. P. (2009). *Pollution of lakes and rivers: a paleoenvironmental perspective,* 2nd Ed. Blackwell.

Smol, J. P., & Douglas, M. S. (1996). Long-term environmental monitoring in arctic lakes and ponds using diatoms and other biological indicators. *Geoscience Canada*, *23*(4).

Smol, J. P., & Douglas, M. S. (2007). Crossing the final ecological threshold in high Arctic ponds. *Proceedings of the National Academy of Sciences*, *104*(30), 12395-12397.

Solomon, S., Qin, D., Manning, M., Averyt, K., & Marquis, M. (Eds.). (2007). *Climate change 2007-the physical science basis: Working group I contribution to the fourth assessment report of the IPCC* (Vol. 4). Cambridge University Press, University of Cambridge.

Stocker, T. F., Qin, D., Plattner, G. K., Tignor, M., Allen, S. K., Boschung, J., ... & Midgley, P. M. (2013). Climate change 2013: The physical science basis. *Contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change*, *1535*.

Stone, R.S., Dutton, E.G., Harris, J.M., and Longenecker, D. (2002). Earlier spring snowmelt in northern Alaska as an indicator of climate change. *Journal of Geophysical Research*, *107*, ACL 10-1–ACL 10-13.

Sullivan, C. A., Meigh, J. R., & Giacomello, A. M. (2003, August). The water poverty index: development and application at the community scale. In *Natural resources forum*(Vol. 27, No. 3, pp. 189-199). Oxford, UK: Blackwell Publishing Ltd.

Tamo, C., & Gajewski, K. (2019). Environmental changes of the last 1000 years on Prince of Wales Island, Nunavut, Canada. *Arctic, Antarctic, and Alpine Research*, *51*(1), 348-365.

Team, R. C. (2019). R: A Language and Environment for Statistical Computing.

Telford, R. J. (2019). palaeoSig: Significance Tests of Quantitative Palaeoenvironmental Reconstructions, R package version (2.0-3). Available at: http://cran.r-project.org/package=palaeoSig).

Telford, R.J. (2020). palaeoSig: Significance Tests of Quantitative Palaeoenvironmental Reconstructions, R package version (2.0-3). Available at: http://cran.r-project.org/package=palaeoSig.

Thomas, E. K., Briner, J. P., Axford, Y., Francis, D. R., Miller, G. H., & Walker, I. R. (2011). A 2000-yr-long multi-proxy lacustrine record from eastern Baffin Island, Arctic Canada reveals first millennium AD cold period. *Quaternary Research*, *75*(3), 491-500.

U. N. Water (2013). Water security and the global water agenda: a UN-water analytical brief. *Hamilton, ON: UN University*.

Walker, I. R. (2001). Midges: Chironomidae and related diptera. In *Tracking environmental change using lake sediments* (pp. 43-66). Springer, Dordrecht.

Walker, I. R., & Cwynar, L. C. (2006). Midges and palaeotemperature reconstruction—the North American experience. *Quaternary Science Reviews*, *25*(15-16), 1911-1925.

Walker, I. R., Smol, J. P., Engstrom, D. R., & Birks, H. J. B. (1991). An assessment of Chironomidae as quantitative indicators of past climatic change. *Canadian Journal of Fisheries and Aquatic Sciences*, *48*(6), 975-987.

Webb, T., & Bryson, R. A. (1972). Late-and postglacial climatic change in the northern Midwest, USA: Quantitative estimates derived from fossil pollen spectra by multivariate statistical analysis. *Quaternary Research*, *2*(1), 70-115.

Wetzel, R. G. (2001). *Limnology: lake and river ecosystems,* 3rd Ed. Elsevier Academic Press, San Diego.

Werner, J. P., Divine, D. V, Ljungqvist, F. C., Nilsen, T., & Francus, P. (2018). Spatio-temporal variability of Arctic summer temperatures over the past 2 millennia. *Climate of the Past*, *14*(4), 527.

Wilson, S. E., & Gajewski, K. (2004). Modern chironomid assemblages and their relationship to physical and chemical variables in southwest Yukon and northern British Columbia lakes. *Arctic, Antarctic, and Alpine Research*, *36*(4), 446-455.

Woo, M. K. (2010). Cold ocean seas and northern hydrology: an exploratory overview. *Hydrology Research*, *41*(6), 439-453.

Wood, S. N. (2011). Fast stable restricted maximum likelihood and marginal likelihood estimation of semiparametric generalized linear models. *Journal of the Royal Statistical Society: Series B (Statistical Methodology)*, *73*(1), 3-36.

Wood, S.N. (2017). *Generalized additive models: an introduction with R,* 2 edition. Boca Rotan, Florida: Chapman and Hall/CRC.

Wright, C. J., Sargeant, J. M., Edge, V. L., Ford, J. D., Farahbakhsh, K., Shiwak, I., ... & IHACC Research Team. (2018). Water quality and health in northern Canada: stored drinking water and acute gastrointestinal illness in Labrador Inuit. *Environmental Science and Pollution Research*, *25*(33), 32975-32987.

Wrona, F. J., Johansson, M., Culp, J. M., Jenkins, A., Mård, J., Myers-Smith, I. H., ... & Wookey, P. A. (2016). Transitions in Arctic ecosystems: Ecological implications of a changing hydrological regime. *Journal of Geophysical Research: Biogeosciences*, *121*(3), 650-674.

Wu, G., Li, L., Ahmad, S., Chen, X., & Pan, X. (2013). A dynamic model for vulnerability assessment of regional water resources in arid areas: a case study of Bayingolin, China. *Water Resources Management*, *27*(8), 3085-3101.

Xing, P., Chen, X., Luo, Y., Nie, S., Zhao, Z., Huang, J., & Wang, S. (2016). The Extratropical Northern Hemisphere Temperature Reconstruction during the Last Millennium Based on a Novel Method. *PLOS ONE*, *11*(1), e0146776.