

TEMPORAL AND SPATIAL CHANGES IN BENTHIC MOLLUSC (BIVALVES AND
GASTROPODS) COMMUNITIES IN INNER FROBISHER BAY, NUNAVUT,
BAFFIN ISLAND OVER FIFTY YEARS

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Abstract

Benthic fauna are a crucial part of the marine ecosystem providing many ecosystem services. Unfortunately, Arctic coastal marine environments are under tremendous pressure from changing climate conditions and it is becoming increasingly important to understand community changes occurring in these environments. Long-term ecological studies in the Canadian Arctic are rare, however, Frobisher Bay provides a unique opportunity to study long-term change in the marine benthos because historical benthic community datasets exist for this region. We focused on the molluscs as indicators of long-term change by comparing community temporal and spatial changes between 1967-1976 and 2016. Significant changes in community composition were observed between these two time periods and shifts in functional trait characteristics were also observed. These changes coincided with long-term environmental change in the region. Our results highlight the need for long-term systematic sampling which is fundamental to our understanding of Arctic marine ecosystems and for identifying long-term ecosystem change.

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Chapter 1 Introduction and Overview

1.1 Introduction

Long-term ecological studies extend beyond the life span of the dominant organisms in a particular ecosystem such that the key processes that structure that ecosystem can be quantified (Strayer *et al.* 1986). This definition, however, requires long-term studies to extend over the generation time of the species being studied and this may not be possible for organisms that are extremely long lived (e.g. 500-1000 year old trees). A more realistic definition of long-term studies are those that extend over a much longer time period than most ecological studies and which examine system attributes that would not otherwise be observed on a shorter term study (Strayer *et al.* 1986). Based on these two definitions, Lindenmayer *et al.* (2012) defines long-term studies as those that extend more than 10 years because it allows for repeated sampling of annual growth cycles and bioclimatic cycles which occur on decadal scales. Long-term studies are vital to identifying a measurable ecological response to natural or anthropogenic environmental change (Carpenter *et al.* 1995) and researchers who have conducted long-term marine-based studies in response to climate change have indicated that decadal scales are required to examine community level changes in the marine benthos (Cusson *et al.* 2007, Renaud *et al.* 2007).

One of the major difficulties with measuring the impact that humans have had on the environment is that pristine, benchmark sites are rare and therefore we do not

have a good baseline to work from (Harris 2012). Another more difficult task in identifying long-term anthropogenic impacts to benthic marine systems is that researchers must be able to differentiate between short- and long-term natural variability and long-term anthropogenic change, ensuring that long-term natural fluctuations in marine systems are not attributed to anthropogenic influences (Gray and Christie 1983, Beuchel and Gulliksen 2008, Novoa *et al.* 2016, Kang *et al.* 2019). Some authors believe that predicting long-term anthropogenic change is an unattainable goal because of the short- term natural variability that exists at different temporal scales (days to years) and which may or may not repeat on a longer time-scale (e.g. Gray and Christie 1983). However, with a growing concern around climate warming and its predicted impacts on Arctic continental shelf benthos (Carmack and McLaughlin 2001, Piepenburg 2005), there is a growing consensus that long-term studies are required to monitor changes in benthic communities. Many authors have called for such studies (e.g., Cusson *et al.* 2007, Renaud *et al.* 2007, Brown *et al.* 2011a, Thurstan *et al.* 2015) to understand how they are linked to environmental processes and how future climate change may influence their distribution, composition, and function (Loeng 2005, Carroll *et al.* 2008).

One group of invertebrates present in the benthos that could be potentially useful for detecting long-term changes are bivalves and gastropods from the phylum Mollusca. Over 46,000 marine molluscs have been identified worldwide with upwards of 150,000 marine molluscs yet to be described (Bouchet *et al.* 2016). Marine molluscs are often abundant in benthic communities (Carey *et al.* 1984, Carroll *et al.* 2009,

Clarke and Crame 2010), and are long-lived, some living over 30 + years (Andrews 1972, Carroll *et al.* 2009, Moss *et al.* 2017, Moss *et al.* 2018). Molluscs have previously been used as monitors and indicators of environmental change because they are sensitive to changing environmental conditions (Fortunato 2015). They can also integrate contamination into their tissues, and they exhibit several behavioural and physiological responses to stressors (Smaal and Widdows 1994, Dame 2012, Novoa *et al.* 2016). Molluscs also have good preservation potential (Aitken 1990, Gordillo and Aitken 2000) and historical records of their presence can be compared with modern records. Molluscan fossil records from the Canadian Arctic Archipelago indicate that the modern circum-Arctic molluscan fauna has evolved as a result of two major geological events: the opening of the Bering Strait between 3.5-3.0 Ma and a connection between the Pacific and Atlantic oceans resulting from deglaciation of North America, Europe and Asia (Golikov and Scarlato 1989, Vermeij 1991, Gordillo and Aitken 2000, Taldenkova 2000, Gladenkov and Gladenkov 2004). Given the impact that climate change and anthropogenic stressors may have on the Arctic marine environment, it is important to document changes that have occurred within molluscan communities to determine both how they respond to long-term change and to determine what environmental factors influence those changes.

Frobisher Bay, located at the southern end of Baffin Island can be used as a natural laboratory for studying long term ecological change. Inner Frobisher Bay experienced a period of systematic observation of the benthic fauna between 1967 and 1976 (Wacasey *et al.* 1979, 1980) and Cusson *et al.* (2007) previously examined small

scale temporal variations observed in these benthic communities during that time. Since the 1960's, long-term environmental data has been collected in this region up until the present time (Government of Canada 2017, 2018a, 2018b). Of concern is that the circumpolar Arctic, and inner Frobisher Bay specifically, have experienced warmer air temperatures, warming sea temperatures, a persistent reduction in sea ice cover, and an earlier nival freshet than previously observed (Government of Canada 2017, Overland *et al.* 2017, Perovich *et al.* 2017, Timmermans *et al.* 2017, Government of Canada 2018a, 2018b). These trends, particularly warming air temperatures, appear to have started in the mid 1970s (Overland *et al.* 2017) and may affect the marine benthos in the long term.

1.2 Research Questions and Hypothesis

This study aims to answer the following research questions:

1. How has the species composition of the molluscan (Bivalvia and Gastropoda) community changed temporally over the last fifty years in the sub-tidal benthos of inner Frobisher Bay?
2. How has the species composition of the molluscan (Bivalvia and Gastropoda) community changed spatially over the last fifty years in inner Frobisher Bay?

I hypothesize that long-term temporal and spatial changes will be observed in the molluscan (Bivalvia and Gastropoda) communities of inner Frobisher Bay resulting in changes to the benthic community structure including molluscan community composition, diversity and relative abundance. I propose that changing environmental conditions over the last five decades as a result of climate warming have influenced these changes.

1.3 Study Area

Frobisher Bay is located along the southeastern coastline of Baffin Island between 62 °N and 64 °N, extends 230 kilometers in a southeasterly direction, is 40 km wide at the southern end and 20 km wide at the northern end (Todd *et al.* 2016; Figure 1.1). At the head of Frobisher Bay is the City of Iqaluit, home to 7740 people (Statistics Canada 2018). Frobisher Bay contains a chain of islands approximately 35 nautical miles to the southeast of Iqaluit which splits the bay into two regions: inner Frobisher Bay and outer Frobisher Bay. Inner Frobisher Bay is shallow and reaches depths of up to 260 meters (NTS Map Sheet Area 25; Hodgson 2005, Todd *et al.* 2016) but most of inner Frobisher Bay is less than 200 m (Andrews *et al.* 1985). By comparison, outer Frobisher Bay reaches depths of up to 600 meters or more (Andrews *et al.* 1985; Todd *et al.* 2016).

Twelve sample stations ranging in depth from 10 to 95 m are located in inner Frobisher Bay within ten kilometres of the City of Iqaluit. The head of Frobisher Bay

is characterized by an extensive shallow offshore zone (Miller *et al.* 1980) and borders Koojesse Inlet which is characterized by extensive tidal flats (McCann *et al.* 1981, Hatcher *et al.* 2014, Hatcher and Forbes 2015). Koojesse Inlet is located just east of the Sylvia Grinnell River, a major outflow into Frobisher Bay. Two channels are situated offshore of the tidal flats: Apex Channel, a shallow narrow channel (minimum depth of 1 m CD) that runs between Long Island and the town of Apex to the east, and a second deeper channel, Navigation Channel, which runs between Long Island and Inuit Head to the west (Hatcher *et al.* 2014, Hatcher and Forbes 2015). Five of the long-term ecology stations are located in Navigation Channel and up to Monument Island where station depths range between 9 to 40 meters. The remaining seven long-term ecology stations are located approximately 10 kilometers southeast of Iqaluit, between Cairn Island and Mair Island along the eastern side of Frobisher Bay where station depths range between 25 and 94 meters (Figure 1.2).

Frobisher Bay is characterized by semi-diurnal tides that range from 7.8 m (neap tide) to 11.3 m (spring tide) (Wengerd 1951, Leech 1998, Dale *et al.* 2002, Hatcher *et al.* 2014, Hatcher and Forbes 2015), however, maximum tides have exceeded 13 m (Miller *et al.* 1980). This tidal influence persists throughout the year including when the bay is ice-covered for eight to nine months of each year (Leech 1998, Dale *et al.* 2002). Ice formation typically begins in late October with complete ice cover in the region by the middle of November. While there is considerable variability from year to year, ice break up typically begins in the middle of June (Leech 1998) and the open water season is typically observed to begin by middle to late July (McCann *et al.* 1981). More recent data

based on a 30-year ice atlas (1981 – 2010) provided by the Canadian Ice Service indicates that the average freeze up date for inner Frobisher Bay is November 19 (December 4 for outer Frobisher Bay) and ice break up in inner Frobisher Bay occurs July 2 (July 16-30 for outer Frobisher Bay; Canadian Ice Service 2013).



Figure 1.1. Location of Frobisher Bay within the Canadian Arctic Archipelago (ESRI 2019).

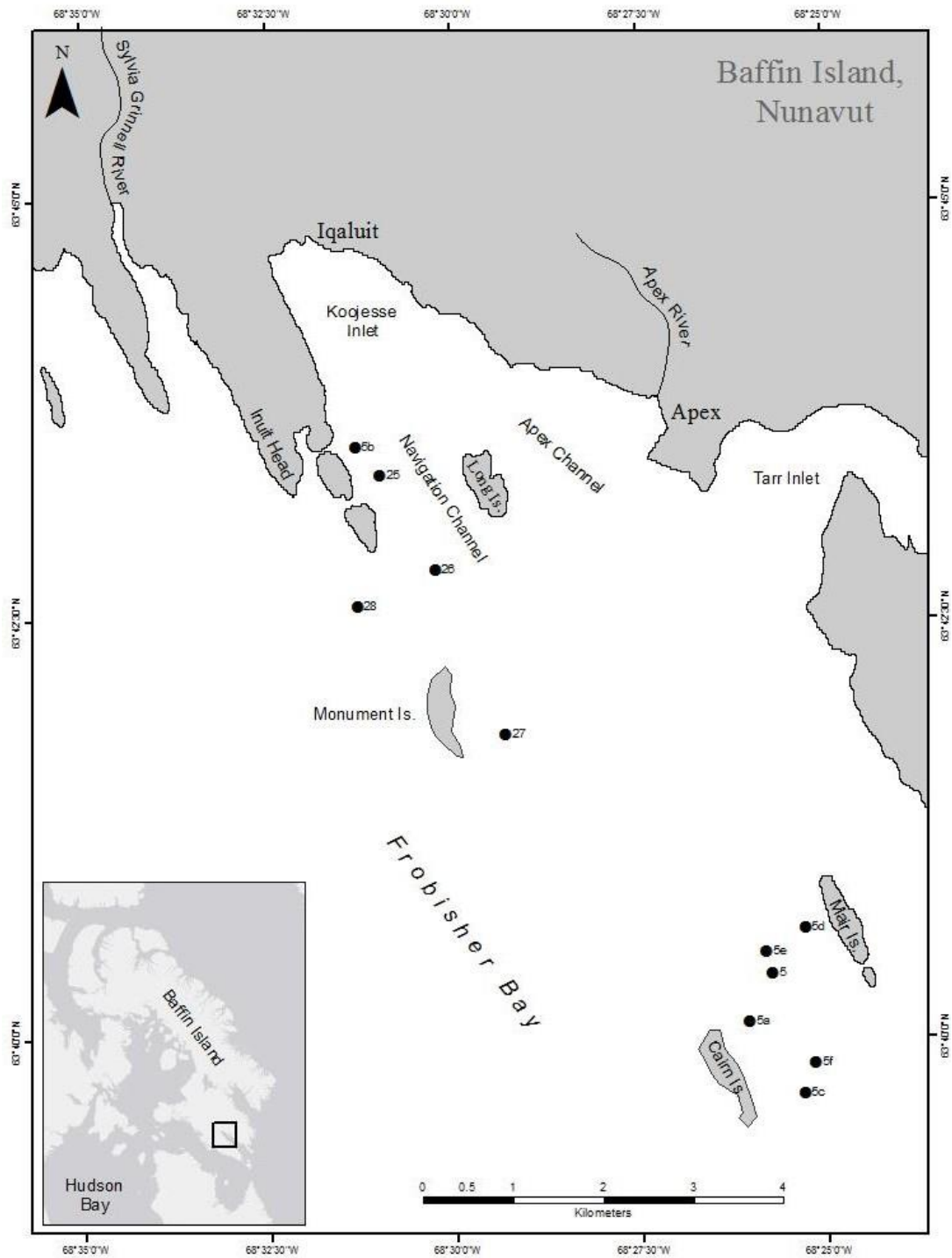


Figure 1.2 Frobisher Bay long-term ecology stations re-drawn from Wacasey (1979, 1980).

1.4 Literature Review

1.4.1 Arctic Change: Global Trends

Climate change is most directly influencing Arctic environments through rising air temperatures which cause sea ice to melt, sea surface temperatures to rise, and sea-level to rise (McLaughlin *et al.* 2011, IPCC 2014). The 2017 Arctic report card headline (issued by the National Oceanic and Atmospheric Administration (NOAA)) states that the “Arctic shows no sign of returning to the reliably frozen region of recent past decades” (Richter-Menge *et al.* 2017). It further states that the Arctic has “reached a ‘new normal’, characterized by long-term losses in the extent and thickness of the sea ice cover and warming sea surface temperatures” (Richter-Menge *et al.* 2017).

The circumpolar Arctic is currently warming at a rate twice that of the global mean temperature (Overland *et al.* 2017) and this has the potential to alter the environment at the Earth’s surface (Dery *et al.* 2016). Sea ice cover is also declining. Significant declines in sea ice extent were observed from 2000-2010 and were some of the lowest records observed over the past 30 years (Forbes 2011, McLaughlin *et al.* 2011). In particular, the Canada Basin had significant losses of both multiyear and first- year ice (McLaughlin *et al.* 2011). On March 7, 2017, the maximum sea ice extent in the Arctic was 14.42 million km², 8% below the 1981-2010 average (Perovich *et al.* 2017). The Arctic Ocean is losing its sea ice cover at a rate of 13.2% per decade based on September monthly averages relative to the 1981-2010 average (Perovich *et al.* 2017). Arctic sea ice is also predominantly

younger and thinner compared to historical records. In 1985 thick, old ice covered 45% of Arctic waters compared to March 2017 where only 21% of thick, multi-year pack ice was observed (Perovich *et al.* 2017).

Sea surface temperatures are also warming in the Arctic. In 2017, the surface of the Barents and Chukchi seas were 4 °C warmer compared to the 1982-2010 August mean temperature and between 1982-2017, the Chukchi Sea experienced an ocean surface warming trend of approximately 0.7 °C per decade (Timmermans *et al.* 2017).

Loss of sea ice in the circumpolar Arctic has also resulted in enhanced light availability, impacting primary productivity which is highly seasonal and dependent on light availability (Frey *et al.* 2017). Satellite observations indicated that primary productivity had shown a widespread increase in 2017 compared to the 2003-2016 mean for most arctic regions with the strongest trends observed in the Barents Sea and Eurasian Arctic regions (Frey *et al.* 2017). The Arctic Ocean is also experiencing increased rates of acidification as a consequence of the loss of sea ice and over the last 200 years, humans have been responsible for a 30-40% increase in concentration of atmospheric CO₂ and about one third of this carbon dioxide has been absorbed by the oceans (Dame 2012).

1.4.2 Environmental Change: Frobisher Bay

Frobisher Bay has experienced similar long-term trends including warmer air temperatures, declining sea ice thickness, and a shortened ice cover season (Government

of Canada 2018a) as have been observed on a global scale. Historical air temperature data from the city of Iqaluit shows a trend of warming temperatures beginning in the mid 1980s. By the mid 1990s, air temperatures appeared more frequently above the 1981-2010 climate normal for each of the selected months of March, June, September and December (Figure 1.3).

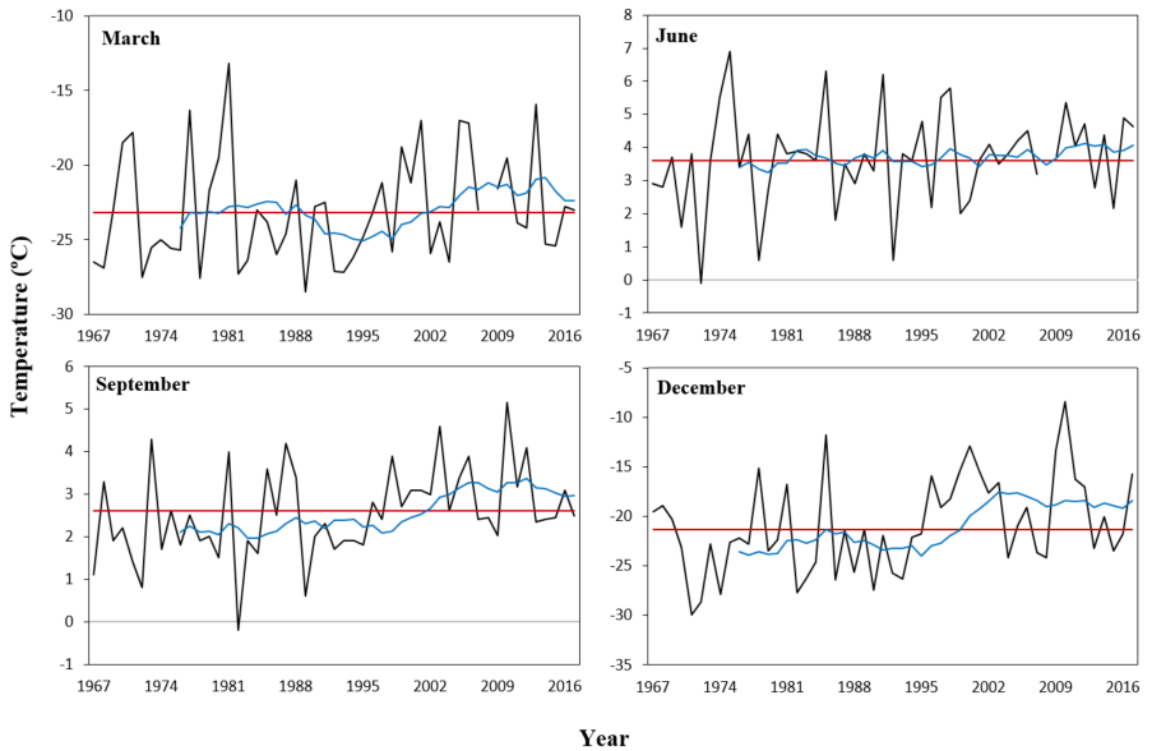


Figure 1.3. Historical mean air temperature trends for select months for the city of Iqaluit between 1967 and 2017. Solid red line refers to mean 1981-2010 climate normal, solid blue line refers to the 10 year moving average air temperature. Data accessed from the Government of Canada (2018a).

This warming trend may be affecting the timing of the nival freshet of the Sylvia Grinnell River and Apex River. The Sylvia Grinnell River is fed by Sylvia Grinnell Lake

and runs 88 kilometers before draining into the inner portion of Frobisher Bay at 63°44'N, 68°34'W, approximately 2 kilometres west of the city of Iqaluit. The Apex River drains into Frobisher Bay near the town of Apex, located approximately 4 kilometers southeast of the city of Iqaluit. Historical discharge data from the Government of Canada (2018b) indicate a strong positive trend in the monthly mean discharge for June for both the Sylvia Grinnell (1971-2015; Figure 1.4) and Apex Rivers (1973-2015) and the Sylvia Grinnell River experienced a subsequent, though slight, negative trend in summer discharge (July-September) that could be indicative of an earlier and more rapid snow melt in June and a decline in summer precipitation.

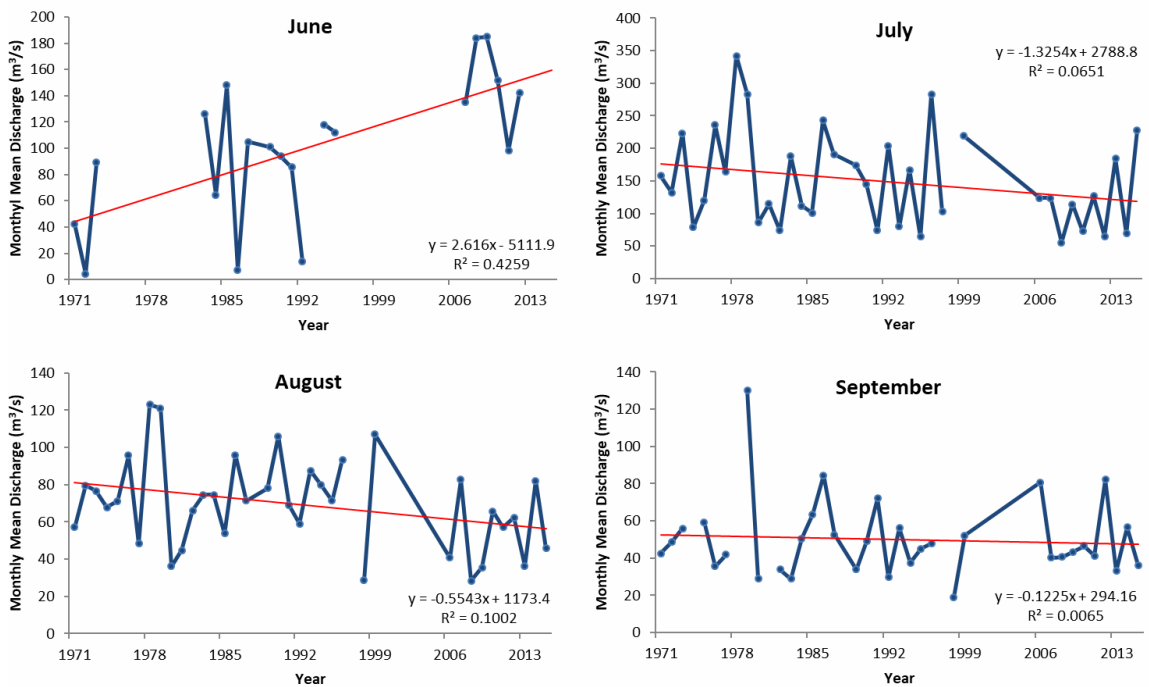


Figure 1.4. Monthly mean discharge rates (m³/s) for the Sylvia Grinnell River, located 2 km west of the city of Iqaluit. Red line indicates trendline. Data accessed from the Government of Canada (2018b).

Ice thickness and the length of the ice season in Frobisher Bay have also changed over time. Maximum ice thickness in Frobisher Bay was measured each year (near the city of Iqaluit) between 1967 and 2016 and shows a declining trend over time (Figure 1.5a). The length of the ice cover season (number of days with ice cover) also shows a declining trend over the same period of time (Figure 1.5b).

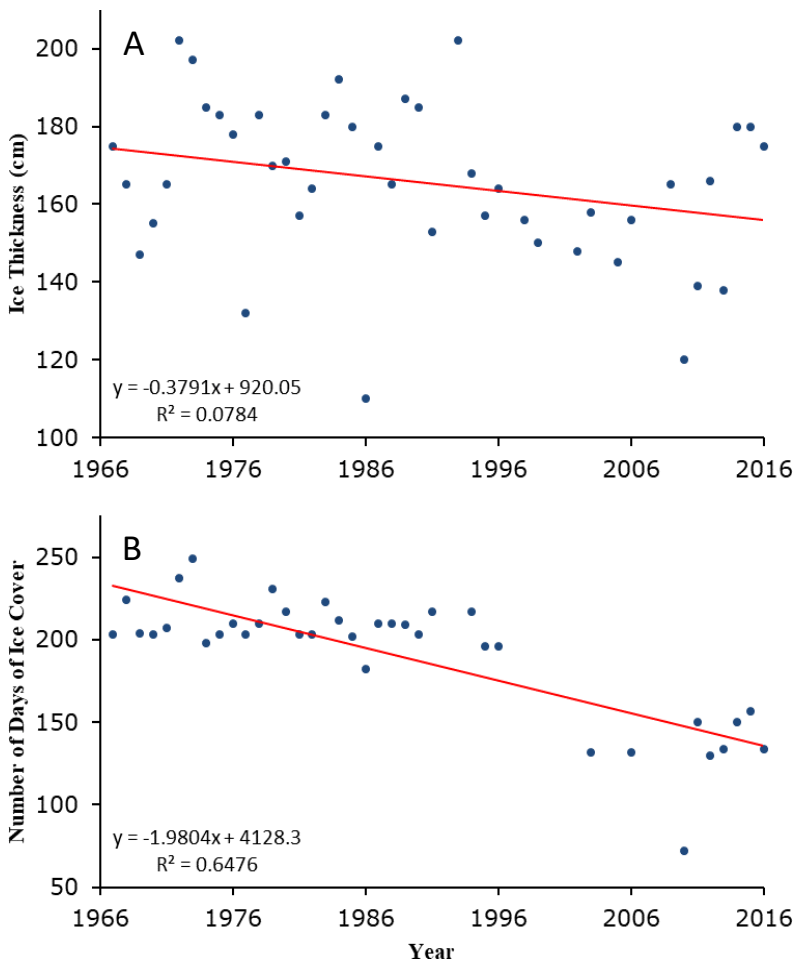


Figure 1.5. (A) Maximum ice thickness (cm) measured each year between 1967 and 2016 near Iqaluit, Nunavut ($p = 0.06899$) showing a non-significant declining trend. (B) Length of ice season (days) measured each year between 1967 and 2016 near Iqaluit Nunavut ($p < 0.0001$) showing a significant declining trend. Data accessed from Government of Canada (2017).

1.4.3 Benthic-Pelagic Coupling

There is a strong consensus that global climate change will profoundly impact marine ecosystems (IPCC 2014), possibly to the community level (Harley *et al.* 2006). It is predicted that future Arctic marine ecosystems will look considerably different in the future causing warmer waters and reduced sea ice that could result in range expansions of new taxa, changes in species abundance, community structure, and the seasonal distribution of taxa (Carmack and McLaughlin 2001, Carmack and Wassmann 2006, Carmack and McLaughlin 2011, Wassmann and Reigstad 2011, Macdonald *et al.* 2015, Renaud *et al.* 2015). In Frobisher Bay, the environmental changes that have occurred over the last 50 years are no exception. Pelagic-benthic coupling (the relationship between the pelagic realm and the benthos; Wassman and Reigstad 2011) is tightly linked in the Arctic where ice cover and light availability affect the quality and quantity of the food supply that reaches the benthos. Therefore, environmental changes that occur at the surface of our oceans will strongly impact the marine benthic communities.

Most of our ocean's seabed consists of sediment which supports a high biodiversity of benthic fauna that are a crucial part of the marine ecosystem (Gougeon *et al.* 2017), many of which provide key ecosystem services (Snelgrove 1999). Benthic organisms consist of epifauna (organisms that live on top of the sediment) and infauna (organisms that reside within the sediments) which together include benthic megafauna and macrofauna. The benthic megafauna includes large-bodied, energy-rich organisms such as fish and invertebrates including large crustaceans,

echinoderms, and molluscs (Blanchard *et al.* 2013a) while the benthic macrofauna typically represents smaller- bodied organisms residing within the sediments such as polychaetes, amphipods, molluscs, ostracods, and cumaceans (Blanchard *et al.* 2013b). The distribution of benthic organisms is highly dependent on temperature, salinity, water movement, water depth, sediment type, and food availability which is tightly linked to pelagic primary productivity (Grebmeier and Barry 1991, Snelgrove 1999, Wei *et al.* 2019).

Temperature is the main determining factor in the distribution of terrestrial organisms from tropical to Arctic environments (Jeffree and Jeffree 1994) but this is less directly a factor in the marine environment. Water depth is a particularly important driver of benthic distributional patterns though water depth is typically a proxy for numerous other physical characteristics including temperature, salinity, and food availability (Roy *et al.* 2014). Water movement influences sediment type and the vertical and horizontal flux of food particles which also affect the distribution of organisms (Grebmeier and Barry 1991). High wave energy environments are associated with coarser sediments dominated by sand or larger grain sizes and low energy environments are dominated by finer sediments such as silts and clays (Snelgrove 1999). Many benthic organisms are either sessile or have limited mobility and are therefore reliant on the water column providing them with food for survival. Benthic organisms feed on plankton and other organic material with suspension feeding organisms removing food particles from the water column and deposit feeding organisms obtaining organic (e.g. meiofauna, microbes) and inorganic food sources

that have settled onto the seabed or live within the sediments (Snelgrove 1997, 1999).

The benthos plays a critical role in nutrient cycling and is an important component of the food web. A complex interaction exists between benthic macrofauna and microbial communities (bacteria, protozoans, and fungi) who help with nutrient cycling through the decomposition of organic matter (Grebmeier and Barry 1991, Kristensen *et al.* 1992, Duchene and Rosenberg 2001). For example, fungi and bacteria decompose particulate organic carbon (primarily algae and fecal detritus; Snelgrove 1997). Macrofauna re-work the sediment and draw down oxygen into the sediment through their feeding, burrowing, and tube building activities (e.g. tentacles of polychaetes, siphons of bivalves, and arms of brittle stars; Kamp and Witte 2005). This re-working can reach a depth of more than 20 cm (Dauwe *et al.* 1998, Duchene and Rosenberg 2001) and aids in nutrient cycling through carbon metabolism and other geochemical cycles (Kristensen *et al.* 1992) and makes nutrients available to different bacterial groups (Dauwe *et al.* 1998, Duchene and Rosenberg 2001, Snelgrove 1999). This re-working of the sediment also re-distributes sediments (Papasprou *et al.* 2006) and modifies sediment chemistry (Norling *et al.* 2007), while also altering sediment stability and near-bed hydrodynamics (Norkko *et al.* 2001).

Some organic carbon is transferred back into the pelagic realm through the food chain. Decomposed dissolved and particulate organic matter is absorbed by bacteria and fungi and supplies macrofauna with food. However, some organic matter is lost to the system through burial and bioturbation and this organic matter becomes

part of the carbon pool stored in seafloor sediments (Snelgrove 1997). Organic matter processed by benthic organisms provides an important link to the pelagic system and to upper trophic levels (Grebmeier and Barry 1991, Snelgrove 1999) as these organisms are a critical source of food for fish, sea birds, and marine mammals such as grey whales, walrus, and bearded seals (Frost and Lowry 1984, Dickson and Gilchrist 2002). Benthic organisms such as clams, scallops, and shrimp are also a valuable food source for humans and commercially important fish species (e.g. cod and Greenland halibut) who rely on benthic organisms as a food source (Carlson *et al.* 1997). These complex links between marine organisms impact global carbon cycling processes in both a direct and indirect manner (Snelgrove 1999).

In the Arctic, pelagic-benthic coupling is primarily driven by the distribution and seasonal dynamics of sea ice (Marcus and Boero 1998, Wassmann and Reigstad 2011) and is a key feature structuring Arctic food webs (Grebmeier and Barry 1991, Conlan and Kvitek 2005, Carmack and Wassmann 2006, Wassmann and Reigstad 2011). It is also an important factor influencing short-term variability in benthic organism abundance in the Arctic (Loeng 2005). Wassmann and Reigstad (2011) provide conceptual models of biogeochemical cycling and climate warming in the seasonal ice zone of the Arctic and they have indicated the loss of sea ice in Arctic regions has already influenced primary productivity from once highly episodic blooms to longer seasonal blooms but at lower concentrations and these rapid changes may continue to result in an ecological response of both pelagic and benthic organisms (Wassmann and Reigstad 2011).

Sea ice has a clear seasonal cycle (Parkinson *et al.* 1999) and coverage and thickness can be highly variable from year to year (Loeng 2005). Sea ice directly impacts the amount of light penetrating through the water (Loeng 2005, Renaud *et al.* 2015). This affects primary production of ice algae present at the base of sea ice and phytoplankton that grows in open water as both of these sources of primary production supply food to the benthos which is tightly linked to ice seasonality (Grainger 1979, Soreide *et al.* 2010). Deposit feeding organisms receive most of their food supply through sedimentation of epontic algae through melting sea ice and from phytoplankton as well as other organic material following the spring bloom (Atkinson and Wacasey 1987) and benthic biomass is directly influenced by the availability of food (Grebmeier and Barry 1991). While some deposit-feeding organisms exhibit selective feeding, most rely on what is available in the sediment and this may impact the benthos seasonally (Ambrose and Renaud 1997). The quantity and composition of organic material that reaches the benthos also changes seasonally and is likely a consequence of changes in ice cover (Ambrose and Renaud 1997). For example, ice algae and phytoplankton production contribute around 90% of the total primary production over Arctic continental shelves, however, ice algae are important earlier in the growing season (Bates *et al.* 2005, Roy *et al.* 2015, Makela *et al.* 2017). These authors noted that suspended particulate organic matter concentrations are high between spring and summer as a result of phytoplankton production in the surface waters of the Chukchi Sea and changing carbon-nitrogen ratios of the suspended particulate matter from spring to summer reflects a significant change in the quality of

material being produced (e.g. a change in the species composition of phytoplankton or the relative contribution of these species; Bates *et al.* 2005). This change in food quality may be a result of a seasonal shift in the type of phytoplankton communities present during different seasons (Bates *et al.* 2005) with microalgae from the sea ice dispersing into the water column as the ice melts in spring and phytoplankton developing throughout the summer (Hsiao 1988). The reduction of sea ice thickness and extent may impact food availability in two ways. Primary production can increase through episodic nutrient availability, increased light availability and increased nutrient discharge from rivers. Nutrient availability can decrease through an increase in water stratification resulting from ice melt and river discharge, a decrease in incident light as a result of increased cloudy weather associated with low pressure systems, and increased turbidity from river discharge (Wassmann and Reigstad 2011).

1.4.4 Identifying benthic community change through long-term studies

Because most benthic fauna are sessile or have limited mobility, and because many taxa have life spans that range from years to decades, the species composition of the benthos can be an excellent indicator from which to measure environmental change over long time scales (Underwood 1996, Beuchel *et al.* 2006, Kedra *et al.* 2010). Long- term studies of benthic communities in cold waters and/or the Arctic have been documented in Arctic fjords around Svalbard, Norway (e.g. Dyer *et al.* 1984, Beuchel *et al.* 2006, Renaud *et al.* 2007, Beuchel and Gulliksen 2008, Kedra *et*

al. 2010, Kortsch *et al.* 2012), the northern Bering Sea (Grebmeier *et al.* 2006), Fram Strait (Taylor *et al.* 2017), the Chukchi Sea (Grebmeier *et al.* 2015), Alaska (Blanchard *et al.* 2002), and the Barents and Kara Seas (Kiyko and Pogrebov 1997, Carroll *et al.* 2009, Kozlovskiy *et al.* 2011) but no longitudinal studies of the benthos have occurred in the Canadian Arctic aside from one study that looked at the direct impacts of an experimental release of oil on Arctic nearshore macrobenthos over a 4-year period in the early 1980s at Cape Hatt, northern Baffin Island (Cross *et al.* 1987, Cross and Thomson 1987; Figure 1.6; Table 1.1).

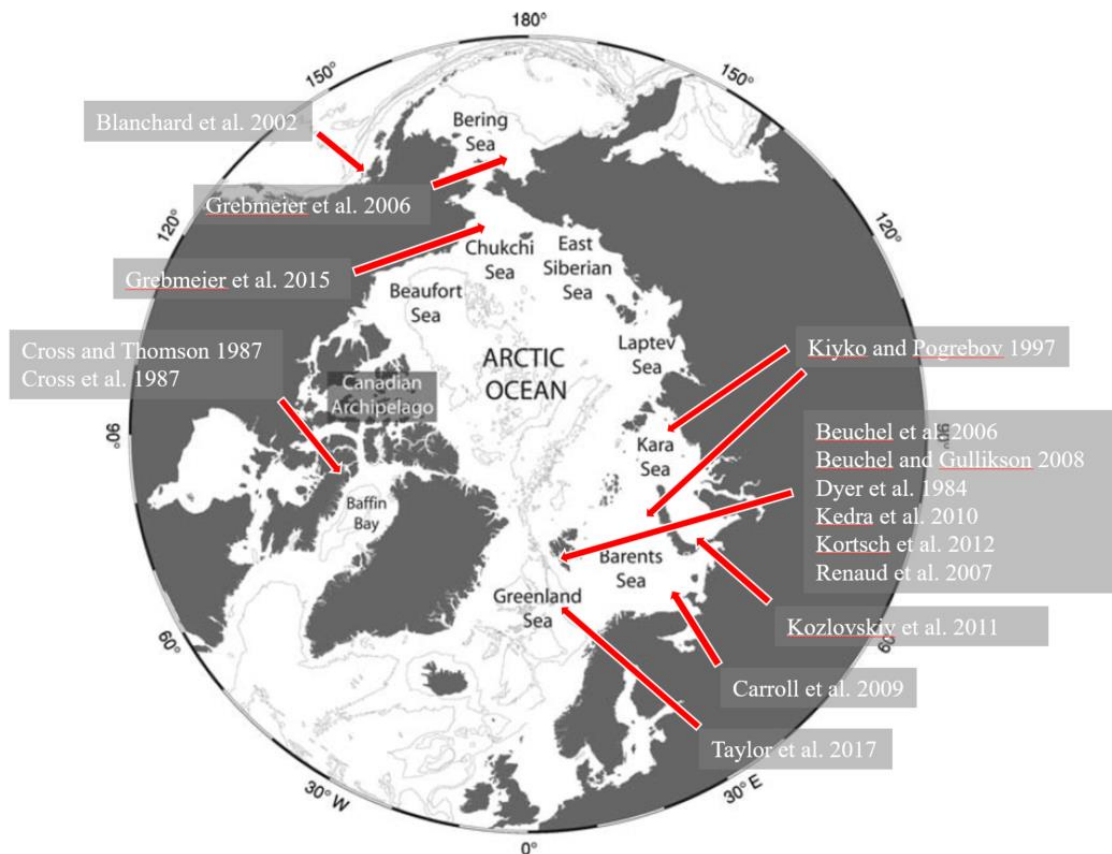


Figure 1.6. Coverage of long-term studies throughout the Arctic Seas. Figure acquired and adapted from Piepenburg 2005.

Table 1.1. Summary of long-term studies of benthic communities and/or species conducted throughout the Arctic Seas.

Reference	Arctic Sea	Study Area	Long-Term Benthic Project
Beuchel <i>et al.</i> 2006 and Beuchel and Gulliksen 2008	Greenland Sea	Kongsfjord, Svalbard, Norway	24 year study (1980-2003) that examined temporal patterns of recolonization and disturbance in a hard bottom marine macrobenthic community.
Dyer <i>et al.</i> 1984	Greenland Sea	Along western coastline of Svalbard, Norway	Compared benthic invertebrate species sampled between 1949-1959 with samples collected between 1978-1981.
Kedra <i>et al.</i> 2010	Greenland Sea	Kongsfjord, Svalbard, Norway	Examined benthic macrofauna communities between 1997/1998 and 2006 along the fjord axis.
Kortsch <i>et al.</i> 2012	Greenland Sea	Kongsfjord and Smeerenburgfjord, Svalbard, Norway	Investigated changes in rocky-bottom community structure between 1980-2010.
Renaud <i>et al.</i> 2007	Greenland Sea	Van Mijenfjord, Svalbard, Norway	Examined changes in the soft-sediment benthic community from samples collected in 1980 and 2000/2001.
Grebmeier <i>et al.</i> 2006	Bering Sea	Shallow shelf of the North Bering Sea	Demonstrate that an ecosystem shift has occurred with a displacement of marine mammal populations, reduction of benthic prey populations, and an increase pelagic fish coinciding with a reduction in sea ice, and increase in air and ocean temperatures.
Taylor <i>et al.</i> 2017	Greenland Sea	HAUSGARTEN long-Term Observatory, Fram Strait	Assessed temporal variability in structure, density, and diversity of megafaunal communities between 2004-2015.
Grebmeier <i>et al.</i> 2015	Chukchi Sea	Throughout Southern Chukchi Sea	Examined macrofaunal and epifaunal composition and biomass and associated environmental drivers for time-series data collected in 2004, 2009, and 2012.
Blanchard <i>et al.</i> 2002	Gulf of Alaska	Port Valdez, Alaska, USA	Examined benthic faunal structure and hydrocarbon concentrations within the sediments over a ten year period (1989-1998).
Carroll <i>et al.</i> 2009	Barents Sea	Southeastern Barents Sea	Analyzed growth rates of the cockle <i>Serripes groenlandicus</i> for almost 70 years (1882-1968) to identify patterns and drivers of natural variability in the

			population and to gauge the potential effects of climate change on the ecosystem.
Kiyko and Pogrebov 1997	Barents Sea and Kara Sea	Throughout the Barents and Kara Sea	Analyzed grab, trawl, and underwater photographs between 1991-1992 and compared these data with changes over the last 60-70 years presented for the Barents Sea.
Kozlovskiy <i>et al.</i> 2011	Kara Sea	Southwestern Kara Sea	Compared the structure and distribution of microbenthic communities from 2007 with samples collected between 1927-1945, 1975, and 1993.
Cross and Thomson 1987 and Cross <i>et al.</i> 1987	Baffin Bay	Cape Hatt, Baffin Island	Examined the effects of an experimental release of oil on Arctic nearshore infauna and epifauna between 1980-1983.

In the Canadian Arctic, there are numerous benthic studies that document benthic fauna but long-term studies are scarce. Canadian Arctic benthic environments are understudied and where studies do exist, they are typically baseline studies that document the biodiversity observed in a given area under study (Carey 1991, Cusson *et al.* 2007, Conlan *et al.* 2008, Piepenburg *et al.* 2011, Wei *et al.* 2019). Long-term studies are expensive and time-consuming to conduct (Wolfe *et al.* 1987, Simkanin *et al.* 2005) and accessibility is an ongoing issue in the Canadian Arctic primarily due to sea ice which restricts accessibility for repeated sampling (Carey 1991).

In the absence of systematically collected long-term data, many authors have called for and have begun to use historical sample data to fill knowledge gaps by combining them with contemporary studies (Wolfe *et al.* 1987, Kiyko and Pogrebov 1997, Cusson *et al.* 2007, Renaud *et al.* 2007, Thurstan *et al.* 2015). In the Canadian Arctic, numerous historical baseline studies on Arctic benthic communities have been conducted (e.g., Ellis 1955, Wacasey *et al.* 1979, Wacasey *et al.* 1980, Thomson 1982, Dale *et al.* 1989, Syvitski *et al.* 1989, Aitken and Fournier 1993, Clough *et al.* 1997, Conlan *et al.* 2008, Brown *et al.* 2011a, Nephin *et al.* 2014). These historical studies provide an opportunity to bridge the gap in knowledge of long-term benthic community change through resampling of these historic sample sites. However, only one study by Cusson *et al.* (2007) has utilized historical benthic sample records to compile a summary of the current state of knowledge related to the biodiversity of benthic assemblages on the Canadian Arctic continental shelf. In their article, these authors highlight the importance of available historical benthic faunal data and call for these data to be

integrated with modern sampling efforts in order to set a baseline from which patterns of benthic biodiversity can be measured in the Canadian Arctic. More recently, Archambault *et al.* (2010) Thurstan *et al.* (2015), and Wei *et al.* (2019) all emphasized the importance of establishing baseline biodiversity datasets across Canada's Arctic with Thurstan *et al.* (2015) specifically emphasizing the importance of filling gaps in our knowledge of marine systems through the use of historical datasets, further stressing the importance of setting a baseline from which future change can be measured.

1.4.5 Molluscs: Indicators of Long-Term Change?

Molluscs (bivalves and gastropods) are ecosystem engineers, creating, modifying, and maintaining habitat for the benthic community (Gutierrez *et al.* 2003). Marine molluscs burrow and bioirrigate the sediment and they exhibit a wide variety of feeding modes (e.g. deposit feeders, suspension feeders, grazers, and predators), all of which aid in modifying the sediments within which they live (e.g. Crooks *et al.* 1999, Gutierrez *et al.* 1999, Buschbaum *et al.* 2009). The shells of molluscs and aggregations of shells also impact the abiotic environment by introducing heterogeneity and complexity into the benthic environment (McLean 1983, Kidwell 1986, Gutierrez *et al.* 2003, van der Zee *et al.* 2012). Taphonomic feedback, the shells left behind by dead molluscs and the shells of live molluscs introduce complexity and heterogeneity into the benthic environment (Kidwell 1986), and they persist over geological time scales, thus affecting the benthic community on both temporal and spatial scales (Gutierrez *et al.*

2003). Mollusc shells can provide hard substrates for other benthic organisms to attach to such as algae, barnacles, sponges, and hydroids and they can also provide refuge for other organisms from predators such as grazing sea urchins, crabs, fish, and shorebirds (Guitierrez *et al.* 2003).

Temporal changes to molluscan communities resulting from anthropogenic stressors and warming Arctic temperatures could therefore impact the benthic community as a whole. One major impact to the circumpolar Arctic oceans that could affect molluscs is that atmospheric CO₂ has been increasing in the atmosphere and has entered the ocean causing ocean acidification (Comeau *et al.* 2010). Molluscs in arctic nearshore environments have tremendous preservation potential (Aitken 1990) but high terrigenous input, strong tides, and sea ice scour in Frobisher Bay make this region not an ideal place for the formation of carbonate deposits in the benthos (Zammit 2017). Changes in ocean acidification could affect this further. For example, ocean acidification can impact the early life stages of molluscs as calcium carbonate is known to be deposited during the larval stage of bivalves (Dame 2012). Bivalves may not be able to grow their calcium carbonate skeletons resulting in the mortality of living individuals (Kurihara 2008, Dame 2012). Empty shells on the seabed may also be dissolved at a greater rate which would ultimately result in reduced habitat availability for other benthic organisms (Dame 2012). Fabry *et al.* (2009) have indicated that changes in CO₂ chemistry have already been observed in Arctic surface waters and these rapid changes emphasize the urgency to monitor ocean acidity in the north and Zammit (2017) concluded that further investigation into dissolution rates of carbonate bioclasts

should be conducted in Frobisher Bay to gain insight into the impacts of ocean acidification on cold-water carbonates in this region. Other environmental changes, such as increased sedimentation rates from river input or increased shoreline erosion associated with increased wave action and increased storm activity (Hatcher and Forbes 2015) could also influence the distribution of molluscs in coastal environments. These changes, in particular, increased wave action and storm activity, occur in response to sea level rise and ice loss in northern regions. For example, most bivalves are either suspension feeders (obtain their food from the water column) or deposit feeders (remove organic matter from the surrounding benthic environment) and where one type is abundant, the other is often reduced (Dame 2012). Suspension feeding bivalves are typically found on coarser sediments in more energetic environments while deposit-feeding bivalves are more commonly associated with muddy low energy environments (Dame 2012). The reworking of sediments by deposit-feeding bivalves creates conditions unsuitable for and stressful for suspension-feeding bivalves and discourages settlement of suspension-feeding larvae (Dame 2012). Increased sedimentation and wave action in coastal regions may therefore also influence the settlement location of suspension-feeding bivalve larvae.

Only a few studies, however, focus specifically on the molluscs as a tool to identify community change. Novoa *et al.* (2016) examined four estuaries in southern California over a 50 year time period and found that bivalve species richness was higher in the 1960s and 1970s compared to the 1980s and mid 2000s. They found that the bivalve communities in these estuaries had undergone dramatic changes such

that the community structure had shifted from the presence of larger, longer-lived bivalves to a predominance of faster-growing, surface-dwelling smaller species. Habitat loss and increased urban and industrial development in these areas resulting in increased contaminant levels were identified as potential contributors to the decline in bivalves in these regions (Novoa *et al.* 2016). Strayer *et al.* (1998, 1999) examined the zebra mussel invasion in the Hudson River which was first observed in May 1991. The zebra mussel population grew rapidly over time and native clams and other sediment dwellers including oligochaetes and amphipods in deeper water were believed to have suffered due to competition for food as there was a decline in phytoplankton biomass of 80-90% over time (Strayer *et al.* 1998, 1999). Rothschild *et al.* (1994) examined the ecological impact of a historical fishery on the eastern oyster *Crassostrea virginica* in Chesapeake Bay. They found that 100 years of increasingly intensive mechanized fishing has caused a leveling profile on the oyster bars (over 50% of the bars from 1907-1982) to the extent that the sediments were no longer able to produce oysters and the remaining un-silted areas are now considered less productive than they once were (Rothschild *et al.* 1994).

Researchers are often left only with historical data sets from which to compare with modern studies. The long-lived nature of marine molluscs make this group of organisms a potentially useful one for identifying long-term change compared with other organisms. For example, polychaetes and amphipods are also an important component of Arctic benthic biomass but exhibit more seasonal variation. Examining change in the structure of mollusc communities allows for the identification of long-term trends

without being distracted by the seasonal noise created by short lived species. By studying a group of organisms that lives longer than the life expectancies of most species in the benthic community, we can attempt to differentiate between short- and long-term natural variability and long-term anthropogenic change, ensuring that long-term natural fluctuations are not attributed to anthropogenic influences (Bowman 1978, Gray and Christie 1983).

1.4.6 Methods for Assessing Long-Term Change

1.4.6.1 Taxonomic and Functional Traits

Utilization of both the taxonomic approach to measure the impact of environmental change on biodiversity and the functional trait approach to measure change in ecosystem function are both valid and complimentary methods for examining long-term change in the marine benthos.

Historical ecological studies have traditionally examined benthic community similarities or changes through taxonomic analysis based on species diversity, species composition, abundance and biomass (Kiyko and Pogrebov 1997, Weigel *et al.* 2016), often in association with abiotic factors (Josefson and Rosenberg 1988, Beuchel *et al.* 2006, Renaud *et al.* 2007, Kedra *et al.* 2010, Kortsch *et al.* 2012, Grebmeier *et al.* 2015). However, this approach does not consider the functional role that each species contributes within the community.

Functional diversity refers to the diversity of species traits present within a

community (Diaz and Cabido 2001) and represents both behavioural and morphological traits displayed by an individual (Bremner *et al.* 2003, Paganelli *et al.* 2012). Functional traits include: feeding mode (e.g. suspension feeder, deposit feeder, etc.), sediment preference (e.g. sand, silt, rock, etc.), life span, mobility, body form, environmental position (e.g. epifauna, infauna, hyperbenthic), living habit (e.g. crevice dwelling, free living, etc.), bioturbation (e.g. biodiffusors, surficial modifiers, etc.), and many others though not all may be ecologically important to measure.

Taxonomically distinct individuals within the community may have evolved similar adaptations leading to functional similarity (Paganelli *et al.* 2012) and so the loss of one species in the community (e.g. decline in species richness) does not necessarily mean a loss of the functional traits that species provided to the community nor the loss of ecosystem function. Additionally, not all species are considered equal and the loss of some species (e.g. keystone species) could have a profound impact on the community while the loss of other species could have little impact (Tilman *et al.* 1997). For example, some oyster species that form oyster beds are considered a keystone species that provide important ecosystem services including providing habitat, protection, and a source of food for many other species (Rodriguez-Perez *et al.* 2019). Oyster beds increase biodiversity and trophic complexity of the sea bottom and mediate ecosystem function and the loss of such beds has a profound effect on the ecosystem services that these species provide (Kent *et al.* 2017).

The use of functional traits to assess the relationship between organisms and ecosystem functioning is becoming increasingly important (Weigel *et al.* 2015) as

functional diversity within the community is a significant factor driving ecosystem processes (Tilman *et al.* 1997, Bremner *et al.* 2003, Petchey and Gaston 2006). In some studies, functional diversity has had a greater impact on ecosystem processes than species diversity (Tilman *et al.* 1997). There has been a substantial amount of research using trait analysis to examine terrestrial plant communities (Tilman *et al.* 1997, Weigel *et al.* 2015) but this approach is new to the marine environment and only a few studies have used functional trait analysis to examine changes to the benthos (Bremner *et al.* 2006, Paganelli *et al.* 2012, van der Linden *et al.* 2012, Clare *et al.* 2015, Kun *et al.* 2019).

1.4.6.2 Habitat Mapping

Habitat mapping has emerged as a valuable visual tool to aid in predicting the spatial distribution of benthic fauna. Anthropogenic threats to the benthic environment are a key driver for producing comprehensive habitat maps that provide a baseline from which future change can be measured (Harris 2012). Understanding the spatial distribution of macrobenthic habitats, their structure, and dynamics is paramount for understanding their vulnerability (Sherman 1991, Zajac 1999, Schumchenia and King 2010, Reiss *et al.* 2014) and for our ability to manage them (Buhl-Mortensen *et al.* 2009, Buhl-Mortensen *et al.* 2012).

Despite this growing body of research, only 5-10% of marine habitats have been mapped worldwide and the circumpolar regions make up only a small portion of this value (Wright and Hayman 2008, Gougeon *et al.* 2017). With emerging technologies,

we can now acquire 100% seabed data coverage using acoustic systems that provide information on seabed geology and geomorphology (Kenny *et al.* 2003, Eastwood *et al.* 2006). By combining acoustical data with physical oceanographic and geological data, as well as biological information (Brown *et al.* 2011b), we have the potential to produce habitat maps that gives the best prediction of the distribution of marine communities for a given area (Foster-Smith *et al.* 2008). Because ground-truthed samples cover only a small percentage of the seabed, the coverage of specific habitats is inferred through the association of remotely sensed data with ground-truthed benthic sample data (Brown *et al.* 2011b).

Combining remotely sensed data with ground-truthed benthic sample data has primarily consisted of utilizing underwater video or still photographs which characterize the epifauna and which can also be used to verify sediment type (Pinn *et al.* 1998, Hewitt *et al.* 2004, Rooper and Zimmermann 2007, Grizzle *et al.* 2008, Copeland *et al.* 2013). More often a combination of underwater video or photographs and infaunal grab samples have been used to classify unique benthic communities (Foster-Smith and Sotheran 2003, Brown *et al.* 2004a, Brown *et al.* 2004b, Foster-Smith *et al.* 2004, Brown and Collier 2008, Buhl-Mortensen *et al.* 2009, Callaway *et al.* 2009, Christensen *et al.* 2009, McGonigle *et al.* 2009). To a lesser extent, infaunal samples have been used on their own in conjunction with multibeam sonar and sediment sample data to produce benthic habitat maps that reflect the infaunal community distribution for a given region (Freitas *et al.* 2003, Zajac *et al.* 2003, Eastwood *et al.* 2006, Freitas *et al.* 2006, Degraer *et al.* 2008, Schumchenia and King 2010, Misiuk *et al.* 2019).

By utilizing modern ground-truthed infaunal and sediment data along with multibeam sonar data collected in Frobisher Bay, a habitat map can be produced that characterizes unique benthic habitats which can be compared with the historical benthic community data (Wacasey *et al.* 1979, 1980). From this, spatial shifts in benthic communities between historical records and modern data may become apparent and this may be used as an indicator of the indirect effects of climate change on the benthos.

1.4 Thesis Structure

This thesis contains two manuscripts and a summary discussion in addition to this introductory chapter. Each chapter is a stand alone paper that has been prepared to be published in the scientific literature. Each chapter contains a literature review, methods, results, and discussion section with some overlap of introductory material occurring between manuscripts.

Chapter 2 examines long-term temporal changes observed in the molluscan (bivalves and gastropods) communities of inner Frobisher Bay. Historical relative abundance sample data collected by Wacasey *et al.* (1979, 1980) was compared with samples collected at the same stations fifty years later as part of the field work component of this thesis. This chapter highlights the importance of historical datasets as invaluable records and baselines from which long-term benthic community change can be measured.

Chapter 3 examines long-term spatial changes that have occurred in the

molluscan (bivalves and gastropods) communities of inner Frobisher Bay. This was accomplished by highlighting the ‘potential distribution’ (the distribution where specific mollusc communities *may* be found) of the modern molluscan communities through the use of MBES data sources and comparing these results with the historical communities.

The summary chapter of this thesis provides a synthesis of the findings in the two manuscript chapters. This chapter highlights the importance of systematic long-term sampling for identifying temporal and spatial change within this group of benthic fauna and provides recommendations for future monitoring given changing climate conditions in the Arctic as well as on-going coastal development that is expected in the Iqaluit region.

1.5 References

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Co-Authorship Statement

Field research was conducted in the waters of inner Frobisher Bay between the City of Iqaluit and Cairn Island onboard the MV *Nulialjuk* and CCGS *Amundsen* between 2015-2017, organized by Dr. Evan Edinger and Dr. Alec Aitken. The author carried out the field sampling in the summer of 2016 with the assistance of Dr. Evan Edinger and Dr. Alec Aitken. The author carried out all laboratory analysis including sediment grain size analysis, total organic carbon analysis and total nitrogen analysis with the assistance of Alison Pye. Mollusc identifications were carried out by the author with the assistance of Dr. Alec Aitken and Dr. Suzanne Dufour. Spatial analysis and mapping methodology was developed with the assistance of Dr. Ben Misiuk. All chapters were written by the author with editorial input from Dr. Evan Edinger and Dr. Alec Aitken.

Chapter 2 Long-term temporal change in the molluscan communities of Frobisher Bay, Nunavut, Canada

2.1 Introduction

The circumpolar Arctic has experienced long-term environmental change including warming air temperatures, warming sea surface temperatures, and losses in the extent and thickness of sea ice (Richter-Menge *et al.* 2017). There is a strong consensus that global climate change will profoundly impact marine ecosystems (IPCC 2014), possibly to the community level (Harley *et al.* 2006) and it is predicted that future Arctic marine ecosystems will look considerably different in the future due to changes expected in the physical environment (Carmack and Wassmann 2006, Carmack and McLaughlin 2001, Carmack and McLaughlin 2011, Wassmann and Reigstad 2011, Macdonald *et al.* 2015, Renaud *et al.* 2015).

Long-term studies are vital to understanding the impact that climate warming will have on the marine environment. The marine benthos specifically can be used as an indicator of long-term environmental change (Kedra *et al.* 2010). Benthic species composition is influenced by a number of factors including water column stratification, water movement, water depth (which is correlated with other environmental variables including temperature and salinity (Roy *et al.* 2014)), sediment type, inorganic and organic sedimentation, and pelagic productivity (Grebmeier and Barry 1991, Snelgrove 1999, Gosling 2004, Renaud 2007). The benthos plays a critical role in nutrient cycling

as ice algae, phytoplankton, and zooplankton provide an important source of organic carbon and nitrogen to the benthos. In turn, organic carbon and nitrogen are transferred back into the pelagic realm through the food chain as the benthos provides a critical source of food to higher trophic levels (Grebmeier and Barry 1991, Snelgrove 1999). Changes to these conditions could therefore result in changes in structure and function of benthic communities. Some benthic fauna have limited mobility or are completely sessile and some have life spans that range from a few years to many decades (Beuchel *et al.* 2006) which makes assessing changes in these communities possible. Marine molluscs (gastropods and bivalves) in particular are an excellent group of organisms with which to examine long-term change because of their long lived nature (Powell and Cummins 1985, Carroll *et al.* 2009).

Long-term benthic community studies have been documented in many parts of the Arctic but few studies have examined long-term benthic community change in the Canadian Arctic. In response to this, historical baseline studies have been used to measure long-term change by looking at “snap-shots in time” by comparing historical baseline data and available Traditional Ecological Knowledge (TEK) with contemporary studies carried out in the same region. Historical studies provide a source of data which can be directly compared with modern sampling through a comparative sampling design while TEK has emerged as an important source of traditional historical ecological information. For example, Misiuk *et al.* (2019) explored the use of the Nunavut Coastal Resource Inventory, a dataset that contains Inuit knowledge of aquatic and coastal species, for mapping marine habitats in Frobisher Bay. This type of data is

thought to be beneficial when used at a broad rather than fine scale to support scientific studies (Misiuk *et al.* 2019). Therefore, the use of multiple sources of historical datasets can be critical to filling data gaps and documenting long-term change (Thurstan *et al.* 2015).

Frobisher Bay, located along the southeastern coast of Baffin Island, Canada, has experienced similar long-term environmental trends as the circumpolar Arctic including warming air temperatures and declining sea ice thickness and areal extent (Government of Canada 2017, Government of Canada 2018a). This region has also experienced rapid population growth and urban development in the coastal city of Iqaluit including the current development of a deep-sea port, located at Inuit Head in inner Frobisher Bay. Between 1967-1976 benthic sediment and infaunal samples were collected in the coastal waters of inner Frobisher Bay in less than 100 m water depth and these data were archived in two technical data reports (Wacasey 1979, 1980). We re-sampled these same stations in 2016 to acquire sediments and infauna to examine how seabed habitats and molluscan communities have changed over the last 50 years. We predict that molluscan community composition and function in Frobisher Bay has experienced a change over the last 50 years.

2.2 Methods

2.2.1 Study Area

Frobisher Bay is located in southeastern Baffin Island, Canada and extends approximately 265 kilometers into the northern Labrador Sea with the inner portion of Frobisher Bay reaches a maximum depth of 272 m (Hodgson 2005). Frobisher Bay is covered by ice for most of the year. Ice formation typically begins around November and ice break-up typically occurs in July (Canadian Ice Service 2013). Sample stations included in this study were located approximately 2 kilometers south of Iqaluit herein referred to as the “Iqaluit” stations and approximately 10 kilometres southeast of Iqaluit near Cairn Island herein referred to as the “Cairn Island” stations (Figure 2.1). The Sylvia Grinnell River is located approximately 2.5 km west of the Iqaluit stations and approximately 10 kilometers north-west of the Cairn Island stations. The Apex River is located approximately 3 kilometers east of the Iqaluit stations and approximately 7 kilometers south of the Cairn Island stations. Both of these rivers provide a source of fresh water and sediment input into Frobisher Bay in the vicinity of the study region.

2.2.2 Sources of Historical Data

Long-term environmental data has been collected in the Frobisher Bay region that measured a number of different parameters. Historical climate data collected by the Government of Canada (2018a) was available for the Iqaluit region (63°45'00.00"N, 68°33'0.00"W) and was examined for warming air temperature trends while historical

ice thickness data collected in Frobisher Bay through the Canadian Ice Thickness Program was examined for changes in both ice thickness and length of the ice cover season in Frobisher Bay (Government of Canada 2017). Mean annual air temperature was calculated from average monthly temperature data while the maximum ice thickness for each year was determined based on weekly ice thickness measurements. The length of the ice cover season was measured as the number of days it was safe to walk on the ice to take a thickness measurement (Government of Canada 2017). Historical hydrometric data for the Sylvia Grinnell River and Apex River were collected by the water office (Government of Canada 2018b) and examined for changes observed in river discharge over time. Average monthly discharges were examined for the months June through October. Between the 1960's and 1980's, oceanographic measurements were also made at various locations in inner Frobisher Bay. Water temperature and salinity data are presented by Lovrity (1981, 1982a, 1982b, 1984, 1987) and these data were compared with oceanographic data collected onboard the CCGS *Amundsen* in 2016 and 2017 (Amundsen Science Data Collection 2019).

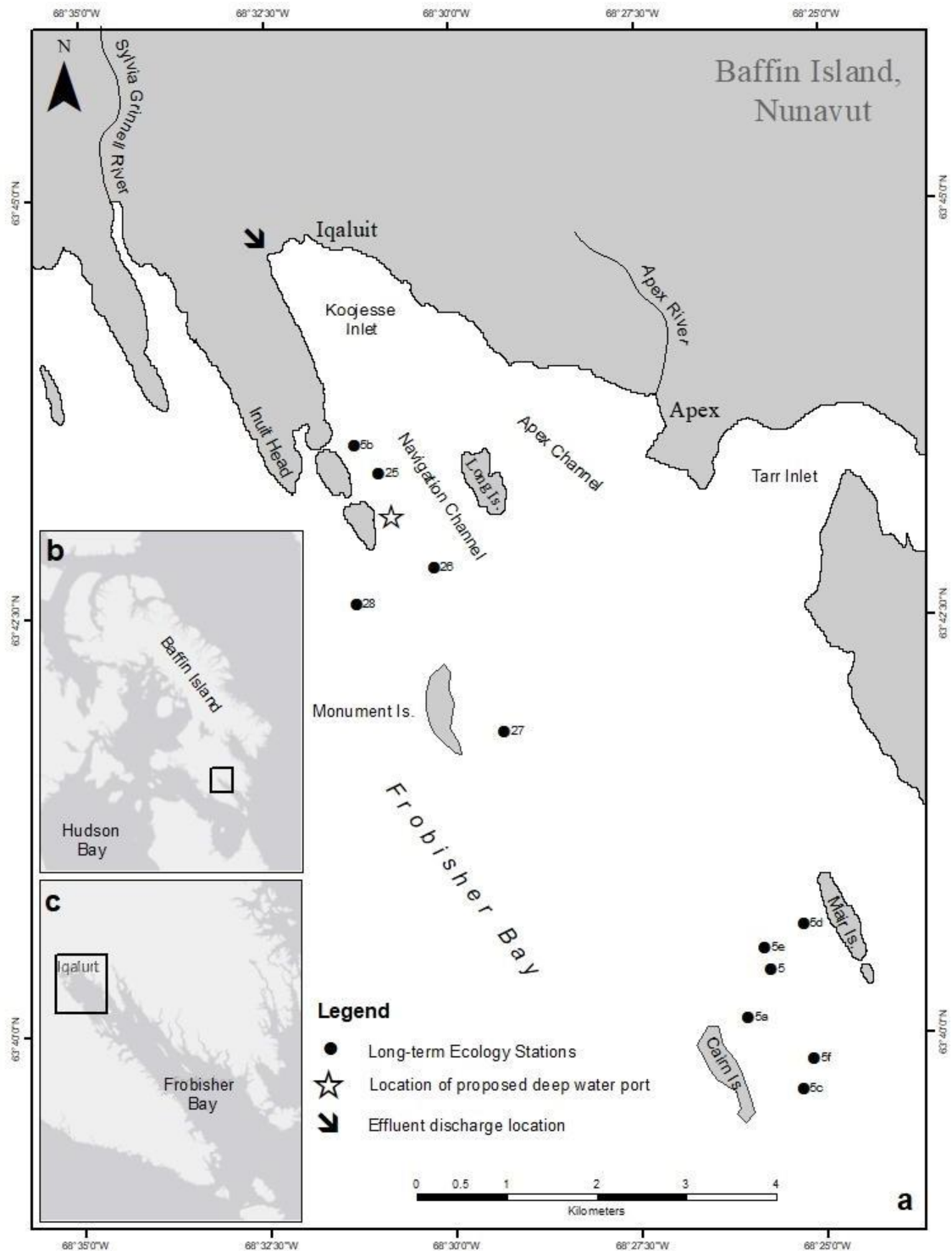


Figure 2.1. Location of long-term ecology stations sampled in Frobisher Bay, Nunavut between 1967 and 1976 and in 2016 (a), inset map of Baffin Island (b), and inset map of Frobisher Bay (c).

2.2.3 Infaunal and Sediment Sampling

Benthic infaunal and sediment samples were collected using a Petersen grab (surface area 0.065 m²) between 1967 and 1976 in the coastal waters of Frobisher Bay. Between 4-6 grabs were collected per station and pooled for a total surface area of between 0.25 – 0.39 m² of sediment sampled per station. Detailed sampling methodology for these historic samples can be found in Wacasey *et al.* (1979, 1980). In 2016, these same stations were re-sampled using a Van Veen grab (surface area 0.111 m²) from the MV Nulialjuk and using a box core (surface area 0.125 m²) from the CCGS Amundsen due to equipment availability. The modern replicate samples from each station were pooled to be comparable with the historical data. Between 2-3 grabs were collected per station with the Van Veen for a total surface area of 0.024 – 0.11 m² of sediment sampled per station after the samples were pooled. Three grabs were collected from one station using the box core and these samples were pooled for a total surface area of 0.129 m² (Figure 2.1). Historical (1967-1976) and modern (2016) samples included in this study were collected when the bay was free of sea ice between the months of July and October. Sediment samples acquired in 2016 were frozen and later analyzed for grain size, total organic carbon (TOC) content (%) and total nitrogen (TN) content (%) in the sediments, and to determine the ratio of carbon to nitrogen in the sediments which provides an indication of the source of the organic matter in the sediments (e.g., terrestrial vs. marine). Protocols for processing of historical sediment and infaunal samples can be found in Wacasey *et al.* (1979, 1980). For modern samples, approximately 100 g of sediment was used to determine grain size composition up to 4 mm, though only silt (<

0.063 mm) and sand (0.063 – 2 mm) fractions were used in this thesis to compare with the historical samples. Sediment samples were dry sieved for five minutes over a sieve shaker to separate the mud, sand and gravel. Many of the samples had grain particles that stuck together and these samples were lightly rinsed through the 0.063 mm sieve with water to break up the particles and re-dried and weighed. The weight of each grain size fraction was divided by the total weight of the sample to determine the proportion of silt and sand in the sediments. Sediment samples were processed for TOC and TN and C:N ratio's in the Stable Isotope Lab at Memorial University. Loss-on-ignition analysis was performed to determine the percentage of organic content in the sediments following the methods of Heiri *et al.* (2001). Triplicate samples collected from each station were oven dried at 60°C for a minimum of 4 hours to dry the samples. All samples were then ashed at 550°C to remove organic content. The ashed weight was subtracted from the pre-ashed weight to determine the organic content in each sample. Triplicate samples were averaged for each station, resulting in a single TOC measurement for each station. Carbon:Nitrogen ratio's were determined using a Carlo-Erba NA1500 Elemental Analyser and ConFLoIII interface. The protocol for these analyses can be found in Appendix I. Analysis of Iqaluit area samples and Cairn Island area samples were run separately.

Infaunal samples were washed over a 0.5 mm sieve (the 2016 box core sample was washed over a 1.0 mm sieve) and organisms were fixed in 10% formalin for 24 hours before being transferred to 70% ethanol. Bivalves and gastropods from each grab sample were identified to the lowest taxonomic level with 84.6% of individuals from the

historical samples identified to the species level and 79.5% of the modern samples identified to the species level. Sampling effort for both the historical and modern samples used in this study is summarized in Table 2.1 and complete sampling details can be found in Appendix 2.

2.2.4 Analysis

General linear models were developed to identify significant long-term changes in the environmental datasets for the response variables temperature (°C), length of ice season (days), maximum ice thickness (cm), average monthly water discharge and the explanatory variable year (Datasets used in these analyses are found in Appendix 3). The models were run using the aov function in RStudio (RStudio Team 2016).

General linear models were also generated to identify changes in grain size and sediment quality over time (Datasets used in analysis found in Appendix 4). The response variables proportion of sand and silt (%), total organic carbon, total nitrogen and carbon-nitrogen ratio and the explanatory variable time period were included in the models using the aov function in RStudio. Initial data exploration pointed to the inclusion of the explanatory variable depth in some of these models as water depth varies among the sampling stations.

Table 2.1. Summary of samples collected in Frobisher Bay between 1967-1976 by Wacasey *et al.* (1979, 1980) and in 2016.

Station	Date Sampled	Latitude (°N) ^a	Longitude (°W) ^a	Depth (m) ^b	Sed. Sample	No. Grabs Pooled	Total Surface Area (m ²)	Station	Date Sampled	Latitude (°N) ^a	Longitude (°W) ^a	Depth (m) ^b	Sed. sample	No. Grabs Pooled	Total Surface Area (m ²)
<i>Cairn Island Stations</i>								<i>Iqaluit Stations</i>							
5	23-Jul-68			45	No	6	0.39	5b	29-Jul-69			15	No	6	0.39
5	20-Aug-68			60	Yes	6	0.39	5b	3-Sep-69			15	Yes	6	0.39
5	3-Sep-68	63°40'23.2	68°25'44.0	60	No	6	0.39	5b	8-Aug-73	63°43'32.2	68°31'18.5	14	Yes	5	0.325
5	8-Oct-68			62	No	6	0.39	5b	19-Aug-76			14	Yes	5	0.325
5	2-Sep-69			53	Yes	Not Collected		5b	10-Oct-16	63°43'32.0	68°31'15.4	8.5	Yes	3	0.333
5	6-Aug-70			72	No	6	0.39								
5	14-Oct-16	63°40'22.5	68°25'45.8	57	Yes	3	0.333	25	8-Aug-73	63°43'21.7	68°30'58.3	30	Yes	5	0.325
								25	18-Aug-76			28	Yes	5	0.325
5a	1-Aug-68			26	Yes	6	0.39	25	10-Oct-16	63°43'21.7	68°30'58.6	28.5	Yes	3	0.333
5a	20-Aug-68	63°40'5.9	68°26'3.1	32	No	6	0.39								
5a	2-Sep-69			36	Yes	Not Collected		26	8-Aug-73	63°42'48.2	68°30'14.0	40	Yes	5	0.325
5a	14-Oct-16	63°40'6.0	68°26'0.9	69.2	Yes	3	0.333	26	10-Oct-16	63°42'45.9	68°30'11.2	35.2	Yes	3	0.333
5c	23-Aug-69	63°39'40.0	68°25'19.2	31	Yes	6	0.39	27	8-Aug-73	63°41'48.8	68°29'18.6	43	Yes	5	0.325
5c	11-Oct-16	63°39'39.8	68°25'17.8	77.2	Yes	3	0.333	27	10-Oct-16	63°41'48.8	68°29'21.2	33.1	Yes	3	0.333
5d	23-Aug-69	63°40'39.4	68°25'17.8	43	Yes	6	0.39	28	13-Aug-73	63°42'35.3	68°31'17.0	30	Yes	4	0.26
5d	11-Oct-16	63°40'39.3	68°25'15.3	25	Yes	3	0.333	28	10-Oct-16	63°42'35.9	68°31'15.9	11.5	Yes	3	0.333
5e	23-Aug-69	63°40'30.7	68°25'49.4	58	Yes	6	0.39	^a Latitude and longitude recorded only once at a station in the historical data.							
5e(box)	16-Jul-16	63°40'30.8	68°25'49.3	63	Yes	3	0.375	The reported latitude and longitude for the 2016 samples are the coordinates of the first pooled replicate sample collected. Appendix 1 lists the coordinates for all replicate samples collected.							
5e	11-Oct-16	63°40'32.4	68°25'49.1	52.3	Yes	3	0.333								
5f	23-Aug-69	63°39.8'	68°26.1'	73	Yes	6	0.39	^b Water depth recorded only once at each station in the historical data. The reported depth for the 2016 samples is the depth of the first pooled replicate sampled. Appendix 1 lists the water depth for all replicate samples collected.							
5f	11-Oct-16	63°39'50.2	68°25'10.6	90.1	Yes	2	0.333								

Species accumulation curves were generated for the historical and modern mollusc samples using the Sobs statistic in Primer v6 where the number of different species observed are successively pooled (Clarke and Warwick 2001). Diversity indices including species richness (S), Shannon Weiner diversity (H'), and Pileou evenness (J') were generated for all pooled historical and modern samples in Primer v6 (Clarke and Gorley 2006). General linear models were then developed to identify significant changes in species richness, diversity, and evenness over time. The response variables S, H' , and J' and the categorical explanatory variable time period (categories: historical samples and modern samples) were included in these models. Initial data exploration emphasized the importance of a time period and depth interaction likely as a result of variable depths at the different stations and because community composition is known to correlate to water depth (Snelgrove 1997). The models were run using the *aov* function in RStudio.

Using Primer v6 (Clarke and Gorley 2006), Analysis of Similarities (ANOSIM) was performed on the molluscan samples to determine if the historical and modern samples were significantly different from each other through generation of a Global R value which provides a measure of significance. Samples were assigned to one of four groups: 1) historical – Iqaluit, 2) modern – Iqaluit, 3) historical – Cairn Island, 4) modern – Cairn Island rather than comparing each sample on a station by station basis. This was done because the historically pooled samples meant no replicates were available for comparison. Similarity Percentage Analysis (SIMPER) was performed to identify species that were driving the similarity and dissimilarity between the groups of samples (datasets used in these analyses are found in Appendix 5). Non-metric multi-dimensional scaling

(nMDS) was performed to visualize the similarities/differences between samples. Bray-Curtis Similarity matrices were generated from the square-root transformed abundance dataset as this transformation reduces the influence of highly abundant species and increases the influence of rare species (Clarke and Warwick 2001). Rare species were not removed from the dataset because preliminary data exploration indicated that the natural groupings of stations was not influenced by their removal. Initial data exploration of the square-root and 4th root transformations confirmed that the less severe transformation (square-root) provided a similar result as the more severe transformation.

All organisms in a system perform a range of functions (Gray 1997) and Biological Traits Analysis (BTA) provides the means to examine the response of benthic community functions to environmental change (Dimitriadis *et al.* 2012, Van Son *et al.* 2013, Bolam *et al.* 2017). Biological Traits Analysis was performed using the *ade4* package in RStudio (Dray and Dufour 2007) to identify functional changes in the bivalve communities over time. Gastropods were not included in this analysis due to the scarcity of information related to biological traits for many of the species included in the historical and modern datasets. Five biological traits were included in the analysis: body size, shell structure (solid, thick and robust shell vs. thin, fragile and brittle shell), feeding habit, sediment preference, and A Marine Biotic Index (AMBI; describes a species sensitivity to organic enrichment). These traits were further subdivided into 17 modalities that describe in more detail a species' functional characteristics (Table 2.2).

Table 2.2. List of trait characteristics included in the functional trait analysis.

Trait	Trait Modalities	Code
Body Size	< 10 mm	BS1
	10-50 mm	BS2
	50-100 mm	BS3
	100-200 mm	BS4
Shell Structure	Solid/ Robust/Thick	SS1
	Thin/Fragile/Brittle	SS2
Feeding Habit	Deposit Feeder	FH1
	Suspension Feeder	FH2
	Scavenger	FH3
Sediment Preference	Silt/Mud	SP1
	Sand	SP2
	Gravel	SP3
	Silt-Mud-Sand-Gravel	SP4
	Bedrock/Boulder/Hard Surface	SP5
AMBI Ecological Group	Very Sensitive to Disturbance	AMBI1
	Indifferent to Disturbance	AMBI2
	Tolerant to Disturbance	AMBI3

The AMBI functional trait refers specifically to an organism’s sensitivity to organic enrichment (Borja *et al.* 2000). Species which are “very sensitive to disturbance” are typically observed in unpolluted conditions and species “indifferent to disturbance” can withstand some variations in organic enrichment, while species which are “tolerant of disturbance” thrive where there is excess organic enrichment (Borja *et al.* 2000). A database of bivalve traits was compiled from trait characteristics obtained from scientific literature, online databases including but not limited to *WoRMS*, *ITIS*, and *BIOTIC*, and personal communication with biologists familiar with various bivalve species (A list of references and online databases used to document bivalve traits can be found in Appendix 6). A trait matrix was developed using the “fuzzy coding” method (Chevenet *et al.* 1994). Trait characteristics for each bivalve species were assigned a value from 0 – 3 which describes the organism’s affinity for a specific trait. A 0 indicated “no affinity” for

a trait while a 3 represented total affinity for a trait. A 1 or 2 indicated partial affinity for a given trait, such that an organism could display some affinity for multiple modalities within a trait with a 2 representing the trait that is more characteristic and a 1 representing a trait that is less characteristic (Chevenet *et al.* 1994). A weighted trait matrix was produced from the bivalve abundance dataset and the bivalve traits dataset. Using the *ade4* package in RStudio, Fuzzy Principal Components Analysis (FPCA) was performed using the weighted trait matrix to visualize the distribution of specific functional traits by station and to identify how the traits at a particular station may have changed over time (the weighted trait matrix used in the analysis can be found in Appendix 7). Fuzzy Correspondence Analysis (FCA) was performed to produce correlation ratios to identify the contribution of each trait to the variance observed among the stations. ANOSIM was performed in Primer v6 to test whether a significant change in functional diversity was observed between the historical and modern samples for both the Iqaluit and Cairn Island regions. Functional diversity was calculated using Rao's Diversity Coefficient and a general linear model was developed to test whether functional diversity had changed significantly over time. The response variable *functional diversity* and the explanatory variable *time period* were included in the model which was run using the *aov* function in RStudio.

A significance level of $\alpha = 0.05$ was used for all statistical analysis and marginally significant results were considered carefully. All models executed in RStudio were tested for homogeneity of variance, independence, and normality to look for violations of model assumptions (Zuur *et al.* 2010).

2.3 Results

2.3.1 Long-term Environmental Data Sources

Mean annual air temperature was $-10.4\text{ }^{\circ}\text{C}$ in 1967 and in 2016 the mean annual air temperature was $-8.3\text{ }^{\circ}\text{C}$. Mean annual air temperature in Iqaluit increased significantly ($F = 8.966$; $p = 0.0043$) over time between 1967 and 2017 (Table 2.3; Figure 2.2a). Sea water temperature and salinity were recorded in July and August between 1980 and 1986 near long term ecology station 26 and bottom temperature at 40 metres depth ranged between $-1.7\text{ }^{\circ}\text{C}$ and $0.4\text{ }^{\circ}\text{C}$ while salinity ranged between 32.2 ppt and 32.9 ppt (Lovrity 1981, 1982a, 1982b, 1984, 1987). In 2016, sea water temperature and salinity were recorded at long term ecology stations 5d and 5g during the month of July onboard the *CCGS Amundsen*, approximately 10 kms away from the historical measurements.

Bottom temperature at 40 metres depth was $-1.306\text{ }^{\circ}\text{C}$ (5d) and $-1.407\text{ }^{\circ}\text{C}$ (5g) while salinity was 32.127 ppt and 32.229 ppt, respectively. These values fall within a similar range of historical data and therefore did not suggest any significant change in water temperature or salinity at depth had occurred between the two time periods. The greater flux of freshwater observed in the Sylvia Grinnell River (identified in Chapter 1) may indicate that freshwater is being trapped above the thermocline/halocline in the inner bay. A lack of comparable sample size precluded statistical analysis here.

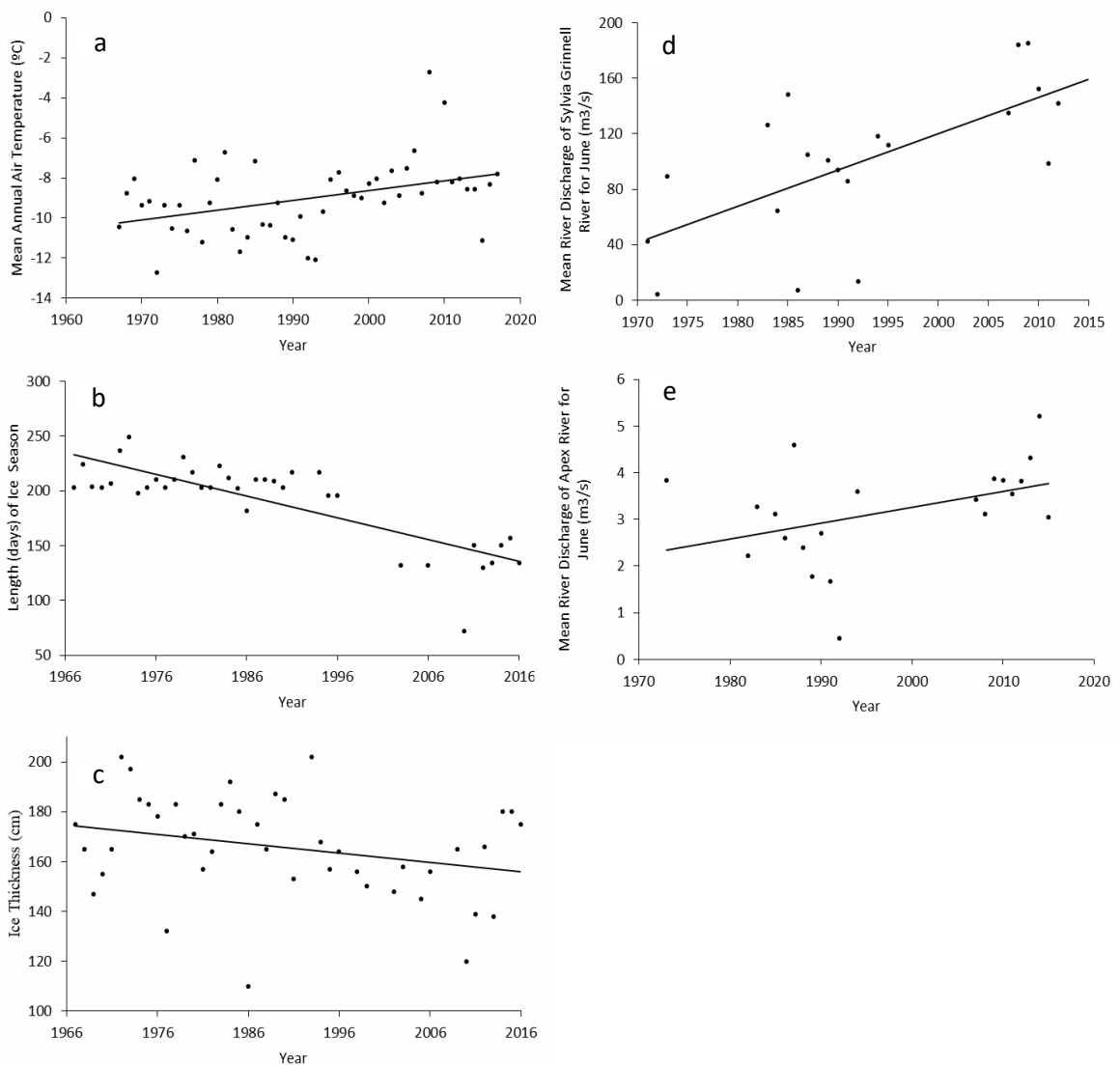


Figure 2.2. Long-term air temperature, sea ice, and water discharge trends observed in Frobisher Bay. a) Significant increase in mean annual temperature from the city of Iqaluit between 1967-2017 ($F = 8.966$, $p = 0.0043$; Government of Canada 2018a), b) Significant decline in the length of the ice cover season in Frobisher Bay near Iqaluit between 1967-2016 ($F = 64.33$, $p = 1.94e^{-9}$; Government of Canada 2017), c) declining trend in sea ice thickness in Frobisher Bay near Iqaluit between 1967-2016 ($F=3.488$, $p = 0.069$), d) Significant decline in average instantaneous discharge for the Sylvia Grinnell River during the month of June ($F = 13.36$, $p = 0.00181$), and e) Significant decline in average instantaneous discharge for the Apex River during the month of June ($F = 6.94$, $p = 0.0168$).

Table 2.3. Results of general linear models for long-term temperature, ice, and river discharge data, sediment samples, and diversity indices for historical and modern samples. Significant findings are in bold. For Iqaluit and Cairn Island analyses, the response variable was initially tested against Time Period, Water Depth and the interaction between TimePeriod and Water Depth. The model is included in the table where more than one explanatory variable is reported. Significant and non-significant relationships are reported where there is only one explanatory variable, Time Period. Only significant relationships are presented for the explanatory variable Water Depth and the interaction (Time Period*Water Depth).

Response Variable	Model/Explanatory Variables	n	F-value	P-value
Mean Annual Temperature	Year	51	8.966	0.0043
Length of Ice Season	Year	43	64.33	1.94e-9
Maximum Ice Thickness	Year	43	3.488	0.069
Sylvia Grinnell River Average Instantaneous Discharge (June)	Year (1971 – 2012)	20	13.36	0.00181
Apex River Average Instantaneous Discharge (June)	Year (1982-2015)	20	6.94	0.0168
<i>Iqaluit Region</i>				
Proportion Sand/Silt (%)	Time Period	23	0.335	0.569
Total Organic Carbon	<i>TOC = TOC ~ TimePeriod + Depth</i>	23	0.489	0.4923
	Time Period		8.850	0.00749
Total Nitrogen	<i>TN = TN ~ TimePeriod + Depth</i>	23	2.073	0.16542
	Depth		9.296	0.00634
Carbon/Nitrogen Ratio	Time Period	26	0.98	0.332
Species Richness (S)	<i>S = S ~ Time Period + Depth</i>	14	1.784	0.209
	Depth		3.269	0.098
Species Diversity (H')	<i>H' = H' ~ Time Period + Depth</i>	14	0.001	0.9751
	Depth		7.156	0.0216
Species Evenness (J')	Time Period	14	1.273	0.281
Functional Diversity	<i>FD = FD ~ Time Period + Depth</i>	14	2.176	0.16824
	Depth		15.79	0.00218

<i>Cairn Island</i>				
Proportion Sand/Silt (%)	Time Period	37	4.089	0.0509
Total Organic Carbon	Time Period	34	12.13	0.00146
Total Nitrogen	Time Period	34	3.694	0.0636
Carbon/Nitrogen Ratio	Time Period	29	1.078	0.308
Species Richness	<i>SR = SR ~ Time Period + Depth</i>			
	Time Period		0.057	0.8155
	Depth	18	4.839	0.0451
Species Diversity	<i>SD = SD ~ Time Period + Depth + Time Period*Depth</i>			
	Time Period		0.398	0.5381
	Depth	18	0.409	0.5328
	Time Period*Depth		9.665	0.0077
Species Evenness	<i>SR = SR ~ Time Period + Depth</i>			
	Time Period	18	0.00	0.9866
Functional Diversity	Depth		2.670	0.1245
	Time Period	18	6.931	0.0197

Between 1967 and 1976 the length of the ice cover season was between 200-250 days and between 2010 and 2016 the length of the ice cover season decreased to 130-157 days. This resulted in a significant negative relationship over time between length of the ice cover season and year ($F=64.33$; $p = 1.94e^{-9}$; Table 2.3; Figure 2.2b) while a declining but non-significant trend was observed between sea ice thickness and time ($F=3.488$; $p = 0.069$; Table 2.3; Figure 2.2c). Long-term average instantaneous river discharges were measured consistently between June and October. Average instantaneous river discharge increased significantly over time during the month of June for both the Sylvia Grinnell River ($F= 13.36$; $p = 0.00181$; Table 2.3; Figure 2.2d) and the Apex River ($F = 6.94$; $p = 0.0168$; Table 2.3; Figure 2.2e). No significant change in river discharge was observed over time between July and October for both rivers. Discharge exhibited a declining trend for July through October in the Sylvia Grinnell River and a declining trend was observed only for the month of July while a positive trend was observed for August through October in the Apex River.

The proportion of sand and silt in the sediments and the amount of total organic carbon and total nitrogen in the sediments did not change significantly over time in the Iqaluit region (Table 2.3; Figure 2.3). Comparatively, the proportion of sand significantly decreased and the proportion of silt significantly increased in the sediments over time in the Cairn Island region ($F=4.089$; $p = 0.0509$; Table 2.3; Figure 2.3). Total organic carbon ($F=12.13$; $p = 0.00146$) significantly increased over time while total nitrogen showed a marginal increase over time ($F = 3.694$; $p = 0.0636$) in the Cairn Island region (Table 2.3; Figure 2.3) suggesting a transition to a lower energy seabed environment.

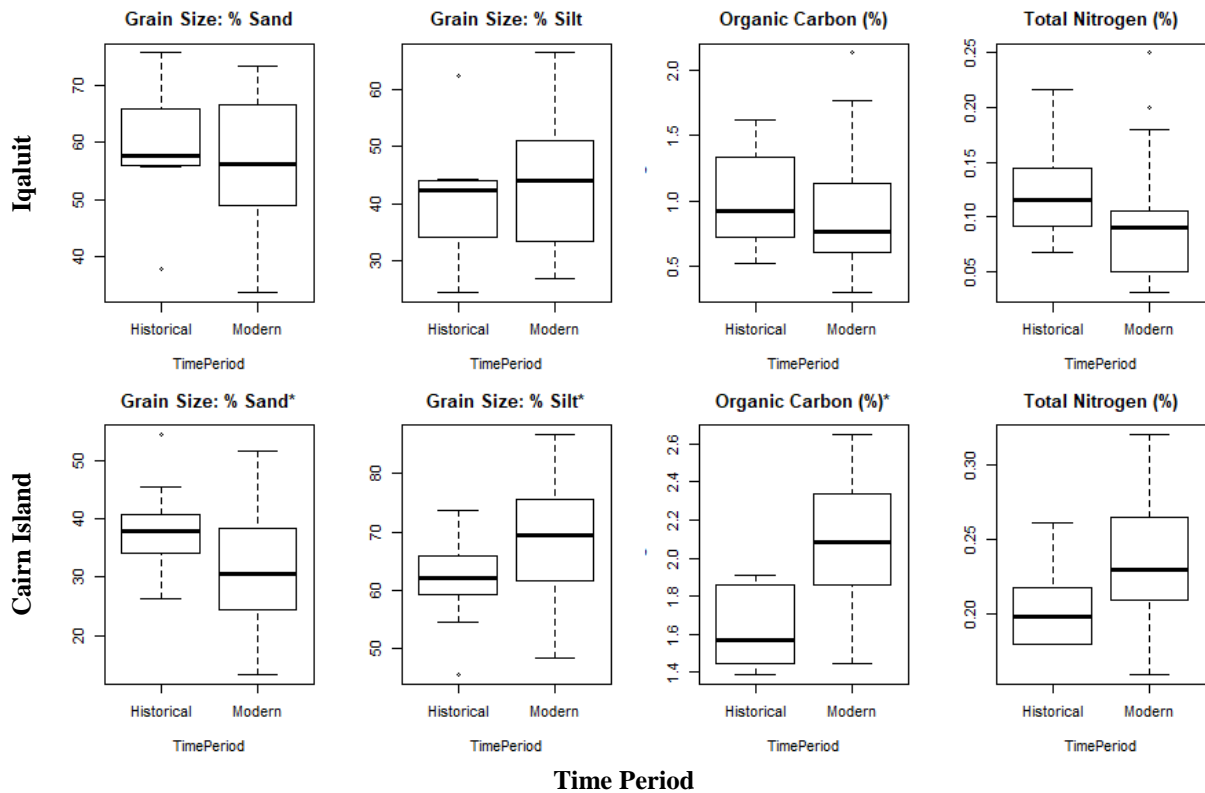


Figure 2.3. Box plots showing historical and modern sediment characteristics for Iqaluit (top row) and Cairn Island (bottom row) regions including % sand, % silt, % total organic carbon, and % total nitrogen. Cairn Island % sand/silt ($F = 4.926$, $p = 0.033$) and % total organic carbon ($F = 12.13$, $p = 0.00146$) were significantly affected by time period (denoted with a *).

Historical and modern carbon-nitrogen ratio's ranged between 3.79:1 and 14.34:1 in the Iqaluit region and between 6.38:1 and 11.39:1 in the Cairn Island region. Typically, values between 4 and 10 are indicative of a marine-derived organic matter because phytoplankton and zooplankton characteristically have C/N ratios in this range (Rumolo *et al.* 2011). Comparatively, terrestrial plants typically exhibit C/N ratios higher than 15 and are therefore indicative of a terrestrial source of carbon and nitrogen (Rumolo *et al.* 2011). These results suggest that the Iqaluit and Cairn Island regions may

have experienced some carbon and nitrogen input from terrestrial sources as some C/N values were above 10:1. In the Iqaluit region, Stations 5b, 26, 27, and 28 all indicate a trend of increased terrestrial input in the sediments and the same is true for stations 5a, 5c, 5d, and 5e in the Cairn Island region which may be a result of increased stream discharge over time. Small sample size precluded our ability to statistically test each site individually. When statistically examined as a region (Iqaluit and Cairn Island), no significant increase in C/N ratio in the sediments was observed over time (Table 2.3; Figure 2.4) indicating that these two regions did not experience an overall increase in terrestrial input of organic matter to the benthos over time.

2.3.2 Mollusc Diversity

Between 1967 and 1976, 12 stations were sampled between 1 and 5 times for a total of 112 grabs which were pooled (5-6 grabs) into 20 samples. Sixty four (64) mollusc species were identified. Of these, 34.4% (22 species) were bivalves and 65.6% (42 species) were gastropods. These same stations were sampled again in 2016 where a total of 692 individuals were identified to the species level from 34 grabs that were pooled (1-3 grabs) into 12 samples to compare with the historical data. Fifty-one (51) mollusc species were identified of which 47.1% (24 species) were bivalves and 52.9% (27 species) were gastropods. Most of the same bivalve species were observed in both the historical and modern samples while some gastropods were less common and appeared either only in the historical samples or only in the modern samples (Table 2.4). Species accumulation

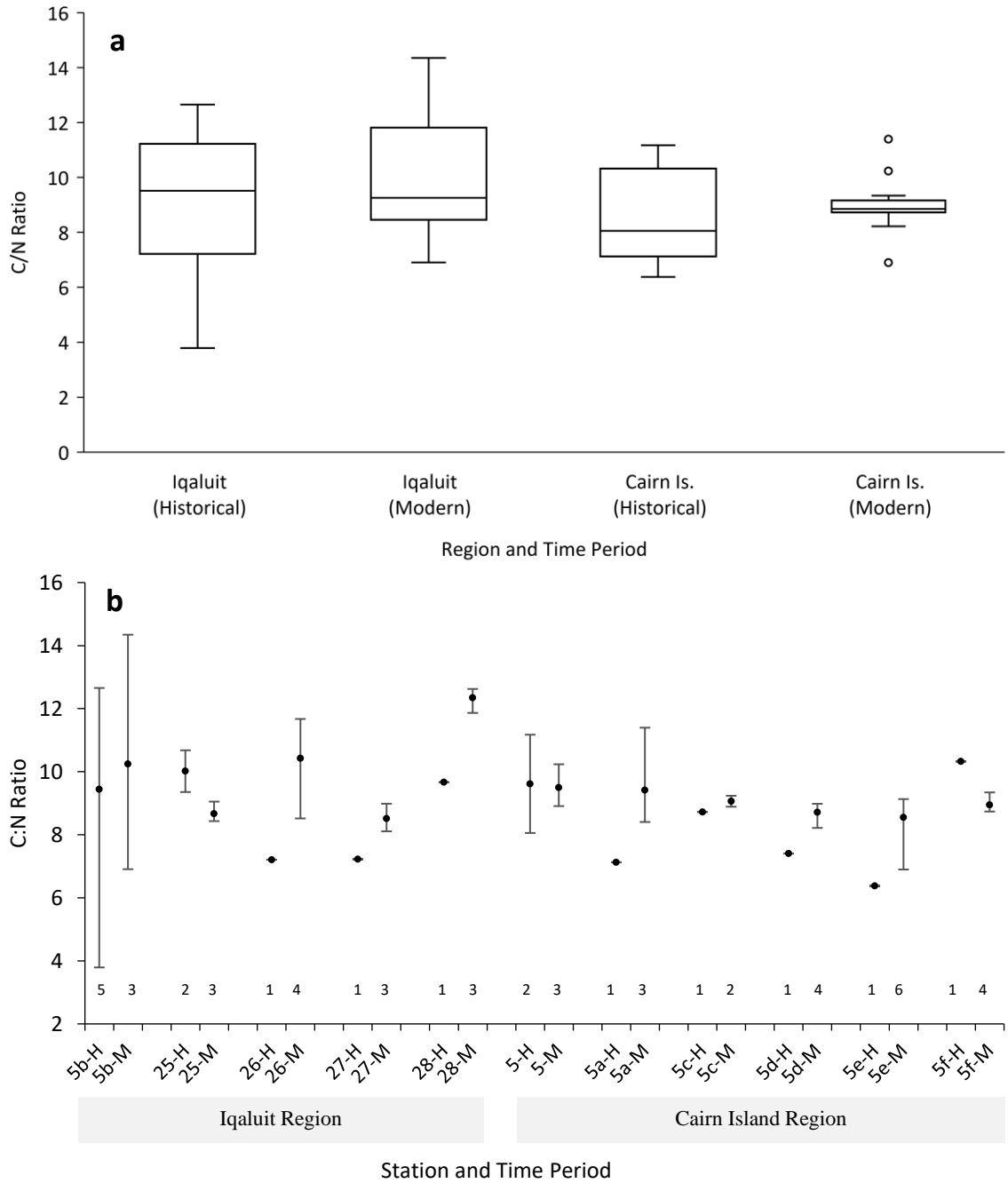


Figure 2.4. C/N ratios in sediment samples collected in Frobisher Bay between 1967 and 1976 and in 2016. Historical and modern samples were compared for the Iqaluit and Cairn Island regions (a) and were compared station by station (b). Individual sites were not statistically tested due to small sample size.

curves generated for the historical and modern pooled samples begin to indicate some flattening of the curve and the standard error observed for both the historical and modern samples overlap for the first ten samples examined (Figure 2.5).

Table 2.4. Bivalve and gastropod molluscs found in Iqaluit and Cairn Island samples in Frobisher Bay in 1967-1976 and 2016.

Species	1967-1976 ^a	2016	Species	1967-1976 ^a	2016
Gastropods					
<i>Admete viridula</i>	X	X	<i>Tachyrhynchus reticulatus</i>	X	X
<i>Alvania moerchi</i>		X	<i>Trichotropis bicarinata</i>	X	
<i>Alvania moerchi</i>	X		<i>Trichotropis conica</i>	X	
<i>Anatoma crispate</i>	X	X	<i>Velutina velutina</i>	X	
<i>Anomalisipho verkruezeni</i>		X	<i>Onoba mighelsii</i>	X	
<i>Ariadnaria borealis</i>	X	X	<i>Philine lima</i>	X	
<i>Astyrus rosacea</i>	X		<i>Propebela arctica</i>	X	
<i>Aulacofusus brevicauda</i>		X	<i>Propebela turricula</i>	X	X
<i>Boreotrophon clathratus</i>		X	<i>Puncturella noachina</i>	X	
<i>Buccinum hydrophanum</i>	X		<i>Retusa obtusa</i>	X	
<i>Buccinum undatum</i>	X		Bivalves		
<i>Cadlina laevis</i>	X		<i>Astarte borealis</i>	X	X
<i>Colus holboelli</i>	X	X	<i>Astarte montagui</i>	X	X
<i>Colus islandicus</i>		X	<i>Axinopsida orbiculata</i>	X	X
<i>Colus pubescens</i>	X	X	<i>Ciliatocardium ciliatum</i>	X	X
<i>Colus sabini</i>		X	<i>Crenella faba</i>		X
<i>Cryptonatica affinis</i>	X	X	<i>Dacrydium vitreum</i>	X	X
<i>Curtitoma decussata</i>		X	<i>Ennucula tenuis</i>	X	X
<i>Curtitoma incisula</i>	X		<i>Hiatella arctica</i>	X	X
<i>Curtitoma violacea</i>	X		<i>Liocyma fluctuosa</i>	X	X
<i>Cylichna alba</i>	X	X	<i>Lyonsia arenosa</i>	X	X
<i>Cylichnoides occultus</i>	X	X	<i>Macoma calcarea</i>	X	X
<i>Ecrobia truncata</i>	X		<i>Macoma loveni</i>		X
<i>Erginus rubellus</i>	X		<i>Macoma moesta</i>	X	X
<i>Euspira pallida</i>	X	X	<i>Macoma torelli</i>	X	X
<i>Flabellina salmonacea</i>	X				

<i>Frigidoalvania cruenta</i>		X	<i>Musculus discors</i>	X	X
<i>Laona finmarchica</i>	X		<i>Musculus niger</i>	X	X
<i>Lepeta caeca</i>	X	X	<i>Mya truncata</i>	X	X
<i>Limneria undata</i>	X		<i>Nuculana minuta</i>	X	X
<i>Margarites costalis</i>	X	X	<i>Nuculana pernula</i>	X	X
<i>Margarites groenlandicus</i>	X	X	<i>Pandora glacialis</i>	X	
<i>Margarites helicinus</i>	X	X	<i>Parvicardium pinnulatum</i>		X
<i>Margarites olivaceus</i>	X	X	<i>Periploma aleuticum</i>	X	
<i>Margarites umbilicalis</i>	X	X	<i>Portlandia arctica</i>		X
<i>Margarites vahli</i>	X		<i>Serripes groenlandicus</i>	X	X
<i>Moelleria costulata</i>	X	X	<i>Similipecten greenlandicus</i>	X	
<i>Nassarius lima</i>	X		<i>Thracia myopsis</i>		X
<i>Nepotilla amoena</i>	X		<i>Thyasira dunbari</i>		X
<i>Neptunea despecta</i>	X		<i>Thyasira gouldi</i>	X	X
<i>Oenopota declivis</i>	X	X	<i>Yoldia hyperborea</i>	X	X
<i>Oenopota pyramidalis</i>	X	X	<i>Yoldiella lenticula</i>		X
<i>Oenopota reticula</i>		X			

Stations 5b, 25, 26, 27, and 28 sampled in the Iqaluit region were located in relatively shallow water (8.5 - 43 m). Species richness ranged between 3 and 22 species and species diversity and evenness were low at most stations sampled in this region (Figure 2.6, Appendix 8). Station 26 experienced the greatest species diversity and the smallest amount of change over time while station 28 experienced the greatest change in species richness over time with a loss of 16 species at this station. The dominant taxa in the historical Iqaluit samples included bivalves *Axinopsida orbiculata*, *Thyasira gouldi*, *Ennucula tenuis* and the gastropods *Cylichna alba* and *Retusa obtusa* while the dominant taxa in the modern Iqaluit samples included the bivalve *Ennucula tenuis*. *Axinopsida orbiculata* and *Thyasira gouldi* were a dominant taxa in the modern Iqaluit samples but were not found in all samples (Table 2.5).

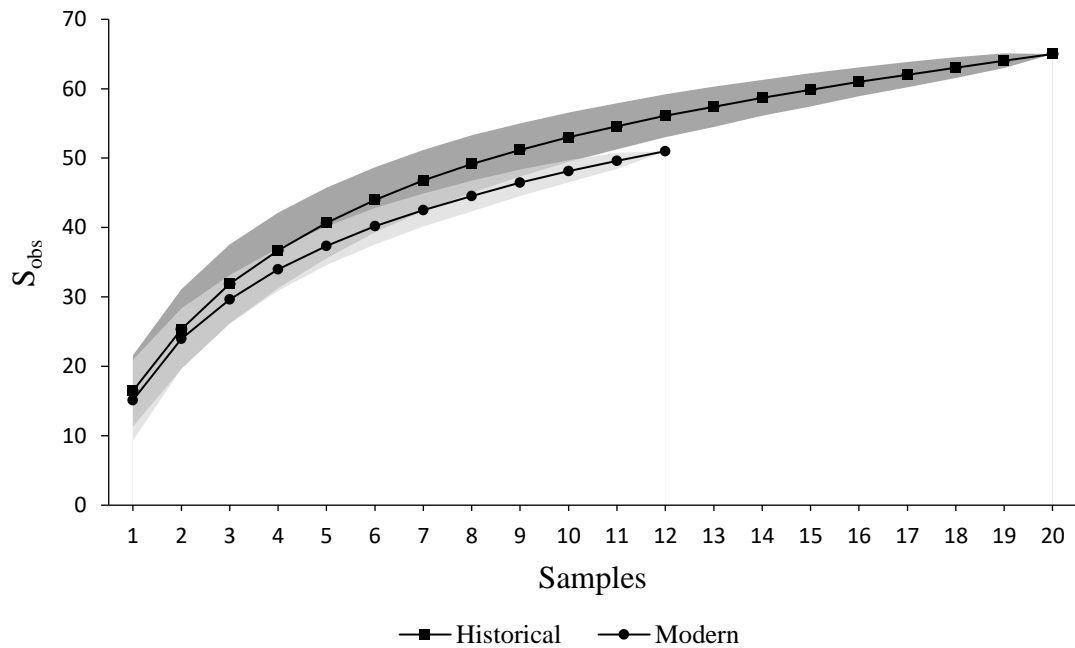


Figure 2.5. Species-accumulation curves (S_{obs}) for historical and modern benthic samples collected in Frobisher Bay between 1967-1976 and 2016. The greyed areas represent the standard deviation around the values.

Station 5, 5a, 5c, 5d, 5e, and 5f sampled near Cairn Island were located in deeper water ranging between 26 – 90.1 m. Species richness was higher overall at these stations compared to the Iqaluit stations; each station had between 11 – 29 species. Species diversity and evenness were also consistently greater at these stations (Figure 2.6, Appendix 8). Station 5c experienced the greatest loss in species richness over time in the Cairn Island region while all other Cairn Island stations experienced gains or losses of only a few species over time. The dominant taxa in the historical Cairn Island samples included the bivalves *Ennucula tenuis*, *Hiatella arctica*, *Musculus discors*, *Nuculana minuta*, *Thyasira gouldi*, and the gastropod *Cylichna alba*. Dominant taxa in the modern Cairn Island samples included the bivalves *Ennucula tenuis*, *Hiatella arctica*, *Macoma*

moesta, *Nuculana pernula*, *Thyasira gouldi*, *Yoldia hyperborea*, and the gastropod *Cylichna alba* (Table 2.5).

Neither species richness, diversity, or evenness changed significantly over time in the Iqaluit and Cairn Island regions (Table 2.3). It is imperative to note, however, that species richness and diversity did significantly change with water depth in the Iqaluit region and there was a significant relationship observed between water depth and species richness, diversity, and evenness. Furthermore, there was a significant interaction between time-period and depth in the Cairn Island region (Table 2.3). Therefore, these significant relationships may have masked changes in species richness, diversity, and evenness over time.

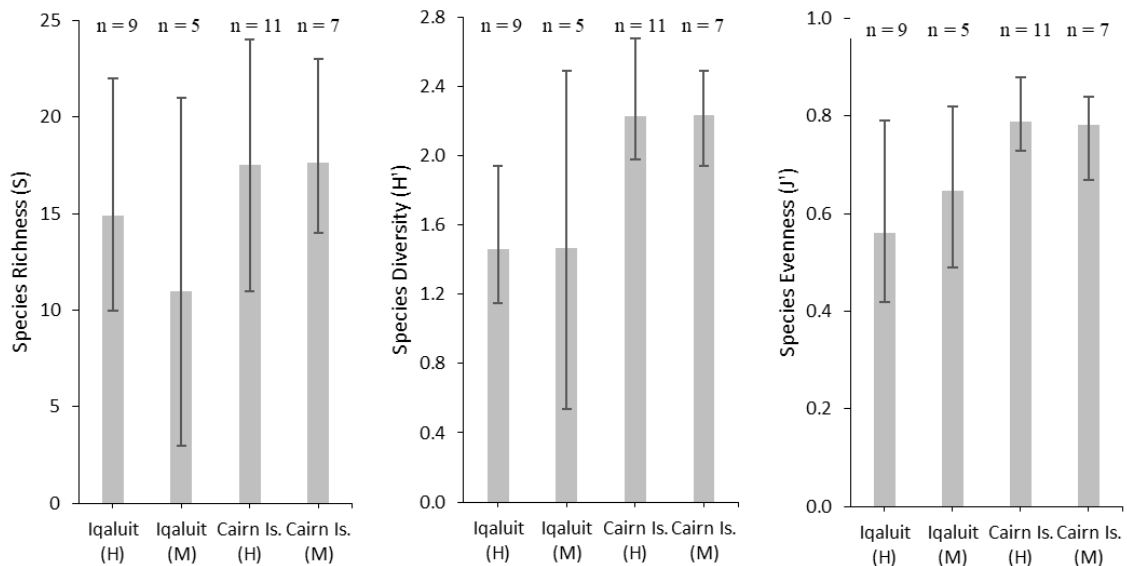


Figure 2.6. Results of diversity indices (species richness (S), Shannon-Weiner diversity (H'), and Pileou's evenness (J')) for historical and modern samples collected in Frobisher Bay.

Table 2.5. Average relative abundance (#/m²) of the most dominant taxa observed in historical and modern samples for the Iqaluit and Cairn Island regions (in bold). Un-bolded values are presented for comparison. Taxa were considered dominant if present in all or all but 1 samples collected in each region during each time period (e.g. present in at least 8/9 historical Iqaluit samples, 4/5 modern Iqaluit samples, 10/11 historical Cairn Island samples, 7/8 modern Cairn Island samples).

Species	Cairn Is (H) (#/m ²)	Cairn Is (M) (#/m ²)	Iqaluit (H) (#/m ²)	Iqaluit (M) (#/m ²)
<i>Axinopsida orbiculata</i>			685.6	87.7
<i>Ennucula tenuis</i>	35.0	20.1	87.3	17.2
<i>Hiatella arctica</i>	26.3	9.2		
<i>Macoma moesta</i>	4.2	11.0		
<i>Musculus discors</i>	40.7	16.1		
<i>Nuculana minuta</i>	19.5	5.0		
<i>Nuculana pernula</i>	3.1	13.1		
<i>Thyasira gouldi</i>	78.4	74.8	260.2	109.1
<i>Yoldia hyperborea</i>	0.0	8.1		
<i>Cylichna alba</i>	7.3	9.5	119.1	8.0
<i>Retusa obtusa</i>			92.4	0.0

2.3.3 Multidimensional Scaling Analysis

The historical mollusc communities in the Iqaluit and Cairn Island regions differed significantly from the modern mollusc communities in the Iqaluit and Cairn Island regions, as confirmed through multivariate analysis (Global R = 0.68, $p = < 0.001$, ANOSIM). The historical Iqaluit samples were significantly different from the modern Iqaluit samples (Global R = 0.627, $p = < 0.001$, ANOSIM) and the Cairn Island historical samples were significantly different from Cairn Island modern samples (Global R = 0.622, $p = < 0.002$, ANOSIM).

SIMPER analysis indicated that the historical Iqaluit stations were 52.3% similar to each other while the modern Iqaluit stations were only 24.6% similar to each other and

in both time periods, the thyasirid bivalve *Axinopsida orbiculata* contributed most significantly to within station similarity (Table 2.6). The historical Iqaluit stations clustered together while the modern Iqaluit stations were more dispersed in the MDS plot (Figure 2.7). The historical and modern Iqaluit samples were 72.69% dissimilar (Table 2.7). The thyasirid bivalves *Axinopsida orbiculata* and *T. gouldi* contributed most significantly to the dissimilarity observed over time, potentially the result of a steep decline in relative abundance of these species in the modern samples compared to the historical samples. The relative abundance of *T. gouldi* was slightly lower in one sample (5e) that was sieved over a 1.0 mm sieve (box core samples) compared to the sample collected at 5e sieved over a 0.5 mm sieve (Van Veen samples) and this was likely due to these small bivalves passing through the 1.0 mm sieve. However, the impact of one sample sieved through a 1.0 mm mesh likely had little influence on the dissimilarity observed between the historical and modern Iqaluit samples given that the modern 5e station plotted amidst all the other modern Iqaluit stations in the nMDS (Figure 2.7). *Cylichna alba*, *Retusa obtusa*, and *Ennucula tenuis* also contributed to over 50% of the dissimilarity between the historical and modern Iqaluit samples (Table 2.7).

Comparatively, the deeper Cairn Island samples did not exhibit such dramatic change in the molluscan community over time. SIMPER analysis indicated that the historical Cairn Island stations were 54.03% similar to each other while the modern Cairn Island stations were 50.71% similar to each other and in both time periods the thyasirid bivalve *Thyasira gouldi* contributed most significantly to within station similarity (Table 2.6). Both the historical and modern samples clustered more closely together in the MDS

plot (Figure 2.7) compared to the Iqaluit stations. The historical and modern Cairn Island samples were 60.0% dissimilar and many species contributed to the dissimilarity observed compared to the Iqaluit region (Table 2.7).

2.3.4 Biological Traits Analysis

The molluscs sampled in Frobisher Bay exhibited 16 trait modalities (Table 2.8). Body size was most commonly small (< 10 mm) or medium (10-50 mm) and shell structure was either solid/robust/thick or thin/fragile/brittle. Bivalves were primarily deposit or suspension feeders. Bivalves exhibited all of the sediment modalities with the majority of bivalves preferring silt/mud or a silt/mud/sand/gravel mix. All three AMBI modalities were present with the majority of bivalves exhibiting the “very sensitive to disturbance” trait. Historical and modern stations 5b, 25, and 28 located near Iqaluit were characterized primarily by molluscs that had solid/thick/robust shells, that were tolerant of disturbance, that were less than < 10 mm in size, that preferred silt/mud sediments, and that were deposit feeders. The historical and modern Cairn Island stations and the remaining Iqaluit stations exhibited a wider range of body sizes and were more commonly suspension feeders. They exhibited a wider range of sediment preferences and were either indifferent to or very sensitive to disturbance.

Table 2.6. Summary of SIMPER Analysis identifying within station similarity among the historical and modern Iqaluit and Cairn Island stations.

Region	Historical Samples				Modern Samples			
	Within Station Similarity (%)	Species	Contribution to within Station Similarity (%)	Cumulative Contribution to within Station Similarity (%)	Within Station Similarity (%)	Species	Cumulative Contribution to within Station Similarity (%)	Cumulative Contribution to within Station Similarity (%)
Iqaluit	52.32	<i>Axinopsida orbiculata</i>	24.85	24.85	24.60	<i>Axinopsida orbiculata</i>	34.26	34.26
		<i>Thyasira gouldi</i>	19.37	44.22		<i>Ennucula tenuis</i>	18.75	53.01
		<i>Cylichna alba</i>	15.61	59.83		<i>Macoma moesta</i>	8.68	61.69
		<i>Ennucula tenuis</i>	12.07	71.9		<i>Macoma calcarea</i>	7.05	68.74
		<i>Retusa obtusa</i>	11.13	83.03		<i>Cylichna alba</i>	6.61	75.35
		<i>Philine lima</i>	3.91	86.94		<i>Thyasira gouldi</i>	6.2	81.55
		<i>Astarte borealis</i>	3.04	89.99		<i>Thracia myopsis</i>	4.94	86.49
		<i>Macoma calcarea</i>	2.4	92.38		<i>Hiatella arctica</i>	2.77	89.27
Cairn Island	54.03	<i>Thyasira gouldi</i>	24.43	24.43	50.71	<i>Thyasira gouldi</i>	25.66	25.66
		<i>Musculus discors</i>	13.84	38.28		<i>Ennucula tenuis</i>	12.47	38.13
		<i>Ennucula tenuis</i>	11.5	49.78		<i>Nuculana pernula</i>	9.71	47.84
		<i>Nuculana minuta</i>	11.4	61.18		<i>Cylichna alba</i>	8.37	56.21
		<i>Hiatella arctica</i>	8.97	70.15		<i>Macoma moesta</i>	6.07	62.28
		<i>Daerydium vitreum</i>	5.99	76.13		<i>Yoldia hyperborea</i>	5.79	68.07
		<i>Cylichna alba</i>	5.09	81.22		<i>Hiatella arctica</i>	5.67	73.74
		<i>Margarites olivaceus</i>	3.89	85.11		<i>Musculus niger</i>	3.07	76.81
		<i>Mya truncata</i>	1.97	87.08		<i>Margarites helycinus</i>	2.91	79.72
		<i>Musculus niger</i>	1.57	88.65		<i>Frigidoalvania cruenta</i>	2.6	82.32
		<i>Lepeta caeca</i>	1.52	90.17		<i>Musculus discors</i>	2.4	84.72
						<i>Macoma loveni</i>	2.18	86.9
						<i>Cryptonatica affinis</i>	1.87	88.76
						<i>Macoma calcarea</i>	1.74	90.51

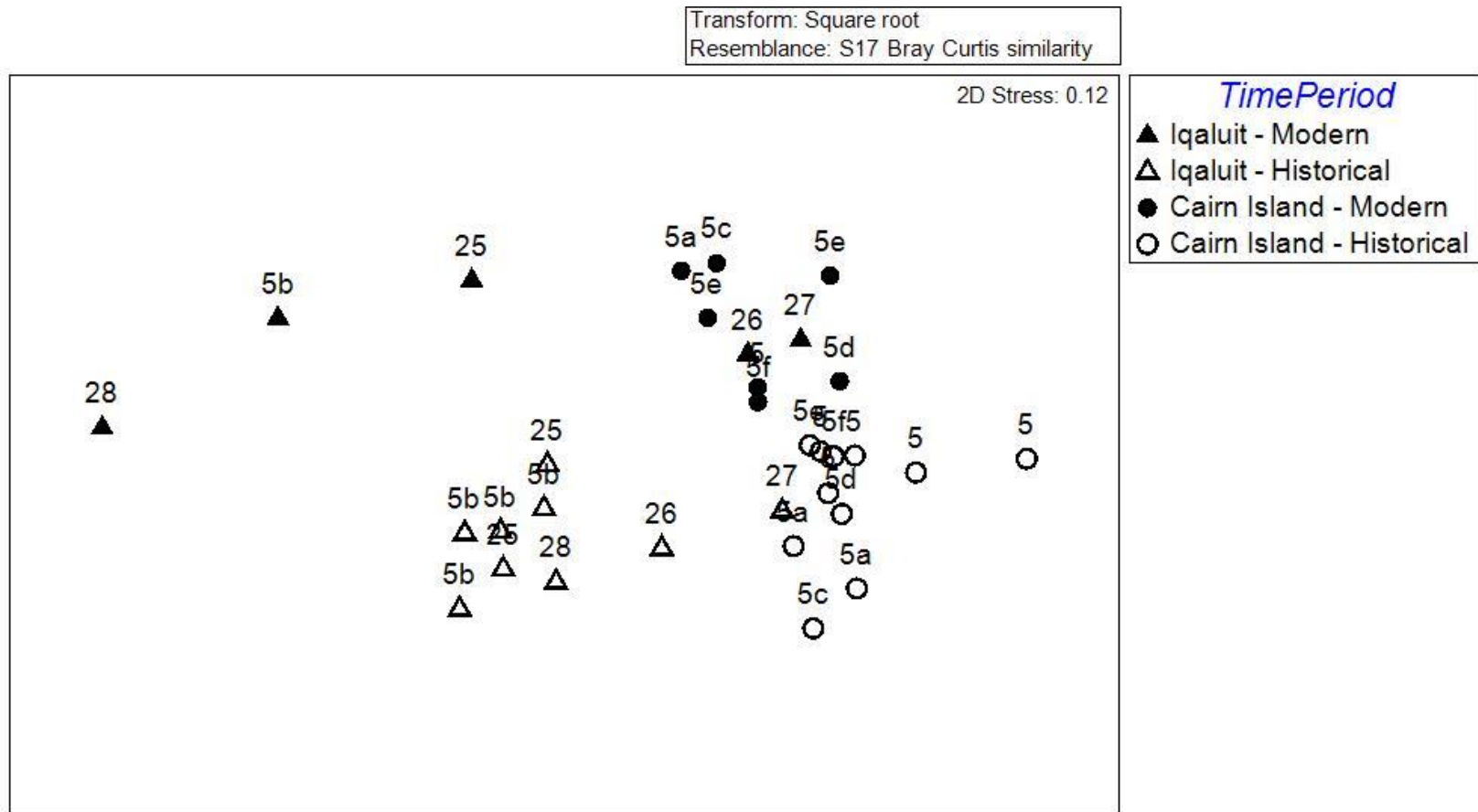


Figure 2.7. Non metric multidimensional scaling plot of the benthic community in Frobisher Bay sampled near Iqaluit and Cairn Island between 1967-1976 (historical) and 2016-2017 (modern). Results are based on square-root transformed data and these communities were deemed significantly different from each other through ANOSIM (Global R = 0.677, all pairwise $p < 0.05$).

Table 2.7. Summary of SIMPER Analysis identifying species that contributed to the dissimilarity between the historical and modern Iqaluit and Cairn Island stations.

Region	Dissimilarity between Historical and Modern Samples (%)	Species Contributing to Dissimilarity	Contribution to Dissimilarity (%)	Cumulative Contribution to Dissimilarity (%)
Iqaluit	72.86	<i>Axinopsida orbiculata</i>	17.41	17.41
		<i>Thyasira gouldi</i>	12.2	29.6
		<i>Cylichna alba</i>	9.12	38.72
		<i>Retusa obtusa</i>	8.69	47.42
		<i>Ennucula tenuis</i>	5.1	52.51
		<i>Astarte borealis</i>	3.36	55.88
		<i>Philine lima</i>	3.23	59.11
		<i>Hiatella arctica</i>	3.19	62.3
		<i>Macoma moesta</i>	3.03	65.33
		<i>Musculus discors</i>	2.72	68.05
		<i>Curtitoma violacea</i>	2.0	70.04
Cairn Island	60.0	<i>Musculus discors</i>	6.0	6.0
		<i>Nuculana minuta</i>	4.95	10.96
		<i>Nuculana pernula</i>	4.13	15.09
		<i>Dacrydium vitreum</i>	4.12	19.2
		<i>Hiatella arctica</i>	3.87	23.07
		<i>Margarites olivaceus</i>	3.6	26.67
		<i>Yoldia hyperborea</i>	3.58	30.25
		<i>Ennucula tenuis</i>	3.45	33.7
		<i>Macoma moesta</i>	3.45	37.15
		<i>Thyasira gouldi</i>	3.44	40.59
		<i>Frigidoalvania cruenta</i>	2.42	43.01
		<i>Macoma loveni</i>	2.31	45.32
		<i>Mya truncata</i>	2.31	47.63
		<i>Macoma calcarea</i>	2.19	49.82
		<i>Cylichna alba</i>	2.05	51.86

Table 2.8. List of functional trait characteristics for bivalves collected in historical and modern samples (Body Size: S – Small, M – Medium, L – Large, XL – X-large; Feeding Mode: SF – Suspension Feeder, DF – Deposit Feeder, S – Scavenger; Shell Structure: S – Solid/Robust/Thick, F – Thin/Fragile/Brittle; Sediment Preference: SMSG – Silt-Mud-Sand-Gravel, SM – Silt/Mud, S – Silt, G – Gravel, B – Bedrock/Boulder/ Hard Surface; AMBI Index: AMBI1 - Very Sensitive to Disturbance, AMBI2 – Indifferent to Disturbance, AMBI3 – Tolerant to Disturbance).

Species	Body Size	Feeding Mode	Shell Structure	Sediment Preference	AMBI Index
<i>Astarte borealis</i>	M	SF	S	SMSG	AMBI1
<i>Astarte montagui</i>	M	SF	S	SMSG	AMBI1
<i>Axinopsida orbiculata</i>	S	DF	S	SM	AMBI3
<i>Ciliatocardium ciliatum</i>	L	SF	S	SMSG	AMBI1
<i>Crenella faba</i>	M				
<i>Dacrydium vitreum</i>	S		F	SM	AMBI1
<i>Ennucula tenuis</i>	M	DF	F	SM and S and G	AMBI2
<i>Hiatella arctica</i>	M and L	SF	F	G and B	AMBI1
<i>Liocyma fluctuosa</i>	M	DF and SF	F	SMSG	AMBI1
<i>Lyonsia arenosa</i>	M			SM	
<i>Macoma calcarea</i>	M	DF and SF	S	SM and G	AMBI2
<i>Macoma loveni</i>	M		F	SM and G	
<i>Macoma moesta</i>	M	DF and SF	F	SM and G	AMBI2
<i>Macoma torelli</i>	M		F	SM and S	AMBI2
<i>Musculus discors</i>	M	SF	F	G and B	AMBI1
<i>Musculus niger</i>	L	SF	F	SM and S	AMBI1
<i>Mya truncata</i>	L	SF	S	SMSG	AMBI2
<i>Nuculana minuta</i>	M	DF	F	SM and G	AMBI1
<i>Nuculana pernula</i>	M	DF	F	SM	AMBI1
<i>Pandora glacialis</i>	M			SM and S	AMBI1
<i>Parvicardium pinnulatum</i>	M		S	SMSG	AMBI1
<i>Periploma aleuticum</i>			F		
<i>Portlandia arctica</i>	M	DF	F	SM	
<i>Serripes groenlandicus</i>	L and XL	SF	F	SM and S	AMBI1
<i>Similipecten greenlandicus</i>	M		F	SM	AMBI1
<i>Thracia myopsis</i>	M		S	SM	AMBI1
<i>Thyasira dunbari</i>	S	DF and SF	F	SM	
<i>Thyasira gouldi</i>	S	DF and SF	F	SM and S	AMBI3
<i>Yoldia hyperborea</i>	M	DF and SF	F	SM	AMBI1
<i>Yoldiella lenticula</i>	S	DF and D	S	SM	AMBI1

Fuzzy Principal Components Analysis (FPCA) explained only 11.0% of the trait variability of which 81.2% was explained by axis 1 and only 10.3% was explained by axis 2. Correlation ratios resulting from Fuzzy Correspondence Analysis (FCA) indicated that no particular trait was a significant contributor to explaining the variability observed. For example, the trait AMBI was the most significant contributor explaining only 23.3% of the variability followed by the traits Feeding Habit (19.3%), Sediment Preference (18.4%), Body Size (17.3%), and lastly Shell Structure (0.6%). ANOSIM performed on the functional trait characteristics for each region and time period confirmed that the functional traits between the historical Iqaluit and historical Cairn Island regions were significantly different from each other (R Statistic = 0.697, $p = 0.001$) but this relationship was less clear for the modern Iqaluit compared to the modern Cairn Island regions due to a low R Statistic (R Statistic = 0.218, $p = 0.053$). Similarly, little functional change occurred between the historical and modern Iqaluit region (R Statistic = 0.026, $p = 0.277$) and between the historical and modern Cairn Island region (R Statistic = 0.265, $p = 0.017$).

The functional trait's: very sensitive to disturbance (AMBI3), thin/fragile/brittle shells (SS2), small body size (< 10 mm; BS1), deposit feeder (FH1), and silt/mud (SP1) fell to the right of axis 1 while all other trait characteristics fell to the left of axis 1. The Iqaluit samples 5b, 25, and 28 fell to the right of axis 1 and along axis 2 while the remaining Iqaluit samples except for modern station 27 and all the Cairn Island samples except for modern station 5e and 5d clustered to the left of Axis 1 with greater spread along axis 2 (Figure 2.8).

The historical station 5b samples clustered together while modern station 5b was shifted slightly upward and to the left of the historical 5b samples. The historical and modern station 25 samples did not cluster as together indicating some degree of functional variability among these samples. Similarly, the historical and modern station 28 samples were not clustered near each other suggesting some functional variability over time. Station 26 experienced a slight downward shift along axis 2 between the historical and modern sample. Station 27 experienced a shift to the right along axis 2 between the historical and modern sample moving towards Iqaluit stations 5b, 25, and 28.

The Cairn Island stations indicated varying trends with the stations 5, 5c, and 5d all exhibiting a slight upward shift to the right along axis 2 over time. One of two modern 5e samples was in close proximity to the historical 5e sample and the other modern 5e sample exhibited a slight upward shift to the right along axis 2. Both the historical and modern 5a and 5f samples clustered closely together, indicating only a very slight shift down axis 2. A shift upward along axis 2 suggests bivalve species are indifferent to disturbance, have solid/robust/thick shells, have medium to x-large body size, and prefer silt, sand, mud, and gravel or a combination of sediments types.

Over time, functional diversity did not change significantly in the Iqaluit region ($F = 2.176$, $p = 0.16824$) but a significant change in functional diversity was observed in the Cairn Island region ($F = 6.931$, $p = 0.0197$; Table 2.3). Functional Diversity (FD) was lower overall at the Iqaluit stations compared to the Cairn Island stations with FD values ranging from 0 to 3 with 0 representing no functional diversity and 3 representing high functional diversity (Figure 2.9).

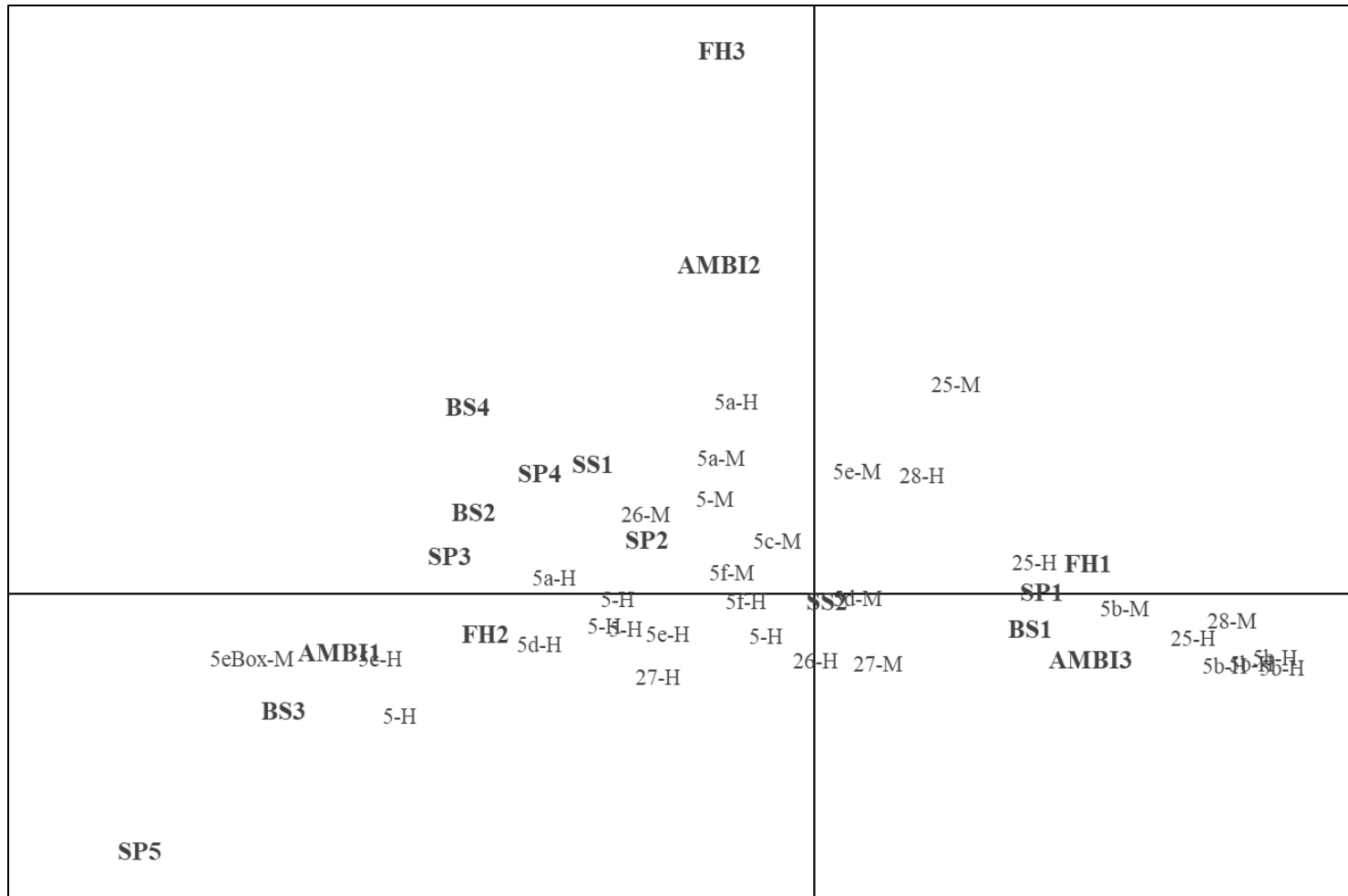


Figure 2.8. Fuzzy correspondence analysis showing station distribution based on the functional trait characteristics SS (shell structure), AMBI (tolerance to disturbance), FH (feeding habit), SP (sediment preference), and BS (body size). Iqaluit Stations are 5b, 25, 26, 27, and 28 and Cairn Island Stations are 5, 5a, 5c, 5d, 5e, and 5f.

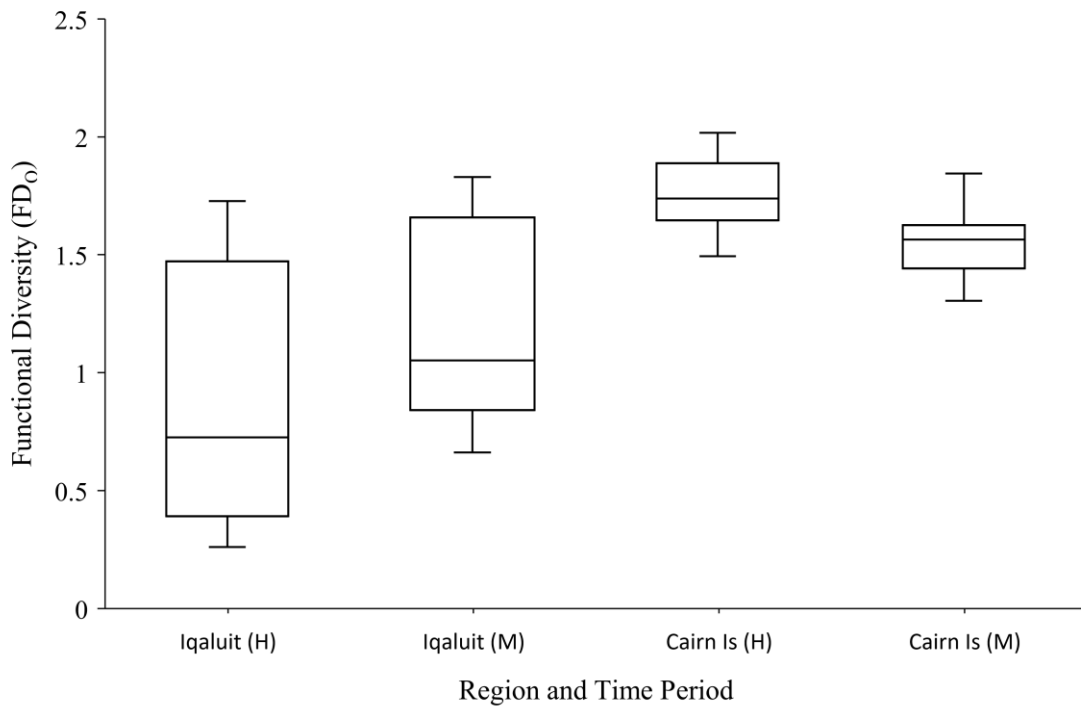


Figure 2.9. Functional diversity calculated from Rao’s Quadratic Entropy (FG_Q) for all historical and modern samples collected near Iqaluit and Cairn Island.

2.4 Discussion

Frobisher Bay experienced significant long-term changes in the local environment between 1967 and 2016 including increased air temperatures, loss of sea ice, and changes in the hydrodynamics of the Sylvia Grinnell River and the Apex River. These changes should be expected to contribute to warming sea surface temperatures and a reduction in sea surface salinities though we were unable to confirm if this translated to a change in sea bottom temperature and salinity over time due to having only a snapshot of environmental conditions during the two time periods examined. The Cairn Island region

experienced a significant increase in the proportion of silt and a decrease in the proportion of sand in the seabed sediments and this region also experienced a significant increase in organic carbon and total nitrogen in the sediments while the Iqaluit region did not experience these same changes. Eight of the eleven stations sampled demonstrated an increase in carbon-nitrogen ratio in the sediments, however, this change was not significant when region and time period were examined statistically.

Carbon-nitrogen ratios increased in 8 of 11 stations sampled and at three Iqaluit stations that value increased to over 10 (10-14 indicates a terrestrial source) suggesting that a change in summer discharge of the Sylvia Grinnell and Apex Rivers may have resulted in an increase in terrestrial organic matter input in the Iqaluit region. However, no statistically significant change in C/N ratios was observed when tested by region (Iqaluit and Cairn Island) indicating that C/N values of sedimentary organic matter were generally indicative of a marine rather than terrestrial origin.

The molluscan communities observed in the coastal waters of inner Frobisher Bay in 2016-2017 exhibited differences in community structure and some functional traits compared to the molluscan communities observed 50 years earlier by Wacasey *et al.* (1979, 1980). Four groupings of samples were tested for significance: Historical Iqaluit, Modern Iqaluit, Historical Cairn Island, and Modern Cairn Island (Figure 2.7). The Iqaluit region exhibited the greatest change in community composition due to the loss of a few previously abundant species while the Cairn Island region exhibited a smaller amount of change, probably due to a more diverse community of molluscs whose abundances varied less significantly over time. Functional trait analysis did not

demonstrated any significant change in functional characteristics over time. Functional diversity increased at three nearshore Iqaluit stations but decreased at the outermost Iqaluit stations and in the Cairn Island region, functional diversity significantly decreased over time. Despite significant long-term changes to the local environment in this region including warming air temperatures, loss of sea ice, and changes in the timing of the nival freshet in the Sylvia Grinnell River and Apex River, overall, neither the Iqaluit or Cairn Island regions experienced significant changes in the benthic community over time.

2.4.1 Long-term Change in the Physical Environment

Coastal benthic communities can be significantly impacted by long-term environmental change (Kedra *et al.* 2010, Brown 2011). In the Arctic, benthic community composition is well known to be tightly linked to pelagic processes (Stasko *et al.* 2018). The loss of arctic sea ice resulting from increased air temperatures affects benthic communities through increased light availability which promotes phytoplankton blooms and which can result in increased organic sedimentation to the benthos (Clark *et al.* 2017). Frobisher Bay experienced a significant loss of annual sea ice between 1967-2017 as well as a decline in sea ice thickness, likely the result of increasing air temperatures in the region. Overeem *et al.* (2011) observed a similar trend along the coastline in the Beaufort Sea including expansion of the open water season from 45 days to 95 days over a 50 year period (Overeem *et al.* 2011). As more light becomes available, the quality and quantity of the food source available to the benthos changes (Hsiao 1992). Benthic fauna receive most of their nutrition from the deposition of organic material from the overlying

water column either from ice algae when sea ice is present or from phytoplankton in the water column when the sea ice has disappeared (Hsiao 1992, McMahon 2006, Clark *et al.* 2017). Changes to the food source available to the benthos can therefore result in changing the structure and function of the benthic community (McMahon 2006) and in regions covered by sea ice, the summer phytoplankton bloom is a major contributor of organic matter and typically occurs in response to increased light availability (Clark *et al.* 2017). For example, during years with only small amounts of ice, Heide-Jorgensen *et al.* (2007) observed greater chlorophyll concentrations in the water column of Disko Bay, West Greenland while Kedra *et al.* (2010) observed greater particulate organic carbon in the sediments of Kongsfjorden, Svalbard as a result of increased primary production in the water column due to warming water temperatures. In this study, ice break up in inner Frobisher Bay occurred between late June and early July in 1967-1976 but ice break-up occurred much earlier – in late April in 2016. The Cairn Island region responded to this increased light availability through a significant overall increase in organic carbon in the sediments and carbon-nitrogen ratios confirm that the source of this organic matter was marine and therefore must be from phytoplankton deposition. Hsiao and Pinkewycz (1983, 1985) measured phytoplankton production weekly or biweekly in the Iqaluit region and Cairn Island region in 1976, and 1979-1981 and observed that phytoplankton blooms typically occurred in mid to late July in Frobisher Bay and in some years there was a second phytoplankton bloom in late August (Hsiao and Pinkewycz 1983, 1985). Phytoplankton blooms occurred quickly with very high concentrations of over 2 million cells/litre present one week and significantly diminished the next. The Iqaluit region

(station 5b) experienced slightly smaller concentrations of phytoplankton compared to the Cairn island region in most years examined except in 1976 when the Iqaluit region experience a 2-fold increase in phytoplankton concentration compared to the Cairn Island region (Hsiao and Pinkewycz 1983, 1985). Unfortunately, no modern phytoplankton data were available to compare the concentration of modern phytoplankton samples with the historical phytoplankton data to support our findings of a significant increase in total organic carbon in the sediments between the two time periods in the Cairn Island region in response to changing environmental conditions including a shorter ice season and therefore greater open water season.

Long-term air temperature rise can also influence river discharge rates and both organic and inorganic sediment loading through snow and glacier melt in Arctic regions (Syvitski 2002). Increased river discharge influences water column stratification, nutrient cycling, primary production, and inorganic sedimentation which all influence the food supply to the benthos. Increased water turbidity reduces light penetration which limits primary production and large sediment fluxes dilute organic matter delivered to the sea bed which reduces the organic matter content of the sea bed through the dilution of large inorganic sediment (Atkinson and Wacasey 1987, Gorlich *et al.* 1987, Thrush *et al.* 2004, Wlodarska-Kowalczyk *et al.* 2005, Wassmann and Reigstad 2011). Svendsen *et al.* (2002) observed that ice-melt and riverine/glacial drainage had a strong impact on the hydrographical conditions of Kongsfjorden, Svalbard which resulted in steep environmental gradients along the fjord. Chou *et al.* (2004) also found that limited organic matter in seabed sediments resulting from excessive clastic sedimentation

resulted in decreased faunal abundance. Long-term chronic sedimentation can disturb benthic communities by smothering or killing organisms (Chou *et al.* 2004, Renaud *et al.* 2007) or by clogging the filtering organs of invertebrates (Wlodarska-Kowalczyk and Weslawski 2001, Wlodarska-Kowalczyk *et al.* 2005) and it can alter the overall sediment composition of the benthos (Gorlich *et al.* 1987, Thrush *et al.* 2004). The mouth of the Sylvia Grinnell River is located approximately 2 km from the Iqaluit stations and approximately 10 km from the Cairn Island stations while the mouth of the Apex River is located approximately 3 km from the Iqaluit stations and 7 km from the Cairn Island stations and both rivers experienced a significant increase in average instantaneous discharge during the month of June suggesting that the timing of freshwater discharge from these rivers has changed over time. The proximity of these rivers to the study region suggest that changes over time in the hydrodynamics of these rivers may have caused change in sedimentary and biotic characteristics of the benthos. Atkinson and Wacasey (1987) measured particulate organic carbon in the water column near station 27 (station closest to the Sylvia Grinnell River) between 1981 and 1985 and confirmed that primary production at this station was significantly reduced due to high turbidity from the Sylvia Grinnell River. These results help support why TOC in the sediments appear lower overall in the Iqaluit region compared to the Cairn Island region (not statistically tested) but they do not help answer why there was an increase in total organic carbon observed over time in the Cairn Island region. The ratio of carbon to nitrogen in the sediments did not significantly change over time in either the Iqaluit or Cairn Island region suggesting that these rivers did not contribute to an increase in supply of terrestrial carbon to the

benthos. However, it is possible that output from these rivers did affect individual stations as stations 5b, 26, and 28 near Iqaluit all appear to have experienced an increase in C/N ratio above a value of 10 (indicative of terrestrial input of organics).

The discharge of sediments in Arctic rivers is typically low compared to temperate and tropical regions (Syvitski 2002) therefore, the author applied a model to predict how increased sediment loads may affect Arctic rivers as a result of global warming and found that for every 20% increase in water discharge, the sediment load would increase by 10% (Syvitski 2002). In this study, the proportion of sand and silt/clay in the sediments did not change over time in the Iqaluit region. In the Cairn Island region, the proportion of sand and silt/clay in the sediments did change over time with the sand component of the sediments declining and silt/clay component increasing. It is therefore possible that there are other sources of sediment that may have influenced these results in the Cairn Island region. Coastal erosion is known to increase where sea ice, especially landfast ice, is lost (Brown 2011, Overeem *et al.* 2011) and where permafrost is thawing (ACIA 2005). Much of the coastline in Frobisher Bay consists of fine-grained tills and glaciomarine sediments (Hodgson 2005) including in Tarr Inlet where these sediments are exposed in the intertidal zone in some areas (Tommy Tremblay pers. comm. 2019).

Tarr Inlet is located next to the mouth of the Apex River and in close proximity to the Cairn Island stations and could be the source of sediments that contributed to finer grain sizes recorded in modern sediments in this region. Comparatively, Koojesse Inlet, located at the head of Frobisher Bay, is in closer proximity to the Iqaluit stations and is primarily composed of glaciomarine sediments that are overlain by a surficial sand/mud

layer (Hatcher *et al.* 2014). However, in their study examining erosional and depositional processes on the Koojesse Inlet tidal flats between 2009-2011 (Hatcher *et al.* 2014), the authors were unable to confirm significant amounts of erosion had occurred on the tidal flats. These results suggest that erosion of the coastline in Frobisher Bay could be occurring at a very slow rate and this could be why no significant change was observed in the sediments in the Iqaluit region even after fifty years.

2.4.2 Long-Term Benthic Community Change

Both the Iqaluit and Cairn Island regions experienced molluscan community change over time when statistically tested through ANOSIM. In the Cairn Island region molluscan community change coincided with observed changes in sediment properties while in the Iqaluit region, the reasons for the changes observed are uncertain. Dissimilarity between the historical and modern Cairn Island region was 60% and numerous species contributed to this dissimilarity with all species contributing only a small portion (< 6.0%) and no single species contributing significantly to the differences observed in this region over time (Table 2.7). Historically, the most dominant molluscan taxa in the Cairn Island region included the bivalves *Ennucula tenuis*, *Hiatella arctica*, *Musculus discors*, *Nuculana minuta*, *Thyasira gouldi*, and the gastropod *Cylichna alba* (Table 2.5). All these species experienced a decline in average relative abundance over time. *H. arctica*, *M. discors*, *N. minuta*, and *T. gouldi* are all considered very sensitive to disturbance while *E. tenuis* and *C. alba* are considered indifferent to disturbance. In the modern Cairn Island region, *Macoma moesta*, *Nuculana pernula*, and *Yoldia hyperborea*

were dominant where they had not been abundant historically. *N. pernula* and *Y. hyperborea* are both considered very sensitive to disturbance while *M. moesta* is considered indifferent to disturbance. The decline in relative abundance of the historically dominant molluscs that are sensitive to disturbance coincides with the significant increase in TOC observed in the sediments in the Cairn Island region. Though there were dominant species that are also considered very sensitive to disturbance in the modern samples, their average relative abundance overall was lower than the historically dominant species.

While the physical changes to the seabed are possible contributors to the change in community composition observed in the Cairn Island region, Renaud *et al.* (2007) suggest that there is no specific physical driver of community change where there is stability in the benthic community. Gray and Christie (1983) observed that long-term environmental cycles (e.g. periods of 3- 4, 6-8, 10-12, and 18-20 years) could be responsible for the temporal variability observed in the benthic community while Powell and Cummins (1985) predicted that species life- spans control community composition to some degree. Longevity data for the mollusc species that contributed to over 50% of the dissimilarity between the historical and modern samples indicates that these species demonstrate a variety of life spans. For example, *M. discors*, *T. gouldi*, and *N. minuta* have a life span ranging from 3-10 years (BIOTIC 2019, Ansell *et al.* 1978) and all experienced a decline in relative abundance over time while *N. pernula* and *M. calcarea* have a life span of 10+ years (Ansell *et al.* 1978, Selin 2010) and these species experienced an increase in relative abundance over time. *H. arctica* has a life span of 3-

10 years (Selin 2010) while *F. cruenta* has a life span of 3 years (Ponder 1984) or less and these species experienced no noticeable change in relative abundance. Unfortunately, a lack of longevity data for the majority of bivalve species observed in Frobisher Bay resulted in exclusion of this trait from the biological traits analysis. Many long-term cycles have been shown to correspond to the maximum life spans of molluscs and Powell and Cummins (1985) suggest that natural long-term cycles may correspond to adult mortality and recruitment and ultimately influence the molluscan community. Therefore, it is possible that not only changes in the sediment composition and quality are influencing the changes observed in the molluscan community near Cairn Island.

Dissimilarity between the historical and modern Iqaluit region was 72.86% and *A. orbiculata*, *T. gouldi*, *C. alba*, *R. obtusa*, and *E. tenuis* contributed most significantly to the differences observed over time with the thyasirid bivalves *A. orbiculata* and *T. gouldi* contributing most significantly to the differences observed. These same species were the most dominant in the historical samples and had the greatest average abundance of all species sampled historically (Table 2.5). *A. orbiculata* and *T. gouldi* cope well with sedimentation, are both typically found in organically enriched across the Arctic (Batstone *et al.* 2014, Dufour Pers. Comm, 2019, Wlodarska-Kowalczyk 2007, Kedra 2010), and are both listed as species that are tolerant of disturbance (WoRMS 2019). Thyasirid bivalves are mobile deposit feeders (Wlodarska-Kowalczyk 2007) that inhabit surface layers of the sediment and that are able to move in unstable rapidly deposited sediments (Ockelmann 1958). Species that are tolerant of disturbance thrive where there is excess organic enrichment (Borja *et al.* 2000) and they occur abundantly in areas such

as in glacial bays (Włodarska-Kowalczyk 2007). The relative abundance of *A. orbiculata* declined significantly at station 5b and 25 while *T. gouldi* experienced a decline in relative abundance at station 26 and 28 and a complete loss of this species was recorded at stations 5b and 25, however, no significant change in sediment grain size composition and no significant change in proportion of organic carbon and nitrogen in the sediments was observed in the Iqaluit region that can explain why these changes occurred.

This study examined only the molluscan communities in Frobisher Bay but other taxa may also have had an influence on the community composition of the benthos and the changes observed over time. For example, the interactions between molluscs and arthropods and annelids could have influenced molluscan community composition. Cusson *et al.* (2007) examined the composition of the Frobisher Bay historical samples and found that these two groups (arthropods and annelids) contributed more to the composition of the benthos than did the molluscs. The interaction between groups of benthic species can have positive or negative effects on community composition through predation, space occupation, disturbance, etc. (Brey 1991). Brey (1991) examined the interaction between a surface deposit feeding polychaete, *Pygospio elegans*, and a surface deposit feeding bivalve, *Macoma balthica*, in the subtidal (Kiel Bay) and intertidal station (Westerhever) of the German Wadden Sea. The author found a strong competition for food and suggested that this competition may affect recruitment of benthic species. Polychaetes are also ecosystem engineers and play an important role in the functioning of benthic communities including recycling and reworking sediments, bioturbating sediments, and burying organic matter through their burrowing and feeding activities

(Hutchings 1998) and these activities could have an influence on the presence/absence and/or abundance of mollusc species present in the community. The community dynamics between the molluscs and other species within the benthic communities in Frobisher Bay could therefore be another influence on changes observed in the molluscan communities over time.

Two potentially significant contributing factors may have influenced the differences observed in molluscan community composition over time: the spatial distribution and associated water depth variability observed and temporal discrepancies in water depths (resulting from inaccuracy of sampling at the same location in both time periods) sampled between the historical and modern samples. In the Iqaluit region, water depth ranged between 11.5 m and 43 m (historical samples) and between 8.5 m and 35.2 m (modern samples) while in the Cairn Island region water depth ranged between 26 m and 73 m (historical samples) and between 25 m and 90.1 m (modern samples).

Due to small sample size, physical and community changes observed over time at individual stations in the Iqaluit region could not be statistically tested and therefore all historical samples were compared to all the modern samples collected in the Iqaluit region. The spatial distribution of the Iqaluit stations was much greater compared to the Cairn Island Stations and water depth increased with distance from the shore. When tested statistically, total organic carbon and total nitrogen in the sediments, species richness, species diversity, and functional diversity all changed significantly with water depth when depth was tested as a response variable. Three of the five Iqaluit stations (5b, 25, and 28) all experienced an increasing trend in C/N ratio above 10 suggesting that the

molluscan communities at these stations may have been influenced by the Sylvia Grinnell River through terrestrial input while station 26 and 27 exhibited community composition and trait characteristics that were more similar to the modern Cairn Island stations than they were to the remaining Iqaluit stations and station 27 was located almost equidistant to the Cairn Island stations. The physical and benthic community patterns observed in the Iqaluit region, therefore, could have been influenced by the spatial distribution of the Iqaluit stations themselves. The Iqaluit region, therefore, could have benefited greatly by the collection of a larger number of historical and modern samples collected closer to shore around stations 5b, 25 and 28 samples sizes which then could have been compared on a station by station basis rather than being included with stations 26 and 27 which appear to have a much different community composition. By conducting all analyses on this group of stations, the differences observed due to spatial distribution of the stations may have masked significant temporal changes observed in both the physical characteristics and community composition observed among individual stations.

Global positioning devices like we have available today were not available in the 1960's and 1970's when the historical samples were collected and the GPS location was recorded only one time for replicate pooled samples despite the un-likelihood that samples were collected in the exact same position given the equipment being used at the time while also factoring in local sampling conditions such as the strong tidal influences of Frobisher Bay. Renaud *et al.* (2007) experienced this same dilemma with the pooled historical dataset used in their multi-decadal study examining the benthic community structure in an Arctic fjord in Svalbard, Norway. The positional data provided in the

historical data reports by Wacasey *et al.* (1979, 1980) did not match the map of historical sample locations therefore the historical maps were loaded into ESRI ArcMap and the sample locations were georeferenced using the positional information on the historical maps. Despite these efforts, water depth at some of the historical stations did not match with the modern sample stations. This meant that for some stations the historical sample was not re-sampled in the same location in 2016. This temporal water depth discrepancy may have influenced the composition of molluscs observed at Iqaluit station 28 which experienced the greatest water depth discrepancy in the Iqaluit region but it may have also played a role in the Cairn Island region as well where a water depth – time period interaction was significantly related to species richness, diversity, and evenness. This was likely the result of deeper water depths sampled in the modern samples compared to the historical samples at three of the Cairn Island stations.

A third potential influence that could have been a significant contributor to the community composition observed in the historical versus the modern samples is discrepancies between sample volume and the number of grabs collected and differences in sieve size used to process samples. Historically, 4-6 grabs were pooled for a total surface area of between 0.25 – 0.39 m² while in the modern samples only 2-3 grabs were pooled for a total surface area of 0.024 – 0.11 m². The historical samples that were collected covered a greater total surface area compared to the modern samples and this could have resulted in a greater diversity of species that were collected. Additionally, this may have influenced the density of each species that was collected compared to the smaller surface area that was sampled 50 years later. The one modern pooled sample

collected by the box core was not directly comparable to the historical samples collected at the same station because it was sieved over a 1.0 mm mesh screen compared to all other samples which were sieved over a 0.5 mm mesh screen. The use of different mesh sizes can have an influence on the observed composition of the benthic community (Hartwell and Fukuyama *et al.* 2015) where small molluscs (< 1.0 mm) could have been sieved out and lost. This issue was minimized as only one sample from the modern Cairn Island group of samples was sieved over a 1.0 mm mesh screen and the same station was also sampled and sieved over a 0.5 mm mesh screen. The 1.0 mm sieved sample fell within the modern Cairn Island group of samples.

Despite observed long-term environmental change and associated physical changes to the environment that were observed, diversity metrics showed no significant changes over time with only functional diversity in the Cairn Island region significantly declining over time. A station by station comparison to identify community change over time was ultimately decided against because of too small of a sample size, difficulties associated with inconsistent collection methods and discrepancies in spatial coverage between the historical and modern samples precluded such analysis. Novoa *et al.* (2016) also cited these inconsistencies and recognized the difficulties of using historic datasets in their study examining spatial and temporal bivalve community change in Southern and Northern Baja California. Using an appropriate time-scale to identify temporal variability is particularly important in measuring long-term change (Beuchel *et al.* 2006, Renaud *et al.* 2007, Kedra *et al.* 2010) as benthic communities are influenced by disturbance on a variety of time scales (seasonal to multi-decadal) which makes distinguishing long-term

change from short term variability difficult (Beuchel and Gulliksen 2008). Renaud *et al.* (2007) suggests examining benthic community change at decadal scales. Fifty years should then certainly be an appropriate time scale to measure benthic community change in Frobisher Bay amid the significant environmental changes that have occurred. Unfortunately, the benthic communities in Frobisher Bay experienced dramatic short term changes in species richness in the historical samples. A 100% increase in molluscan species richness was observed between 1973 and 1976 at Station 25 while a 70% increase in species richness was observed between July and September 1969 (Appendix 8). Cusson *et al.* (2007) observed this trend for the whole macrofaunal community at station 27 when they examined interannual and annual benthic community change in Frobisher Bay using the historical samples collected by Wacasey *et al.* (1979, 1980). Beuchel *et al.* (2006) also observed similarly large fluctuations of up to 80% in the coverage of an algae species measured between just two years in their study examining long-term patterns in rocky bottom community structure in relation to climate variability over a 23 year period and Bergmann *et al.* (2011) documented inter-annual change in the mean relative abundance of *Gersemia fruticosa* (~ 0.28 ind/m² in 2002 to ~ 0.48 ind/m² in 2004), burrowing crustaceans (~ 0.62 ind/m² in 2002 to ~ 0.98 ind/m² in 2004), the sea pig *Elpidia heckeri* (~ 1.1 ind/m² in 2004 to ~ 0.2 ind/m² in 2007), and the crinoid *Bathycrinus carpenterii* (~ 3.0 ind/m² in 2004 to ~ 1.8 ind/m² in 2004). The implications for this study are that large seasonal and inter-annual variation may have obscured the identification of long-term change with regards to species diversity indices.

2.4.3 Conclusion

Long-term environmental change has occurred in Frobisher Bay including warming air temperatures, loss of sea ice, and changing hydrodynamic conditions and some of these factors may have influenced the benthic community composition over fifty years. This study examined temporal change in molluscan communities separated by 50 years amid changes in the local environment. A significant change in sediment characteristics was observed in the Cairn Island region and this translated to changes in the associated molluscan benthic community over time. The absence of consistent long-term monitoring of these molluscan communities also limits our understanding of the extent of the change observed. Data on the range of natural variability that may exist within these communities was limited and samples sizes were small therefore short-term natural variability was not examined and ultimately made it difficult to distinguish between short-term natural variability and long-term change. Better standardization of sampling for long-term monitoring is required and has been highlighted by others (e.g. Wei *et al.* 2019). Future research should continue to utilize historical datasets as they are an invaluable tool with which to examine benthic Arctic communities in “pristine” conditions but consistent long-term monitoring should also take place in order to gain an understanding of the natural fluctuations that exist within the benthic community being examined and to be able to distinguish this from long-term change.

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Chapter 3 Long-term spatial change observed in the molluscan (Bivalvia and Gastropoda) communities of Frobisher Bay, NU

3.1 Introduction

Habitat mapping has become an invaluable tool for predicting the spatial distribution of benthic fauna and can be used as a baseline from which to measure long-term change (Harris 2012). This is particularly important in the face of rapid environmental and anthropogenic change in polar regions (Aitken *et al.* 2008) as it is anticipated that Arctic marine ecosystems will look considerably different in the future as a result of changing physical conditions including warmer air and sea temperatures and longer open water seasons (Carmack and McLaughlin 2001, Carmack and McLaughlin 2011, Wassmann and Reigstad 2011, Carmack and Macdonald *et al.* 2015, Renaud *et al.* 2015). The circumpolar Arctic has experienced long-term environmental change including rising air and sea temperatures and the loss of significant amounts of sea ice (Vinnikov *et al.* 1999, Comiso *et al.* 2006, Grebmeier 2012, Richter-Menge 2017) as well as increasing anthropogenic pressures from increased population growth and infrastructure development in Arctic coastal cities.

Benthic processes are tightly linked to pelagic processes (Stasko *et al.* 2018). Warming Arctic air temperatures result in significant losses of sea ice which increases light availability, and greater wind-driven mixing of the water column. This results in higher planktonic primary productivity and less ice algae which can result in changes in the quality and quantity of the food source that reaches the benthos (Roy *et al.* 2015).

These changes could affect the distribution of benthic fauna in different ways. For example, rocky-bottom communities in two Svalbard fjords have experienced a climate-driven regime shift over a 30-year period which saw benthic taxa with boreal affinities expanding along the coast (Kortsch *et al.* 2012). In the North Atlantic, Drinkwater (2006) observed Atlantic fish species (e.g. cod, haddock, herring) moving northward along the west coast of Greenland and Arctic fish species retreating northward during the 1920's and 1930's and this occurred in conjunction with warming air and sea temperatures in the northern North Atlantic and high Arctic and in conjunction with a northward spread of benthic species including the mussel *Mytilus edulis*, and *Asterias* starfish including *Asterias rubens*. In this instance, the author argued that bottom-up processes as a result of increased phytoplankton and zooplankton production were the primary cause of these changes (Drinkwater 2006). Some northern coastal regions have also experienced increased anthropogenic pressure through population growth (e.g. Statistics Canada 2018) and coastal development (e.g. Aarluk Consulting Inc. *et al.* 2005) and these changes also have the potential to influence the composition and distribution of benthic communities which are quick to respond to changes in their environment (Grebmeier 2012). For example, the Centre for Water Resource Studies (2015) examined the impact of waste water effluent on the marine benthos in five arctic communities throughout Nunavut. Near the city of Iqaluit, a city that has experienced a rapidly growing population, annual waste water volume is 552,600 m³/year. As a result, the authors observed anoxic sediments that were devoid of benthic fauna up to 580 m away

from the waste water discharge site based on benthic samples collected with a hand core from shore.

Mapping the distribution of benthic communities is becoming increasingly attainable through the integration of traditional benthic surveys (e.g. *in situ* sampling) with multibeam echosounder (MBES) acoustic technology (Copeland et al 2011). Traditionally, benthic samples are collected for infauna or epifauna to characterize the benthic community at a specific location and time, however, this type of sampling typically covers only a very small sampling area. MBES are capable of surveying large regions of the sea floor to map geophysical characteristics including bathymetry (water depth) and backscatter (acoustic return strength, a proxy for the hardness of the sea bottom; Harris and Baker 2012). Benthic community composition is determined in part by geologic features such as sea floor hardness, substrate type, and other physical characteristics (Kostylev and Hannah 2007, Brown *et al.*, 2011, Copeland *et al.*, 2011). Because benthic fauna are relatively stationary or have limited mobility they are constantly exposed to the surrounding physical environment (Silberberger *et al.* 2019) and they can be sensitive to disturbance and slow to recover (Conlan and Kitvek *et al.* 2005). Marine molluscs in particular are an important component of the ecosystem and perform many important functions such as providing a hard surface for other organisms to attach to (e.g. mussel beds provide a place for algae, barnacles, and anthozoans to settle), providing protection for other organisms (e.g. oyster shell beds provide protection for juvenile species such as *Dungeness crab*), they create complexity and heterogeneity on the sea bottom and help maintain high species richness (Gutierrez *et al.* 2003).

Therefore, changes in the composition and distribution of mollusc communities could have a profound effect on the ecosystem services that molluscs provide (van der Zee *et al.* 2012, Novoa *et al.* 2016). Molluscs often dominate the biomass of nearshore benthic communities (McDonald *et al.* 1981, Feder *et al.* 1994b, Carroll *et al.* 2009, Dame 2012), they are long-lived, living upwards of 30 years (Powell and Cummins 1985), and their shells persist in the marine environment over geological time scales (Aitken 1990, Aitken and Fournier 1992, Gutierrez *et al.* 2003). Molluscs have previously been used as indicators of ecosystem health because of their long lived nature, because they are tolerant to a wide range of environmental conditions and because of the behavioural and physiological responses they display in response to changes in their environment (Dame 2012), thereby making them an excellent group of organisms from which to measure spatial change. By combining *in situ* molluscan community samples with the physical characteristics of the sea bed using MBES data, maps can be produced that demonstrate the potential distribution of the mollusc communities in question from a specific region of interest (e.g. Misiuk *et al.* 2019a). In areas where historical benthic community datasets exist, these modern maps can then be used as a tool from which to measure the extent of spatial change that has already occurred.

Frobisher Bay, located at the southern end of Baffin Island, has experienced significant long-term environmental change and as a result, the molluscan communities of Frobisher Bay have undergone long-term temporal change in community structure and function (Chapter 2). This paper aims to answer whether long-term spatial shifts have also occurred within the mollusc communities of Frobisher Bay. By developing modern

day mollusc community distribution maps using MBES bathymetry and backscatter data from Frobisher Bay, the potential distribution of the modern day mollusc communities can be compared with the observed historical communities to measure the extent of spatial change that has occurred over the past 50 years in this region.

3.2 Methods

3.2.1 Study Area

Frobisher Bay is located in southeastern Baffin Island, Canada. Frobisher Bay reaches depths of 600 m but the inner portion of Frobisher Bay is less than 200 m water depth. Multibeam data was collected throughout Frobisher Bay while benthic samples were collected in less than 100 m water depth and in relatively close proximity to the city of Iqaluit which is located at the head of Frobisher Bay.

3.2.2 Multibeam Data Collection

Multibeam echosounder (MBES) technology uses sound beams to map water depth (bathymetry (m)) and sea bottom roughness/hardness (backscatter (dB)) simultaneously (Harris and Baker 2012). MBES data were collected in Frobisher Bay between 2006-2010 and 2014-2017 from the *CCGS Amundsen* using Kongsberg EM 300 and EM 302 echosounders and between 2012-2016 MBES data was collected from the Nunavut Fisheries Research Vessel *M/V Nulialjuk* using Kongsberg EM 3002 (300 kHz;

2012-2013) and EM 2040C (variable 200-400 kHz; 2014-2016) echosounders (Deering *et al.* 2018). Bathymetry and backscatter rasters were generated from the multibeam data with a 10 m resolution. Complete details for processing of the multibeam data can be found in Deering *et al.* (2018) and Misiuk *et al.* (2019b).

3.2.3 Benthic Sampling and Mollusc Identification

Sediment and benthic infaunal samples at eleven stations were collected between July and October 1967-1976 onboard the M.V. *Calanus* by the Arctic Biological Station using a Petersen Grab (surface area 0.065 m²; Wacasey 1979, 1980). Detailed sampling methodology for the historical samples can be found in Wacasey *et al.* (1979, 1980). These stations were re-sampled in 2016. On July 16, 2016 one box core sample (station 5e) was collected (surface area 0.125 m²) onboard the CCGS *Amundsen* and between October 10-14, 2016 the remaining stations were sampled onboard the MV *Nulialjuk* using a Van Veen grab (surface area 0.111 m²). Five stations were located near the city of Iqaluit herein referred to as the “Iqaluit” stations and six stations were located near Cairn Island herein referred to as the “Cairn Island” stations (Figure 3.1). Up to six grab samples were collected and pooled at each station for samples collected between 1967-1976. In 2016, up to three grabs samples were collected at each station and pooled in order to be comparable with the historical samples. All historical and modern samples were collected between July and October when Frobisher Bay was ice free. Replicate infaunal samples were washed over a 0.5 mm sieve (the 2016 box core sample was

washed over a 1.0 mm sieve). Organisms were fixed in 10% buffered formalin for 24 hours then transferred to 70% ethanol for longer term preservation. Molluscs were identified to the lowest taxonomic level possible with 84.6% of individuals from the historical samples identified to the species level and 79.5% of individuals from the modern samples identified to the species level. Table 3.1 summarizes the sampling effort for both the historical and modern samples.

3.2.4 Data Analysis

The historical samples were reported by Wacasey *et al.* (1979, 1980) as number of individuals per m² and for comparison, the modern mollusc samples were reported in the same way. The historical and modern mollusc samples were combined into a single spreadsheet and the dataset was standardized to percent total abundance to minimize the influence of differences in sampling methods between the historical and the modern samples (See Appendix 9 for complete dataset used in analysis). In this way, the dataset reports the proportion of each species contributing to a given community and ignores large differences in absolute abundance that may be attributed to sampling effort. Non-metric multidimensional scaling (nMDS) plots and dendograms were generated using PRIMER v6 (Clarke and Gorley 2006) to visualize the distribution of unique molluscan communities. Square-root and presence/absence transformations were applied to determine whether species abundance structure had an influence on the composition of molluscan communities.

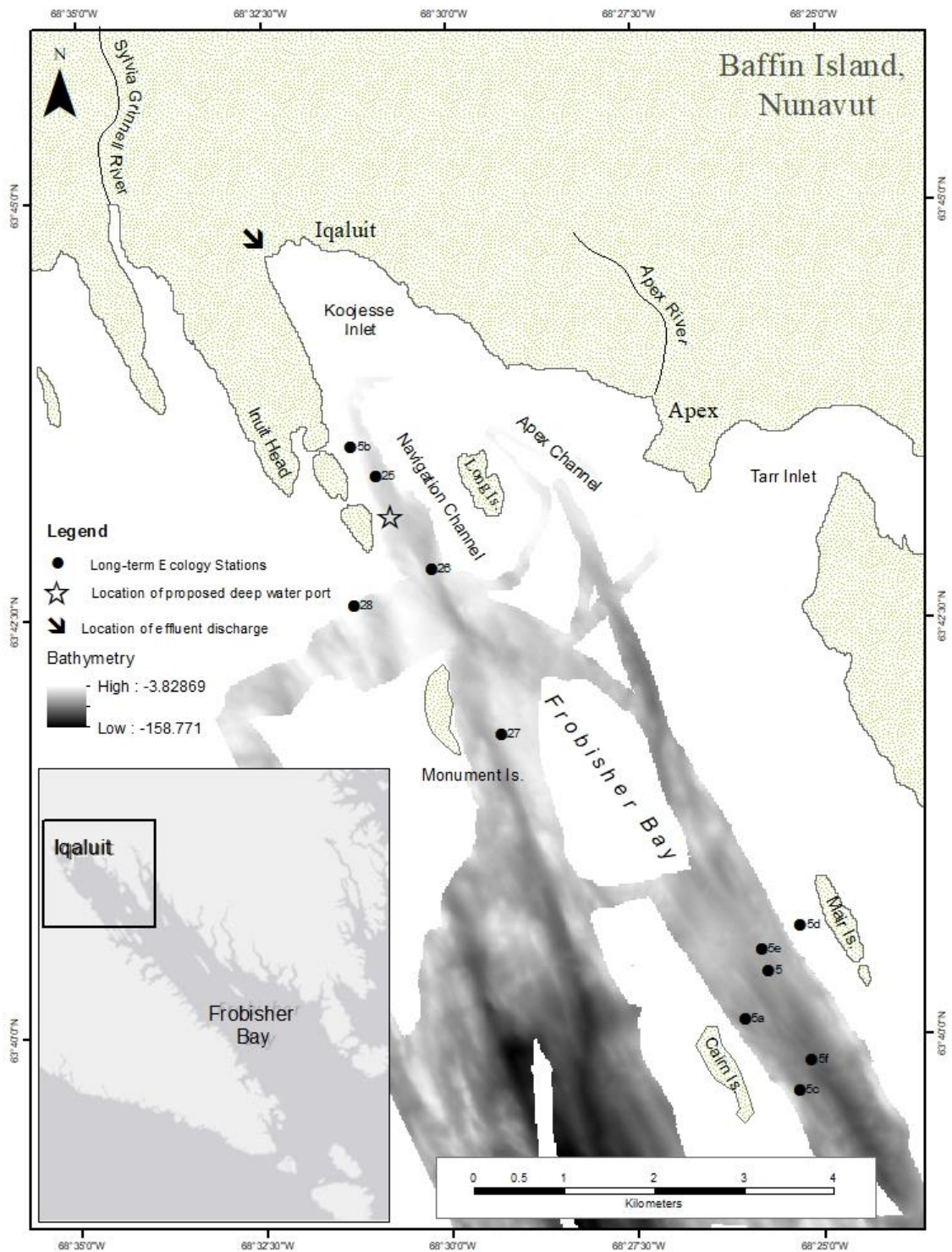


Figure 3.1. Long-term ecology stations sampled in Frobisher Bay, Nunavut between 1967-1976 and in 2016.

Table 3.1. Summary of sampling effort for benthic infaunal samples collected by Van Veen grab and box core in Frobisher Bay between 1967-1976 and in 2016.

Station	Date	No. Replicates Pooled	Total Surface Area of Pooled Samples (m ²)	Water Depth (m)	Latitude (DD)	Longitude (DD)		
					Rep. 1 ¹	Rep. 1 ¹		
5b	Jul-29-1969	6	0.390	15	63.7256	-68.5218		
	Sep-3-1969	6	0.390	15				
	Aug-8-1973	5	0.330	14				
	Aug-19-1976	5	0.330	14				
	Oct-10-2016	3	0.072	15.4			63.7255	-68.5209
25	Aug-8-1973	5	0.330	30	63.7227	-68.5162		
	Aug-18-1976	5	0.330	28				
	Oct-10-2016	3	0.333	28.5			63.7227	-68.5163
26	Aug-8-1973	5	0.330	40	63.7134	-68.5039		
	Oct-10-2016	3	0.333	37.8			63.7128	-68.5031
27	Aug-8-1973	5	0.330	43	63.7098	-68.5214		
	Oct-10-2016	3	0.333	33.1			63.6969	-68.4892
28	Aug-13-1973	4	0.250	30	63.6969	-68.4885		
	Oct-10-2016	3	0.218	11.5			63.71	-68.5211
5	Jul-23-1968	6	0.390	45	63.6731	-68.4289		
	Aug-20-1968	6	0.390	60				
	Sep-3-1968	6	0.390	60				
	Oct-8-1968	6	0.390	62				
	Aug-6-1970	6	0.390	72				
	Oct-11-2016	3	0.278	58.6			63.6729	-68.4294
5a	Aug-1-1968	6	0.390	26	63.6683	-68.4342		
	Aug-20-1968	6	0.390	32				
	Oct-14-2016	3	0.333	70			63.6683	-68.4336
5c	Aug-23-1969	6	0.390	31	63.6611	-68.422		
	Oct-11-2016	3	0.333	77.2			63.6611	-68.4216
5d	Aug-23-1969	6	0.390	43	63.6776	-68.4216		
	Oct-11-2016	3	0.333	27			63.6776	-68.4209
5e	Aug-23-1969	6	0.390	58	63.6752	-68.4304		
	Oct-11-2016	3	0.305	55.4			63.6757	-68.4303
	Jul-16-2016(Box)	3	0.375	63			63.6752	-68.4304
5f	Aug-23-1969	6	0.390	73	63.6642	-68.4195		
	Oct-11-2016	2	0.167	90.1			63.6639	-68.4196

¹Latitude and Longitude of the historical samples reflect the georeferenced historical sample locations. Latitude and longitude of the modern samples reflect the first of three replicate samples. See Appendix 1 for complete list of all replicate samples collected.

The presence/absence transformation compared the historical and modern communities based solely on species presence while the square-root transformation put more emphasis on the contribution of each species in the community with regards to its abundance. Initial data exploration indicated that the 4th root transformation produced similar results as the square-root transformation therefore the less severe transformation was used. Rare species were not removed from the dataset prior to the presence/absence and square-root transformations being applied as preliminary data exploration indicated that their removal did not influence the natural groupings of stations. Analysis of similarities (ANOSIM) was performed using PRIMER v6 to confirm that the groups of stations were significantly different from each other and these groups were assigned the designations “*Community I, II, III, etc.*” for the square-root transformed analysis and “*Community A, B, C, etc.*” for the presence/absence analysis. Similarity percentage analysis (SIMPER) was performed on each community to identify the dominant species contributing most significantly to within community similarity.

Water depth is well known to be one of the most important variables that structures benthic communities (Piepenburg *et al.* 1996, Piepenburg and Schmid 1996, Jones *et al.* 2007, Soltwedel *et al.* 2009, Bluhm *et al.* 2011, Roy *et al.* 2014, Vedenin *et al.* 2018). Therefore, general linear models were developed using the non-transformed pooled sample data for species richness (R), species diversity (H'), species evenness (J'), and for sediment grain size composition using the statistical program RStudio to determine whether these indices changed significantly with increasing water depth and to help explain unique community observations. Violation of model assumptions were

examined by testing for homogeneity of variance, independence, and normality (Zuur *et al.* 2010).

3.2.5 Distribution Maps of Modern Mollusc Communities

Maps that demonstrate the “potential distribution” of each modern community reflected in the square-root transformed analysis and the presence-absence analysis were produced using the spatial analysis package in ESRI ArcMap version 10.4.1. Figure 3.2 demonstrates the workflow followed to produce the maps of the potential distribution of each community.

The first steps in developing maps that highlight the potential distribution of the modern mollusc communities involved determining the sample area around each station from which the range of bathymetry and backscatter values could be used to characterize the physical characteristics of seabed habitats occupied by mollusc communities. This was important because replicate samples at each station were not collected in the exact same sampling location and therefore there was some variation in water depth (bathymetry) and sediment reflectivity (backscatter) between the replicate samples. Because the mollusc communities were identified based on pooled replicate samples, the physical characteristics of the sea bottom for each station needed to encompass the characteristics of all replicate samples.

First, the “mean center” (e.g. the geographic centre between three replicate samples) of each of the 11 stations was determined based on the triplicate samples collected at each station (Step 1; Figure 3.2). Next, the distance between mean center and each replicate sample at each station was measured using the “measure” tool to obtain a distance measurement (Step 2; Figure 3.2). This step was completed to define a sampling error distance given that each replicate sample was not collected in the exact same location. The greatest sampling error distance that was measured among all the stations was 61 m and this distance was used to draw an error buffer around the mean-center at each station using the “buffer” tool (Step 3; Figure 3.2). In this way, there was a buffered area of 61 m around the mean centre of each station that encompassed all replicate samples. The “extract by mask” tool was then used to extract the bathymetry and backscatter raster values within the buffered regions (Step 4; Figure 3.2) and the “raster to point” tool was used to convert the values of each raster cell to a point value (Step 5; Figure 3.2). The range of bathymetry and backscatter values from the buffered regions were then recorded for each modern station and boxplots were produced using the square-root transformed and presence/absence communities to display the range of bathymetry and backscatter values for each community observed.

The raster calculator was then utilized to determine the distribution of the different communities based on their bathymetry and backscatter values (Step 6; Figure 3.2). The minimum and maximum bathymetry and backscatter values for each modern mollusc community were included in the raster calculator using the equation:

Potential Community Distribution for Community X = Con(Backscatter $\geq a$) &
(Backscatter $\leq b$) & (Bathymetry $\geq c$) & (Bathymetry $\leq d$), 1,0)

Where X represents identified communities A, B, C, D (presence/absence analysis), or I, II, III, IV, V, VI (square-root transformed analysis), where *a*, *b*, *c*, *d* represent the minimum or maximum bathymetry or backscatter values for each community and where *Con* referred to the condition being examined. The minimum and maximum bathymetry and backscatter values were used rather than the interquartile range because at some stations, the bathymetry and backscatter values for specific replicate samples fell outside the interquartile range and these values were included by using the minimum and maximum values. This calculation was run for each modern mollusc community (square-root and presence/absence transformation method) and maps were produced that demonstrate the potential distribution for each community using both transformation methods. The historical communities were then added to the maps as point values to identify the direction of any spatial shifts that had occurred in the mollusc communities over time. The total coverage area of each modern community using the abundance structure community data and the total coverage area of each modern community using the composition community data was determined. The total area of overlap between any two mollusc communities was determined using the “clip” tool in ArcMap where one mollusc community was clipped to another where there was overlap between the two communities. These values were converted to a “proportion of coverage” and “proportion

of overlap” to determine the relative size and relative overlap of each modern community compared to the others.

The resulting maps that were produced through the mapping processes include a single biotope map that demonstrates the distribution of the modern communities while the other two maps produced are deconstructed biotope maps with the historical communities added as points (where the historical samples were collected) in order to identify the extent of spatial change over time of each community. These maps were produced based on the square-root transformed and presence-absence transformed molluscan community data.

3.3 Results

Twenty historical pooled samples representing twelve stations were collected between 1967 and 1976 and these were compared with thirty one grabs and three box core samples that were pooled to represent eleven stations collected in 2016 to identify whether any spatial shifts in community structure had occurred over a period of fifty years in inner Frobisher Bay, Nunavut. Sixty-four mollusc species (22 bivalves and 42 gastropods) were identified in the historical samples in water depths ranging between 14 and 72 m compared to fifty-one mollusc species (24 bivalves and 27 gastropods) observed in the modern samples in water depths ranging between 11.5 m and 90.1 m (Chapter 2).

3.3.1 MBES Coverage

Only a small portion of the large bathymetry and backscatter multibeam echosounder raster dataset that was collected in Frobisher Bay was used in this study. The total area included in this analysis covered an area of 30.35 km². The bathymetry (water depth in meters) of the study region ranged from 3 m to 158 m water depth with water depths less than 60 m found at the Iqaluit stations and water depths greater than 40 m found at the Cairn Island stations (Figure 3.3a). Backscatter values ranged from -18.67 to -39.01 dB (Figure 3.3b).

Misiuk *et al.* (2019b) previously characterized the sediments in the Iqaluit region as gravelly muddy sand ((g)mS), gravelly sandy mud ((g)sM), and muddy sand (mS) while in the Cairn Island region the sediments were characterized as gravelly sandy mud (g)sM. Grain size composition in the Iqaluit region was different from the grain size composition in the Cairn Island region but only the Cairn Island region experienced a temporal change in grain size composition (Chapter 2). Deering *et al.* (2018) noted that the MBES data indicated that the Iqaluit region (including Iqaluit stations 5b, 25, 26, 27, and 28) had previously been subjected to sea ice scouring. In this study, the proportion of sand in the sediment was found to significantly decrease with water depth while the proportion of silt in the sediment significantly increased with water depth ($F = 24.52$; $p = 1.46e^{-5}$; Figure 3.4).

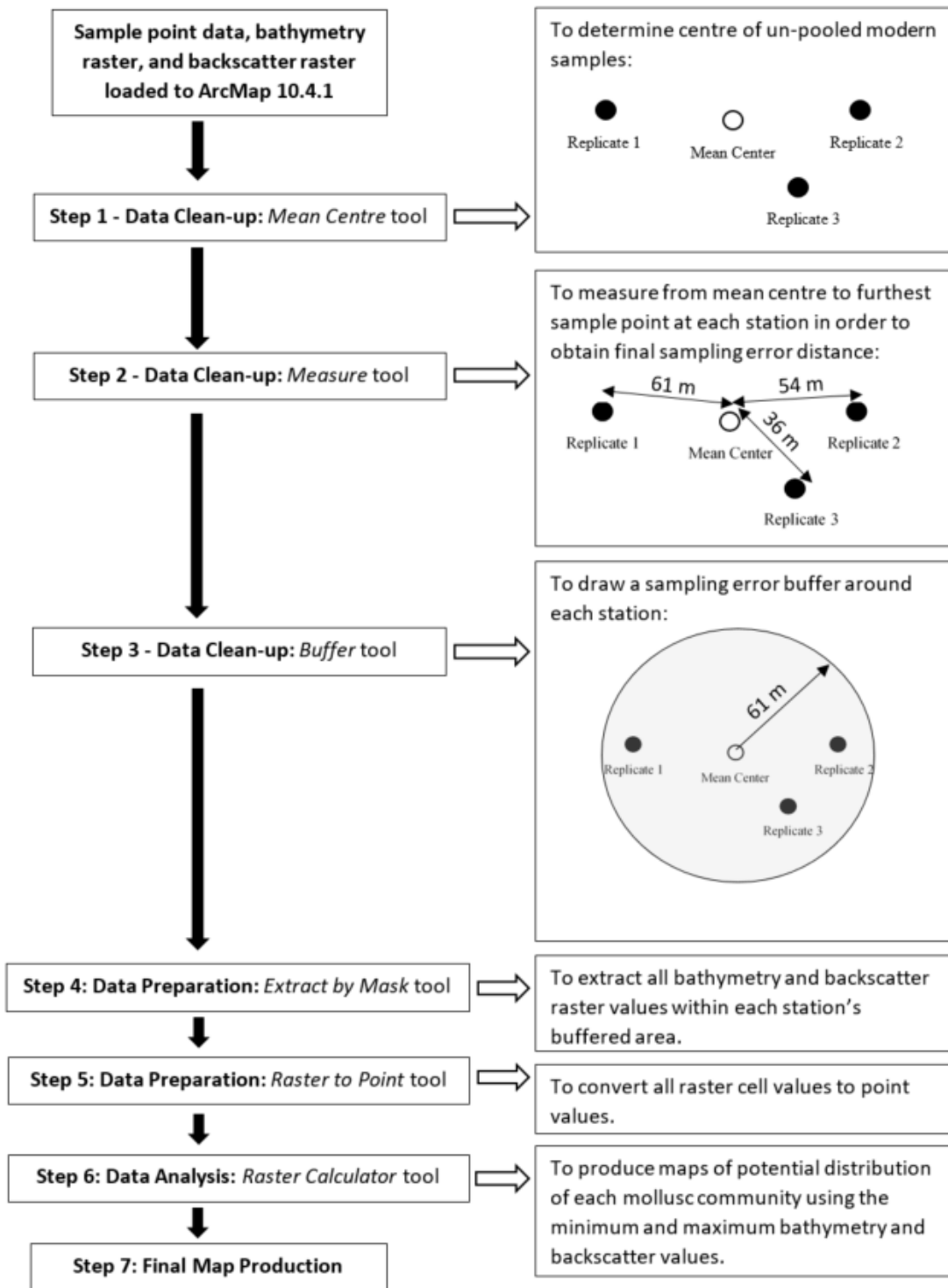


Figure 3.2. Flow chart outlining the steps and ESRI ArcMap tools utilized in production of maps that demonstrate the potential distribution of the molluscan communities observed in Frobisher Bay.

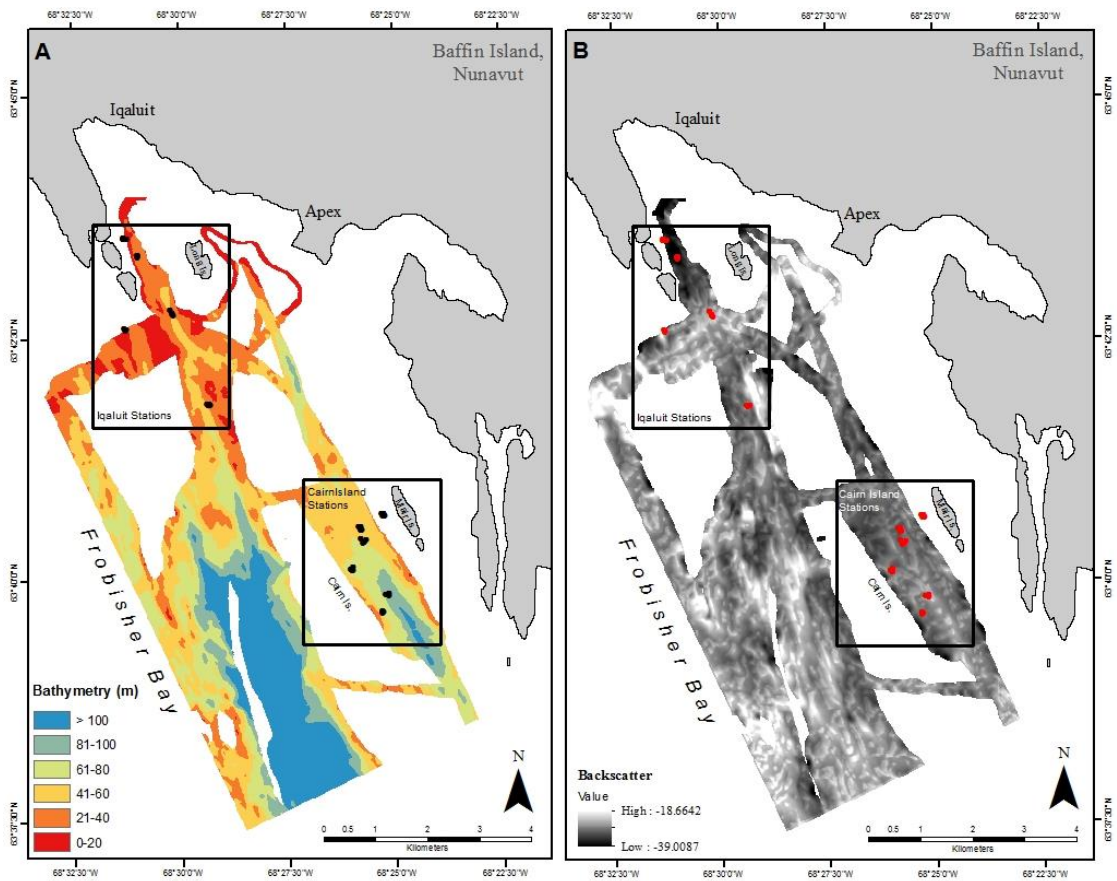


Figure 3.3. Bathymetry (a) and backscatter (b) coverage of study area in inner Frobisher Bay, Nunavut including the location of mollusc samples collected between 1967-1976 and in 2016 (black and red dots).

3.3.2 Mollusc Communities

Species richness (R) did not significantly increase with water depth but species diversity (H' ; $F = 19.33$; $p < 0.001$) and species evenness (J' ; $F = 21.08$; $p < 0.001$) did significantly increase with water depth (Figure 3.4).

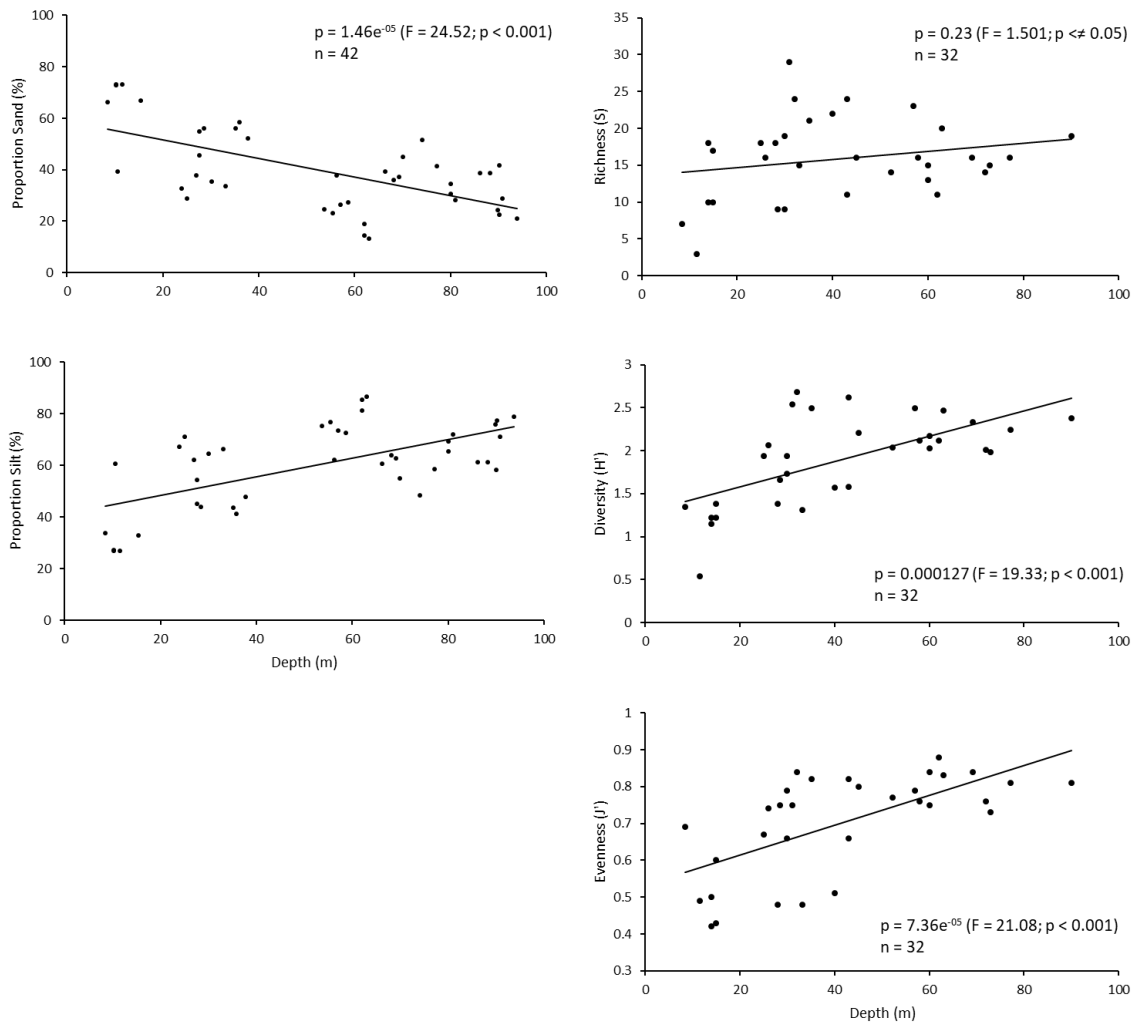


Figure 3.4. Changes observed in sediment characteristics, species richness, species diversity, and species evenness with water depth for samples collected in 2016 in Frobisher Bay.

Analysis of Similarities (ANOSIM) confirmed that the 6 groupings of stations identified using the abundance structure community data were significantly different from each other (Global $R = 0.868$; all pairwise tests with $p < 0.05$; Figure 3.5ab; Table 3.2). SIMPER analysis identified the percent similarity observed among each grouping

which ranged between 41.49 – 66.16% similarity and these groupings were assigned the Community designations I-IV based on the mollusc species that contributed most significantly to each assemblage (Table 3.2).

Four of the six communities (Community I, II, III, and IV) were dominated by the thyasirid bivalve *Thyasira gouldi* with small differences in the remaining associated species observed. Community I also contained the small to medium bivalves *Ennucula tenuis* and *Nuculana pernula*, and the small gastropod *Cylichna alba*, Community II also contained the small to medium bivalve *Ennucula tenuis*, Community III also contained the small to medium bivalves *Ennucula tenuis* and *Musculus discors* and Community IV also contained the small to medium bivalves *Musculus discors*, *Nuculana minuta*, and the small gastropod *Margarites olivaceus*. Comparatively, Community V was dominated by the thyasirid bivalve *Axinopsida orbiculata* and the small gastropod *Cylichna alba* only and VI was dominated by only the thyasirid bivalve *Axinopsida orbiculata*.

Analysis of similarities (ANOSIM) confirmed that the 4 groupings of stations identified using the composition community data were significantly different from each other (ANOSIM; Global R = 0.752; all pairwise tests with $p < 0.05$; Figure 3.5cd; Table 3.2). SIMPER analysis confirmed the percent similarity observed among each grouping which ranged between 20-59.71% similarity and these groupings were assigned the Community designations A-D based on the mollusc species that contributed most significantly to each assemblage (Table 3.2).

Community A was primarily composed of two small thyasirid bivalves *Axinopsida orbiculata* and *Thyasira gouldi*, a small gastropod *Cylichna alba*, and some medium sized bivalves *Ennucula tenuis* and *Macoma calcarea*. Community B and Community C were both represented by the thyasirid bivalve *Thyasira gouldi* and otherwise contained small to medium sized bivalves with Community B also represented by the bivalves *Ennucula tenuis*, *Nuculana pernula*, *Yoldia hyperborea*, *Macoma moesta* and the small gastropod *Cylichna alba* as well as other molluscs to a lesser degree and Community C was represented by the bivalves *Hiatella arctica*, *Musculus discors*, *Nuculana minuta*, and *Ennucula tenuis* and many other molluscs to a lesser degree. Finally, Community D was represented only by the small thyasirid bivalve *Axinopsida orbiculata*.

3.3.3 Mollusc Community Distribution

Despite community differences between the square-root transformed data and the presence/absence transformed data, the modern mollusc samples grouped together in the same way indicating that these transformations did not alter the modern mollusc community composition. Only the historical samples exhibited some differences between transformation methods. Community A corresponded with Community V, Community B corresponded with Community I, Community C corresponded with Community II, and

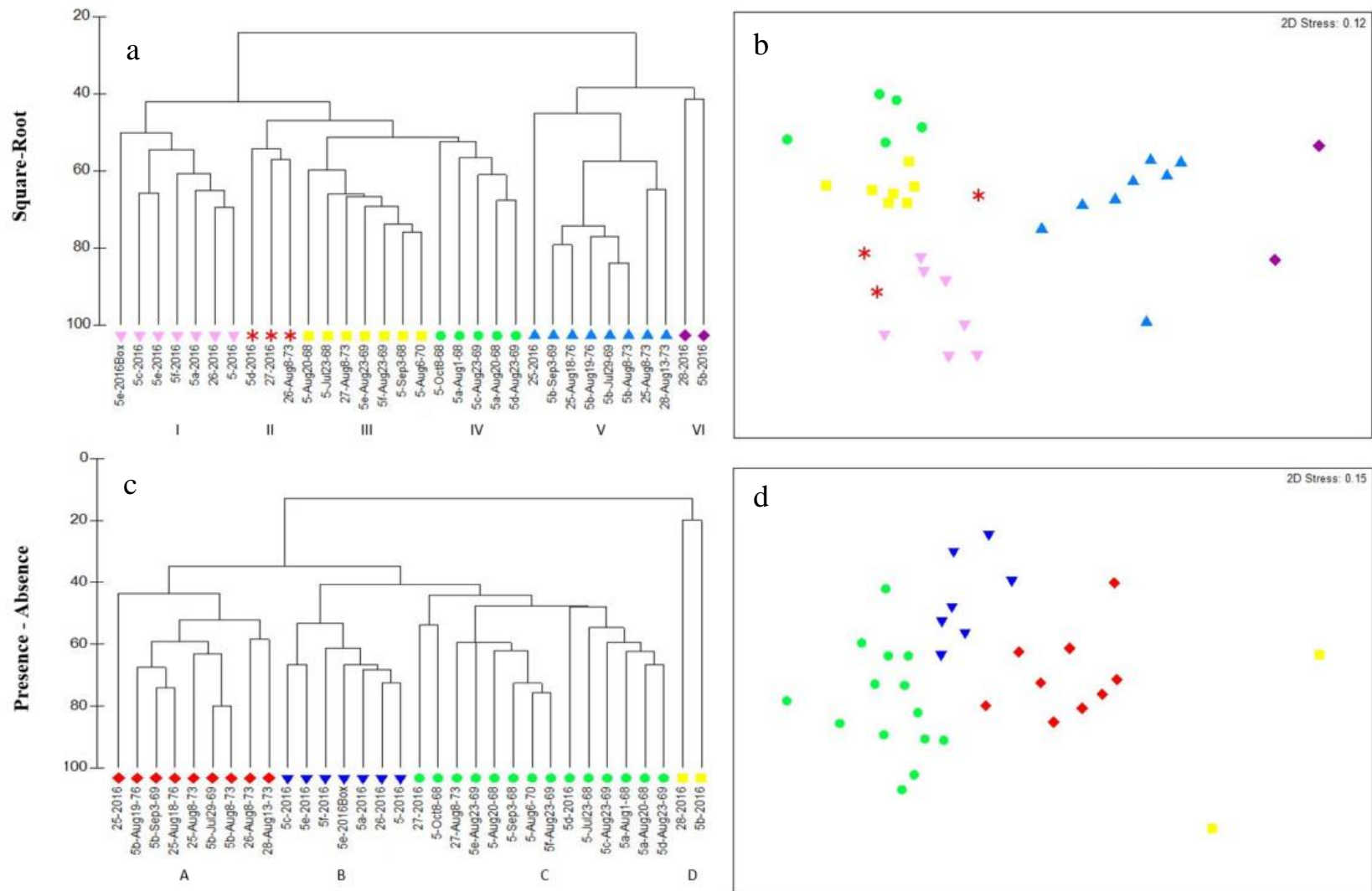


Figure 3.5. Mollusc communities identified through nMDS (non metric Multidimensional Scaling) and associated dendrogram resulting from presence-absence and square-root transformed analyses.

Table 3.2. Mollusc community descriptions as identified through SIMPER (Similarity Percentages) analysis based on nMDS of presence/absence and square-root transformed benthic community data.

Community	Global R	Percent Similarity Among Samples Within Each Community (%)	Species Contributing to Similarity Within Each Community (% Contribution)
<i>Presence/Absence transformed analysis</i>			
A	0.752	55.09	<i>Axinopsida orbiculata</i> (13.03%), <i>Ennucula tenuis</i> (13.03%), <i>Cylichna alba</i> (13.03%), <i>Macoma calcarea</i> (10.39%), <i>Thyasira gouldi</i> (9.59%), <i>Retusa obtusa</i> (9.59%), <i>Philine lima</i> (6.71%), <i>Astarte borealis</i> (4.51%), <i>Curtitoma violácea</i> (3.55%), <i>Macoma moesta</i> (3.04%), <i>Serripes groenlandicus</i> (2.37%), <i>Yoldia hyperborea</i> (1.93%)
B		59.71	<i>Ennucula tenuis</i> (9.19%), <i>Nuculana pernula</i> (9.19%), <i>Thyasira gouldi</i> (9.19%), <i>Yoldia hyperborea</i> (9.19%), <i>Cylichna alba</i> (9.19%), <i>Macoma moesta</i> (6.61%), <i>Hiatella arctica</i> (6.42%), <i>Musculus niger</i> (6.42%), <i>Cryptonatica affinis</i> (4.29%), <i>Macoma calcárea</i> (4.05%), <i>Macoma loveni</i> (2.7%), <i>Frigidoalvania cruenta</i> (2.69%), <i>Margarites helycinus</i> (2.61%), <i>Astarte borealis</i> (2.61%), <i>Astarte montagui</i> (2.41%), <i>Musculus discors</i> (2.31%), <i>Serripes groenlandicus</i> (1.38%)
C		50.59	<i>Thyasira gouldi</i> (12.13%), <i>Hiatella arctica</i> (10.38%), <i>Musculus discors</i> (10.33%), <i>Nuculana minuta</i> (10.33%), <i>Ennucula tenuis</i> (10.09%), <i>Cylichna alba</i> (10.09%), <i>Dacrydium vitreum</i> (4.79%), <i>Margarites olivaceus</i> (4.47%), <i>Lepeta caeca</i> (3.6%), <i>Mya truncata</i> (3.3%), <i>Musculus niger</i> (2.94%), <i>Nuculana pernula</i> (2.16%), <i>Ciliatocardium ciliatum</i> (1.38%), <i>Euspira pallida</i> (1.37%), <i>Macoma moesta</i> (1.27%), <i>Velutina velutina</i> (1.23%), <i>Margarites umbilicalis</i> (1.2%)
D		20.00	<i>Axinopsida orbiculata</i> (100.0%)
<i>Square-root transformed analysis</i>			
I	0.868	56.43	<i>Thyasira gouldi</i> (23.49%), <i>Ennucula tenuis</i> (10.74%), <i>Nuculana pernula</i> (9.86%), <i>Cylichna alba</i> (7.52%), <i>Yoldia hyperborea</i> (7.24%), <i>Macoma moesta</i> (6.25%), <i>Hiatella arctica</i> (5.73%), <i>Musculus niger</i> (4.42%), <i>Cryptonatica affinis</i> (2.85%), <i>Macoma calcárea</i> (2.74%), <i>Frigidoalvania cruenta</i> (2.26%), <i>Macoma loveni</i> (2.11%), <i>Musculus discors</i> (1.95%), <i>Astarte montagui</i> (1.85%), <i>Astarte borealis</i> (1.71%)
II		55.22	<i>Thyasira gouldi</i> (43.93%), <i>Ennucula tenuis</i> (12.14%), <i>Cylichna alba</i> (9.62%), <i>Hiatella arctica</i> (8.96%), <i>Lepeta caeca</i> (6.1%), <i>Macoma moesta</i> (5.73%), <i>Nuculana pernula</i> (5.63%)

III	66.16	<i>Thyasira gouldi</i> (26.82%), <i>Ennucula tenuis</i> (14.5%), <i>Musculus discors</i> (13.71%), <i>Nuculana minuta</i> (10.3%), <i>Hiatella arctica</i> (10.11%), <i>Dacrydium vitreum</i> (9.75%), <i>Cylichna alba</i> (7.0%)
IV	56.96	<i>Thyasira gouldi</i> (21.01%), <i>Musculus discors</i> (12.89%), <i>Nuculana minuta</i> (9.48%), <i>Margarites olivaceus</i> (9.34%), <i>Hiatella arctica</i> (7.98%), <i>Mya truncata</i> (6.07%), <i>Ennucula tenuis</i> (5.74%), <i>Margarites umbilicalis</i> (2.78%), <i>Astarte montagui</i> (2.72%), <i>Cylichna alba</i> (2.66%), <i>Anatoma crispata</i> (2.66%), <i>Lepeta caeca</i> (2.61%), <i>Erginus rubellus</i> (2.11%), <i>Margarites vahli</i> (1.84%), <i>Tachyrhynchus reticulatus</i> (1.48%)
V	61.4	<i>Axinopsida orbiculata</i> (38.55%), <i>Cylichna alba</i> (15.13%), <i>Ennucula tenuis</i> (11.08%), <i>Thyasira gouldi</i> (19.91%), <i>Retusa obtusa</i> (10.21%), <i>Macoma calcarea</i> (3.25%), <i>Philine lima</i> (3.21%)
VI	41.49	<i>Axinopsida orbiculata</i> (100.0%)

Community D corresponded with Community VI. Community III and IV were represented by historical samples only. Community I(B) covered the largest area with 12.2 km² (40.0%) coverage while community II(C) covered 1.6 km² (5.2%) of the study region. Community I(B) and II(C) shared 8.15% overlap. The remaining modern community coverage was very small. Community V(A) covered only 0.066 km² (0.2%) and community VI(D) covered 0.81 km² (2.7%). Community III and IV had no coverage on the modern map because these communities represented historical samples only. 15.7% of the study area was unclassified and this was primarily due to water depth as no benthic communities were sampled in depths greater than 90 m (Table 3.3).

Table 3.3. Summary of benthic community coverage in Frobisher Bay.

Community¹	Coverage in Study Region (km²)	Proportion of Community in Study Region (%)	Proportion of Overlap between Communities (%)
Community I (B)	12.22	40.26	8.15 (II/C)
Community II (C)	1.566	5.160	8.15 (I/B)
Community III	0.000	0.000	0.00
Community IV	0.000	0.000	0.00
Community V (A)	0.066	0.220	0.00
Community VI (D)	0.812	2.680	0.00
Total Area of Study Region	30.35	--	--
Unclassified Area	15.69	--	--

¹Roman numerals refer to communities that were subject to square-root transformation and letter designations refer to communities that were subject to presence-absence transformation.

There was only minimal overlap in bathymetry (water depth) for each of the modern communities. Community I(B) exhibited the greatest depth range from 34.0 m to

90.7 m, Community II(C) ranged from 21.5 m to 46.5 m, Community V(A) ranged from 22.4 m to 33.7 m and Community VI(D) was shallowest and ranged from 10.8 m to 21.7 m. Backscatter ranges were narrow with overlap occurring at three of the four communities. Community I(B) ranged from -29.5 to -26.6 dB, Community II(C) ranged from -28.8 to -27.6 dB, and Community VI(D) ranged from -31.9 to -25.9 dB. Community V(A) did not overlap with the other communities and ranged from -34.7 to -32.0 dB (Table 3.4; Figure 3.6).

Table 3.4. Range of bathymetry and backscatter values used to determine modern mollusc community spatial distribution in Frobisher Bay.

Mollusc Community	Bathymetry (m)		Backscatter (dB)	
	Minimum	Maximum	Minimum	Maximum
Community I (B)	-90.6590	-34.0273	-29.4620	-26.6174
Community II (C)	-46.0.502	-25.0854	-28.7573	-27.6316
Community III ¹	--	--	--	--
Community IV ¹	--	--	--	--
Community V (A)	-33.6928	-22.4053	-34.6992	-32.0107
Community VI (D)	-21.7119	-10.8321	-31.9744	-25.8811

¹Community III and IV were not mapped as these communities were not present in the modern samples.

The resulting biotope map of the modern mollusc communities observed in inner Frobisher Bay demonstrated a spatial shift in the composition of the molluscan communities and their preferred habitat (Figure 3.7). Community I/B is characteristic of a mixed small bodied bivalve and gastropod community that is sensitive to or indifferent

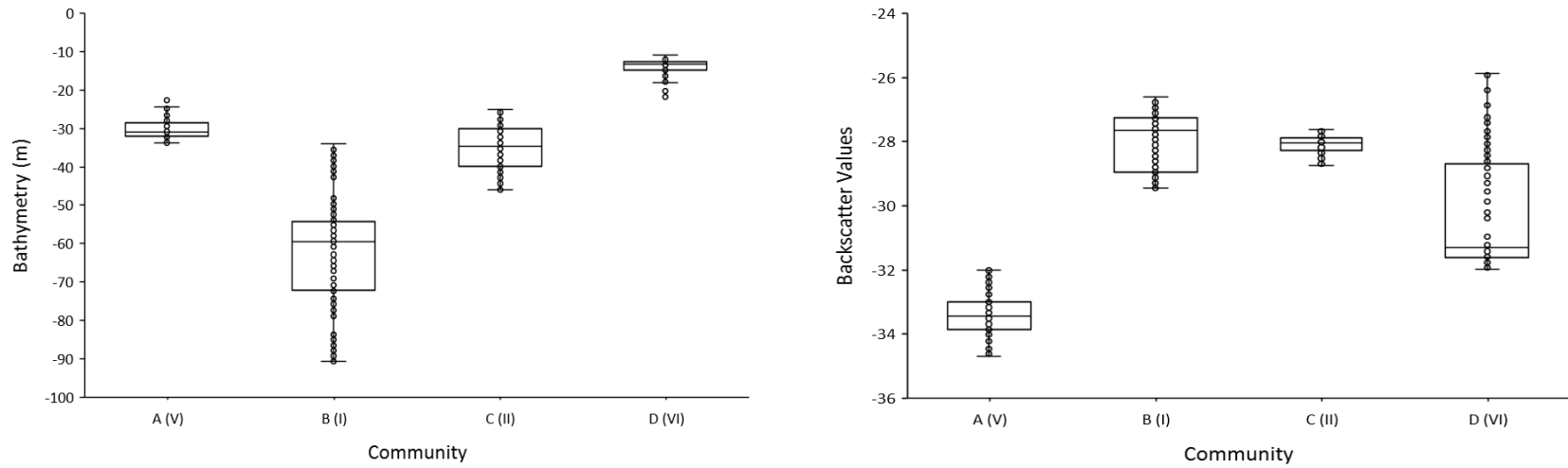


Figure 3.6. Range of bathymetry and backscatter values associated with each modern mollusc community in Frobisher Bay for the presence-absence and square-root transformed analyses.

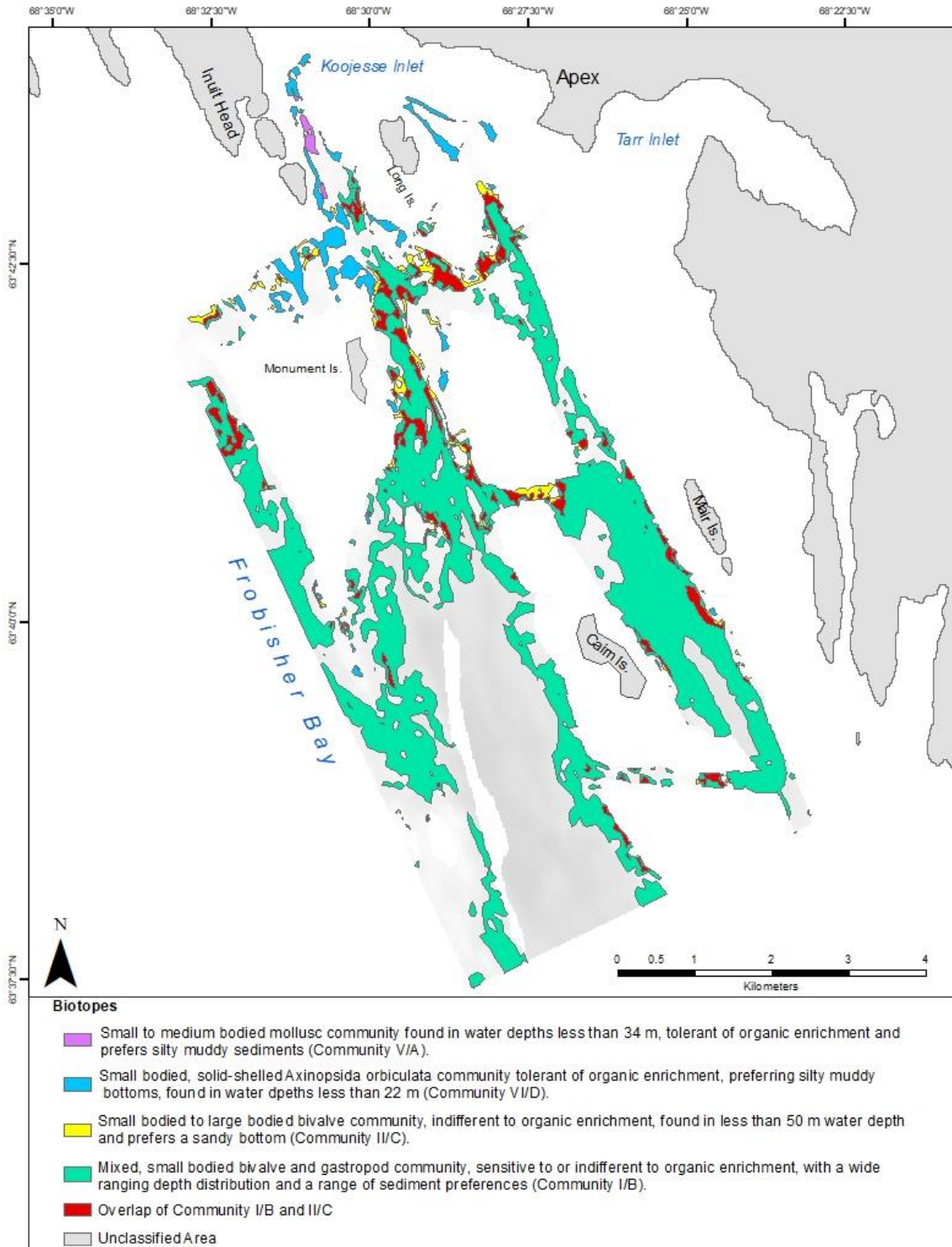


Figure 3.7. Biotope map of the molluscan communities observed in inner Frobisher Bay in 2016. Coverage area of each biotope is derived from multibeam bathymetry and backscatter datasets from the study area.

to organic enrichment, with a wide ranging depth distribution and a range of sediment types. Community II/C is characteristic of a small bodied to large bodied bivalve community that is indifferent to organic enrichment, found in less than 50 m water depth, and prefers a sandy bottom. Community V/A is characteristic of a small to medium sized bivalve community found in water depths less than 34 m that is tolerant of organic enrichment and prefers silty muddy sediments, and Community VI/D is characteristic of a small bodied solid-shelled *Axinoposida orbiculata* community that is tolerant of organic enrichment, prefers silty muddy bottoms, and is found in water depths less than 22 m.

3.3.4 Mollusc Community Spatial Shifts (Square-Root Transformation)

Six mollusc communities (I, II, III, IV, V, and VI) were observed in the square-root transformed multivariate analysis. Historically, the mollusc communities were represented by four communities: Communities II, III, IV, and V. Fifty years later, there were still four mollusc communities present but two historical communities had been lost (Community III and IV) and two new communities had been gained (Community I and VI; Table 3.5; Figure 3.8).

Community I and Community VI experienced expansion of their potential distribution as both of these communities had not been observed historically but were observed in the modern samples. Community I exhibited a wide ranging distribution throughout the study area with a more limited presence in the shallower regions of inner Frobisher Bay. The functional traits exhibited by this modern community included molluscs that were either very sensitive to disturbance or indifferent

to disturbance, were suspension feeders, had small to large or large body sizes and preferred a range of sediment types (based on stations 26, 5, 5a, 5c, 5e, and 5f that represented modern Community I; Chapter 2). Community VI demonstrated a greater distribution throughout the Iqaluit region with only a small presence in other regions of the study area (Figure 3.8). The functional traits exhibited by this modern community included molluscs that were tolerant of disturbance, had solid/robust/thick shells, preferred silt/mud, were deposit feeders, and had a small body size (based on stations 5b and 28 that represented modern Community VI; Chapter 2).

Community II expanded and shifted further out into Frobisher Bay over time (Figure 3.8). Historically, Community II was found only at station 26 which was located relatively close to Iqaluit. This community was lost at historical station 26 but appeared at modern station 27 (located part way between the Iqaluit stations and Cairn Island stations) and station 5d (located near Mair Island). When historical station 26 transitioned from Community II to Community I the bivalve *Nuculana pernula* and the gastropod *Cylichna alba* became more important contributors to within community similarity at Community I along with *Ennucula tenuis* while *Thyasira gouldi* contributed less (Table 3.5). Historically, the area covered by modern Community II was characteristic of functional traits that included bivalves that overall were indifferent to disturbance, preferred sandy bottoms, had thin/fragile/brittle shells, and had medium-large body size (based on historical station 26 which once represented Community II; Chapter 2). The change in functional traits in Community II was subtle as the modern functional trait characteristics of community II were also represented by similar trait characteristics as historical Community II. Modern Community II indicates the bivalve species may have a

slightly stronger affinity to be scavengers than they previously had (based on modern station 27 and 5d that now represents this community; Chapter 2).

Community III represented historical stations 27, 5, 5e, and 5f which were located between Iqaluit and Cairn Island and the area between Cairn Island and Mair Island. Community IV represented historical stations 5a, 5c, and 5d, which were located solely in the Cairn Island region. The potential distribution of both Community III and IV was reduced as these communities were completely absent in the modern samples (Table 3.5; Figure 3.8). Historical Station 27 experienced a loss of *Musculus discors* when it shifted from Community III to Community II and historical stations 5, 5e, and 5f experienced a loss of *Musculus discors* and the gain of *Nuculana pernula* and slight increase in *Cylichna alba* when these stations shifted from Community III to Community I. Historical stations 5a, 5c, and 5d experienced a loss of *Nuculana minuta* and *Margarites olivaceus* when these communities shifted away from Community IV. The functional trait characteristics that historically represented these communities were lost, though some semblance of these communities was retained due to the widespread coverage of Community I.

Community V was present in the shallowest stations in the Iqaluit region including station 5b, 25, and 28. The distribution of Community V was reduced over time as this community only persisted in the area surrounding station 25 (Table 3.5; Figure 3.8). When station 5b and 28 transitioned to Community VI, the thyasirid bivalve *Axinopsida orbiculata* and the gastropod *Cylichna alba* were reduced while the thyasirid bivalve *Thyasira gouldi* and the bivalves *Musculus discors* and *Nuculana minuta* were

gained. Historically, the area covered by modern Community V was characteristic of functional traits that included molluscs that were tolerant of disturbance, had solid/robust/thick shells, preferred silt/mud, were deposit feeders, and had a small body size (based on stations 5b, 25 and 28 that historically represented Community V; Chapter 2). The change in functional traits in Community V were very slight with the modern community represented by molluscs that very strongly exhibit the trait characteristics of being tolerant to disturbance, having small body size, preferring silt/mud sediments, and being deposit feeders (based on modern 26 that now represents this community; Chapter 2).

3.3.5 Mollusc Community Spatial Shifts (Presence/Absence Transformation)

Historically, mollusc communities at the eleven stations represented only two communities using the presence/absence transformation: Community A and C. Fifty years later, four mollusc communities were observed: Community A, B, C and D (Table 3.6, Figure 3.9). The distribution of Community A was reduced over time. Community A historically encompassed station 5b, 25, 26, and 28 in the Iqaluit region but in the modern samples this community only covered the region surrounding station 25. Station 5b and 28 were the shallowest stations and were both very close to shore. These stations experienced a loss of diversity including the loss of *Enncula tenuis*, *Cylichna alba*, *Macoma calcarea*, and *Thyasira gouldi* and became dominated by the thyasirid bivalve *Axinopsida orbiculata* in the modern samples when they shifted to Community D. Station 26 lost the species *Axinoposida orbiculata* and *Macoma calcarea* when it shifted to

Community B but numerous other species were present at this station in the modern sample. Community C shifted an undetermined amount. The modern distribution map indicates that this community is still present throughout the study region but it no longer overlaps with 5 of the 7 stations historically classified as Community C. Station 27 in the Iqaluit region and station 5d in the Cairn Island region remained as Community C while stations 5, 5a, 5c, 5e, and 5f in the Cairn Island region all shifted to Community B due to the loss of the small to medium sized bivalves *Hiatiella arctica* and *Musculus discors* in the historical samples and the presence of *Yoldia hyperborea*, *Macoma moesta*, and the gastropod *Cylichna alba* in the modern samples at these stations.

Table 3.5. Mollusc community shifts observed in Frobisher Bay based on square-root transformed analysis.

Station	Change	Historical Community	Historical Community (largest contributors to community)		Modern Community	Modern Community (largest contributors to community)
5b	Yes	Community V	<i>Axinopsida orbiculata</i> (38.55%), <i>Cylichna alba</i> (15.13%)	→	Community VI	<i>Axinopsida orbiculata</i> (100.0%)
25	No	Community V	<i>Axinopsida orbiculata</i> (38.55%), <i>Cylichna alba</i> (15.13%)	→	Community V	<i>Axinopsida orbiculata</i> (38.55%), <i>Cylichna alba</i> (15.13%)
26	Yes	Community II	<i>Thyasira gouldi</i> (43.93%), <i>Ennucula tenuis</i> (12.14%)	→	Community I	<i>Thyasira gouldi</i> (23.49%), <i>Ennucula tenuis</i> (10.74%), <i>Nuculana pernula</i> (9.86%), <i>Cylichna alba</i> (7.52%)
27	Yes	Community III	<i>Thyasira gouldi</i> (26.82%), <i>Ennucula tenuis</i> (14.5%), <i>Musculus discors</i> (13.71%)	→	Community II	<i>Thyasira gouldi</i> (43.93%), <i>Ennucula tenuis</i> (12.14%)
28	Yes	Community V	<i>Axinopsida orbiculata</i> (38.55%), <i>Cylichna alba</i> (15.13%)	→	Community VI	<i>Axinopsida orbiculata</i> (100.0%)
5	Yes	Community III and IV	<i>Thyasira gouldi</i> (26.82%), <i>Ennucula tenuis</i> (14.5%), <i>Musculus discors</i> (13.71%) And <i>Thyasira gouldi</i> (21.01%), <i>Musculus discors</i> (12.89%), <i>Nuculana minuta</i> (9.48%), <i>Margarites olivaceus</i> (9.34%)	→	Community I	<i>Thyasira gouldi</i> (23.49%), <i>Ennucula tenuis</i> (10.74%), <i>Nuculana pernula</i> (9.86%), <i>Cylichna alba</i> (7.52%)
5a	Yes	Community IV	<i>Thyasira gouldi</i> (21.01%), <i>Musculus discors</i> (12.89%), <i>Nuculana minuta</i> (9.48%), <i>Margarites olivaceus</i> (9.34%)	→	Community I	<i>Thyasira gouldi</i> (23.49%), <i>Ennucula tenuis</i> (10.74%), <i>Nuculana pernula</i> (9.86%), <i>Cylichna alba</i> (7.52%)
5c	Yes	Community IV	<i>Thyasira gouldi</i> (21.01%), <i>Musculus discors</i> (12.89%), <i>Nuculana minuta</i> (9.48%), <i>Margarites olivaceus</i> (9.34%)	→	Community I	<i>Thyasira gouldi</i> (23.49%), <i>Ennucula tenuis</i> (10.74%), <i>Nuculana pernula</i> (9.86%), <i>Cylichna alba</i> (7.52%)
5d	Yes	Community IV	<i>Thyasira gouldi</i> (21.01%), <i>Musculus discors</i> (12.89%), <i>Nuculana minuta</i> (9.48%), <i>Margarites olivaceus</i> (9.34%)	→	Community II	<i>Thyasira gouldi</i> (43.93%), <i>Ennucula tenuis</i> (12.14%)
5e	Yes	Community III	<i>Thyasira gouldi</i> (26.82%), <i>Ennucula tenuis</i> (14.5%), <i>Musculus discors</i> (13.71%)	→	Community I	<i>Thyasira gouldi</i> (23.49%), <i>Ennucula tenuis</i> (10.74%), <i>Nuculana pernula</i> (9.86%), <i>Cylichna alba</i> (7.52%)
5f	Yes	Community III	<i>Thyasira gouldi</i> (26.82%), <i>Ennucula tenuis</i> (14.5%), <i>Musculus discors</i> (13.71%)	→	Community I	<i>Thyasira gouldi</i> (23.49%), <i>Ennucula tenuis</i> (10.74%), <i>Nuculana pernula</i> (9.86%), <i>Cylichna alba</i> (7.52%)

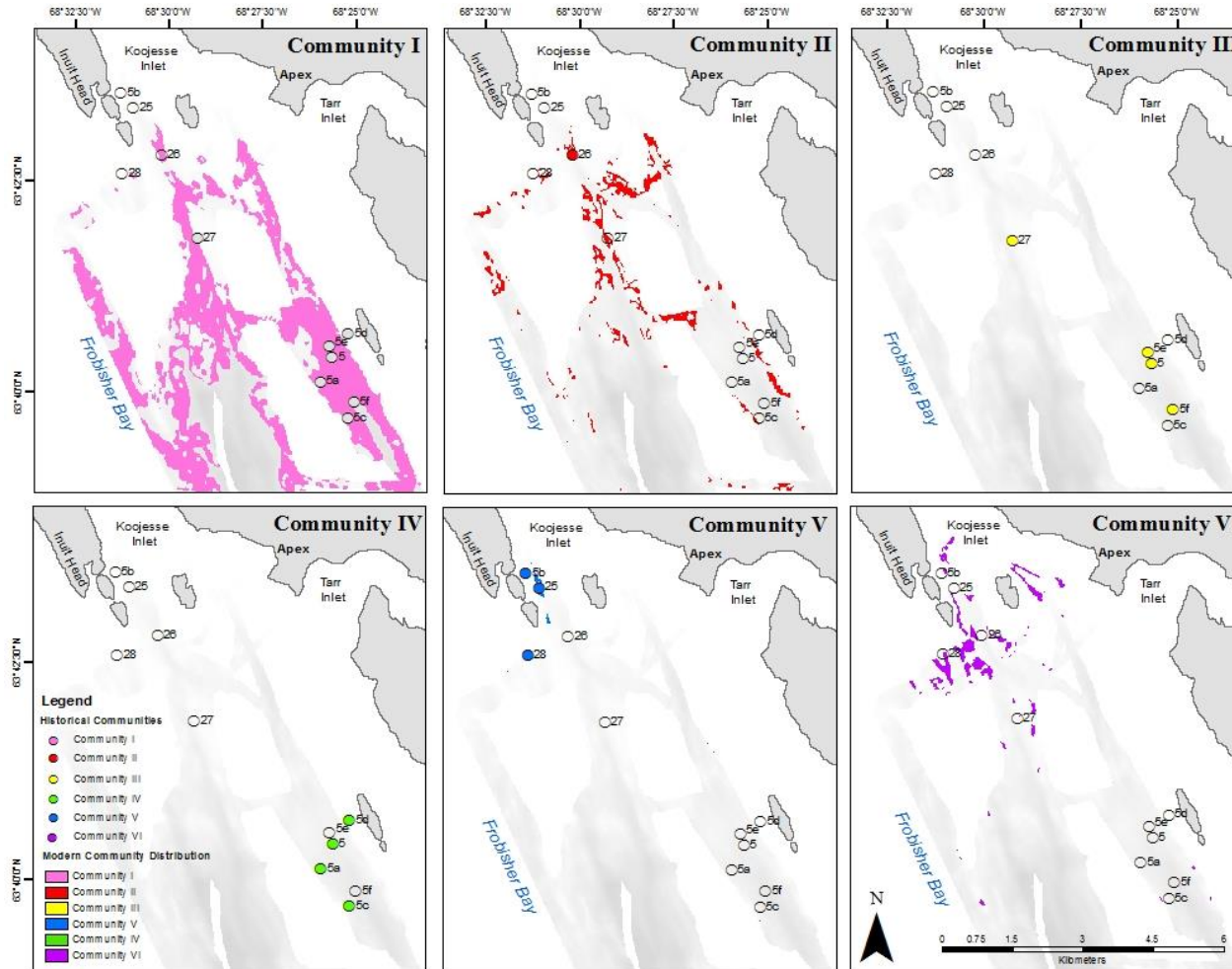


Figure 3.8. Community distribution maps of mollusc communities observed in Frobisher Bay based on square-root transformed community analysis. Colour circles represent the presence of each community historically overlaid on the distribution map indicating the current spatial distribution of each community.

Table 3.6. Mollusc community shifts observed in Frobisher Bay based on presence/absence transformed analysis.

Station	Change	Historical Community	Historical Community Description (largest contributors to community)		Modern Community	Modern Community Description (largest contributors to community)
5b	Yes	Community A	<i>Axinopsida orbiculata</i> (13.03%), <i>Ennucula tenuis</i> (13.03%), <i>Cylichna alba</i> (13.03%), <i>Macoma calcarea</i> (10.39%), <i>Thyasira gouldi</i> (9.59%)	→	Community D	<i>Axinopsida orbiculata</i> (100.0%)
25	No	Community A	<i>Axinopsida orbiculata</i> (13.03%), <i>Ennucula tenuis</i> (13.03%), <i>Cylichna alba</i> (13.03%), <i>Macoma calcarea</i> (10.39%), <i>Thyasira gouldi</i> (9.59%)	→	Community A	<i>Axinopsida orbiculata</i> (13.03%), <i>Ennucula tenuis</i> (13.03%), <i>Cylichna alba</i> (13.03%), <i>Macoma calcarea</i> (10.39%), <i>Thyasira gouldi</i> (9.59%)
26	Yes	Community A	<i>Axinopsida orbiculata</i> (13.03%), <i>Ennucula tenuis</i> (13.03%), <i>Cylichna alba</i> (13.03%), <i>Macoma calcarea</i> (10.39%), <i>Thyasira gouldi</i> (9.59%)	→	Community B	<i>Ennucula tenuis</i> (9.19%), <i>Nuculana pernula</i> (9.19%), <i>Thyasira gouldi</i> (9.19%), <i>Yoldia hyperborea</i> (9.19%), <i>Cylichna alba</i> (9.19%), <i>Macoma moesta</i> (6.61%)
27	No	Community C	<i>Thyasira gouldi</i> (12.13%), <i>Hiatella arctica</i> (10.38%), <i>Musculus discors</i> (10.33%), <i>Nuculana minuta</i> (10.33%), <i>Ennucula tenuis</i> (10.09%)	→	Community C	<i>Thyasira gouldi</i> (12.13%), <i>Hiatella arctica</i> (10.38%), <i>Musculus discors</i> (10.33%), <i>Nuculana minuta</i> (10.33%), <i>Ennucula tenuis</i> (10.09%)
28	Yes	Community A	<i>Axinopsida orbiculata</i> (13.03%), <i>Ennucula tenuis</i> (13.03%), <i>Cylichna alba</i> (13.03%), <i>Macoma calcarea</i> (10.39%), <i>Thyasira gouldi</i> (9.59%)	→	Community D	<i>Axinopsida orbiculata</i> (100.0%)
5	Yes	Community C	<i>Thyasira gouldi</i> (12.13%), <i>Hiatella arctica</i> (10.38%), <i>Musculus discors</i> (10.33%), <i>Nuculana minuta</i> (10.33%), <i>Ennucula tenuis</i> (10.09%)	→	Community B	<i>Ennucula tenuis</i> (9.19%), <i>Nuculana pernula</i> (9.19%), <i>Thyasira gouldi</i> (9.19%), <i>Yoldia hyperborea</i> (9.19%), <i>Cylichna alba</i> (9.19%), <i>Macoma moesta</i> (6.61%)
5a	Yes	Community C	See Station 5 description	→	Community B	See Station 5 description
5c	Yes	Community C	See Station 5 description	→	Community B	See Station 5 description
5d	No	Community C	<i>Thyasira gouldi</i> (12.13%), <i>Hiatella arctica</i> (10.38%), <i>Musculus discors</i> (10.33%), <i>Nuculana minuta</i> (10.33%), <i>Ennucula tenuis</i> (10.09%)	→	Community C	<i>Thyasira gouldi</i> (12.13%), <i>Hiatella arctica</i> (10.38%), <i>Musculus discors</i> (10.33%), <i>Nuculana minuta</i> (10.33%), <i>Ennucula tenuis</i> (10.09%)
5e	Yes	Community C	<i>Thyasira gouldi</i> (12.13%), <i>Hiatella arctica</i> (10.38%), <i>Musculus discors</i> (10.33%), <i>Nuculana minuta</i> (10.33%), <i>Ennucula tenuis</i> (10.09%)	→	Community B	<i>Ennucula tenuis</i> (9.19%), <i>Nuculana pernula</i> (9.19%), <i>Thyasira gouldi</i> (9.19%), <i>Yoldia hyperborea</i> (9.19%), <i>Cylichna alba</i> (9.19%), <i>Macoma moesta</i> (6.61%)
5f	Yes	Community C	See Station 5e description	→	Community B	See Station 5e description

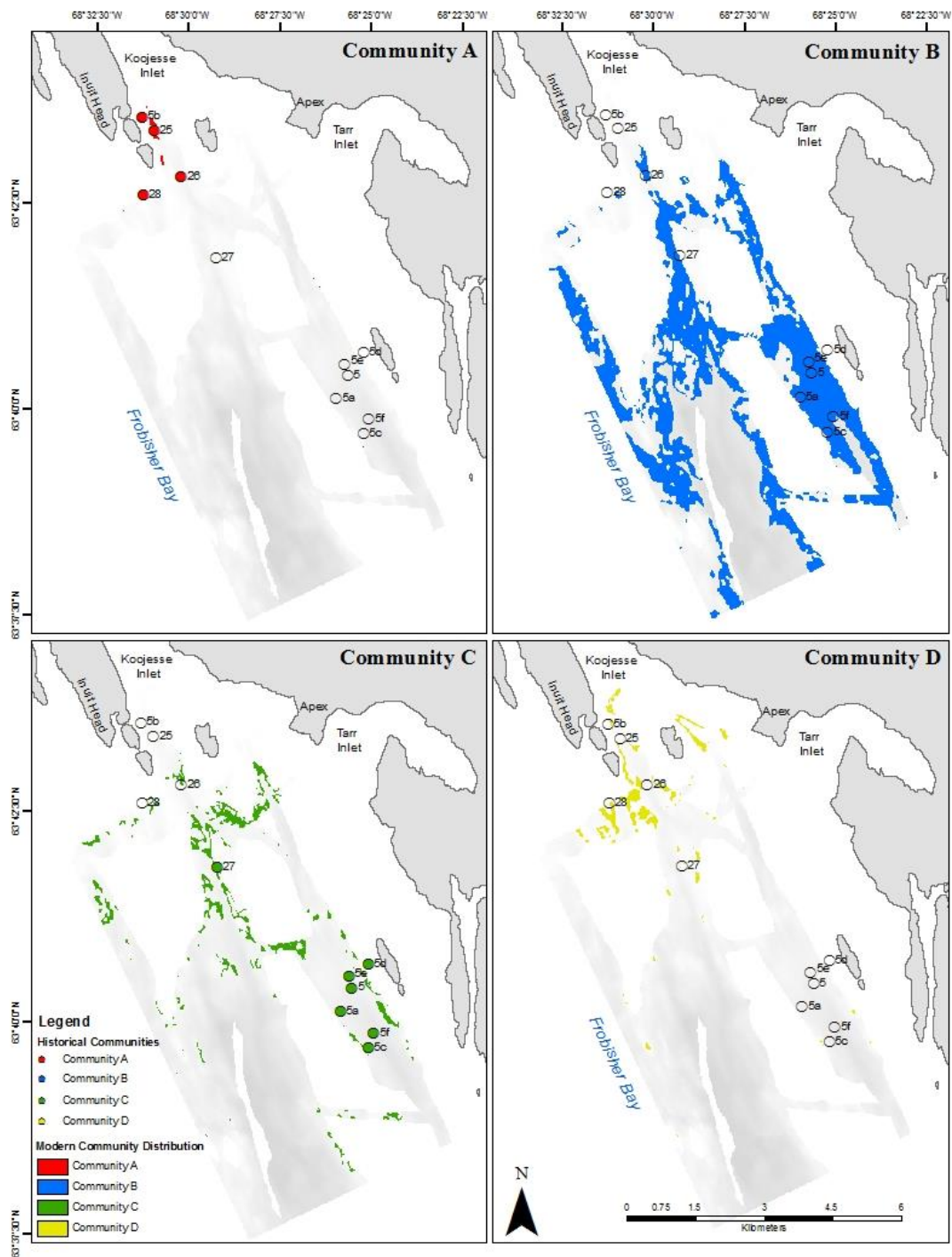


Figure 3.9. Community distribution maps of mollusc communities observed in Frobisher Bay based on presence-absence transformed community analysis. Colour circles represent the presence of each community historically overlaid on the distribution map indicating the current spatial distribution of each community.

3.4 Discussion

The biotope map produced here demonstrates the potential distribution of the modern molluscan communities based on MBES bathymetry and backscatter data. Examination of the distribution of individual modern communities with the historical molluscan communities overlaid on these maps demonstrates the spatial changes that were observed among the molluscan communities of Frobisher Bay over five decades.

Non-metric multidimensional scaling analysis with a presence/absence transformation demonstrated the existence of two historically unique communities (Community A and C) separated predominantly by geographic region (ie. Iqaluit region stations and Cairn Island region stations) and after fifty years, there were four unique molluscan communities present (Community A, B, C and D). Community B and Community D experienced expansion in their spatial distribution given that these communities had not been observed historically while Community A experienced a decline in its spatial distribution and Community C appears to have shifted its spatial distribution to areas of Frobisher Bay not historically sampled. Non-metric multidimensional scaling analysis with a square-root transformation demonstrated the existence of four historically unique communities (Community II, III, IV, and V) and after fifty years, two of those historical communities were lost (Community III and IV) while two new communities were observed (Community I and VI). Community I, II, and VI experienced expansion in their spatial distribution while Community III, IV, and V

experienced a decline in their spatial distribution based on where these communities had first been observed historically.

3.4.1 Habitat Mapping

Multibeam echosounder (MBES) technology has become a common tool used in predictive habitat mapping (Brown *et al.* 2011, Kostylev *et al.* 2008) with the resulting bathymetry data characterizing water depth and the backscatter data characterizing sea bottom hardness over the area that is sampled. These data layers are typically used in conjunction with *in situ* benthic samples to produce a predictive habitat map through either a top-down (unsupervised classification) or bottom-up (supervised classification) approach (Brown *et al.* 2011). In this way, the majority of *in situ* samples are included in the production of a distribution map while a small proportion of the samples are used to test the accuracy of the map. This study was limited to a very small sample size which precluded our ability to take a top-down or bottom-up approach to mapping the distribution of mollusc communities in Frobisher Bay. We applied a simplified approach similar to the “abiotic surrogates” approach described by Brown *et al.* (2011) where the bathymetry and backscatter data layers were utilized to identify patterns in the environmental data but where no *in situ* samples were used to test the resulting maps accuracy. The distribution patterns of each community that were identified were based on the range of bathymetry and backscatter values found within the buffered regions around each station sampled and those ranges were combined based on assigned

community. The abiotic surrogates approach is more commonly applied at a broad scale as was done by Roff *et al.* (2003) who applied a geophysical framework to the entire Canadian coastline and to the Scotian Shelf, however, this method has also been applied at smaller scales (Brown *et al.* 2011). Cochrane and Lafferty (2002) performed textural analysis of side-scan sonar data to distinguish between rocky and sandy habitats in the Northern Channel Islands along the California coast with a range of 220 km, while Marsh and Brown (2009) classified the seabed over Stanton Bank Area IV, 115 km northwest of Malin Head, Ireland (as part of the Mapping European Seabed Habitats program), an area of only 64 km², using multibeam echo-sounder bathymetry and backscatter data. Our approach was a more simplified design and on an even smaller scale (~ 30 km²). The distribution maps produced here highlight the potential habitat that each community may occupy based solely on water depth and sea bottom hardness. In the Arctic, water depth is well known to be one of the most important variables that structures benthic communities (Bluhm *et al.* 2011, Jones *et al.* 2007, Piepenburg *et al.* 1996, Piepenburg and Schmid 1996, Roy *et al.* 2014, Soltwedel *et al.* 2009, and Vedenin *et al.* 2018). The Frobisher Bay samples ranged in water depth from 11.5 to 90.1 m and species diversity and species evenness was found to increase significantly with water depth (Figure 3.4). This may be due to ice scouring in the shallower depths near Iqaluit (Deering *et al.* 2019) or from other coastal influences. Furthermore, the mollusc communities separated out by water depth with minimal overlap between communities (Figure 3.6). Sediment characteristics (e.g. grain size) play an equally important role in the distribution of benthic communities (Snelgrove *et al.* 1997). Sea bottom characteristics are defined by the hydrodynamics of a

given area where fine-grain sediments are found in quieter waters compared to coarse-grained sediments which are found in stronger currents. Benthic species observed in these varying conditions reflect adaptations to these sediment characteristics (Eltringham 1971). Differences in the sediment composition were observed between the Iqaluit and Cairn Island regions with gravelly muddy sand, gravelly sandy mud, and muddy sand observed in the Iqaluit region and gravelly sandy mud observed in the Cairn Island region (Misiuk *et al.* 2019b, Chapter 2). Furthermore, the proportion of sand and silt in the sediments were found to change significantly with water depth throughout the study region (Figure 3.4). Therefore, these observations provide support for using solely the bathymetry and backscatter environmental data to demonstrate the potential distribution of the molluscan communities.

3.4.2 Community Spatial Shifts

Many of the historical stations observed in Frobisher Bay have experienced statistically significant spatial change in molluscan community composition over a 50 year period based on multivariate analysis despite no major losses or gains of mollusc species. Therefore, it is imperative to determine to what extent these communities have changed and whether these communities should be classified as new or “novel” communities. Hobbs *et al.* (2006) coined the term “novel ecosystems” in recognition of new combinations of species being observed as a result of “human action, environmental change, and the impacts of deliberate and inadvertent introduction of species from other

regions” (Hobbs *et al.* 2006). A novel ecosystem has undergone a complete transformation from its original historic system and has crossed a threshold from which restoration back to the historical state is unlikely (Hobbs *et al.* 2013). Some stations in Frobisher Bay experienced a greater change in species composition over time. For example, Station 5b, 25 and station 28 (Community A; presence/absence transformation) all historically contained numerous mollusc species including the thyasirid bivalves *Axinopsida orbiculata* and *Thyasira gouldi* as well as the bivalves *Ennucula tenuis* and *Macoma calcarea*, and the gastropod *Cylichna alba*. Even the historical square-root transformed community (Community V) represented multiple species including *Axinopsida orbiculata* and *Cylichna alba*. But in the modern samples, station 5b and 28 experienced a loss in species richness with only the thyasirid bivalve *Axinopsida orbiculata* abundant at these stations and the distribution of Community A(V) was reduced to the area surrounding station 25. These stations were located closest to shore and the changes in composition observed could be due to numerous factors.

One possible reason for the reduction in spatial coverage of Community A(V) and the expansion of Community D(VI) could be an increased input of organic carbon in the sediments at the modern sample stations compared to the historical stations (Chapter 2). For example, the waste water treatment plant in Iqaluit was constructed in 1964 and discharged raw sewage directly into Koojesse Inlet (Prosko *et al.* 2016). Primary treatment was eventually implemented and an evaluation of the wastewater treatment facility in 2002 indicated a move forward to secondary treatment but was fraught with building deficiencies (Prosko *et al.* 2016). Upgrades to waste water treatment were again

implemented in 2011 (Stantec 2020). This outfall is located approximately 2 kilometers from station 5b and 25. In 2015, the Centre for Water Resource Studies (2015) conducted a study on the benthic fauna around the outfall and observed high organic enrichment in the sediments associated with sediments devoid of benthic fauna up to 580 m away from the outfall site. The authors did not sample below the low tide line and it is possible that the effects of the outfall site could extend further into the bay. The deposition of sediments from nearby rivers can also result in increased sedimentation in coastal zones. Conlan *et al.* (2008) observed that inshore fauna present near the Mackenzie River along the Beaufort Shelf were dominated by the bivalve *Portlandia arctica* and species in this area of the Beaufort Shelf are adaptable to conditions including enhanced sediment transport and coastal erosion. An increase in mean river discharge in both the Sylvia Grinnell and Apex Rivers over time during the month of June suggest that changes in river discharge dynamics may have had an influence on sediment transport into Frobisher Bay over time and significant changes in sediment grain size and organic carbon and nitrogen in the sediments in the Cairn Island region support this (Chapter 2). C/N ratios from terrestrial sources are typically higher than 15 while C/N ratios with a marine origin have ratios between 4-10 (Rumolo *et al.* 2011).

Station 5b, 26, 27, and 28 all had a higher C:N in the modern samples compared to the historical samples suggesting that there may have been some input of terrestrial sourced organic carbon, possibly from a change in the hydrodynamics observed in the Sylvia Grinnell River over the last fifty years though no significant trend was observed (Chapter 2). *Axinopsida orbiculata* is characterized as a species that is abundant in areas

of increased sedimentations and organically enriched environments (Batstone *et al.* 2014, Dufour pers. comm., 2019, Wlodarska-Kowalczyk 2007, Kedra 2010) and one that thrives where there is excess organic enrichment (Borja *et al.* 2000). The reduction in coverage of Community A(V) therefore could have resulted from the loss of other bivalves (e.g. *Ennucula tenuis* and *Macoma calcarea*) that were considered indifferent to disturbance (e.g. can tolerate only some variation in organic enrichment) while the expansion of Community D(VI) could have benefited from the elevated levels of organic enrichment observed in this area.

Other factors that could have influenced the change in community distribution observed in the Iqaluit region. Ice scour was observed in the analyzed MEBS data in less than 50 m water depth (Deering *et al.* 2018) in the Iqaluit region. Frobisher Bay is covered by sea ice from November to July (Canadian Ice Service 2013). Ice scour is a common occurrence along arctic shores and causes large-scale disturbance to the benthos by re-working the sediments and crushing benthic biota in its path (Conlan *et al.* 1998, Conlan and Kvitek 2005, Gutt 2001, Smale *et al.* 2008). While sea ice scouring can be destructive, it also provides a feeding opportunity for scavengers such as gastropods and other species (e.g. amphipods and isopods) which first colonize ice scours (Conlan *et al.* 1998). Conlan and Kvitek (2005) found that juvenile bivalves were often early colonizers in ice scours and that the abundance of some bivalve species in the ice scours significantly increased as the community aged when they looked at the recolonization rate of soft-sediment ice scours in Barrow Strait in the Canadian Arctic Archipelago. This suggests that while ice scouring may alter community composition, it is not

necessarily detrimental to the existence of the pre-scoured benthic community and a gradual shift (over decades) back to the pre-scoured community can occur, though many Arctic coastal regions may consistently be responding to the effects of ice scouring (Conlan and Kvitek 2005, Conlan *et al.* 2008). The length of time it takes for the benthic community to recovery from a scouring event in shallow water environments is unknown (Smale *et al.* 2008) and Conlan and Kvitek (2005) have indicated that it can take upwards of a decade for the benthic community to recover to its pre-scoured condition and it could be over 40 years before ice scours would no longer be visible. It is therefore a possibility that in the Iqaluit region, which has shown evidence of ice scouring in the past to maximum depth of 50 m (Deering *et al.* 2018), could have contributed to the differences observed in the molluscan community composition between the two time periods.

Coastal erosion and its resulting sedimentation could also influence the composition of the benthos and therefore the spatial distribution of communities in the Iqaluit region. Sea ice processes in conjunction with tidal processes may impact the benthos through sedimentation. Coastal erosion results from a feedback loop where warming air temperatures result in warming sea temperatures and sea ice loss. This increases wave exposure along the coastline which then increases erosion along coasts that are already subjected to permafrost melt as a result of global warming (ACIA 2005, Frederick *et al.* 2016, Manson *et al.* 2005). The Beaufort Sea coastline exhibits some of the greatest erosion rates in the Arctic (Frederick *et al.* 2016) and Brown *et al.* (2011) observed a sparse community of benthic infaunal organisms in Sachs Harbour, along the southwest coast of Banks Island, NTW and attributed this to active sediment transport in

this region which regularly experiences coastal erosion. However, the coastline of southeastern Baffin Island is quite rocky and steep with mostly rocky beaches and only localized sandy beaches, though tidal flat areas may have finer grained sediments (Miller *et al.* 1980). A study of the sand flats in Koojoose inlet near Iqaluit did not reveal significant erosion or deposition of sediments between 2009 and 2011 (Hatcher *et al.* 2014) and Hatcher and Forbes (2015) indicated that erosional retreat of the coast is not a concern in the Iqaluit region.

Another factor that could have influenced the species composition of the different communities is discrepancies in water depth among the historical and modern sampling periods, particularly at station 28 in the Iqaluit region. While this could partially be due to large 11 m tidal ranges near Iqaluit (Hatcher *et al.* 2014, Hatcher and Forbes 2015) and sampling at high tide versus low tide, some of the depth discrepancies were much larger than this tidal range. Between 1967-1976 when the historical samples were collected, water depth was recorded as 30 m at station 28. In 2016 when this station was re-sampled the water depth was significantly lower with a water depth of 11.5 m, a difference of 18.5 m. This suggests that there was some spatial inaccuracy during the sampling process which resulted in a water depth discrepancy between the two sampling periods. These spatial discrepancies were minimized in this study through the measurement of a “sampling error buffer” that was placed around the mean centre of the modern stations. The buffered region was used to more broadly define the water depth (bathymetry) and sea bottom hardness (backscatter) at each station. By imposing the buffer around the station, a greater range of bathymetry and backscatter values was

captured and the depth discrepancies were minimized. However, these water depth discrepancies could have serious implications for benthic community composition, especially where faunal distribution is related to water depth. For example, the thyasirid bivalves *Axinopsida orbiculata* and *Thyasira gouldi* were both very abundant in the Frobisher Bay samples. They are both found to occur in areas with high volumes of inorganic sedimentation (Wlodarska-Kowalczyk and Pearson 2004) but *Axinopsida orbiculata* was more prevalent at the shallower Iqaluit stations closer to shore (with a lower abundance of *T. gouldi* also present in the Iqaluit region; Chapter 2).

Comparatively, *T. gouldi* was more abundant in the deeper Cairn Island stations (Chapter 2). *A. orbiculata* prefers shallow water compared to *T. gouldi* (Dufour 2019 pers. comm.) and in their study examining the macrozoobenthos of Kongsfjord, Svalbard, Kaczmarek *et al.* (2005) also observed *A. orbiculata* to be more prevalent in waters around 15 m compared to *T. gouldi* which was observed more commonly in deeper waters (e.g. 50 m). The Iqaluit region experienced a reduction in the relative abundance of *T. gouldi* at two of the five stations sampled including station 28 and a complete loss of this species at another two Iqaluit stations. Therefore, it is possible that water depth discrepancies between the two sampling periods due to inaccurate or imprecise location data could have contributed to the changes observed in the distribution of the mollusc communities.

It is difficult to confirm if the mollusc communities in inner Frobisher Bay have reached a point where they are unlikely to return to their historic state. For example, McCann *et al.* (1981) summarized the findings of Ellis (1955, 1960, 1969) who observed many of the same bivalve and gastropod species in 1955, 1960 and 1961 and these

species persisted through the 1960's and 1970's as observed by Wacasey (1979, 1980) and still into 2016-2017 as observed in Chapter 2. Most of the stations sampled historically have only experienced small changes in mollusc species composition over time. These communities could therefore be classified as "hybrid" communities (Hobbs *et al.* 2009). Hybrid communities have experienced a significant change in composition or function but still represent some characteristics of their historic system (Hobbs *et al.* 2009). These systems are more likely to prevail in areas that are dominated by long lived species who are tolerant of large environmental variations. The molluscs are a group of organisms that are long lived and can dominate the biomass in benthic communities (Feder *et al.* 1994a, Powell and Cummins 1985). Despite the loss of historical communities and the presence of new communities in inner Frobisher Bay, the majority of the stations experienced only small changes in species composition of the dominant taxa despite being designated as new distinct communities. For example, the presence/absence transformed analysis indicated that all six of the Cairn Island stations plus station 27 in the Iqaluit region were historically designated as Community C represented by the species *Thyasira gouldi*, *Hiatella arctica*, *Musculus discors*, *Nuculana minuta*, and *Ennucula tenuis*. After fifty years, four of these six stations transformed to Community B and were represented by the species *Ennucula tenuis*, *Nuculana pernula*, *Thyasira gouldi*, *Yoldia hyperborea*, *Cylichna alba*, and *Macoma moesta*. Some species persisted over the 50-year timeframe of this study while some species were lost and others appeared. Historical Community C persisted over time and its distribution was either reduced in size as seen by the loss of this community at most stations, or it shifted

to different areas of the study area, or this community was lost at the stations sampled but persisted in other regions that were not sampled historically. New Community B has a wide potential distribution but the distribution overlap between historical Community C and modern Community B suggest that these two communities may to a certain extent occupy similar habitats and that these communities may not be so different.

A possible reason for the spatial shifts observed in Community B(I) and Community C(II) is that there was a significant change observed in the sediment characteristics in the Cairn Island region including an increase in the proportion of silt (and subsequent decrease in the proportion of sand) in the sediments, and a significant increase in total organic carbon and total nitrogen within the sediments (tests conducted in Chapter 2). The change in sediment composition in this region could be the result of sedimentation from Tarr Inlet while an increase in organic carbon and nitrogen could be the result of greater light availability due to a loss of sea ice and these factors could be what influenced changes in species composition over time (as previously discussed in Chapter 2), though other factors including riverine discharge and urbanization discussed earlier could also be factors affecting the sedimentation here.

It could be that hybrid communities may revert back to their historical characteristics with time (Hobbs *et al.* 2013b) and that the community changes and shifts observed are simply a result of temporal variability or patchiness within the benthic communities of inner Frobisher Bay. For example, Cusson *et al.* (2007) performed multivariate analysis on the entire benthic infaunal community dataset in inner Frobisher Bay using the historical benthic data collected by Wacasey *et al.* (1979, 1980) at the same

sampling stations as this paper as part of their study examining the biodiversity of benthic assemblages on the Arctic continental shelf. They observed that the structure of the benthic assemblages exhibited significant community differences between seasons and years and they suggested that these observed differences may actually be greater than the spatial variations in community structure between stations (Cusson *et al.* 2007). This same trend was observed in Chapter 2 specifically in the molluscs. This suggests that extensive temporal variability exists within a single station and this variability may mask any meaningful spatial change given the small scale of the study area and despite significant temporal differences in the communities being observed.

Patchiness of benthic communities within marine soft sediments at small scales is also well known to exist (Morrisey *et al.* 1992). Morrisey *et al.* (1992) observed that the abundances of infauna in soft sediments were patchy at a range of spatial scales from 1 metre to several kilometers while Volckaert (1987) observed patchiness in the distribution of polychaetes in soft sediments at scales less than 10 cm, 10 to 50 cm, and greater than 50 cm. The distance between replicate samples collected using a benthic grab is unknown and depends on water depth and water movement but samples are expected to be representative of the community at a given location (Morrisey *et al.* 1992). Samples in this study were pooled to be comparative to the historical data and in doing so, this should have reduced any effect of patchiness within replicate grabs.

Small sample size and spatial discrepancy between the historical and modern samples may be two additional factors that influenced the changes in community distribution within the study region and would suggest that the mollusc communities may

not have shifted as significantly as the distribution maps suggest. Two transformation methods were employed to compare the historical samples with the distribution of the modern mollusc communities but the samples collected cover only a small portion of the 0.35 km² study region. It is entirely possible that there were more molluscan communities present historically that were not sampled, that modern mollusc communities were present historically but were not sampled, or that historical communities that were lost are actually still present but were not re-sampled.

The benthic communities sampled in Frobisher Bay have experienced some degree of change in their spatial distribution over the last 50 years and many factors may have contributed to this change. Many authors have voiced the importance of using historically datasets as baselines from which to measure future change in the absence of long-term datasets (e.g. Wolfe *et al.* 1987, Kiyko and Pogrebov 1997, Cusson *et al.* 2007, Renaud *et al.* 2007, Thurstan *et al.* 2015, Novoa *et al.* 2016) while other authors have cautioned against the comparison of historical and modern datasets (e.g. Cusson *et al.* 2007) especially given that the temporal and spatial variability of the historical benthic communities in Frobisher Bay were found to be of similar magnitude. We recognized the limitations of comparing historical and modern datasets and focussed this study on the molluscs which are long-lived species in an effort to identify long-term community change. This was a first attempt to map spatial shifts over time in the molluscan communities of inner Frobisher Bay using solely bathymetry and backscatter multibeam data. While a larger modern sample size would have aided in a more accurate image of the current potential distribution of the mollusc communities in this region, the historical

samples provide a snapshot of what these communities once looked like in comparison to the modern community. This dataset provides as a useful benchmark dataset and a basis for future sampling from which to measure on-going spatial change in the benthos of Frobisher Bay given the future predictions around climate change and its potential impact on Arctic systems and considering anthropogenic impacts including continuous infrastructure development that are on-going in Frobisher Bay.

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Chapter 4 Conclusions

Long-term studies are crucial to our understanding of ecological responses to natural and anthropogenic environmental change (Carpenter *et al.* 1995). Lindenmayer *et al.* (2012) defines long-term studies as those that extend more than 10 years because it allows for repeated sampling of annual growth cycles and bioclimatic cycles which occur on decadal scales. This definition was adopted by numerous Arctic benthic ecologists who have previously conducted long-term studies of rocky and soft bottom benthic communities in various regions across the Arctic (e.g. Dyer *et al.* 1984, Kiyko and Pogrebov 1997, Beuchel *et al.* 2006, Grebmeier *et al.* 2006, Renaud *et al.* 2007, Beuchel and Gulliksen 2008, Carroll *et al.* 2009, Kedra *et al.*, 2010, Kozlovskiy *et al.* 2011, Kortsch *et al.* 2012, and Grebmeier *et al.* 2015) in response to environmental change.

In the circumpolar Arctic, the on-going effects of climate change have resulted in warming at twice the global rate (Richter-Menge *et al.* 2017), the implications of which include accelerated sea ice melt and sea water temperature rise (Richter-Menge 2017). These changes can have a profound effect on the surrounding benthic environment through increased light availability and primary production in surface waters and these changes directly influence the benthic communities that respond directly to pelagic processes (Wassman and Reigstad 2011). Despite the need for documenting long-term benthic community change in a warming Arctic, repeated long-term sampling is particularly difficult to accomplish in regions that are covered by sea ice for much of the year (Carey 1991). It is therefore imperative to utilize existing historical datasets in

combination with modern studies to answer questions about long-term temporal and spatial changes affecting benthic communities in response to a changing climate. This thesis is one of the first long-term studies to examine both temporal and spatial change in the benthic communities within the Canadian Arctic.

4.1 Research Outcomes

We used molluscs (phylum *Mollusca*), a group of benthic invertebrates, as an indicator species to detect long-term temporal and spatial community change within Frobisher Bay in light of the on-going effects of climate change in the Canadian Arctic. Historical molluscan sample data collected by Wacasey *et al.* (1979, 1980) was compared with modern molluscan sample data collected at the same stations 50 years later to identify long-term temporal (Chapter 2) and long-term spatial (Chapter 3) community change over a 50 year period by comparing two “snap-shots” in time. Long-term environmental data were incorporated into the analysis to help support our findings.

In Chapter 2, we observed that the mollusc communities in two regions, the Iqaluit region and Cairn Island region, had experienced a change in community composition between the two time periods and functional diversity between the two time periods had also been reduced in the Cairn Island region. These findings were observed in conjunction with changes observed in sediment grain size characteristics and sediment quality in the Cairn Island region in addition to a significant long-term decline in air temperature, significant losses of sea ice, and a change in the hydrology of the Sylvia

Grinnell River and Apex River, all repeatedly measured in the vicinity of the long-term ecology stations over the course of the study period (Government of Canada 2017 and Government of Canada 2018a, 2018b). Changes in the physical environment of the Iqaluit region were slightly more difficult to identify but influences of sedimentation and organic enrichment may be potential factors that influenced community composition in this region, though other forces may have played a part. Where there is stability in community structure, it can often be difficult to identify specific drivers of community change (Renaud *et al.* 2007). It is true, that while changes in community composition were observed, no significant decline in species richness or diversity were found and most historical and modern stations retained at least similar characteristics in terms of species composition. This indicates that benthic community function is being maintained in inner Frobisher Bay. Therefore, we cannot confirm that changing climate conditions in this region are responsible for the community changes observed in this study without looking at repeatedly sampled long-term trends. Therefore, these findings highlight the importance of systematic long-term sampling that can paint a more complete picture of the community level and functional changes that have occurred in the molluscan communities of inner Frobisher Bay.

In Chapter 3, we took the approach of utilizing bathymetry and backscatter coverage data to produce distribution maps that highlighted the “potential distribution” of the modern molluscan communities. This approach was utilized because sample size was too small and precluded our ability to test the accuracy of the resulting maps. Square-root transformed data analysis of the environmental data identified four molluscan

communities within the historical sample data and four molluscan communities within the modern sample data, however, only two of these communities persisted over both time periods and all but one station experienced a transition to a new community over time. Comparatively our presence-absence data analysis identified two historical communities and four modern communities and eight of the eleven stations experienced a transition to a new community over time. In both analyses, molluscan communities were observed to separate by water depth and backscatter (reflectivity of the sea bottom which is a measure of sea bottom hardness). Environmental factors that may have contributed to the spatial shifts observed in the communities close to Iqaluit include an increase in terrestrial sourced carbon in the sediments as a result of changing hydrographic conditions in the Sylvia Grinnell River while in the Cairn Island region, the spatial shifts in community composition observed may be the result of significant changes in sediment characteristics (grain size composition, total carbon and total nitrogen in the sediments). The effects of urbanization in Iqaluit which has experienced rapid population growth from 900 in 1964 to 7,740 in 2016 (Statistics Canada 2019) may have also impacted the benthos. Iqaluit has experienced significant infrastructure development along the coast and the coastal waters and the benthos may have been impacted by raw sewage disposal into the tidal flats near the LTE stations over the last fifty years. Other factors not identified in this study may have also influenced the modern spatial distribution of the molluscan communities observed. In this chapter we emphasized the need for a larger sample size in order to test the accuracy of the predictive habitat map as our small sample

size precluded our ability to incorporate in-situ biological sample data into the habitat map.

4.2 Limitations and Recommendations

The primary limitations of this thesis were a lack of systematic long-term sampling, small sample sizes, a lack of long-term environmental data associated with the stations sampled (e.g. bottom temperature, salinity, phytoplankton concentrations, etc.), and discrepancies in temporal and spatial coverage of the stations sampled.

A lack of systematic long-term sampling and small sample sizes precluded our ability to monitor shorter-term temporal change within the molluscan communities of Frobisher Bay and therefore made it difficult to distinguish between long-term change and natural shorter-term fluctuations. Data on the range of natural variability that may exist within these communities was limited to one station within the historical samples which experienced greater inter-annual and seasonal variation in species richness than was observed between the historical and modern time periods. A lack of supporting environmental data associated with the stations sampled resulted in having to rely on unrelated datasets to support the molluscan community changes observed and these datasets did not necessarily correspond to the timeline of this study. Small sample size also limited our ability use separate training and testing datasets to predict the distribution of the modern communities. Lastly, discrepancies in temporal and spatial coverage of sampling sites and in sampling methods is a common limitation to comparing historical

datasets with modern datasets (Novoa *et al.* 2016). These discrepancies can ultimately mask the long-term changes that are being sought. For example, some of the stations sampled in Frobisher Bay (e.g. Station 28) experienced a large difference in water depth when the historical sample was collected compared to when the modern sample was collected. Water depth is a proxy for many environmental factors which affect the distribution of benthic organisms (Roy *et al.* 2014) and if there is a high degree of patchiness within the benthic community, these factors could all contribute to the differences in community structure observed among the molluscs at these particular stations.

We recommend that future research should continue to utilize historical datasets as they are an invaluable tool with which to examine historic benthic Arctic community structure in “pristine” conditions and which can be used as a benchmark from which to measure long-term community change. In addition to the stations sampled in this study, an additional 158 benthic grab samples were collected throughout Frobisher Bay for sediment and/or biota onboard the MV *Nulialjuk* in 2016 but were not processed and utilized in this study due to the scope of this project (Appendix 10). These samples, along with the samples used as part of this thesis, can also be used as a benchmark dataset from which to measure future change in the benthic communities of Frobisher Bay.

We recommend that consistent long-term monitoring of the benthos should occur in order to gain an understanding of the natural fluctuations that exist within the benthic community being examined so that long-term community change can be distinguished

from natural shorter-term variability within the community. This includes setting up a sampling design with an appropriate sample size that will be comparable in the long-term and that would be comparable with historical data. In light of the development of Iqaluit's deep-sea port and the associated dredging of the southern tip of Koojesse Inlet (Tranter 2019) after sampling was conducted for this thesis, we further recommend that consistent long-term monitoring of the benthos of Frobisher Bay should continue to occur given the effects that dredging will have on the benthos in this region and so that long-term recovery of the benthic communities in this area can be documented. Both the historical and modern dataset utilized in this study can be used as a benchmark from which to measure these changes.

4.3 Emerging Scientific Questions

Our knowledge of Arctic benthic communities is continuing to grow but the vastness of the Arctic and the difficulties and limitations associated with sampling in the North limit our ability to conduct repetitive sampling. Fortunately, the city of Iqaluit is the gateway to Frobisher Bay and is one of the more accessible locations from which to conduct sampling in the marine environment.

Within Frobisher Bay, the shallow coastal environment is currently experiencing some disturbance due to current and on-going infrastructure development. In light of these coastal pressures, it is important to ask how infrastructure development such as the installation of a deep water port off of Indian Head may impact the benthos in this region.

This port is currently being developed with dredging of the seabed taking place between July and November 2019. The historical Frobisher Bay samples collected between 1967-1976 and again in 2016 provide excellent baseline datasets from which to measure these changes. The development of the deep-water port also allows for an opportunity to examine the rate of recovery of shallow water benthic ecosystems affected by infrastructure development in the Arctic.

This study highlighted some of the long-term datasets that are available for the Frobisher Bay region (e.g. air temperature, ice cover and thickness) but other excellent environmental (e.g. oceanographic data) and biological (e.g. phytoplankton production) historical datasets also exist, providing a snapshot back in time to what the coastal marine environment once looked like. In this thesis, we collected benthic infaunal samples to compare with a historical dataset, but oceanographic data and data related to primary production in Frobisher Bay were not collected (though some data sets have been collected from the CCGS Amundsen through ArcticNet science cruises). One question that could help answer whether climate related changes are affecting the benthos is to conduct a long-term study that examines long-term oceanographic and primary productivity changes in Frobisher Bay as these were noticeable data gaps in this thesis.

The long-term ecology samples collected during this thesis were only a small subset of samples collected in Frobisher Bay during the 2016 field season. Once processed, this dataset provides an excellent benchmark dataset from which any number of studies could branch off. This dataset also provides an opportunity from which to conduct

repeated sampling in support of building one of the first long-term systematically sampled datasets in the Canadian North.

4.4 Conclusion

This thesis aimed to answer questions about long-term community change in the benthic molluscan communities of Frobisher Bay. Thus far, research on soft bottom benthos in the Canadian Arctic has primarily been focussed on baseline studies. Baseline studies dot the Canadian Arctic but to our knowledge, no long-term studies have been conducted to document changes to the benthos in relation to the ongoing effects of climate change. Canada is trailing behind compared to other countries which have conducted such studies. This thesis was a first step in conducting a long-term analysis of molluscan community change in the Canadian Arctic and it has provided insight into some possible factors that influenced both the temporal and spatial changes observed within the molluscan communities of Frobisher Bay over the last fifty years. Despite the difficulties associated with using historical datasets to answer important questions about long-term temporal and spatial change in Arctic benthos, the findings of this thesis indicate that historical datasets are invaluable records and baselines from which future change can and should be measured.

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Appendices

Appendix 1. Total organic carbon and total nitrogen sample processing methodology provided by the Stable Isotope Lab Coordinator, Alison Pye, Memorial University of Newfoundland.

Carlo-Erba NA1500 Elemental Analyser and ConFloIII Interface: NC setup

The Carlo-Erba NA1500 Elemental Analyser (EA) consists of an autosampler, oxidation and reduction ovens, water trap, gas chromatographic (GC) column and a thermal conductivity meter (TCD).

The entire EA system is continuously flushed with He (carrier gas) at a rate of 90-110 ml/min. The sample, sealed in a tin capsule, is loaded into the autosampler. The autosampler drops the capsule into the oxidation reactor (1050°C) just as a pulse of oxygen, flushed by He, arrives. Reaction of O₂ with the tin creates a “flash combustion” (temperature instantaneously increases to 1800°C) which totally oxidizes the sample into combustion products. The combustion gases pass through an oxidation catalyst, CrO₃, which ensures complete oxidation of the sample, and silvered cobaltous/cobaltic oxide, which removes halides and SO₂. The gas mixture passes through the reduction reactor (650°C), reduced copper, which reduces nitrogen oxides to N₂ and also absorbs excess O₂. The gases pass through a Mg(ClO₄)₂ water trap and the remaining gases (N₂, CO₂) enter the chromatographic column, a 3 m stainless steel Poropak QS 50/80 mesh column held at 40-100°C, dependent on sample type and gas(es) of interest. The individual gases are separated as they pass through the column and when they reach the TCD, they are detected as separate gas peaks: first N₂, then CO₂. The TCD output signal for each is proportional to the concentration of each combustion gas, allowing elemental determination (%N, %C) based on sample weight.

From here the He carries the gases to the ConFloIII interface. This unit has split tubes, open to the atmosphere, which allow a portion of the He and combustion gases to enter directly into the ion source of the mass spectrometer (MS) (DeltaVPlus) via fused glass capillaries. During operation, He from the EA continuously flows into the MS (hence the term EA-CF). All gases exiting the EA also enter the ion source, but the instrument only records signals for the gases of interest, as defined through the software and by instrument configuration. The ConFloIII also injects reference gases from gas cylinders into the He stream through the glass capillaries.

For some procedures, large sample sizes are required that may result in too much of a gas being produced (may cause damage to the ion source or pumps). In these instances, all or a portion of the gas from the EA must be diluted. For dilution, He is injected through another capillary into the split tube and into the stream of gases coming from the EA, forcing a higher portion of the gases to flow outside the tube, thereby reducing the amount entering the MS source.

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Appendix 2. All samples collected in Frobisher Bay aboard the M.V. *Calanus* (1967-1976), M.V. *Nulialjuk* (2016), and CCGS *Amundsen* (2016).

Station	Rep.	No. Pooled Reps	Date Sampled	Time Sampled	Lat. (DD)	Long. (DD)	Water Depth (m)	Vessel	Grab Sampler	Depth Sed. Sample (m)	Length Sed. Sample (m)	Width Sed. Sample (m)	Area Sampled (m ²)	Sed.	Biota
<i>Historical Samples</i>															
5	N/A	6	23-Jul-68	N/A	63.6731	-68.4289	45	M.V. Calanus	Petterson	N/A	N/A	N/A	0.39	N	Y
5	N/A	6	20-Aug-68	N/A	63.6731	-68.4289	60	M.V. Calanus	Petterson	N/A	N/A	N/A	0.39	Y	Y
5	N/A	6	3-Sep-68	N/A	63.6731	-68.4289	60	M.V. Calanus	Petterson	N/A	N/A	N/A	0.39	N	Y
5	N/A	6	8-Oct-68	N/A	63.6731	-68.4289	62	M.V. Calanus	Petterson	N/A	N/A	N/A	0.39	N	Y
5	N/A	N/A	2-Sep-69	N/A	63.6731	-68.4289	53	M.V. Calanus	Petterson	N/A	N/A	N/A	0.39	Y	N
5	N/A	6	6-Aug-70	N/A	63.6731	-68.4289	72	M.V. Calanus	Petterson	N/A	N/A	N/A	0.39	N	Y
5a	N/A	6	1-Aug-68	N/A	63.6683	-68.4342	26	M.V. Calanus	Petterson	N/A	N/A	N/A	0.39	Y	Y
5a	N/A	6	20-Aug-68	N/A	63.6683	-68.4342	32	M.V. Calanus	Petterson	N/A	N/A	N/A	0.39	N	Y
5a	N/A	N/A	2-Sep-69	N/A	63.6683	-68.4342	36	M.V. Calanus	Petterson	N/A	N/A	N/A	0.39	Y	N
5c	N/A	6	23-Aug-69	N/A	63.6611	-68.422	31	M.V. Calanus	Petterson	N/A	N/A	N/A	0.39	Y	Y
5d	N/A	6	23-Aug-69	N/A	63.6776	-68.4216	43	M.V. Calanus	Petterson	N/A	N/A	N/A	0.39	Y	Y
5e	N/A	6	23-Aug-69	N/A	63.6752	-68.4304	58	M.V. Calanus	Petterson	N/A	N/A	N/A	0.39	Y	Y
5f	N/A	6	23-Aug-69	N/A	63.6642	-68.4195	73	M.V. Calanus	Petterson	N/A	N/A	N/A	0.39	Y	Y
5b	N/A	6	29-Jul-69	N/A	63.7256	-68.5218	15	M.V. Calanus	Petterson	N/A	N/A	N/A	0.39	N	Y
5b	N/A	69	3-Sep-69	N/A	63.7256	-68.5218	15	M.V. Calanus	Petterson	N/A	N/A	N/A	0.39	Y	Y
5b	N/A	5	8-Aug-73	N/A	63.7256	-68.5218	14	M.V. Calanus	Petterson	N/A	N/A	N/A	0.33	Y	Y
5b	N/A	5	19-Aug-76	N/A	63.7256	-68.5218	14	M.V. Calanus	Petterson	N/A	N/A	N/A	0.33	Y	Y
25	N/A	5	8-Aug-73	N/A	63.7227	-68.5162	30	M.V. Calanus	Petterson	N/A	N/A	N/A	0.33	Y	Y
25	N/A	5	18-Aug-76	N/A	63.7227	-68.5162	28	M.V. Calanus	Petterson	N/A	N/A	N/A	0.33	Y	Y
26	N/A	5	8-Aug-73	N/A	63.7134	-68.5039	40	M.V. Calanus	Petterson	N/A	N/A	N/A	0.33	Y	Y
27	N/A	5	8-Aug-73	N/A	63.7098	-68.5214	43	M.V. Calanus	Petterson	N/A	N/A	N/A	0.33	Y	Y
28	N/A	4	13-Aug-73	N/A	63.6969	-68.4885	30	M.V. Calanus	Petterson	N/A	N/A	N/A	0.25	Y	Y
<i>Modern Samples</i>															

25	G1		10-Oct-16	7:05	63.72269167	-68.51627	28.5	M.V. Nulialjuk	Van Veen	0.03	0.37	0.30	0.1110	Y	Y
25	G2		10-Oct-16	7:15	63.722415	-68.516296	27.6	M.V. Nulialjuk	Van Veen	0.07	0.37	0.30	0.1110	Y	Y
25	G4		10-Oct-16	7:35	63.72261667	-68.516466	27.6	M.V. Nulialjuk	Van Veen	0.10	0.37	0.30	0.1110	Y	Y
26	G2		10-Oct-16	8:45	63.712755	-68.503121	35.2	M.V. Nulialjuk	Van Veen	0.05	0.37	0.30	0.1110	Y	Y
26	G3		10-Oct-16	8:55	63.712595	-68.503075	35.9	M.V. Nulialjuk	Van Veen	0.07	0.37	0.30	0.1110	Y	Y
26	G4		10-Oct-16	9:05	63.71231333	-68.502588	37.8	M.V. Nulialjuk	Van Veen	0.07	0.37	0.30	0.1110	Y	Y
27	G1		10-Oct-16	17:30	63.69688167	-68.489226	33.1	M.V. Nulialjuk	Van Veen	0.09	0.37	0.30	0.1110	Y	Y
27	G2		10-Oct-16	17:35	63.69708333	-68.488943	30.1	M.V. Nulialjuk	Van Veen	0.08	0.37	0.30	0.1110	Y	Y
27	G3		10-Oct-16	17:40	63.69699833	-68.489645	???	M.V. Nulialjuk	Van Veen	0.08	0.37	0.30	0.1110	Y	Y
28	G1		10-Oct-16	10:30	63.70996333	-68.521091	11.5	M.V. Nulialjuk	Van Veen	0.03	0.37	0.30	0.1110	Y	Y
28	G4		10-Oct-16	10:40	63.70998833	-68.521396	10.3	M.V. Nulialjuk	Van Veen	0.03	0.28	0.30	0.0833	Y	Y
28	G5		10-Oct-16	10:45	63.71012167	-68.521781	10.2	M.V. Nulialjuk	Petite Ponar	0.05	0.16	0.16	0.0240	Y	Y
5b	G2		10-Oct-16	14:00	63.725545	-68.520935	8.5	M.V. Nulialjuk	Petite Ponar	0.03	0.16	0.16	0.0240	Y	Y
5b	G3		10-Oct-16	14:05	63.72553833	-68.52046	10.5	M.V. Nulialjuk	Petite Ponar	0.05	0.16	0.16	0.0240	Y	Y
5b	G4		10-Oct-16	14:10	63.72573167	-68.521918	15.4	M.V. Nulialjuk	Petite Ponar	0.03	0.16	0.16	0.0240	Y	Y
5	G1		10-Nov-16	8:55	63.67292333	-68.429376	57	M.V. Nulialjuk	Van Veen	0.09	0.19	0.30	0.0555	Y	Y
5	G2		10-Nov-16	9:00	63.67350667	-68.428265	58.6	M.V. Nulialjuk	Van Veen	0.13	0.37	0.30	0.1110	Y	Y
5	G3		10-Nov-16	9:05	63.673585	-68.430486	56.3	M.V. Nulialjuk	Van Veen	0.08	0.37	0.30	0.1110	Y	Y
5a	G7		14/10/2016	7:10	63.66833667	-68.433588	69.2	M.V. Nulialjuk	Van Veen	0.12	0.37	0.30	0.1110	Y	Y
5a	G8		14/10/2016	7:15	63.66823	-68.433846	68.1	M.V. Nulialjuk	Van Veen	0.09	0.37	0.30	0.1110	Y	Y
5a	G9		14/10/2016	7:20	63.66869667	-68.433573	70	M.V. Nulialjuk	Van Veen	0.07	0.37	0.30	0.1110	Y	Y
5c	G1		10-Nov-16	13:30	63.661055	-68.421603	77.2	M.V. Nulialjuk	Van Veen	0.10	0.37	0.30	0.1110	Y	Y
5c	G2		10-Nov-16	13:40	63.660845	-68.422138	66.3	M.V. Nulialjuk	Van Veen	0.08	0.37	0.30	0.1110	Y	Y
5c	G4		10-Nov-16	13:45	63.66101667	-68.421953	74.1	M.V. Nulialjuk	Van Veen	0.07	0.37	0.30	0.1110	Y	Y
5d	G1		10-Nov-16	7:55	63.67759333	-68.420925	25	M.V. Nulialjuk	Van Veen	0.07	0.37	0.30	0.1110	Y	Y
5d	G2		10-Nov-16	8:00	63.67804833	-68.422216	27	M.V. Nulialjuk	Van Veen	0.10	0.37	0.30	0.1110	Y	Y
5d	G3		10-Nov-16	8:20	63.67785167	-68.421238	23.9	M.V. Nulialjuk	Van Veen	0.08	0.37	0.30	0.1110	Y	Y
5e	G1		10-Nov-16	7:00	63.67566833	-68.430296	52.3	M.V. Nulialjuk	Van Veen	0.13	0.28	0.30	0.0833	Y	Y

5e	G2		10-Nov-16	7:25	63.67572333	-68.431281	53.7	M.V. Nulialjuk	Van Veen	0.05	0.37	0.30	0.1110	Y	Y
5e	G3		10-Nov-16	7:30	63.67519167	-68.429913	55.4	M.V. Nulialjuk	Van Veen	0.08	0.37	0.30	0.1110	Y	Y
5f	G6		10-Nov-16	14:10	63.663945	-68.419608	90.1	M.V. Nulialjuk	Van Veen	0.09	0.37	0.30	0.1110	Y	Y
5f	G7		10-Nov-16	14:20	63.66412833	-68.42056	88.2	M.V. Nulialjuk	Van Veen	0.06	0.19	0.30	0.0555	Y	Y
5f	G8		10-Nov-16	14:30	63.66423833	-68.41944	90.2	M.V. Nulialjuk	Van Veen	N/A	N/A	N/A	N/A	Y	Y
5f	G9		10-Nov-16	14:40	63.66399167	-68.419753	89.9	M.V. Nulialjuk	Van Veen	N/A	N/A	N/A	N/A	Y	Y
5g	G1		10-Nov-16	11:20	63.662085	-68.414433	93.8	M.V. Nulialjuk	Van Veen	0.06	0.37	0.30	0.1110	Y	Y
5g	G2		10-Nov-16	11:20	63.662085	-68.414425	92.8	M.V. Nulialjuk	Van Veen	N/A	N/A	N/A	N/A	Y	Y
5g	G3		10-Nov-16	11:20	63.66272333	-68.41404	86.1	M.V. Nulialjuk	Van Veen	N/A	N/A	N/A	N/A	Y	Y
5g	G4		10-Nov-16	11:20	63.66222	-68.413978	90.8	M.V. Nulialjuk	Van Veen	0.11	0.37	0.30	0.1110	Y	Y
FB2-1(5g)	Rep1		16-Jul-16	19:39	63.66358333	-68.422383	80	CCGS Amundsen	Box Core	0.15	0.51	0.25	0.1290	Y	Y
FB2-1(5g)	Rep2		16-Jul-16	19:53	63.6635	-68.422	80	CCGS Amundsen	Box Core	0.15	0.51	0.25	0.1290	Y	Y
FB2-1(5g)	Rep3		16-Jul-16	20:06	63.6635	-68.421666	81	CCGS Amundsen	Box Core	0.15	0.51	0.25	0.1290	Y	Y
FB2-2(5e)	Rep1		16-Jul-16	18:39	63.67523333	-68.43035	63	CCGS Amundsen	Box Core	0.15	0.51	0.25	0.1290	Y	Y
FB2-2(5e)	Rep2		16-Jul-16	18:59	63.67528333	-68.430466	62	CCGS Amundsen	Box Core	0.15	0.51	0.25	0.1290	Y	Y
FB2-2(5e)	Rep3		16-Jul-16	19:14	63.67521667	-68.430483	62	CCGS Amundsen	Box Core	0.15	0.51	0.25	0.1290	Y	Y
* Van Veen - 22D x 37L x 30W (cm); Petite Ponar - 11D x 15.5L x 15.5D (cm); Peterson Grab - Approx 30 x 30 (cm)															

Appendix 3. Supporting long-term environmental data collected in Frobisher Bay.

Temperature

Year	Month	Mean Temperature (°C)
1967	January	-23.5
1967	February	-35.6
1967	March	-26.5
1967	April	-17.4
1967	May	-0.8
1967	June	2.9
1967	July	7.7
1967	August	7.2
1967	September	1.1
1967	October	-6.2
1967	November	-14.6
1967	December	-19.5
1968	January	-27.5
1968	February	-24.2
1968	March	-26.9
1968	April	-10.5
1968	May	-4.2
1968	June	2.8
1968	July	6.3
1968	August	6.7
1968	September	3.3
1968	October	0
1968	November	-12
1968	December	-18.9
1969	January	-19.8
1969	February	-16.9
1969	March	-23
1969	April	-19.5
1969	May	-3.6
1969	June	3.7
1969	July	9.8
1969	August	6.9
1969	September	1.9
1969	October	-5.4

1969	November	-10.5
1969	December	-20.3
1970	January	-24.1
1970	February	-26.3
1970	March	-18.5
1970	April	-16.7
1970	May	-6.9
1970	June	1.6
1970	July	5.9
1970	August	6.5
1970	September	2.2
1970	October	-3.2
1970	November	-9.9
1970	December	-23.1
1971	January	-22.4
1971	February	-26.9
1971	March	-17.8
1971	April	-12.9
1971	May	-4
1971	June	3.8
1971	July	6.6
1971	August	7.1
1971	September	1.4
1971	October	-3.2
1971	November	-11.9
1971	December	-29.9
1972	January	-32.4
1972	February	-31.1
1972	March	-27.5
1972	April	-15.3
1972	May	-6.9
1972	June	-0.1
1972	July	5.7
1972	August	5.2
1972	September	0.8
1972	October	-7

1972	November	-15.6
1972	December	-28.6
1973	January	-29.1
1973	February	-29.8
1973	March	-25.5
1973	April	-14.3
1973	May	-3.3
1973	June	3.6
1973	July	7.3
1973	August	8
1973	September	4.3
1973	October	-2.9
1973	November	-7.6
1973	December	-22.8
1974	January	-30.7
1974	February	-26.3
1974	March	-25
1974	April	-17.2
1974	May	-2.8
1974	June	5.5
1974	July	8.6
1974	August	7
1974	September	1.7
1974	October	-5.1
1974	November	-13.9
1974	December	-27.9
1975	January	-29.7
1975	February	-24.8
1975	March	-25.6
1975	April	-16.2
1975	May	-3.2
1975	June	6.9
1975	July	7.7
1975	August	8.3
1975	September	2.6
1975	October	-3
1975	November	-12.6
1975	December	-22.6
1976	January	-25.4
1976	February	-29.4
1976	March	-25.7

1976	April	-14.7
1976	May	-2.7
1976	June	3.4
1976	July	6
1976	August	5.1
1976	September	1.8
1976	October	-10.4
1976	November	-13.3
1976	December	-22.2
1977	January	-16.2
1977	February	-24.9
1977	March	-16.3
1977	April	-14.1
1977	May	-2.5
1977	June	4.4
1977	July	8.1
1977	August	7
1977	September	2.5
1977	October	-3.8
1977	November	-7
1977	December	-22.8
1978	January	-30.7
1978	February	-22.2
1978	March	-27.6
1978	April	-15.9
1978	May	-6.3
1978	June	0.6
1978	July	5.8
1978	August	6.8
1978	September	1.9
1978	October	-10
1978	November	-21.9
1978	December	-15.1
1979	January	-21.6
1979	February	-32.2
1979	March	-21.7
1979	April	-11.2
1979	May	-0.5
1979	June	2.7
1979	July	7.5
1979	August	6.3

1979	September	2
1979	October	-3.5
1979	November	-15.3
1979	December	-23.5
1980	January	-20.4
1980	February	-25.3
1980	March	-19.5
1980	April	-15.8
1980	May	-1
1980	June	4.4
1980	July	7.4
1980	August	7.7
1980	September	1.5
1980	October	-3.5
1980	November	-10.1
1980	December	-22.4
1981	January	-21.1
1981	February	-22.1
1981	March	-13.2
1981	April	-13.3
1981	May	-4.8
1981	June	3.8
1981	July	9
1981	August	7.5
1981	September	4
1981	October	-2.2
1981	November	-11.4
1981	December	-16.8
1982	January	-18.8
1982	February	-28.9
1982	March	-27.3
1982	April	-16.5
1982	May	-5.6
1982	June	3.9
1982	July	7.5
1982	August	6.6
1982	September	-0.2
1982	October	-5.9
1982	November	-13.8
1982	December	-27.7
1983	January	-33.9

1983	February	-31.5
1983	March	-26.4
1983	April	-13.3
1983	May	-6.1
1983	June	3.8
1983	July	7.7
1983	August	5.9
1983	September	1.9
1983	October	-5.7
1983	November	-16.2
1983	December	-26.2
1984	January	-33.3
1984	February	-31.7
1984	March	-23
1984	April	-15.7
1984	May	-5.1
1984	June	3.6
1984	July	9
1984	August	6
1984	September	1.6
1984	October	-4.5
1984	November	-13.8
1984	December	-24.6
1985	January	-17.9
1985	February	-24.9
1985	March	-23.8
1985	April	-17.4
1985	May	-4
1985	June	6.3
1985	July	8.9
1985	August	8.2
1985	September	3.6
1985	October	-3.4
1985	November	-9.6
1985	December	-11.8
1986	January	-25.9
1986	February	-20.1
1986	March	-26
1986	April	-12.9
1986	May	-3.5
1986	June	1.8

1986	July	8.8
1986	August	5.9
1986	September	2.5
1986	October	-10.8
1986	November	-17.3
1986	December	-26.4
1987	January	-28.3
1987	February	-29.2
1987	March	-24.6
1987	April	-16.2
1987	May	-7.7
1987	June	3.5
1987	July	7.6
1987	August	6
1987	September	4.2
1987	October	-4.1
1987	November	-14.1
1987	December	-21.4
1988	January	-28.2
1988	February	-26.5
1988	March	-21
1988	April	-12.6
1988	May	-4.4
1988	June	2.9
1988	July	7.2
1988	August	7.8
1988	September	3.4
1988	October	-1.2
1988	November	-12.7
1988	December	-25.6
1989	January	-31.6
1989	February	-30.7
1989	March	-28.5
1989	April	-13.2
1989	May	-7.6
1989	June	3.8
1989	July	8.6
1989	August	7
1989	September	0.6
1989	October	-6.9
1989	November	-11.7

1989	December	-21.3
1999	January	-29.4
1990	February	-31.9
1990	March	-22.8
1990	April	-17.4
1990	May	-5.2
1990	June	3.3
1990	July	8.3
1990	August	6.1
1990	September	2
1990	October	-6.5
1990	November	-12.3
1990	December	-27.4
1991	January	-32.1
1991	February	-29
1991	March	-22.5
1991	April	-17.8
1991	May	-7.1
1991	June	6.2
1991	July	9.2
1991	August	8.2
1991	September	2.3
1991	October	-5
1991	November	-9.8
1991	December	-21.9
1992	January	-25.4
1992	February	-33.4
1992	March	-27.1
1992	April	-19.2
1992	May	-8.3
1992	June	0.6
1992	July	7.3
1992	August	6.7
1992	September	1.7
1992	October	-2.8
1992	November	-18.4
1992	December	-25.7
1993	January	-31.5
1993	February	-34.6
1993	March	-27.2
1993	April	-18.9

1993	May	-4.1
1993	June	3.8
1993	July	6.2
1993	August	6.2
1993	September	1.9
1993	October	-3.9
1993	November	-16.4
1993	December	-26.3
1994	January	-26.5
1994	February	-27.1
1994	March	-26.2
1994	April	-13.4
1994	May	-2.8
1994	June	3.6
1994	July	7.3
1994	August	6
1994	September	1.9
1994	October	-3.5
1994	November	-13.6
1994	December	-22.1
1995	January	-23.6
1995	February	-28.8
1995	March	-24.8
1995	April	-9.6
1995	May	-0.9
1995	June	4.8
1995	July	7.2
1995	August	8
1995	September	1.8
1995	October	-3.5
1995	November	-5.7
1995	December	-21.8
1996	January	-26.7
1996	February	-22.8
1996	March	-23.2
1996	April	-8.7
1996	May	-3.8
1996	June	2.2
1996	July	8.9
1996	August	6.2
1996	September	2.8

1996	October	
1996	November	-11.8
1996	December	-15.9
1997	January	-25.1
1997	February	-31.1
1997	March	-21.2
1997	April	-15.4
1997	May	-1.1
1997	June	5.5
1997	July	8.1
1997	August	7.2
1997	September	2.4
1997	October	-3
1997	November	-10.8
1997	December	-19.1
1998	January	-28.9
1998	February	-30.2
1998	March	-25.8
1998	April	-12.9
1998	May	-2.8
1998	June	5.8
1998	July	7
1998	August	8.4
1998	September	3.9
1998	October	-3.5
1998	November	-9.4
1998	December	-18.2
1999	January	-28
1999	February	-29
1999	March	-18.8
1999	April	-10.9
1999	May	-4.4
1999	June	2
1999	July	7.4
1999	August	6.8
1999	September	2.7
1999	October	-4.8
1999	November	-15.4
1999	December	-15.5
2000	January	-27.4
2000	February	-28.6

2000	March	-21.2
2000	April	-12.4
2000	May	-5.9
2000	June	2.4
2000	July	9
2000	August	8.7
2000	September	3.1
2000	October	-4.9
2000	November	-9.2
2000	December	-12.9
2001	January	-28.9
2001	February	-27.9
2001	March	-17
2001	April	-12.9
2001	May	-3.2
2001	June	3.6
2001	July	9.9
2001	August	7
2001	September	3.1
2001	October	-1.8
2001	November	-13
2001	December	-15.4
2002	January	-28.7
2002	February	-29.9
2002	March	-25.9
2002	April	-15.3
2002	May	-4.2
2002	June	4.1
2002	July	8.7
2002	August	7.5
2002	September	3
2002	October	-1.6
2002	November	-11
2002	December	-17.6
2003	January	-21.1
2003	February	-30.8
2003	March	-23.8
2003	April	-13.4
2003	May	-0.8
2003	June	3.5
2003	July	9

2003	August	7.8
2003	September	4.6
2003	October	-1.3
2003	November	-8.7
2003	December	-16.6
2004	January	-25.6
2004	February	-23.2
2004	March	-26.5
2004	April	-14.9
2004	May	-1.9
2004	June	3.8
2004	July	8.4
2004	August	6.4
2004	September	2.6
2004	October	-1.1
2004	November	-10.4
2004	December	-24.2
2005	January	-31.1
2005	February	-22.6
2005	March	-17
2005	April	-10
2005	May	-2.5
2005	June	4.2
2005	July	7.7
2005	August	7.1
2005	September	3.4
2005	October	-0.8
2005	November	-7.7
2005	December	-21
2006	January	-26.4
2006	February	-21.3
2006	March	-17.2
2006	April	-11.3
2006	May	-0.6
2006	June	4.5
2006	July	9.4
2006	August	8.3
2006	September	3.9
2006	October	-0.6
2006	November	-9.2
2006	December	-19.1

2007	January	-24.4
2007	February	-18.8
2007	March	-23
2007	April	-14.1
2007	May	-5.9
2007	June	3.2
2007	July	6.6
2007	August	8.2
2007	September	2.4
2007	October	-4.6
2007	November	-11.3
2007	December	-23.6
2008	January	
2008	February	
2008	March	
2008	April	
2008	May	
2008	June	
2008	July	
2008	August	7
2008	September	2.4
2008	October	-3.3
2008	November	-14.4
2008	December	-24.2
2009	January	-24.4
2009	February	-24.8
2009	March	-21.6
2009	April	-14.7
2009	May	-5.4
2009	June	3.7
2009	July	10.5
2009	August	7.3
2009	September	2
2009	October	-5.5
2009	November	-12.1
2009	December	-13.4
2010	January	-21.6
2010	February	-17.4
2010	March	-19.5
2010	April	-9.9
2010	May	-1.7

2010	June	5.3
2010	July	9.3
2010	August	9.2
2010	September	5.2
2010	October	0.8
2010	November	-2.2
2010	December	-8.5
2011	January	-16.9
2011	February	-28.2
2011	March	-23.8
2011	April	-17.4
2011	May	-5
2011	June	4
2011	July	8.8
2011	August	7.3
2011	September	3.2
2011	October	-4.7
2011	November	-9.5
2011	December	-16.3
2012	January	-26.9
2012	February	-24.8
2012	March	-24.2
2012	April	-13.2
2012	May	-0.6
2012	June	4.7
2012	July	7.5
2012	August	7.2
2012	September	4.1
2012	October	-3.4
2012	November	-10
2012	December	-17.1
2013	January	-24.9
2013	February	-24.3
2013	March	-15.9
2013	April	-10.7
2013	May	-6.7
2013	June	2.8
2013	July	7.2
2013	August	7.6
2013	September	2.3
2013	October	-1.6

2013	November	-15.2
2013	December	-23.2
2014	January	-19.3
2014	February	-25.8
2014	March	-25.3
2014	April	-17.8
2014	May	-1.7
2014	June	4.4
2014	July	9.1
2014	August	7.4
2014	September	2.4
2014	October	-3.4
2014	November	-12.6
2014	December	-20.1
2015	January	-31.2
2015	February	-32.1
2015	March	-25.4
2015	April	-14.7
2015	May	-3.5
2015	June	2.2
2015	July	4.2
2015	August	5.7
2015	September	2.4
2015	October	-4.8
2015	November	-12.9
2015	December	-23.5
2016	January	-23.6
2016	February	-24.8
2016	March	-22.8
2016	April	-11.8
2016	May	-1.4
2016	June	4.9
2016	July	6.2
2016	August	8.8
2016	September	3.1
2016	October	-6.1
2016	November	-10.7
2016	December	-21.7
2017	January	-20.4
2017	February	-27.7
2017	March	-23

2017	April	-14.9
2017	May	-2.4
2017	June	4.6
2017	July	7.4
2017	August	8
2017	September	2.5
2017	October	-3.3
2017	November	-8.9
2017	December	-15.7

Length of Ice Season and Ice Thickness

Year	Ice Season Length (Days)	Max Ice Thickness (cm)
1967	203	175
1968	224	165
1969	204	147
1970	203	155
1971	207	165
1972	237	202
1973	249	197
1974	198	185
1975	203	183
1976	210	178
1977	203	132
1978	210	183
1979	231	170
1980	217	171
1981	203	157
1982	203	164
1983	223	183
1984	212	192
1985	202	180
1986	182	110
1987	210	175
1988	210	165
1989	209	187
1990	203	185
1991	217	153
1992		
1993		202
1994	217	168

1995	196	157
1996	196	164
1997		
1998		156
1999		150
2000		
2001		
2002		148
2003	132	158
2004		
2005		145
2006	132	156
2007		
2008		
2009		165
2010	72	120
2011	150	139
2012	130	166
2013	134	138
2014	150	180
2015	157	180
2016	134	175

1986	7.32	243	96	84.5
1987	105	191	71.4	52.5
1989	101	174	78	33.9
1990	93.8	145	106	49
1991	85.7	74	68.9	72.2
1992	13.7	204	58.9	29.8
1993		80.2	87.6	56.2
1994	118	167	79.8	37.4
1995	112	64.6	71.4	45
1996		283	93.5	47.9
1997		103		
1998			28.7	19
1999		219	107	52.1
2006		124	40.8	80.8
2007	135	124	82.7	40.3
2008	184	55.4	28.4	40.7
2009	185	114	35.4	43.3
2010	152	72.8	65.8	46.5
2011	98.3	127	57.2	41.2
2012	142	65.3	62.4	82.1
2013		184	36.3	33
2014		69	82	56.6
2015		228	45.8	36.2

Sylvia Grinnell River Discharge

Year	Month			
	June	July	Aug	Sep
1971	42.2	158	57.2	42.5
1972	4.4	132	79.6	48.6
1973	89.3	223	76.6	56
1974		78.7	67.9	
1975		120	71.2	59.3
1976		236	95.7	35.5
1977		164	48.3	41.9
1978		342	123	
1979		283	121	130
1980		86.2	36.2	28.9
1981		115	44.8	
1982		73.8	66.2	33.9
1983	126	188	74.5	28.8
1984	64.5	112	74.6	50.6
1985	148	101	53.8	63.5

Apex River Discharge

Year	June	July	Aug	Sept	Oct
1973	3.84	2.66	0.913	1.44	
1974		0.379	1.05		
1975		1.48	1.03	0.806	
1976		2.44	0.895	0.47	
1977		1.62	0.612	0.437	
1978		4.93	1.63		
1979		2.24	1.13	1.42	
1980		0.896	0.34	0.57	
1981		0.901	0.325		
1982	2.22	1.06	0.567	0.673	0.021
1983	3.27	1.41	0.179	0.154	
1985	3.11	1.46	0.975	1.41	
1986	2.6	3.59	2.13	1.94	0.099
1987	4.59	2.5	1.46	1.14	
1988	2.39	2.84	1.31	0.888	0.253

1989	1.78	1.89	1.2	0.471	0.031
1990	2.7	2.04	2.12	1.26	0.108
1991	1.67	0.469	1.16	2.07	0.269
1992	0.457	3.57	0.601	0.45	0.189
1993		0.863	1.93	0.972	0.357
1994	3.6	0.968	1.21	0.863	0.745
1995		0.751	1.5	1.31	0.251
2006				1.59	1.6
2007	3.43	2.18	2.19	0.525	0.046
2008	3.11	1.01	0.652	1.09	0.15
2009	3.87	1.61	1.02	1.5	0.077
2010	3.83	0.947	1.71	1.18	1.13
2011	3.55	1.44	0.954	0.974	0.162
2012	3.82	0.728	1.01	2.05	0.578
2013	4.32	2.81	0.501	0.872	1.21
2014	5.22	0.883	1.63	1.13	0.257
2015	3.05	3.61	0.778	0.6	0.158

Appendix 4. Sediment grain size (sand and silt fractions) data collected by Wacasey *et al.* (1979, 1980) between 1967-1976 and compared with grain size (sand and silt fractions) collected in Frobisher Bay in 2016).

Iqaluit Grain Size

Station	Replicate	Date	Time Period	Sand (%)	Silt (%)	Depth (m)
5b		3-Sep-69	Historical	66.7	33.3	15
5b		8-Aug-73	Historical	37.8	62.2	14
5b		19-Aug-76	Historical	58.6	41.4	14
25		8-Aug-73	Historical	56.4	43.6	30
25		18-Aug-76	Historical	65.2	34.8	28
26		8-Aug-73	Historical	56.8	43.2	40
27		8-Aug-73	Historical	55.7	44.3	43
28		13-Aug-73	Historical	75.6	24.4	30
25	G1	10-Oct-16	Modern	56.1	43.9	28.5
25	G2	10-Oct-16	Modern	54.9	45.1	27.6
25	G4	10-Oct-16	Modern	45.7	54.3	27.6
26	G2	10-Oct-16	Modern	56.2	43.8	35.2
26	G3	10-Oct-16	Modern	58.6	41.4	35.9
26	G4	10-Oct-16	Modern	52.1	47.9	37.8
27	G1	10-Oct-16	Modern	33.7	66.3	33.1
27	G2	10-Oct-16	Modern	35.3	64.7	30.1
27	G3	10-Oct-16	Modern	54.5	45.5	
28	G1	10-Oct-16	Modern	73.2	26.8	11.5
28	G4	10-Oct-16	Modern	73.2	26.8	10.3
28	G5	10-Oct-16	Modern	72.8	27.2	10.2
5b	G2	10-Oct-16	Modern	66.3	33.7	8.5
5b	G3	10-Oct-16	Modern	39.4	60.6	10.5
5b	G4	10-Oct-16	Modern	67	33	15.4

Cairn Island Grain Size

Station	Replicate	Date	Time Period	Sand (%)	Silt (%)	Depth (m)
5a		1-Aug-68	Historical	45.5	54.5	26
5a		2-Sep-69	Historical	30	70	36
5		20-Aug-68	Historical	40.8	59.2	60
5		2-Sep-69	Historical	39	61	53
5		2-Sep-69	Historical	26.3	73.7	53
5c		23-Aug-69	Historical	54.4	45.6	31
5d		23-Aug-69	Historical	38.1	61.9	43
5e		23-Aug-69	Historical	37.7	62.3	58

5f		23-Aug-69	Historical	34.7	65.3	73
5g		2-Sep-69	Historical	34.1	65.9	73
5	G1	14-Oct-16	Modern	26.4	73.6	57
5	G2	14-Oct-16	Modern	27.3	72.7	58.6
5	G3	14-Oct-16	Modern	37.9	62.1	56.3
5a	G7	14-Oct-16	Modern	37.1	62.9	69.2
5a	G8	14-Oct-16	Modern	36.1	63.9	68.1
5a	G9	14-Oct-16	Modern	45	55	70
5c	G1	11-Oct-16	Modern	41.3	58.7	77.2
5c	G2	11-Oct-16	Modern	39.3	60.7	66.3
5c	G4	11-Oct-16	Modern	51.5	48.5	74.1
5d	G1	11-Oct-16	Modern	28.9	71.1	25
5d	G2	11-Oct-16	Modern	37.9	62.1	27
5d	G3	11-Oct-16	Modern	32.8	67.2	23.9
5e (FB2-2)	G1	16-Jul-16	Modern	13.3	86.7	63
5e (FB2-2)	G2	16-Jul-16	Modern	18.8	81.2	62
5e (FB2-2)	G3	16-Jul-16	Modern	14.4	85.6	62
5e	G2	11-Oct-16	Modern	24.7	75.3	53.7
5e	G3	11-Oct-16	Modern	23.2	76.8	55.4
5f	G6	11-Oct-16	Modern	41.7	58.3	90.1
5f	G7	11-Oct-16	Modern	38.7	61.3	88.2
5f	G8	11-Oct-16	Modern	22.5	77.5	90.2
5f	G9	11-Oct-16	Modern	24.2	75.8	89.9
5g	G1	11-Oct-16	Modern	21.1	78.9	93.8
5g	G3	11-Oct-16	Modern	38.6	61.4	86.1
5g	G4	11-Oct-16	Modern	28.8	71.2	90.8
5g (FB2-1)	G1	16-Jul-16	Modern	30.6	69.4	80
5g (FB2-1)	G2	16-Jul-16	Modern	34.6	65.4	80
5g (FB2-1)	G3	16-Jul-16	Modern	28.1	71.9	81

Iqaluit Organic Total Organic Carbon and Total Nitrogen

Station	Year	Date	Time Period	TotalN (%)	OrgC(%)	Depth (m)
25	1973	8-Aug-73	Historical	0.093	0.87	30
25	1976	18-Aug-73	Historical	0.103	1.1	28
A-25-G1	2016	10-Oct-16	Modern	0.08	0.68	28.5
A-25-G2	2016	10-Oct-16	Modern	0.08	0.71	27.6
A-25-G4	2016	10-Oct-16	Modern	0.1	0.83	27.6
26	1973	8-Aug-73	Historical	0.136	0.98	40
A-26-G2	2016	10-Oct-16	Modern	0.1	1.08	35.1

A-26-G2	2016	10-Oct-16	Modern	0.1	1.18	35.2
A-26-G3	2016	10-Oct-16	Modern	0.1	0.97	35.9
A-26-G4	2016	10-Oct-16	Modern	0.11	0.97	37.8
27	1973	8-Aug-73	Historical	0.216	1.56	43
A-27-G1	2016	10-Oct-16	Modern	0.2	1.77	33.1
A-27-G2	2016	10-Oct-16	Modern	0.25	2.13	30.1
A-27-G3	2016	10-Oct-16	Modern	0.18	1.42	
28	1973	13-Aug-73	Historical	0.09	0.87	30
A-28-G1	2016	10-Oct-16	Modern	0.05	0.59	11.5
A-28-G4	2016	10-Oct-16	Modern	0.05	0.62	10.3
A-28-G5	2016	10-Oct-16	Modern	0.04	0.51	10.2
5b	1969	3-Sep-69	Historical	0.067	0.52	15
5b	1973	8-Aug-73	Historical	0.153	0.58	14
5b	1976	19-Aug-73	Historical	0.128	1.62	14
A-5b-G2	2016	10-Oct-16	Modern	0.04	0.3	8.5
A-5b-G3	2016	10-Oct-16	Modern	0.07	0.63	10.5
A-5b-G4	2016	10-Oct-16	Modern	0.03	0.37	15.4

Cairn Island Total Organic Carbon and Total Nitrogen

Station	Year	Date	Time Period	TotalN	OrgC	Depth (m)
B-5-G1	2016	11-Oct-16	Modern	0.25	2.32	57
B-5-G2	2016	11-Oct-16	Modern	0.25	2.24	58.6
B-5-G3	2016	11-Oct-16	Modern	0.2	2.09	56.3
B-5a-G7	2016	14-Oct-16	Modern	0.2	1.71	69.2
B-5a-G8	2016	14-Oct-16	Modern	0.23	2.59	68.1
B-5a-G9	2016	14-Oct-16	Modern	0.24	1.98	70
B-5c-G1	2016	10-Oct-16	Modern	0.23	2.08	77.2
B-5c-G2	2016	10-Oct-16	Modern	0.21	1.95	66.3
B-5c-G3	2016	10-Oct-16	Modern	0.2	1.74	74.1
FB2-2-Rep1	2016	16-Jul-16	Modern	0.27	2.33	63
FB2-2-Rep2	2016	16-Jul-16	Modern	0.25	2.24	62
FB2-2-Rep3	2016	16-Jul-16	Modern	0.27	2.4	62
B-5d G1	2016	10-Oct-16	Modern	0.32	2.65	25
B-5d G2	2016	10-Oct-16	Modern	0.22	1.99	27
B-5d G3	2016	10-Oct-16	Modern	0.27	2.37	23.9
B-5e-G1	2016	10-Oct-16	Modern	0.23	2.01	52.3
B-5e-G2	2016	10-Oct-16	Modern	0.16	1.45	53.7
B-5e-G3	2016	10-Oct-16	Modern	0.23	1.57	55.4
B-5f-G6	2016	10-Oct-16	Modern	0.2	1.82	90.1

B-5f-G7	2016	10-Oct-16	Modern	0.22	1.97	88.2
B-5f-G8	2016	10-Oct-16	Modern	0.21	1.85	90.2
B-5f-G9	2016	10-Oct-16	Modern	0.21	1.87	89.9
B-5g-G1	2016	10-Oct-16	Modern	0.26	2.31	93.8
B-5g-G3	2016	10-Oct-16	Modern	0.27	2.34	86.1
B-5g-G4	2016	10-Oct-16	Modern	0.27	2.34	90.8
FB2-1-Rep1	2016	16-Jul-16	Modern	0.25	2.25	80
FB2-1-Rep2	2016	16-Jul-16	Modern	0.28	2.5	80
FB2-1-Rep3	2016	16-Jul-16	Modern	0.19	1.66	81
5a	1968	1-Aug-68	Historical	0.261	1.86	26
5	1968	20-Aug-68	Historical	0.18	1.45	60
5c	1969	23-Aug-69	Historical	0.18	1.57	31
5d	1969	23-Aug-69	Historical	0.212	1.57	43
5e	1969	23-Aug-69	Historical	0.218	1.39	58
5f	1969	23-Aug-69	Historical	0.185	1.91	73

Iqaluit Carbon/Nitrogen Ratios

Station	Time_Period	C_N_Ratio
5b - H	Historical	7.76
5b - H	Historical	12.08
5b - H	Historical	10.94
5b - H	Historical	3.79
5b - H	Historical	12.66
5b - M	Modern	6.91
5b - M	Modern	9.47
5b - M	Modern	14.35
25 - H	Historical	9.35
25 - H	Historical	10.68
25 - M	Modern	8.43
25 - M	Modern	9.05
25 - M	Modern	8.52
26 - H	Historical	7.21
26 - M	Modern	11.29
26 - M	Modern	11.67
26 - M	Modern	10.22
26 - M	Modern	8.52
27 - H	Historical	7.22
27 - M	Modern	8.98
27 - M	Modern	8.44

27 - M	Modern	8.11
28 - H	Historical	9.67
28 - M	Modern	12.55
28 - M	Modern	11.87
28 - M	Modern	12.63

Cairn Island Carbon/Nitrogen Ratios

Station	Time_Period	C_N_Ratio
5 - H	Historical	8.06
5 - H	Historical	11.17
5 - M	Modern	9.34
5 - M	Modern	8.91
5 - M	Modern	10.24
5a - H	Historical	7.13
5a - M	Modern	8.46
5a - M	Modern	11.39
5a - M	Modern	8.40
5c - H	Historical	8.72
5c - M	Modern	8.89
5c - M	Modern	9.24
5d - H	Historical	7.41

5d - M	Modern	8.812183
5d - M	Modern	8.216718
5d - M	Modern	8.981982
5d - M	Modern	8.821561
5e - H	Historical	6.376147
5e - M	Modern	8.815789
5e - M	Modern	9.132075
5e - M	Modern	6.898678
5e - M	Modern	8.701493
5e - M	Modern	8.976
5e - M	Modern	8.78022
5f - H	Historical	10.32432
5f - M	Modern	9.34359
5f - M	Modern	8.851351
5f - M	Modern	8.735849
5f - M	Modern	8.843602

Appendix 5. Relative abundance (#/m²) of molluscs collected in Frobisher Bay.

	<i>Astarte borealis</i>	<i>Astarte montagui</i>	<i>Axinopsida orbiculata</i>	<i>Ciliatocardium ciliatum</i>	<i>Crenella faba</i>	<i>Dacrydium vitreum</i>	<i>Ennucula tenuis</i>	<i>Hiatella arctica</i>	<i>Lyonisia arenosa</i>	<i>Macoma calcarea</i>	<i>Macoma loveni</i>	<i>Macoma moesta</i>	<i>Macoma torelli</i>	<i>Musculus discors</i>
25-2016			60.1				48.0			3.0		18.0		
26-2016	6.0	6.0					9.0	15.0		6.0		30.0		9.0
27-2016				12.0			15.0	15.0	3.0			9.0		
28-2016			50.4		4.6		0.0			4.6				
5b-2016	13.9		152.6				13.9							
5-2016	7.2	7.2		7.2		3.6	36.0	18.0		3.6		21.6		7.2
5a-2016	3.0	6.0		3.0			18.0			9.0	6.0	24.0		
5c-2016							15.0	6.0			6.0	3.0		
5d-2016							12.0	3.0				6.0		6.0
5e-2016							32.8	3.3				3.3		
5f-2016	6.0					12.0	24.0	6.0		6.0	18.0			6.0
5e-2016Box		2.7		10.7		2.7	2.7	18.7		2.7	2.7	8.0		45.3
5a-Aug1-68	7.5	15					107.5			5				20
5a-Aug20-68	5	15					37.5	35						37.5
5-Jul23-68						17.5	30	35						15
5-Aug20-68				5		30	12.5	2.5						10
5-Sep3-68						12.5	25	25						22.5
5-Oct8-68				2.5				10						17.5
5-Aug6-70						17.5	52.5	22.5				2.5		55
5c-Aug23-69		5				5	15	67.5		35				197.5
5d-Aug23-69	2.5	2.5		2.5		17.5	25	45				5		22.5
5e-Aug23-69				2.5		12.5	20	15				5		30
5f-Aug23-69						32.5	25	5		5				20
A5b-Jul29-69			437.5				20	2.5		2.5				
5b-Sep3-69	7.5	2.5	660				20	7.5				12.5		2.5
5b-Aug8-73			693				39			3				
5b-Aug19-76	3		1722				27	3		36				
25-Aug8-73	9		93				45			6				
25-Aug18-76	24		1380				135			15		6		
26-Aug8-73	72		27			6	60	57	3	6		6		87
27-Aug8-73	3					3	48	72						66
28-Aug13-73	136	16	472				392		4.0	8.0		116.0	32	

	<i>Musculus niger</i>	<i>Mya truncata</i>	<i>Nuculana minuta</i>	<i>Nuculana pernula</i>	<i>Pandora glacialis</i>	<i>Parvicardium pinnulatum</i>	<i>Periploma aleuticum</i>	<i>Portlandia arctica</i>	<i>Serripes groenlandicus</i>	<i>Similipecten greenlandicus</i>	<i>Thracia myopsis</i>	<i>Thyasira dunbari</i>	<i>Thyasira gouldi</i>	<i>Yoldia hyperborea</i>
25-2016									3.0				0.0	15.0
26-2016	6.0	3.0	3.0	9.0				3.0			3.0		75.1	6.0
27-2016	6.0			3.0							6.0		252.3	
28-2016														
5b-2016											13.9	13.9		
5-2016	3.6		10.8	18.0				7.2					115.3	3.6
5a-2016	6.0			21.0				15.0	6.0				66.1	15.0
5c-2016				12.0					6.0		9.0		63.1	9.0
5d-2016		9.0	3.0	3.0									102.1	
5e-2016	3.3			3.3									55.7	6.6
5f-2016	18.0	6.0	6.0	24.0									108.1	12.0
5e-2016Box	2.7		0.0	10.7					2.7		5.3		13.3	2.7
5a-Aug1-68	2.5	7.5	25										95	
5a-Aug20-68		15	20										95	
5-Jul23-68	2.5	2.5	10										65	
5-Aug20-68			30				2.5			2.5			75	
5-Sep3-68			20	5	2.5								52.5	
5-Oct8-68	2.5	2.5	7.5										20	
5-Aug6-70	2.5		10	2.5	5		2.5						87.5	
5c-Aug23-69		22.5	45		2.5		5		2.5				137.5	
5d-Aug23-69	5	2.5	7.5										67.5	
5e-Aug23-69			22.5	2.5			5						85	
5f-Aug23-69	2.5	2.5	17.5	2.5									82.5	
A5b-Jul29-69		2.5											52.5	
5b-Sep3-69								5					72.5	
5b-Aug8-73													39	
5b-Aug19-76						3							48	3
25-Aug8-73								3					105	
25-Aug18-76		3		3					3				372	3
26-Aug8-73		3		15									819	
27-Aug8-73			12										234	
28-Aug13-73	4		28	32									600	4

	<i>Yoldiella lenticula</i>	<i>Admete viridula</i>	<i>Alvania moerchi</i>	<i>Alvania moerchi</i>	<i>Anatoma crispata</i>	<i>Anomalisipho verkruezeni</i>	<i>Ariadnaria borealis</i>	<i>Ariadnaria borealis</i>	<i>Astyris rosacea</i>	<i>Aulacofusus brevicauda</i>	<i>Boreotrophon clathratus</i>	<i>Buccinum hydrophanum</i>	<i>Buccinum undatum</i>	<i>Cardina laevis</i>	<i>Colus holboelli</i>	<i>Colus pubescens</i>	<i>Colus sabini</i>
25-2016		3.0															
26-2016		9.0														3.0	
27-2016			3.0														
28-2016																	
5b-2016						27.7	13.9										
5-2016	10.8										3.6						
5a-2016																	
5c-2016	6.0																3.0
5d-2016	0.0		6.0		3.0			9.0									
5e-2016	3.3		3.3		0.0					6.6							
5f-2016																	
5e-2016Box											2.7				5.3		
5a-Aug1-68																	
5a-Aug20-68					32.5							2.5					
5-Jul23-68					2.5									2.5		2.5	
5-Aug20-68															2.5		
5-Sep3-68															5		
5-Oct8-68																	
5-Aug6-70																	
5c-Aug23-69		2.5		5	30		2.5									2.5	
5d-Aug23-69					17.5												
5e-Aug23-69																	
5f-Aug23-69																	
A5b-Jul29-69																	
5b-Sep3-69																	
5b-Aug8-73																	
5b-Aug19-76																	
25-Aug8-73												3					
25-Aug18-76																	
26-Aug8-73															6		
27-Aug8-73							6								6		
28-Aug13-73		4													4		

	<i>Cryptonatica affinis</i>	<i>Curtitoma decussata</i>	<i>Curtitoma incisula</i>	<i>Curtitoma violacea</i>	<i>Cylichna alba</i>	<i>Cylichnooides ocellatus</i>	<i>Ecrobia truncata</i>	<i>Erginus rubellus</i>	<i>Euspira pallida</i>	<i>Flabellina salmonacea</i>	<i>Frigidoalvania cruenta</i>	<i>Lepeta caeca</i>	<i>Limneria undata</i>	<i>Margarites costalis</i>	<i>Margarites groenlandicus</i>	<i>Margarites helacinus</i>
25-2016					6.0	6.0										
26-2016	3.0	3.0			9.0	18.0										
27-2016					9.0	0.0						12.0			3.0	
28-2016																
5b-2016																
5-2016	10.8				10.8	3.6					10.8					3.6
5a-2016					3.0	9.0										3.0
5c-2016	3.0				9.0						6.0					3.0
5d-2016					6.0							6.0		3.0		3.0
5e-2016	3.3				22.9						9.8					
5f-2016		6.0			12.0						6.0	6.0				6.0
5e-2016Box	2.7				2.7											
5a-Aug1-68					5							5				
5a-Aug20-68					5			22.5	5							
5-Jul23-68					7.5								2.5			
5-Aug20-68					2.5		5		2.5							
5-Sep3-68			5		5				5			2.5				
5-Oct8-68												12.5				
5-Aug6-70					10				2.5							
5c-Aug23-69					25			20				2.5		2.5	10	
5d-Aug23-69			2.5		2.5			10				5				
5e-Aug23-69			2.5		5	2.5										
5f-Aug23-69					5				2.5			2.5				
A5b-Jul29-69				7.5	105											
5b-Sep3-69	2.5			5	45											
5b-Aug8-73				6	162											3
5b-Aug19-76			15	57	354					21						
25-Aug8-73					75											
25-Aug18-76			3	9	210											
26-Aug8-73			3		60							6				
27-Aug8-73					21											
28-Aug13-73					40				8							

	Margarites olivaceus	Margarites umbilicalis	Margarites vahli	Moelleria costulata	Nassarius lima	Nepotilla amoena	Neptunea despecta	Oenopota declivis	Oenopota pyramidalis	Oenopota reticula	Onoba mighelsii	Philine lima	Propebela arctica
25-2016													
26-2016													
27-2016	3.0	3.0											
28-2016													
5b-2016													
5-2016	3.6												
5a-2016													
5c-2016								3.0					
5d-2016				3.0					3.0				
5e-2016													
5f-2016										6.0			
5e-2016Box													
5a-Aug1-68	40	5											
5a-Aug20-68	10	15	20	2.5							2.5		
5-Jul23-68	2.5												
5-Aug20-68											20		
5-Sep3-68													
5-Oct8-68	10	2.5											
5-Aug6-70	12.5												
5c-Aug23-69	20	2.5	10	15									
5d-Aug23-69	22.5		15										
5e-Aug23-69						2.5							
5f-Aug23-69	2.5												
A5b-Jul29-69												20	
5b-Sep3-69					2.5							17.5	5
5b-Aug8-73												6	6
5b-Aug19-76					3			6				24	
25-Aug8-73													
25-Aug18-76					3							27	15
26-Aug8-73		3					6					12	
27-Aug8-73													
28-Aug13-73												24	

	<i>Propebela turricula</i>	<i>Puncturella noachina</i>	<i>Retusa obtusa</i>	<i>Scabrotrophon fabricii</i>	<i>Tachyrhynchus reticulatus</i>	<i>Trichotropis bicarinata</i>	<i>Trichotropis conica</i>	<i>Velutina velutina</i>
25-2016								
26-2016								
27-2016								
28-2016								
5b-2016								
5-2016								
5a-2016								
5c-2016								
5d-2016					3.0			
5e-2016	3.3							
5f-2016								
5e-2016Box					2.7			
5a-Aug1-68		7.5			5			2.5
5a-Aug20-68		37.5	2.5		5	2.5	5	2.5
5-Jul23-68			12.5				7.5	
5-Aug20-68						2.5		
5-Sep3-68								
5-Oct8-68				2.5				
5-Aug6-70								
5c-Aug23-69		2.5	22.5		20			
5d-Aug23-69	2.5		5	2.5			2.5	5
5e-Aug23-69			10					2.5
5f-Aug23-69						2.5		
A5b-Jul29-69			202.5					
5b-Sep3-69	2.5		57.5					
5b-Aug8-73			102					
5b-Aug19-76	15		192				6	
25-Aug8-73			30					
25-Aug18-76	12		75					
26-Aug8-73	3	6	36					
27-Aug8-73								3
28-Aug13-73			44					

Appendix 6. Data sources utilized in development of bivalve trait database.

Databases	Website
Arctic Ocean Diversity	http://www.arcodiv.org/seabottom/bivalves/Serripes_groenlandicus.html
Biological Traits Information Catalog (BIOTIC)	http://www.marlin.ac.uk/biotic/browse.php
Encyclopedia of Life (EOL)	http://eol.org/pages/614282/details
ETI BioInformatics Marine Species Identification Portal	http://species-identification.org/index.php
Gladys Archerd Shell Collection at Washington State University Tri-Cities Natural History Museum	http://shells.tricity.wsu.edu/ArcherdShellCollection/ShellCollection.html
Malacolog Version 3.3.2: Western Atlantic gastropod database	http://www.malacolog.org
Marine Bivalves of the British Isles	http://naturalhistory.museumwales.ac.uk/BritishBivalves/home.php?
Neogene Marine Biota of Tropical America (NMITA)	http://porites.geology.uiowa.edu/database/mollusc/mollusclifestyles.htm
North Atlantic Register for Marine Species (NARMS)	http://www.vliz.be/vmdcdata/narms/index.php
Norwegian Biodiversity Information Centre	http://www.biodiversity.no
Norwegian Biodiversity Information Centre	http://www.biodiversity.no
The marine flora and fauna of Norway	http://www.seawater.no/index.html
The Marine Life Information Network (MarLIN)	https://www.marlin.ac.uk/species/detail/2163
World Register of Marine Species (WoRMS)	http://www.marinespecies.org/
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Appendix 7. Weighted Trait Matrix of bivalve molluscs collected in Frobisher Bay.

Traits by Species

	<i>Astarte borealis</i>	<i>Astarte montagui</i>	<i>Ciliatocardium ciliatum</i>	<i>Parvicardium pinnulatum</i>	<i>Similipecten greenlandicus</i>	<i>Serripes groenlandicus</i>	<i>Hiatella arctica</i>	<i>Lyonsia arenosa</i>	<i>Mya truncata</i>	<i>Dacrydium vitreum</i>	<i>Musculus discors</i>	<i>Musculus niger</i>	<i>Crenella faba</i>	<i>Nuculana minuta</i>	<i>Nuculana pernula</i>	<i>Ennucula tenuis</i>	<i>Pandora glacialis</i>	<i>Periploma aleuticum</i>	<i>Macoma calcarca</i>	<i>Macoma moesta</i>	<i>Macoma loveni</i>	<i>Macoma torelli</i>	<i>Thracia myopsis</i>	<i>Axinopsida orbiculata</i>	<i>Thyasira gouldi</i>	<i>Thyasira dunbari</i>	<i>Liocyma fluctuosa</i>	<i>Portlandia arctica</i>	<i>Yoldia hyperborea</i>	<i>Yoldiella lenticula</i>
BS1	0	0	0	0	0	0	0	0	0	3	0	0	0	0	2	0	0	0	0	0	0	0	3	3	3	0	0	0	3	
BS2	3	3	0	3	3	0	2	3	0	0	3	0	3	3	3	2	3	0	3	3	3	3	3	0	0	0	3	3	3	0
BS3	0	0	3	0	0	2	1	0	3	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
BS4	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SS1	3	3	3	2	0	0	0	0	3	0	0	0	0	0	0	0	0	0	2	0	0	0	2	0	0	0	0	0	0	3
SS2	0	0	0	2	3	3	3	0	0	3	3	3	0	3	3	3	0	3	2	3	3	3	2	3	3	3	3	3	3	0
AMBI1	3	3	3	3	3	3	3	0	0	3	3	3	0	3	3	0	3	0	0	0	0	0	3	0	0	0	3	0	3	3
AMBI2	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	3	0	0	3	3	0	3	0	0	0	0	0	0	0	0
AMBI3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	3	0	0	0	0	0	0
FH1	0	0	0	0	0	0	0	0	0	0	0	0	0	3	3	3	0	0	2	2	0	0	0	3	1	3	3	3	2	3
FH2	3	3	3	0	0	3	3	0	3	0	3	3	0	0	0	0	0	0	2	2	0	0	0	0	2	3	3	0	1	0
FH3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3
SP1	0	0	0	0	3	2	0	3	2	3	0	2	0	2	3	2	2	0	2	2	2	2	3	3	2	3	0	3	3	3
SP2	0	0	0	0	0	2	0	0	2	0	0	2	0	0	0	1	2	0	0	0	2	2	0	0	2	0	0	0	0	0
SP3	0	0	0	0	0	0	1	0	0	0	1	0	0	1	0	1	0	0	1	1	0	0	0	0	0	0	0	0	0	0
SP4	3	3	3	3	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0
SP5	0	0	0	0	0	0	2	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Station by Species

	B-5a-Aug1-68	B-5a-Aug20-68	B-5-Jul23-68	B-5-Aug20-68	B-5-Sep3-68	B-5-Oct8-68	B-5-Aug6-70	B-5c-Aug23-69	B-5d-Aug23-69	B-5e-Aug23-69	B-5f-Aug23-69	A-5b-Jul29-69	A-5b-Sep3-69	A-5b-Aug8-73	A-5b-Aug19-76	A-25-Aug8-73	A-25-Aug18-76	A-26-Aug8-73	A-27-Aug8-73	A-28-Aug13-73
<i>Astarte borealis</i>	7.5	5	0	0	0	0	0	0	2.5	0	0	0	7.5	0	3	9	24	72	3	136
<i>Astarte montagui</i>	15	15	0	0	0	0	0	5	2.5	0	0	0	2.5	0	0	0	0	0	0	16
<i>Ciliatocardium ciliatum</i>	0	0	0	5	0	2.5	0	0	2.5	2.5	0	0	0	0	0	0	0	0	0	0
<i>Parvicardium pinnulatum</i>	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0
<i>Similipecten greenlandicus</i>	0	0	0	2.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
<i>Serripes groenlandicus</i>	0	0	0	0	0	0	0	2.5	0	0	0	0	5	0	0	3	3	0	0	0
<i>Hiatella arctica</i>	0	35	35	2.5	25	10	22.5	67.5	45	15	5	2.5	7.5	0	3	0	0	57	72	0
<i>Lyonsia arenosa</i>	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	4
<i>Mya truncata</i>	7.5	15	2.5	0	0	2.5	0	22.5	2.5	0	2.5	2.5	0	0	0	0	3	3	0	0
<i>Dacrydium vitreum</i>	0	0	17.5	30	12.5	0	17.5	5	17.5	12.5	32.5	0	0	0	0	0	0	6	3	0
<i>Musculus discors</i>	20	37.5	15	10	22.5	17.5	55	198	22.5	30	20	0	2.5	0	0	0	0	87	66	0
<i>Musculus niger</i>	2.5	0	2.5	0	0	2.5	2.5	0	5	0	2.5	0	0	0	0	0	0	0	0	4
<i>Crenella faba</i>	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
<i>Nuculana minuta</i>	25	20	10	30	20	7.5	10	45	7.5	22.5	17.5	0	0	0	0	0	0	0	12	28
<i>Nuculana pernula</i>	0	0	0	0	5	0	2.5	0	0	2.5	2.5	0	0	0	0	0	3	15	0	32
<i>Ennucula tenuis</i>	108	37.5	30	12.5	25	0	52.5	15	25	20	25	20	20	39	27	45	135	60	48	392
<i>Pandora glacialis</i>	0	0	0	0	2.5	0	5	2.5	0	0	0	0	0	0	0	0	0	0	0	0
<i>Periploma aleuticum</i>	0	0	0	2.5	0	0	2.5	5	0	5	0	0	0	0	0	0	0	0	0	0
<i>Macoma calcarea</i>	5	0	0	0	0	0	0	35	0	0	5	2.5	0	3	36	6	15	6	0	8
<i>Macoma moesta</i>	0	0	0	0	0	0	2.5	0	5	5	0	0	12.5	0	0	0	6	6	0	116
<i>Macoma loveni</i>	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
<i>Macoma torelli</i>	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	32
<i>Thracia myopsis</i>	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
<i>Axinopsida orbiculata</i>	0	0	0	0	0	0	0	0	0	0	0	438	660	693	1722	93	1380	27	0	472

<i>Thyasira gouldi</i>	95	95	65	75	52.5	20	87.5	138	67.5	85	82.5	52.5	72.5	39	48	105	372	819	234	600
<i>Thyasira dunbari</i>	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
<i>Liocyma fluctuosa</i>	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
<i>Portlandia arctica</i>	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
<i>Yoldia hyperborea</i>	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	3	0	0	4
<i>Yoldiella lenticula</i>	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

	A-25-2016	A-26-2016	A-27-2016	A-28-2016	A-5b-2016	B-5-2016	B-5a-2016	B-5c-2016	B-5d-2016	B-5e-2016	B-5f-2016	B-5g-2016	B-5g-2016Box	B-5e-2016Box
<i>Astarte borealis</i>	0	6	0	0	13.9	7.2	3	0	0	0	6	0	0	0
<i>Astarte montagui</i>	0	6	0	0	0	7.2	6	0	0	0	0	4.5	2.7	2.7
<i>Ciliatocardium ciliatum</i>	0	0	12	0	0	7.2	3	0	0	0	0	0	2.7	10.7
<i>Parvicardium pinnulatum</i>	0	0	0	0	0	0	0	0	0	0	0	0	0	0
<i>Similipecten greenlandicus</i>	0	0	0	0	0	0	0	0	0	0	0	0	0	0
<i>Serripes groenlandicus</i>	3	0	0	0	0	0	6	6	0	0	0	0	0	2.7
<i>Hiatella arctica</i>	0	15	15	0	0	18	0	6	3	3.3	6	22.5	21.3	18.7
<i>Lyonsia arenosa</i>	0	0	3	0	0	0	0	0	0	0	0	0	0	0
<i>Mya truncata</i>	0	3	0	0	0	0	0	0	9	0	6	0	0	0
<i>Dacrydium vitreum</i>	0	0	0	0	0	3.6	0	0	0	0	12	4.5	2.7	2.7
<i>Musculus discors</i>	0	9	0	0	0	7.2	0	0	6	0	6	9	5.3	45.3
<i>Musculus niger</i>	0	6	6	0	0	3.6	6	0	0	3.3	18	18	8	2.7
<i>Crenella faba</i>	0	0	0	4.6	0	0	0	0	0	0	0	0	0	0
<i>Nuculana minuta</i>	0	3	0	0	0	10.8	0	0	3	0	6	0	2.7	0
<i>Nuculana pernula</i>	0	9	3	0	0	18	21	12	3	3.3	24	4.5	0	10.7
<i>Ennucula tenuis</i>	48	9	15	0	13.9	36	18	15	12	32.8	24	4.5	2.7	2.7
<i>Pandora glacialis</i>	0	0	0	0	0	0	0	0	0	0	0	0	0	0
<i>Periploma aleuticum</i>	0	0	0	0	0	0	0	0	0	0	0	0	0	0

<i>Macoma calcarea</i>	3	6	0	4.6	0	3.6	9	0	0	0	6	0	2.7	2.7
<i>Macoma moesta</i>	18	30	9	0	0	21.6	24	3	6	3.3	0	27	13.3	8
<i>Macoma loveni</i>	0	0	0	0	0	0	6	6	0	0	18	4.5	0	2.7
<i>Macoma torelli</i>	0	0	0	0	0	0	0	0	0	0	0	0	0	0
<i>Thracia myopsis</i>	0	3	6	0	13.9	0	0	9	0	0	0	9	0	5.3
<i>Axinopsida orbiculata</i>	60.1	0	0	50.4	153	0	0	0	0	0	0	0	0	0
<i>Thyasira gouldi</i>	0	75.1	252	0	0	115	66.1	63.1	102	55.7	108	99.1	42.7	13.3
<i>Thyasira dunbari</i>	0	0	0	0	13.9	0	0	0	0	0	0	0	0	0
<i>Liocyma fluctuosa</i>	0	0	0	0	0	0	0	0	0	0	0	0	0	0
<i>Portlandia arctica</i>	0	3	0	0	0	7.2	15	0	0	0	0	0	0	0
<i>Yoldia hyperborea</i>	15	6	0	0	0	3.6	15	9	0	6.6	12	13.5	16	2.7
<i>Yoldiella lenticula</i>	0	0	0	0	0	10.8	0	6	0	3.3	0	0	0	0

Weighted Trait Matrix

	B-5a-Aug1-68	B-5a-Aug20-68	B-5-Jul23-68	B-5-Aug20-68	B-5-Sep3-68	B-5-Oct8-68	B-5-Aug6-70	B-5c-Aug23-69	B-5d-Aug23-69	B-5e-Aug23-69	B-5f-Aug23-69	A-5b-Jul29-69	A-5b-Sep3-69	A-5b-Aug8-73	A-5b-Aug19-76	A-25-Aug8-73	A-25-Aug18-76	A-26-Aug8-73	A-27-Aug8-73	A-28-Aug13-73
BS1	500	360	308	340	245	60	420	458	305	333	395	1510	2238	2274	5364	684	5526	2676	807	4000
BS2	433	378	205	158	250	95	375	1020	260	250	195	52.5	130	87	195	135	423	801	483	1912
BS3	27.5	80	47.5	17.5	25	30	27.5	140	70	22.5	17.5	10	17.5	0	3	6	15	66	72	8
BS4	2.5	0	2.5	0	0	2.5	2.5	2.5	5	0	2.5	0	5	0	0	3	3	0	0	4
SS1	100	105	7.5	15	0	15	0	153	30	7.5	17.5	1325	2010	2085	5253	318	4251	318	9	1888
SS2	760	675	525	495	488	173	765	1495	585	593	573	230	360	240	321	471	1596	3162	1305	3640
AMBI1	210	338	240	240	263	120	345	975	315	255	240	7.5	75	0	36	36	99	711	468	660
AMBI2	360	158	97.5	37.5	75	7.5	165	218	97.5	75	97.5	75	97.5	126	189	153	477	225	144	1644
AMBI3	285	285	195	225	158	60	263	413	203	255	248	1470	2198	2196	5310	594	5256	2538	702	3216
FH1	503	268	185	203	203	42.5	288	388	175	230	228	1430	2138	2241	5373	531	4974	1149	414	3628
FH2	358	513	295	203	248	145	420	1230	393	323	265	125	245	84	189	258	879	2319	891	1920

FH3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
SP1	485	335	273	333	253	65	380	535	278	310	375	1468	2200	2241	5397	597	5226	1941	597	3896
SP2	318	258	170	163	135	50	243	345	175	190	200	130	175	117	123	261	891	1704	516	1664
SP3	158	130	90	55	92.5	35	143	360	105	92.5	72.5	25	42.5	42	66	51	156	216	198	544
SP4	75	75	2.5	15	0	10	0	37.5	25	7.5	2.5	2.5	30	0	18	27	75	219	9	456
SP5	40	145	100	25	95	55	155	530	135	90	50	5	20	0	6	0	0	288	276	0

	A-25-2016	A-26-2016	A-27-2016	A-28-2016	A-5b-2016	B-5-2016	B-5a-2016	B-5c-2016	B-5d-2016	B-5e-2016	B-5f-2016	B-5g-2016	B-5g-2016Box	B-5e-2016Box
BS1	276.3	243.3	786.9	151.2	527.3	461.1	234.3	237.3	330.3	242.6	408.3	319.8	141.6	53.4
BS2	204	291	123	27.6	111.2	367.2	333	159	84	111.8	294	270	176.1	283.1
BS3	6	36	63	0	0	46.8	33	18	30	9.9	60	58.5	45.4	61.6
BS4	3	6	6	0	0	3.6	12	6	0	3.3	18	18	8	5.4
SS1	186.3	63	48	160.4	527.3	104.4	54	36	27	9.9	48	31.5	21.6	56.2
SS2	258	513.3	912.9	9.2	111.2	741.9	549.3	378.3	405.3	324.9	714.3	639.3	349.5	352.6
AMBI1	54	189	126	0	83.4	291.6	180	144	45	59.4	270	256.5	184.2	312.6
AMBI2	207	144	72	13.8	41.7	183.6	153	54	81	108.3	108	94.5	56.1	40.2
AMBI3	180.3	225.3	756.9	151.2	457.8	345.9	198.3	189.3	306.3	167.1	324.3	297.3	128.1	39.9
FH1	396.3	231.1	324.3	160.4	541.2	421.3	324.1	186.1	168.1	193.7	306.1	207.1	122.9	80.3
FH2	66	363.2	621.6	9.2	83.4	435.8	285.2	177.2	270.2	144.4	366.2	427.7	253.4	299.1
FH3	0	0	0	0	0	32.4	0	18	0	9.9	0	0	0	0
SP1	369.3	327.2	600.6	160.4	569	511.4	423.2	294.2	273.2	229.8	516.2	400.7	200.3	133.8
SP2	54	177.2	531.6	0	13.9	273.8	186.2	165.2	234.2	150.8	324.2	247.7	104.1	45.5
SP3	69	72	39	4.6	13.9	97.2	51	24	30	39.4	48	63	48	77.4
SP4	0	39	36	0	41.7	64.8	36	0	9	0	24	13.5	16.2	40.2
SP5	0	48	30	0	0	50.4	0	12	18	6.6	24	63	53.2	128

Appendix 8 Results of diversity indices (species richness (S), Shannon-Weiner diversity (H'), and Pileou's evenness (J')) for historical and modern samples collected in Frobisher Bay.

Station	Date	S	H'	J'	Station	Date	S	H'	J'
<i>Stations between Cairn and Mair Islands</i>					<i>Stations near Iqaluit</i>				
5	23-Jul-68	16	2.21	0.80	5b	29-Jul-69	10	1.38	0.60
5	20-Aug-68	15	2.03	0.75	5b	03-Sep-69	17	1.22	0.43
5	03-Sep-68	13	2.17	0.84	5b	08-Aug-73	10	1.15	0.50
5	08-Oct-68	11	2.12	0.88	5b	19-Aug-76	18	1.22	0.42
5	06-Aug-70	14	2.01	0.76	5b	10-Oct-16	7	1.35	0.69
5	14-Oct-16	23	2.49	0.79					
5a	01-Aug-68	16	2.06	0.74	25	08-Aug-73	9	1.73	0.79
5a	20-Aug-68	24	2.68	0.84	25	18-Aug-76	18	1.38	0.48
5a	14-Oct-16	16	2.33	0.84	25	10-Oct-16	9	1.66	0.75
5c	23-Aug-69	29	2.54	0.75	26	08-Aug-73	22	1.57	0.51
5c	11-Oct-16	16	2.24	0.81	26	10-Oct-16	21	2.49	0.82
5d	23-Aug-69	24	2.62	0.82	27	08-Aug-73	11	1.58	0.66
5d(box)	16-Jul-16	20	2.47	0.83	27	10-Oct-16	15	1.31	0.48
5d	11-Oct-16	18	1.94	0.67	28	13-Aug-73	19	1.94	0.66
5e	23-Aug-69	16	2.12	0.76	28	10-Oct-16	3	0.54	0.49
5e	11-Oct-16	14	2.04	0.77					
5f	23-Aug-69	15	1.98	0.73					
5f	11-Oct-16	19	2.38	0.81					

Appendix 9. Percent abundance of molluscs collected in Frobisher Bay (1967-1976 and 2016).

	<i>Astarte borealis</i>	<i>Astarte montagui</i>	<i>Axinopsida orbiculata</i>	<i>Ciliatocardium ciliatum</i>	<i>Crenella faba</i>	<i>Dacrydium vitreum</i>	<i>Ennucula tenuis</i>	<i>Hiatella arctica</i>	<i>Lyonsia arenosa</i>	<i>Macoma calcarea</i>	<i>Macoma loveni</i>	<i>Macoma moesta</i>	<i>Macoma torelli</i>	<i>Musculus discors</i>	<i>Musculus niger</i>	<i>Mya truncata</i>
25-2016	0.0	0.0	37.0	0.0	0.0	0.0	29.6	0.0	0.0	1.9	0.0	11.1	0.0	0.0	0.0	0.0
26-2016	2.6	2.6	0.0	0.0	0.0	0.0	3.8	6.4	0.0	2.6	0.0	12.8	0.0	3.8	2.6	1.3
27-2016	0.0	0.0	0.0	3.4	0.0	0.0	4.2	4.2	0.8	0.0	0.0	2.5	0.0	0.0	1.7	0.0
28-2016	0.0	0.0	84.6	0.0	7.7	0.0	0.0	0.0	0.0	7.7	0.0	0.0	0.0	0.0	0.0	0.0
5b-2016	5.6	0.0	61.1	0.0	0.0	0.0	5.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5-2016	2.2	2.2	0.0	2.2	0.0	1.1	11.0	5.5	0.0	1.1	0.0	6.6	0.0	2.2	1.1	0.0
5a-2016	1.4	2.8	0.0	1.4	0.0	0.0	8.5	0.0	0.0	4.2	2.8	11.3	0.0	0.0	2.8	0.0

5c-2016	0.0	0.0	0.0	0.0	0.0	0.0	9.3	3.7	0.0	0.0	3.7	1.9	0.0	0.0	0.0	0.0
5d-2016	0.0	0.0	0.0	0.0	0.0	0.0	6.3	1.6	0.0	0.0	0.0	3.2	0.0	3.2	0.0	4.8
5e-2016	0.0	0.0	0.0	0.0	0.0	0.0	20.4	2.0	0.0	0.0	0.0	2.0	0.0	0.0	2.0	0.0
5f-2016	2.0	0.0	0.0	0.0	0.0	4.1	8.2	2.0	0.0	2.0	6.1	0.0	0.0	2.0	6.1	2.0
5e-2016Box	0.0	1.8	0.0	7.1	0.0	1.8	1.8	12.5	0.0	1.8	1.8	5.4	0.0	30.4	1.8	0.0
5a-Aug1-68	2.1	4.2	0.0	0.0	0.0	0.0	30.3	0.0	0.0	1.4	0.0	0.0	0.0	5.6	0.7	2.1
5a-Aug20-68	1.2	3.5	0.0	0.0	0.0	0.0	8.7	8.1	0.0	0.0	0.0	0.0	0.0	8.7	0.0	3.5
5-Jul23-68	0.0	0.0	0.0	0.0	0.0	8.0	13.8	16.1	0.0	0.0	0.0	0.0	0.0	6.9	1.1	1.1
5-Aug20-68	0.0	0.0	0.0	2.4	0.0	14.6	6.1	1.2	0.0	0.0	0.0	0.0	0.0	4.9	0.0	0.0
5-Sep3-68	0.0	0.0	0.0	0.0	0.0	6.7	13.3	13.3	0.0	0.0	0.0	0.0	0.0	12.0	0.0	0.0
5-Oct8-68	0.0	0.0	0.0	2.8	0.0	0.0	0.0	11.1	0.0	0.0	0.0	0.0	0.0	19.4	2.8	2.8
5-Aug6-70	0.0	0.0	0.0	0.0	0.0	6.1	18.4	7.9	0.0	0.0	0.0	0.9	0.0	19.3	0.9	0.0
5c-Aug23-69	0.0	0.7	0.0	0.0	0.0	0.7	2.0	9.2	0.0	4.8	0.0	0.0	0.0	26.9	0.0	3.1
5d-Aug23-69	0.8	0.8	0.0	0.8	0.0	5.9	8.4	15.1	0.0	0.0	0.0	1.7	0.0	7.6	1.7	0.8
5e-Aug23-69	0.0	0.0	0.0	1.1	0.0	5.6	8.9	6.7	0.0	0.0	0.0	2.2	0.0	13.3	0.0	0.0
5f-Aug23-69	0.0	0.0	0.0	0.0	0.0	15.5	11.9	2.4	0.0	2.4	0.0	0.0	0.0	9.5	1.2	1.2
5b-Jul29-69	0.0	0.0	51.3	0.0	0.0	0.0	2.3	0.3	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.3
5b-Sep3-69	0.8	0.3	71.2	0.0	0.0	0.0	2.2	0.8	0.0	0.0	0.0	1.3	0.0	0.3	0.0	0.0
5b-Aug8-73	0.0	0.0	65.4	0.0	0.0	0.0	3.7	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0
5b-Aug19-76	0.1	0.0	67.8	0.0	0.0	0.0	1.1	0.1	0.0	1.4	0.0	0.0	0.0	0.0	0.0	0.0
25-Aug8-73	2.4	0.0	25.2	0.0	0.0	0.0	12.2	0.0	0.0	1.6	0.0	0.0	0.0	0.0	0.0	0.0
25-Aug18-76	1.0	0.0	60.1	0.0	0.0	0.0	5.9	0.0	0.0	0.7	0.0	0.3	0.0	0.0	0.0	0.1
26-Aug8-73	5.5	0.0	2.1	0.0	0.0	0.5	4.6	4.4	0.2	0.5	0.0	0.5	0.0	6.7	0.0	0.2
27-Aug8-73	0.6	0.0	0.0	0.0	0.0	0.6	10.1	15.2	0.0	0.0	0.0	0.0	0.0	13.9	0.0	0.0
28-Aug13-73	6.9	0.8	24.0	0.0	0.0	0.0	19.9	0.0	0.2	0.4	0.0	5.9	1.6	0.0	0.2	0.0

	<i>Nuculana minuta</i>	<i>Nuculana pernula</i>	<i>Pandora glacialis</i>	<i>Parvicardium pinnulatum</i>	<i>Periploma aleuticum</i>	<i>Portlandia arctica</i>	<i>Serripes groenlandicus</i>	<i>Similipeten greenlandicus</i>	<i>Thracia myopsis</i>	<i>Thyasira dunbari</i>	<i>Thyasira gouldi</i>	<i>Yoldia hyperborea</i>	<i>Yoldiella lenticula</i>	<i>Admete viridula</i>	<i>Alvania moerchi</i>	<i>Alvania moerchi</i>	<i>Anatoma crispata</i>
25-2016	0.0	0.0	0.0	0.0	0.0	0.0	1.9	0.0	0.0	0.0	0.0	9.3	0.0	1.9	0.0	0.0	0.0
26-2016	1.3	3.8	0.0	0.0	0.0	1.3	0.0	0.0	1.3	0.0	32.1	2.6	0.0	3.8	0.0	0.0	0.0
27-2016	0.0	0.8	0.0	0.0	0.0	0.0	0.0	0.0	1.7	0.0	71.2	0.0	0.0	0.0	0.8	0.0	0.0
28-2016	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5b-2016	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	5.6	5.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5-2016	3.3	5.5	0.0	0.0	0.0	2.2	0.0	0.0	0.0	0.0	35.2	1.1	3.3	0.0	0.0	0.0	0.0
5a-2016	0.0	9.9	0.0	0.0	0.0	7.0	2.8	0.0	0.0	0.0	31.0	7.0	0.0	0.0	0.0	0.0	0.0

5c-2016	0.0	7.4	0.0	0.0	0.0	0.0	3.7	0.0	5.6	0.0	38.9	5.6	3.7	0.0	0.0	0.0	0.0
5d-2016	1.6	1.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	54.0	0.0	0.0	0.0	3.2	0.0	1.6
5e-2016	0.0	2.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	34.7	4.1	2.0	0.0	2.0	0.0	0.0
5f-2016	2.0	8.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	36.7	4.1	0.0	0.0	0.0	0.0	0.0
5e-2016Box	0.0	7.1	0.0	0.0	0.0	0.0	1.8	0.0	3.6	0.0	8.9	1.8	0.0	0.0	0.0	0.0	0.0
5a-Aug1-68	7.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	26.8	0.0	0.0	0.0	0.0	0.0	0.0
5a-Aug20-68	4.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	22.0	0.0	0.0	0.0	0.0	0.0	7.5
5-Jul23-68	4.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	29.9	0.0	0.0	0.0	0.0	0.0	1.1
5-Aug20-68	14.6	0.0	0.0	0.0	1.2	0.0	0.0	1.2	0.0	0.0	36.6	0.0	0.0	0.0	0.0	0.0	0.0
5-Sep3-68	10.7	2.7	1.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	28.0	0.0	0.0	0.0	0.0	0.0	0.0
5-Oct8-68	8.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	22.2	0.0	0.0	0.0	0.0	0.0	0.0
5-Aug6-70	3.5	0.9	1.8	0.0	0.9	0.0	0.0	0.0	0.0	0.0	30.7	0.0	0.0	0.0	0.0	0.0	0.0
5c-Aug23-69	6.1	0.0	0.3	0.0	0.7	0.0	0.3	0.0	0.0	0.0	18.7	0.0	0.0	0.3	0.0	0.7	4.1
5d-Aug23-69	2.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	22.7	0.0	0.0	0.0	0.0	0.0	5.9
5e-Aug23-69	10.0	1.1	0.0	0.0	2.2	0.0	0.0	0.0	0.0	0.0	37.8	0.0	0.0	0.0	0.0	0.0	0.0
5f-Aug23-69	8.3	1.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	39.3	0.0	0.0	0.0	0.0	0.0	0.0
5b-Jul29-69	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	6.2	0.0	0.0	0.0	0.0	0.0	0.0
5b-Sep3-69	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.0	0.0	0.0	7.8	0.0	0.0	0.0	0.0	0.0	0.0
5b-Aug8-73	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.7	0.0	0.0	0.0	0.0	0.0	0.0
5b-Aug19-76	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	1.9	0.1	0.0	0.0	0.0	0.0	0.0
25-Aug8-73	0.0	0.0	0.0	0.0	0.0	0.0	0.8	0.0	0.0	0.0	28.5	0.0	0.0	0.0	0.0	0.0	0.0
25-Aug18-76	0.0	0.1	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	16.2	0.1	0.0	0.0	0.0	0.0	0.0
26-Aug8-73	0.0	1.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	62.9	0.0	0.0	0.0	0.0	0.0	0.0
27-Aug8-73	2.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	49.4	0.0	0.0	0.0	0.0	0.0	0.0
28-Aug13-73	1.4	1.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	30.5	0.2	0.0	0.2	0.0	0.0	0.0

	<i>Anomalisipho verkruezeni</i>	<i>Ariadnaria borealis</i>	<i>Ariadnaria borealis</i>	<i>Asyris rosacea</i>	<i>Aulacofusus brevicauda</i>	<i>Boreotrophon clathratus</i>	<i>Buccinum hydrophanum</i>	<i>Buccinum undatum</i>	<i>Cadlina laevis</i>	<i>Colus holboelli</i>	<i>Colus pubescens</i>	<i>Colus sabinii</i>	<i>Cryptonatica affinis</i>	<i>Curitoma decussata</i>	<i>Curitoma incisula</i>	<i>Curitoma violacea</i>	<i>Cylichna alba</i>
25-2016	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.7
26-2016	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.3	0.0	1.3	1.3	0.0	0.0	3.8
27-2016	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.5
28-2016	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5b-2016	11.1	0.0	5.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5-2016	0.0	0.0	0.0	0.0	0.0	1.1	0.0	0.0	0.0	0.0	0.0	0.0	3.3	0.0	0.0	0.0	3.3
5a-2016	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.4

5c-2016	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.9	1.9	0.0	0.0	0.0	5.6
5d-2016	0.0	0.0	4.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.2
5e-2016	0.0	0.0	0.0	0.0	4.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.0	0.0	0.0	0.0	14.3
5f-2016	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.0	0.0	0.0	4.1
5e-2016Box	0.0	0.0	0.0	0.0	0.0	1.8	0.0	0.0	0.0	3.6	0.0	0.0	1.8	0.0	0.0	0.0	1.8
5a-Aug1-68	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.4
5a-Aug20-68	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.2
5-Jul23-68	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.1	0.0	1.1	0.0	0.0	0.0	0.0	0.0	3.4
5-Aug20-68	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.2	0.0	0.0	0.0	0.0	0.0	0.0	1.2
5-Sep3-68	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.7	0.0	0.0	0.0	0.0	2.7	0.0	2.7
5-Oct8-68	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5-Aug6-70	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.5
5c-Aug23-69	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	3.4
5d-Aug23-69	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.8	0.0	0.8
5e-Aug23-69	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.1	0.0	2.2
5f-Aug23-69	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.4
5b-Jul29-69	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.9	12.3
5b-Sep3-69	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0	0.0	0.5	4.9
5b-Aug8-73	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.6	15.3
5b-Aug19-76	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.6	2.2	13.9
25-Aug8-73	0.0	0.0	0.0	0.0	0.0	0.0	0.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	20.3
25-Aug18-76	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.4	9.1
26-Aug8-73	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.0	0.0	0.0	0.0	0.2	0.0	4.6
27-Aug8-73	0.0	1.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.3	0.0	0.0	0.0	0.0	0.0	0.0	4.4
28-Aug13-73	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	2.0

	<i>Cylichnoides occultus</i>	<i>Ecerobia truncata</i>	<i>Erginus rubellus</i>	<i>Euspira pallida</i>	<i>Flabellina salmonacea</i>	<i>Frigidoalvania cruenta</i>	<i>Lepeta caeca</i>	<i>Limneria undata</i>	<i>Margarites costalis</i>	<i>Margarites groenlandicus</i>	<i>Margarites helicinus</i>	<i>Margarites olivaceus</i>	<i>Margarites umbilicatis</i>	<i>Margarites vahli</i>	<i>Moelleria costulata</i>	<i>Nassarius lima</i>
25-2016	3.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
26-2016	7.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
27-2016	0.0	0.0	0.0	0.0	0.0	0.0	3.4	0.0	0.0	0.8	0.0	0.8	0.8	0.0	0.0	0.0
28-2016	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5b-2016	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5-2016	1.1	0.0	0.0	0.0	0.0	3.3	0.0	0.0	0.0	0.0	1.1	1.1	0.0	0.0	0.0	0.0
5a-2016	4.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.4	0.0	0.0	0.0	0.0	0.0

5c-2016	0.0	0.0	0.0	0.0	0.0	3.7	0.0	0.0	0.0	0.0	1.9	0.0	0.0	0.0	0.0
5d-2016	0.0	0.0	0.0	0.0	0.0	0.0	3.2	0.0	1.6	0.0	1.6	0.0	0.0	0.0	1.6
5e-2016	0.0	0.0	0.0	0.0	0.0	6.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5f-2016	0.0	0.0	0.0	0.0	0.0	2.0	2.0	0.0	0.0	0.0	2.0	0.0	0.0	0.0	0.0
5e-2016Box	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5a-Aug1-68	0.0	0.0	0.0	0.0	0.0	0.0	1.4	0.0	0.0	0.0	0.0	11.3	1.4	0.0	0.0
5a-Aug20-68	0.0	0.0	5.2	1.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.3	3.5	4.6	0.6
5-Jul23-68	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.1	0.0	0.0	0.0	1.1	0.0	0.0	0.0
5-Aug20-68	0.0	2.4	0.0	1.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5-Sep3-68	0.0	0.0	0.0	2.7	0.0	0.0	1.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5-Oct8-68	0.0	0.0	0.0	0.0	0.0	0.0	13.9	0.0	0.0	0.0	0.0	11.1	2.8	0.0	0.0
5-Aug6-70	0.0	0.0	0.0	0.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.4	0.0	0.0	0.0
5c-Aug23-69	0.0	0.0	2.7	0.0	0.0	0.0	0.3	0.0	0.3	1.4	0.0	2.7	0.3	1.4	2.0
5d-Aug23-69	0.0	0.0	3.4	0.0	0.0	0.0	1.7	0.0	0.0	0.0	0.0	7.6	0.0	5.0	0.0
5e-Aug23-69	1.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5f-Aug23-69	0.0	0.0	0.0	1.2	0.0	0.0	1.2	0.0	0.0	0.0	0.0	1.2	0.0	0.0	0.0
5b-Jul29-69	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5b-Sep3-69	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3
5b-Aug8-73	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.0
5b-Aug19-76	0.0	0.0	0.0	0.0	0.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1
25-Aug8-73	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
25-Aug18-76	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1
26-Aug8-73	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.0
27-Aug8-73	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
28-Aug13-73	0.0	0.0	0.0	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

	<i>Nepotilla amoena</i>	<i>Neptunea despecta</i>	<i>Oenopota declivis</i>	<i>Oenopota pyramidalis</i>	<i>Oenopota reticula</i>	<i>Onoba mighelsii</i>	<i>Philine lima</i>	<i>Propebela arctica</i>	<i>Propebela turricula</i>	<i>Puncturella noachina</i>	<i>Retusa obtusa</i>	<i>Scabrotrophon fabricii</i>	<i>Tachyhynchus reticulatus</i>	<i>Trichotropis bicarinata</i>	<i>Trichotropis conica</i>	<i>Velutina velutina</i>
25-2016	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
26-2016	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
27-2016	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
28-2016	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5b-2016	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5-2016	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5a-2016	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

5c-2016	0.0	0.0	1.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5d-2016	0.0	0.0	0.0	1.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.6	0.0	0.0	0.0
5e-2016	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5f-2016	0.0	0.0	0.0	0.0	2.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5e-2016Box	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.8	0.0	0.0	0.0
5a-Aug1-68	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.1	0.0	0.0	1.4	0.0	0.0	0.7
5a-Aug20-68	0.0	0.0	0.0	0.0	0.0	0.6	0.0	0.0	0.0	8.7	0.6	0.0	1.2	0.6	1.2	0.6
5-Jul23-68	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	5.7	0.0	0.0	0.0	3.4	0.0
5-Aug20-68	0.0	0.0	0.0	0.0	0.0	9.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.2	0.0	0.0
5-Sep3-68	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5-Oct8-68	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.8	0.0	0.0	0.0	0.0
5-Aug6-70	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5c-Aug23-69	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	3.1	0.0	2.7	0.0	0.0	0.0
5d-Aug23-69	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.8	0.0	1.7	0.8	0.0	0.0	0.8	1.7
5e-Aug23-69	1.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.4	0.0	0.0	0.0	0.0	1.1
5f-Aug23-69	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.2	0.0	0.0
5b-Jul29-69	0.0	0.0	0.0	0.0	0.0	0.0	2.3	0.0	0.0	0.0	23.8	0.0	0.0	0.0	0.0	0.0
5b-Sep3-69	0.0	0.0	0.0	0.0	0.0	0.0	1.9	0.5	0.3	0.0	6.2	0.0	0.0	0.0	0.0	0.0
5b-Aug8-73	0.0	0.0	0.0	0.0	0.0	0.0	0.6	0.6	0.0	0.0	9.6	0.0	0.0	0.0	0.0	0.0
5b-Aug19-76	0.0	0.0	0.2	0.0	0.0	0.0	0.9	0.0	0.6	0.0	7.6	0.0	0.0	0.0	0.2	0.0
25-Aug8-73	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	8.1	0.0	0.0	0.0	0.0	0.0
25-Aug18-76	0.0	0.0	0.0	0.0	0.0	0.0	1.2	0.7	0.5	0.0	3.3	0.0	0.0	0.0	0.0	0.0
26-Aug8-73	0.0	0.5	0.0	0.0	0.0	0.0	0.9	0.0	0.2	0.5	2.8	0.0	0.0	0.0	0.0	0.0
27-Aug8-73	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.6
28-Aug13-73	0.0	0.0	0.0	0.0	0.0	0.0	1.2	0.0	0.0	0.0	2.2	0.0	0.0	0.0	0.0	0.0

Appendix 10. Inventory of grab attempts made and samples collected in 2016 onboard the MV Nulialjuk using Van Veen and Petite Ponar grab samplers in Frobisher Bay.

Date	Station	Rep	Latitude (DD)	Longitude (DD)	Water Depth (m)	Success	Sediment	Biota	Grab	2016 Nulialjuk Cruise Leg	Notes
10/10/2016	A-IF1	G1	63.71371333	-68.509375	17.4	yes	yes	yes	Van Veen	3d	
10/10/2016	A-IF1	G2	63.71353167	-68.50934667	16.4	yes	yes	yes	Van Veen	3d	
10/10/2016	A-IF1	G3	63.71405333	-68.50955333	19.1	yes	yes	yes	Van Veen	3d	
10/10/2016	A-IF18	G1	63.703575	-68.49289333	34.8	yes	yes	yes	Van Veen	3d	
10/10/2016	A-IF18	G2	63.70396667	-68.49259167	33.2	yes	yes	yes	Van Veen	3d	
10/10/2016	A-IF18	G3	63.70390833	-68.49249333	32.8	yes	yes	yes	Van Veen	3d	
14/10/2016	A-IF19	G3	63.67462167	-68.503955	37.3	no			Van Veen	3d	blank
14/10/2016	A-IF19	G4	63.67452333	-68.50344667	39	no			Van Veen	3d	blank
14/10/2016	A-IF19	G1	63.67484833	-68.505155	27	yes	yes	yes	Van Veen	3d	
14/10/2016	A-IF19	G2	63.674805	-68.50456833	33.7	yes	yes	yes	Van Veen	3d	
14/10/2016	A-IF19	G5	63.67472833	-68.50476833	32.9	yes	yes	yes	Van Veen	3d	good
10/10/2016	A-IF2	G1	63.70412833	-68.53883333	26	no			Van Veen	3d	blank
10/10/2016	A-IF2	G2	63.70392833	-68.53860167	32.8	yes	yes	yes	Van Veen	3d	
10/10/2016	A-IF2	G3	63.70407	-68.53808167	28.3	yes	yes	yes	Van Veen	3d	
10/10/2016	A-IF2	G4	63.704075	-68.53807667	28.3	yes	yes	yes	Van Veen	3d	
10/10/2016	A-IF20	G1	63.70692	-68.51989667	11.1	???			Van Veen	3d	
10/10/2016	A-IF20	G2	63.70722	-68.519125	14.6	yes	yes	yes	Petite Ponar	3d	
10/10/2016	A-IF20	G3	63.70747667	-68.518935	16.7	yes	yes	yes	Petite Ponar	3d	
10/10/2016	A-IF20	G4	63.70661333	-68.52117667	17.1	yes	yes	yes	Petite Ponar	3d	
14/10/2016	A-IF21	G1	63.66958167	-68.50067167	63.7	yes	yes	yes	Van Veen	3d	
14/10/2016	A-IF21	G2	63.669705	-68.50062	60.4	yes	yes	yes	Van Veen	3d	
14/10/2016	A-IF21	G3	63.66955	-68.50172	55.4	yes	yes	yes	Van Veen	3d	
11/10/2016	A-IF22	G1	63.6656	-68.50311667	56.4	yes	yes	yes	Van Veen	3d	
11/10/2016	A-IF22	G2	63.66561167	-68.50313833	56.4	yes	yes	yes	Van Veen	3d	
11/10/2016	A-IF22	G3	63.66565	-68.50329333	54.4	yes	yes	yes	Van Veen	3d	
10/10/2016	A-IF61	G1	63.71916833	-68.47457167	24.6	yes	no	yes	Van Veen	3d	bio, no sed
10/10/2016	A-IF61	G2	63.719495	-68.47418333	23.2	yes	yes	yes	Petite Ponar	3d	

10/10/2016	A-IF61	G3	63.71930667	-68.47328	22.1	yes	yes	yes	Petite Ponar	3d	
10/10/2016	A-IF61	G4	63.719255	-68.47323	23.1	yes	yes	yes	Petite Ponar	3d	
10/10/2016	A-IF61	G5	63.71899833	-68.472945	23.1	yes	yes	yes	Petite Ponar	3d	
10/10/2016	A-IF62	G2	63.71106333	-68.50926333	14.6	no			Van Veen	3d	blank
10/10/2016	A-IF62	G1	63.71069333	-68.50937333	12.7	yes	yes	yes	Van Veen	3d	
10/10/2016	A-IF62	G3	63.71094333	-68.509285	14.3	yes	yes	no	Van Veen	3d	no bio
10/10/2016	A-IF62	G4	63.71081333	-68.50903	14	yes	yes	yes	Van Veen	3d	
10/10/2016	A-IF62	G5	63.71085833	-68.50857167	15.4	yes	yes	yes	Van Veen	3d	
14/10/2016	A-IF63	G1	63.681635	-68.47696667	70.5	yes	yes	yes	Van Veen	3d	
14/10/2016	A-IF63	G2	63.68094833	-68.477575	83.4	yes	yes	yes	Van Veen	3d	
14/10/2016	A-IF63	G3	63.68128667	-68.47692167	72.4	yes	yes	yes	Van Veen	3d	
11/10/2016	A-IF68	G1	63.68119	-68.48211167	75.1	yes	yes	yes	Van Veen	3d	
11/10/2016	A-IF68	G2	63.68112833	-68.48212167	74.8	yes	yes	yes	Van Veen	3d	
11/10/2016	A-IF68	G3	63.68097833	-68.48214	73.3	yes	yes	yes	Van Veen	3d	
14/10/2016	A-IF69	G1	63.68095333	-68.49540833	54.1	yes	yes	yes	Van Veen	3d	
14/10/2016	A-IF69	G2	63.680985	-68.49543833	53.5	yes	yes	yes	Van Veen	3d	
14/10/2016	A-IF69	G3	63.68085833	-68.49554833	52.9	yes	yes	yes	Van Veen	3d	
10/10/2016	A-IF70	G1	63.704635	-68.533275	10.5	???			Van Veen	3d	
10/10/2016	A-IF70	G2	63.70458167	-68.53265	11.3	yes		no	Van Veen	3d	no bio, just rock
10/10/2016	A-IF70	G3	63.70452167	-68.53277333	10.8	yes	yes	yes	Petite Ponar	3d	
10/10/2016	A-IF70	G4	63.70451333	-68.53305667	10.7	yes	yes	yes	Petite Ponar	3d	
14/10/2016	B-IF24	G2	63.65374667	-68.487325	84.1	yes	no	yes	Van Veen	3d	rock; no sed, just biota
14/10/2016	B-IF24	G5	63.65384	-68.48766833	83.3	yes	no	yes	Van Veen	3d	no sed; biota only - bryozoans
14/10/2016	B-IF24	G1	63.65392167	-68.48682833	92.8				Van Veen	3d	
14/10/2016	B-IF24	G3	63.65381	-68.48754	84.6				Van Veen	3d	
14/10/2016	B-IF24	G4	63.65393333	-68.48757167	87.9				Van Veen	3d	rock only
13/10/2016	B-IF33	G1	63.63272	-68.47208	80.1	yes	yes	yes	Van Veen	3d	
13/10/2016	B-IF33	G2	63.63317	-68.47228833	79.3	yes	yes	yes	Van Veen	3d	
13/10/2016	B-IF33	G3	63.63320167	-68.47209833	79.9	yes	yes	yes	Van Veen	3d	
8/10/2016	B-IF35	G3	63.56992333	-68.353975	149	no			Van Veen	3c	one rock
8/10/2016	B-IF35	G1	63.570665	-68.35378167	144	yes	yes	yes	Van Veen	3c	good return

8/10/2016	B-IF35	G2	63.57050167	-68.35385833	145	yes	yes	yes	Van Veen	3c	some return
14/10/2016	B-IF64	G1	63.66596833	-68.46362833	77.9	yes	yes	yes	Van Veen	3d	
14/10/2016	B-IF64	G2	63.66606	-68.46354	77.9	yes	yes	yes	Van Veen	3d	
14/10/2016	B-IF64	G3	63.66628667	-68.46531167	87.2	yes	yes	yes	Van Veen	3d	
14/10/2016	B-IF66	G2	63.65542333	-68.49100833	83.3	no			Van Veen	3d	blank
14/10/2016	B-IF66	G1	63.65538	-68.49108833	85.4	yes	yes	yes	Van Veen	3d	good
14/10/2016	B-IF66	G3	63.65517	-68.48985333	92.6	yes			Van Veen	3d	half good
14/10/2016	B-IF66	G4	63.65515333	-68.49185333	72.8	yes	yes	yes	Van Veen	3d	good
11/10/2016	B-IF72	G1	63.65129833	-68.45164333	70.2	yes	yes	yes	Van Veen	3d	
11/10/2016	B-IF72	G2	63.65130333	-68.45099667	68.9	yes	yes	yes	Van Veen	3d	
11/10/2016	B-IF72	G3	63.65117	-68.466455	64.8	yes	yes	yes	Van Veen	3d	
11/10/2016	B-IF73	G1	63.654235	-68.496595	56.8	yes	yes	yes	Van Veen	3d	
11/10/2016	B-IF73	G2	63.65425167	-68.49535	63.1	yes	yes	yes	Van Veen	3d	
11/10/2016	B-IF73	G3	63.65415333	-68.49727	50.5	yes	yes	yes	Van Veen	3d	
14/10/2016	B-IF74	G2	63.65569333	-68.45251333	85.3	no			Van Veen	3d	just water
14/10/2016	B-IF74	G1	63.65551333	-68.45151333	80.5	yes			Van Veen	3d	just some pebbles
14/10/2016	B-IF74	G3	63.65525	-68.453025	92.4	yes	yes		Van Veen	3d	small sed sample
14/10/2016	B-IF74	G4	63.65573	-68.45208333	82.7				Van Veen	3d	
14/10/2016	B-IF74	G5	63.65588667	-68.45178667	82.1				Van Veen	3d	
12/10/2016	C-IF26	G1	63.65410167	-68.59800333	156	yes	yes	yes	Van Veen	3d	
12/10/2016	C-IF26	G2	63.65422167	-68.59816833	158	yes	yes	yes	Van Veen	3d	
12/10/2016	C-IF26	G3	63.65404333	-68.598285	149	yes	yes	yes	Van Veen	3d	
12/10/2016	C-IF27	G3	63.64824833	-68.61381167	47.6	no			Van Veen	3d	didn't trigger
12/10/2016	C-IF27	G1	63.648155	-68.61392	47.8	yes	yes	yes	Van Veen	3d	
12/10/2016	C-IF27	G2	63.64829833	-68.61368	47.4	yes	yes	yes	Van Veen	3d	
12/10/2016	C-IF36	G3	63.66667333	-68.64210167	142	no			Van Veen	3d	blank
12/10/2016	C-IF36	G1	63.667055	-69.64563	143	yes	yes	yes	Van Veen	3d	
12/10/2016	C-IF36	G2	63.66691	-68.64436	143	yes	yes	yes	Van Veen	3d	
12/10/2016	C-IF36	G4	63.66636667	-68.64474333	142	yes	yes	yes	Van Veen	3d	good
12/10/2016	C-IF37	G1	63.66773667	-68.57288	83.9	yes	yes	yes	Van Veen	3d	
12/10/2016	C-IF37	G2	63.66762333	-68.57250167	85.7	yes	yes	yes	Van Veen	3d	
12/10/2016	C-IF37	G3	63.667685	-68.57218333	87.9	yes	yes	yes	Van Veen	3d	

12/10/2016	C-IF38	G1	63.66380667	-68.59985167	208	no			Van Veen	3d	did not close
12/10/2016	C-IF38	G4	63.664275	-68.59812667	182	no			Van Veen	3d	didn't close
12/10/2016	C-IF38	G2	63.66349667	-68.59858	201	yes	yes	yes	Van Veen	3d	good
12/10/2016	C-IF38	G3	63.66428167	-68.60018333	205	yes	yes	no	Van Veen	3d	sed only, no bio
12/10/2016	C-IF38	G5	63.66397167	-68.59665667	170				Van Veen	3d	
12/10/2016	C-IF5	G1	63.67968333	-68.63673167	138	no			Van Veen	3d	blank
12/10/2016	C-IF5	G3	63.680115	-68.635925	138	no			Van Veen	3d	blank
12/10/2016	C-IF5	G2	63.67995333	-68.63601	137	yes	yes	no	Van Veen	3d	sed only, no bio
12/10/2016	C-IF5	G4	63.68031	-68.635225	135	yes	yes	yes	Van Veen	3d	good
12/10/2016	C-IF5	G5	63.680365	-68.63436833	126	yes	yes	yes	Van Veen	3d	good
12/10/2016	C-IF5	G6	63.68055833	-68.63376667	115	yes	yes	yes	Van Veen	3d	
13/10/2016	C-IF53	G1	63.62679167	-68.60497333	121	no			Van Veen	3d	blank
13/10/2016	C-IF53	G2	63.62659	-68.60547333	128	no			Van Veen	3d	blank
13/10/2016	C-IF53	G4	63.62693833	-68.604385	114	no			Van Veen	3d	blank
13/10/2016	C-IF53	G5	63.62683667	-68.60489333	119	no			Van Veen	3d	blank
13/10/2016	C-IF53	G3	63.626295	-68.60583333	135	yes	yes	yes	Van Veen	3d	good
13/10/2016	C-IF53	G6	63.62657667	-68.60538667	126	yes	yes	yes	Van Veen	3d	good
12/10/2016	C-IF54	G1	63.63368333	-68.60850167	95.9	yes	yes	yes	Van Veen	3d	
12/10/2016	C-IF54	G2	63.63376333	-68.60783167	92.9	yes	yes	yes	Van Veen	3d	
12/10/2016	C-IF54	G3	63.63375667	-68.60774333	93.8	yes	yes	yes	Van Veen	3d	
5/10/2016	C-IF55	G2	63.62530167	-68.58357667	99.2	no			Van Veen	3c	no return
5/10/2016	C-IF55	G1	63.62564167	-68.58240167	91.9	yes	yes	yes	Van Veen	3c	good return
5/10/2016	C-IF55	G3	63.62549167	-68.583025	95.4	yes	yes	yes	Van Veen	3c	good return
5/10/2016	C-IF55	G4	63.62557667	-68.58323333	94.7	yes	yes	yes	Van Veen	3c	good return
5/10/2016	C-IF6	G1	63.62250667	-68.60412833	156	yes	yes	yes	Van Veen	3c	good return
5/10/2016	C-IF6	G2	63.62239667	-68.60327833	156	yes	yes	yes	Van Veen	3c	good return
5/10/2016	C-IF6	G3	63.62234333	-68.60357	155	yes	yes	yes	Van Veen	3c	good return
8/10/2016	D-IF30	G1	63.54396667	-68.50076833	139	yes	yes	yes	Van Veen	3c	good return; sponge in sediment, picture taken, thrown back
8/10/2016	D-IF30	G2	63.54342833	-68.50014833	138	yes	yes	yes	Van Veen	3c	good return
8/10/2016	D-IF30	G3	63.54352167	-68.49974333	137	yes	yes	yes	Van Veen	3c	
8/10/2016	D-IF31	G1	63.54456667	-68.48700667	140	yes	yes	yes	Van Veen	3c	good return

8/10/2016	D-IF31	G2	63.544485	-68.48691833	140	yes	yes	yes	Van Veen	3c	good return
8/10/2016	D-IF31	G3	63.54441833	-68.48695833	139	yes	yes	yes	Van Veen	3c	good return
13/10/2016	D-IF32	G1	63.58537833	-68.54966	80.4	yes	yes	yes	Van Veen	3d	camera already completed; on top of moraine
13/10/2016	D-IF32	G2	63.58554833	-68.54854167	78.6	yes			Van Veen	3d	rock only
13/10/2016	D-IF32	G3	63.5853	-68.55009	77.2	yes	yes	yes	Van Veen	3d	
13/10/2016	D-IF32	G4	63.651935	-68.54931	75.7	yes	yes	yes	Van Veen	3d	
4/10/2016	D-IF41	G1	63.471905	-68.36087	120	no			Van Veen	3c	no return
4/10/2016	D-IF41	G2	63.47228667	-68.36209167	121	no			Van Veen	3c	no return
4/10/2016	D-IF41	G3	63.47288333	-68.36201833	128	yes	yes	yes	Van Veen	3c	good return
4/10/2016	D-IF41	G4	63.47211667	-68.36241333	119	yes	yes	yes	Van Veen	3c	good return
4/10/2016	D-IF41	G5	63.47161667	-68.361725	117	yes	yes	yes	Van Veen	3c	good return
5/10/2016	D-IF42	G1	63.58537833	-68.54877667	80.4	no			Van Veen	3c	no return
5/10/2016	D-IF42	G3	63.58528833	-68.54810667	78.8	no			Van Veen	3c	no return
5/10/2016	D-IF42	G4	63.58543167	-68.548605	80.8	no			Van Veen	3c	no return; called off due to wind
5/10/2016	D-IF42	G2	63.584685	-68.54720667	74.1	yes	yes	yes	Van Veen	3c	good return
13/10/2016	D-IF56	G1	63.61427333	-68.56571833	97.7	yes			Van Veen	3d	rock only
13/10/2016	D-IF56	G2	63.61459833	-68.56535833	97.8	yes	yes	yes	Van Veen	3d	
13/10/2016	D-IF56	G4	63.61455167	-68.565715	96.9	yes	yes	yes	Van Veen	3d	
13/10/2016	D-IF56	G3	63.614445	-68.56578167	97.3	yes	yes	yes	Van Veen	3d	
5/10/2016	D-IF58	G1	63.53838667	-68.48333833	139	no			Van Veen	3c	no return; high winds, come back later
8/10/2016	D-IF58	G2	63.53882833	-68.48174833	140	no			Van Veen	3c	one rock
8/10/2016	D-IF58	G3	63.53890333	-68.48261833	138	yes	yes	yes	Van Veen	3c	good return
8/10/2016	D-IF58	G4	63.53872667	-68.48208333	139	yes	yes	yes	Van Veen	3c	good return
8/10/2016	D-IF59	G1	63.558175	-68.47186333	157	yes	yes	yes	Van Veen	3c	good return
8/10/2016	D-IF59	G2	63.55780167	-68.47063667	154	yes	yes	yes	Van Veen	3c	good return
8/10/2016	D-IF59	G3	63.55793	-68.47268333	158	yes	yes	yes	Van Veen	3c	good return
8/10/2016	D-IF60	G3	63.55923167	-68.50763667	194	no			Van Veen	3c	one rock
8/10/2016	D-IF60	G1	63.559225	-68.50765167	195	yes	yes	yes	Van Veen	3c	good return
8/10/2016	D-IF60	G2	63.55896667	-68.50772	188	yes	yes	yes	Van Veen	3c	good return

13/10/2016	D-IF7	G1	63.60474167	-68.56825167	58.6	yes	yes	yes	Van Veen	3d	
13/10/2016	D-IF7	G2	63.60497667	-68.56787667	58.5	yes	yes	yes	Van Veen	3d	
13/10/2016	D-IF7	G3	63.60497667	-68.567505	62	yes	yes	yes	Van Veen	3d	
8/10/2016	D-IF76	G1	63.54604667	-68.49785	116	yes	yes	yes	Van Veen	3c	good return
8/10/2016	D-IF76	G2	63.54586333	-68.49746	114	yes	yes	yes	Van Veen	3c	good return
8/10/2016	D-IF76	G3	63.54599833	-68.49701167	115	yes	yes	yes	Van Veen	3c	good return
8/10/2016	D-IF79	G2	63.54501833	-68.452115	147	no			Van Veen	3c	one rock
8/10/2016	D-IF79	G3	63.54509	-68.45248833	149	no			Van Veen	3c	no return
8/10/2016	D-IF79	G4	63.544995	-68.45276167	153	no			Van Veen	3c	no return
8/10/2016	D-IF79	G1	63.54526333	-68.450975	139	yes	yes	yes	Van Veen	3c	good return
8/10/2016	D-IF79	G5	63.54536333	-68.45296833	146	yes	yes	yes	Van Veen	3c	good return
5/10/2016	D-IF8	G1	63.48892167	-68.39145	89.1	yes	yes	yes	Van Veen	3c	good return
5/10/2016	D-IF8	G2	63.48857667	-68.393135	77.5	yes	yes	yes	Van Veen	3c	good return
5/10/2016	D-IF8	G3	63.48860667	-68.39036167	92.5	yes	yes	no	Van Veen	3c	single rock
5/10/2016	D-IF8	G4	63.488425	-68.388095	99.2	yes	yes	no	Van Veen	3c	single rock
5/10/2016	D-IF8	G5	63.48924333	-68.38953167	97.9	yes	yes	no	Van Veen	3c	single rock
13/10/2016	D-IF81	G3	63.5903	-68.546965	57.7	no			Van Veen	3d	just water
13/10/2016	D-IF81	G1	63.59028167	-68.54716167	57.2	yes	yes	yes	Van Veen	3d	camera already completed
13/10/2016	D-IF81	G2	63.59022333	-68.54705	57.5	yes	yes	yes	Van Veen	3d	
13/10/2016	D-IF81	G4	63.59023333	-68.54686	58	yes	no	yes	Van Veen	3d	large sponge
4/10/2016	E-IF1	G0	63.40450667	-68.279515	123	no			Van Veen	3c	no return
4/10/2016	E-IF10	G1	63.39581333	-68.209005	106	no			Van Veen	3c	no return
4/10/2016	E-IF10	G2	63.39547167	-68.210895	99.5	yes	yes	yes	Van Veen	3c	good return
4/10/2016	E-IF10	G3	63.39567833	-68.210375	100	yes	yes	yes	Van Veen	3c	good return
4/10/2016	E-IF10	G4	63.39579833	-68.21099	101	yes	yes	yes	Van Veen	3c	good return
7/10/2016	E-IF12	G1	63.35163833	-67.83734833	145	no			Van Veen	3c	no return
7/10/2016	E-IF12	G2	63.35193667	-67.83731167	146	yes	yes	yes	Van Veen	3c	some return
7/10/2016	E-IF12	G3	63.35197	-67.837925	148	yes	yes	yes	Van Veen	3c	some return
7/10/2016	E-IF12	G4	63.352135	-67.83821667	148	yes	yes	yes	Van Veen	3c	some return
4/10/2016	E-IF42	G1	63.34986667	-68.23403333	57.6	yes	yes	yes	Van Veen	3c	good return
4/10/2016	E-IF42	G2	63.34956667	-68.23385	58.4	yes	yes	yes	Van Veen	3c	good return
4/10/2016	E-IF42	G3	63.34948333	-68.23451667	61.6	yes	yes	???	Van Veen	3c	some return

8/10/2016	E-IF45	G1	63.46544833	-68.080225	180	yes	yes	yes	Van Veen	3c	some return
8/10/2016	E-IF45	G2	63.46533167	-68.07950667	178	yes	yes	yes	Van Veen	3c	some return; two shells; lost the screen
8/10/2016	E-IF45	G3	63.46529167	-68.08013	177	yes	yes	yes	Van Veen	3c	some return
4/10/2016	E-IF9	G1	63.36550833	-68.30791667	100	yes	yes	yes	Van Veen	3c	good return
4/10/2016	E-IF9	G2	63.36572	-68.30966667	97.2	yes	yes	yes	Van Veen	3c	good return
4/10/2016	E-IF9	G3	63.36544167	-68.307075	101	yes	yes	yes	Van Veen	3c	good return
4/10/2016	E-IFI	G1	63.40461333	-68.28007333	122	yes	yes	yes	Van Veen	3c	good return
4/10/2016	E-IFI	G2	63.40430167	-68.279305	124	yes	yes	yes	Van Veen	3c	good return
4/10/2016	E-IFI	G3	63.40428333	-68.28031667	119	yes	yes	yes	Van Veen	3c	good return
7/10/2016	F-IF17	G1	63.23082	-67.56952333	197	no			Van Veen	3c	no return
7/10/2016	F-IF17	G2	63.23133	-67.56857333	198	yes	yes	no	Van Veen	3c	some return; mostly rocks
7/10/2016	F-IF17	G3	63.23118	-67.56864833	201	yes	yes	no	Van Veen	3c	some return; two rocks
5/10/2016	IFPH1	G2	63.73771	-68.680935	51	no			Van Veen	3c	no return
5/10/2016	IFPH1	G1	63.73762833	-68.68139333	51.2	yes	yes	yes	Van Veen	3c	good return
5/10/2016	IFPH1	G3	63.73748	-68.68029	50.4	yes	yes	yes	Van Veen	3c	good return
5/10/2016	IFPH1	G4	63.73737667	-68.67993333	50.3	yes	yes	yes	Van Veen	3c	good return
12/10/2016	IFPH2	G1	63.71376667	-68.647515	34.3	yes	yes	yes	Van Veen	3d	
12/10/2016	IFPH2	G2	63.71331667	-68.6478	32.1	yes	yes	yes	Van Veen	3d	
12/10/2016	IFPH2	G3	63.713845	-68.64776167	38.3	yes	yes	yes	Van Veen	3d	