# Oceanography and Underwater Acoustics in Resolute Bay, Nunavut: 2012-2015

by

Caitlin O’Neill
Bachelor of Science, University of Victoria, 2008

A Thesis Submitted in Partial Fulfillment

of the Requirements for the Degree of

MASTER OF SCIENCE

in the School of Earth and Ocean Sciences

# Supervisory Committee

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Dr. Svein Vagle (School of Earth and Ocean Sciences)
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Dr. Stan Dosso (School of Earth and Ocean Sciences)
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Dr. Ross Chapman (School of Earth and Ocean Sciences)
**Departmental Member**

# Abstract

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Resolute Bay, a remote Arctic bay opening into Parry Channel, in the Canadian Arctic Archipelago, hosts diverse populations of marine mammals and fish at various times each year. These animals migrate through the bay following patterns linked to food availability and oceanographic conditions; however, these patterns are not well understood. The focus of this study was to measure the oceanographic properties of the waters in and around Resolute Bay and to record underwater sounds to obtain marine mammal temporal patterns and ambient sound levels. Results showed the water properties in Resolute Bay differed from the waters outside of the bay. Dissolved oxygen saturation levels in Resolute Bay decreased during ice-covered times, with lowest levels between May and July. Dissolved oxygen was replenished after the ice left the bay. Sudden changes in salinity, temperature, and dissolved oxygen were observed in Resolute Bay when outside waters entered. Mean third-octave band sound pressure levels were 85.3 dB re 1 µPa during high ice concentration, and 95.6 dB re 1 µPa during ice-free and freeze-up periods, and reached a maximum of 145.3 dB re 1 µPa when vessels were present. Belugas (*Delphinapterus leucas*) and narwhals (*Monodon monocero*) were only present in periods of low ice concentration, while bearded seals (*Erignathus barbatus*) and ringed seals (*Pusa hispida*) remained throughout the entire year.

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# 1 Introduction

This thesis is a part of the research conducted by the Ocean Tracking Network (OTN). OTN is an international aquatic animal tracking network with the objective of acquiring knowledge and understanding of animal movements and habitats, and how they are linked to environmental conditions (http://oceantrackingnetwork.org). By collecting this important data, OTN aspires to build a knowledge base to help transform the management and policies of the world's oceans. This includes developing an understanding of the consequences of environmental variably and change, as well as the effects of human activities on these habitats and species. To collect these data, OTN uses a combination of acoustic telemetry, biologging, and oceanographic technologies in numerous different study environments. This variety of disciplines encourages communication and collaboration among researchers. OTN chose to focus their research across the entire Canadian continent and its three ocean arenas: Atlantic, Arctic, and Pacific. In each arena, studies were chosen to occur in continental shelf regions where minimal prior research has been carried out, as continental shelves are important areas for primary production and play a key role for marine ecosystems (Cooke et al., 2011; Hussey et al., 2015). One of the study areas, chosen as a part of the Canadian Arctic arena, was Resolute Bay, Nunavut. The research conducted in Resolute Bay under OTN's funding included fish telemetry, ringed seal tracking, oceanography, and marine mammal presence by underwater acoustics (e.g. Kessel et al., 2015). This thesis presents the results of the OTN's physical oceanographic and underwater acoustics research in Resolute Bay, Nunavut.

## 1.1 Background

Resolute Bay is a remote bay located on the southwest corner of Cornwallis Island on the north side of Parry Channel. Parry Channel is a natural waterway running east-west through the central Canadian Arctic Archipelago, connecting Baffin Bay in the east with the Beaufort Sea in the west (see Figure 1). Waters through Parry Channel flow eastward from the Arctic Ocean to Baffin Bay and the Atlantic Ocean, due to the difference in sea level (Bailey, 1957; Collin, 1962). The rest of the Canadian Archipelago is a series of narrow channels with basins and sills. This complex topography dictates water circulation and water mass transport throughout this region (Carmack, 2000).

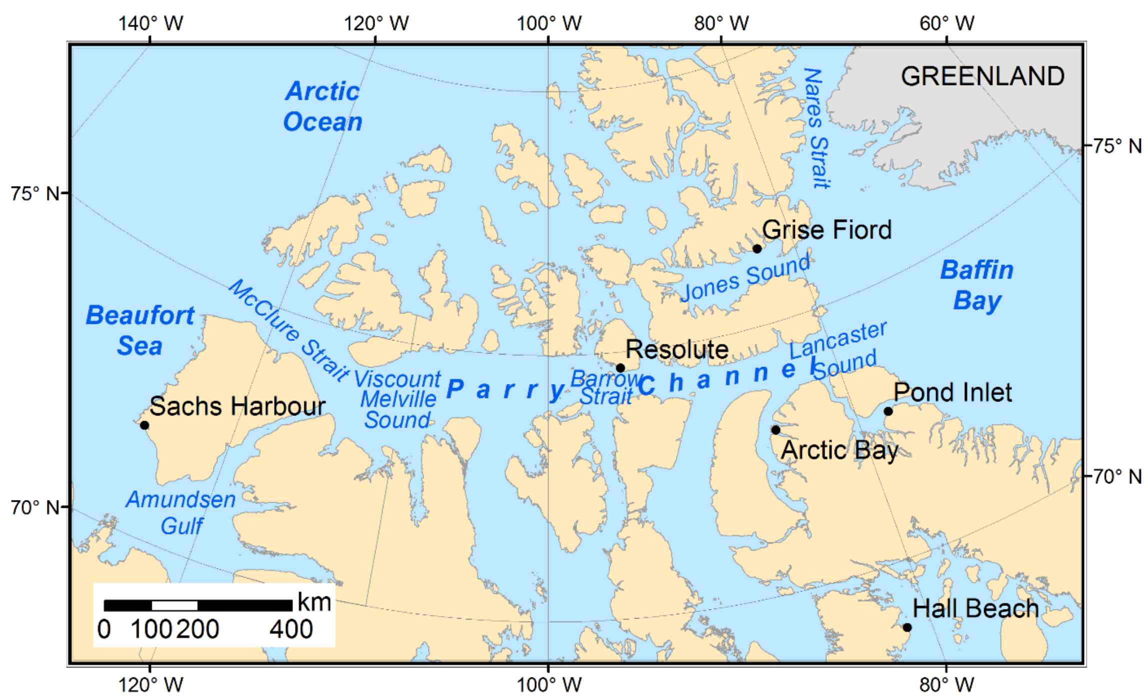


**Figure 1. Map of the Canadian Arctic Archipelago showing place names and waterways.**

Within Parry Channel, west of Lancaster Sound and south of Cornwallis Island, is Barrow Strait. Barrow Strait is the most restricted section of Parry Channel, only 52 km wide at its narrowest part, and 125 m deep. This bottleneck point is subject to amplified tidal currents, which mixes the transiting waters, producing more homogenous waters than in the basins to the west and east. However, the water column in Barrow Strait is unexpectedly stratified, causing flow reversal near the sill depth (Prinsenberg and Bennett, 1987; Rudels, 1986). With the lighter, fresher surface water flowing eastward, this exchange flow should increase during the summer due to freshwater influx and decrease during the winter due to less freshwater and increased surface-flow friction from sea-ice coverage (Melling, 2000).

Oceanographic and biologic measurements were carried out in Barrow Strait and Resolute Passage from 1983 to 1993 and from 2001 to 2009 by the Bedford Institute of Oceanography (Department of Fisheries and Oceans, DFO, Canada) and the Freshwater Institute (DFO; e.g. Conover et al., 1999; Michel et al., 2006). Surface waters were saltier and colder prior to the 1980s and between 2000 and 2006. However, in the 1980s and 1990s, the surface waters were warmer and fresher with increased salinity stratification in the upper water column. Below the sill depth (~125 m), temperatures were observed to increase with depth and the salinity profile slope changed, indicating Atlantic-origin waters (Michel et al., 2006).

Atlantic-origin water enters the Arctic Ocean through Fram Strait, whereas Pacific-origin water enters through the Bering Strait. The relatively fresh Pacific water occupies the upper ~200 m of the water column, on top of the denser, saltier Atlantic water. This 200 m upper layer is comprised of three water masses: a seasonal mixed layer, Pacific-origin summer water, and Pacific-origin winter water. Atlantic-origin and Pacific-origin water are present in the western region of the Canadian Arctic Archipelago. As these waters transit east through Parry Channel to Barrow Strait, they undergo mixing and geochemical modification. These processes cause the base of the seasonal mixed layer to become progressively shallower, colder, and more saline (McLaughlin et al., 2004).

The shallow sill of Barrow Strait, southwest of Cornwallis Island, separates Parry Channel into western and eastern regimes. The deep layer of Atlantic-origin waters is strongly constrained by this sill, which contributes to vertical mixing. East of the sill is Lancaster Sound, where there is an intersection of multiple currents: eastward flow from the Canadian Basin, southward flow from the Arctic Ocean through Nares Strait and Jones Sound, and northward flow of Atlantic-origin water along the western coast of Greenland (Jones and Coote, 1980). However, almost all of the water flowing through Lancaster Sound is of Pacific origin (Jones et al., 2003).

Sea ice is found in the Archipelago throughout the year, with a large seasonal and inter-annual variation in distribution and ice type. Ice concentrations remain high throughout the year in the western high Arctic and along the north coast of the Canadian Arctic Archipelago. Ice break-up occurs in the southern half of the Canadian Arctic Archipelago in late July, with the annual minimum ice concentrations occurring in mid-September. New ice starts to form in October and by mid-November the Canadian Arctic Archipelago is completely ice covered again (McLaughlin et al., 2004). Between 1968 and 2008 decreases in ice concentration were observed in western Lancaster Sound/Eastern Barrow Strait: $-3.7 \pm 5.0\%$ per decade of annual ice concentration and $-7.2 \pm 11.3\%$ per decade of multi-year ice concentration. It was found that reductions in sea ice concentration and ice thickness were related to increases in early-summer surface air temperature (Tivy et al., 2011).

This decrease in sea ice concentration is one of the notable changes observed due to climate change. Reduced sea ice concentration has opened up shipping passages, allowing commercial and pleasure craft into places that have not seen or heard them before (Johannessen et al., 2004), as well as changing the habitat of many Arctic species. It is important to understand these complex habitats to determine how species will be affected by climate change. In addition, it is important to establish baseline records of oceanographic measurements and ambient sound throughout the Arctic to be able to assess the extent of future climate changes.

Marine mammals can be affected by increased ambient sound levels and vessel traffic (Richardson et al., 1995). Several species of marine mammals have been documented to inhabit the waters near Resolute Bay. Ringed seals (*Pusa hispida*) and bearded seals (*Erignathus barbatus*), and harp seals (*Pagophilus groenlandicus*) are present year-round near Cornwallis Island and in Resolute Bay (Matley et al., 2015; Kingsley et al., 1985; Welch et al., 1993; Duignan et al., 1997). Bowhead whales (*Balaena mysticetus*), which have been tagged off west Greenland, have been observed to have transited across Baffin Bay in June and into the Canadian Arctic Archipelago in the summer, travelling as far as 95°W in Barrow Strait and into adjacent fiords (Dueck et al., 2006). In 2004 an aerial survey was conducted for the first time in Barrow Strait to estimate bowhead whale numbers, but not enough whales were seen to produce a reliable estimate in this area (Cosens et al., 2006). Walrus (*Odobenus rosmarus*) are found on the southwest side of Cornwallis Island in the spring and summer (Stewart, 2008). Resolute Bay is included in the summer range of the Baffin Bay narwhal (*Monodon monocero*) population, with narwhals observed near the southwest side of Cornwallis Island during an aerial survey in

August 2004 (Richard, 2010; Richard et al., 2010), and biological samples taken during a local hunt in September 2010 (Matley et al., 2015).

Belugas (*Delphinapterus leucas*) are the most commonly-sighted whale in the waters of Resolute Bay in the summer. Between July 17 and August 15, 1996, 11 female belugas were tagged at Somerset Island and were tracked travelling up the northeast side of Somerset Island, along Barrow Strait, and south along the west side of Somerset Island. During that transit, one whale travelled up to Resolute Bay. During the following month, the female belugas travelled back north and east with tagged male belugas, where multiple whales travelled along the southern shoreline of Cornwallis Island, including Resolute Bay (Richard et al., 2001). A similar migration route was recorded during separate tagging studies between 1988 and 1993 (Smith and Martin, 1994).

## 1.2 Research Objectives

The objectives of this study are to measure ambient sound levels near Resolute Bay, Nunavut, investigate temporal patterns of marine mammal presence in the area, and determine baseline oceanographic conditions and water movement mechanisms in Resolute Bay. With this information, we hope to gain knowledge and understanding of the current state of this complex marine ecosystem.

Underwater acoustic recordings were made between 2013 and 2015 with an autonomous acoustic recorder, which was deployed outside Resolute Bay. This captured sound from transiting vessels, marine mammal vocalizations, ice-generated sounds, and environmental sounds. There have been very few studies in the Canadian Arctic that have used underwater acoustic recordings to study marine mammal presence. However, aerial surveys have been carried out to conduct population estimation studies, and a small number of animal tagging studies have also been completed (e.g. Richard, 2010; Richard et al., 2010; Richard et al., 2001; Smith and Martin, 1994). Marcoux et al. (2011) recorded narwhals at two locations in the southeastern part of the Canadian Arctic Archipelago: Repulse Bay and Koluktoo Bay, Nunavut. Their study concluded that passive acoustic monitoring was a viable technique for the local monitoring of narwhals in Nunavut. This thesis work expands on this technique, by using passive acoustic monitoring for observing multiple Arctic species.

There have also been only a small number of (unclassified) studies that have recorded ambient sound levels in the Canadian Arctic, including Barrow Strait (e.g. Heard et al., 2013; Pelavas et al., 2012; Reeves et al., 2016; Thorleifson et al., 1974). These studies have focused on using acoustics to monitor rapid sea ice processes and pack ice breakup, vessel detection, horizontal and vertical directionality of ambient sound, and the dominant mechanisms governing underwater ambient sound in the Canadian Arctic. None of these measurements were year-long, covering the full range of ambient sound conditions. This thesis aims to characterize the ambient sound levels for a complete year of acoustic recording near Resolute Bay.

There are numerous shallow bays in the Canadian Arctic Archipelago, with Resolute Bay being one of seven along the 100 km coastline of south Cornwallis Island. These bays are of ecological importance, as they are inhabited by Arctic cod, a major component of Arctic marine food webs (Welch et al., 1993). Therefore, it is important to understand the water movements and ecological habitat of these bays and how they could be impacted in the future by climate change. There have been previous studies conducted in larger bodies of water in the Canadian Arctic Archipelago, such as Barrow Strait and

Lancaster Sound, but few studies have focused on characterizing the water and associated water movements in these shallow Arctic embayments. Resolute Bay is a marine habitat for many Arctic species, and the local Inuit would be directly affected by temporal and spatial changes in animal presence or migration patterns due to climate change. Therefore, this thesis focuses on defining the oceanographic properties and water movement in Resolute Bay and how they correlate to animal presence, to help understand how climate change will impact this ecosystem.

# 2 Methods

## 2.1 Instrumentation

Oceanographic and acoustic measurements of the waters in and near Resolute Bay were obtained by numerous moorings from 2012 to 2015, including Satlantic benthic pods, RBR loggers, a Teledyne 300-kHz Acoustic Doppler Current Profiler (ADCP), and an Autonomous Multichannel Acoustic Recorder (AMAR, JASCO Applied Sciences Ltd.). In 2012, two benthic pods were deployed on the seafloor, one in the basin of the northern end of Resolute Bay (referred to as the inner-bay benthic pod), and one outside the southwest side of the bay (referred to as the outside-bay benthic pod). In 2013, a third benthic pod was deployed in the channel west of the bay (referred to as the channel benthic pod). A 300-kHz ADCP was mounted on the inner-bay benthic pod in 2014. Six RBR internally recording data loggers were also deployed between 2013 and 2015, which included two dissolved oxygen saturation (DO) loggers[1]; two temperature (T) loggers; one conductivity and temperature (CT) logger; and one conductivity, temperature, and depth (CTD) logger. The DO and CT/CTD loggers were deployed as pairs on their respective moorings, such that dissolved oxygen saturation, salinity (derived from the conductivity measurements), and temperature were recorded at two separate locations in the bay, in addition to the benthic pods. An AMAR was deployed between 2013 and 2015, approximately 200 m northeast of the outside-bay benthic pod. The locations and deployment durations of the oceanographic and acoustic moorings are given in Table 2.1 to Table 2.3 and shown in Figure 2.1.

[1] The dissolved oxygen saturation levels were defined with 15°C waters. This did not affect the saturation levels presented in this report, but it would affect absolute dissolved oxygen levels.

**Table 2.1. Instruments collecting data from 2012 to 2013.**

| *Instrument* | *Latitude (°N)* | *Longitude (°W)* | *Deployment Date* | *Retrieval Date* | *Instrument Depth (m)* |
|---|---|---|---|---|---|
| Inner-Bay Benthic Pod | 74.68548 | 94.86194 | Aug. 1, 2012 | Aug. 9, 2013 | 33 |
| Outside-Bay Benthic Pod | 74.64791 | 94.83300 | Aug 2, 2012 | Aug. 9, 2013 | 55 |

**Table 2.2. Instruments collecting data from 2013 to 2014. Sample rates are given in Table 2.4 to Table 2.7.**

| *Instrument* | *Latitude (°N)* | *Longitude (°W)* | *Deployment Date* | *Retrieval Date* | *Instrument Depth (m)* |
|---|---|---|---|---|---|
| Inner-Bay Benthic Pod | 74.68549 | 94.86194 | Aug. 18, 2013 | Aug. 21, 2014 | 33 |
| Outside-Bay Benthic Pod | 74.64791 | 94.83300 | Aug. 18, 2013 | Aug. 21, 2014 | 55 |
| Channel Benthic Pod | 74.62482 | 94.91563 | Aug. 18, 2013 | Aug. 30, 2014 | 120 |
| RBR CTD and DO loggers | 74.68281 | 94.84127 | Aug. 22, 2013 | Aug. 17, 2014 | 18 |
| RBR CT and DO loggers | 74.68967 | 94.85187 | Aug. 22, 2013 | Aug. 28, 2014 | 21 |
| RBR T logger | 74.67994 | 94.87189 | Aug. 22, 2013 | Aug. 17, 2014 | 18 |
| RBR T logger | 74.67726 | 94.83083 | Aug. 22, 2013 | Aug. 14, 2014 | 18 |
| AMAR | 74.64625 | 94.83723 | Aug. 5, 2013 | Aug. 11, 2014 | 57 |

**Table 2.3. Instruments collecting data from 2014 to 2015. Sample rates are given in Table 2.4 to Table 2.7.**

| *Instrument* | *Latitude (°N)* | *Longitude (°W)* | *Deployment Date* | *Retrieval Date* | *Instrument Depth (m)* |
|---|---|---|---|---|---|
| Inner-Bay Benthic Pod and ADCP | 74.68553 | 94.86235 | Aug. 26, 2014 | Aug. 11, 2015 | 33 |
| Outside-Bay Benthic Pod | 74.64813 | 94.83308 | Sep. 1, 2014 | Aug. 14, 2015 | 55 |
| Channel Benthic Pod | 74.62480 | 94.91418 | Sep. 1, 2014 | Aug. 14, 2015 | 120 |
| RBR CTD and DO loggers | 74.68412 | 94.86695 | Aug. 24, 2014 | Aug. 13, 2015 | 18 |
| RBR CT and DO loggers | 74.66899 | 94.82024 | Sep. 3, 2014 | Aug. 13, 2015 | 21 |
| RBR T logger | 74.69029 | 94.86210 | Aug. 24, 2014 | Aug. 13, 2015 | 18 |
| RBR T logger | 74.69110 | 94.85193 | Aug. 24, 2014 | Aug. 13, 2015 | 18 |
| AMAR | 74.64613 | 94.83612 | Aug. 15, 2014 | Aug. 10, 2015 | 57 |

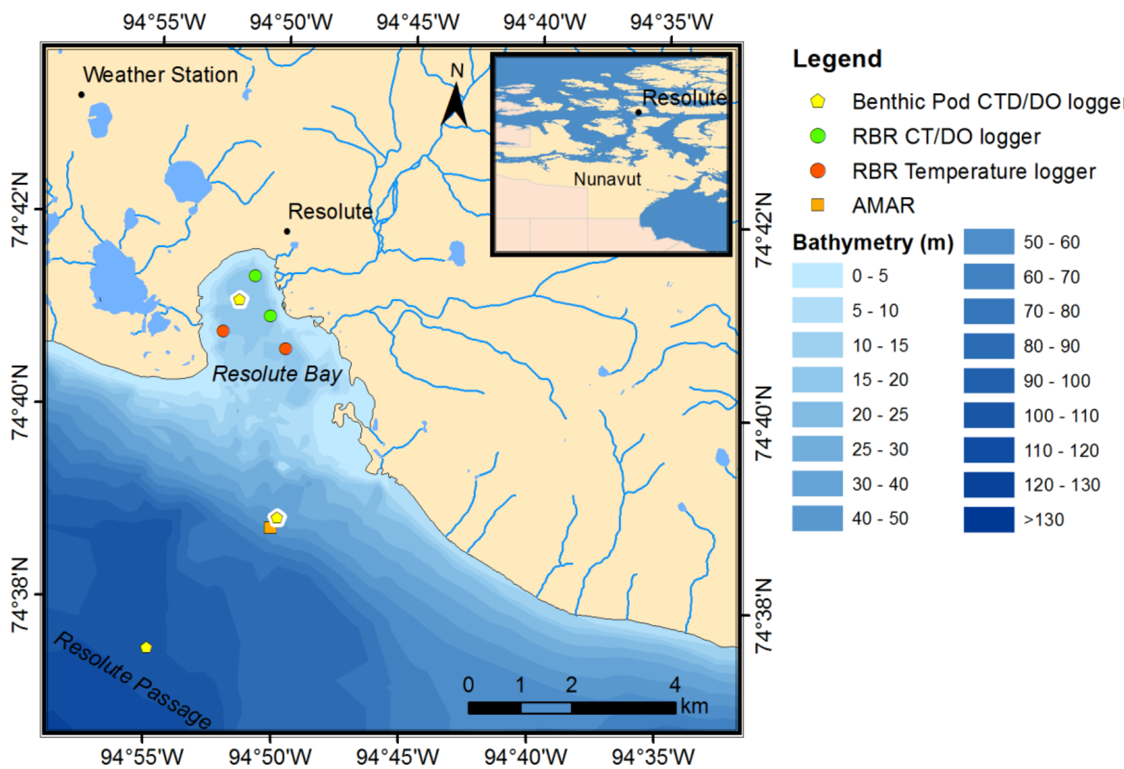


**Figure 2.1. Locations of moorings in and near Resolute Bay, Nunavut. White halo indicates moorings that were deployed from August 2012 to August 2015. All other moorings were deployed from August 2013 to August 2015. Bathymetry from Canadian Hydrographic Service (2009).**

As shown in Figure 2.1, Resolute Bay is located on the southwest corner of Cornwallis Island, in the Canadian Arctic Archipelago, on the north side of Parry Channel. It consists of an inner basin with depths up to 35 m, and a 3 to 10 m deep sill across the mouth of the bay. The northern half of the bay is 1.7 km across, which opens to a 4 km wide mouth into Resolute Passage. Three freshwater rivers feed into Resolute Bay during the summer months, all with small flow volumes. The Mecham River, located on the northeast side of Resolute Bay, had daily discharge rates between 0 and 13 $m^3/s$ between June 26 and October 20, 2013[2] (Water Survey of Canada, 2016). The other two rivers have smaller

[2] Incomplete dataset. No data between July 17 and August 18, 2013.

discharge rates (personal observation, 2013-2015). Untreated sewage output from the hamlet of Resolute discharges into the northeastern part of the bay. The land surrounding Resolute Bay is moderately flat, with rounded hills of limited extent and maximum elevations of less than 200 m.

The Satlantic benthic pods recorded water temperature, salinity, pressure, and dissolved oxygen, sampling for 30 s every hour at resolutions of 1, 1, 1, and 5 s respectively. Each benthic pod consisted of a cylindrical float around two PVC enclosure pressure cases and a Seabird 37-SIP microCAT C-T recorder. The instruments recorded temperature and salinity with an accuracy of 0.002°C and 0.0003 S/m. One of the PVC pressure cases housed the internal memory, processing board, and a Paroscientific Digiquartz pressure sensor with 3.5 cm accuracy. It also had an externally mounted Aanderaa dissolved oxygen sensor with an 8 s response time and <5% dissolved oxygen saturation accuracy. The second pressure case was filled with D-cell batteries, which were the power source for the benthic pod. Each instrument on each benthic pod was calibrated in-shop before being shipped to Resolute Bay, and a pre-deployment test measurement was performed before each deployment.

The benthic pod is a static mooring, anchored to the seafloor with a 250 lb convex steel plate, as shown in Figure 2.2 (a). A cylindrical float, used for retrieval, surrounds the autonomous instruments, battery pack, logging electronics, and acoustic release. The sensors for the CTD and dissolved oxygen were located 0.5 m above the seafloor. The in-bay, outside-bay, and channel benthic pods were deployed in water depths of 33, 55, and 120 m, respectively.

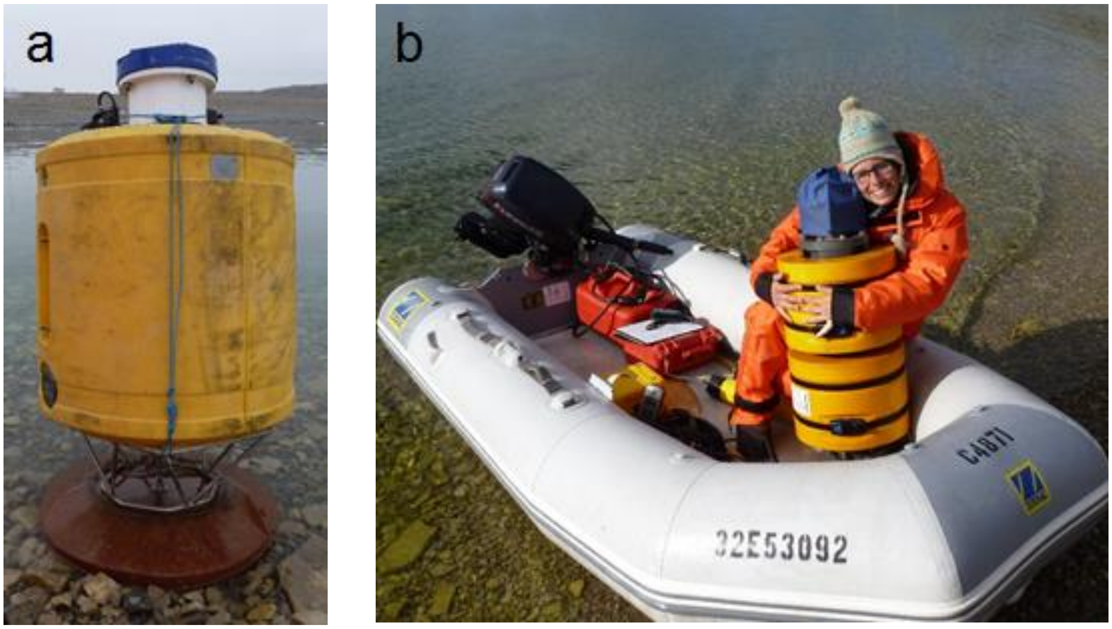


**Figure 2.2. (a) Satlantic benthic pod mooring with ADCP. (b) Author and retrieved AMAR with float collars.**

The benthic pod deployed outside the bay included a 5-element vertical thermistor array deployed with a float above the benthic pod. The temperature loggers were spaced by 5 m, originating 2.5 m above the benthic pod sensors. These RBR TR-1050 loggers recorded temperature every 30 s and have a 0.003°C accuracy. This benthic pod mooring also had a Chelonia C-POD, which was moored 5.5 m above the seafloor. The C-POD continuously monitored underwater sound at frequencies between 20 and 160 kHz for cetacean clicks. It used digital waveform characterisation to select and internally log time, centre frequency, sound pressure level, duration, and bandwidth of detected clicks. The C-POD recorded for approximately 4 months after each annual deployment in August. A second C-POD was moored either with or near the in-bay benthic pod, collecting data in 2012 and 2013, but not in 2014. From August 2014 to August 2015, a Teledyne 300 kHz ADCP collected water velocity measurements. It was mounted at the top of the inner-bay benthic pod, 1 m above the seafloor. However, the data from these instruments will not be considered in the work presented in this thesis, as the extra oceanographic data did not contribute to the understanding of the water processes in Resolute Bay and there was not enough time to process the C-POD data.

Six RBR loggers, deployed in four locations in the bay, were added to the Resolute Bay oceanographic instrument array in summer 2013. These were deployed such that there were 2 additional DO and CT/CTD moorings and two temperature-only moorings. These loggers recorded values every 2 to 24 s between August 2013 and August 2014 and every 60 s between August 2014 and August 2015, as shown in Table 2.4 and Table 2.5. The RBR loggers were deployed on seafloor-anchored moorings, 3 m above the seafloor, with acoustic releases. The CTD/DO, CT/DO, and both T loggers, were deployed in water depths of 18, 21, and 18 m, respectively. The CT and CTD loggers have an accuracy of 0.003 mS/cm, 0.002°C, and 0.05%, and the DO loggers have an accuracy of 2% and a response time of approximately 10 s.

**Table 2.4. Sampling rates of RBR loggers from August 2013 to August 2014.**

| *Instrument* | *Sampling Rate (s)* |
|---|---|
| RBR CTD logger | 24 |
| RBR CT logger | 22 |
| RBR DO loggers | 2 |
| RBR T loggers | 3 |

**Table 2.5. Sampling rates of RBR loggers from August 2014 to August 2015.**

| *Instrument* | *Sampling Rate (s)* |
|---|---|
| RBR CTD logger | 60 |
| RBR CT logger | 60 |
| RBR DO loggers | 60 |
| RBR T loggers | 60 |

Underwater sound level measurements were obtained with an AMAR, fitted with a Geospectrum M8E-V35 omni-directional hydrophone with –164 dB re V/μPa nominal sensitivity. The AMAR, shown in Figure 2.2 (right), recorded acoustic data with 24-bit resolution to internal solid-state flash memory, with the recording schedule outlined in Table 2.6 and Table 2.7. The recording schedule was optimized to capture the high frequency clicks of cetaceans during the summer and ambient sound levels throughout the winter when the whales were not present. The instrument was deployed in 60 m of water, suspended 3 m from the seafloor on a floating mooring with an Edgetech PORT MFE (Push Off Release Transponder, Medium Frequency Extended life) acoustic release. A sinking ground line was attached to the seafloor anchor for back-up retrieval.

**Table 2.6. 2013-2014 AMAR recording schedule.**

| *Sample Rate (kHz)* | *Duration (s)* | *Duty Cycle Length (days)* | *Recording Dates* |
|---|---|---|---|
| 96 | 113 | 60 | August 5, 2013 – October 6, 2013 |
| Sleep | 127 | | |
| 16 | 340 (5.6 minutes) | 257 | October 6, 2013 – June 20, 2014 |
| Sleep | 3260 (54.3 minutes) | | |
| 96 | 113 | 10 | June 20, 2014 – June 30, 2014 |
| Sleep | 127 | | |

**Table 2.7. 2014-2015 AMAR recording schedule.**

| *Sample Rate (kHz)* | *Duration (s)* | *Duty Cycle Length (days)* | *Recording Dates* |
|---|---|---|---|
| 96 | 113 | 80 | August 15, 2014 – November 3, 2014 |
| Sleep | 127 | | |
| 32 | 340 (5.6 minutes) | 281 | November 3, 2014 – August 10, 2015 |
| Sleep | 3260 (54.3 minutes) | | |

The AMAR was calibrated in-shop and in the field before deployment with a 42AA or 42AC pistonphone calibrator (G.R.A.S. Sound & Vibration A/S), which generates a known 250 Hz reference tone accurate to 0.1 dB at the AMAR hydrophone sensor. The resulting measured sound pressure level obtained from the in-field pistonphone calibration was used in subsequent data analysis.

CTD casts, providing salinity and temperature profiles, were performed every summer at various stations around Resolute Bay, as shown in Figure 2.3 and Table 2.8. In 2012, 20 stations were selected throughout the bay and in subsequent summers these stations, as well as 3 additional stations, were sampled. One of the CTD profiles measured at station R is shown in Figure 2.4.

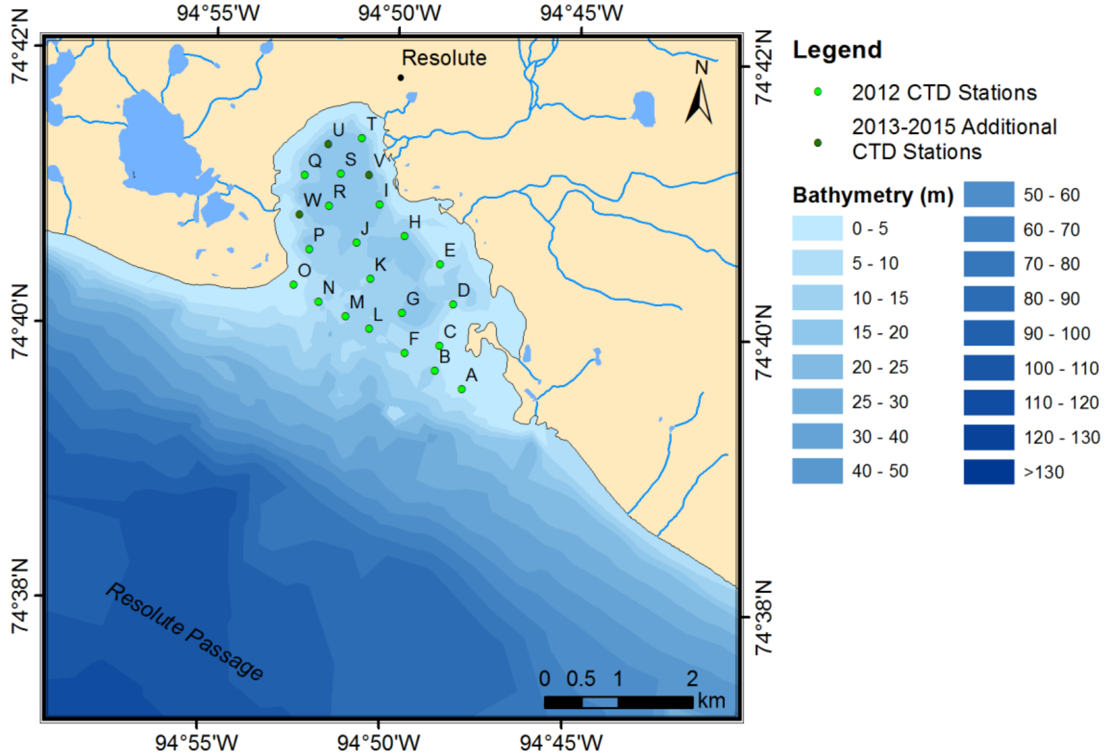


**Figure 2.3. Map of CTD cast stations in Resolute Bay. Bathymetry from Canadian Hydrographic Service (2009).**

**Table 2.8. CTD cast stations in Resolute Bay.**

| *CTD Station* | *Latitude (°N)* | *Longitude (°W)* |
|---|---|---|
| A | 74.66000 | –94.80000 |
| B | 74.66213 | –94.81250 |
| C | 74.66517 | –94.81083 |
| D | 74.67023 | –94.80500 |
| E | 74.67500 | –94.81167 |
| F | 74.66417 | –94.82667 |
| G | 74.66900 | –94.82833 |
| H | 74.67833 | –94.82833 |
| I | 74.68200 | –94.84000 |
| J | 74.67733 | –94.85000 |
| K | 74.67300 | –94.84333 |
| L | 74.66691 | –94.84313 |
| M | 74.66833 | –94.85417 |
| N | 74.67000 | –94.86667 |
| O | 74.67200 | –94.87833 |
| P | 74.67633 | –94.87167 |
| Q | 74.68533 | –94.87500 |
| R | 74.68167 | –94.86333 |
| S | 74.68567 | –94.85833 |
| T | 74.69000 | –94.84917 |
| U | 74.68917 | –94.86444 |
| V | 74.68556 | –94.84528 |
| W | 74.68056 | –94.87667 |

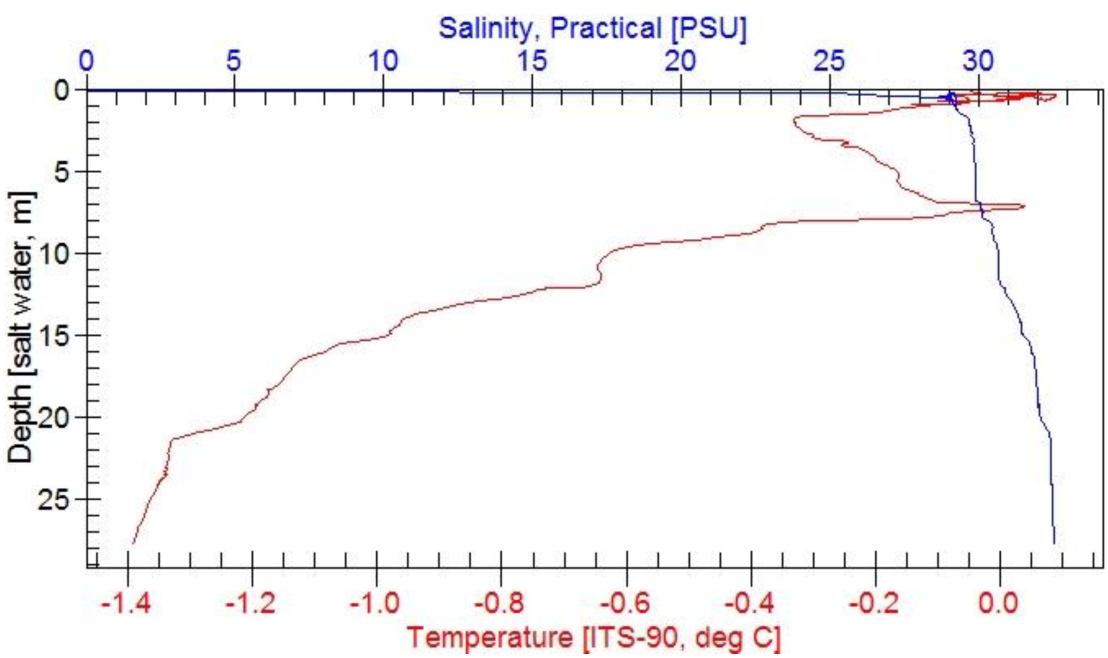


**Figure 2.4. CTD profile at station R on August 11, 2014 during ebb tide.**

## 2.2 Data Analysis

The 30-s hourly samples of benthic pod data were averaged to create a time series of hourly temperature, salinity, and dissolved oxygen saturation. These data, along with the RBR logger data, were de-spiked and processed with a 24-hour cut-off low-pass Butterworth filter to remove tidal variability. Aberrant salinity spikes, likely from instrument error, were manually removed. When describing dissolved oxygen levels in this report, it is in reference to dissolved oxygen saturation.

Temperature versus salinity plots are presented in Chapter 3 with reference to sigma-t ($\sigma_T$). Sigma-t is a simplified unit used to represent the density of seawater, such that $\sigma_T(S,T) = \rho(S,T)-1000$ kg/m$^3$, where $\rho(S,T)$ is the density (in kg/m$^3$) of a sample of seawater at temperature T and salinity S.

Daily ice cover concentrations for Resolute Bay were obtained from the Canadian Ice Service online archives (Canadian Ice Service, 2016). Daily average wind speeds and air temperatures recorded at the Resolute Bay weather station were obtained from the Environment and Climate Change Canada online archives (Weather Canada, 2015). The Resolute Bay weather station is located 5 km northwest from Resolute Bay (see Figure 2.1).

Data analysis of the underwater acoustics data was performed using JASCO Applied Sciences' automated software. Ambient sound processing was used to create spectrograms and calculate broadband, decade-band, and third-octave band sound pressure levels (SPLs, referenced to 1 µPa), as well as power spectral density (referenced to 1 µPa$^2$/Hz), which were compared to the Wenz Curves (Wenz, 1962).

The Wenz curves, as shown in Figure 2.5, display ranges of ambient spectral levels as a function of frequency. Even though large variability ranges are given, the Wenz curve levels are generalized and therefore were used for approximate comparisons only.

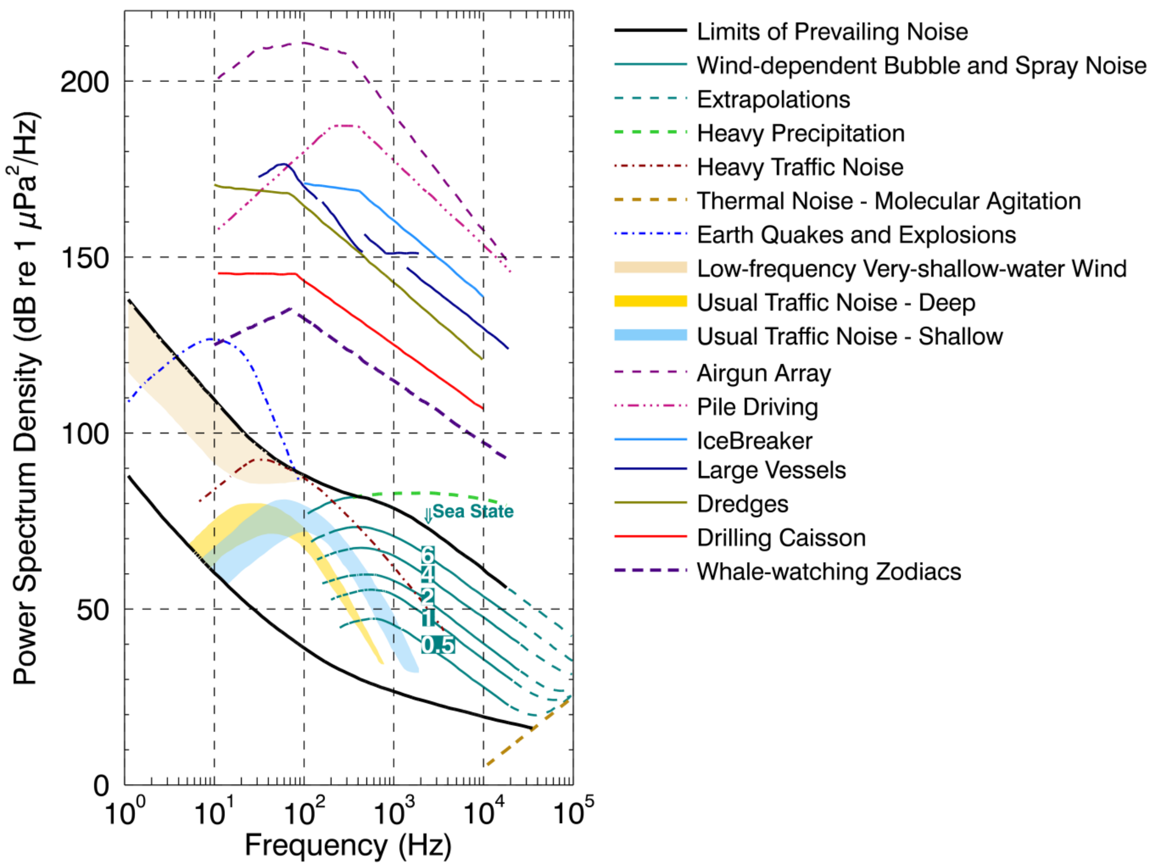


**Figure 2.5. Wenz (1962) curves of various natural and anthropogenic underwater sound source spectra. The legend identifies component spectra. An estimate of the ambient sound to be expected in a particular situation can be made by selecting and combining the pertinent component spectra (Ross, 1976; Urick, 1983; Scrimger and Heitmeyer, 1991; Erbe and Farmer, 2000; Erbe 2002, 2009).**

Spectrograms were created with Hamming-windowed fast Fourier transforms (FFTs), with 1 Hz resolution and 50% window overlap, then 1-minute average spectra were calculated by averaging the 120 FFTs. In addition to the spectrograms, a time-series of broadband and decade-band sound pressure levels are presented in Chapter 4 for frequency bands of 10 Hz to 48 kHz (for 96 kHz sample rate), 10 Hz to 16 kHz (for 32 kHz sample rate), 10-100 Hz, 100-1000 Hz, 1-10 kHz, and 10-16 kHz.

Statistical distributions of the sound pressure level in each third-octave band are also presented, as well as spectral level percentiles as histograms of each frequency bin per 1 minute of data. The 5th, 25th, 50th, 75th, and 95th percentiles are plotted. The 95th percentile curve is the frequency-dependent level exceeded by 5% of the 1 minute averages. Equivalently, 95% of the 1 minute spectral levels are below the 95th percentile curve. The 50th percentile is the median of the 1-minute spectral averages.

### 2.2.1 Automated Marine Mammal Detectors

Two automated detectors (developed by JASCO Applied Sciences Ltd.) were used to identify marine mammal vocalizations in the acoustic recordings. A tonal call detector was employed to identify generic marine mammal calls, which included bearded seal down-sweeps, up-sweeps, and trills; ringed seal double thumps; and beluga whistles. A second detector identified cetacean clicks. These detectors have been used successfully in previous studies (e.g. Martin et al., 2014; Delarue et al., 2015).

The tonal call detector identified marine mammal vocalizations in the acoustic data. First, spectrograms are created using the parameters outlined in Table 2.9. These spectrograms are then normalised by the median value in each frequency bin for each detection window in order to attenuate long spectral rays in the spectrogram due to vessel noise, and to enhance weaker transient biological sounds. The normalized spectrograms are then converted to a binary format by setting all the time-frequency bins that exceed the detection threshold (see Table 2.9) to 1 and the other bins to 0. A variation of the flood-fill algorithm is used to join adjacent bins and create contours (Nosal, 2008).

Classification parameters are calculated for each contour, which are then processed through a call-sorting algorithm to determine if the contour matches the definition provided for a specific marine mammal call (see Table 2.10).

**Table 2.9. FFT and detection window settings used to detect the marine mammal tonal calls. Values are based on JASCO's experience and empirical evaluation on a variety of data sets.**

| *Species* | *Call Type* | *FFT* | | | *Detection Window (s)* | *Detection Threshold* |
|---|---|---|---|---|---|---|
| | | *Resolution (Hz)* | *Frame Length (s)* | *Time step (s)* | | |
| Bearded Seal | down-sweep | 2 | 0.2 | 0.05 | 10 | 3 |
| Bearded Seal | up-sweep | 2 | 0.2 | 0.05 | 10 | 3 |
| Bearded Seal | full trill | 4 | 0.25 | 0.125 | 10 | 3 |
| Ringed Seal | low frequency double thump | 20 | 0.05 | 0.025 | 5 | 4 |
| Beluga | low frequency whistle | 16 | 0.03 | 0.015 | 5 | 3 |
| Beluga | high frequency whistle | 64 | 0.015 | 0.005 | 5 | 3 |
| Narwhal | whistle | 16 | 0.032 | 0.02 | 30 | 3 |

**Table 2.10. Call sorter definitions for the marine mammal tonal calls.**

| *Species* | *Call Type* | *Frequency (Hz)* | *Duration (s)* | *Bandwidth (Hz)* | *Other* |
|---|---|---|---|---|---|
| Bearded Seal | down-sweep | 200-1500 | 1-10 | >100 | Sweep rate: –500 to –530 Hz/s Maximum instantaneous bandwidth: 120 Hz |
| Bearded Seal | up-sweep | 150-2000 | 1-6 | >100 | Sweep rate: 100 to 1000 Hz/s Maximum instantaneous bandwidth: 120 Hz |
| Bearded Seal | full trill | 125-8200 | 10-90 | >500 | Sweep rate: –150 to –5 Hz/s |
| Ringed Seal | low frequency double thump | 10-250 | 0.2-1 | >20 | |
| Beluga | low frequency whistle | 1000-5000 | 0.5-5 | >300 | Maximum instantaneous bandwidth: 1000 Hz. |
| Beluga | high frequency whistle | 4000-20000 | 0.3-3 | >700 | Maximum instantaneous bandwidth: 5000 Hz. |
| Narwhal | whistle | 1500-20000 | 0.4-4 | >400 | Maximum instantaneous bandwidth: 700 Hz. |

The click detector identified cetacean clicks in the acoustic data. All clicks detected are assumed to be from beluga. First, the acoustic data are processed through an 8-kHz cut-off high-pass filter. The use of this threshold frequency retains the high frequency marine mammal clicks, while reducing unwanted signals such as vessels, marine mammal tonal calls, and weather-related noise. The filtered data are then summed to create a 0.5 ms root-mean-square (rms) time series, as most marine mammal clicks have a duration between 0.1 and 1 ms. Possible click events are identified in the time series with a Teager-Kaiser energy detector (see description in Kandia and Stylianou, 2006). For each click, the maximum peak signal is located within 1 ms of the identified click. The time series is then searched forwards and backwards to determine the time period that encompasses when the local data maxima are within 12 dB of each identified click peak. Once the click window is established, the classification parameters are computed including the number of zero-crossings within the click, the median time separation between zero-crossings, and the slope of the change in time separation between zero-crossings. To compare the extracted classification parameters to the click template, the Mahalanobis distance is calculated for each click (Mahalanobis, 1936; Brereton, 2015; De Maesschalck et al., 2000). The Mahalanobis distance is defined as

$$MD_i = \sqrt{(x_i - \bar{x})^T \mathrm{C}_x^{-1} (x_i - \bar{x})}, \quad (1)$$

where $x_i$ is the column vector (p × 1) comprised of the p calculated classification parameters of the unclassified click $i$, $\bar{x}$ is the mean column vector (p × 1) of the unclassified clicks, and $C_x$ is the known covariance matrix. Each cetacean species has an associated covariance matrix, which was calculated based on thousands of manually identified clicks in JASCO Applied Sciences' internal acoustics database. For each detected click, the MD is calculated for each possible known $C_x$. The $C_x$ that yields the smallest MD classifies the click to the associated species. If each calculated MD is greater than the pre-defined threshold, then the click is classified as unknown. A visual representation of this procedure is shown in Figure 2.6.

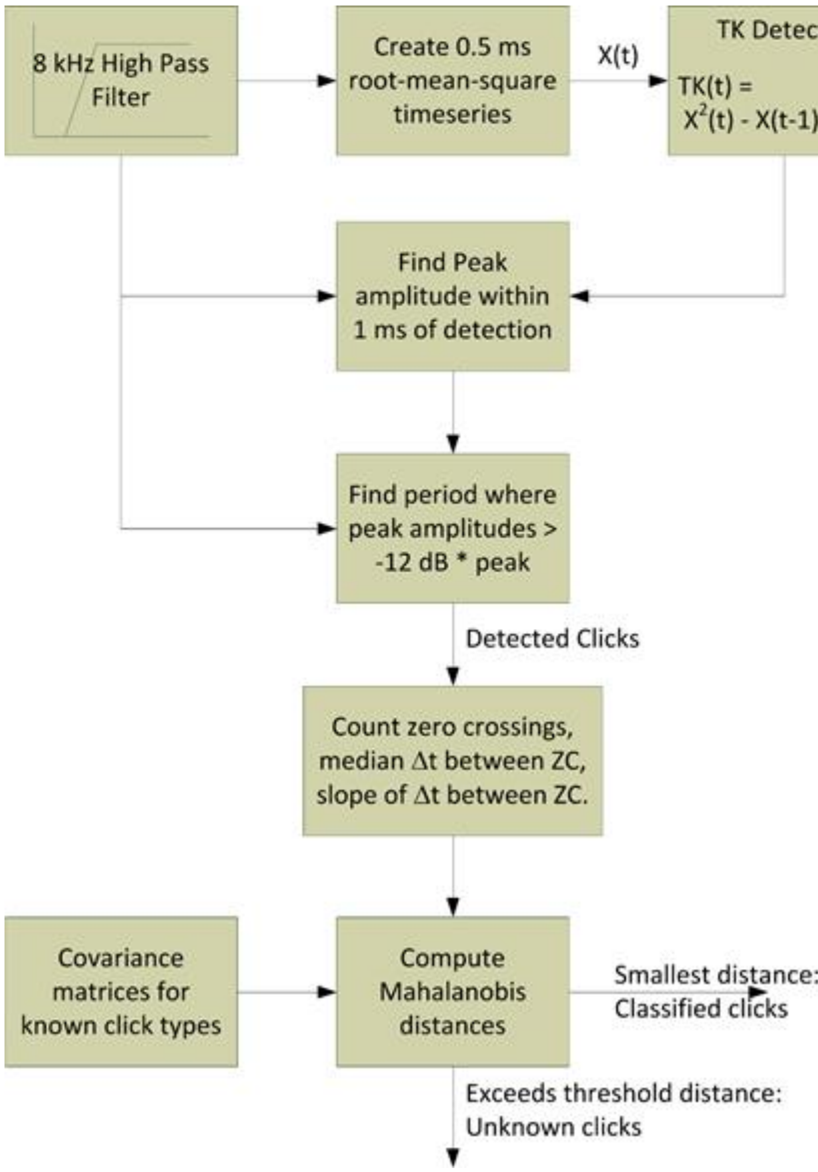


**Figure 2.6. Algorithm for JASCO Applied Sciences' click detector (Martin et al., 2015).**

Validation of the detectors was manually performed by reviewing 8 of the 16 kHz and 14 of the 96 kHz files from 2013-2014, as well as 11 of the 32 kHz and 10 of the 96 kHz files from 2014-2015. These spot-checks were used to evaluate the performance of the automated detectors at different time periods and for the different species. The manual validation found that the bearded seal detector was under-estimating bearded seal call counts, although more in-depth manual analysis would be needed to define a specific ratio. In addition, many false detections due to ice noise were found in October and November.

The manual validation also provided information that was used to refine the detector results for the cetacean clicks and calls. The click detections were edited to only retain results when over 1000 clicks were present in a 1-minute file. For the beluga whistle results, a combination of three classifiers were used, high whistle, low whistle, and narwhal whistle, as they all picked up different components of the beluga repertoire observed in the Resolute Bay datasets. Any 1-minute files with less than 4 detections were removed for each whistle classifier. These three sets of results were then summed to produce the beluga whistle results.

# 3 Results – Oceanography

This chapter presents an overview of the oceanographic results derived from the measurements described in Chapter 2. The underwater acoustics results are presented in Chapter 4.

Tides in Resolute Bay are minimal, with a maximum height range of ±1 m, as shown in Figure 3.1. Neap tides vary between ±0.1 m and ±0.5 m and spring tides vary between ±0.5 m and ±1 m. These are mixed tides, with a higher high water and lower high water as well as higher low water and lower low water per ~24.5 hr tidal period.

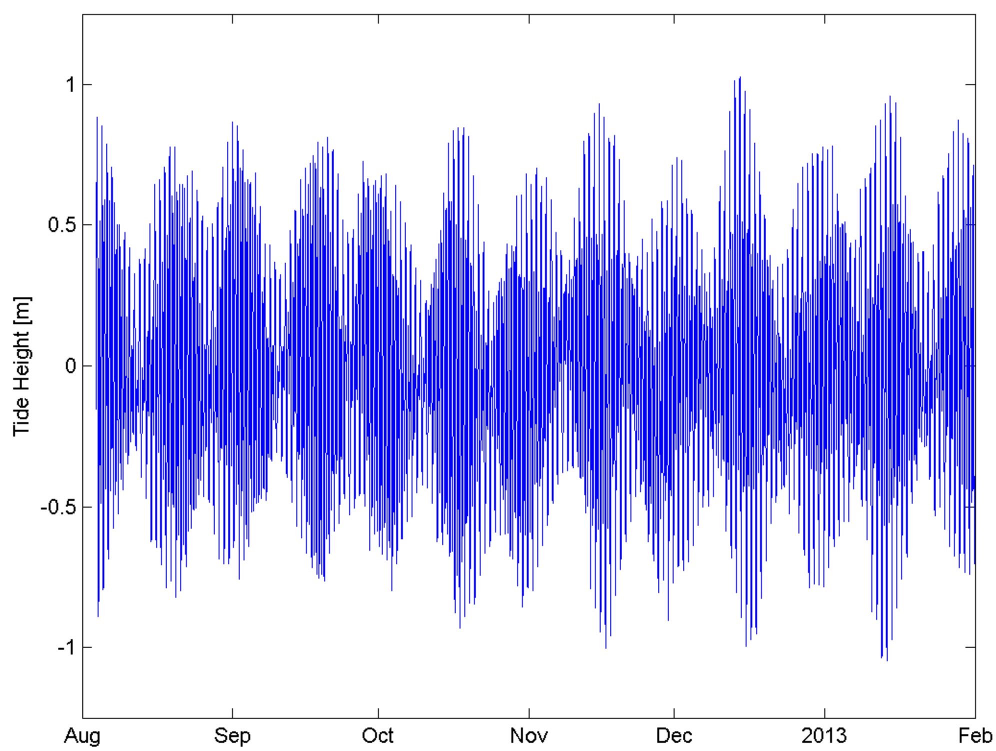


**Figure 3.1. Tide height in Resolute Bay, as measured on inner-bay benthic pod from August 2012 to February 2013.**

## 3.1 2012–2013 Deployment

Figure 3.2 shows the ice concentration percentage in Resolute Bay during the first set of deployments. In the summer of 2012, Resolute Bay was ice free between July 21 and

October 14. Ice freeze-up occurred quickly, progressing from 0% to 90% concentration in 2 days. On October 31, Canadian Ice Services stopped analyzing this region for the winter, and therefore it is assumed that the ice concentration is near 100% after this date, although this is not necessarily the case. Ice break-up started on July 22, and the bay was ice free on August 7, 2013.

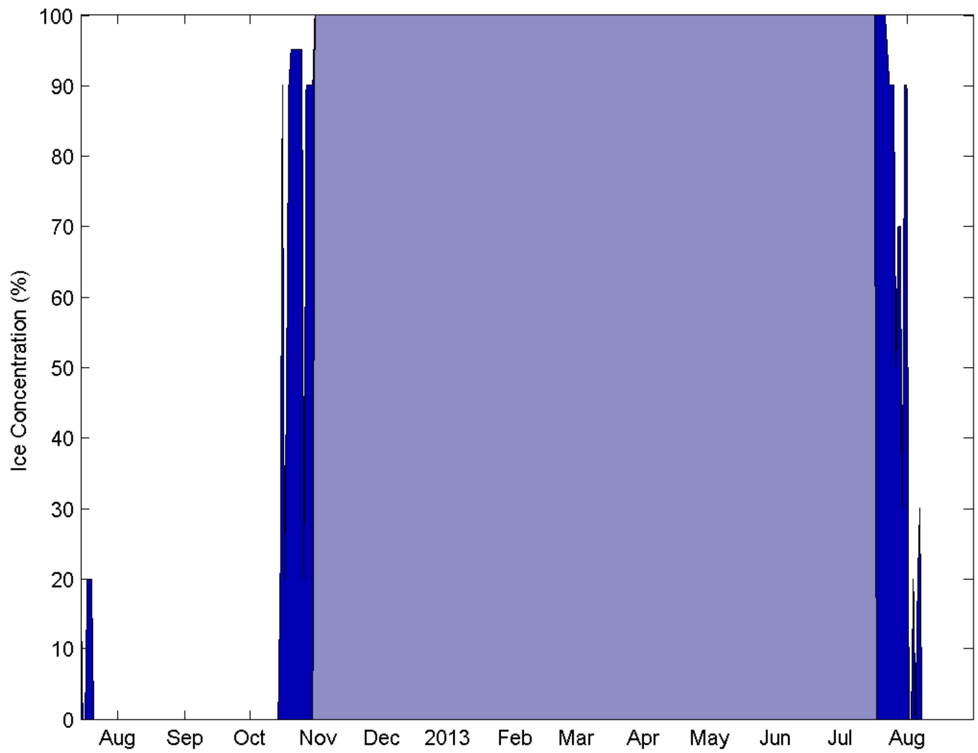


**Figure 3.2. Ice concentration in Resolute Bay from August 2012 to August 2013. Light shaded area represents assumed 100% ice concentration when Canadian Ice Services did not analyze ice concentration data in this area.**

The inner-bay benthic pod (see location in Figure 2.1) recorded temperature, salinity, and dissolved oxygen at the deepest section of Resolute Bay between August 1, 2012, and August 9, 2013, as shown in Figure 3.3.

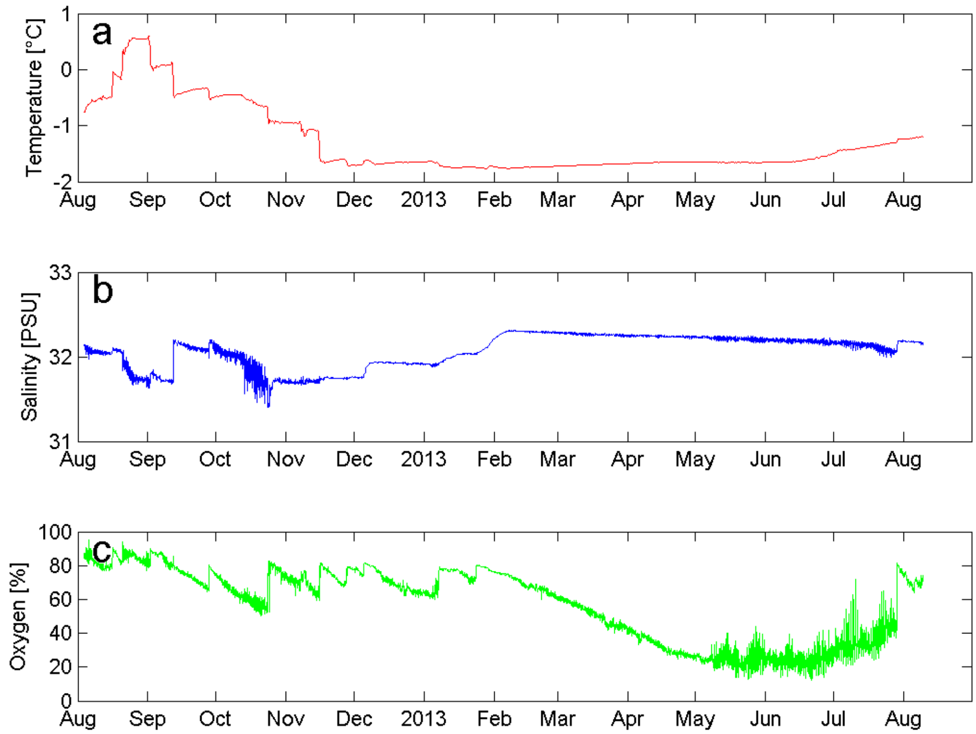


**Figure 3.3. (a) Temperature, (b) salinity, and (c) dissolved oxygen saturation levels at the inner-bay benthic pod.**

In August 2012, water temperatures gradually increased, with two abrupt increases on August 16 and 20. During the first sudden increase, temperature increased 0.41°C over 16 hours, and during the second sudden increase, temperature increased 0.51°C over 18 hours. The gradual increase in water temperature is likely due to lack of ice concentration and above-freezing air temperatures, as shown in Figure 3.4. As the air temperatures dropped below the freezing level, the water temperature also decreased. The water temperature rapidly decreased by 0.5°C (0.6 to 0.1°C) over an 18-hour period on September 1. A second significant temperature drop of more than 0.6°C occurred over a 20-hour period on September 11. Subsequent temperature drops occurred on September 27, October 23, and November 15, 2012. From mid-November 2012 to mid-June 2013, the water temperature stayed relatively constant, hovering between –1.76 and –1.59°C. In mid-June 2013, the water temperature started to gradually increase at a rate of 0.008°C/day, continuing until the end of the instrument deployment in mid-August 2013.

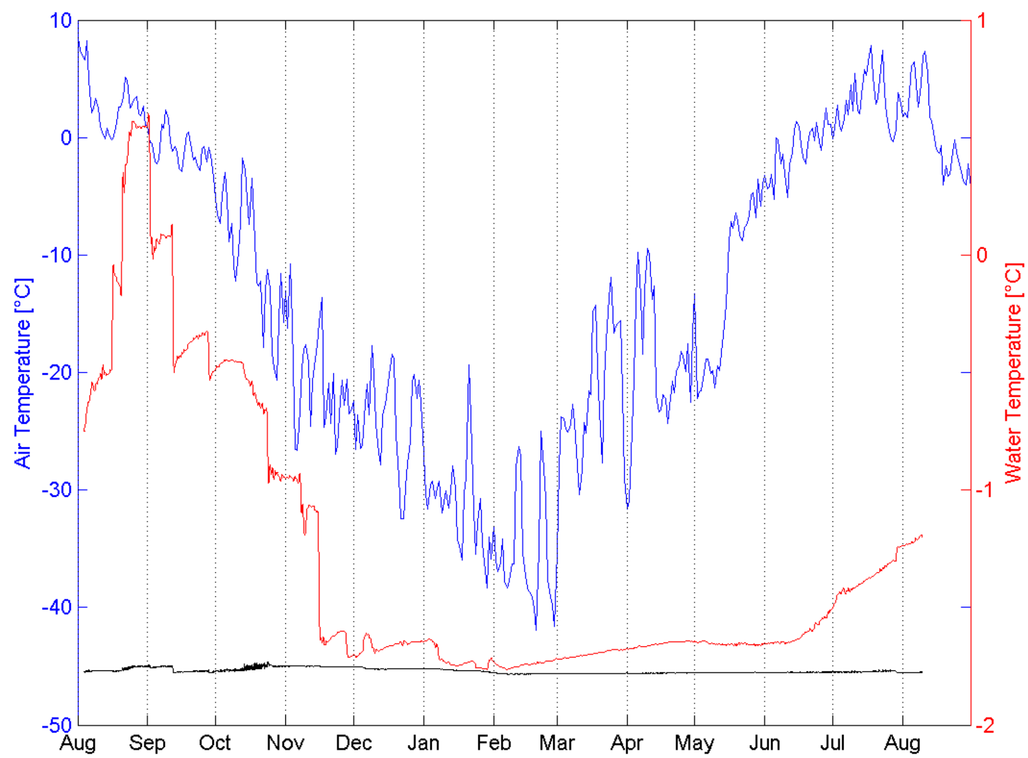


**Figure 3.4. Resolute Bay air temperature and water temperature at inner-bay benthic pod from August 2012 to August 2013. Freezing temperature of the sea water (adjusted for salinity, dissolved oxygen saturation, and pressure) measured at inner-bay benthic pod is shown with solid black line and referenced to the right y-axis.**

The large temperature steps observed at the inner-bay benthic pod (Figure 3.3(a)) correlate to steps in salinity (Figure 3.3, middle), although there is not a consistent relationship between the temperature and salinity steps. When the first abrupt temperature change was measured on August 16, 2012, salinity increased by 0.07 PSU over 1 hour. On August 20, the temperature increased significantly again, but this time salinity decreased by 0.21 PSU in 4 hours. Salinity also suddenly increased on September 1, when temperature decreased. The largest measured step in salinity occurred on

September 11, when it jumped from 31.68 to 32.19 PSU in 8 hours. This corresponded to a temperature drop of 0.61°C in 20 hours. On October 23, salinity decreased by 0.23 PSU in only 3 hours, at the same time as the water temperature decreased. However, 15 hours after this occurrence, salinity jumped back to a level comparable to that before the event, but temperature did not change. During all these events, sudden changes in salinity occurred faster than their corresponding changes in temperature. An abrupt increase in salinity also occurred on December 5, when it rapidly changed from 31.75 to 31.92 PSU in 57 hours. During this event, the temperature only increased 0.06°C in 15 hours, a minor change compared to other abrupt temperature changes observed. After December 5, 2012, the salinity slowly decreased at a rate of 0.001 PSU/day, until January 6, 2013. Over the next 10 days, salinity increased at a rate of 0.01 PSU/day and then plateaued for 7 days. Between January 23 and February 9, 2013, salinity increased by 0.274 PSU, at a rate of 0.0161 PSU/day. Between February 9 and July 1, 2013, salinity slowly decreased by 0.1420 PSU, at a rate of 0.0010 PSU/day. From May 5, 2013 to the end of the observation in mid-August, 2013, only small variations in salinity were observed, likely due to tidal influence.

As these abrupt shifts in both temperature and salinity were occurring, dissolved oxygen saturation levels changed suddenly as well (Figure 3.3, bottom). On August 16, 2012, during the first measured temperature and salinity shift, dissolved oxygen increased from 78 to 91% in 8 hours. Subsequently, on August 20, when temperature abruptly increased and salinity abruptly decreased, dissolved oxygen increased by 7% in 4 hours. Dissolved oxygen also suddenly increased on September 1 with salinity, as temperature dropped. On September 27, dissolved oxygen levels abruptly increased 15% in 4 hours, which was 4 days after a sudden drop in temperature and increase in salinity. On October 23, when temperature decreased and salinity suddenly increased, there were 3 dissolved oxygen spikes within 24 hours. Sudden increases in dissolved oxygen occurred November 15, November 27, December 5, January 7, and January 23. On November 15, temperature also significantly decreased and salinity slightly increased. Temperature decreased on November 27, with dissolved oxygen, although salinity remained constant. As discussed above, on December 5, 2013, significant changes in both temperature and salinity were observed. On January 7 and 23, 2013, when a significant sudden increase in dissolved oxygen was measured, the rate of salinity change started to increase and temperature gradually decreased. After January 23, 2013, dissolved oxygen levels fell by 56%, at a rate of 0.6%/day, until May 6, 2013, with minimal daily variance. After this date there was only a slow downward trend in dissolved oxygen levels with time. However, both dissolved oxygen levels and salinities varied significantly daily, likely due to tidal influence. Greater dissolved oxygen variability occurred between May and August, when ice was melting and ice concentration was decreasing in waters near Resolute. The increase in open water likely allowed for more wind-driven water movement into Resolute Bay, causing increased variability in the dissolved oxygen levels. On July 29, dissolved oxygen levels suddenly increased 40% in 4 hours, which also corresponded to a sudden increase in salinity of 0.13 PSU in 14 hours, starting 4 hours before the dissolved oxygen saturation showed change. Also, 3 hours before the salinity started going up, the temperature started to increase by 0.06°C in 27 hours.

The sudden changes in temperature, salinity, and dissolved oxygen are likely the result of an influx of water coming into the deep part of Resolute Bay, refreshing and replenishing semi-stagnant water in this part of the bay. There was not a significant volume of water entering the bay from local rivers and streams during the deployment period, suggesting that this water must have come in from Resolute Passage. It is plausible that during open-ice periods, winds could push water over the sill and into Resolute Bay, but it is difficult to determine this by comparing the available wind speed and wind direction data with the inner-bay water temperature as shown in Figure 3.5.

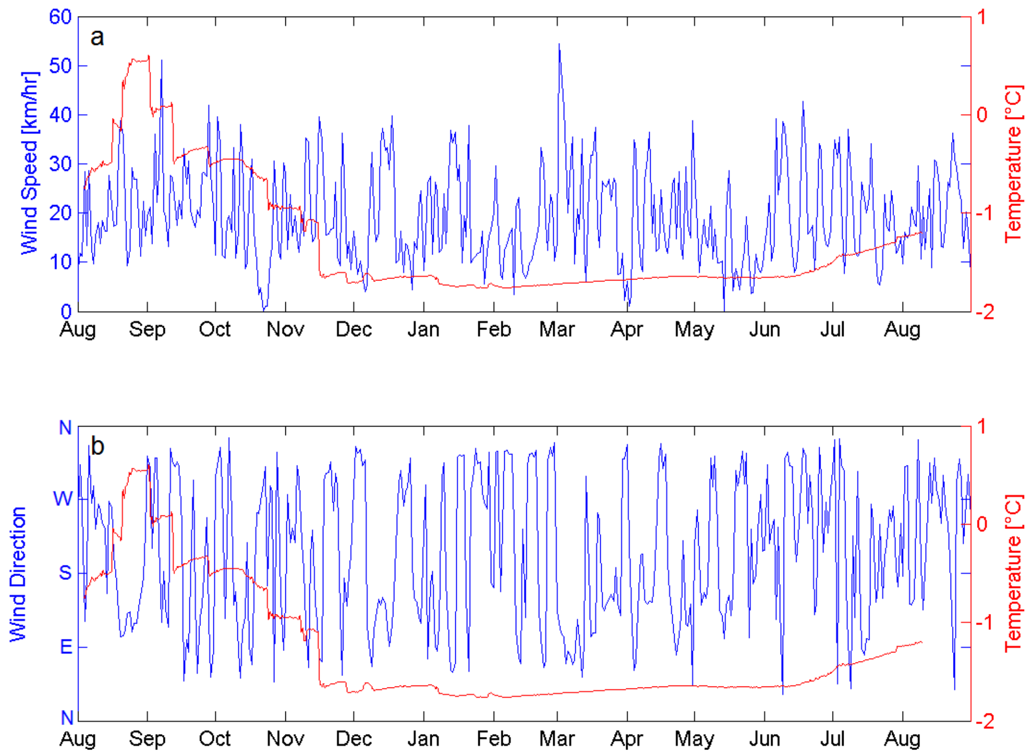


**Figure 3.5. (a) Wind speed and (b) wind direction measured at Resolute Bay (Environment Canada) and water temperature at inner-bay benthic pod from August 2012 to February 2013**

On August 15, 2012, average wind speed was measured to be 28 km/hr from the west and on August 20, 2012, average wind speed was 39 km/hr from the east. These two maximum wind speed times correlate to the sudden increases in temperature on August 16 and 20, 2012, although the wind directions are opposite each other. A wind direction from the west would cause water in the channel to be pushed into Resolute Bay. A wind direction from the east would cause water on the east side of the bay to be pushed towards the inner-bay benthic pod, causing upwelling in the east side of the bay.

On August 31 and September 26, prior to the sudden drops in temperature on September 1 and 27, average wind speeds were 15 and 28 km/hr, and daily average wind directions were from the southwest and south, respectively. Both of these directions would cause the water from Resolute Passage to be pushed into Resolute Bay. In addition, as shown in Figure 3.4, air temperature was near freezing on September 26. This colder air temperature could have caused cold water and/or a thin layer of ice to form at the surface, which was then mixed downwards. The air temperature also was near freezing on September 11, another day that observed a significant temperature decrease. On September 10, the wind was 13 km/hr from the east, where water would be pushed across Resolute Bay towards the west, so it is likely that air temperature played more of a role in this case, rather than water coming in from Resolute Passage.

During the ice-free time period, the maximum average daily wind speed of 51 km/hr occurred on September 7, but it did not correspond with any sudden changes in temperature, salinity, or dissolved oxygen. This could be due to the fact that the wind was from the east, which would not bring any Resolute Passage water into Resolute Bay. The lack of observed effect also indicates that the water in Resolute Bay likely had limited stratification, as the strong wind would cause mixing and upwelling.

There was 0% ice concentration during the significant temperature changes observed in Resolute Bay from August to mid-October, so the majority of the water movement and mixing was probably due to the wind and during this time period. However, the wind did not account for all the changes observed during this time, and significant temperature changes were still observed after October 15, when the ice concentration increased to 90% and dampened the wind effect. Without any obvious correlations between observed local meteorological conditions and the observed water properties, it is possible that external currents or other bodies of water, such as from Parry Channel, caused the sudden observed changes in Resolute Bay. It is likely that it is a combination of local and remote wind speed, wind direction, ice concentration, and tides that ultimately affect the waters in Resolute Bay. Further, with the data at hand it is not possible to separate these effects.

Figure 3.6 shows a water temperature versus salinity plot at the inner-bay benthic pod at a depth of 33 m. In the summer ice-free months, the bottom water in the bay is the warmest, due to warm air temperatures. From October to December, ice concentration dramatically increased due to decreasing air and water temperature. Freeze-up, between January and March, 2013, produced increasing salinity caused by brine rejection from the ice. From April to August 2013, the salinity gradually decreased and temperature gradually increased, signifying ice melt.

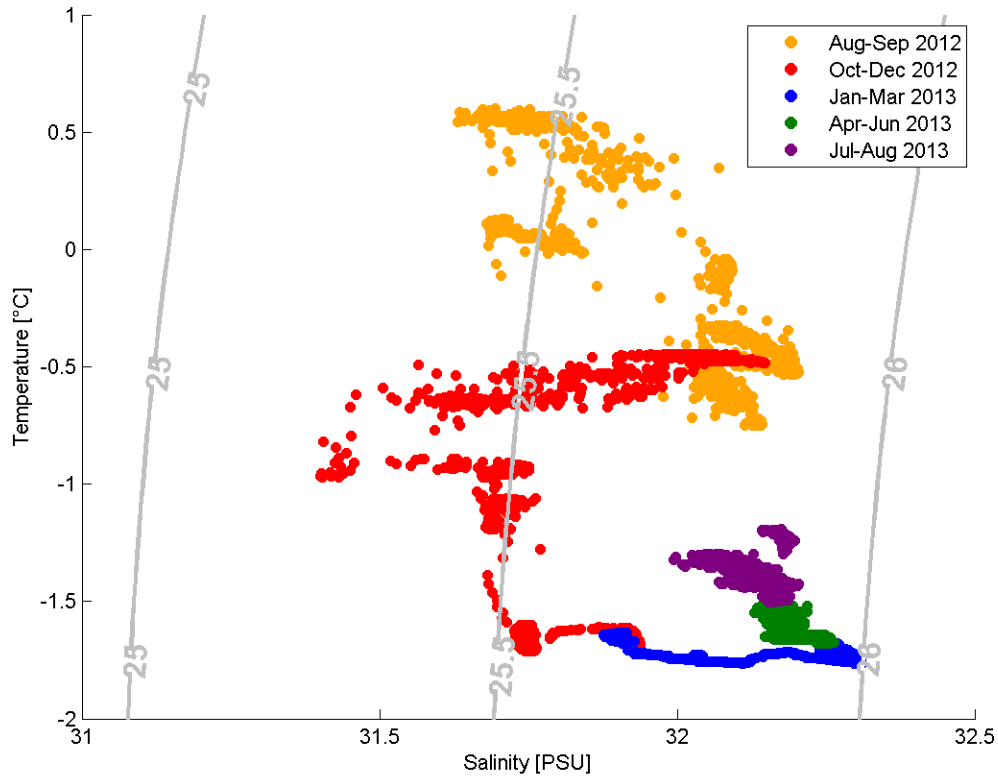


**Figure 3.6. Temperature versus salinity plot of seasonal water at the inner-bay benthic pod at a depth of 33 m. $\sigma_T$ is shown by grey lines.**

Temperature, salinity, and dissolved oxygen saturation levels measured on the outside-bay benthic pod did not vary as much as the inner-bay benthic pod, as shown in Figure 3.7. The step-like features observed on the inner-bay benthic pod were not detected outside of Resolute Bay.

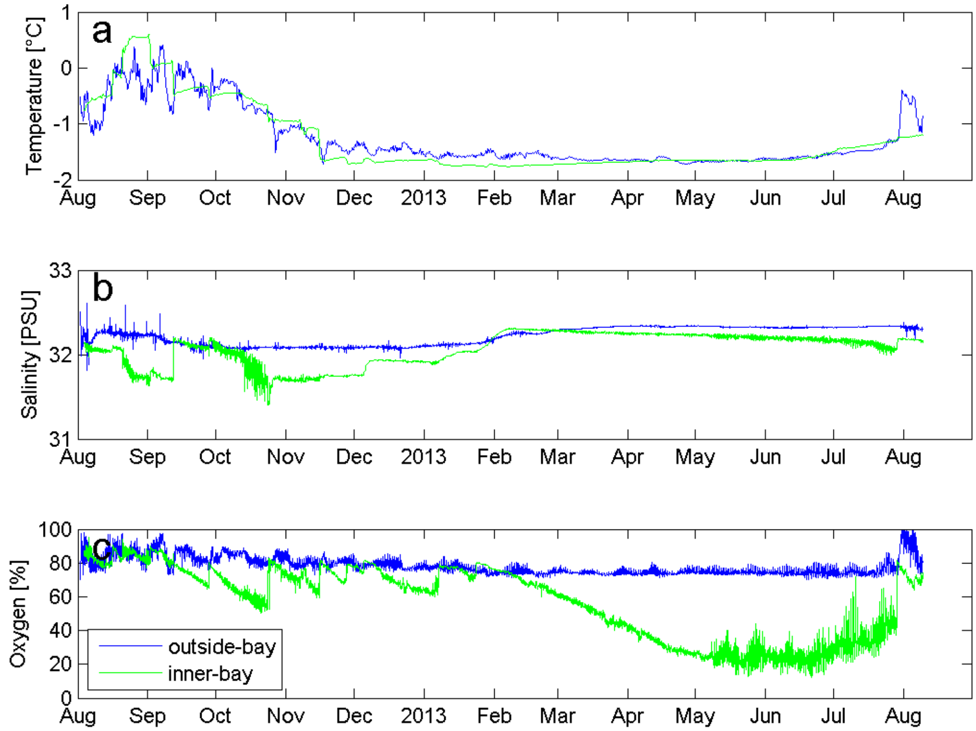


**Figure 3.7. Comparison of (a) temperature, (b) salinity, and (c) dissolved oxygen saturation at inner-bay and outside-bay benthic pod at 33 m and 55 m, respectively.**

An increasing trend in water temperature was observed from the beginning of the measurements to August 26, 2012. Then water temperature decreased at the end of August, preceding the significant drop in temperature measured on the inner-bay benthic pod on September 1, 2012. Temperatures then increased at the beginning of September, followed by another decrease between September 7 and 10, which, as observed before, occurred right before the abrupt temperature decrease in Resolute Bay on September 11. On September 27, both the outside-bay and inner-bay benthic pods observed a decrease in temperature, perhaps due to the strong winds that day (27 km/hr from the west). Three days after the inner-bay temperatures abruptly decreased on October 23 and November 15, the outside-bay temperatures decreased as well. Temperatures on the outside-bay benthic pod then suddenly increased and subsequently gradually decreased until May, when they started to gradually increase until July 29, 2013. Then, as ice break-up started, temperatures suddenly increased 0.88°C in 46 hours. However, the temperature suddenly decreased by 0.60°C when Resolute Bay became ice free.

The salinity stayed fairly constant, between 31.8 and 32.6 PSU, during the deployment period, even though a slight decline was observed between August and October 2012. After staying constant until the end of January, the salinity slowly increased until March before staying steady until the end of the measurement period on August 9, 2013. Unexplainable salinity spikes were observed in the hourly averaged data between August and October. It is difficult to determine whether these spikes were due to environmental changes or instrument error, as there were no other similar instruments nearby during this time with which to compare.

The dissolved oxygen level outside Resolute Bay did not experience the low levels that the inner-bay waters did. The minimum measured dissolved oxygen saturation level was approximately 70% at the outside-bay benthic pod, but varied slightly with the tides, as shown in Figure 3.8. This correlation could be caused by the tides moving the water vertically or laterally.

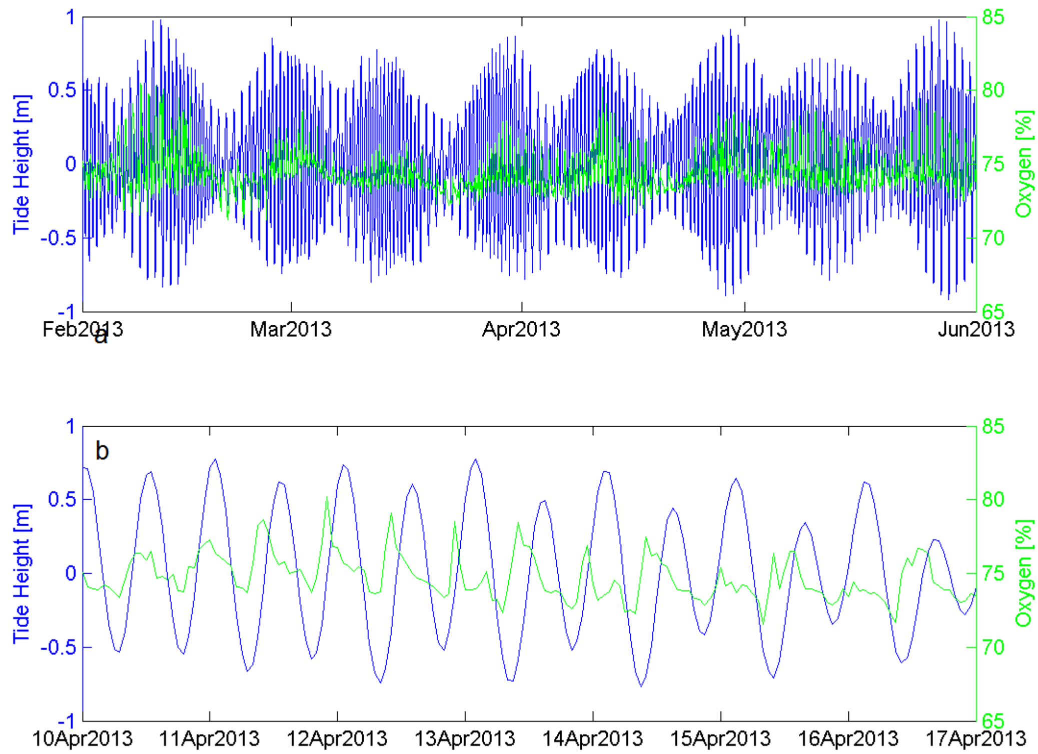


**Figure 3.8. Tide height and dissolved oxygen saturation at outside-bay benthic pod for (a) 4 months and (b) 1 week during the deployment period.**

The seasonal temperature versus salinity plot for the outside-bay benthic pod is shown in Figure 3.9. Similar to the inner-bay benthic pod, the highest temperatures occurred in August and September 2012. In October through December, the water cooled as salinity stayed constant. Between January and March 2013 temperature stayed constant as salinity increased, and from April to June the water mass stayed constant. In July and August 2013, the water warmed by 1°C as salinity stayed constant.

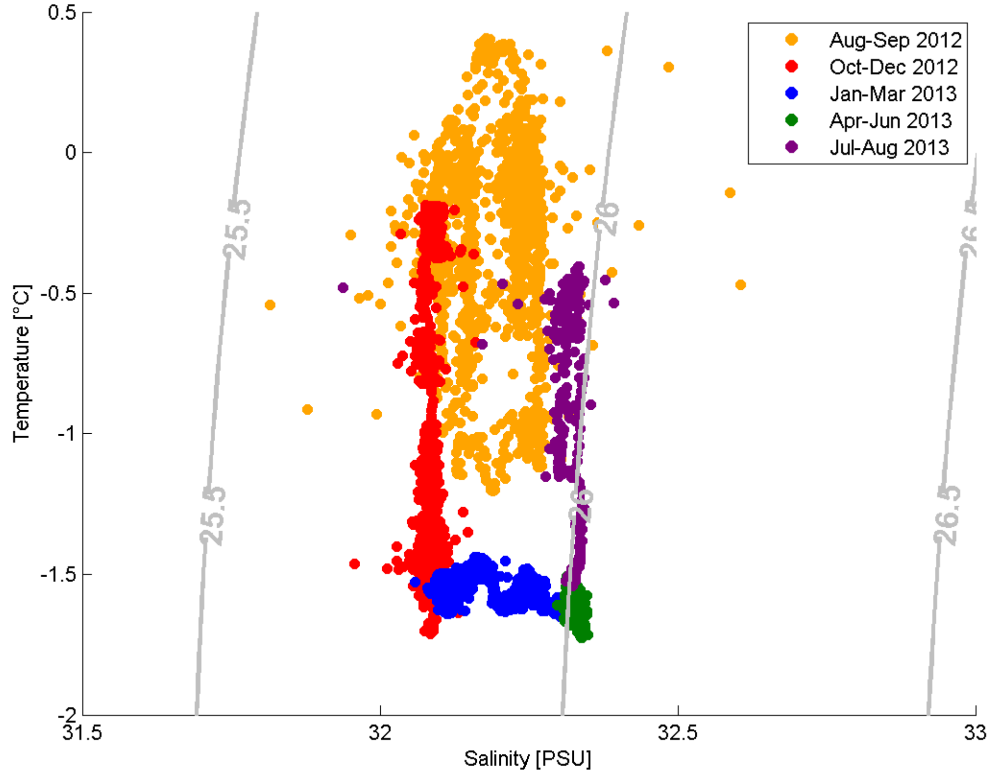


**Figure 3.9. Temperature versus salinity plot of seasonal water at the outside-bay benthic pod at a depth of 55 m. $\sigma_T$ is shown by grey lines.**

## 3.2 2013–2014 Deployment

Ice concentration for the second set of deployments in and near Resolute Bay is shown in Figure 3.10. There was more ice present during this deployment than the first deployment. The first week of August 2013 consisted of 10 to 30% ice concentration in Resolute Bay, then the bay became ice free on August 7. The ice reappeared a month earlier than in 2012, on September 15, 2013, and there was between 90 and 95% ice concentration until October 7. On October 8, Canadian Ice Services stopped analyzing this area, and it is assumed that ice concentration was 100% from this point onwards, until they resumed analysis on July 19, 2014. Ice break-up started on July 25, 2014, but Resolute Bay was not ice free until August 8. This ice-free period did not last long, as on

August 18, the ice came back to between 20 and 50% concentration, and stayed until August 24.

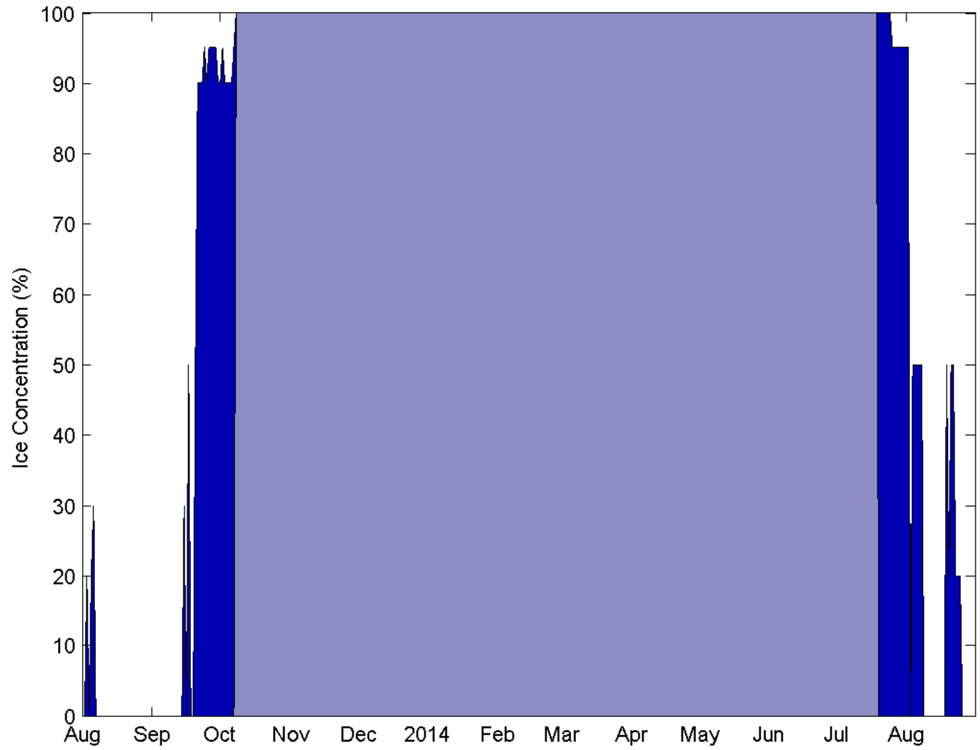


**Figure 3.10. Ice concentration in Resolute Bay from August 2013 to August 2014. Light shaded area represents assumed 100% ice concentration when Canadian Ice Services did not analyze ice concentration data in this area.**

In summer of 2013, the two benthic pods were retrieved and re-deployed along with additional oceanographic moorings in and near Resolute Bay, including 5 temperature loggers. The recorded temperatures at each mooring are shown in Figure 3.11.

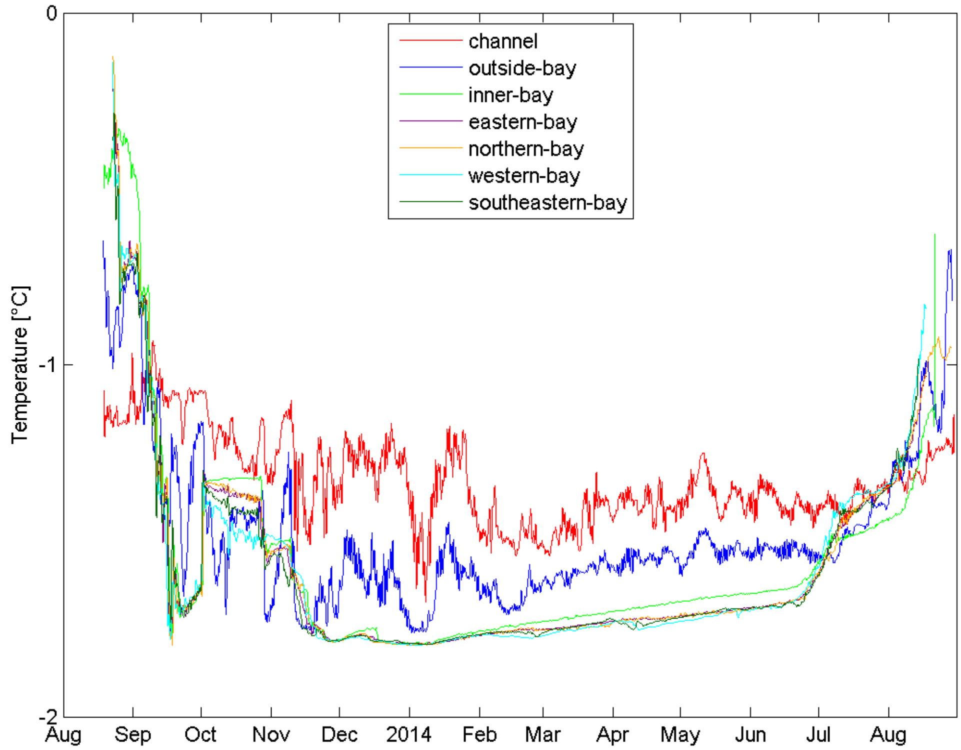


**Figure 3.11. Temperature at each oceanographic mooring deployed near and in Resolute Bay from August 2013 to August 2014.**

Overall temperatures during this deployment were colder than measured the previous year—all of the water temperatures were below 0°C. The channel benthic pod had the most consistent measured temperatures, between –0.93 and –1.67°C. It had higher temperatures than all the other mooring locations between mid-September 2013 and July 2014, but had the coldest water outside of these dates. The lower relative water temperatures in the summer months were expected, as the channel benthic pod was in deeper water, and thus less affected by the warmer summer air temperatures.

The outside bay benthic pod had a similar fluctuation pattern to the channel benthic pod, but approximately 0.3°C cooler temperatures, aside from July and August 2013 and 2014, when the outside bay temperatures were greater than the channel temperatures.

Between mid-November 2013 and July 2014, the outside-bay benthic pod recorded higher temperatures than all the other temperatures loggers in Resolute Bay. In the summer months, the outside-bay water temperature went up to –0.65°C. The temperatures measured on the channel and outside-bay benthic pods varied much more than at the other temperature loggers in Resolute Bay.

Along with the inner bay benthic pod, four RBR temperature loggers were deployed at shallower depths in different parts of Resolute bay: western-bay, northern-bay, eastern-bay, and southeastern-bay. All of these recorded similar temperatures at the same time. In August 2013, the inner bay benthic pod recorded temperatures 0.3°C colder than the other loggers in Resolute Bay. From August 22 to 26, the four shallow in-bay loggers dropped 0.66°C, at a rate of –0.20°C /day, which brought them to similar temperature as the outside-bay benthic pod. During the same time period, the inner-bay benthic pod gradually increased in temperature, then had a temperature decrease on August 31, dropping 0.38°C in 4 days, at a rate of –0.09°C/day, ending at a similar temperature as all other in-bay temperature loggers and the outside-bay benthic pod. From September 4 to 16, the inner and outside-bay benthic pods and the in-bay temperature loggers all were at very similar temperatures.

Salinity values for the second deployment period from August 2013 to August 2014 are shown in Figure 3.12.

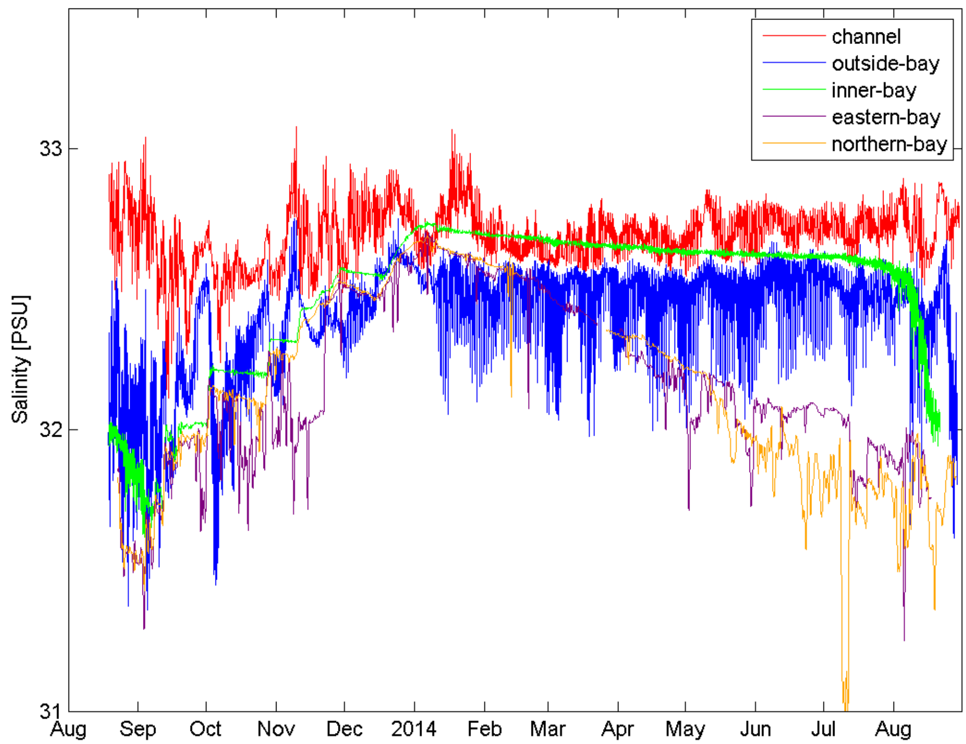


**Figure 3.12. Salinity at each oceanographic mooring deployed near and in Resolute Bay from August 2013 to August 2014.**

Salinity oscillated corresponding to the tidal cycles at the channel and outer-bay benthic pods. These were static moorings, and therefore the observed fluctuations must be due to horizontal and/or vertical water movement. Salinity was greatest at the channel benthic pod for the entire deployment duration. This location also had the least amount of intra-annual salinity variability. The outside-bay benthic pod also observed oscillating salinity with the tidal cycles. Salinity at the inner-bay benthic pod and the eastern-bay and northern-bay loggers did not show the same tidal oscillation that the channel and outside-bay benthic pods did. The inner-bay benthic pod displayed a step-like pattern, similar to the previous year. From mid-August to the beginning of September, the inner-bay benthic pod had decreasing salinity. It then had an abrupt increase in salinity of

0.32 PSU for 48 hours starting on September 12. On October 1, there was another abrupt increase in salinity, this time 0.19 PSU in 17 hours. Afterward, the salinity plateaued, and another abrupt increase occurred on October 28: 0.13 PSU in 20 hours. Then salinity plateaued again, and abruptly increased by 0.12 PSU on November 10. Salinity values then increased at a lower rate until November 29, when they gradually decreased until December 18, after which they started to increase at a similar rate as the last increase. On January 6, 2014, salinity values at the inner bay benthic pod were the greatest at 32.74 PSU. After this high point, salinity slowly decreased at a rate of –0.0008 PSU/day until August 7. On August 8, 2014, the first day of 2014 that Resolute Bay was free of ice, salinity values started decreasing at a rate of –0.04 PSU/day until the end of the deployment.

The eastern-bay and northern-bay loggers recorded similar salinities for the majority of the deployment until mid-May. From mid-May to August 11, the eastern-bay logger recorded saltier water than the northern-bay logger. From August 11 to the end of the deployment, the salinities in the eastern and northern-bay loggers were similar again. The salinities on the eastern and northern-bay loggers were consistently less than the inner-bay benthic pod, likely due to the loggers being in shallower, and thus less dense/less salty, water. They followed a similar increasing step pattern as the inner-bay benthic pod, although often the northern and eastern-bay loggers measured the sudden increases on average approximately 13 hours before the inner-bay benthic pod. A significant sudden drop in salinity was measured on the northern-bay logger on July 8, 2014. Salinity went from 31.97 PSU to 31.04 PSU in 30 hours and stayed at this low value until July 11, when salinity jumped back up to 31.96 PSU in 23 hours. The eastern-bay and northern-bay loggers had significantly more salinity variation than the inner-bay benthic pod over the entire deployment duration.

Dissolved oxygen saturation in the channel, outside-bay, inner-bay, eastern-bay, and northern-bay is shown in Figure 3.13.

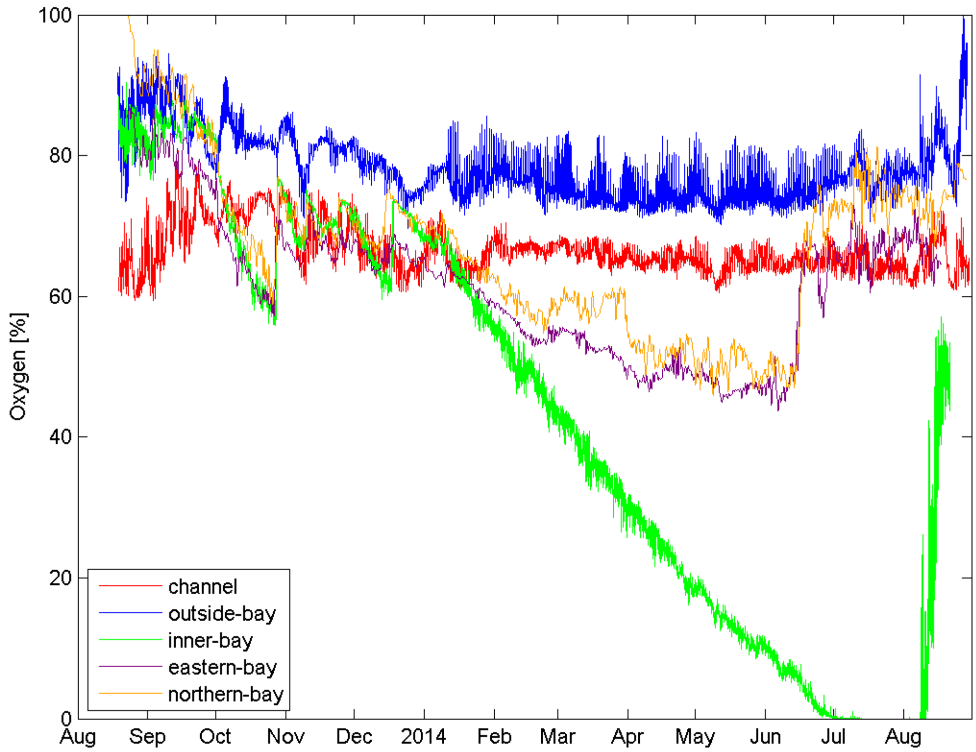


**Figure 3.13. Dissolved oxygen saturation at each oceanographic mooring deployed near and in Resolute Bay from August 2013 to August 2014.**

The outside-bay benthic pod had the greatest dissolved oxygen saturation values between August 2013 and 2014, between 70 and 101%. Dissolved oxygen saturation levels recorded on the outside-bay and channel benthic pods oscillated up to 10% with the tide cycles. Dissolved oxygen saturation values in the channel were between 59 and 81%. The inner-bay, eastern-bay, and northern-bay loggers recorded similar dissolved oxygen saturation values between August and mid-December 2013. The inner-bay and northern-bay dissolved oxygen saturation values continued to be similar until mid-January 2014, while the eastern-bay values were lower during this time period. Between mid-January and June 2014, the northern-bay had the greatest dissolved oxygen saturation values between the in-bay loggers, while the inner-bay benthic pod had the least amount of dissolved oxygen. In June, the eastern-bay and northern-bay loggers had similar dissolved oxygen saturation values and then the northern-bay had greatest dissolved oxygen saturation values in Resolute Bay for the remainder of the deployment.

The three loggers in Resolute Bay followed the same dissolved oxygen trend. From August to mid-September 2013, dissolved oxygen saturation stayed relatively constant, followed by a decrease in oxygen levels by a rate of –0.9%/day. On October 26, dissolved oxygen saturation suddenly increased by 19% in 35 hours, followed by a gradual decrease by a rate of –0.8%/day. Another abrupt increase of dissolved oxygen occurred on November 8, followed by gradual decrease, and another abrupt increase on November 23. Dissolved oxygen saturation then decreased by a rate of –0.6%/day and another sudden increase of 13% was observed on December 17. After this last sudden increase, the inner-bay benthic pod dissolved oxygen percentage was at 74%. It then decreased at a rate of –0.4%/day until June 25, when it reached 0%. Negative dissolved oxygen saturation levels (likely due to a calibration effect) were measured until August 9, when dissolved oxygen values suddenly increased at a rate of 6%/day until the end of the deployment, when it was at approximately 50%.

The northern-bay and eastern-bay loggers followed the same sudden increase then gradual decrease pattern as the inner-bay benthic pod, but they showed a less steep decline in dissolved oxygen saturation following the last sudden increase, with the northern-bay logger having greater dissolved oxygen levels than the eastern-bay logger. The northern-bay logger had dissolved oxygen saturation decrease by 27% between December 15 and June 13, at a rate of –0.1%/day. The eastern-bay logger had dissolved oxygen saturation decrease by 23% between December 15 and June 9, at a rate of –0.1%/day. Both the northern-bay and eastern-bay loggers then observed a sudden increase of dissolved oxygen saturation of 23 and 21%, respectively. After these increases, the northern-bay dissolved oxygen levels were greater than the eastern-bay dissolved oxygen levels for the remainder of the deployment.

## 3.3 2014–2015 Deployment

Ice concentrations in Resolute Bay between August 2014 and August 2015 are shown in Figure 3.14. In summer 2014, there was not a long period of 0% ice concentration, as in the previous two years. Rather, ice moved in and out of Resolute Bay throughout August and September, with ice concentration between 0 and 50%. On October 2, 2014, the bay had 90% ice concentration, and ice concentration remained between 80 and 95% until October 21, when Canadian Ice Services stopped analyzing ice concentration for this region. Ice break-up in 2015 occurred on July 10. Ice concentration went from 100% to 0% in a single day. Resolute Bay was ice free until the end of deployment period, except on August 9, when there was 20% ice concentration.

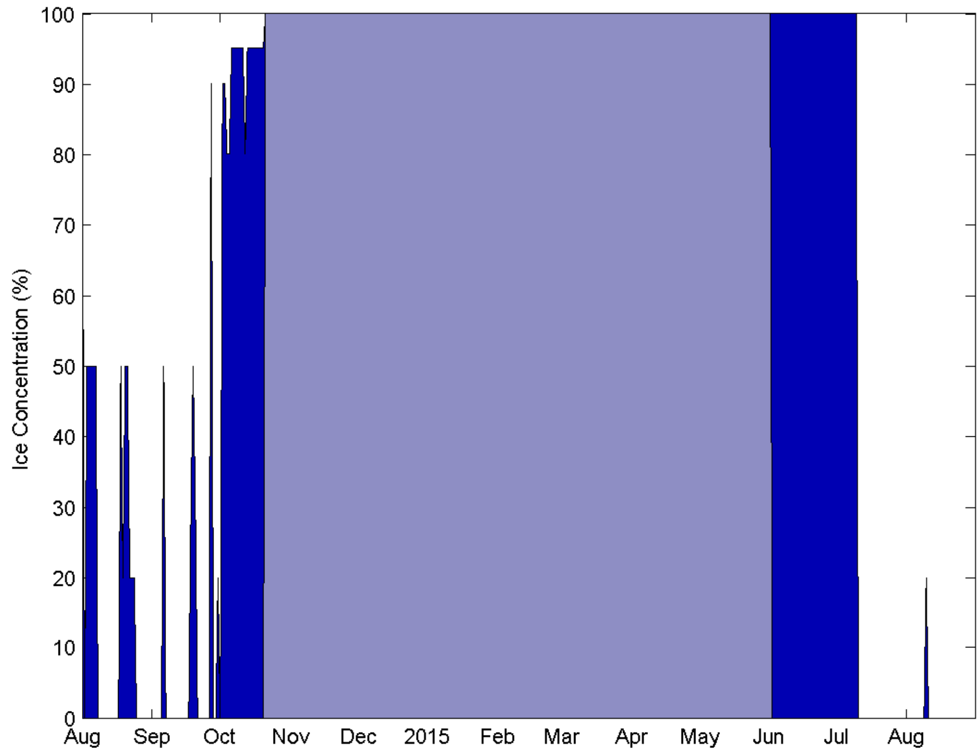


**Figure 3.14. Ice concentration in Resolute Bay from August 2014 to August 2015. Light shaded area represents assumed 100% ice concentration when Canadian Ice Services did not analyze ice concentration data in this area.**

In the summer of 2014, the 7 oceanographic moorings deployed in 2013 were retrieved and re-deployed at the same locations. The temperatures at each location from August 2014 to August 2015 are shown in Figure 3.15.

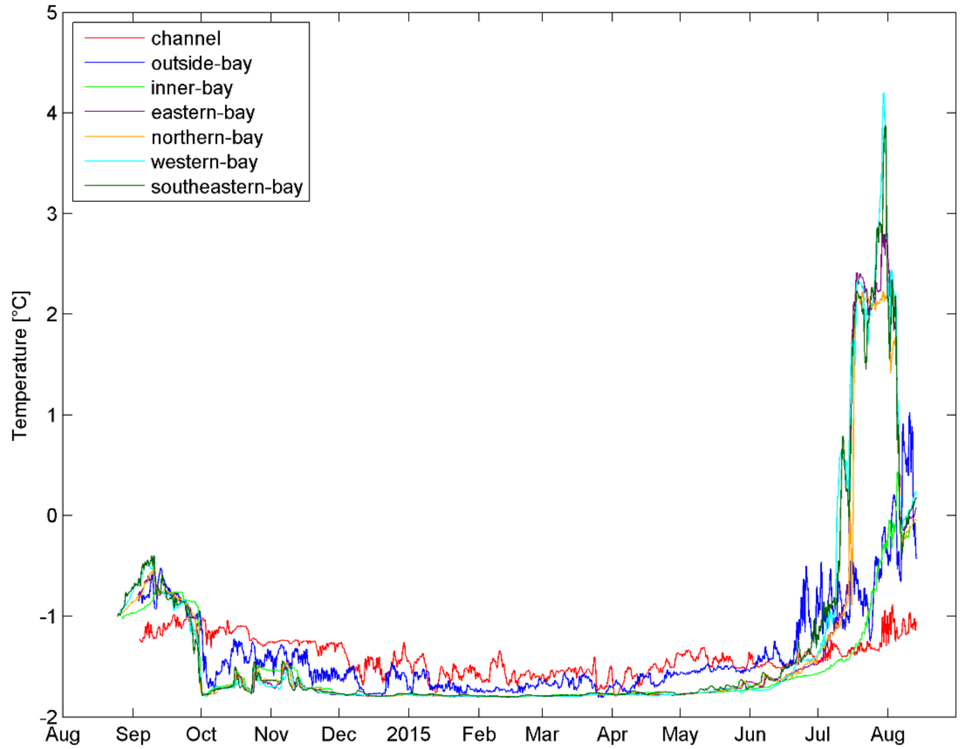


**Figure 3.15. Temperature at each oceanographic mooring deployed near and in Resolute Bay from August 2014 to August 2015.**

Similar to the two prior deployments, temperatures measured at the channel benthic pod varied the least, between –1.79 and –0.89°C. In September 2014 the channel benthic pod water was the coldest of all stations, but when freeze-up started on the first days of October, the water at the other stations became colder than at the channel benthic pod. The lower relative water temperatures in the summer months were expected, as the channel benthic pod was in deeper water, and thus less affected by the warmer summer air temperatures (see Figure 3.16). Water temperatures measured at the channel benthic pod slowly decreased between October 2014 and January 2015. They then stayed relatively constant until April, when they slowly started to increase until the end of the deployment in August.

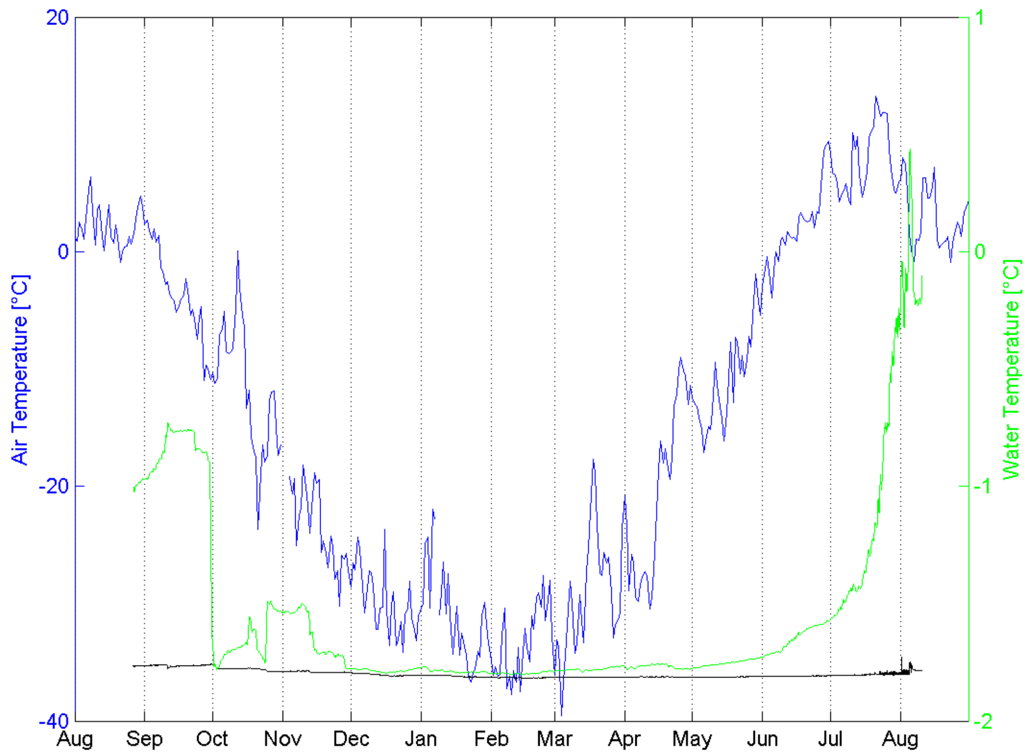


**Figure 3.16. Air temperature measured at Resolute Bay and water temperature at inner-bay benthic pod from August 2014 to August 2015. Freezing temperature of the sea water (adjusted for salinity, dissolved oxygen saturation, and pressure) measured at inner-bay benthic pod is shown with solid black line and referenced to the right y-axis.**

The outside-bay benthic pod measured similar temperatures as the inner-bay benthic pod and RBR loggers from August to October 2014. Water temperatures gradually increased from August until the beginning of September, then gradually decreased for the rest of September. On September 30, the outside-bay benthic pod temperature decreased 0.61°C in 48 hours. This sudden decrease was followed by a sudden increase in temperature of 0.15°C in 14 hours, followed by another sudden decrease of 0.31°C in 33 hours. Temperature recorded at the outside-bay benthic pod then followed a gradual increase until mid-October with small variations likely due to tides. Temperature slowly decreased from mid-October to mid-December 2014, then stayed relatively constant, within 0.3°C, until the beginning of April 2015, when temperatures gradually started to increase until mid-June. On June 20, 2015, water temperatures at the outside-bay benthic pod started to fluctuate significantly, between –1.47 and –0.46°C, until July 24. Then temperatures increased with a pattern of sudden increase followed by a lesser decline. This pattern occurred three times consecutively, with each pattern lasting 4 days. Then, on August 6, in 24 hours, water temperatures at the outside-benthic pod increased 1.57°C to 0.91°C. Fluctuations around this temperature occurred until a sudden decrease of 1.08°C on August 11, at the rate of –0.7°C/day.

All of the moorings deployed inside Resolute Bay recorded similar temperatures between August 2014 and August 2015. The temperatures follow the same pattern as the outside-bay benthic pod, gradually increasing until September 10, 2014, and then gradually decreasing for 2 weeks. This peak is less pronounced for the inner-bay benthic pod. Figure 3.16 shows a comparison between air temperature at Resolute and water temperatures measured at the inner-bay benthic pod. The gradual increase at the beginning of the deployment was likely due to the warm, above-freezing air temperatures. The air temperature then decreased and dropped below the freezing point on September 8, 2014, 2 days before the water temperatures started to gradually decrease. A sudden drop of 6.27°C in air temperature occurred on September 27, 2014, which was mirrored by sudden drops of water temperature throughout Resolute Bay. Starting on September 28, the northern-bay logger temperature decreased 0.79°C in 77 hours and the eastern-bay logger decreased 0.76°C in 71 hours. Then on September 29, in chronological order, the southeastern-bay logger dropped 0.52°C in 51 hours, the western-bay logger decreased 0.54°C in 45 hours, and the inner-bay benthic pod dropped

0.92°C in 56 hours. This sequential order of a sudden decrease in temperature starts at the northern most part of Resolute Bay and follows in a clockwise motion around the shallower in-bay loggers, with the deepest mooring the last one to observe the decrease in water temperature. On October 2, when ice concentrations increased to 90%, the water temperature at the inner-bay benthic pod was 0.01°C above the freezing temperature (see Figure 3.16).

After the sudden decrease in water temperature, all 5 bay loggers slowly increase in temperature at a rate of 0.006°C/day during the first 2 weeks of October. On October 15, the southeastern-bay logger measured a sudden increase temperature by 0.19°C over 27 hours. Next, the western-bay logger observed a sudden increase in temperature, although it was much more subdued, with temperatures rising 0.08°C in 18 hours. The next location to measure a sudden temperature increase was at the northern-bay logger. Here water temperatures increased 0.16°C in 33 hours. A few hours after that increase in temperature started, the southeastern-bay logger started recording an increase of 0.10°C in 20 hours. Continuing with the clockwise spatial pattern of increasing temperature, the eastern-bay recorded a temperature increase of 0.25°C in 27 hours. Lastly, the inner-bay benthic pod experienced a 0.26°C increase of temperature in 28 hours.

The inner-bay benthic pod temperature stayed constant until November 12, when it sharply decreased by 0.17°C in 66 hours, and then had another sudden small decrease of 0.06°C in 34 hours on November 27. The other loggers in Resolute Bay measured a decrease in temperature, followed by 9 days of constant temperature, and another increase in temperature. The decrease in temperature was measured at the different stations throughout the bay in the following order: southeastern-bay, western-bay, northern-bay, and eastern-bay, which replicated the clockwise direction observed on the other sudden temperature shifts. Although the decrease in temperature was measured in a more chaotic order: southeastern-bay, northern-bay, western-bay, then eastern-bay. These decrease and increase in temperature were not as sudden as the previous ones, and the decrease occurred before the inner-bay benthic pod temperature decrease on November 12.

Water temperatures measured in Resolute Bay stayed fairly constant, with minimal variation, between mid-November 2014 and May 2015. In May water temperatures began a slow increase, perhaps due to solar radiation melting the ice, as there was 24-hour daylight during this time. At the beginning of June, air temperatures rose above freezing, which caused water temperatures to increase at a higher rate than the previous month. On July 8, the western-bay logger temperature increased 1.51°C in 49 hours, followed by the southeastern-bay logger increasing 1.70°C in 77 hours, followed by the eastern-bay logger increasing 3.19°C in 88 hours, followed by the northern-bay logger increasing 2.84°C in 29 hours. This is another example of the clockwise water movement pattern observed in Resolute Bay. These large temperature increases were likely due to the departure of ice from Resolute Bay on July 10, which produced good conditions for wind-forced mixing. Ice break-up in Resolute Passage likely occurred a little earlier, which is why the temperature increase started while Resolute Bay still had 100% ice concentration. The greatest water temperatures recorded were 4.20°C on July 29 and 3.88°C on July 30, on the western-bay logger and southeastern-bay logger, respectively. This was likely because these two loggers were the shallowest and thus influenced the most by the warm air temperatures in the summer of 2015.

The average wind speed and direction on September 27, 2014, the same day the sudden drop in air temperature, was 32 km/hr from the west, as shown in Figure 3.17. On September 29, when all the loggers in the bay recorded a significant drop in temperature, average wind speeds were even greater, at 37 km/hr. Resolute Bay was not ice covered at this time, so the wind could have pushed colder surface water into the bay. Also, the wind likely assisted with the mixing of the colder surface water to the lower water depths where the loggers were. The next sudden shifts of temperature occurred when Resolute Bay was 100% ice covered, so wind would not have likely played a significant role in these sudden temperature changes. Rather these abrupt events were likely influenced by tidal cycles and/or the movement of nearby bodies of water causing the outside-bay water to come into the bay.

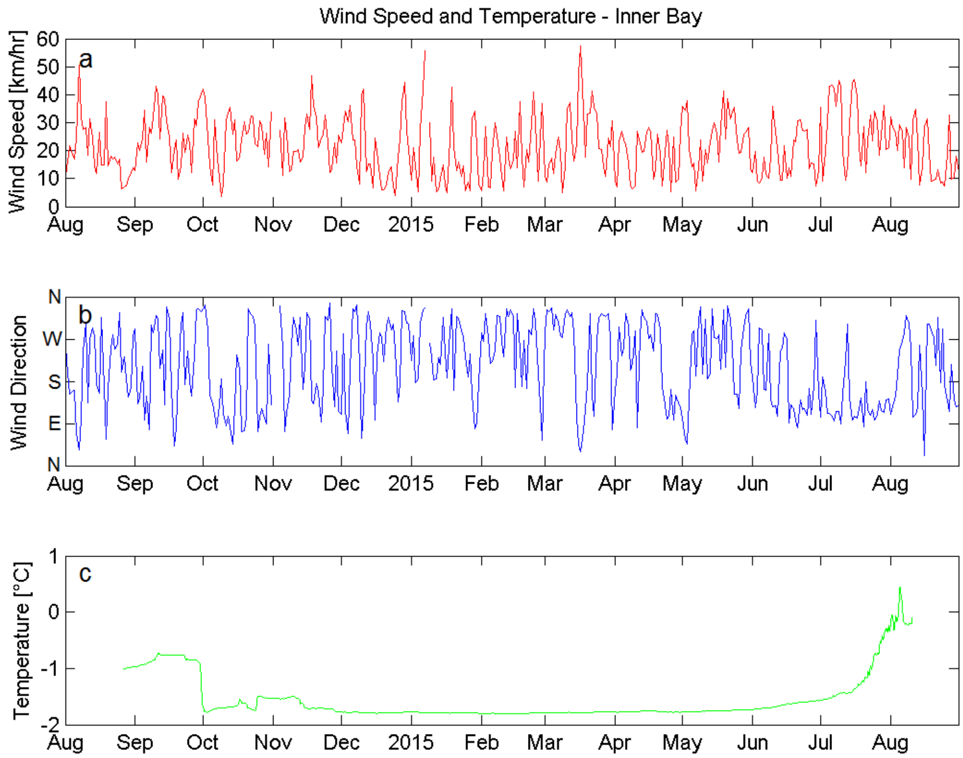


**Figure 3.17. (a) Wind speed and (b) wind direction measured at Resolute Bay and (c) water temperature measured at inner-bay benthic pod.**

Figure 3.18 shows the salinities recorded in and near Resolute Bay from August 2014 to August 2015.

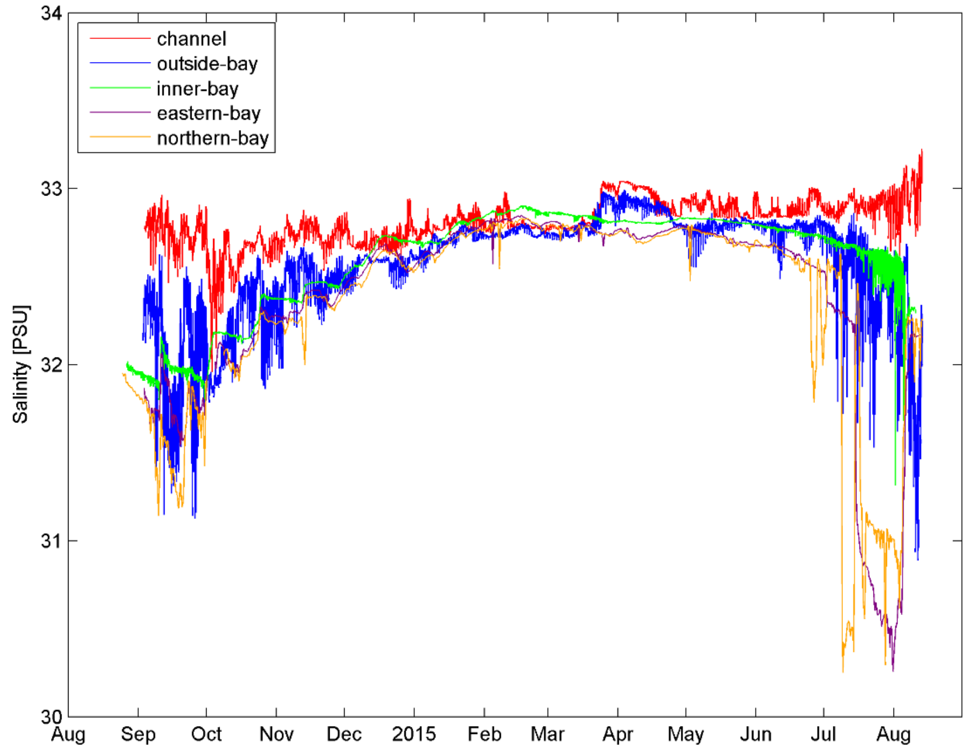


**Figure 3.18. Salinity at each oceanographic mooring deployed near and in Resolute Bay from August 2014 to August 2015.**

The channel benthic pod measured the greatest salinity values over the deployment duration. It also had the most consistent salinities, while the eastern and northern-bay loggers varied the most. The channel benthic pod measured salinities between 31.96 and 33.23 PSU and the northern-bay logger measured salinity between 30.25 and 32.83 PSU. The outside-bay benthic pod measured fresher water in August through October. At the beginning of October, when the ice started to form, the salinities measured on the outside-bay benthic pod began to slowly increase. For two days starting on March 23, 2015, both the channel and outside-bay benthic pods measured a rapid increase in salinity. This was likely due to an influx of water from a larger body of water such as Barrow Strait, as the Resolute Bay loggers did not see the same change and the water was

100% ice covered at this time and surface air temperature was −25.65°C – far below freezing. The outside-bay benthic pod varied on a fine scale, similar to the channel benthic pod, likely due to tides. The loggers inside Resolute Bay did not record similar fine-scale variations, rather they experienced restrained values with significant sudden changes throughout the deployment.

From August to December 2014, the salinity loggers in Resolute Bay all followed the same pattern: gradual decrease, then a sudden increase. On September 9, the northern-bay logger increased in salinity by 0.57 PSU in 33 hours. On September 10, the eastern-bay logger started to increase in salinity by 0.37 PSU in 29 hours, and an hour later the inner-bay benthic pod started to increase in salinity 0.36 PSU in 26 hours. This was likely caused by high tides occurring at Resolute Bay (see Figure 3.19) and the saltier water coming over the sill and mixing with the waters in the bay.

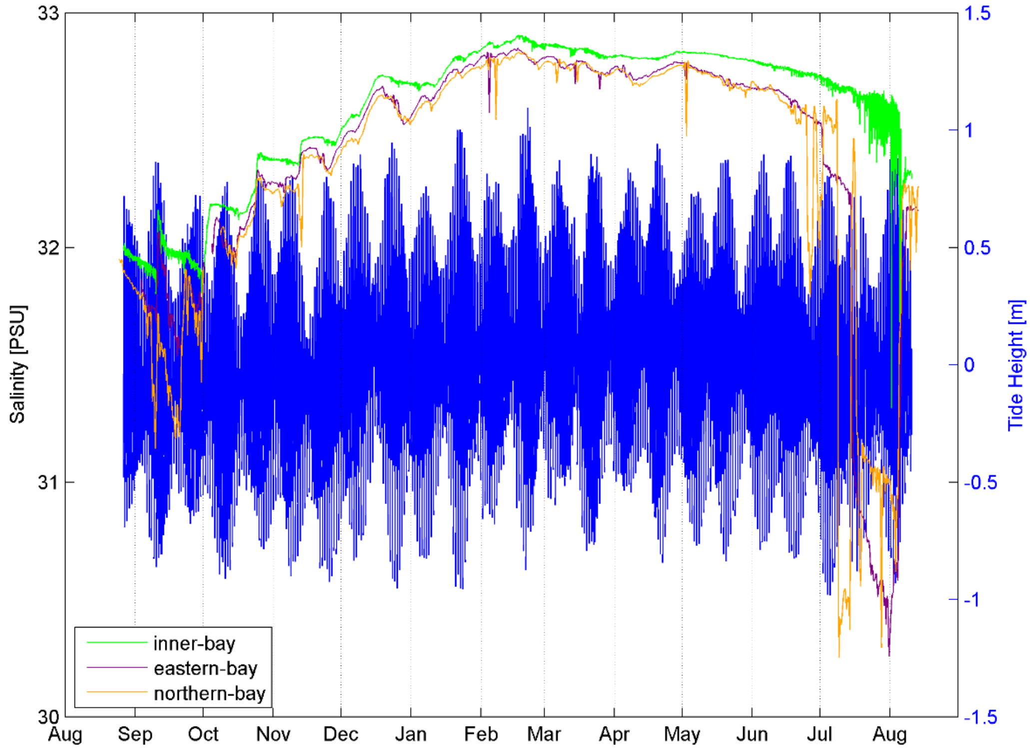


**Figure 3.19. Tide height at inner-bay benthic pod and salinity at loggers in Resolute Bay from August 2014 to August 2015.**

On September 21 the northern-bay logger then the eastern-bay logger observed another sudden increase in salinity, although the inner-bay benthic pod continued to record a slow decrease of salinity at this time. The saltier water did not mix into the deeper waters where the benthic pod was in this case. On September 30, all three loggers in Resolute Bay recorded a sudden increase in salinity in the order of: northern-bay, eastern-bay, then inner-bay. This occurred again on October 23 and November 12 between periods of gradually decreasing salinities. On November 24, salinity values in Resolute Bay began to increase gradually, rather than in sudden instances. This trend continued until mid-February 2015, when salinity slowly started decreasing until mid-June. From June 24 to July 2, the northern-bay logger had a sudden decrease in salinity followed by a large increase back to the previous level, followed by a similar large sudden dip and recovery. Neither of the other two stations observed the same pattern, but the eastern-bay salinity did suddenly drop on June 30. The greatest rapid drop in salinity was measured on July 8 when the northern-bay logger measured salinity going from 32.63 PSU to 30.28 PSU at a rate of –0.09 PSU/hr. On July 15 the salinity values of this logger suddenly went back to where they were before. It is difficult to explain these erratic sudden changes. They do not seem to reflect what the other loggers recorded during the same time period, so it may be due to instrument error. On July 14, 2015, 4 days after Resolute Bay was free of ice, the eastern-bay logger salinity decreased at a rate of –0.04 PSU/hr, followed by the northern-bay logger salinity decreasing at a rate of –0.04 PSU/hr on July 15. Both loggers then sudden increased on August 4. The inner-bay benthic pod recorded a gradual decrease in salinity during summer 2015, with more variability due to tides starting on July 22. A sudden decrease of –0.79 PSU was measured on the inner-bay benthic pod on August 5, then salinity slowly increased until the end of the deployment.

Dissolved oxygen saturation between August 2014 and August 2015 are shown in Figure 3.20 for the channel, outside-bay, and inner-bay benthic pods and the eastern-bay and northern-bay loggers.

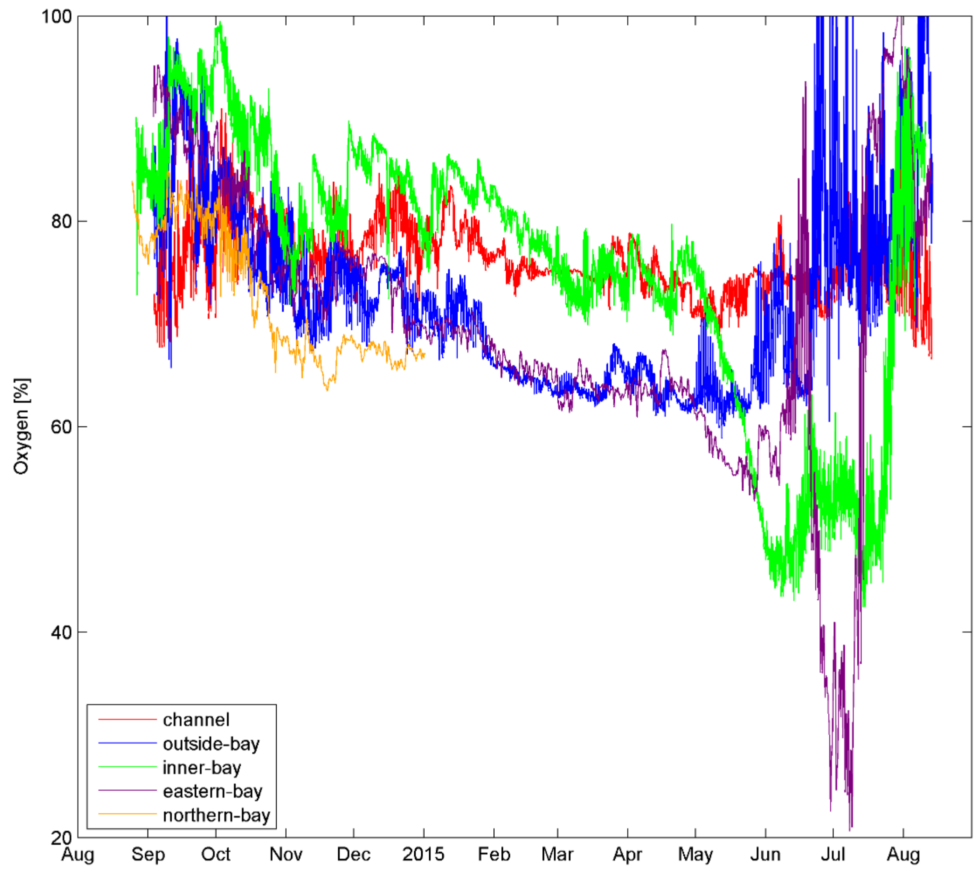


**Figure 3.20. Dissolved oxygen saturation at each oceanographic mooring deployed in and near Resolute Bay from August 2014 to August 2015. The northern-bay logger did not record good data after December 2014 and therefore these data were removed.**

All of the benthic pods show fine-scale changes, likely caused by tidal activity. The channel benthic pod had fine-scale variability likely due to tidal activity. From the beginning of the deployment to October 6, dissolved oxygen saturation gradually increased at a rate of 0.2%/day. At this time the channel was 95-100% ice covered and dissolved oxygen saturation decreased at a rate of 0.06%/day until May 5, 2015. During the next two months dissolved oxygen varied between 70 and 80%, and then started to decrease on July 15 until the end of the deployment.

The outside-bay benthic pod measured greater dissolved oxygen saturation than the channel benthic pod in the summer months (August and September 2014 and July and August 2015), but recorded lower saturation at other times. It observed a similar trend throughout the deployment period. Dissolved oxygen saturation increased at a rate of 2%/day from the beginning of the deployment until September 13. Then dissolved oxygen saturation decreased at a rate of 0.2%/day until April 29, 2015. In May and June dissolved oxygen varied between 60 and 80%. On June 21, 2015, dissolved oxygen increased suddenly and there were large variations, between 70 and 100%, for the remainder of the deployment, with a gradual increasing trend.

The inner-bay benthic pod recorded the greatest dissolved oxygen saturation overall from the beginning of the deployment until May 2015. Similar to the other instruments, it showed a short decreasing period at the beginning followed by a faster increase in dissolved oxygen. It then had a gradual decline at a rate of 0.08%/day until April 29, 2015, and then a sharper decrease at a rate of 0.9%/day until June 1. Dissolved oxygen then hovered between 40 and 60% until July 21, when it increased at a rate of 4%/day. Saturation then varies between 80 and 100% for the remainder of the deployment.

The greatest annual variation of dissolved oxygen saturation was measured by the eastern-bay logger. It also recorded the lowest dissolved oxygen saturation value during this deployment: 21%. The dissolved oxygen at the eastern-bay logger slowly decreased at a rate of 0.1%/day between August 2014 and May 27, 2015. On May 27, dissolved oxygen saturation increased 6% at a rate of 3%/day, then decreased gradually. Between June 6 and 15, dissolved oxygen saturation increased by 29% at a rate of 3%/day, including increases and decreases. For the last two weeks of June, dissolved oxygen saturation at the eastern-bay logger decreased, reaching a minimum on June 29. Dissolved oxygen saturation then varied between 20 and 40% until July 9, when they increased at a rate of 10%/day until July 16, when dissolved oxygen was at 91%. Values then stayed elevated until July 30, when they decreased to 79% on August 6, and then slowly increase for the remainder of the deployment.

The northern-bay logger had decreasing dissolved oxygen saturation levels for the last week of August, then this trend reversed and saturation levels increased for a week. From September 9 to the end of December, the northern-bay logger followed a similar decreasing rate as the eastern-bay logger. Dissolved oxygen saturation levels for this logger past December 2014 were removed from the dataset as they were unrealistic and dissimilar to all previous dissolved oxygen measurements made in Resolute Bay during this study, indicating instrument problems.

# 4 Results – Underwater Acoustics

Underwater sound was recorded and analyzed to characterize ambient sound levels and to determine marine mammal presence. Ambient sound results are presented in decade-band and third-octave band plots, spectrograms, and power spectral density plots. The underwater acoustic data were also processed with an automatic detector to identify marine mammal calls. Call detections for bearded seals, ringed seals, and beluga whales (whistles and clicks) are presented for each deployment period. These results are presented in the following sections for the 2013-2014 and 2014-2015 deployments.

The results presented include daily call count plots, which, for this study, simply indicate the number of calls detected in the acoustic data for each day. The AMAR did not record continuously, and no adjustment was applied to compensate for the duty cycle, so the presented results do not actually represent the number of call counts expected in a day. Also, the two sample rates for each annual recording had different duty cycles. The lower sample rate (16 or 32 kHz) recorded 340 s (5.6 mins) every hour (9% duty cycle), as opposed to 113 s every 4 mins (47% duty cycle) at periods with 96 kHz sample rate (see Table 2.6 and Table 2.7). Since there was no duty cycle-weighting applied to the data, the difference in duty cycles for these two recording periods causes the daily call counts during the 9% duty cycle time period to be significantly lower than the daily call counts during the 47% duty cycle.

The accuracy of the call detector is reduced during the ice-covered months, due to ice-generated noise causing false positive detections; therefore, there is decreased confidence in the species presence/absence during this time period. The manual validation determined that the detector underestimated the presence of bearded seals, but due to the small number of manual validations, a specific correction ratio could not be estimated accurately. The manual validation did find walrus vocalizations in the acoustic data in June and July, but they were not picked up by the detector, and therefore those results are not presented here.

Marine mammal call rates can vary between individuals and over time, and may depend on both age and sex of the animals. Therefore, the numbers of calls for any given species do not necessarily represent the relative abundance of animals, but the results do give a good indication of animal presence or absence. Also, the recording bandwidth of the AMAR (10 Hz to 48 kHz) did not fully capture the wide range of frequencies of the whale vocalizations, nor the possible complete time range of the migrating whales, as the higher sample rate was programmed for only 70 or 80 days.

Beluga clicks have been recorded over a wide range of frequencies, from 30 to 120 kHz (Au et al., 1985; Roy et al., 2010; Sjare and Smith, 1986a). Therefore, clicks were only recorded by the AMAR when the whales broadcasted narrow-bandwidth clicks with a lower centre frequency or broadband clicks with a wide enough bandwidth to include the upper recording frequencies of the AMAR. Belugas have been known to adapt their click to frequencies with lower ambient sound levels, and to generate higher intensity signals to overcome ambient sound levels. It has been observed that the use of higher intensities produced wider bandwidths, and it is likely that whales intentionally use wider bandwidths to scan larger areas. Belugas also change their click frequency depending on the size of their click target — producing higher frequencies for smaller targets (Au et al., 1985; Roy et al., 2010).

## 4.1 2013–2014 Deployment

In 2013-2014, the AMAR hydrophone had a water ingress problem that caused a linear signal degradation, which was noticeable at the beginning of December 2013 and continued to get worse throughout the remainder of the recording period (until June 30, 2014). To compensate for the signal degradation, a best-fit line was estimated from each third-octave band. This line was then used to determine a daily gain, which was applied to each third-octave band. The corrected ambient sound results are presented in the next section.

The signal correction cannot be applied to the marine mammal vocalization results. The signal degradation affected the marine mammal detector by decreasing the signal to noise ratio, and therefore underestimating the number of calls. Fewer calls were able to be detected the further into the dataset the detector progressed. Fortunately, a new, problem-free hydrophone was used in 2014-2015. The 2014-2015 acoustic data are therefore more reliable and robust, and therefore it is recommended to focus on these results.

### 4.1.1 Ambient Sound

Broadband and decade-band sound pressure levels between August 5 and October 6, 2013, are shown with the corresponding spectrogram in Figure 4.1. The broadband sound pressure levels during the ice free period between the start of the deployment and mid-September were between 100 and 110 dB re 1 µPa with spikes up to 135 dB re 1 µPa. In mid-September, when the ice came into the bay, sound levels were between 110 and 120 dB re 1 µPa with spikes up to 145 dB re 1 µPa. During both time periods the loud spikes were due to boat traffic in the bay. These elevated levels remained with no spikes for the remainder of September and the first week of October, 2013.

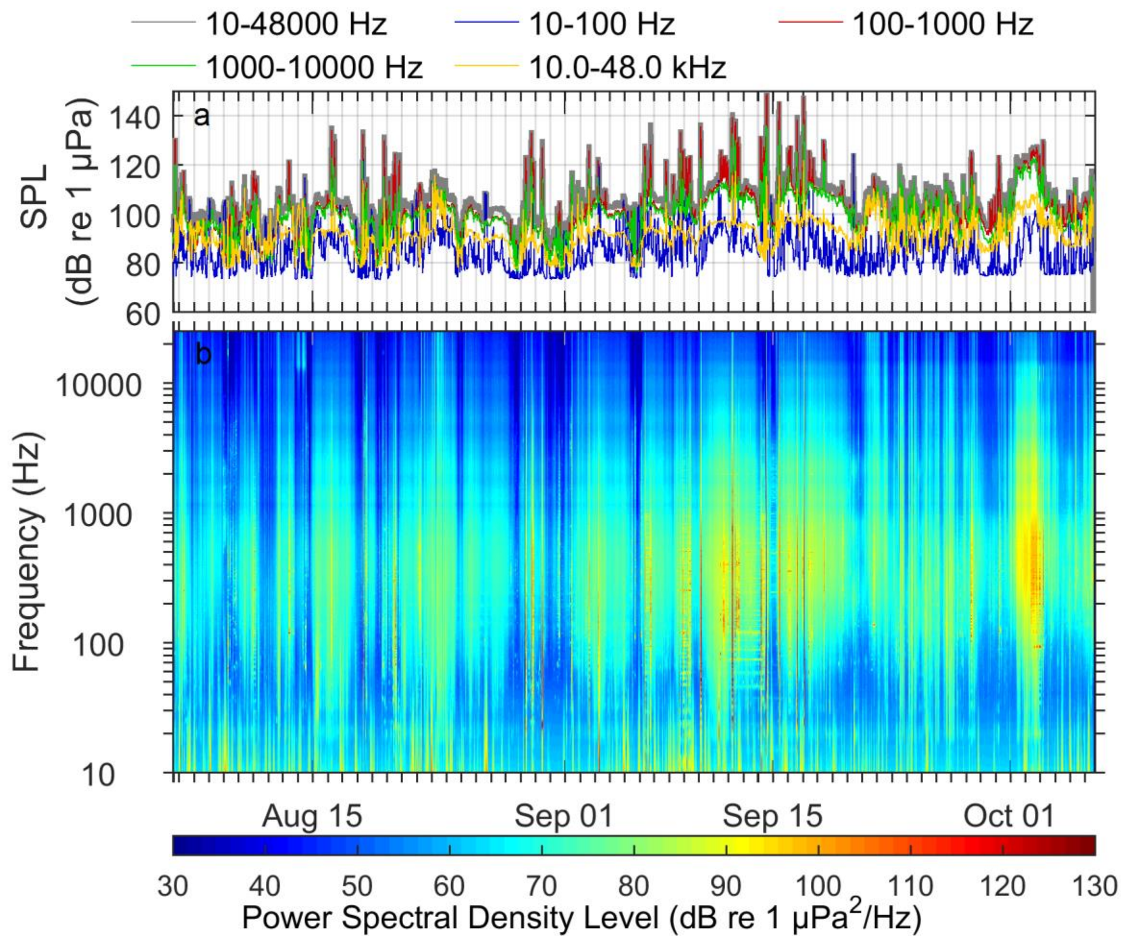


**Figure 4.1. (a) Broadband and decade-band sound pressure levels and (b) spectrogram of underwater sound from August 5 to October 6, 2013.**

Figure 4.2 shows the statistical distribution of third-octave band sound pressure levels from August 5 to October 6, 2013 and the corresponding power spectral density in relation to the expected minimum and maximum levels (Figure 2.5). The boxes of the statistical distributions encompass the first ($L_{25}$), second ($L_{50}$), and third ($L_{75}$) quartiles. The maximum and minimum ranges of the data are indicated by whiskers. The bold black line, $L_{eq}$, specifies the rms of the levels in each third-octave. The third-octave bands with greatest $L_{eq}$ (above 100 dB re 1 μPa) during August 5 to October 6, 2013 are between 80 and 1300 Hz. $L_{eq}$ between 90 and 950 Hz were greater than the upper boundary of the

Wenz curve and $L_{eq}$ between 950 and 3000 Hz were near the upper boundary, while the other frequencies were within the bounds. As shown in Figure 2.5, the elevated levels between 90 and 3000 Hz correspond to higher than usual vessel traffic in shallow waters.

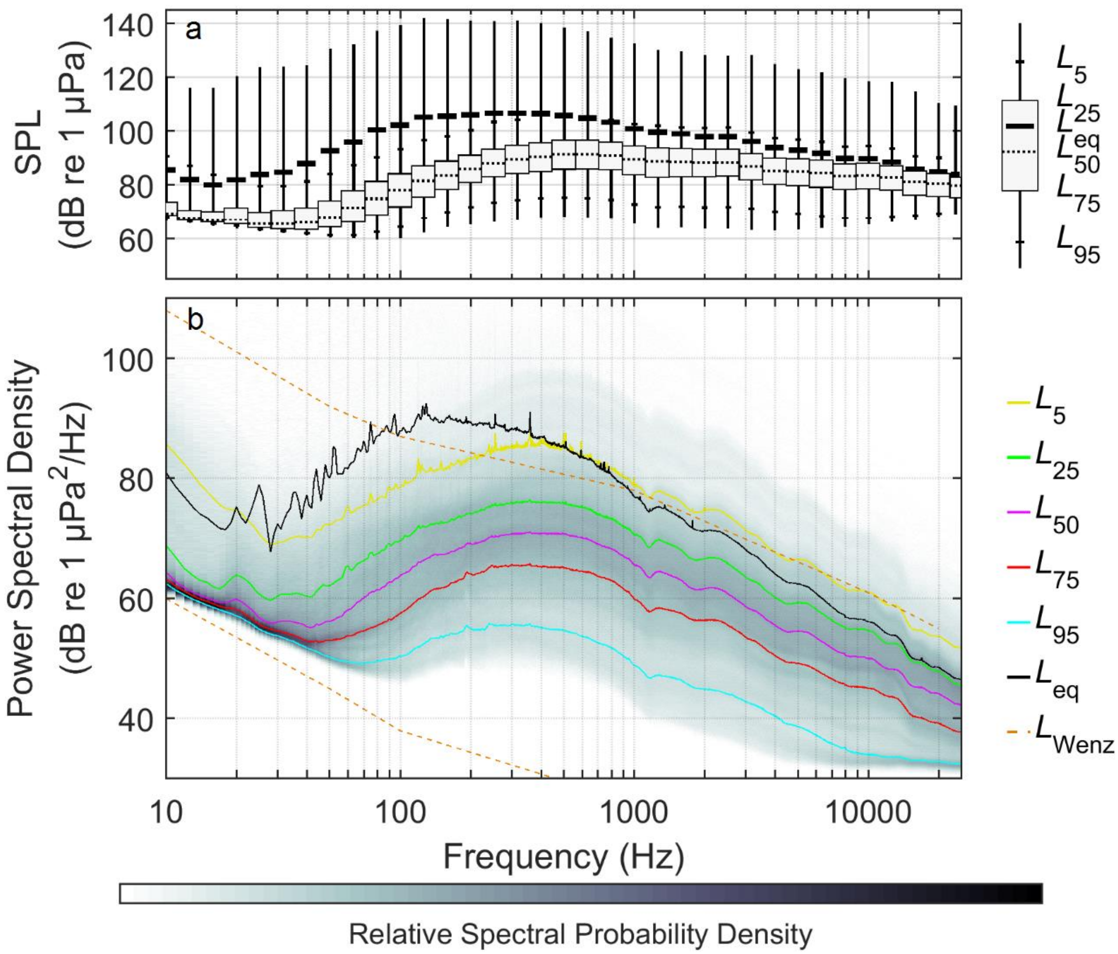


**Figure 4.2. (a) Distribution of third-octave band sound pressure levels from August 5 to October 6, 2013. (b) Percentile exceedance levels of the power spectral density. The dashed lines are the limits of prevailing noise from the Wenz curves (see Figure 2.5).**

Broadband and decade-band sound pressure levels between October 6, 2013, and June 30, 2014, are shown with the corresponding spectrogram in Figure 4.3. The elevated SPLs due to ice noise, between 100 and 120 dB re 1 µPa, continued until mid-November, 2013. Broadband SPLs then decreased to between 90 and 105 dB re 1µPa, with the 10-

100 Hz decade band dominating. The low frequency elevated sound levels had a semidiurnal pattern caused by high velocity water flow across the hydrophone, and thus the broadband ambient sound levels are artificially elevated. From March 2014 until the end of deployment (June 30, 2014), broadband SPLs are between 80 and 100 dB re 1μPa, due to a decreased level of hydrophone flow noise.

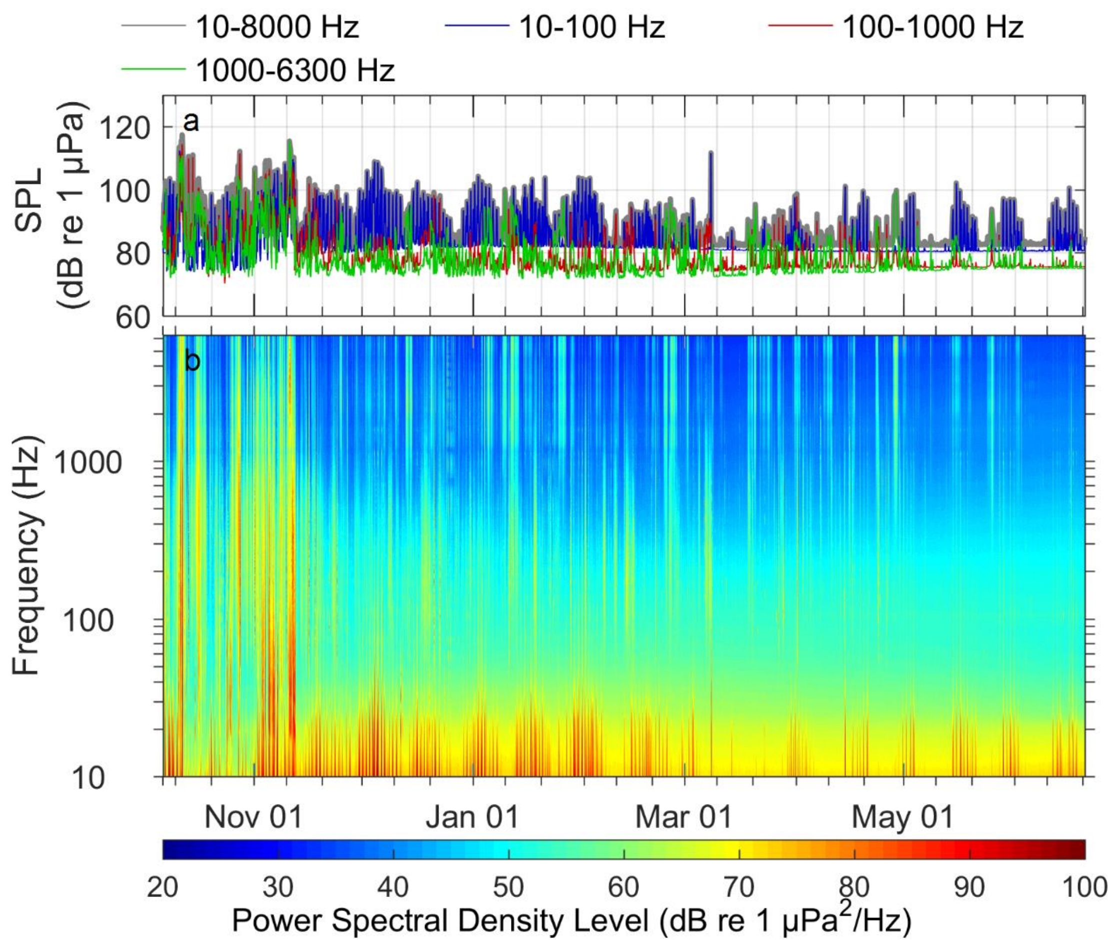


**Figure 4.3. (a) Broadband and decade-band sound pressure levels and (b) spectrogram of underwater sound from October 6, 2013, to June 30, 2014.**

Figure 4.4 shows the observed sound levels from October 6, 2013, to June 30, 2014, which corresponds to the same time period as in Figure 4.3. These results were significantly lower ($L_{eq}$ below 80 dB re 1 μPa) than the results presented between August

5 to October 6, 2013 in Figure 4.2. The average difference between $L_{25}$ and $L_{75}$ is 4.1 dB re 1 µPa. $L_{eq}$ was closer to the lower bounds than the upper bounds of the Wenz curves at all frequencies.

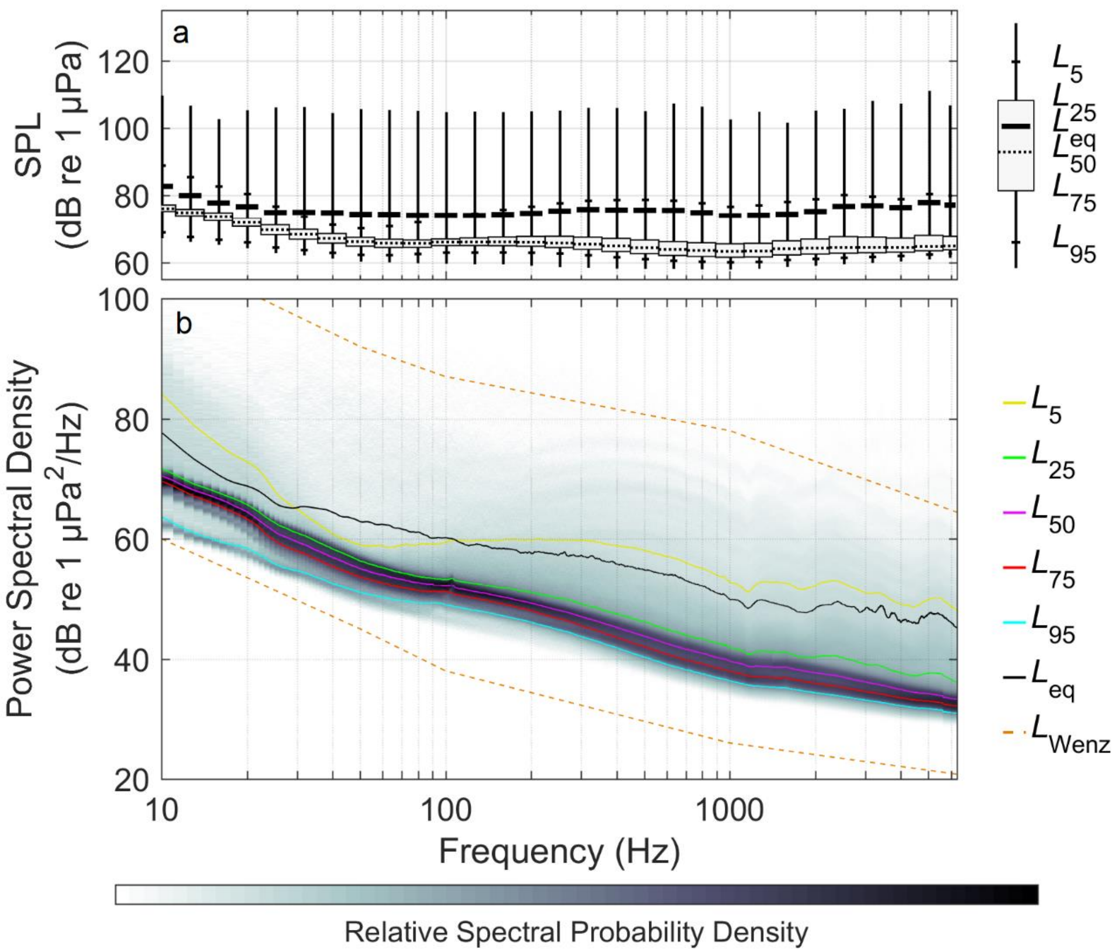


**Figure 4.4. (a) Distribution of third-octave band sound pressure levels from October 6, 2013, to June 30, 2014. (b) Percentile exceedance levels of the power spectral density. The dashed lines are the limits of prevailing noise from the Wenz curves (see Figure 2.5).**

### 4.1.2 Marine Mammal Vocalizations

Bearded seals make many types of underwater vocalizations: trills, moans, ascents, and sweeps (Stirling et al., 1983; Cleator et al., 1989; Risch et al., 2007). It is believed that bearded seals vocalize to communicate territory and for courtship (Burns, 1981; Cleator et al., 1989; Van Parijs et al., 2001, 2003). Bearded seals often produce distinctive trills, comprised of prolonged frequency down-sweeps (Risch et al., 2007; Cleator et al., 1989). A spectrogram of a bearded seal trill is shown in Figure 4.5. This frequency sweep lasted 25 s, starting at 1500 Hz and decreasing to 300 Hz.

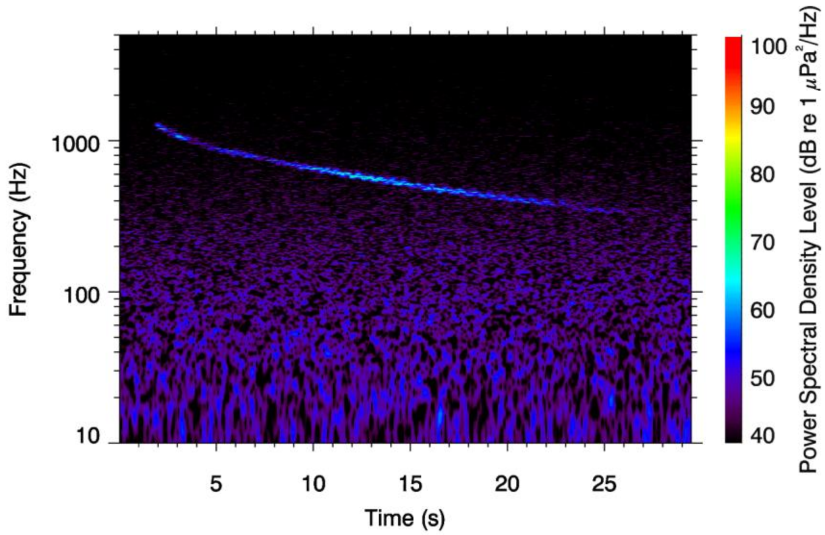


**Figure 4.5. Spectrogram of a bearded seal trill.**

Daily bearded seal call detections from August 2013 to June 2014 are shown in Figure 4.6. Bearded seals were present near Resolute Bay on August 9, 10, and 12, and then they appear to have left and then returned on August 28 and stayed until the beginning of September. They were then present throughout the majority of September and the beginning of October. They were absent in the winter, but came back on June 16, 2014, and stayed until the end of the recording time on June 30, 2014. Ice concentrations around Resolute Bay were 100% at this time, but this does not seem to have deterred the bearded seals. Bearded seal calls were detected during all hours of the day.

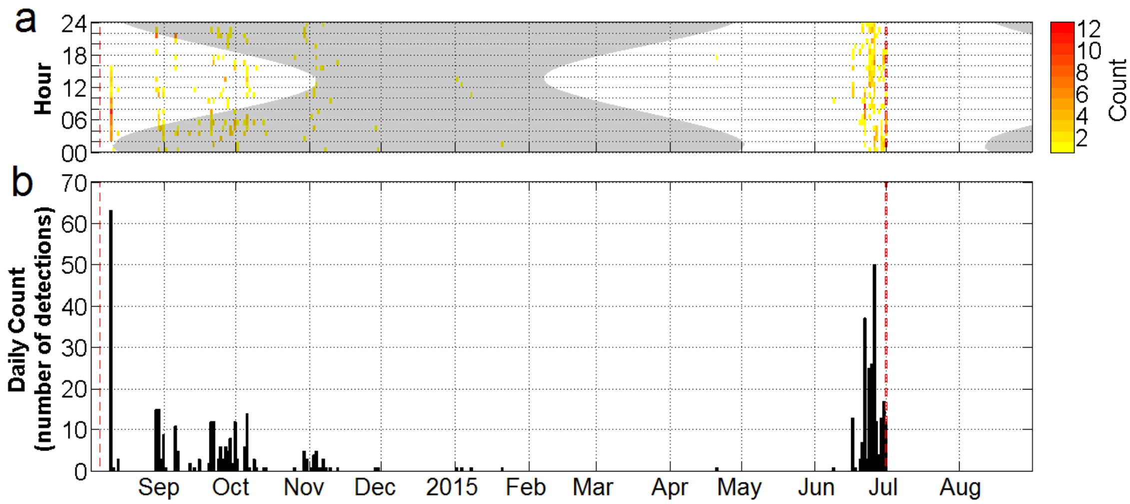


**Figure 4.6. (a) Hourly and (b) daily bearded seal call detections between August 2013 and June 2014. The red dashed lines indicate the recording start and end dates. The shaded area shows the hours of darkness.**

Ringed seals also make a variety of sounds underwater, although their vocalizations are less complex and much lower in source level than bearded seal vocalizations. Ringed seal vocalizations include clicks, rub-like sounds, squeaks, yelps, and double thumps. A spectrogram of ringed seal double thump calls is shown in Figure 4.7. These double thumps are impulsive sounds primarily between 100 and 1000 Hz.

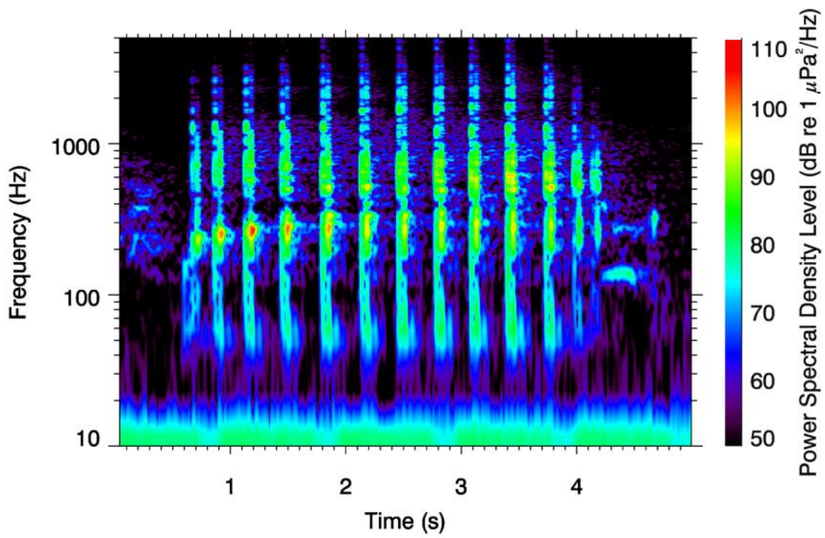


**Figure 4.7. Spectrogram of ringed seal double thump calls.**

Daily ringed seal call detections from August 2013 to June 2014 are shown in Figure 4.8. Ringed seal detections occurred almost daily between August 6, 2013 and January 2014. Similar to bearded seals, ringed seals stay near Resolute Bay, even with 100% ice concentration. Even though ringed seal calls were not detected throughout the remainder of this recording period, ringed seals were likely still present, as the hydrophone issue would have made it difficult for the AMAR to record the low source level ringed seal calls. This is supported by local knowledge, as well as the fact that ringed seal calls were detected throughout the subsequent 2014-2015 deployment (see Figure 4.17). Ringed seal calls were detected during all hours of the day. The majority of the call counts were contributed to ringed seal vocalizations, but a number of low frequency grunt-like sounds caused false positives, slightly over-estimating the number of daily ringed seal call counts. The grunt-like sounds recorded are not known vocalization types for bearded seals nor ringed seals. There is a possibility that the sounds were produced by fish species that are present in Resolute Bay year-round, such as Arctic cod (Welch et al., 1993) and four-horn and short-horn sculpin (McMeans et al., 2013). There has been no research conducted on the sounds of Arctic cod, but they are closely related to Atlantic cod, which are known to vocalize (Rowe et al., 2006; Wilson et al., 2014).

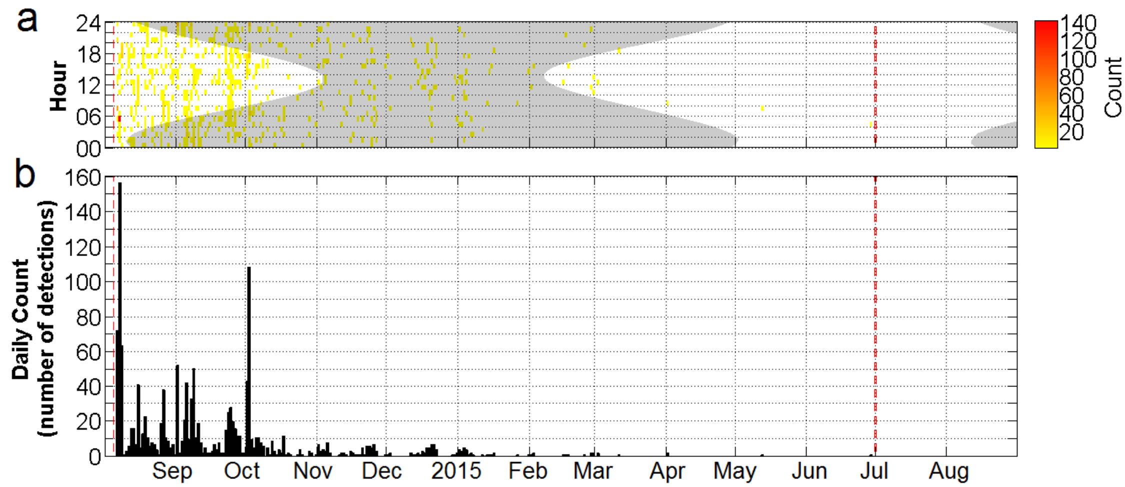


**Figure 4.8. (a) Hourly and (b) daily ringed seal call detections between August 2013 and June 2014. The red dashed lines indicate the recording start and end dates. The shaded area shows the hours of darkness. These results are predominantly ringed seal calls, but may also include fish sounds.**

Beluga whales have one of the most diverse underwater vocalization repertoires. They produce complex whistles as well as clicks. Clicks are used for social communication as well as echolocation to find prey and define surroundings (Le Bot et al., 2015; Richardson et al., 1995). Alternatively, calls are believed to be used for communication, and perhaps identification (Panova et al., 2012; Sjare and Smith, 1986b). A spectrogram of beluga whistles and clicks is shown in Figure 4.9. The clicks are impulsive sounds made at high frequencies, in this example above 30 kHz, and the whistles are undulating signals between 1 and 10 kHz over multiple seconds.

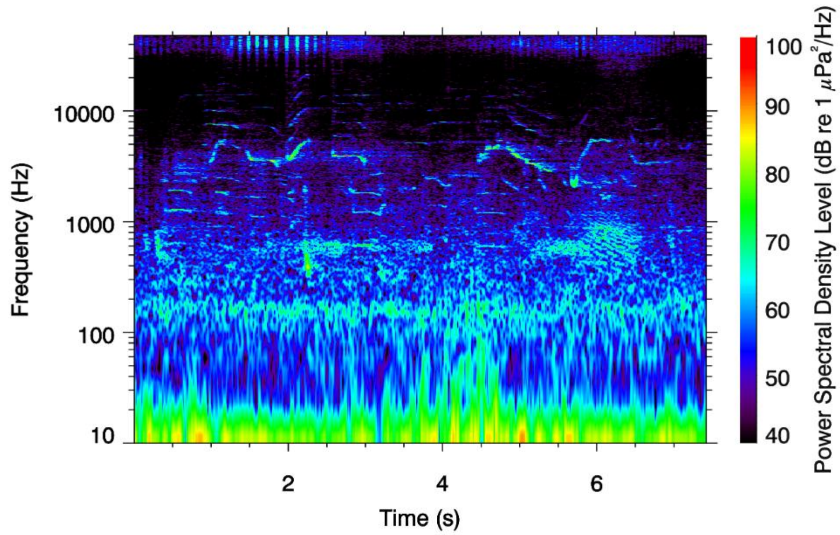


**Figure 4.9. Spectrogram of beluga clicks and whistles. Clicks are above 30 kHz, while whistles are between 1 and 10 kHz.**

Daily beluga whistle detections from August 2013 to June 2014 are shown in Figure 4.10. The number of whistle detections was greatest on August 6, 9, and 29. Beluga whistles were also detected on a few days in August, including August 31, and September 6, 15, 16, and 20. Whistles were detected during all hours of the day.

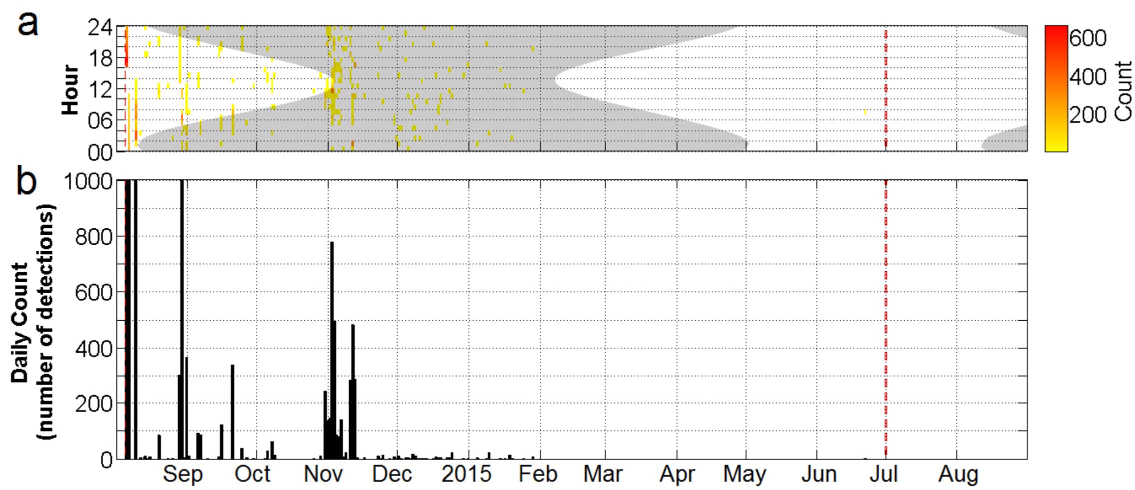


**Figure 4.10. (a) Hourly and (b) daily beluga whistle detections between August 2013 and June 2014. The red dashed lines indicate the recording start and end dates. The shaded area shows the hours of darkness. Detections in November and throughout winter are likely false detections caused by sound produced by shifting ice. Results presented are primarily beluga calls, but may include narwhals.**

Daily beluga click detections from August 2013 to June 2014 are shown in Figure 4.10. A significant number of clicks were detected on three days: August 9 and September 16 and 25, 2013. No other days in the recording period detected a significant number of clicks, although this was expected between October 6, 2013 and June 20, 2014, as the clicks were outside of the reduced recording bandwidth. Clicks were detected during daylight hours only, although this may be bias due to a small sample size.

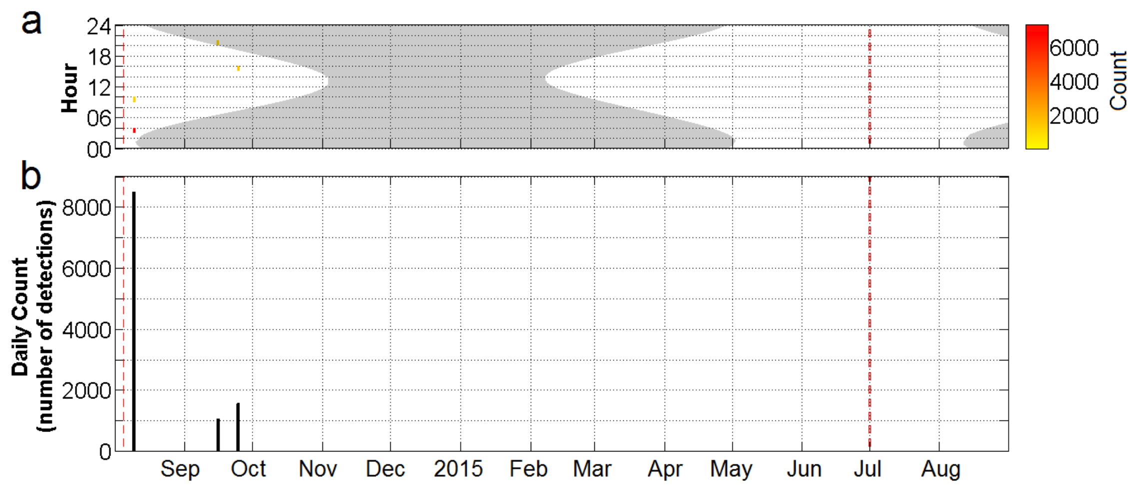


**Figure 4.11. Hourly and daily beluga click detections between August 2013 and June 2014. The red dashed lines indicate the recording start and end dates. The shaded area shows the hours of darkness. Results presented are primarily beluga calls, but may include narwhals.**

## 4.2 2014–2015 Deployment

### 4.2.1 Ambient Sound

Broadband and decade-band sound pressure levels between August 15 and November 3, 2014, are shown with the corresponding spectrogram in Figure 4.12. The semidiurnal pattern of elevated sound levels between 10 and 20 Hz was caused by water flowing past the hydrophone during periods of high tidal velocity, which was also recorded in the 2013-2014 acoustic data. This is also apparent in the 32 kHz dataset (see Figure 4.14). Recorded underwater sounds in the summer, ice-free months, have sections of high broadband SPLs, caused by vessel activity. Broadband levels when vessels were present increased to 145.3 dB re 1 µPa from 105 to 110 dB re 1 µPa. At the end of September, when ice-freeze-up occurred, high intensity thermal ice-cracking impulses dominated the spectrum; this also occurs sporadically throughout October. Broadband sound pressure levels during ice freeze-up were around 110 dB re 1 µPa, and dropped to 80 to 85 dB re 1 μPa at times with minimal ice noise. The mean third-octave band sound pressure level was 95.6 dB re 1 μPa from August 15 to November 3, 2014.

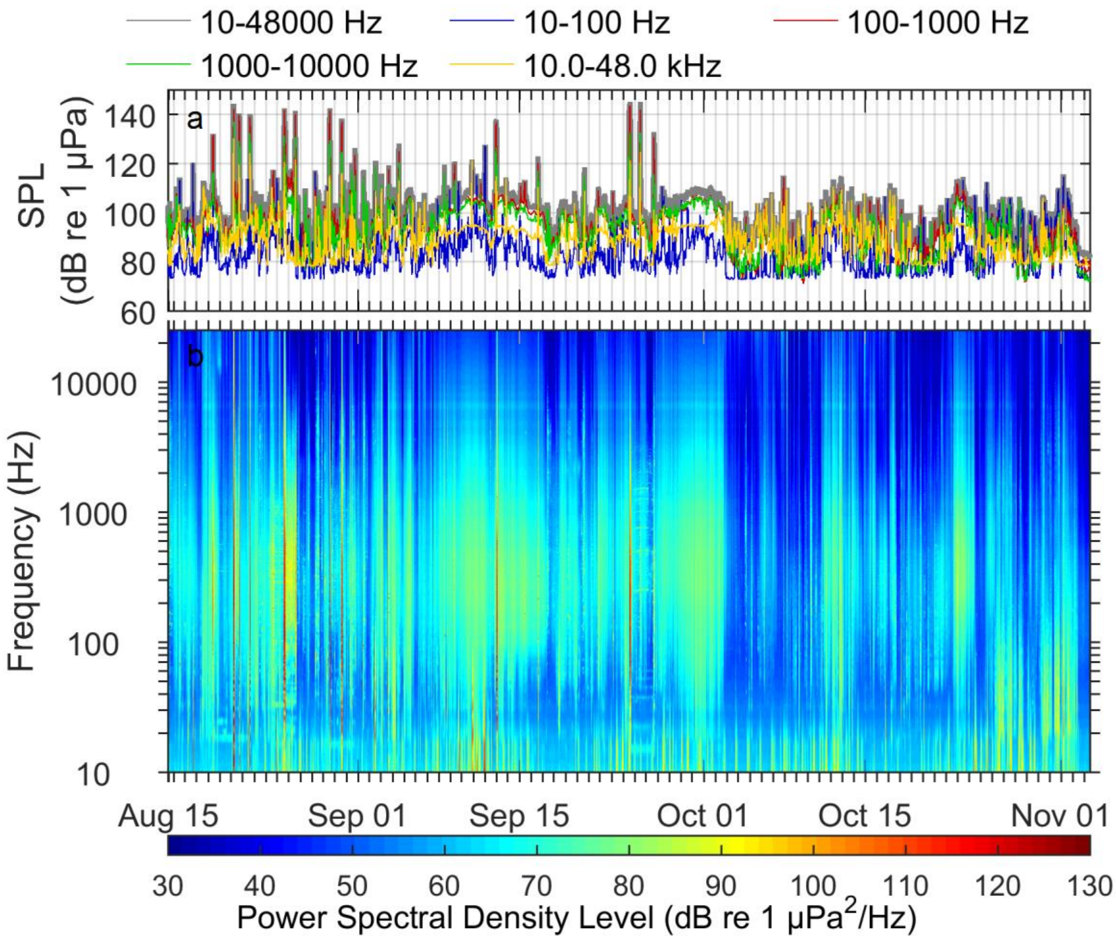


**Figure 4.12. (a) Broadband and decade-band sound pressure levels and (b) spectrogram of underwater sound from August 15 to November 3, 2014.**

Figure 4.13 shows the distribution of third-octave band sound pressure levels from August 15 to November 3, 2014 and the corresponding power spectral density in relation to the expected minimum and maximum levels (Figure 2.5). The third-octave bands with greatest $L_{eq}$ during August 15 to November 3, 2014 are between 80 and 600 Hz. The third-octave $L_{eq}$ (over time) were between 5 to 25 dB higher than the third-octave $L_{50}$ calculated over this recording period, with a greater spread at the lower half of the frequency spectrum (10 to 1000 Hz). This large difference is attributed to a large number of brief but high intensity thermal ice-cracking events during October and November, as well as local boats that sporadically travel in and out of the bay during low ice concentration times (August to September). These both contribute to the mean but have little influence on the median. $L_{eq}$ between 100 and 400 Hz were equal to the upper boundary of the Wenz curve, while the other frequencies were well within the bounds.

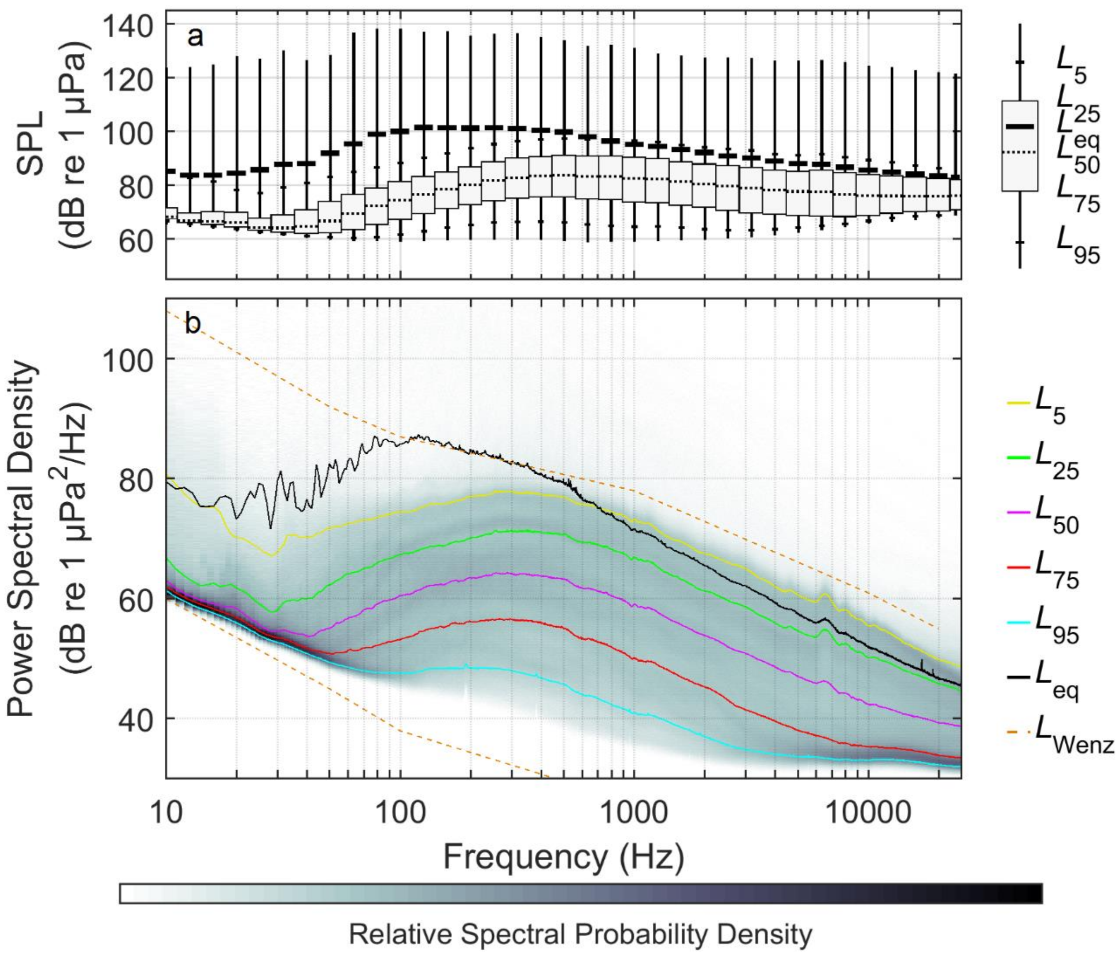


**Figure 4.13. (a) Distribution of third-octave band sound pressure levels from August 15 to November 3, 2014. (b) Percentile exceedance levels of the power spectral density. The dashed lines are the limits of prevailing noise from the Wenz curves (see Figure 2.5).**

Broadband and decade band sound pressure levels between November 3, 2014 and August 10, 2015, are shown with the corresponding spectrogram in Figure 4.14. Ice noise, from thermal cracking and ice floe rubbing, continues to dominate the ambient sound spectrum between November 3 and mid-December, 2014, with broadband SPLs around 105 dB re 1 µPa. After the ice noise decreased, perhaps due to more stable and solidified ice floes creating less rubbing noises, ambient broadband SPLs varied between 95 and 100 dB re 1 µPa throughout the winter and early spring with the 2-12.5 kHz decade band contributing the most to the overall broadband sound levels. The 10-32 Hz decade band experienced the highest sound levels between May 1 and June 20, 2015, as a result of flow noise on the hydrophone. Flow noise did not increase during this time frame; rather, the other decade bands became quieter after the vessels and most marine mammals left. After June 20 the sound in the 200-1600 Hz decade band dominated, likely as a result of the large number of bearded seal vocalizations during this time (Figure 4.16). On July 1, ice break-up caused the sound pressure levels to increase from 100 dB re 1 µPa to 110 dB re 1 µPa, where they stayed until the ice left the bay on July 9. The broadband SPLs increased to 145 dB re 1 µPa for a period when a vessel was present on August 2. After the vessel passed, broadband levels went back to 105-110 dB re 1 µPa with the 200-1600 Hz and 2-12.5 kHz decade bands comprising most of the broadband SPLs.

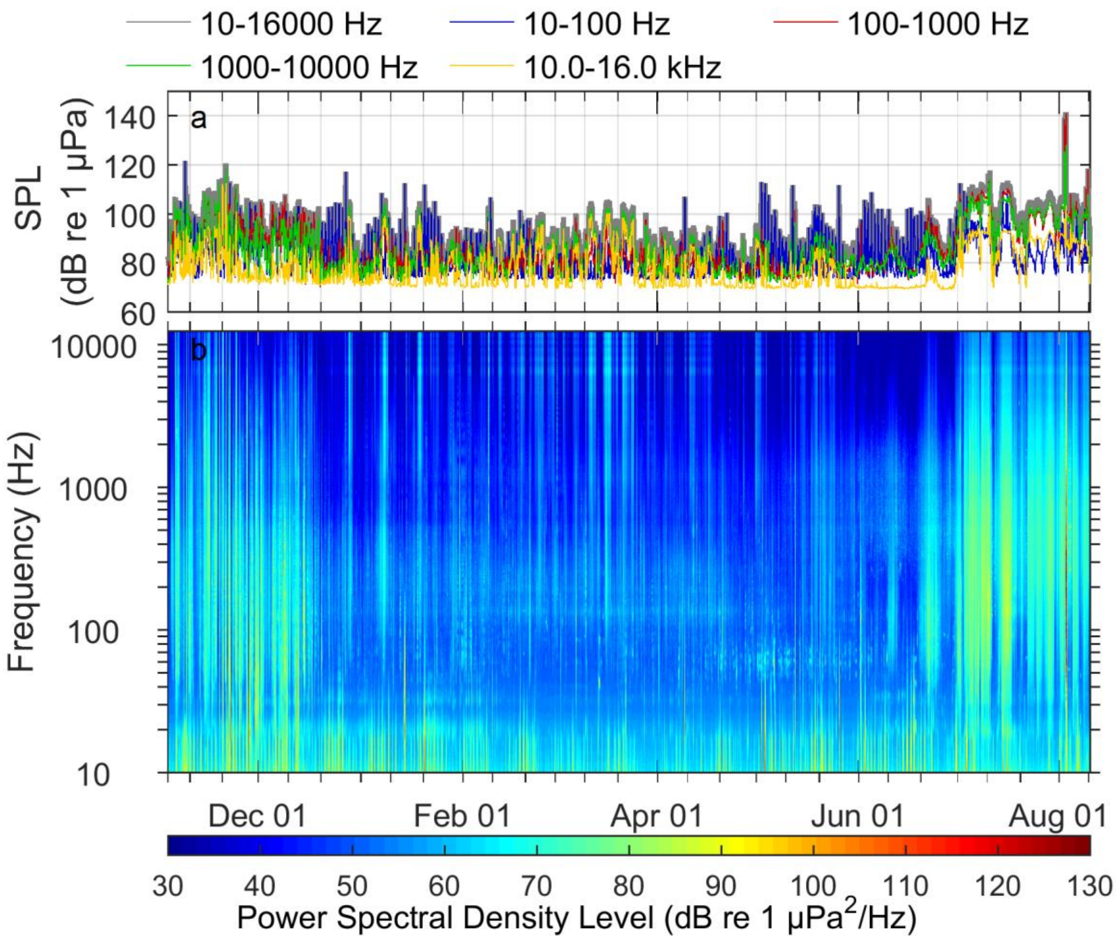


**Figure 4.14. (a) Broadband and decade-band sound pressure levels and (b) spectrogram of underwater sound from November 3, 2014, to August 10, 2015.**

Figure 4.15 shows the observed sound levels from November 3, 2014, to August 10, 2015, which corresponds to the same time period as in Figure 4.14. The third-octave bands with greatest $L_{eq}$ during this period were between 100 and 400 Hz, with the difference between $L_{25}$ and $L_{75}$ being less than in the period between August 15 and November 3, 2014. $L_{eq}$ was between the upper and lower bounds of the Wenz curves at all measured frequencies.

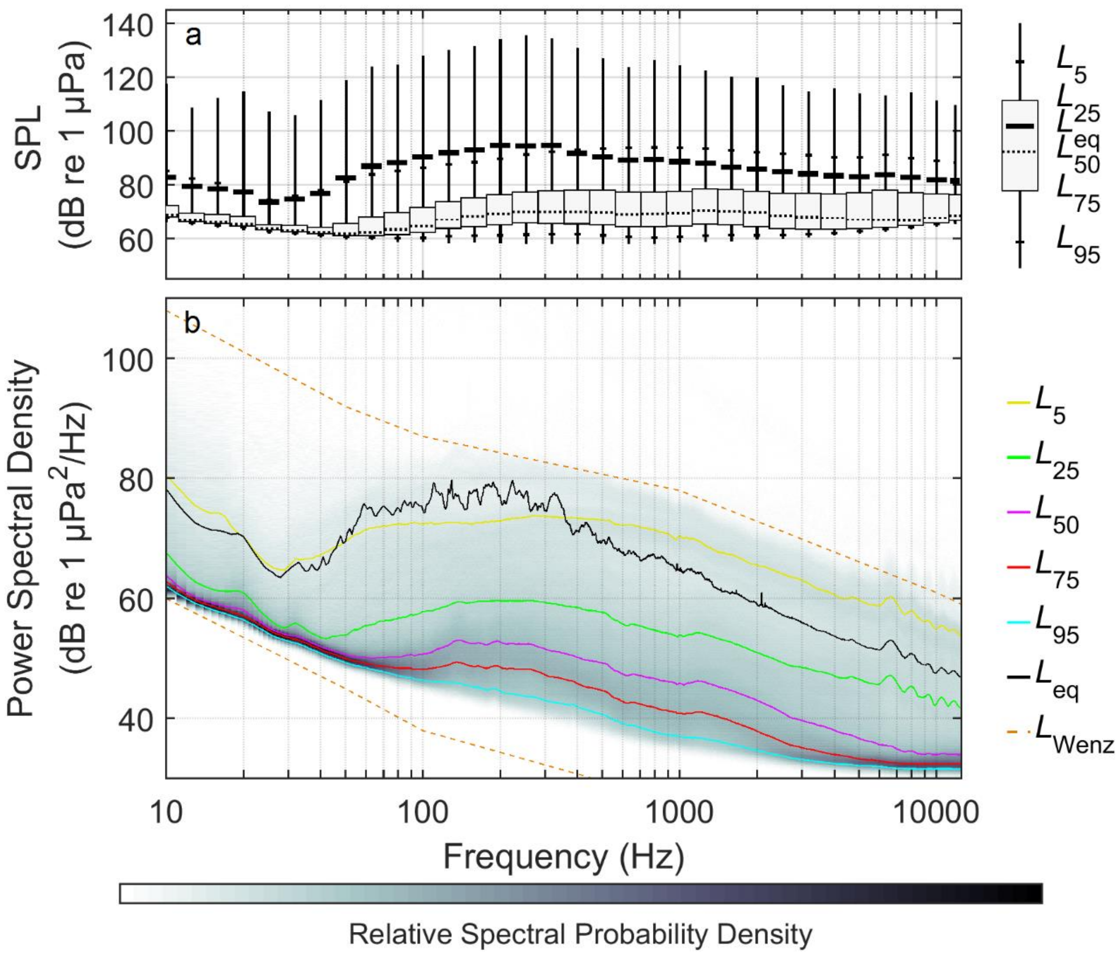


**Figure 4.15. (a) Distribution of third-octave band sound pressure levels from November 3, 2014, to August 10, 2015. (b) Percentile exceedance levels of the power spectral density. The dashed lines are the limits of prevailing noise from the Wenz curves (see Figure 2.5).**

#### 4.2.2 Marine Mammal Vocalizations

Daily bearded seal call detections from August 2014 to August 2015 are shown in Figure 4.16. Bearded seals mostly vocalized between May and July 2015. Then suddenly on July 1, 2015, the daily call counts dropped significantly (from 313 to 0 in 5 days). There was only a small (less than 30 per day) number of calls detected for the rest of the deployment period. Bearded seals have been known to do the majority of their vocalizing in the early summer, during their mating season (Frouin-Mouy et al., 2016), so the elevated number of call counts in this time period is likely from an increased number of vocalizations rather than an increased number of bearded seals. Bearded seal calls were detected during all hours of the day, and did not show a preference for vocalizing at night, which was observed for bearded seals in the northeastern Chukchi Sea (Frouin-Mouy et al., 2016). This is likely due to the lack of darkness in Resolute Bay during this period.

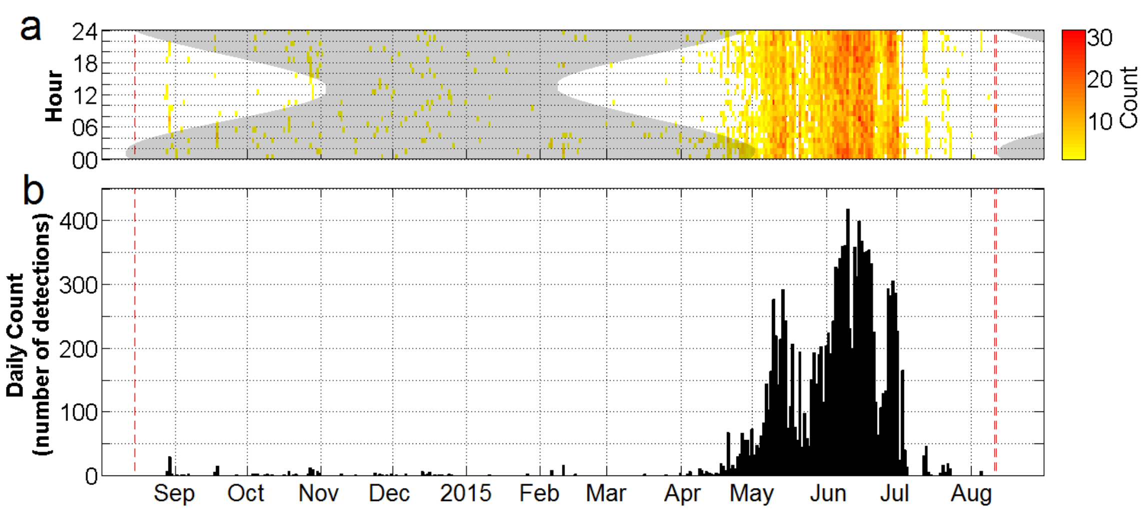


**Figure 4.16. (a) Hourly and (b) daily bearded seal call detections between August 2014 and 2015. The red dashed lines indicate the recording start and end dates. The shaded area shows the hours of darkness.**

The daily observed ringed seal call counts from August 2014 to August 2015 are summarized in Figure 4.17. Similar to the 2013-2014 deployment period, ringed seal calls were most common between August and November. Ringed seal calls were also present throughout the winter and were detected during all hours of the day. Similar to the 2013-2014 dataset, low-frequency unidentifiable grunt sounds were present, which led to false positive ringed seal call detections.

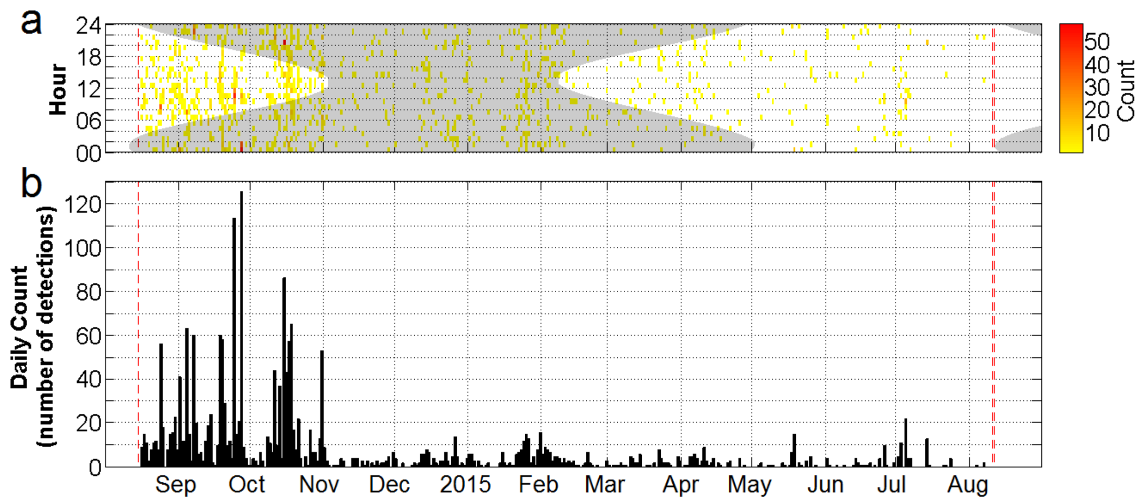


**Figure 4.17. (a) Hourly and (b) daily ringed seal call detections between August 2014 and 2015. The red dashed lines indicate the recording start and end dates. The shaded area shows the hours of darkness. These results are predominantly ringed seals, but they may also include fish sounds.**

Daily beluga whistle detections from August 2014 to August 2015 are shown in Figure 4.18. Daily beluga whistle detections were greatest on August 29, September 6, and October 27 and 28, 2014. The manual validation found that the counts for the dates in October as well as for the winter months were false detections due to rubbing ice floe noise. However, the beluga whistles on October 20, 2014, are correct detections. Daily call counts in October were less than in August and September, which was likely due to ice concentrations suddenly increasing up to 90% on October 2, and staying between 80 and 95% for the rest of October (Figure 3.14). In August and September when there were more calls detected, ice concentrations were between 0 and 50%. Beluga whistles were detected during all hours of the day.

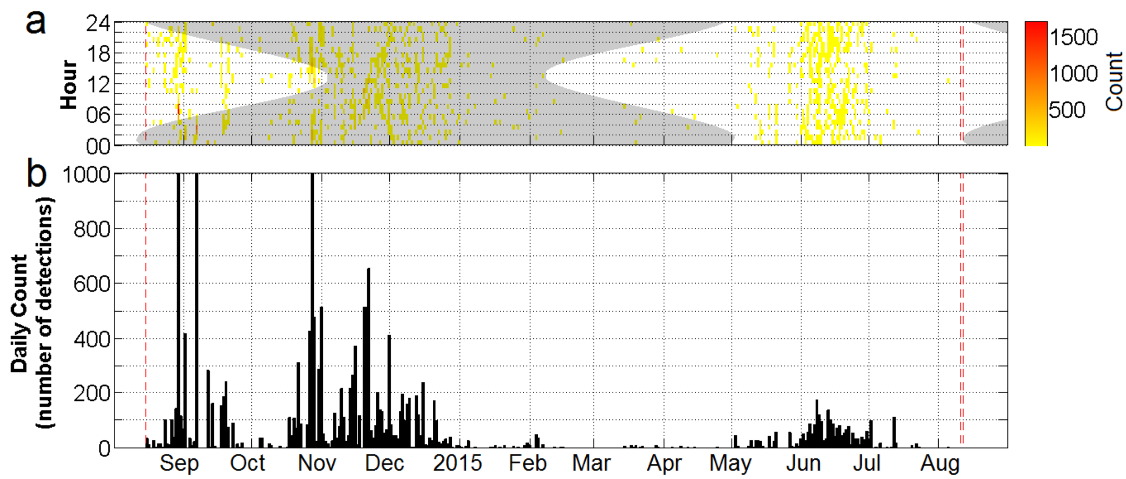


**Figure 4.18. (a) Hourly and (b) daily beluga whistle detections between August 2014 and 2015. The red dashed lines indicate the recording start and end dates. The shaded area shows the hours of darkness. Detections at the beginning of November and throughout winter are likely false detections caused by ice noise. Results presented are primarily beluga calls, but may include narwhal calls.**

Daily beluga click detections from August 2014 to August 2015 are summarized in Figure 4.19. Beluga clicks were detected on August 28 and 29 and September 6, 11, 14, and 19, 2014. On August 29 and September 6, high numbers of beluga whistles were detected as well (Figure 4.18). After November 3, 2014, the AMAR sample rate was too low to pick up high-frequency beluga clicks. Beluga clicks were detected during all hours of the day.

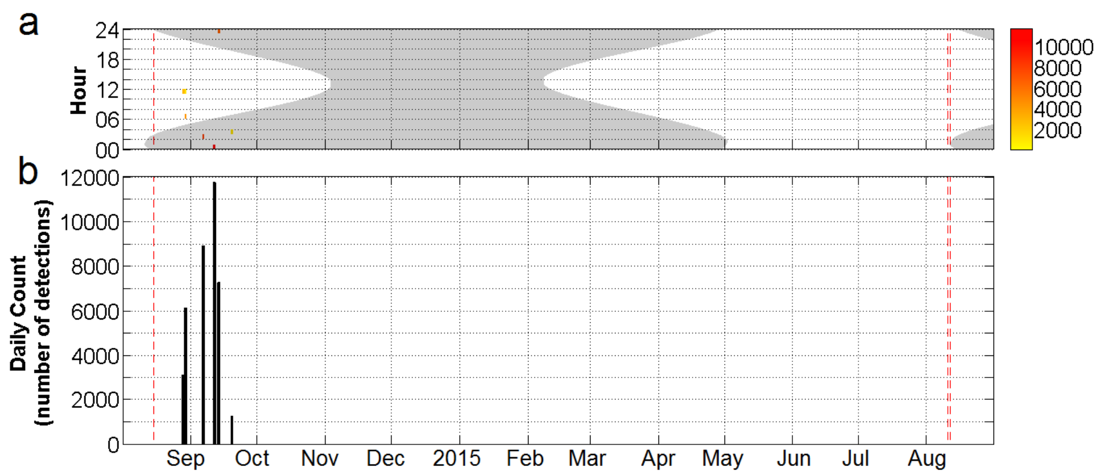


**Figure 4.19. (a) Hourly and (b) daily beluga click detections between August 2014 and 2015. The red dashed lines indicate the recording start and end dates. The shaded area shows the hours of darkness. Results presented are primarily beluga calls, but may include narwhals.**

# 5 Discussion

## 5.1 Annual Variability in Water Properties

The year to year variability of temperature, salinity, and dissolved oxygen for the two deployments of the channel benthic pod is shown in Figure 5.1. Temperatures and salinities between August 2013 and August 2015 were relatively similar but with slightly saltier waters between February and August 2015 compared to the year before. The mean temperature and salinity between August 2013 and August 2014 were –1.33°C and 32.69 PSU, while between August 2014 and August 2015 the corresponding values were –1.42°C and 32.81 PSU respectively. The mean dissolved oxygen saturation level was approximately 9% higher during the August 2014 to August 2015 period than the same period the year before (76% versus 67% respectively).

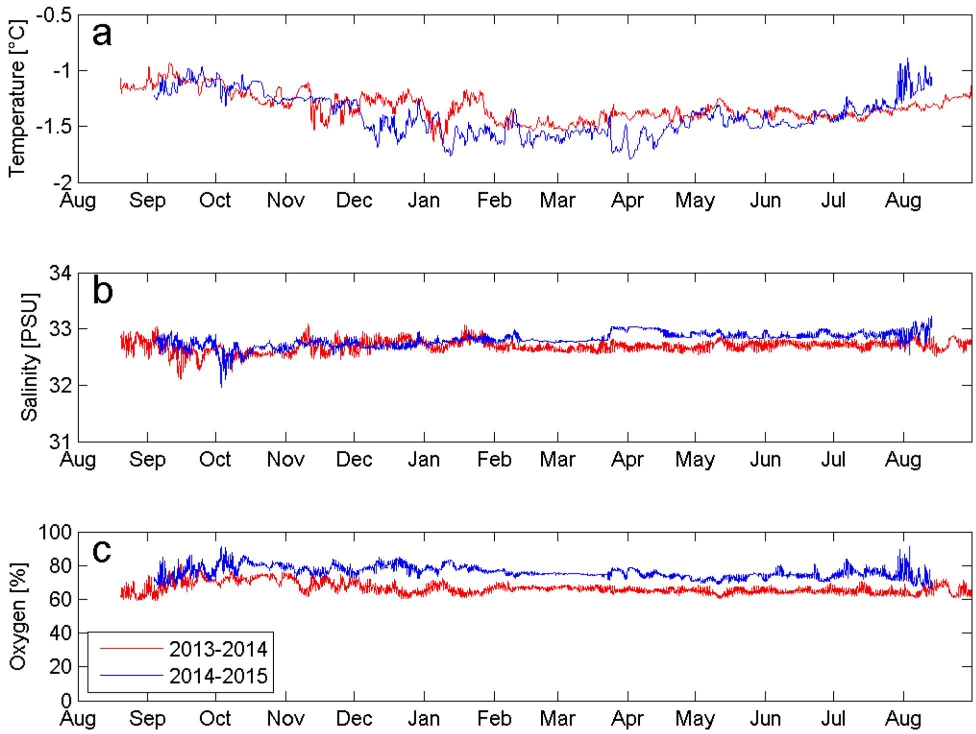


**Figure 5.1. (a) Temperature, (b) salinity, and (c) dissolved oxygen saturation measured at the channel benthic pod from 2013 to 2015.**

A temperature versus salinity plot of seasonal water measurements at the channel benthic pod from 2013 to 2015 is shown in Figure 5.2. Compared to the other benthic pods, the channel pod sensors showed the lowest variability in both temperature and salinity. As expected, July through September had the warmest water, followed by October through December, when the water cooled as the air temperatures dropped. January through March and April and through June had the lowest, but relatively stable, temperatures. Both years showed a similar trend with warmer fresher water in the summer, followed by autumn cooling and then saltier cold water in the winter. April through June had the most consistent salinity values and October through December had the freshest water.

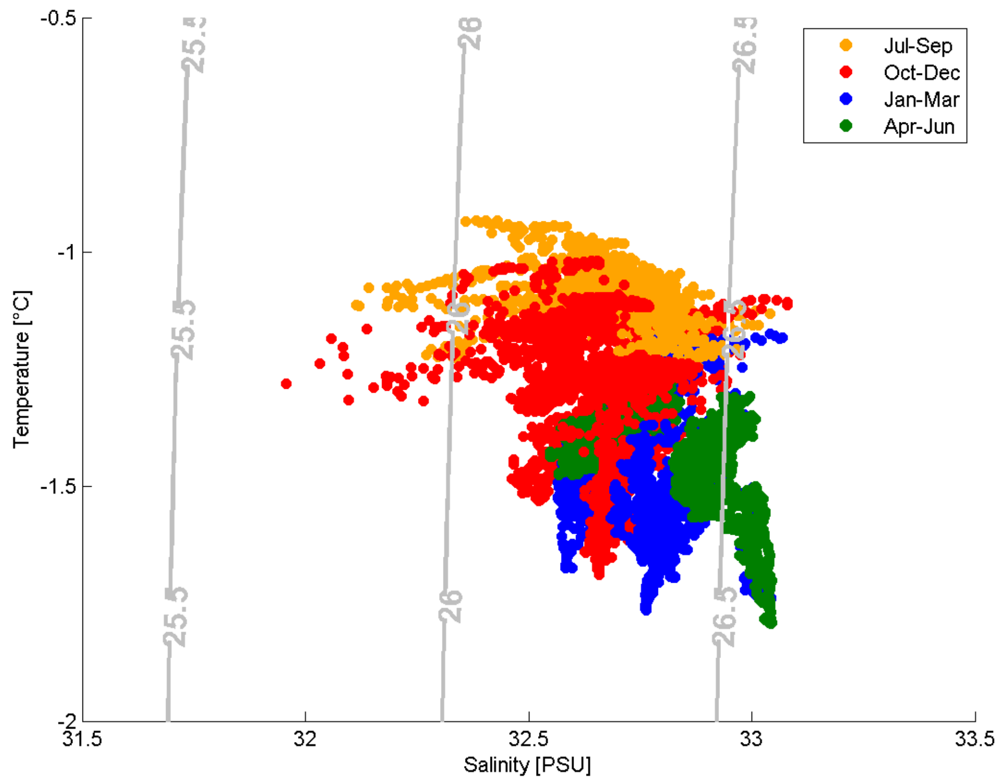


**Figure 5.2. Temperature versus salinity plot of seasonal water measured at the channel benthic pod from 2013 to 2015. $\sigma_T$ is shown by grey lines.**

Temperature, salinity, and dissolved oxygen saturation measured on the outside-bay benthic pod over a three-year period from 2012 to 2015 are shown in Figure 5.3. Here the temperatures were greatest between August and December 2012, and between June and August 2015. In 2012, Resolute Bay experienced a longer ice-free period and a late ice freeze-up date (October 14) compared to the other measured years (September 15, 2013 and October 2, 2014). The longer ice-free period enabled the water to absorb more radiation heat, and the late ice freeze-up date enabled the radiation heat to continue to have an effect later in the year. In combination, these environmental conditions created higher water temperatures between August and December 2012 than during the same months in 2013 and 2014.

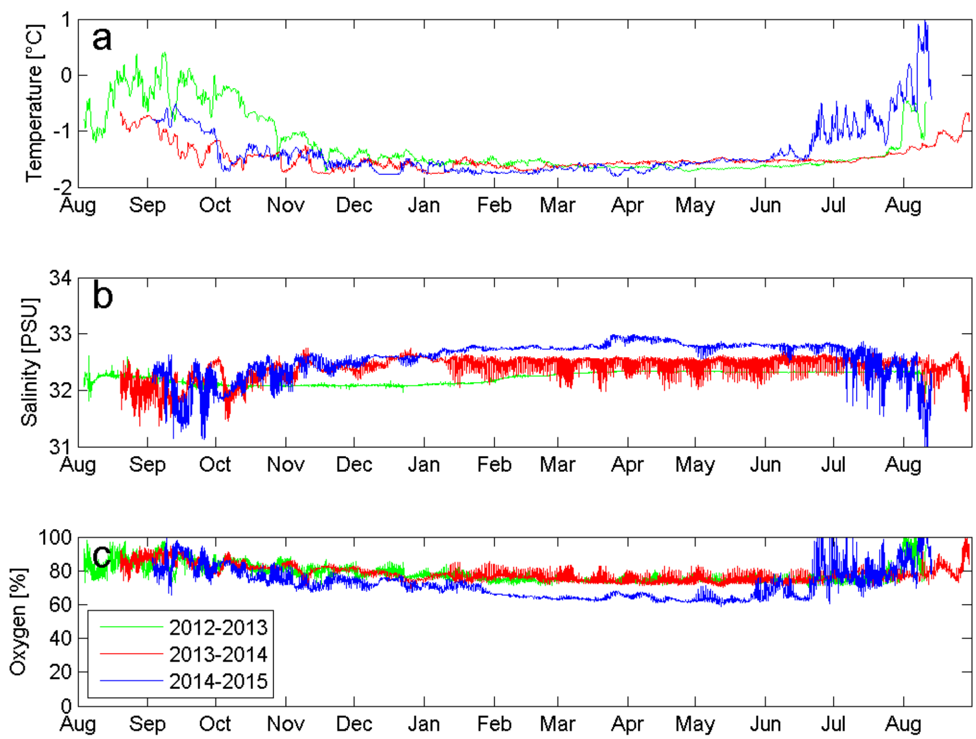


**Figure 5.3. (a) Temperature, (b) salinity, and (c) dissolved oxygen saturation measured at the outside-bay benthic pod from 2012 to 2015.**

Between December and June, the yearly water temperatures were similar – approximately –1.7°C. The salinities had similar annual trends, with 2012-2013 being the least variable. Salinities were lowest in the summer and fall, and increased through the winter and spring. In the winter and spring, 2014-2015 had the highest salinities, followed by 2013-2014. Dissolved oxygen values were nearly identical between 2012 and 2014. However, in the winter and spring of 2015, the dissolved oxygen saturation levels were between 7 and 12% lower than the same time period for the two previous years.

A seasonal temperature versus salinity plot of the outside-bay benthic pod during the three annual deployments is shown in Figure 5.4. Similar to the channel benthic pod, the outside-bay benthic pod had the greatest temperatures from July through September. This time period also had the most year to year variability in both temperature and salinity. October through December had stable salinity and decreasing temperature in 2012-2013 and stable temperatures with varying salinities for the other two years. January through March consistently had the same temperatures, with increasing salinities, and April through June had consistent salinities with increasing temperatures.

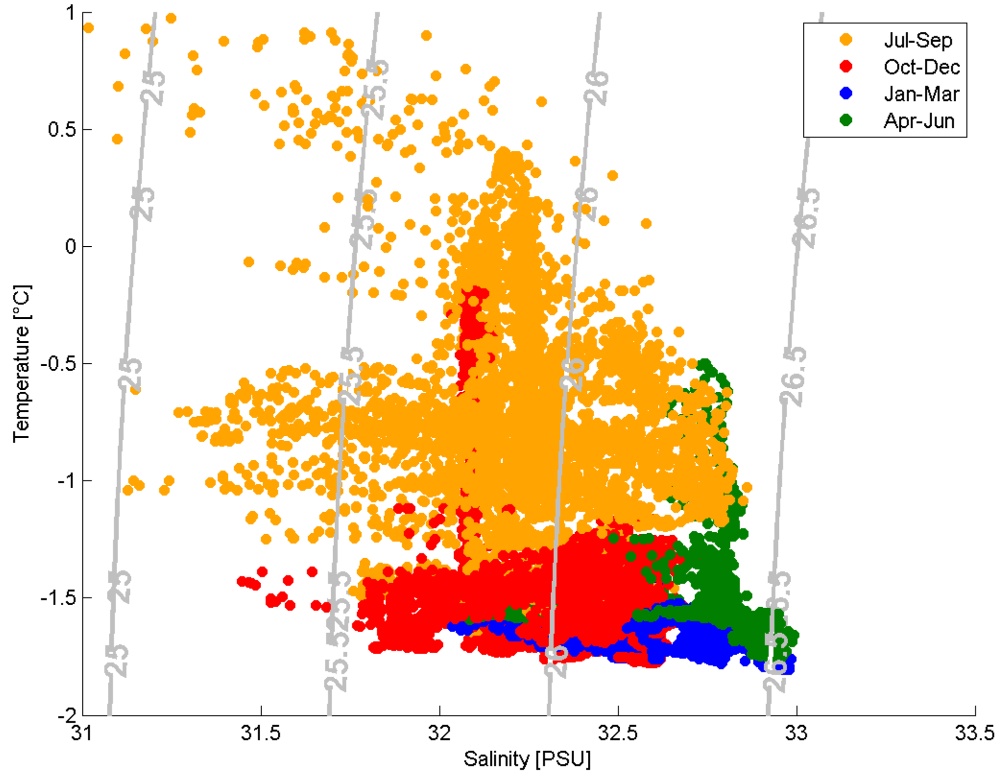


**Figure 5.4. Temperature versus salinity plot of seasonal water measured at the outside-bay benthic pod from 2012 to 2015. $\sigma_T$ is shown by grey lines.**

Figure 5.5 shows the temperature, salinity, and dissolved oxygen saturation measured at the inner-bay benthic pod during the three deployment periods. Similar to the outside-bay benthic pod, temperatures were highest between August and December 2012, due to the longer ice-free period and the late ice freeze-up date. Higher water temperatures were also observed in July and August 2015, which was due to ice break-up occurring earlier (on July 10) than the previous years (July 22 and 25). Water temperatures between December and July were very similar each year, followed by a gradual increase in July and August. The summer and fall of 2012 had the greatest number of abrupt temperature changes, although these did occur to some extent every year.

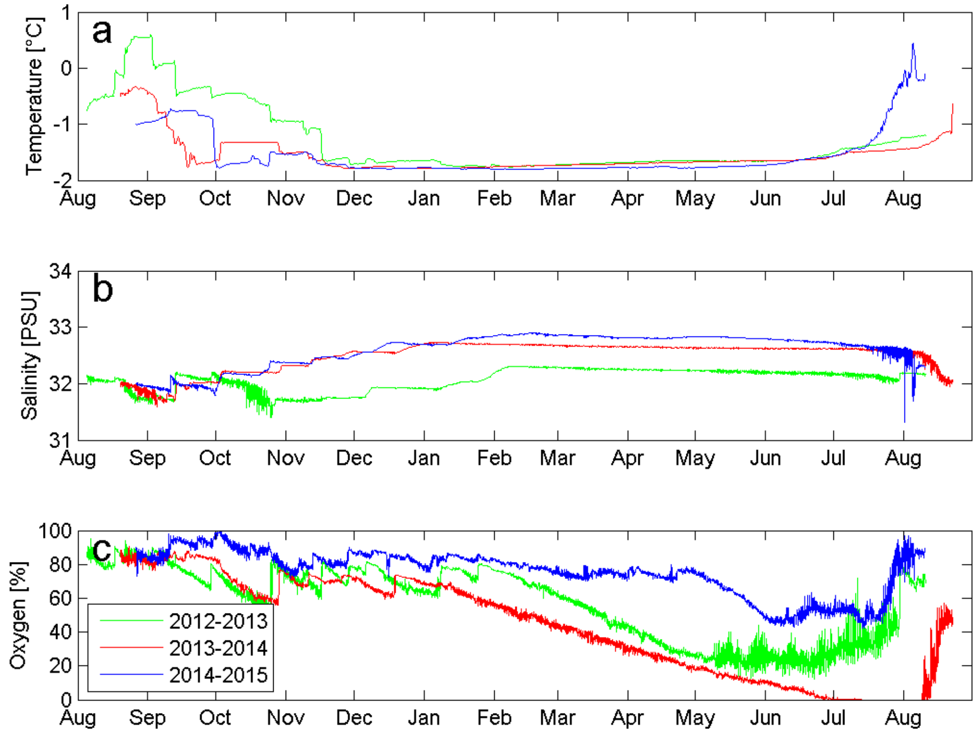


**Figure 5.5. (a) Temperature, (b) salinity, and (c) dissolved oxygen saturation measured at the inner-bay benthic pod from 2012 to 2015.**

Salinities were observed to have an increasing step-pattern with an underlying gradual increase from August to February in 2013-2014 and 2014-2015. The steps were likely caused by wind-driven mixing of outside bay waters coming into Resolute Bay. The gradual increase was likely caused by brine rejection from ice formation, where salt is excluded from the ice crystals. This increases the density of the surface water, and in combination with surface cooling, the water sinks (Ruddimann, 2001; Lake and Lewis, 1970). In 2012, the ice did not form in Resolute Bay until the middle of October, which caused a delayed onset of the gradual increase observed earlier in 2013 and 2014, when the ice formed in mid-September and the beginning of October, respectively.

Overall, 2014-2015 had the highest salinities, while 2012-2013 had the lowest salinities. The 2013-2014 and 2014-2015 deployment periods had very similar salinity trends, with values in 2014-2015 approximately 0.2 PSU greater than in 2013-2014 during the winter and spring months. The remainder of the year they had comparable values, following a similar increasing step-pattern in the summer and fall, and very slowly decreasing during the winter and spring. The 2012-2013 deployment period had a similar trend between November and August, but unlike the following two years, had a greater decrease of salinity in October.

The dissolved oxygen saturation levels were highest during the 2014-2015 deployment. This year had the smallest decline during the winter and spring months, with a minimum saturation value of 42%. The lowest dissolved oxygen levels were observed in summer of 2014, when they fell to 0%. The 2013-2014 period also experienced the year to year lowest overall dissolved oxygen levels. All three years displayed similar annual trends with decreasing rates and sudden renewal events from August to February, followed by a gradual decrease until July when the dissolved oxygen levels started increasing.

A seasonal temperature versus salinity plot for the inner-bay benthic pod for the three deployments is shown in Figure 5.6. The temperatures and salinities in July and September varied greatly from year to year, from –1.76 to 0.6°C and from 31.32 to 32.74 PSU. October through December showed cooling with varying salinities in 2012, while in the other two years, the temperature stayed constant while salinity increased. A constant temperature with increasing salinity was also observed in January through March, while temperature and salinity remained constant throughout April, May, and June.

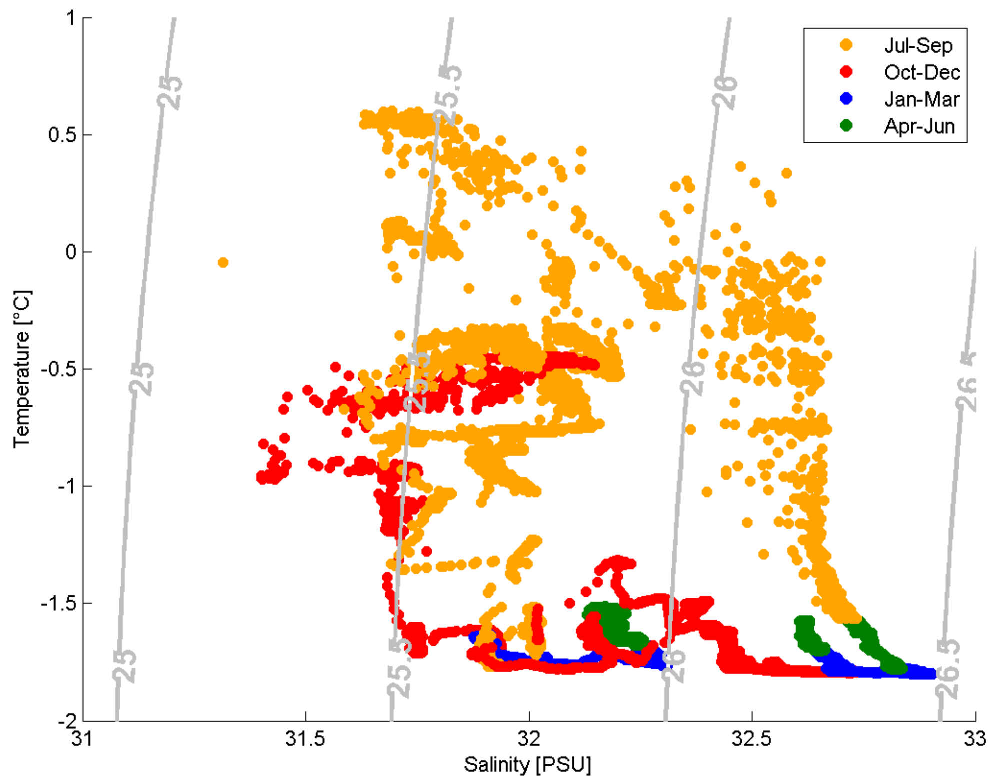


**Figure 5.6. Temperature versus salinity plot of seasonal water measured at the inner-bay benthic pod from 2012 to 2015. $\sigma_T$ is shown by grey lines.**

Annual comparison of temperature, salinity, and dissolved oxygen in northern Resolute Bay from August 2013 to August 2015 is shown in Figure 5.7. In both years, temperatures decreased from August until October, albeit at different rates. Temperatures were almost identical between the two years over the November to July period, with a consistent value of approximately –1.78°C. This was followed by an increase in temperatures in July and August. In 2015, this increase was approximately 4.2°C, compared to 0.7°C in 2014.

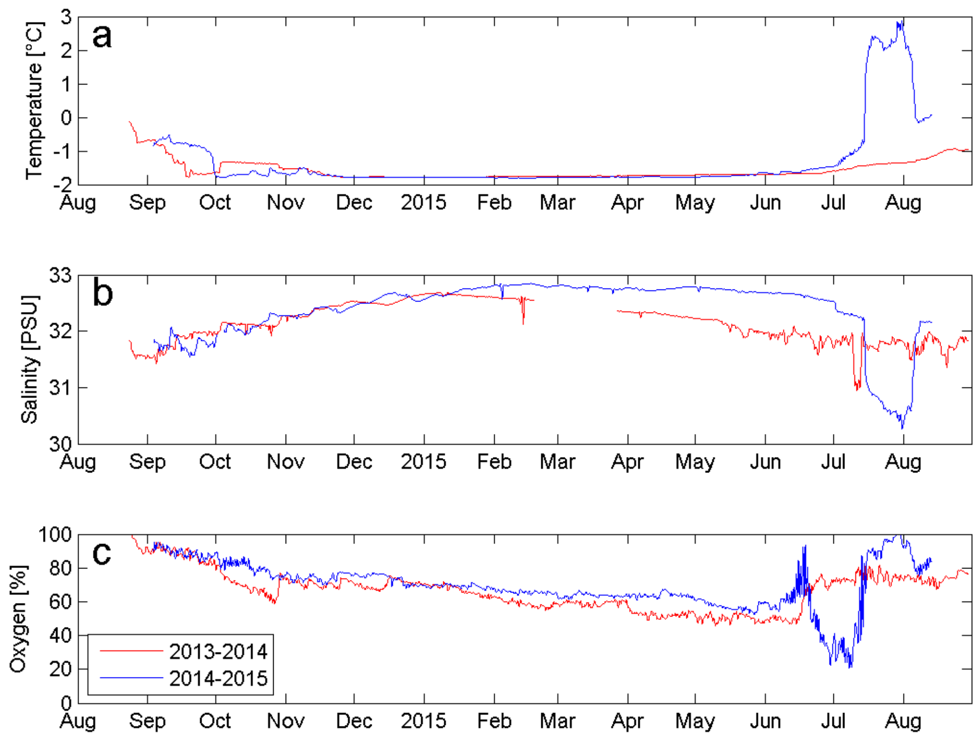


**Figure 5.7. (a) Temperature, (b) salinity, and (c) dissolved oxygen saturation measured at northern-bay RBR loggers from 2013 to 2015.**

Salinity values in both measurement years showed the same increasing trend from August to February. Then salinities in both years gradually decreased until July, with the first deployment decreasing at a faster rate. In mid-July 2015, there was a sudden drop in salinity, which was not observed in the summer of 2014.

Dissolved oxygen levels in northern Resolute Bay in 2013 and 2014 decreased at a similar rate from August to June. In mid-June of both years, a sudden increase in dissolved oxygen was observed. In the first deployment (2014), dissolved oxygen levels plateaued after this, but in the second deployment (2015), dissolved oxygen levels decreased to a minimum of 21% and then increased, with higher measured values in August 2015 than in August 2014.

Figure 5.8 shows a temperature versus salinity plot of seasonal water measured at the northern-bay RBR loggers from August 2013 to August 2014 and August 2014 to August 2015. The most prominent feature is the high temperature and low salinity water that was observed in the summer of 2015. Each year between October and December, the water cooled significantly, to between –1.3 and –1.8°C, and became saltier, likely due to the brine rejection caused by the ice forming. Each year also showed small salinity changes from January through March. Between April and June, one year (2015) had a slight increase in temperature and a decrease in salinity, which was not observed in the other year (2014).

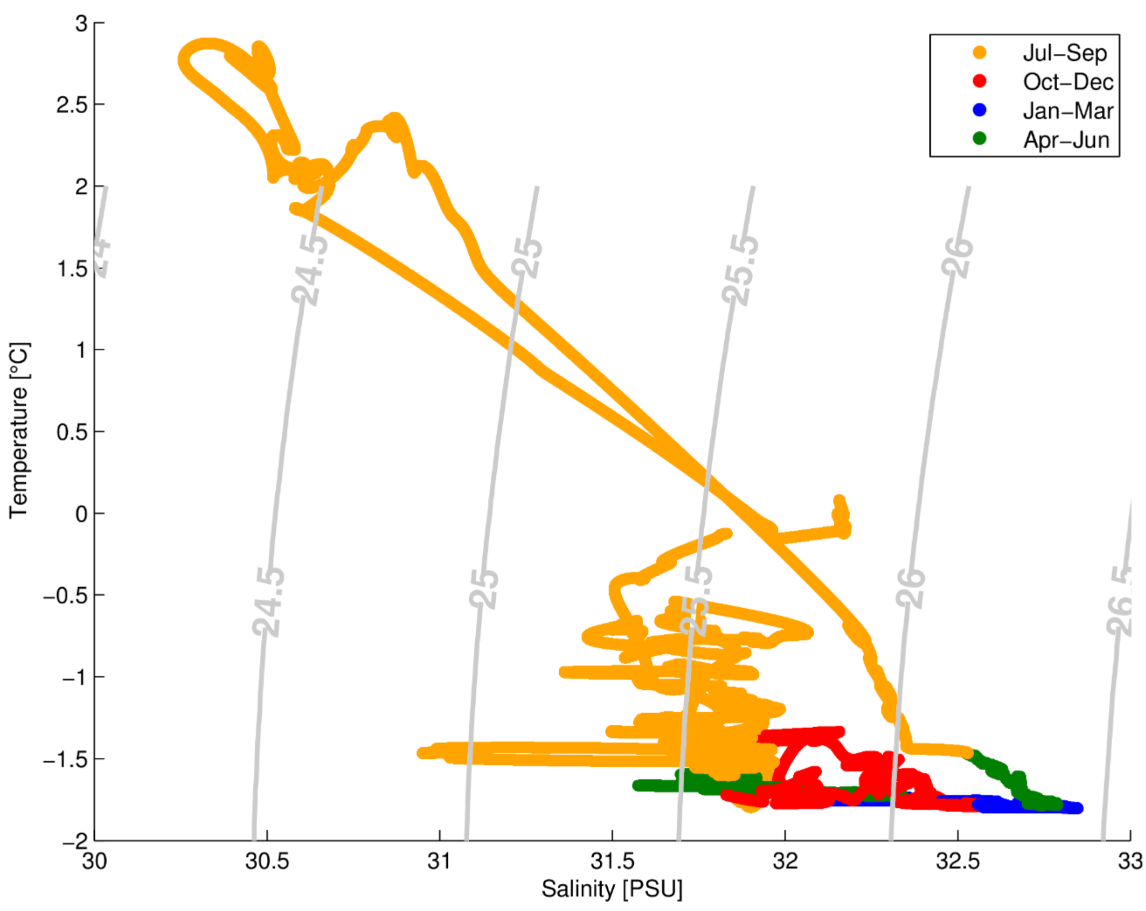


**Figure 5.8. Temperature versus salinity plot of seasonal water measured at the northern-bay RBR logger from 2013 to 2015. $\sigma_T$ is shown by grey lines.**

Figure 5.9 shows the temperature, salinity, and dissolved oxygen measured at the eastern Resolute Bay RBR loggers from August 2013 to August 2014 and August 2014 to August 2015. The annual variability for all three water properties at this location was very similar to the annual comparison made at the northern Resolute Bay RBR loggers (Figure 5.7). Both years showed similar trends, with the summer of 2015 having significantly higher temperatures and significantly lower salinities.

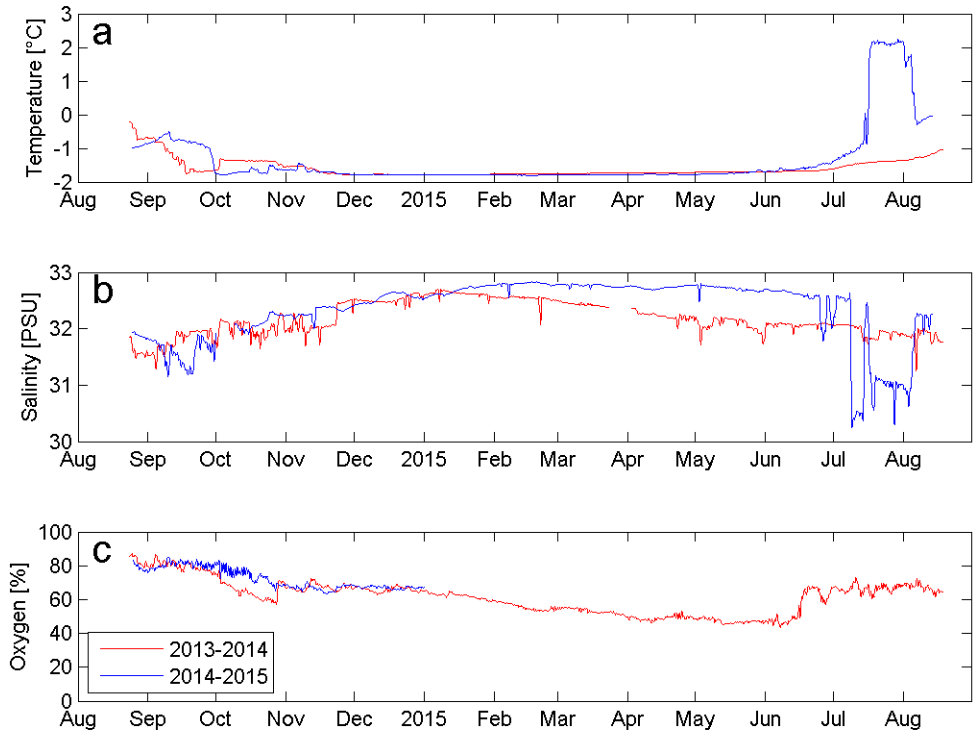


**Figure 5.9. (a) Temperature, (b) salinity, and (c) dissolved oxygen saturation measured at the eastern-bay RBR logger from 2013 to 2015.**

Figure 5.10 shows a temperature versus salinity plot of seasonal water measured at the eastern-bay RBR loggers from August 2013 to August 2015. This is similar to the temperature versus salinity plot at the eastern-bay RBR logger (Figure 5.8). Warmer temperatures and varying salinities were observed in the summer months (July through

September), likely due to the warm air temperatures and melting ice. In October through December, temperatures cooled and salinity increased with significantly less variability. The coldest, most consistent temperatures were measured between January and March; and in April through June, the water warmed a little and salinity decreased.

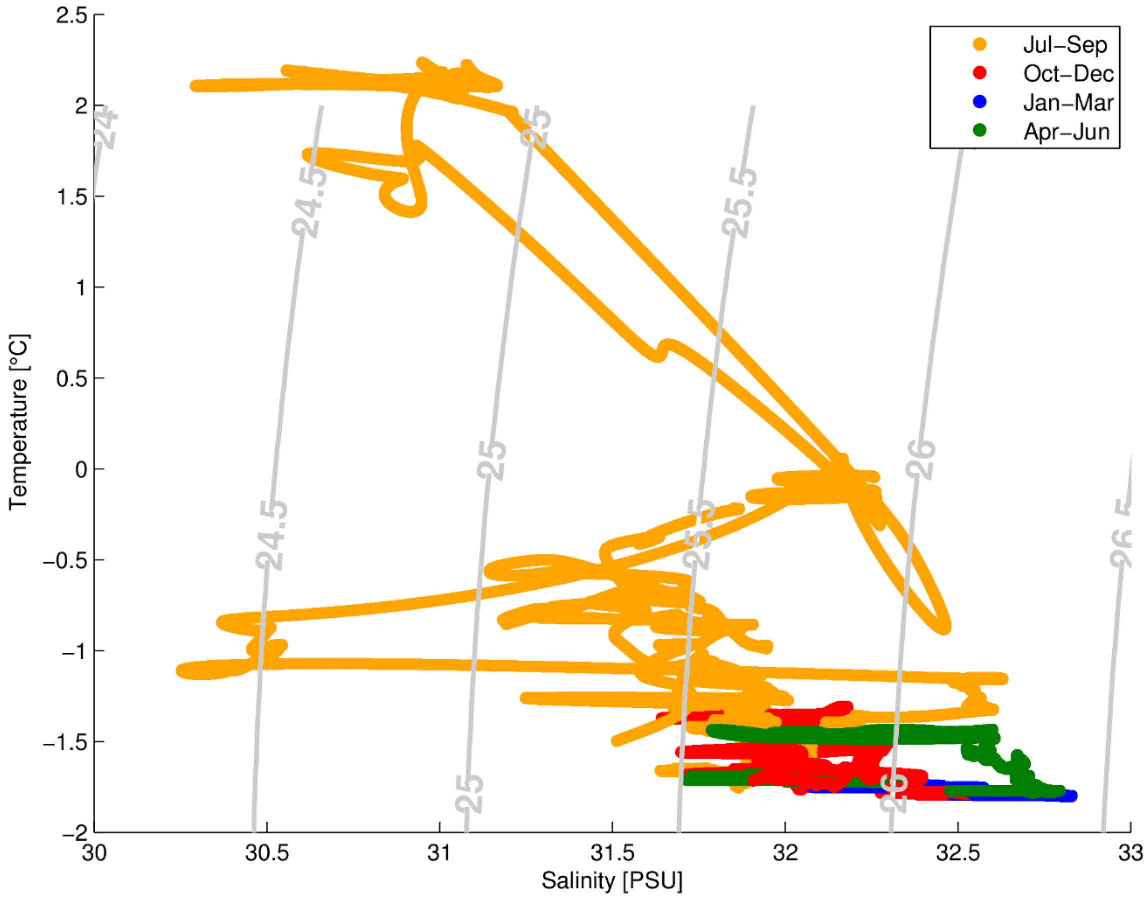


**Figure 5.10. Temperature versus salinity plot of seasonal water measured at the eastern-bay RBR logger from 2013 to 2015. $\sigma_T$ is shown by grey lines.**

## 5.2 Water Masses

The water in the Canadian Arctic Archipelago (CAA) is a mixture of Atlantic Water (AW) and Pacific Water (PW). AW comes up through Fram Strait and into the Canadian Basin, while PW travels up through the Bering Strait and into the Canadian Basin. The

Canadian Basin feeds these water masses into Parry Channel through McClure Strait on the west and Byam Martin Channel and Penny Strait to the north. During the eastward transit through Parry Channel, the PW and AW undergo mixing. The shallow sill (~125 m) at Barrow Strait restricts the flow eastward across Parry Chanel, constraining the deep layer of AW (Mclaughlin et al., 2004).

AW is defined to be any water with salinity greater than 35.0 PSU (Swift and Aagaard, 1981). This water was not observed in the Resolute Bay dataset presented here, as all of the measured waters had salinities below 33.5 PSU. AW is generally found in the Arctic between depths of 200 and 1600 m and in Parry Channel where water depths are greater than approximately 135 m (Mclaughlin et al., 2004). The deepest instrument used in this study was located at a depth of 120 m (channel benthic pod), which was likely not deep enough to observe AW.

Layered on top of the AW, there are three water mass components that make up the top 200 m of water, ordered from deepest to shallowest they are: Pacific-origin winter water, Pacific-origin summer water, and seasonal mixed water. In the summer, the seasonal mixed layer contains fresh water from river outflow and sea-ice melt, and is characterized by low salinities ($24<S<31$ PSU), warm temperatures, low nutrient concentrations, and high dissolved oxygen saturations. This water is the upper-most layer, and is approximately 30 m thick in Barrow Strait and 50 m thick in the Canadian Basin. Below this layer is the Pacific-origin summer water, found at depths of approximately 30 to 70 m. This water is characterized by relatively warm temperatures and higher salinities ($31<S<32$ PSU), with increasing nutrient and decreasing oxygen saturations. Winter waters, found approximately between 70 and 180 m, are identified by a temperature minimum near S=33.1 PSU and maximum nutrient concentrations (Mclaughlin et al., 2004).

The channel benthic pod, at 120 m, observed salinities between 32.0 and 33.2 PSU and temperatures between –0.9 and –1.8°C (Figure 5.1). The temperature minimum during each year occurred at approximately S=33.0, which corresponds to Pacific-origin winter water. In 2012-2013, salinities between 31.8 and 32.6 PSU were observed on the outside-bay benthic pod, located at 55 m (Figure 5.3). During this deployment period the water temperatures were warmer (up to 0.4°C), and the temperature minimum occurred at S=32.3 PSU, which corresponds to Pacific-origin summer water. In 2013-2014 and 2014-2015, outside-bay waters had salinities between 31.0 and 33.0 PSU, with temperature minimums at 32.6 and 33.0 PSU, respectively. This corresponds to Pacific-origin summer water in 2013-2014 and Pacific-origin winter water in 2014-2015.

In Resolute Bay, the inner-bay benthic pod at 33 m observed salinities between 31.4 and 32.9 PSU and temperatures between –1.8 and 0.6°C (Figure 5.5), representing Pacific-origin summer water. Near the bottom of the northern and eastern parts of Resolute bay, at depths of 18 and 21 m, respectively, the salinities were observed to vary between 31.0 and 32.7 PSU and temperatures between –1.8 and –0.1°C in 2013-2014 (Figure 5.7 and Figure 5.9), suggesting the presence of Pacific-origin summer water. These depths are shallower than the described 30 m upper boundary for Pacific-origin summer water, but since Resolute does not have much freshwater run-off compared to other parts of the CAA and Canadian Basin, perhaps there is a thinner layer of seasonal mixed water and a thicker layer of Pacific-origin summer water in the bay (Carmack et al., 2016). In 2014-2015, salinities were between 30.3 and 32.8 PSU and temperatures were between –1.8 and 2.9°C. The lower temperatures and higher salinities, corresponding to Pacific-origin summer water, were present until July 2015. At the beginning of July, the Pacific-origin summer water was replaced by a seasonal mixed layer comprised of lower salinities and higher temperatures.

There were three general water masses observed in and around Resolute Bay: channel water, outside-bay water, and inside-bay water. The water properties measured in Resolute Bay itself varied significantly throughout each year, while the channel water remained relatively constant. The outside-bay benthic pod showed a combination of the two, staying relatively constant for most of the year; however, the water properties were also influenced by changing weather and ice concentration in the summer, but not to the extent the inner-bay water properties were. The channel and outside-bay waters had fine-scale variation due to tidal activity, which was not observed inside Resolute Bay. This could have been the result of a bottom gradient or horizontal advection. The channel water was generally the warmest, followed by the outside-bay water, aside from in the summer when the water temperatures outside and in the bay increased. The channel water was also the saltiest, while the outside-bay water salinity levels were similar to those measured in Resolute Bay. Dissolved oxygen levels were the lowest and most varied in Resolute Bay, whereas dissolved oxygen saturation in the channel and outside-bay were fairly consistent each year, with tidal variability.

## 5.3 Water Movement

Water movement in Resolute Bay is influenced by many factors. A shallow, 10 m sill located at the mouth of the bay (Figure 2.1) restricts water movement in and out of the bay. Water in the bay is replenished throughout the year by tidal motion and general archipelago circulation at depths above the sill. This brings in nutrients, which, in combination with light, leads to ice algae growth in early spring and phytoplankton growth throughout the summer months, in the absence of ice.

Tidal height and temperature measured at a depth of 33 m at the inner-bay benthic pod in August to December, 2012 are shown in Figure 5.11. The larger spring tides caused more outer-bay water to flow over the sill into Resolute Bay. This effect can clearly be seen on August 20, September 1, and November 16, 2012.

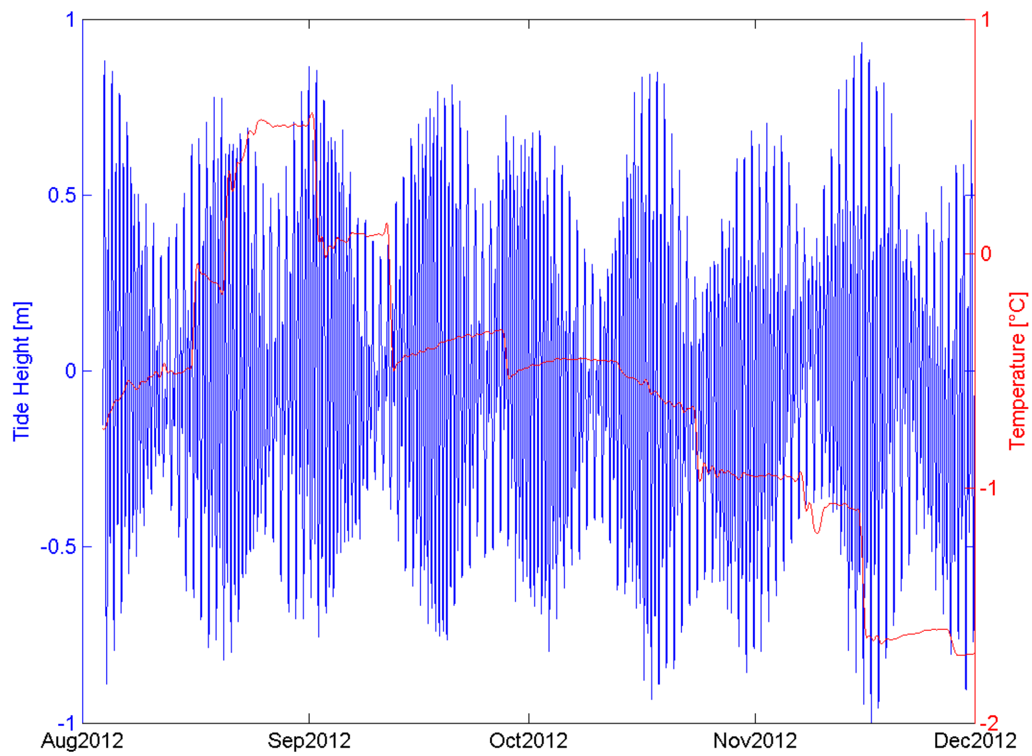


**Figure 5.11. Tide height and water temperature at inner-bay benthic pod from August to December 2012.**

Ice algae, which grow on the underside of sea ice, produce oxygen. When the ice melts, the algae are released into the water column, sink to the seafloor, and are consumed by zooplankton and bacteria, which also consume oxygen. This increase in oxygen consumption can lead to areas with low dissolved oxygen saturation levels (Renaud et al., 2007). This likely contributed to the gradual decrease of dissolved oxygen saturation levels observed in Resolute Bay in the spring. This decline was more severe in the deep waters (33 m) of Resolute Bay, but it was still apparent at the shallower depths (18 to 21 m) throughout the bay. This decline was not observed at the outside-bay or channel locations, where there was a more open environment for water transport and mixing.

The near-bottom dissolved oxygen saturation levels were replenished in Resolute Bay during the summer months, likely from the absence of ice allowing an increase of wind-driven mixing of both the inside-bay and outside-bay waters. The observed increase in oxygen saturation was also likely augmented by phytoplankton production.

Throughout the fall and winter months, when dissolved oxygen saturation levels were slowly decreasing, sudden abrupt increases in dissolved oxygen saturation levels were observed. Even though Resolute Bay had 100% ice concentration during this time, Resolute Passage likely had some open-ice sections. This may have allowed wind-driven mixing to occur, pushing the saltier, warmer, and oxygen-rich water from outside the bay (and from the channel) into Resolute Bay. This external water could then mix with the water in the bay, which caused the observed sudden changes in the water properties. These sudden changes were observed most frequently at the deeper water depths in Resolute Bay, but also at the other instruments in the bay. Mixing of water in Resolute Bay occurred in a clockwise motion, as observed in the 2014-2015 temperature data (see Figure 3.15).

## 5.4 Oceanography and Underwater Acoustics Relationship

Low levels of dissolved oxygen in Resolute Bay affect the temporal and spatial patterns of migrating Arctic cod (*Boreogadus saida*), which come into the bay during open water season and ice-covered periods (Welch et al., 1993; Kessel et al., 2015). Kessel et al. (2015) observed a significant positive relationship between Arctic cod presence/absence and dissolved oxygen in Resolute Bay. As a key species in the Arctic ecosystem, Arctic cod transfer up to 75% of all energy flow from lower to upper trophic levels through their biomass alone. Arctic cod represent the primary food source of most marine mammal predators in the high Arctic including beluga, narwhal and ringed seals, all of which are important species for subsistence and traditional food sources for the Inuit (Crawford and Jorgenson, 1996; Welch et al., 1993) (Welch, Bergmann et al. 1992, Crawford and Jorgenson 1996, Asselin, Barber et al. 2011). A lack of suitable Arctic cod habitat would therefore likely affect the temporal and spatial patterns of cod predators, which would also have a negative effect on the local hunters.

Figure 5.12 presents dissolved oxygen saturation levels and daily ringed seal call detections and beluga whistle detections between August 2014 and 2015. The AMAR will pick up marine mammals vocalizing inside and outside Resolute Bay, but the animals are likely to be near Resolute Bay when Arctic cod are present, as belugas use the shallow waters of the bay to corral Arctic cod for feeding. Belugas are present when there is less than 100% ice coverage, which is also when dissolved oxygen levels are high. The calls detected in June 2015 are likely from belugas transiting by Resolute Bay, as the bay was completed covered by ice then. Ringed seals vocalize the most when dissolved oxygen levels are highest in September through November. The number of daily ringed seal calls is slightly less in May and June, compared to the rest of the ice-covered months, which is when dissolved oxygen levels in the bay are lower than 75%. However, at the end of July, when dissolved oxygen levels in the bay become higher than 75%, there is not an increase of ringed seal daily call counts. Overall, the two years of data do not resolve any discernable relationship between marine mammal presence and dissolved oxygen levels. However, the resolution of this study is limited, and low oxygen levels at specific locations/times (e.g., eastern-bay in July) could correlate with a lower presence of marine mammals (due to an absence of Arctic cod), and go undetected.

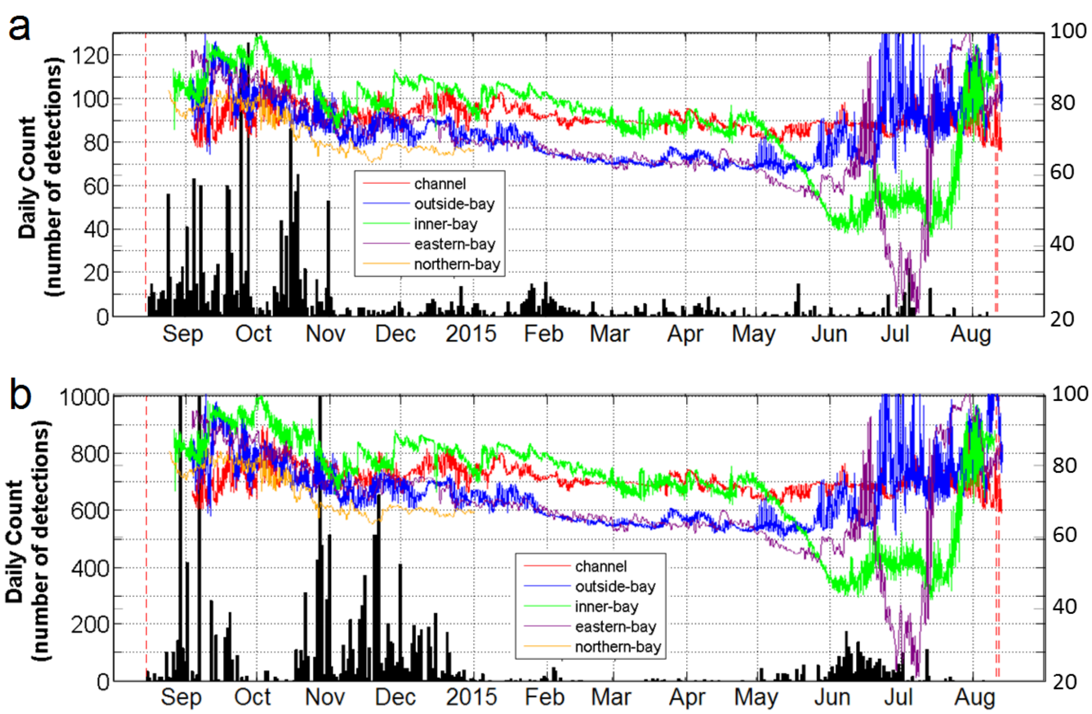


**Figure 5.12. (a) Daily ringed seal call detections and (b) daily beluga whistle detections with dissolved oxygen saturation at each oceanographic mooring deployed near and in Resolute Bay between August 2014 and 2015. The red dashed lines indicate the recording start and end dates. Beluga whistle detections at the beginning of November and throughout winter are likely false detections caused by ice noise. Results presented are primarily beluga calls, but may include narwhal calls.**

Decreased ice extent caused by climate change will facilitate wind-driven mixing in Resolute Bay. This will likely lead to shorter periods or elimination of low dissolved oxygen saturation, as this study found dissolved oxygen levels to decrease during 100% ice concentration and be replenished when the ice was not present. Between 1968 and 2008 annual sea ice cover has decreased by –3.7 ± 5.0% per decade in eastern Barrow Strait. (Tivy et al., 2011). Longer periods of high dissolved oxygen saturation levels may extend Arctic cod residency.

Finally, lower sea ice concentrations also might lead to decreases of ice algae biomass, causing a domino effect of less food for copepods and amphipods, less food for Arctic cod, and therefore less food for the upper-level Arctic marine predators such as seals and whales (Bradstreet and Cross, 1982). Reduced ice extent also expands the habitat of predominantly southern marine mammal species, such as killer whales, which increases predation risks for indigenous Arctic species, as well as increases risks of disease and parasite infections (Kovacs et al., 2010).

Marine mammals could also be negatively impacted by increased vessel traffic, another result of decreased sea ice concentrations. Vessel traffic causes increased sound levels, potentially disrupting marine mammal behaviour and communication, vessel-animal collisions, and potential risks from oil spills. Beluga reactions to vessels are varied, depending on a whale’s behaviour and experience, sound propagation conditions, boat sound characteristics, and boat behaviour (Richardson et al., 1995). In Lancaster Sound, during the spring, Cosens and Dueck (1993) observed belugas reacting strongly to noise from an icebreaker, swimming rapidly away when a ship approached within 25 to 30 km.

# 6 Conclusions

This thesis presents the results of a three-year (2012 to 2015) study of the physical oceanographic and underwater acoustic characteristics in and near Resolute Bay, Nunavut. These data were analyzed to study the temporal and spatial variability of water properties in the bay, to establish baseline ambient sound levels, and to determine the presence/absence of several marine mammal species and the possible relationships with environmental factors based on the temporal patterns of recorded vocalizations.

Strong inter-annual oceanographic variability was observed in and outside Resolute Bay, with the greatest variability occurring in the bay. Michel et al. (2006) also reported inter-annual variability in the water masses in Barrow Strait from 1983 to 2003. They observed significant changes after 2000, including saltier and colder surface waters, and decreased stratification in the upper water column. Temporal oceanographic variability was also observed on finer scales (approximately 12 hours), due to the influence of tide cycles.

All of the measurement locations in Resolute Bay observed sudden increases and decreases in temperature, salinity, and dissolved oxygen saturation. Therefore, it is important for future studies to employ long-term measurements (greater than six months) to develop an accurate picture of the changing water properties in Resolute Bay.

The water properties measured near the bottom just outside the bay and in Resolute Passage further out were warmer and saltier than at the in-bay measurement locations, suggesting that Resolute Bay does not have the same water circulation as Resolute Passage. Rather than consistent water properties, the in-bay locations showed sudden significant changes in temperature, salinity, and dissolved oxygen, likely from Resolute

Passage water intermittently coming over the sill at the mouth of the bay and mixing with the water in the bay. Despite the different water depths and locations of the measurements in Resolute Bay, all observed very similar water properties, indicating mixing within the bay itself, with and without ice.

The acoustic recordings indicated that both ringed and bearded seals were present year-round, while beluga whales were present only in the summer during ice-free months. Bearded seal call detections were elevated between May and July, which significantly contributed to the underwater soundscape during these months. Ambient sound conditions during ice-free times were characterized by sharp peaks from local vessel activity, increasing broadband sound pressure levels from 105 to 110 dB re 1 μPa up to 145.3 dB re 1 μPa. Broadband sound pressure levels during ice freeze-up were around 110 dB re 1 μPa, and dropped to 80 to 85 dB re 1 μPa at times with minimal ice noise.

Resolute Bay is a complex marine ecological environment and many factors influence its water movement and properties and the presence of marine mammals. Due to the large number of inter-related variables, it is difficult to determine how and by how much this marine habitat will be affected by climate change. The measurements collected and analyzed in this thesis will contribute to establishing baseline records in this region to be used to quantify climate change effects in the future.

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