MEASURING THE DISTRIBUTION OF NORTH ATLANTIC RIGHT WHALES (*EUBALAENA GLACIALIS*) ACROSS MULTIPLE SCALES FROM THEIR VOCALIZATIONS: APPLICATIONS FOR ECOLOGY AND MANAGEMENT

by

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"What are you going to do with the time you have here?"
-Danielle Moore, 2019

May this thesis be a reminder that you can surmount anything,
no matter how sour the lemons...

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ABSTRACT

The objective of this thesis was to assess the distribution of North Atlantic right whales, *Eubalaena glacialis* (NARW), in Canadian waters using passive acoustic monitoring (PAM) technology at daily to seasonal time-scales, and over sub-regional to continental-shelf spatial-scales, to help advance their conservation. Using a network of PAM platforms, I estimated the quasi-synoptic NARW distribution from the Bay of Fundy to the Labrador Sea, revealing that the current geographic distribution of the species may be constrained to temperate-subarctic latitudinal ranges. In a performance study, I identified the strengths and weaknesses of acoustic gliders equipped with a real-time PAM system as a tool to inform dynamic fishery management designed to minimize NARW entanglements in the Gulf of St Lawrence. Overall, my thesis provides critical information needed to implement PAM in decision-making to mitigate human caused risks to NARWs as well as improve Canada's ability to economically and sustainably monitor the species.

LIST OF ABBREVIATIONS USED

CEOTR	Coastal Environmental Observation Technology and Research
DFM	Dynamic fisheries management
DFO	Fisheries and Oceans Canada
DMON	Digital acoustic monitoring device
DOM	Dynamic ocean management
GPS	Global positioning system
GSL	Gulf of Saint Lawrence
LFDCS	Low-frequency detection and classification system
MEOPAR	Marine Environmental Observation, Prediction and Response network
NAFO	Northwest Atlantic Fisheries Organization
NARW	North Atlantic right whale
NEFSC	Northeast Fisheries Science Center
NOAA	National Oceanic and Atmospheric Administration
OTN	Ocean Tracking Network
PAM	Passive acoustic monitoring
TC	Transport Canada
WHOI	Woods Hole Oceanographic Institution

GLOSSARY

Note: The terms below are italicised throughout the text.

Acoustic glider: Slocum glider mounted with a hydrophone that continuously records underwater sounds along the tracklines of a designated survey plan. In this study, these recordings are analysed in near real-time for the presence of NARW upcalls.

***Buffer cell*s**: The DFO NARW dynamic management *grid cells* that are located adjacent to the *grid cells* through which the glider transits during a survey (Figure 3.1). Within a *survey unit*, there are 8 *grid cells* adjacent to each *surveyed cell* through which the glider transits. *Buffer cell*s are defined by DFO.

Conditional NARW encounter probability: This was calculated from the number of NARW detections from all *monitoring platform*s that occurred within a *grid cell* divided by the total NARW detections in the GSL. This is an estimate of the probability a NARW encounter will be within each *grid cell* in the GSL, given a NARW is present and encountered by a monitoring platform (*i.e.,* detected).

Deployment locations: Geographic location of recorders for each deployment analyzed in Chapter 2. There may be multiple recorders per deployment location. Analogous to a recording station.

Fishery-area: Designated area within which a commercial fishery is regulated by either NAFO or DFO.

Fishery-area closure: A *fishery-area* can be closed to fishing activities for a determined period of time. These regulations are set by the DFO. See *temporary closure* and *seasonal closure*.

Flight plan: A predetermined path along which the glider travels during its deployment. The path constitutes a set of waypoints along a survey track.

Glider flight plan: A pre-defined trackline through a set of contiguous *grid cells* along which a *monitoring platform* (*e.g.,* acoustic glider) transits during a survey.

Grid cells: Grid cells (10 minutes of latitude x 10 minutes of longitude in dimension) delineated by the NAFO and used to manage the snow crab fishery in the GSL (DFO, 2018). The grid cells provided the boundaries for the implementation of NARW dynamic fisheries management in the GSL. *Surveyed cell*s and *buffer cell*s are types of *grid cells* defined in this. If a right whale is detected within a *surveyed cell*, this cell along with the 8 adjacent *buffer cell*s will be closed to fishing for 15 days (Section 3.2.1). Each grid cell has a unique DFO identification code (*e.g.,* HA36).

Monitoring platform: An acoustic or visual platform, such as a glider, moored buoy, plane, or vessel that surveys the ocean for NARW.

NARW distribution climatology: The non-effort corrected NARW sightings and acoustic detections aggregated in each *grid cell* in the GSL during 2015 through 2019. This was used to estimate the conditional NARW encounter probability.

Recording days: The total number of active recorders on a given day (*e.g.,* if there were 3 active recorders on 01 January, 2016, there were 3 *recording days* on that day).

Recording regions: The 42 unique *deployment locations* were divided into eleven geographic *recording regions* of Atlantic Canadian waters based on areas important to NARWs, *e.g.,* potential feeding habitats, migratory corridors, or geographical context (the regions are defined in Figure 2.1).

Seasonal closure: If a NARW is detected within a given *grid cell*, or within a given adjacent grid cell, on two separate days within a 15-day period, by any *monitoring platform*, the given *grid cell* is put under a seasonal closure for the rest of the season until Nov 15, 2020 (Figure 3.1). This effectively closes all fixed-gear fishing in the given *grid cell* for the year.

***Shared buffer cell*s**: Overlapping grid cells among adjacent *survey unit*s. As the glider moves from one *survey unit* to the next there is an overlap among the *buffer cell*s of the two *survey unit*s (Figure 3.1). These shared cells are considered previously surveyed as the glider moves to the next grid cell in its survey.

***Snow crab fishery-areas**:* Areas in the GSL designated by DFO for regulatory purposes, and overlap the *grid cells* designated by NAFO. The southern GSL has four snow crab areas, 12, 12E, 12F and 19, each overlapping with multiple *grid cells*.

Spectrograms: Visual representation of a sound or signal in the time-frequency domain, showing three dimensions, time on the x-axis, frequency on the y-axis, and the amplitude of a frequency at a given time on a heat map or colour/brightness scale.

Survey effort: The amount of NARW monitoring effort by a *monitoring platform* per unit time (usually hours or days) or space (nautical miles).

Survey grid: The total number of *surveyed cell*s and *unique buffer cell*s distributed within the *flight plan*. For management purposes, the *survey grid* is also defined as all *grid cells* within which dynamic management protocols could be activated by a NARW detection.

Survey unit: A cluster of nine *grid cells* (with a total area of 30 minutes of longitude by 30 minutes of latitude) that are subject to fishery-area closure if a NARW is detected by a *monitoring platform*. The *survey unit* includes the 8 *buffer cell*s centered on 1 *surveyed cell* (Figure 3.1).

Surveyed cell: *Grid cells* through which a *monitoring platform* transits along its *flight plan*.

Temporary closure: If a NARW is detected within a *grid cell* by any *monitoring platform*, an area of 3x3 *grid cells,* centered on the *grid cell* with the NARW detection will be closed to fishing for 15 days, including the gear removal period (DFO, 2020a). Once the closure is issued by DFO, fishermen are given at least 72 hours to remove any deployed fishing gear from the closed area and may not place new gear within this area until the area is re-opened to fishing. The time given to remove gear varies depending on weather conditions, but can be upwards of 120 hours.

Unique buffer cells: Buffer cells that are considered surveyed by the glider only once for the whole survey grid (Figure 3.1).

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Chapter 1 GENERAL INTRODUCTION

1.1 Background

The relationship between large whales and coastal communities in Canada is delicate. While whales can provide an economic resource for communities hosting marine ecotourism, they also present a hazard to maritime commerce. Shipping and commercial fishing can be particularly harmful marine activities as whales continue to be injured and/or killed by vessel strikes and entanglements in commercial fishing gear. A species that is especially vulnerable to industrial marine activities is the North Atlantic right whale, *Eubalaena glacialis* (NARW). The close proximity of NARWs to coastal waters of eastern North America made this species a target for extensive exploitation by whalers from the 1500s to early 1900s, which depleted the population nearly to extinction (Schaeff and Kraus, 1993; Kenney *et al.*, 1995; Reeves, 2001). While the NARW population size has increased since the species gained protection from commercial whaling in 1935, the population has not recovered to pre-whaling numbers (Reeves, 2001). The population size reached a peak of 482 in 2010 and since has experienced a declining trend (Pace *et al.*, 2017). Pace *et al.* (2017) estimated the population to be ~458 individuals in 2015, which decreased to as low as ~356 at the end of 2019 (Pettis et al., 2021).

This species suffers from low reproductive rates, likely driven by a combination of low prey availability, stress from entanglements, and high anthropogenic mortality (Meyer-Gutbrod *et al.*, 2015; Hoop *et al.*, 2017; Meyer-Gutbrod and Greene, 2017). Vessel strikes and fishing-gear entanglements are the leading contemporary causes of known NARW mortalities (Knowlton and Kraus, 2001; Vanderlaan and Taggart, 2007; Conn and Silber, 2013; Van Der Hoop *et al.*, 2013; Daoust *et al.*, 2017). In July 2020, the International Union for the Conservation of Nature upgraded the NARW status to Critically Endangered due to the declining population trend and consistently high mortality rate from human activities (Cooke, 2020). If these high mortality and low reproductive rates continue, the rate of population decline of ~5.3% per year is not sustainable and the species could be functionally extinct within the next 30 years (*i.e.,* no more breeding females; Meyer-Gutbrod *et al.*, 2018).

There were an unprecedented 21 reported NARW mortalities in Canadian waters during 2017-2019. Canadian survey efforts and NARW management measures, until 2015 and 2017 respectively, have been concentrated in the Roseway Basin critical habitat, on the western Scotian Shelf, and the Grand Manan Basin critical habitat, in the outer Bay of Fundy (Figure 1.1). These are habitats where the whales are known to have aggregated during summer and fall to feed and socialize. In 2010, a shift in the whale distribution occurred across the Gulf of Maine and south eastern Canadian waters, consisting of a decrease in occurrence in the Grand Manan and Roseway Basins critical habitats and starting in 2015 an increase in occurrence was documented in the southern Gulf of Saint Lawrence (GSL; Khan *et al.*, 2014; Pettis and Hamilton, 2015, 2016; Davis *et al.*, 2017; Meyer-Gutbrod *et al.*, 2018; Davies *et al.*, 2019; Record *et al.*, 2019; Simard *et al.*, 2019) as well as in the northern GSL in 2016 (Daoust *et al.*, 2017). The increase in NARW presence and the lack of NARW protection measures in the GSL amplified the risk of entanglement and ship strike in this region and led to an unusually severe mortality event that began in 2017, when at least 12 individual whales died and five were entangled in fishing gear (Daoust *et al.*, 2017; Bourque *et al.*, 2020).

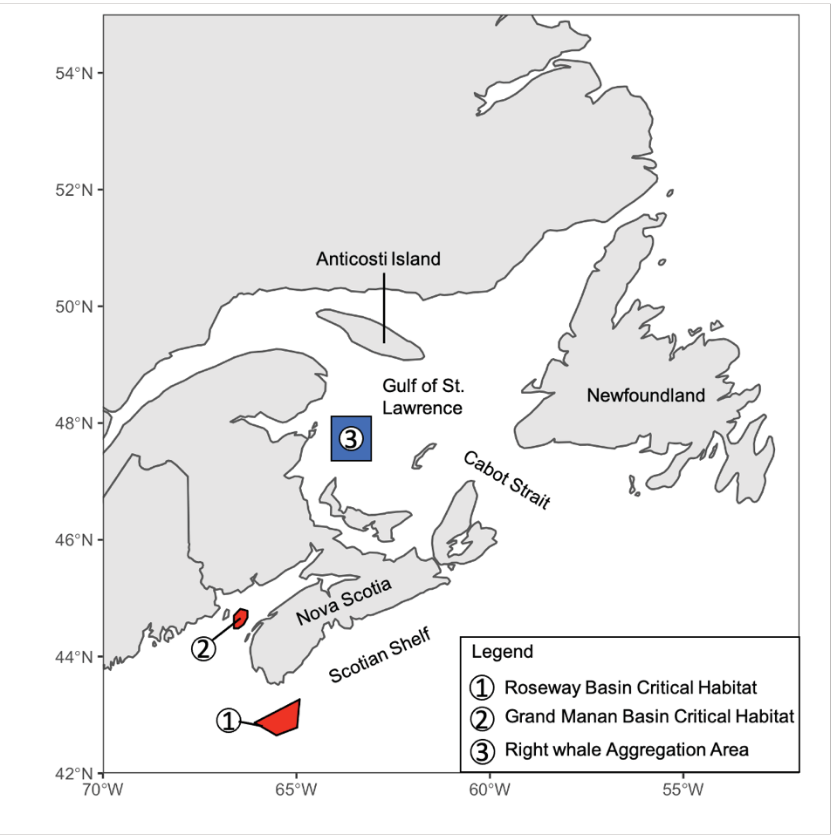


Figure 1.1 Canadian critical habitats designated for the North Atlantic right whale (DFO 2014) shown in red and the aggregation area in the southern Gulf of Saint Lawrence (GSL) in blue. NARWs have been observed throughout the southern GSL, north of Anticosti Island off Mingan, and in the Saint Lawrence Estuary as far west as Tadoussac, QC.

The Canadian government has the legislative responsibility under the Species at Risk Act (2003) to protect aquatic species including the NARW. In response to the 2017 mortality crisis attributed to vessel strikes and fishing gear entanglements, Fisheries and Oceans Canada (DFO) and Transport Canada each initiated new management measures to reduce the risk of entanglement and vessel strikes in Atlantic Canada, focusing on the GSL. These included mandatory static and dynamic vessel speed reduction zones and *fishery-area closures*, among other measures (summarized by Davies and Brillant, 2019). The implementation and annual review of the management measures are informed by an increase in visual and acoustic surveys to detect the presence of NARWs. However, these measures have been primarily informed by visual monitoring by trained marine mammal observers from aircraft. Both survey types include near real-time monitoring capabilities. Since 2017, the management measures have evolved as the government adapted to the new information on whale distribution. Although there were no observed mortalities in the GSL in 2018, nine were reported dead in 2019 (Bourque *et al.*, 2020; Pettis *et al.*, 2020). The impact of these mortalities on the population size cannot be overstated; this species will become functionally extinct with this level of mortality. The risks must be reduced. Risk reduction depends upon our ability to detect these rare, cryptic animals over a very large area of ocean and at a reasonable cost.

Given the variability in the NARW occurrence, effective mitigation measures are dependent on information about the spatial and temporal distribution of the species at multiple scales. Broad scale (*i.e.,* 1000-10000 km; the range of the species) analyses of movement patterns and distribution of the species in Atlantic Canada are critical to identifying the overlap between whale distribution and either fixed-gear fishing zones or high traffic shipping zones, and to provide knowledge to inform suitable habitat models. Such information includes movement patterns outside and among the known NARW habitats, migratory corridors in and out of the GSL, and the northern extent of their range in Canadian waters. Near real-time and subregional-scale (*i.e.,* in and around fishing zones, shipping zones and/or habitats) distributional information is needed to identify areas where there may be risks requiring dynamic management of fishing and shipping. Although the standard aerial visual surveys methods used to inform the current management measures in Canadian waters have the benefit of providing particular types of information (*e.g.,* photo-ID and health assessments), they remain expensive and weather-limited. Furthermore, aerial visual surveillance has the added benefit of being able to cover large areas, but the data collected are more limited than with vessel surveys and there is the inherent risk to pilots and observers flying over water. Passive acoustic monitoring (PAM) is a cost-effective monitoring tool that can be applied over the range of scales needed to provide a synoptic perspective on NARW movement patterns and the intensive monitoring at the sub-regional scales needed to support the implementation of dynamic fishery closures and vessel slow-down zones.

PAM can be used to complement visual surveys by providing data on NARW presence over large scales in time (days to years) and space (10s to 1000s km) using fixed (*e.g.,* bottom mounted) and/or mobile (*e.g.,* glider-mounted) hydrophone platforms. The method requires listening to underwater environments for diagnostic sounds produced by species' of interest. NARWs produce a range of sounds (calls) generally between 100-2500 Hz. One of these calls, the "upcall", is produced by both sexes and all age-classes across all known NARW habitats (Figure 1.2; Parks *et al.*, 2011) and it is the most distinctive call used to acoustically determine NARW presence. Various studies have demonstrated the applicability of this tool for NARW monitoring throughout the species range (*e.g.,* Davis *et al.*, 2017) and within regional habitats (*e.g.,* Mellinger *et al.*, 2007; Clark *et al.*, 2010; Durette-Morin *et al.*, 2019). PAM is a powerful monitoring tool, with strong potential to facilitate efficient monitoring and sustainable management of NARWs.

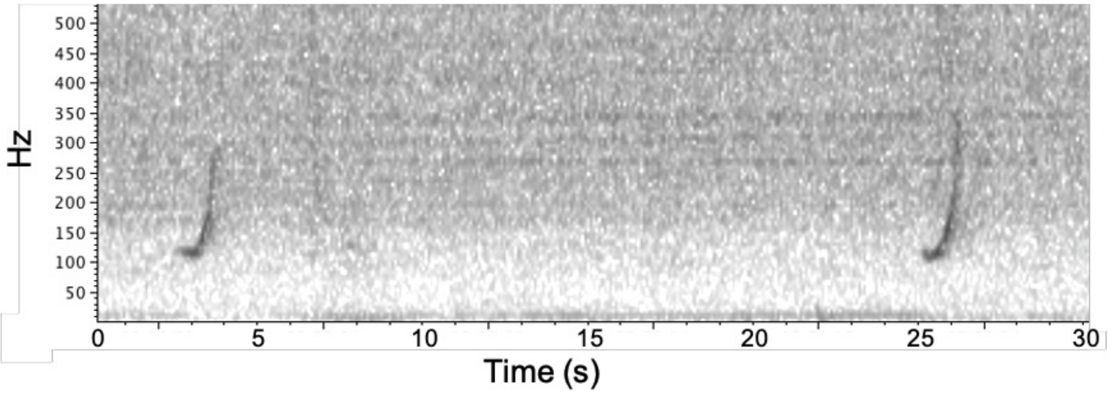


Figure 1.2 Spectrogram of a typical NARW upcall analysed with sampling rate of 48 kHz, FFT of 8192, an overlap of 50%, and Hann Window.

1.2 Objectives and thesis structure

The objective of this thesis is to measure the distribution of NARWs in Canadian waters using PAM technology in real-time and at seasonal time scales, and over subregional to broad spatial scales, to help advance the conservation of NARWs. The objectives of Chapter 2 are to define the contemporary northern extent of the species distribution in Canadian waters, identify the primary NARW migratory corridor into the GSL, and explore potential previously unidentified high use habitats within Atlantic Canadian waters. I estimate the quasi-synoptic NARW distribution across the Atlantic Canadian shelf waters from the Bay of Fundy to the Labrador Sea using a network of fixed (bottom mounted) and mobile (glider-mounted) PAM hydrophone platforms. The objective of Chapter 3 is to model survey flight plans for an *acoustic glider* platform equipped with a near real-time

PAM system. I present a performance study wherein PAM flight plans were modeled using various parameters and compared to optimize whale detection probability in areas associated with the 2020 dynamic fishing management plan implemented by DFO in the GSL. I tested the highest scoring model during a pilot field study in the GSL where the NARW detections were used to trigger *fishery-area closures*. Overall, my thesis research was designed to research the potential for implementing PAM in the decision-making process for the mitigation of human caused risks to NARWs as well as improve Canada's ability to economically and sustainably monitor the species.

This thesis is divided into 4 chapters, including this introductory chapter (Chapter 1), two data chapters (Chapters 2 and 3), and a concluding chapter (Chapter 4) summarizing the main results and advancements made through this thesis work. A subset of the data included in Chapter 2 is found in a DFO Research Document provided for the Canadian Science Advisory Secretariat (Durette-Morin *et al.*, in review) and the primary results were included in a Science Advisory report (DFO, 2019a). I intend to publish the contents of the Chapters 2 and 3 in the primary literature; therefore, each chapter is presented as a distinct publishable unit.

Chapter 2 CONTEMPORARY DISTRIBUTION OF NORTH ATLANTIC RIGHT WHALES ON THE EASTERN CANADIAN CONTINENTAL SHELF MEASURED USING PASSIVE ACOUSTIC MONITORING

2.1 Introduction

Quantifying variation in marine mammal distribution is crucial for the implementation of effective conservation strategies, the challenge is that many species are cryptic, evasive, and migratory. Passive acoustic monitoring (PAM) is commonly used to study the distribution of whale species over various time (hours to years) and spatial scales (10 to 10,000 km). PAM can provide information on whale acoustic presence in remote locations, during periods of days and seasons, or during weather conditions that are not possible using visual monitoring methods (*e.g.,* Stafford *et al.*, 1999; Nieukirk *et al.*, 2004; Širović *et al.*, 2004; Munger *et al.*, 2005; Moore *et al.*, 2006; Širović *et al.*, 2007; Stafford *et al.*, 2007). PAM has provided valuable insights into the distribution of whales, for example, by identifying migratory routes (*e.g.,* humpbacks, Stevick *et al.*, 2011), characterizing the distribution of cryptic species (Klinck *et al.*, 2012; Stanistreet *et al.*, 2017; Hildebrand *et al.*, 2019) and explaining variability in habitat use (Wiggins, 2003; Moore *et al.*, 2006; Baumgartner and Fratantoni, 2008; Bittencourt *et al.*, 2016; Davis *et al.*, 2017).

The known range of the North Atlantic right whale (NARW), *Eubalaena glacialis*, spans the eastern Continental Shelf of North America from the winter calving grounds off Florida and Georgia to feeding grounds off New England and Atlantic Canada. The known feeding grounds are occupied at different periods throughout the year (*e.g.,* Cape Cod Bay in the winter and spring, Gulf of Maine in the spring and summer, Gulf of Saint Lawrence (GSL) in the spring, summer, and fall, and the Bay of Fundy/Western Scotian Shelf region in the summer and fall). The whales have been occasionally observed further north off Newfoundland, Greenland, Iceland (Sigurjónsson *et al.*, 1989, 1991; Knowlton *et al.*, 1992) and Norway (Jacobsen *et al.*, 2004). Some of the population seasonally migrates between calving and feeding grounds, especially pregnant females (CETAP, 1982; Winn *et al.*, 1986; Cole *et al.*, 2013). However, some individuals are present in the known feeding grounds year-round (Morano *et al.*, 2012; Cole *et al.*, 2013; Bort *et al.*, 2015; Davis *et al.*, 2017). Information about variation in the distribution of the NARW throughout its range is critical for the mitigation of anthropogenic threats that are having significant impacts on the recovery of the species (Pace *et al.*, 2017; see Chapter 1).

NARW occurrence and movement from the Gulf of Maine northward is strongly influenced by the abundance and distribution of their preferred prey (Pendleton *et al.*, 2009; Pershing *et al.*, 2009; Record *et al.*, 2019). The whales preferentially consume lipid-rich copepods of the genus *Calanus* (Kann and Wishner, 1995; Baumgartner *et al.*, 2003). NARW habitat abandonment events, such as that observed in Great South Channel in the 1990s and in the Gulf of Maine and Roseway Basin since 2010, have been linked to decadal-scale local reductions in the abundance of their primary prey, the copepod *Calanus finmarchicus,* in and around these habitats (Kenney, 2001; Patrician and Kenney, 2010; Davies *et al.*, 2015; Grieve *et al.*, 2017; Meyer-Gutbrod and Greene, 2017; Hayes *et al.*, 2018). Since 2010, NARW occurrence decreased precipitously in their critical habitats in the Gulf of Maine and on the Scotian Shelf and increased in the southern GSL (Khan *et al.*, 2014; Pettis and Hamilton, 2015, 2016; Meyer-Gutbrod *et al.*, 2018; Davies *et al.*, 2019; Record *et al.*, 2019; Simard *et al.*, 2019). *C. finmarchicus* is sensitive to advective transport in ocean currents and climate change, meaning it is possible that the NARW distribution shift may continue to progress northward and more persistently into Atlantic Canadian waters as their food source and supply mechanisms continue to change (Meyer-Gutbrod & Greene, 2017).

Dedicated NARW visual surveys have been conducted among the Canadian critical habitats in Roseway Basin and Grand Manan Basin (Figure 1.1) since 1978 (CETAP, 1982), and a few PAM studies took place intermittently starting around 1999 (*e.g.,* Laurinolli *et al.*, 2003; Vanderlaan *et al.*, 2003; Mellinger *et al.*, 2007; Parks *et al.*, 2007, 2009; Durette-Morin *et al.*, 2019). The critical habitats were identified as having conditions that facilitated foraging success because oceanographic processes aggregate NARW food resources (Baumgartner *et al.*, 2003; Michaud and Taggart, 2011; Davies *et al.*, 2014; DFO, 2014; Davies *et al.*, 2015). During 2010 through 2014, NARWs were observed in fewer numbers with shorter residency compared to previous years in these areas, and there was virtually no knowledge and no survey effort to find them outside of these areas for five years (Davies and Brillant 2019). The distribution of NARWs in Canadian waters during this period will likely never be known to any great extent.

NARW visual and acoustic surveys, directed by the knowledge of prey aggregating factors, led to the 2015 discovery of a relatively unknown NARW habitat in the southern GSL (Cole *et al.*, 2015; Pettis and Hamilton, 2017; Meyer-Gutbrod *et al.*, 2018). In 2015, three NARWs were found dead in the GSL. This now high-use area has since been monitored consistently with visual aerial and/or vessel-based survey efforts during the spring, summer and fall months beginning in 2015 and by acoustic monitoring that has been conducted from 2011 through 2020 (DFO, 2019a; Simard *et al.*, 2019). Through these monitoring efforts, the distribution and seasonal presence of NARWs in the GSL is being thoroughly characterized and used to inform conservation management plans that are now (2020) in place in the GSL. Nevertheless, NARWs continued to die in unprecedented numbers and the lack of protection measures within Canadian waters between 2010 and 2017 was devastating to the population (see Chapter 1).

A description of the contemporary NARW occurrence in Canadian waters is needed to improve the ability to successfully mitigate anthropogenic threats to the species and respond rapidly to distributional changes, such as known habitat abandonment and new habitat occupancy that have been documented since 2010. Despite the increase in survey effort in the GSL, and to a lesser extent in the waters of Atlantic Canada (Lawson and Gosselin, 2009; DFO, 2019a), NARW distribution outside the critical habitats and southern GSL remains poorly described. The large gaps in survey effort highlighted the need for a synoptic analysis of the movements of NARWs in locations where sightings and acoustic detections have been largely opportunistic (*e.g.,* Davis *et al.*, 2017). Fisheries and ship traffic activity in many areas off eastern Canada are potential threats to NARWs, emphasizing the need to identify where these threats might overlap with the occurrence of the species. Areas such as the Cabot Strait and the Strait of Belle Isle have been identified as potential migratory corridors (DFO, 2019a; Simard *et al.*, 2019) and are near areas modeled as suitable habitats based on prey availability (Plourde *et al.*, 2019). Since these

Straits are the only two entry points to the GSL for vessels and whales, the risk is assumed to be high. However, the paucity of NARW detections in these areas is undoubtedly a function of low monitoring effort (Simard *et al.*, 2019) and the difficultly of detecting migrating whales outside of their aggregation areas.

Furthermore, the extent of the historical and current northern range of the NARW distribution remains ambiguous. Prior to the 1900s, NARWs seemed to have contributed to only a small portion of landings in important Basque whaling areas in Red Bay and the Strait of Belle Isle (Gaskin, 1991; Rastogi *et al.*, 2004; McLeod *et al.*, 2009) and since then very few were reported captured prior to their protection from commercial whaling in 1935 (Mead, 1986). In the last 50 years, limited survey efforts have sighted few NARWs east of Newfoundland (Hay, 1982; Lien *et al.*, 1989). In the event that the distribution of NARW occurrence continues to shift north, as climate change continues to alter coastal ecosystems, monitoring of NARW occurrence across Atlantic Canadian waters will be needed, at the least, as a base line to identify if further changes are occurring.

The objective of this Chapter is to characterize the contemporary (2015-2017) large scale spatial and temporal variation in NARW occurrence in Atlantic Canadian waters using a comprehensive PAM network with coverage spanning multiple ecosystems, from the north-temperate Scotian Shelf to the subarctic Labrador Sea. In addition to providing new information on their range, I aim to identify NARW migratory corridors and explore potential previously unidentified high-use habitats.

2.2 Methods

2.2.1 Data collection

Acoustic data were collected using various acoustic recording devices deployed in Atlantic Canadian waters during the period of 2015 through 2017 by four different agencies: Autonomous Multichannel Acoustic Recorders (AMARs) deployed by Fisheries and Oceans Canada (DFO) Maritimes Region and JASCO Applied Sciences, Multi-Electronic Autonomous Underwater Recorders for Acoustic Listening (AURALs) deployed by DFO Newfoundland and Labrador Region, and AMARs and Teledyne-Webb

Research Slocum gliders equipped with the digital acoustic monitoring (DMON; Johnson and Hurst, 2007) hydrophone deployed by Dalhousie University. Recorders collected data continuously or were duty cycled using various sampling rates and recording schedules (Appendix A.1, Table A.1.1). Mooring locations were determined to address different objectives. PAM moorings were placed in NARW habitats to investigate NARW occurrence in selected regions (*e.g.,* Roseway Basin and Emerald Basin), while other locations were chosen to monitor all cetacean species at risk (*e.g.,* Moors-Murphy *et al.*, 2018), monitor multispecies in Marine Protected Areas, and assessing broad-scale ambient and anthropogenic noise throughout eastern Canada (Delarue *et al.*, 2018).

In this chapter, data from a total of 82 deployments were analysed, including 13 acoustic glider deployments and 69 moored hydrophone deployments. These deployments spanned 42 unique PAM *deployment locations* (Figure 2.1, 2.2). These locations were divided into eleven geographic *recording regions* of Atlantic Canadian waters based on areas important to NARWs as potential feeding habitats and/or migratory corridors, as well as geographical context (Figure 2.1). The regions are presented orthogonally west to east and south to north relative to the coastline as follows: Bay of Fundy (BOF), Western Scotian Shelf (WSS), Eastern Scotian Shelf (ESS), Grand Bank (GB), Southern Newfoundland (SNL), Cabot Strait (CSt), Southern GSL (sGSL), Western Newfoundland (WNL), Strait of Belle Isle (StBI), Eastern Newfoundland (ENL), and Labrador Coast (Lab).

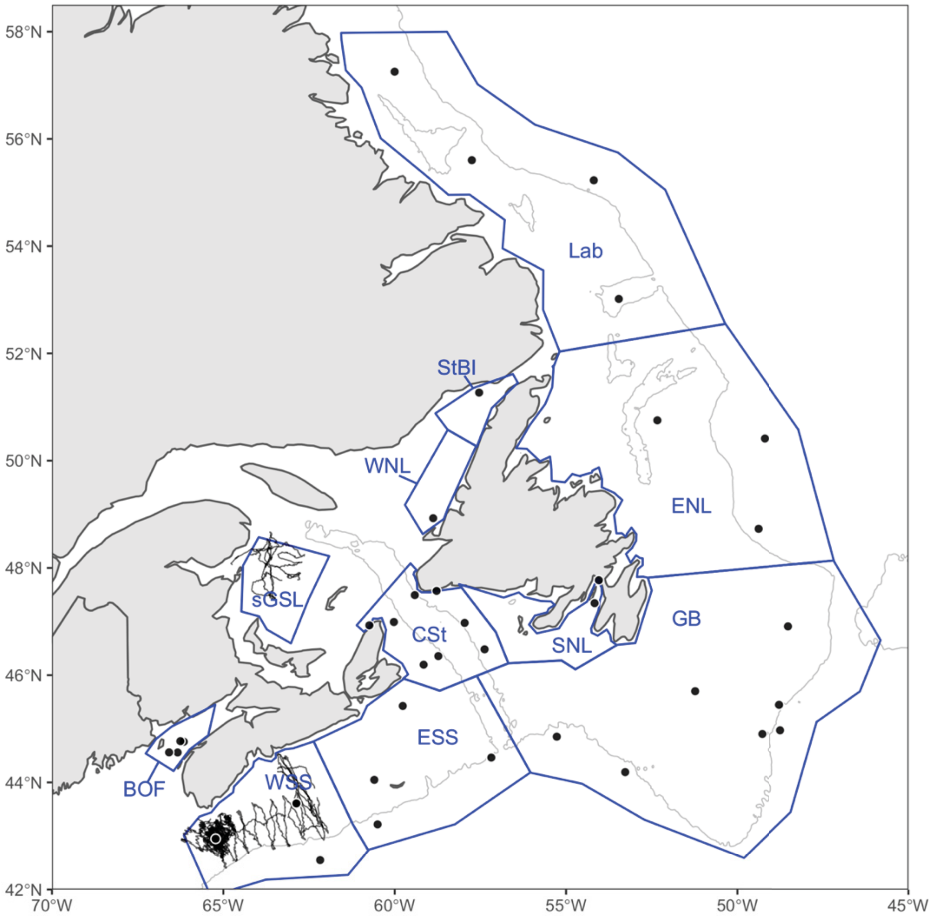


Figure 2.1 Deployments locations of the 2015-2017 PAM recording system analysed in this study. Black line-tracks are shown for the PAM Slocum gliders and closed circles for the PAM moorings. The recording regions are outlined by blue polygons and labeled from North to South as follows; Lab - Labrador Coast, ENL - Eastern Newfoundland, StBI - Strait of Belle Isle, WNL - Western Newfoundland, sGSL - Southern Gulf of Saint Lawrence, CSt - Cabot Strait, SNL - Southern Newfoundland, GB - Grand Bank, ESS - Eastern Scotian Shelf, WSS - Western Scotian Shelf, and BOF – Bay of Fundy. The 400 m isobath is shown in light grey. Deployment location-specific data within each region is shown in Appendix A.1.

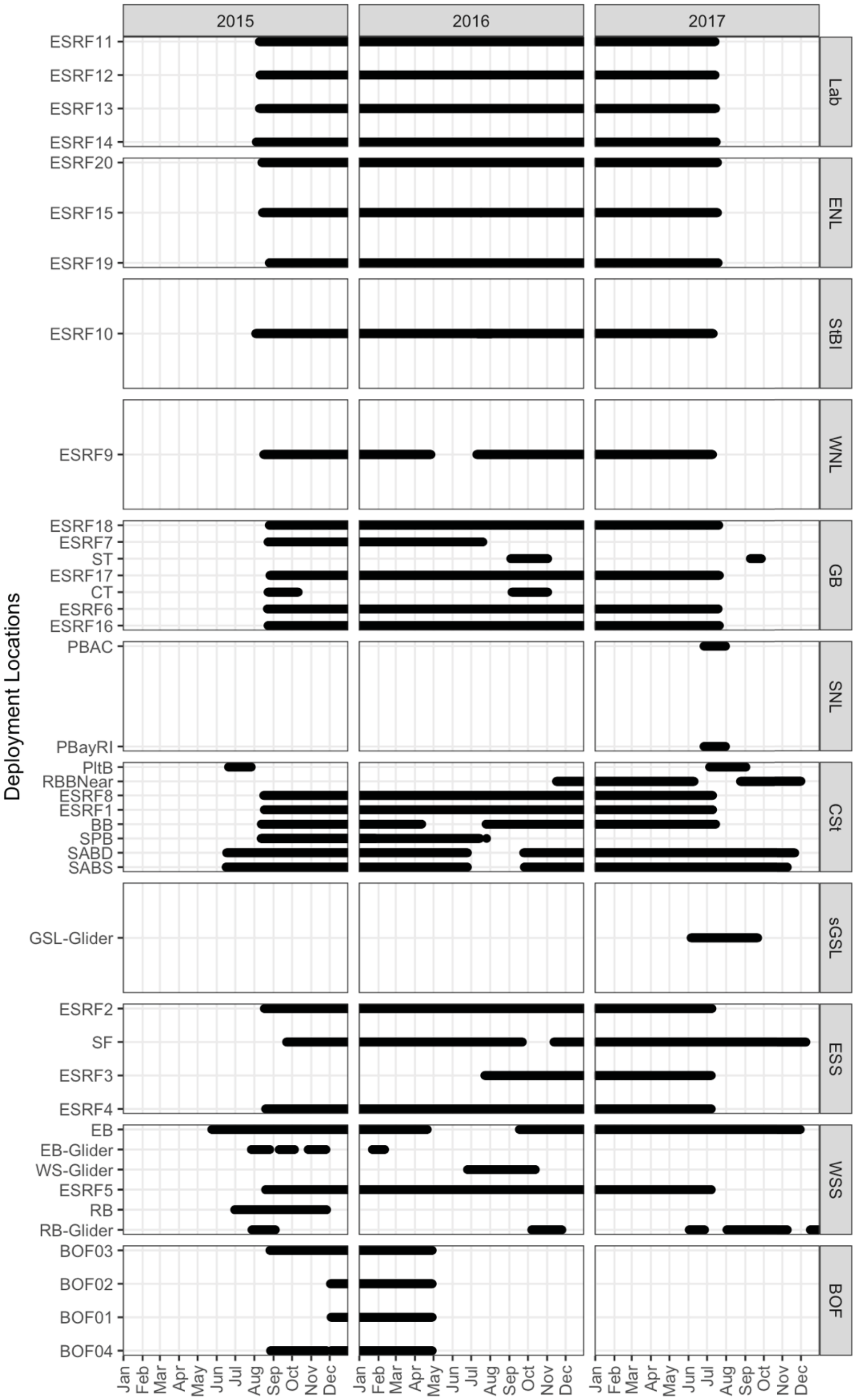


Figure 2.2 Recording effort of 2015-2017 PAM platform deployments analysed in this study. The regions displayed in Figure 2.1 are labeled from North to South as follows; Lab - Labrador Coast, ENL - Eastern Newfoundland, StBI - Strait of Belle Isle, WNL - Western Newfoundland, sGSL - Southern Gulf of Saint Lawrence, CSt - Cabot Strait, SNL - Southern Newfoundland, GB - Grand Bank, ESS - Eastern Scotian Shelf, WSS - Western Scotian Shelf, and BOF – Bay of Fundy. Associated deployment locations within each region are indicated on the y-axis. Deployment location-specific data within each region is shown in Appendix A.1.

2.2.2 Data processing and analysis

Data processing protocols followed the methods of a study by Davis *et al.* (2017). All recordings were processed using IDL-based software called the low-frequency detection and classification system (LFDCS; Baumgartner and Mussoline, 2011), designed to automate the detection and classification of NARW upcalls (so-called 'auto-detections') from the raw acoustic data. All auto-detections classified as NARW upcalls were validated by a trained analyst through aural and visual inspection of *spectrograms*. Only the auto-detections confirmed by the analyst (Clair Evers, DFO, or the author) to be true NARW upcalls were used in the subsequent analysis; false detections were discarded. Davis *et al.* (2017) investigated detector performance and determined that the LFDCS has a daily missed NARW detection rate of ~25%. This means that NARW upcalls will sometimes be present on the acoustic record and audible to an analyst, but the auto-detector algorithm is not sensitive enough to detect them. Missed detections are likely not an important issue for this broad-scale analysis because NARW presence is quantified at weekly, monthly, and seasonal time scales. The true missed detection rate will likely differ within and among the recording systems and deployment locations analyzed in this study. For example, auto-detector sensitivity depends on the amplitude and character of ambient noise. Furthermore, no assumptions were made regarding animal behaviours or calling rates and thus no interpretation can be made regarding animal abundance (but see Durette-Morin *et al.*, 2019). NARW calling rate may vary by season and behavioral state (*e.g.,* traveling vs. socializing vs. feeding), however it is not possible to control for these factors in this study. The results presented can therefore be considered the minimum estimate of presence.

Daily presence of NARW upcalls, defined as any day with at least one validated NARW upcall, was used as the unit of measurement for NARW presence in this study. Statistics on NARW presence were derived over three spatial scales and two temporal scales. The daily presence data were aggregated spatially either by *deployment location*, by *region* (defined in Figure 2.2), or by the entirety of Atlantic Canada. The daily presence data were aggregated temporally at either weekly or monthly scales, depending on the analysis being conducted. Aggregating the daily presence time series over these periods is equivalent to smoothing the data through time. Temporal variation in presence was then characterized as the proportion of survey days within each week or month when NARWs were present.

These data were used to identify several patterns. First, the annual calendar dates and duration of the NARW occupancy period were defined using the number of consecutive months with presence at each spatial scale. Second, spatial variability in the period of NARW presence was compared among regions to identify migratory patterns along a latitudinal gradient between 42° and 57° N. Third, variability in presence was compared among deployment locations within each region. Fourth, seasonal presence was categorised as either sporadic or persistent; periods with consecutive weeks with daily presence were considered as periods of persistent presence. Fifth, the quarterly effort-corrected median of monthly presence was calculated for each of the 11 regions and among three broad-scale shelf domains: the 'core' NARW domain, the 'transition' domain where NARW presence is sporadic, and the 'northern' domain where NARW are rarely present. Only regions with presence were included in a domain. The core domain included three regions: ESS, WSS, and BOF. These southern regions have been extensively surveyed and NARWs occur there regularly. The transition domain included one region; the CSt migratory corridor. The northern domain included three regions: StBI, WNL, and GB. The sGSL was omitted from this analysis due to limited recording effort in the region included this study. However, Simard *et al.* (2019) have already defined the occupancy period in this region. To conduct the analysis in the present study, daily presence was aggregated by *region* or domain and month. The monthly data were then effort corrected by dividing the number of days with acoustic presence in a month by number of days with at least one recorder in that *region* or domain, and month. The resulting metric can be interpreted as the effort corrected proportion of months with NARW acoustic presence. For each quarter of the calendar year, beginning in January, the median of monthly presence per unit effort was calculated for each month with recording effort over all three years included in this study. In the results, I refer to this measure as the probability of detecting a NARW.

2.3 Results

A total of 19,684 *recording days* were reviewed, and of these, NARWs were present on 615 (3%) of all *recording days*. NARW upcalls were present on 45 of the 82 recording deployments analysed (55%), and 28 of the 42 unique PAM *deployment locations* (67%). NARW upcalls were detected among 9 of the 11 Atlantic Canadian *regions*. NARWs were detected in Atlantic Canadian waters during all months of the year (Figure 2.3a). However, the increased acoustic presence in the later half of the calendar year suggests NARW presence varies with season; the majority of upcalls were detected from June through December (7 consecutive months with >50% daily presence; Figure 2.3a). This seasonal pattern was not an artefact of effort bias. If bias were the cause, a similar pattern in the total number of *recording days* (*i.e.,* recording effort) would be expected. However, the observed minimum in the effort time series occurred during the period of maximum whale presence (Figure 2.3b). Furthermore, a test with multiple random permutations of the daily presence data showed that the seasonal signal was not sensitive to the effort variation across all *regions*, but was sensitive to the limited recording effort in the sGSL region (Appendix A.2, Figure 2.4). The seasonal signal observed in Figure 2.3a remains even when the sGSL data were omitted (Figure A.2.2).

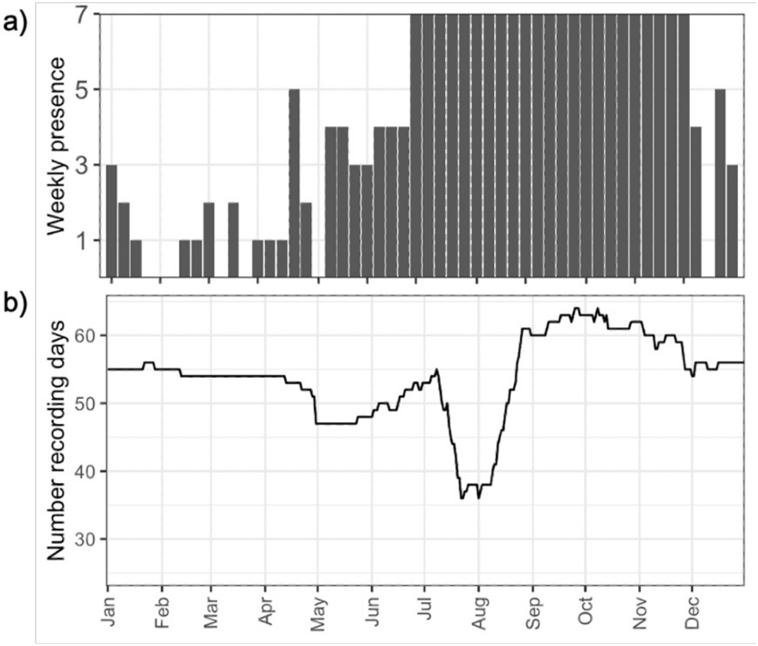


Figure 2.3 a) The number of days per week with at least one NARW upcall detection per day across all recorders analysed for this study in Atlantic Canadian waters aggregated over all years analysed, b) Number of recording days each day across all recorders analysed for this study in Atlantic Canadian waters aggregated over all years analysed. Recording days are defined as the total number of active recorders on a given day.

Within a calendar year, the earliest NARW detections occurred among the most southern regions, on the western and eastern Scotian Shelf (ESS, WSS) and in the Bay of Fundy (BOF, Figure 2.4, 2.5). In the BOF, 487 *recording days* were analyzed over 4 deployments between 26 Aug 2015 and 28 Apr 2016, and NARWs occurred from the start of the deployments through 21 Jan 2016 (6% of *recording days* with presence). NARWs were only detected at *deployment location* BOF03, with the exception of one day with an acoustic presence at the BOF04 *deployment location* on 21 Jan 2016 (Figure A.3.1). NARWs were present in every month on the Scotian Shelf, with the exception of Mar on the WSS and Apr on the ESS. Daily presence was sporadic during the first five months of the calendar year, becoming more persistent from Jun through Dec on the WSS (Figure 2.4). Detections were concentrated in Roseway Basin (RB), which included both glider and AMAR platforms (Figure 2.2). Presence in RB was higher in each of 2015 and 2016 compared to 2017 (70, 75 and 13% of *recording days*, respectively). NARWs were present less often in Emerald Basin (EB) in both 2015 and 2016 (17% of *recording days* with NARW). Glider and AMAR data showed similar patterns in both RB and EB. The only exception is that the first EB-glider deployment in 2015 detected higher acoustic occurrence compared to the EB-AMAR deployment during the same period. The only glider deployment on the WSS that did not detect NARWs was the 2016 EB-glider deployment.

Daily presence was lower and less persistent in the ESS region compared to the WSS region. All deployment platforms in this region were AMARs. NARW occurrence was concentrated at the ESRF3 and ESRF2 deployment locations. NARWs occurred more often at deployment location ESRF2 than ESRF3; NARWs were present at ESRF2 during eight unique periods, each lasting at least two consecutive weeks. ESRF3 had only a single instance when NARWs were present for two consecutive weeks. The two recorders on the continental break, ESRF5 and ESRF4, each recorded few or no acoustic detections with the exception of one and six days respectively in Jun 2017. Both recorders were at depths between 1777 – 1831 m. Furthermore, within both Scotian Shelf regions, presence was lower in 2017 relative to 2015 and 2016 during Aug through Dec in all three years.

Following their arrival on the Scotian Shelf, NARWs then began occupying the CSt in early May where they remained sporadically present for eight months, until mid-Dec. Though a higher number of recorders were deployed in this region (4546 *recording days*) relative to other regions, the NARW presence was sporadic throughout the entire period. NARWs were present on 1% of *recording days* in the CSt. In 2017, NARWs were present on only 3 days in this region.

NARWs occupied all regions within the GSL, these regions included the southern GSL (sGSL), western Newfoundland (WNL), and the Strait of Belle Isle (StBI). The only archival data available for this study in the sGSL region was one 109 day-long glider deployment in 2017. Similar to the glider deployments on the WSS, acoustic occurrence in the sGSL region was persistent from Jun through Sep (Figure 2.4). NARW calls were detected on 74% of *recording days*. At the entrance of the GSL in the CSt region, the Pleasant Bay deployment location (PltB) had very little recording effort, with two short deployments in 2015 and 2017 with a total of 152 *recording days* (Figure 2.2, Figure A.3.1). However, NARWs were detected in Jun and Jul on 3% of *recording days*. Along the outer edge of the GSL, in the WNL region, NARWs were present on one day on 27 Oct 2016, despite near continuous recording effort over 622 *recording days* (Figure 2.4). Lastly, at the northern entrance to the GSL, NARW presence in the StBI region occurred as early as mid-Aug and as late as mid-Oct, when the spatial distribution of the whales was most consistent in other regions in Atlantic Canada (Figure 2.5). Despite the continuous recording effort in the StBI region, NARWs were detected on 2% of 733 *recording days* and were not detected in 2015 or in 2017.

Recordings in and around the Newfoundland and Labrador regions, the probable northern extent of the population distribution, consisted of southern Newfoundland (SNL), the Grand Bank (GB), eastern Newfoundland (ENL), and the Labrador (Lab) regions. NARWs were detected on one day on 14 Jul 2017 on both month-long recordings in the SNL region (Figure 2.4). Acoustic presence was detected on 10 days on the GB (0.3% of *recording days* at this region) between Aug and early Dec. Acoustic presence was detected at 3 of the 10 deployment locations in this region, ESRF6, ESRF7, and Stn4-ST (Figure A.3.1). The ESRF6 recorder was one of three in this region at a depth >300 m but the only one with NARW presence. The two most northerly regions in this analysis, the ENL and Lab regions on the Labrador Shelf, contained no NARW acoustic occurrence (Figure 2.4). Of the seven recorders in these regions, four were at a depth >300 m. However, a few detections in the Lab region at the ESRF11 and ESRF12 deployment locations, were categorized as 'possible' NARW upcalls due to the confounding potential presence of other marine mammals that make calls similar to or within the same frequency band as NARWs (*e.g.,* humpback whales, bowhead whales, and bearded seals). Furthermore, these platforms had a high degree of ambient noise created by ice. Therefore, it was not possible to conclude definite lack of NARW acoustic presence in this region.

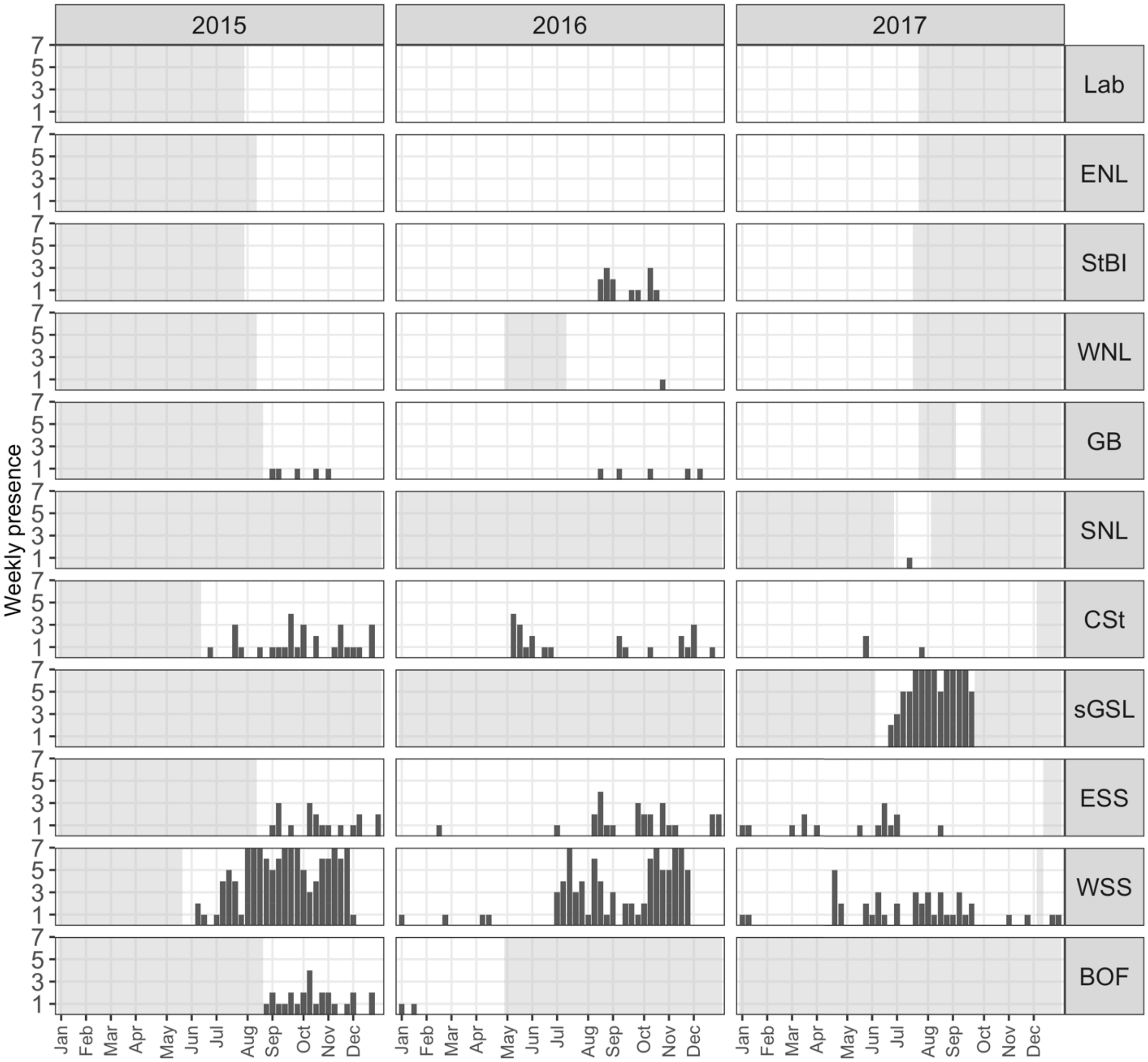


Figure 2.4 The number of days per week with at least one NARW upcall detection per day and region. Light grey polygons indicate periods with no recording effort in that region. Refer to Figure 2.2 for the location of regions; Labrador Coast (Lab), Eastern Newfoundland (ENL), Strait of Belle Isle (StBI), Western Newfoundland (WNL), Grand Bank (GB), Southern Newfoundland (SNL), Cabot Strait (CSt), southern Gulf of Saint Lawrence (sGSL), Eastern Scotian Shelf (ESS), Western Scotian Shelf (WSS), and Bay of Fundy (BOF). Deployment location-specific data within each region is shown in Appendix A.1.

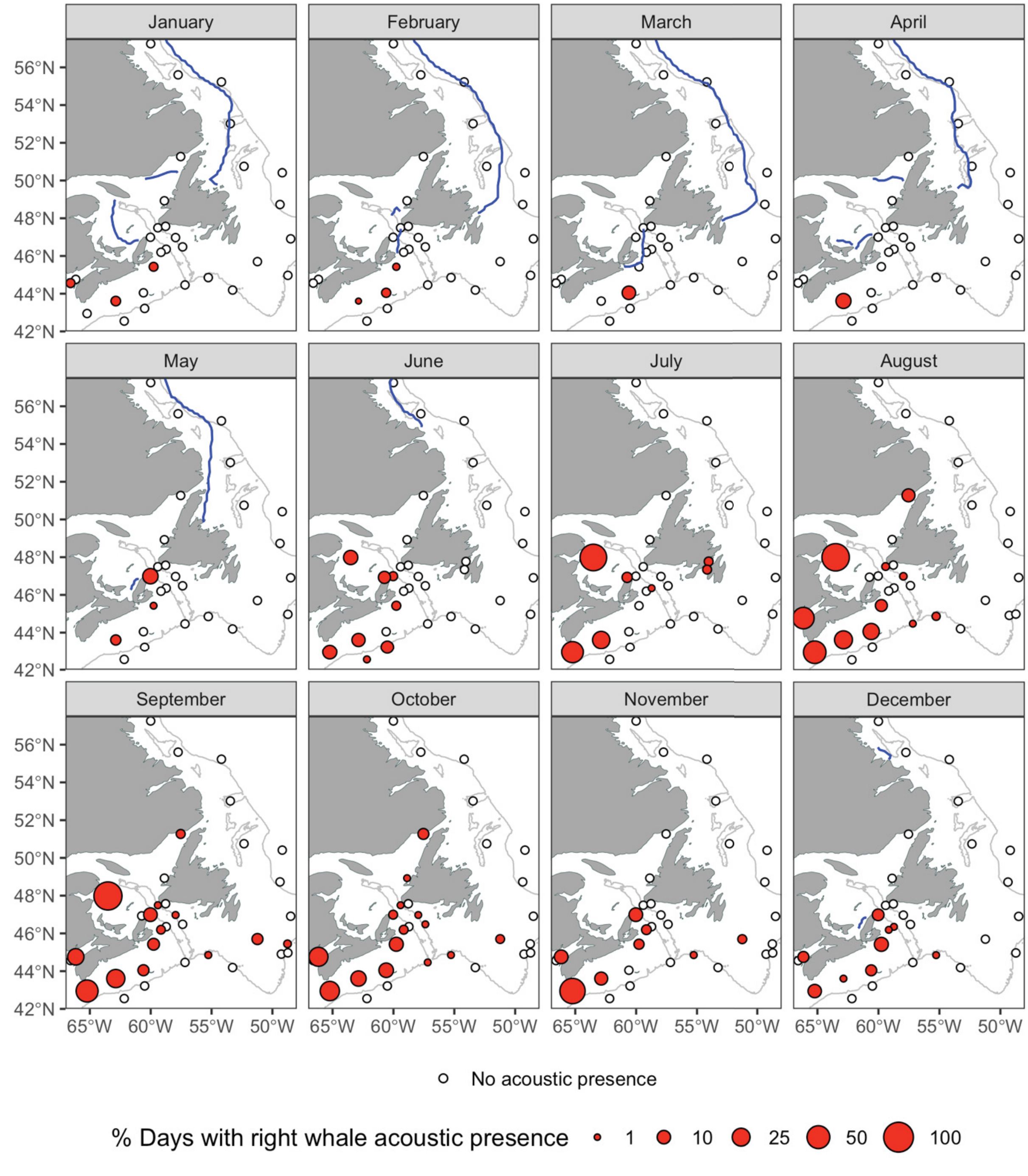
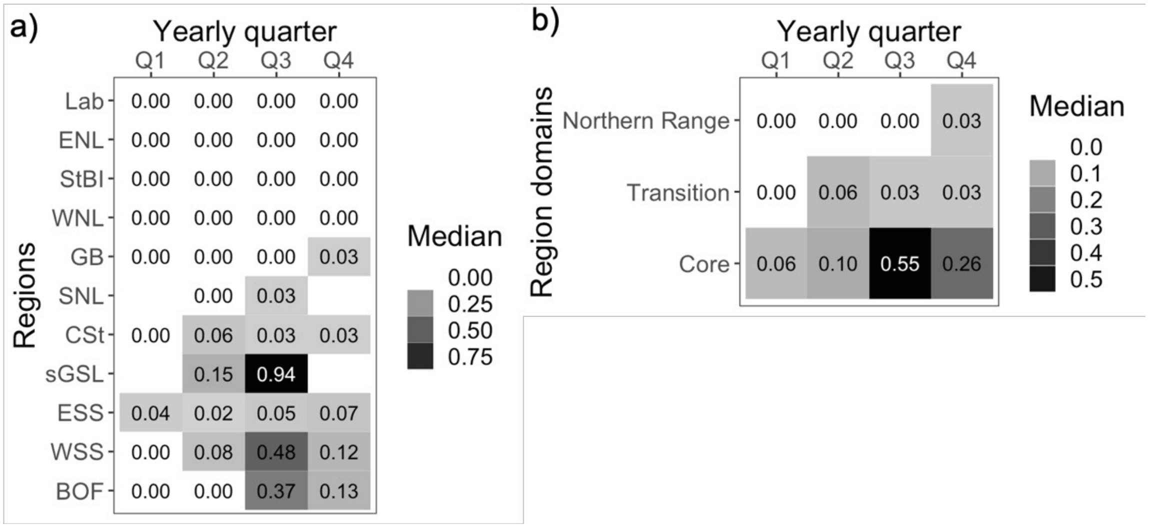


Figure 2.5 Spatial distribution of NARW presence in Canadian waters per calendar month. Red symbols denote deployment locations where NARW were present, and open symbols denote deployment locations where NARWs were absent. The size of each symbol denotes the percent of recording days within each month, aggregated over all years, when NARW were present. Blue contours denote monthly median extent of ice-cover from 1987 to 2010, data taken from the National Snow & Ice Data Center. Deployment location-specific data within each region is shown in Appendix A.1.

The quarterly medians of the detection probability further indicate spatial variation and seasonal patterns among regions and among the three broad-scale domains (Figure 2.6). Only 7 of the 11 regions had at least one quarter with a median above zero (Figure 2.6a). Among the different regions, the highest medians were during Q3, which included the sGSL, WSS, and BOF (0.94, 0.48, and 0.37 respectively). Despite the variability in recording effort (Figure 2.2), generally, the NARW acoustic occurrence was highest in the core domain (ESS, WSS, and BOF), diminished in the transition domain (CSt), and was rare north of Cabot Strait (Figure 2.6b).



Regions	Q1	Q2	Q3	Q4
Lab	0.00	0.00	0.00	0.00
ENL	0.00	0.00	0.00	0.00
StBI	0.00	0.00	0.00	0.00
WNL	0.00	0.00	0.00	0.00
GB	0.00	0.00	0.00	0.03
SNL		0.00	0.03	
CSt	0.00	0.06	0.03	0.03
sGSL		0.15	0.94	
ESS	0.04	0.02	0.05	0.07
WSS	0.00	0.08	0.48	0.12
BOF	0.00	0.00	0.37	0.13

Region domains	Q1	Q2	Q3	Q4
Northern Range	0.00	0.00	0.00	0.03
Transition	0.00	0.06	0.03	0.03
Core	0.06	0.10	0.55	0.26

Figure 2.6 a) Quarterly median of monthly probability of detecting NARW acoustic presence among different regions. Each month among the three years with recording effort was effort corrected for number of days with at least one recorder in the region. b) Quarterly median of monthly probability of detecting NARW acoustic presence among different domains; Northern range domain included StBI, WNL, GB, Transition domain included CSt, and the Core domain included ESS, WSS, and BOF. Yearly quarters defined as Q1; Jan – Mar, Q2; Apr – Jun, Q3; Jul – Sept, Q4; Oct – Dec.

2.4 Discussion

2.4.1 Seasonal distribution of North Atlantic right whales in Canadian waters

The variable timing of upcall presence among Atlantic Canadian regions suggests NARWs exhibit a seasonal migration pattern. NARW upcalls were present during all months of the year, indicating that individuals are present in Atlantic Canadian waters throughout the calendar year. NARWs were present most consistently on the Scotian Shelf. In the Cabot Strait and in the sGSL they occurred in spring, summer and fall (between May and Dec). The seasonal pattern of occurrence in the Cabot Strait was consistent with the known NARW occupancy period in the sGSL. Occurrence in the sGSL was consistent across all months monitored, spanning Jun through Sep. NARW occurrence in the Cabot Strait was more sporadic than that in the sGSL but spanned approximately the same time period of May through Dec. If NARWs enter the sGSL through the Cabot Strait, which is the most logical route (see Section 2.4.2), then individuals can be expected to occur within the sGSL during the same period. The results for this region are consistent with occurrence information derived from additional visual monitoring and PAM in these regions. Visual monitoring documented NARWs as early as 13-May in 2019 and as late as 12-Dec in 2017 (Johnson, 2018), while PAM detected NARWs from late-Apr and early-May through to mid-Nov (DFO, 2019a; Simard *et al.*, 2019).

There was very little acoustic presence north of the Cabot Strait; upcalls were rare and occurred only during the summer and fall in the Strait of Belle Isle and the Grand Banks regions. NARW acoustic presence at the ESRF7 and stn4-ST deployment locations in the Grand Bank region in Sep coincided in time with the seasonal maximum in abundance of *Calanus finmarchicus* stage CIV and CV, measured near Flemish Cap (Pepin *et al.*, 2013). This suggests a limited number of whales were possibly searching for food sources in these more northern waters. However, reduced NARW occurrence during the winter and early spring months in all regions is not surprising, especially in the more northern regions (CSt, GSL, WNL, StBI, Lab), due to the extended presence of sea ice (Environment Canada, 2011; Figure 2.5) and associated annual minimum in food abundance (Head *et al.*, 2013; Pepin *et al.*, 2013).

Whether or not waters east of Newfoundland and Labrador are within the contemporary range of NARWs remains unclear. The historical geographic distribution range of NARWs extends as far north as Newfoundland, Greenland, Iceland, and Norway (Knowlton *et al.*, 1992; Jacobsen *et al.*, 2004; Mellinger *et al.*, 2011). However, in this study there was no valid acoustic detections in subarctic regions northeast of Newfoundland and Labrador among the various deployment locations. Despite the difficulty of detecting NARWs in the northern waters due to environmental and biological factors, the population does not seem to be currently exploiting the regions near the recorders to any measurable extent. Nevertheless, NARWs were recently sighted along the northern coast of Newfoundland on 29 Sep, 2019 and along the southwest coast of Iceland on 23 Jul, 2018 (Johnson, 2018). Both sightings were of single animals. It is therefore probable that NARWs were not present in these waters in large numbers at the time of this study, but that single animals sporadically travel through these waters. Given that these waters fall within the geographic distribution range of *C. finmarchicus* (Conover, 1988; Melle *et al.*, 2014; Record *et al.*, 2018), NARW occurrence in these waters is possible. Furthermore, the whales could be in these northern waters but travelling further inshore or offshore, outside the detection range of the hydrophones. Regardless, with water temperatures rising due to climate change, prey availability may continue to decrease in the south, driving NARWs further north in search of food (Grieve *et al.*, 2017). This study provides an important baseline with which to compare and interpret future NARW distribution. It is crucial to continue monitoring these locations to track further distributional shifts.

2.4.2 Potential areas with regular North Atlantic right whale presence outside of known aggregation areas

Temporal patterns of NARW acoustic detections indicate that the species is present in known aggregation areas more consistently (with higher and more persistent daily presence) compared to other areas where recorders were present, with the exception of Emerald Basin. However, Davies *et al.* (2013) hypothesized that this habitat may not have suitable prey aggregating features similar to its neighbouring Roseway Basin. Nevertheless, the persistent occurrence that was similar across both basins in Aug and Sep suggests that Emerald Basin could also be considered an important habitat for NARWs (Moore, 2017).

Other areas in Atlantic Canadian waters have been hypothesized as suitable NARW foraging habitats within which NARW occurrence remains largely unknown. Though most of the NARW acoustic presence in the ESS region was from the ESRF2 deployment location, it was not as persistent as that detected in the known feeding habitats. However, ESRF2 deployment location is located near an area predicted to be a suitable feeding habitat by Plourde *et al.* (2019). The low acoustic presence at this deployment location could be a result of the placement location of the recorders. This highlights the importance of strategically placing recorders within predicted suitable habitats.

The results of this study provide new information on NARW occurrence in known aggregation areas. Following the observed distributional shift of NARWs since 2010 (Pettis and Hamilton, 2016; Davis *et al.*, 2017), very few NARWs have been recently sighted within Roseway Basin (Pettis and Hamilton, 2015; Johnson, 2018). In consequence, inferences have been made about NARW abandonment of the Critical Habitats based on these inconsistent visual survey data (Hamilton *et al.*, 2007; Batten and Burkill, 2010; Patrician and Kenney, 2010; Van Der Hoop *et al.*, 2012; Brillant *et al.*, 2015; Davies *et al.*, 2015). Though there have been fewer visual sightings, there was consistent acoustic presence in Roseway Basin in 2015 and 2016, especially relative to other sites monitored (with the exception of the GSL). As previously observed by Durette-Morin *et al.* (2019), these results are evidence that NARW had not abandoned all identified Critical Habitats (such as Roseway Basin) and that NARWs regularly used this habitat in 2015 and 2016. However, the decrease in detection levels in Roseway Basin in 2017 may indicate a shift in habitat use during this period, where the whales could be passing through the basin rather than aggregating there. This emphasises the importance of continual monitoring of a habitat.

2.4.3 North Atlantic right whale migratory corridors to the Gulf of Saint-Lawrence

Daily NARW presence was rare and more sporadic in migratory corridors such as the ESS, CSt, GB regions despite the elevated recording effort relative to that in aggregation areas. It is likely that the acoustic detections of whales are few in regions where the whales are traveling. Therefore, the total time that whales are within the detection range of each hydrophone is shorter in migratory corridors than aggregation areas. Furthermore, it has been documented in various habitats that NARW behaviour is the primary determinant of calling rate (Matthews *et al.*, 2001; Parks *et al.*, 2005, 2011; Matthews *et al.*, 2014). The lower NARW occurrence in the ESS and CSt may indicate these regions are a different type of habitat, rather than an aggregation area where high acoustic presence would be expected. Though calling rates of travelling whales remains largely unknown, the whales may produce calls less frequently in these regions while transiting among aggregation habitats. In such regions, the whales are far more likely to be detected with continuous monitoring.

The higher acoustic presence of NARWs in the CSt, compared to the StBI, suggests that the CSt is the primary migratory corridor used by NARWs into the GSL. Though the recording effort was much greater in the CSt compared to the StBI region, seven compared to one recorder respectively, most acoustic presence in the CSt was at the ESRF1 deployment location. The similar occupancy period between CSt and GSL also suggests NARWs continually transit via the Strait throughout the foraging season. Furthermore, the geographic position of the CSt is consistent with these results, given that it is the shortest route from the Scotian Shelf into the GSL and the extended period of ice cover, generally from Jan – Apr in StBI compared to the CSt, generally from Feb – Mar (Environment Canada, 2011; Figure 2.5).

NARWs were not detected in either the CSt and StBI regions between 2011 and 2013 based on moored recorders (Simard *et al.*, 2019), despite being in similar locations to the ESRF1 and ESRF10 deployment locations. However, the increase in NARW occurrence in the CSt from the 2011-2013 period to the 2015-2017 period indicates an elevated occurrence of NARW in the GSL (DFO, 2019a; Simard *et al.*, 2019). Additional monitoring would be necessary to further characterise the relative importance of these entryways into the GSL as migratory corridors. Nevertheless, given the narrow entrance to the GSL, the CSt is a bottleneck for a number of large and medium-sized vessels as well as the NARWs passing through, and thus, should be considered as an area of high interest for threat mitigation.

2.4.4 Advantages and limitations of using passive acoustic monitoring technologies as a tool to monitor North Atlantic right whale presence

The purpose of this study was to extend the baseline of what has been described as the contemporary distributional range of the species by Davis *et al.* (2017). As with any monitoring method, PAM has limitations, which may influence the interpretation of the results. The current analysis assumes an equal probability of detecting a NARW among all regions and monitoring platforms that may not be valid. Variation may exist as a result of differences among recording systems, their detection ranges, and deployment locations, local bathymetry and environmental conditions (including anthropogenic activities and associated noise), the vocal behaviours and calling rates of the animals, and the accuracy and reliability of the autodetection program (Baumgartner and Mussoline, 2011; Davis *et al.*, 2017). Thus, it is possible that PAM missed NARW presence, especially if the whales were not calling. Therefore, the results represent the minimum estimates of daily NARW presence and caution should be taken when interpreting the seasonal distribution among regions, as absence of acoustic detections may not infer absence of NARW occurrence.

This study highlights the advantages of PAM as a means of monitoring the presence of NARWs over extended periods across large spatial scales. Despite being much more limited, visual monitoring does provide crucial information on population demographics from photography and genetic sampling. In such cases, PAM can complement visual monitoring by providing insights into areas and times of potential importance on which to focus visual survey efforts. PAM can also be conducted when and where visual monitoring may be logistically difficult or impossible, as PAM is demonstrably less costly and can be continuous regardless of daily, seasonal, weather and light conditions.

2.4.5 Future studies

While the overall spatial coverage included in this study is large, these PAM efforts do not adequately cover all possible areas used by NARWs in Atlantic Canada. To pursue this, future work must include the continued collection of acoustic data throughout the region. The continued acoustic monitoring effort should include areas of interest for NARW presence that require more monitoring effort, or areas that are potentially used by NARW that have had minimal monitoring effort to date. Further studies of NARW vocal variability will increase our knowledge of calling behaviour (*e.g.,* travelling, socializing, and foraging whales and how this varies among seasons and habitats) while advancing our ability to use different call types (*e.g.,* gunshots and moans) to detect NARW presence.

2.4.6 Conclusions

The results presented in this analysis indicate the minimum NARW presence in various areas of Atlantic Canada in the 2015-2017 period. Though NARW calls were detected generally throughout the calendar year, the greatest occurrence was on the Scotian

Shelf, year-round, and in the central regions of eastern Canada (such as around the CSt and in the GSL) from May to Dec. Though detections were more sporadic in the CSt region, the higher acoustic presence relative to the StBI suggests that the CSt is likely the primary migratory corridor into the GSL used by NARWs. The lack of definite acoustic presence east of Newfoundland and Labrador indicate that the current geographic distribution of the species may be constrained to more temperate-subarctic ecosystems. However, this study also indicates that continued broad-scale acoustic monitoring in Atlantic Canada is necessary to assess long-term NARW distribution trends and changes therein.

Chapter 3 ACOUSTIC GLIDERS TO TRIGGER REAL-TIME DYNAMIC FISHERY MANAGEMENT RESTRICTIONS THAT PROTECT NORTH ATLANTIC RIGHT WHALES IN CANADA; A PERFORMANCE STUDY

3.1 Introduction

A major part of world economy relies on ocean based industries such as commercial fishing and shipping that have numerous and diverse impacts on at-risk marine mammals, turtles, and large fish around the world including vessel strikes and incidental bycatch of non-target species (Lewison *et al.*, 2004; Peckham *et al.*, 2007; Žydelis *et al.*, 2009; Croxall *et al.*, 2012; Lewison *et al.*, 2014). Human activities are frequently managed for conservation purposes through regional strategies that are static in space over seasonal, annual and longer periods (Lewison *et al.*, 2004; Grantham *et al.*, 2008; Vanderlaan *et al.*, 2008; Game *et al.*, 2009; Lewison *et al.*, 2015). While conceptually simple, regional management areas that are fixed in space over long periods are not optimized to protect mobile species (Hyrenbach *et al.*, 2000). These species have distributions that vary depending on specific oceanographic conditions, that affect organisms such as planktonic prey aggregations, that are ephemeral and move with ocean currents (Haury *et al.*, 1978).

Dynamic ocean management (DOM) is a modern conservation approach that, at least conceptually, is optimized to mitigate harm to at-risk mobile species (Hazen *et al.*, 2013; Hobday *et al.*, 2014; Hazen *et al.*, 2018). Mitigation of harm may only be required when species are determined to be present (Lewison *et al.*, 2015). The approach can be appealing to both economic- and conservation-minded stakeholders; restrictions of ocean industry operations can potentially occur on shorter time scales and at larger spatial scales compared to what is possible with static spatial management (Welch *et al.*, 2020).

Although DOM processes vary depending on the target species that is managed, in order to work, DOM generally follows the five steps I operationally define below:

1) Data collection; trusted assets are deployed to acquire data on the distribution of a target species. This can take place using telemetry, satellite, visual, or acoustic monitoring. The collection of oceanographic and environmental habitat data associated with the presence of the target species can also be used as proxy for target species distribution. The data collection step is often conducted by science institutes, non-governmental organizations, or locally by the mariners.

2) Data analyses; the data collected are processed to provide quality-controlled distribution data of the target species. This can take the form of analysts validating the data, statistical or extensive modeling analyses. This data analysis step is often conducted by science institutes or governmental organizations.

3) Dissemination of species distribution data; the distribution data are made available to interested stakeholders, often publicly available using online platforms (*e.g.,* Whalemap.ocean.dal.ca; Johnson, 2018), or directly communicated to interested parties (*e.g.,* industry or government organisations).

4) Regulatory measures are issued; once the species distribution data are in the hands of regulators, the responsible management agencies (*e.g.,* governmental or industrial agencies) issue the appropriate dynamic management measures.

5) Compliance by marine industry users; marine industry users voluntarily or obligatorily comply to the implemented measures (*e.g.,* areas of avoidance due to high bycatch reports, fishery-areas closures, or speed reduction zones may be activated).

In practice, the five steps above should form a closed loop; the resulting compliance and risk reduction should help determine future improvements in the management plan and the monitoring therein. While such measures appear as optimal solutions, DOMs can be challenging and expensive to implement. As it is not yet a widely used practice in marine conservation, examples of operational DOM in the marine conservation literature are rare.

One of the major challenges of DOM is the ability to collect and disseminate target species distribution data through real-time monitoring. Near real-time monitoring, in this context, means the collection and reporting of information on the identification and location of a particular marine species on a time scale of one to three days. Examples range in scale and expense from simple approaches such as local fisherman reporting local bycatch of turtles over a high frequency two way radio (Alfaro-Shigueto *et al.*, 2012; Little *et al.*, 2015) to using locational predictions from computationally intensive habitat-use models using satellite or telemetry tags to ground truth (*e.g.,* tuna, Hobday and Hartmann, 2006; turtles, Hobday *et al.*, 2011; Howell *et al.*, 2015; blue whales, Hazen *et al.*, 2017).

There are numerous strategies to obtain distribution data to inform DOM, each with advantages and limitations. Habitat suitability models can provide wide range locational predictions of target species (*i.e.,* proxy distribution data). However, as they are largely based on oceanographic data, they require in-depth knowledge of how the target species uses a given environment. This requires numerous years of data collection and is rarely useable for immediate risk mitigation especially for data deficient species in locations where environmental data are also deficient. Furthermore, many such models (*e.g.,* water temperature preference of tuna and turtles; Hobday and Hartmann, 2006; Hazen *et al.*, 2018) are ground-truthed using data obtained from tags mounted on the target animal. These can present a risk to animals especially if the species is endangered. Conversely, monitoring a target species using human observers aboard vessels or aircraft can provide non-proxy distribution data in near real-time. However, these methods are weather and daylight dependent, are associated with a level of risk to the human observers, and are costly.

Autonomous ocean *monitoring platform*s such as unmanned aerial vehicles (*e.g.,* drones) and automated underwater vehicles (*e.g.,* underwater *acoustic gliders*) have increasingly been used to monitor species presence (*e.g.,* turtles, Jones *et al.*, 2006; Hodgson *et al.*, 2013; Bevan *et al.*, 2015) including in near real-time (*e.g.,* Baumgartner *et al.*, 2013). In this chapter I focus on underwater acoustic vehicles (UAVs). There have been studies on the detection range and detection capabilities of these platforms (*e.g.,* Baumgartner *et al.*, 2013, 2020; Johnson *et al.*, 2020) that have established the efficacy of UAVs for acoustic monitoring of several species of large whales, including the NARW. This work represents the first study, to my knowledge, to assess how UAVs can be efficiently used to inform DOM. Important considerations needed to assess the efficiency of using such platforms include the following: the kind of platform assets that may be available, the number of assets needed to efficiently cover a given area, the location and duration of the deployments, the dissemination of the target species distribution data collected, and the time and space scales of the regulations associated with the distribution data gathered by the asset. The gliders are slow moving; they can only cover a certain amount of area during a given period. It is important to strategically allocate the glider monitoring effort for an efficient survey. Both the DOM protocol and *flight plans* of the monitoring assets need to balance the allocation of limited *survey effort* and cost over a designated area in a way that maximizes the probability of detecting the species of interest based on (usually) limited knowledge of the species distribution.

Following an unprecedented human-caused North Atlantic right whale (NARW) mortality event which began in 2017, when 12 individuals were found dead and five were found entangled in fishing gear (Daoust *et al.*, 2017; Davies and Brillant, 2019), Fisheries and Oceans Canada (DFO) and Transport Canada (TC) each implemented new mitigation measures to reduce the risk of entanglement and vessel strikes, respectively, in the Gulf of Saint Lawrence (GSL), Canada. These measures include mandatory static and dynamic fishery-area closures and vessel speed reductions, supplemented by an increase in visual and acoustic *survey effort*s to detect the presence of NARWs (DFO, 2020b). In this Chapter, I present a performance study wherein I model *flight plan*s for a near real-time glider asset to fit a specific and well-defined DOM protocol implemented by DFO to mitigate entanglement risk to NARWs in 2020. The DOM protocol, described in the Methods section, was designed and implemented to reduce the risk of fishing gear entanglements, particularly with snow crab fishing gear (See Chapter 1 and 2 for more details). The monitoring asset used in this study is a profiling Slocum electric glider equipped with a hydrophone that is capable of detecting and classifying NARW calls in near real-time (Baumgartner *et al.*, 2020, 2019, 2014, 2013; Baumgartner and Mate, 2005, 2003; Baumgartner and Mussoline, 2011). I then tested a modeled *flight plan* during a summer 2020 pilot mission in the GSL where the NARW detections were used to trigger fishery-area closures during the mission. To my knowledge, this was the first such mission wherein an acoustic glider was used to trigger a fishery related DOM protocol.

Specifically, I focus here on addressing the following objectives: 1) to define metrics that characterize the efficiency of the acoustic glider for triggering the NARW DOM protocol in the GSL, 2) to explain variation in the efficiency of various modeled glider *flight plan*s in relation to the known NARW distribution, 3) to select optimal *flight plan* models for the most efficient use of the gliders relative to one or more efficiency measurements. The results of this study will identify the strengths and weaknesses of gliders as a DOM tool and determine how gliders can best be used to mitigate unintentional harm to NARWs from fisheries in the GSL for a given set of DOM protocol parameters.

3.2 Methods

3.2.1 Dynamic fixed-gear fisheries management plan

In 2018 DFO initiated a dynamic fisheries management (DFM) plan to mitigate entanglement harm from fixed gear fisheries (primarily snow crab and lobster) to NARWs in the GSL (DFO, 2019a, 2019b, 2020b). This was the first time DFM has been used to reduce entanglement risk to NARWs in Canada. The plan was modified in 2019 and again in 2020 as more was learned about the distribution of NARW and threats in the region. The 2020 DFM plan is implemented as follows. First, the GSL is subdivided into 10 minutes of latitude by 10 minutes of longitude unique *grid cells*, each covering between 213 to 254 km^2 (Figure 3.1). This grid system was delineated by the Northwest Atlantic Fisheries Organization (NAFO) and is used to manage the snow crab fishery in Atlantic Canadian waters (DFO, 2018). If a NARW is detected within a *grid cell* by any *monitoring platform*, a temporary closure is activated, or 'triggered', for 15 days, including the gear removal period (DFO, 2020a). The area closed is a 3x3 *survey unit* centered on the *grid cell* with the NARW detection. The *survey unit* includes the *surveyed cell* (*i.e.,* the cell containing the detection) and 8 *buffer cell*s surrounding the *surveyed cell* (Figure 3.1). *Buffer cell*s are triggered to close a large enough area to account for NARW movement after the detection has been made. NARWs are known to travel up to 80 km d^{-1} (Baumgartner and Mate, 2005). Once a temporary closure is triggered, fishers are given at least 72 hours to remove their fishing gear from the *survey unit* and may not place any new gear within the *survey unit*.

The gear removal period can be longer if the weather forecast is not suitable for fishing. DFO is then responsible for surveying the *survey unit* with an aerial platform at least twice, on different days during the 15-day closure. Additionally, the second flight must occur within five days of the scheduled re-opening date for the grid cell. If a NARW is not detected again within the *survey unit* or within adjacent cells of the *survey unit* during the 15-day closure, then the *survey unit* reopens to fishing on day 16. If a NARW is detected within the *survey unit*, or within an overlapping *survey unit*, on a second day within a 15-day period by any *monitoring platform*, that *survey unit*, or the overlapping cells among the overlapping *survey unit*s, are then put under a seasonal closure, and will be closed until November 15, 2020 (Figure 3.1). This effectively ends fixed gear fishing in those *grid cells* for the year. As of 16 July 2020, prior to this study, 71 *grid cells* were closed for the season in the GSL (DFO, 2020c).

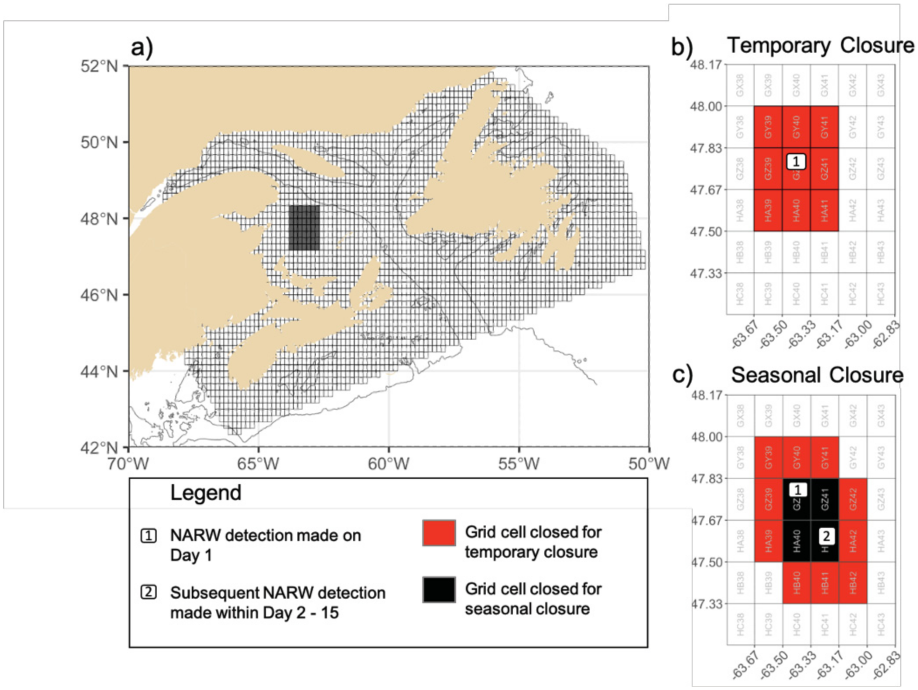


Figure 3.1 The dynamic fishery management plan to mitigate entanglement harm to North Atlantic right whales from fixed gear fisheries (primarily snow crab and lobster) in the Gulf of Saint Lawrence (GSL), as implemented by Fisheries and Oceans Canada in 2020. a) GSL fishery grid, consisting of 10 latitude minute by 10 longitude minute unique grid cells which can be closed to fishing if a NARW is detected. The cells highlighted in dark grey represent the grid cells used in the example of closure types b and c; b) example of a temporary closure; c) example of a seasonal closure.

The DFM plan relies on near real-time NARW detections derived from several *monitoring platform*s. Visual surveillance takes place using aircraft flown by DFO, TC and the USA National Oceanic and Atmospheric Administration (NOAA), as well as several vessel-based platforms from government, non-government, and academic organizations. Two types of near real-time passive acoustic monitoring (PAM) devices were being used to monitor whales by their calls in 2020: Slocum gliders equipped with digital acoustic monitoring (DMON; Johnson and Hurst, 2007; Baumgartner *et al.*, 2013, 2019) hydrophones and moored acoustic Viking buoys (https://ogsl.ca/viking/). Slocum gliders are deployed by a collaborative research group including the Coastal Environmental Observation Technology and Research (CEOTR) glider group, the Ocean Tracking Network (OTN), Dalhousie University, University of New Brunswick, Woods Hole Oceanographic Institution (WHOI), and the Marine Environmental Observation, Prediction and Response network (MEOPAR).

3.2.2 Near real-time North Atlantic right whale acoustic monitoring from Slocum gliders

The autonomous platform used to monitor NARW in this performance study is a G3 Slocum Glider (henceforth glider; Teledyne Webb Research), an autonomous electric underwater vehicle that when mounted with a PAM system can monitor for the acoustic presence of cetaceans. A variety of other oceanographic sensors can be integrated within the science bay of the glider to monitor oceanographic conditions, *e.g.,* a CTD to monitor water temperature, salinity, and density, depth sensors, echosounder to monitor zooplankton, and an optode to monitor water oxygen content. The length of a glider deployment can vary from weeks to months depending on the type of battery used; alkaline or lithium (here a lithium battery was used). The glider typically moves at a slow nominal horizontal speed of 0.65 km h^{-1} while profiling the water column (Baumgartner *et al.*, 2020) with an estimated detection range of 30 - 40 km (Baumgartner *et al.*, 2019). Because a deployment can last from weeks to months, the glider can survey a large area of 100s to 1000s km of track length.

Gliders move through the water using a buoyancy pump located at the bow of the glider. By using triggers from the integrated altimeter and depth sensor, the glider can change its density relative to the water to move up and down through the water column.

From this buoyancy driven motion, the glider is propelled forward with the aid of short glide wings. The glider can maintain pre-programmed navigation using a compass and a rudder located at the stern of the glider allowing it to navigate along waypoints. Every 2 - 6 hours, the glider surfaces to obtain its location using a global positioning system (GPS) receiver and starts a two-way data transmission session using an Iridium satellite service. At this time, the glider uploads the oceanographic sensor data (including the near-real time acoustic data) and instrument status information to a ground station and downloads information from the glider technicians regarding any changes to instrument parameters (*e.g.,* profiling depth) and mission waypoints. Once the session is complete, the glider resumes its movement through the water column until the next scheduled surfacing and Iridium communication. Through these surfacing intervals, the glider can be piloted to fly a *flight plan*, defined as a predetermined set of waypoints along the pre-programmed survey track.

The glider, mounted with a DMON in combination with the low-frequency detection and classification system program (LFDCS; Baumgartner and Mussoline, 2011; Baumgartner *et al.*, 2013), can record and process audio data continuously and detect calls of sei (*Balaenoptera borealis*), fin (*Balaenoptera physalus*), North Atlantic right (*Eubalaena glacialis*), humpback (*Megaptera novaeangliae*), and blue (*Balaenoptera musculus*) whales as the glider travels through the water column. The LFDCS processes the audio data to produce pitch tracks of characterized sounds that can be classified by species (Baumgartner and Mussoline, 2011). The latter is done by comparing the attributes of each pitch track to the pitch track of identified and classified calls within a call library for the five species mentioned above using a quadratic discriminant function analysis. Up to 8 kB of the classified pitch tracks are then sent from the DMON instrument to the glider every hour. If many detections are recorded during this time it is possible that the 8 kB pitch track limit will be exhausted and additional pitch tracks will not be uploaded via Iridium. However, the complete set of DMON recordings are archived onboard the glider and can be recovered and comprehensively assessed once the glider is recovered at the end of the mission.

During the Iridium communication sessions at the surface, the glider sends the oceanographic and pitch track data to a shore-based server (for this study the server was located at Dalhousie University). The data are then automatically uploaded to the WHOI servers and passed to a public website (dcs.whoi.edu). An analyst (the author of this thesis) then validates the pitch tracks at least once every 24 hours using a protocol developed by WHOI and the NOAA's Northeast Fisheries Science Center (NEFSC; dcs.whoi.edu/#protocol; Baumgartner *et al.*, 2019). The validation procedure is as follows. The analyst examines tally periods of 15 minutes consisting of a series of acoustic time-frequency plots with associated pitch tracks. The analyst confirms whether each tally period contains a valid detection, a possible detection, or no detection for each of the baleen whale species mentioned above. This is done by weighing the classification information, the shape, and the amplitude of each pitch track as well as whether it is in a pattern or is isolated from noise pitch tracks of similar amplitude. Once the validation process is complete, the detection data are sent to all interest groups, including DFO and is automatically presented on a public website (whalemap.ocean.dal.ca; Johnson, 2018), which is used by the marine industry, managers, and government regulators for DOM regulations.

Glider deployments rely on the expertise of numerous individuals. The CEOTR group, based at Dalhousie University lead all glider operations used in this project, including the deployments, piloting, and maintenance of the gliders. Since 2011, the group has performed over 120 missions and the gliders have collectively been at sea for over 3100 days. The team has had training from Teledyne Webb Research among other advanced training classes. The analysts performing the real-time marine mammal acoustic validations (in this case the author) were trained by Mark Baumgartner with the LFDCS protocol mentioned above (dcs.whoi.edu/#protocol; Baumgartner *et al.*, 2019) and collectively have validated 34 glider deployments in the GSL, Roseway Basin, and on the Scotian Shelf since 2015.

3.2.3 Designing the acoustic glider flight plan

This performance study aims to design glider *flight plans* to most efficiently monitor an area for the presence of NARW within the confines of the DFM protocols implemented by the DFO in April 2020. In this study I define an efficient *flight plan* as one that conservatively fits the DFM protocols by maximizing the glider's potential to survey as many fishery-areas as possible where whales are likely to be present. To achieve this, the performance of the different *flight plan* models was quantified using two metrics:

1) The number of *grid cells* surveyed by the glider within a *flight plan*. This includes the *grid cells* the glider travels through, and the *unique buffer cells*, which are the *grid cells* adjacent to those the glider travels through.
2) The glider's *conditional NARW encounter probability* as determined by the spatial overlap between the flight plans and NARW spatial climatology.

The *flight plan* models are a georeferenced set of contiguous *grid cells* through which the glider travels along a (mostly) straight line path. The grid cells used in this study were the fishery-area grids implemented by DFO (Fig. 3.1). The study comprised five steps:

Step 1: Develop a set of non-geo-referenced glider *flight plan* models that vary in shape and size.

Step 2: Use NARW sightings data from 2015-2019 to develop a spatial climatology of NARW encounter probability by aggregating all detections in each DFO grid cell.

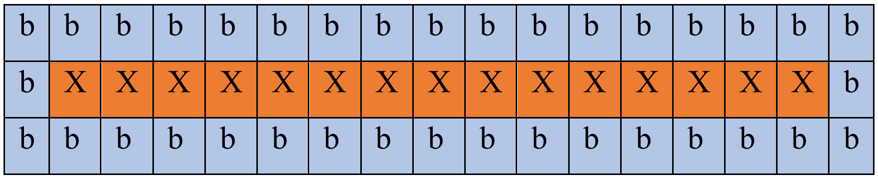
Step 3: Geo-reference each flight plan model by varying its orientation and deployment location relative to the NARW encounter probability.

Step 4: Compare the performance of each geo-referenced *flight plan* relative to how many unique *grid cells* it covers (metric 1) and the probability of NARW encounter (metric 2). Choose the *flight plan* that performs best.

Step 5: Empirically test the chosen *flight plan* model in a pilot deployment to study *acoustic glider* performance within the 2020 DFM framework.

Step 1: Glider flight plan model

Glider *flight plan* models are non-geo-referenced *survey grid*s. Each *survey grid* contains all *grid cells* considered surveyed by the glider, which have the potential to undergo a DFO fishery-area closure if a NARW is detected by the glider. There are two types of *grid cells* in a *survey grid*. The first type of cell is called a *surveyed cell*, which is a *grid cell* the glider travels through (see cells marked by the orange 'X' in Figure 3.2). The second type of cell is called a *buffer cell*. *Buffer cells* are the eight cells surrounding each *surveyed cell* (see cells marked by the purple 'b' in Figure 3.2). Even though *buffer cells* are not surveyed, they will be closed if a whale is detected by the glider in an adjacent *surveyed cell*.



b	b	b	b	b	b	b	b	b	b	b	b	b	b	b	b	b
b	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	b
b	b	b	b	b	b	b	b	b	b	b	b	b	b	b	b	b

Figure 3.2 Example of survey grid for a straight-line glider flight plan containing 15 surveyed cells (orange, X) and unique buffer cells (purple, b).

The shape of the *survey grid* affects its size. To illustrate this concept, consider two example *survey grid*s below (Figure 3.3). Time step one (*i.e.,* day one) shows a *survey unit*, which includes a *surveyed cell* containing the glider and eight *buffer cell*s. At time step two (*i.e.,* day two) the glider has two options, it can either transition horizontally or diagonally to the next grid cell. In Figure 3.3, the top panel shows the result when the glider has moved from one *survey unit* (X_1) to the next horizontal contiguous unit (X_2). There is an overlap among six cells of X_1 and X_2, meaning that these six cells are subject to closure on both survey days. I define these cells as *shared buffer cell*s. However, if at time step two the glider has moved to the next diagonal contiguous unit (X_2), the number of *shared buffer cell*s is only four. Diagonal movement is therefore more efficient for the purpose of maximizing the *survey grid* because the number of *unique buffer cells* is greater, and the number of *shared buffer cells* is lower. This assumption does not consider the location of the glider and distance traveled within each cell.

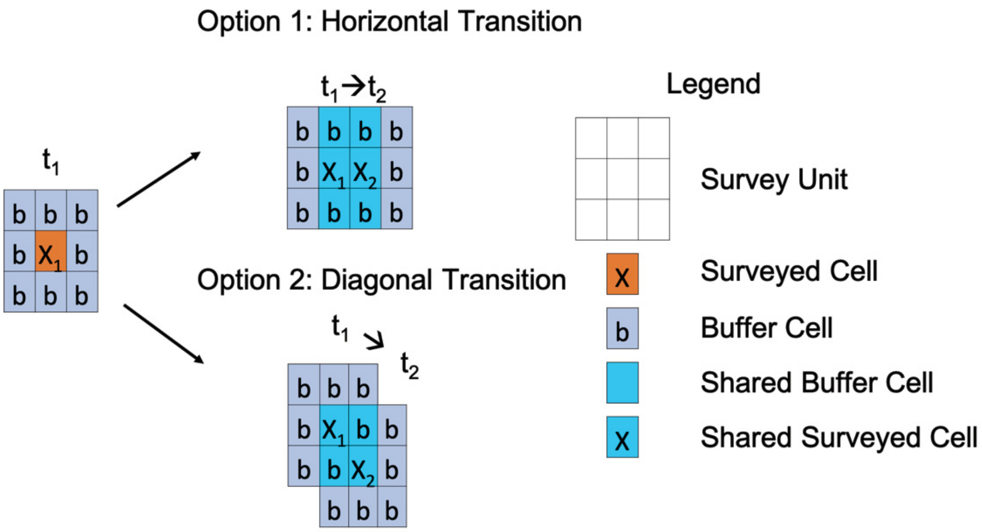


Figure 3.3 Model glider flight plan illustrating the concept of shared buffer cells. The diagram shows two time steps (t) of the model where the glider transitions between contiguous grid cells (X_1 to X_2) connected either horizontally (Option 1) or diagonally (Option 2).

Each non-georeferenced model satisfied the following three conditions:

- I assume that a G3 Slocum glider travels at a constant speed over ground of 0.5 knots. Glider speed over ground is in reality variable and unpredictable due to ocean currents. The average over a suite of Dalhousie-based Slocum glider deployments (2014 - 2020) is canonically 0.5 knots (K.T.A. Davies, personal communication). At this speed a glider travels horizontally or diagonally through a single *grid cell* of 10 minutes of latitude by 10 minutes of longitude within 20 and 28 hours respectively.
- The model must maximize the number of *surveyed cell*s that are separated from other *surveyed cell*s by exactly two *buffer cell*s. This condition maximizes the *survey grid* because *buffer cell*s can be closed without the glider being physically present in a cell.
- The period of each *flight plan* is set at 15 days. This condition helps maximize the *survey grid* while also allowing each *grid cell* to be re-surveyed once every 15 days. This condition would support the DFO temporary closure protocol within the *survey grid* for the duration of a glider mission. Glider missions last between 30 and 180

days depending on the battery and instrumental configuration of the glider, meaning each flight plan could be repeatedly surveyed 2 - 12 times. If a temporary closure is triggered by the glider, DFO is required to conduct aerial surveillance at least twice in that grid cell within a 15-day period following the detection. The glider is not relied on to trigger a seasonal closure, and so in this exercise I only seek to use the glider to trigger temporary closures.

Based on all the conditions described above, I developed a set of non-georeferenced glider *flight plan* models. Six different shapes were tested with various levels of complexity: a sinusoid, a five-shape, a sawtooth, a rectangle, a spiral, and a line (Models A through F in Figure 3.4). The number of *grid cells* in the *survey grid* was tallied for each *flight plan*. A *flight plan* model was ranked higher (*i.e.,* more efficient) if it had a larger *survey grid* and a greater number of *unique buffer cell*s.

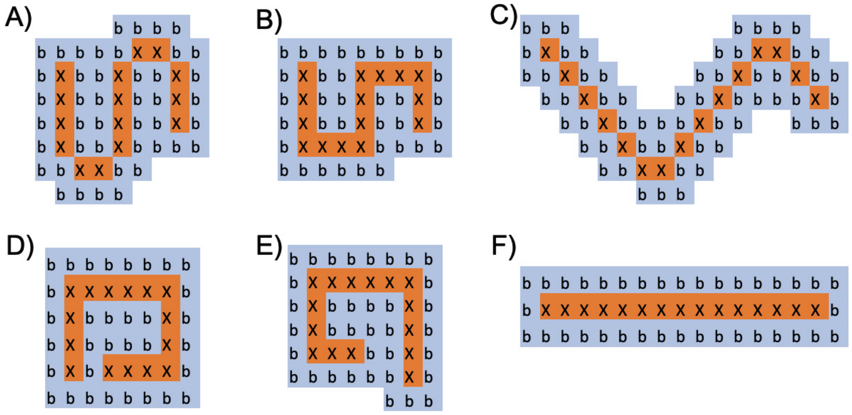


Figure 3.4 Modeled glider flight plan configurations tested in this study, Models A) Sinusoid, B) Five-shape, C) Sawtooth, D) Rectangle, E) Spiral, and F) Line. Purple cells marked with b represent unique buffer cells, while the orange cells marked with x are surveyed cells.

Step 2: Probability of a glider encountering a North Atlantic right whale

A *flight plan* is more efficient at closing fishery-areas if the glider detects NARWs within the *survey grid*. The placement of the grid relative to the ocean is important. I account for this in my modeling exercise by incorporating an estimate of the conditional NARW encounter probability within each *grid cell* in the GSL. This estimate uses non-effort corrected NARW sightings and acoustic detections aggregated in each *grid cell* in the GSL during 2015 through 2019 (Figure 3.5). The domain containing all 99 *grid cells* with at least one detection is bordered in red in Figure 3.5. Effort corrected data were not used because the effort data are not available for 2018 and 2019. The probability of the glider encountering a NARW within each grid cell was modeled using Equation 3.1. The probability that each 15-day *flight plan* encounters NARWs is quantified by the sum of probabilities, $\sum P(encounter)$, of each cell contained in a *survey grid*.

$$P(encounter) = \frac{detections\ in\ a\ cell}{total\ detections\ in\ GSL} \qquad \text{(Eq. 3.1)}$$

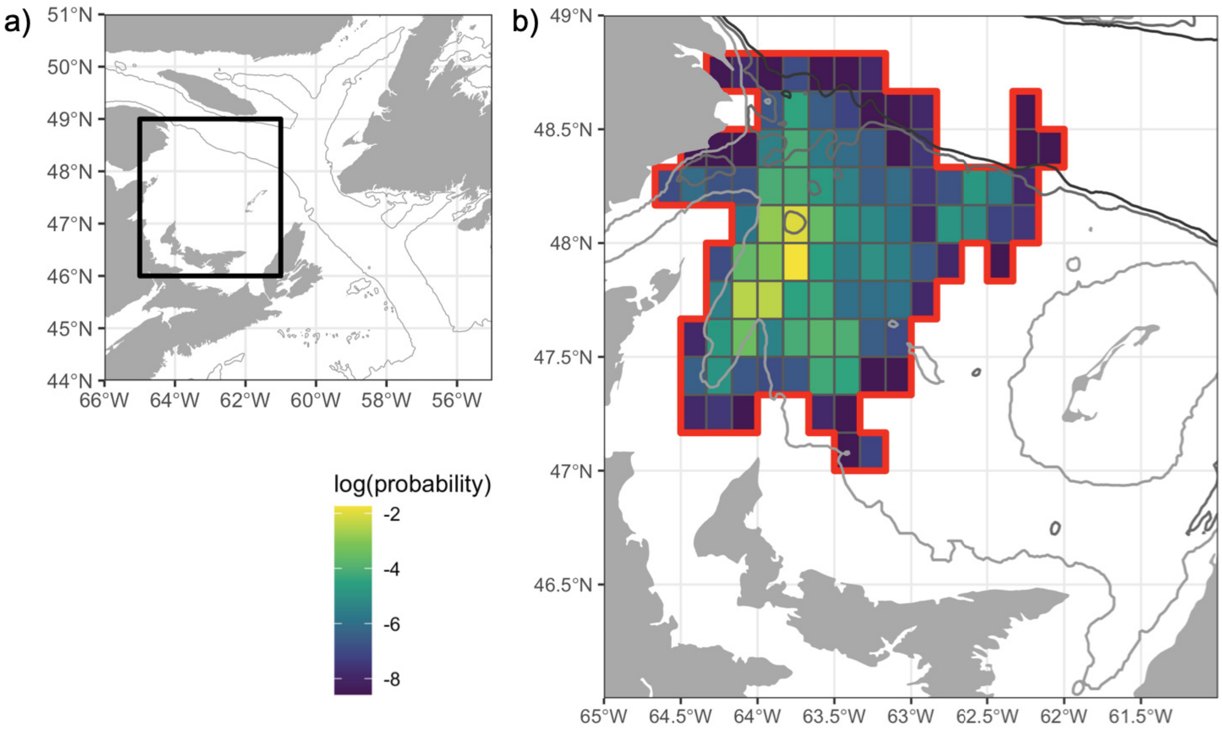


Figure 3.5 a) Gulf of Saint Lawrence (GSL) with 200m isobath, b) Log of NARW encounter probabilities within each fishery grid cell of NARW aggregation area in the southern GSL. Detection data (visual and acoustic) are aggregated over years 2015-2019 (source: whalemap.ocean.dal.ca). The area outlined in red represents largest cluster of adjacent grid cells (n = 99) containing NARW presence (at least one detection). The color scale depicts the relative probability of encountering a NARW within each grid cell. White cells represent absence of NARW detections or absence of survey effort.

Step 3: Geo-reference each flight plan model

Next, the six *flight plan*s developed in Step 1 were oriented in space to find the best glider deployment location and orientation within the 99 *grid cells* that comprise the NARW distribution climatology (Figure 3.5). The purpose was to identify the *flight plan* that maximizes the spatial overlap between a *flight plan* and NARW encounter probability. Some *flight plan*s were rotated by 90^{o} to test whether the rotated plan was more likely to encounter NARWs than the un-rotated plan, given the apparent latitude-longitude asymmetry in the NARW distribution. Each rotated plan was considered as a new model. For each model, the starting position producing the highest sum of probabilities was chosen as the optimal deployment position. More efficient *flight plan*s have a higher probability of encountering a NARW.

Step 4: Flight plan evaluation

The *flight plan* metrics were depicted in a scatter plot to illustrate the relative ranking of the models. A *flight plan* model was ranked higher if it had a larger *survey grid* <u>and</u> a higher probability of encountering a NARW.

Step 5: Pilot study

The *flight plan* that ranked the highest was used in an *acoustic glider* deployment during summer 2020. Waypoints were positioned at the center of each *survey grid* cell. The selected *flight plan* was repeated until the end of the glider deployment. A G3 Slocum glider manned with a DMON, a pumped CTD, optode, flurometer, Vemco mobile transceiver (vmt) to track tagged fish, and an echosounder (Acoustic Zooplankton Fish Profiler, azfp; ASL Environmental Sciences) was deployed for a six-week mission starting 17 Jul and ending 29 Aug in the sGSL. The glider was configured to continuously record and transmit near-real time data every ~4 hours.

3.4 Results

Step 1: Glider flight plan model

Six unique glider *flight plan*s were modeled (Figure 3.4, Models A through F). The six resulting *survey grid*s contained between 48 and 75 *grid cells*. These were ranked in order of survey efficiency, with larger *survey grid*s being more efficient. The number of *surveyed cell*s was nearly identical among all models and was of limited value for model ranking. The number of *buffer cell*s was much more variable among models and was the major determining factor in the size of the *survey grid*.

The Sawtooth and the Sinusoid-shaped models (Model C and A respectively, Figure 3.4) scored highest for this performance metric, covering 75 and 59 cells respectively (Table 3.1). These models contained 67% and 22% more *unique buffer cell*s, respectively, than other models. This is because their shapes maximize diagonal transitions which minimizes *shared buffer cell*s. The other four models performed similarly to one another, varying by at most 3 *unique buffer cell*s (Table 3.1). However, it is immediately evident that the Sawtooth, the highest ranked model, has a potentially significant drawback in that it leaves large gaps with no *survey effort* between each "V" of the glider track (Figure 3.4, Model C). This suggests Sinusoid may be the best model overall for this performance metric.

Table 3.1 Modeled glider flight plans (Models A through F; Figure 3.4) designed to optimize the model as the first performance metric; the number of grid cells that would be considered surveyed by the glider within a flight plan. The survey grid (surveyed cells and unique buffer cells) and associated number of Surveyed Cells and Unique Buffer Cells is shown for each model. Flight plans are ranked from highest to lowest Survey Grid.

Model Name	Model ID	*Surveyed Cell*s	***Survey Grid***	Unique Buffer
Sawtooth	C	15	**75**	60
Sinusoid	A	15	**59**	44
Five	B	15	**51**	36
Spiral	E	15	**51**	36
Line	F	15	**51**	36
Rectangle	D	15	**48**	33

Steps 2 & 3: Probability of a glider encountering a North Atlantic right whale

Next, the six *flight plan*s were oriented to find the best glider deployment location and initial navigation orientation (latitudinal or longitudinal) relative to the NARW distribution climatology (Figure 3.5) to maximize the spatial overlap between a *flight plan* and NARW encounter probability. The resulting 12 models had a varying $\sum P(encounter)$ ranging between 0.736 and 0.944 (Table 3.2). These were ranked in order of survey efficiency, with the highest $\sum P(encounter)$ being more efficient. The Sinusoid model rotated at 90° (Model A2) scored highest for this performance metric, with a $\sum P(encounter)$ of 0.944 (Figure 3.6), however, the majority of the models (67%) had a $\sum P(encounter)$ ranging between 0.912 and 0.944 (Table 3.2). In contrast, the stretched unidirectional models (the Sawtooth and Line shaped models, Figure 3.4, Models C and F) were not as beneficial for this efficiency metric with a percent decrease in $\sum P(encounter)$ of 7 and 26% respectively compared to the most efficient model.

Table 3.2 Glider flight plan models designed to optimize the second performance metric, NARW detection probability, $\sum P(encounter)$. Flight plans are ranked from highest to lowest $\sum P(encounter)$. Column three lists the starting cell that produced the highest $\sum P(encounter)$ for a given model. Models A) Sinusoid, B) Five, C) Sawtooth, D) Rectangle, E) Spiral, F) Line. Models 1) Non-rotated and 2) Rotated at 90º. Models configurations are shown in Figure B.1.

Model Name	Model ID	Starting Cells	$\sum P(encounter)$
Sinusoid (Rotated 90º)	A2	GW35	**0.944**
Spiral (Rotated 90º)	E2	HA36	**0.940**
Sinusoid	A1	GW35	**0.930**
Five (Rotated 90º)	B2	GV36	**0.926**
Rectangle (Rotated 90º)	D2	GV36	**0.923**
Spiral	E1	GZ37	**0.919**
Five	B1	GX36	**0.914**
Rectangle	D1	GY36	**0.912**
Sawtooth (Rotated 90º)	C2	GZ37	**0.881**
Sawtooth	C1	GV34	**0.829**
Line (Rotated 90º)	F2	GZ37	**0.750**
Line	F1	GY35	**0.736**

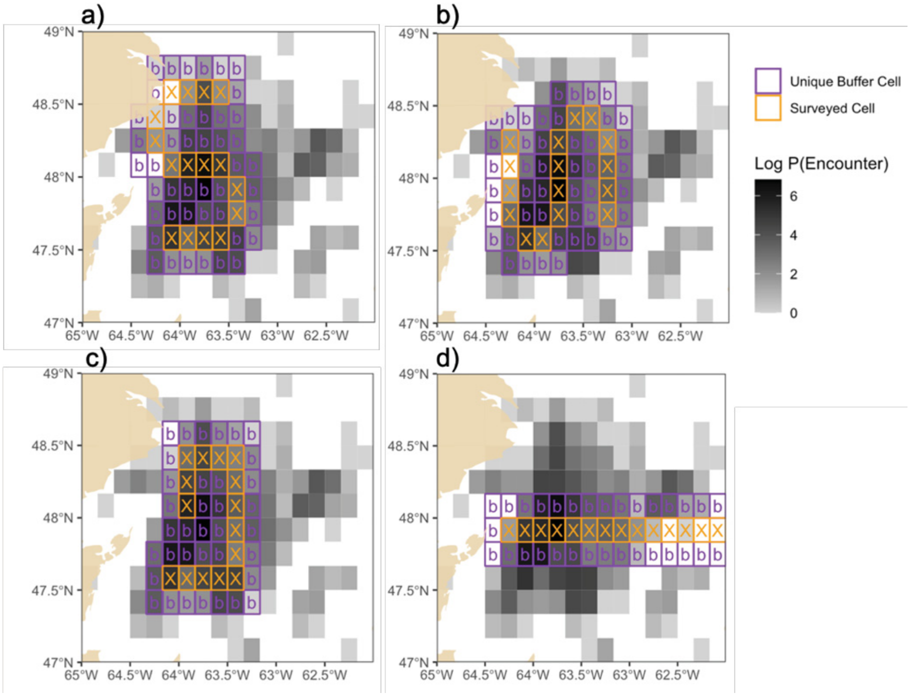


Figure 3.6 a - c) The three flight plan models that scored highest and d) that scored lowest for the second performance metric; NARW detection probability ($\sum P(encounter)$), overlaid with NARW distribution climatology (gray scale). a) Sinusoid rotated at 90º (Model A2) starting at grid cell GW35; $\sum P(encounter) = 0.944$, b) Spiral rotated at 90º (Model E2) starting at grid cell HA36; $\sum P(encounter) = 0.940$, c) Sinusoid (Model A1) starting at grid cell GW35; $\sum P(encounter) = 0.930$, d) Line (Model F1) starting at grid cell GY35; $\sum P(encounter) = 0.736$. Surveyed cells are illustrated with the orange x and unique buffer cells are illustrated with the purple b. All model configurations are shown in Figure B.1.

Step 4: Flight plan performance comparison

The only *flight plan* that ranked among the top models for both performance metrics was the Sinusoid model rotated at 90º (Figure 3.7 Model A2, Figure 3.6a). Although the Sawtooth models (Figure 3.4 Model C1, C2) ranked the highest for the first performance metric, they did not rank highly in the second performance metric (Figure 3.7) because the shape of the models and the shape of the NARW distribution are so different. The Line models (Figure 3.4 Models F) were consistently ranked lower than other models. Though they vary in their performance with the first metric, the cluster of models A, B, D, E rank similarly with the second performance metric (Figure 3.7).

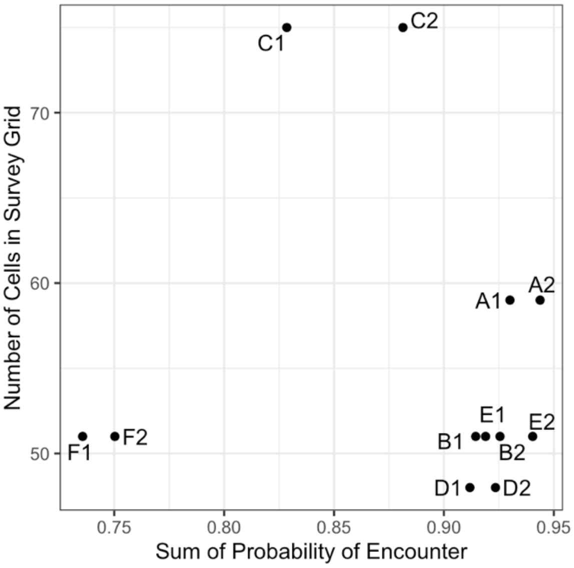


Figure 3.7 Aggregated data for both performance metrics; the survey grid (number of surveyed cells and unique buffer cells) and the NARW detection probability, $\sum P(encounter)$*, of each flight plan model. Models A) Sinusoid, B) Five, C) Sawtooth, D) Rectangle, E) Spiral, F) Line. Models 1) Non-rotated and 2) rotated at 90°. All model configurations are shown in Figure B.1.*

Step 5: Pilot deployment in the southern Gulf of Saint Lawrence

A pilot glider mission was executed during the summer 2020 field season using the highest ranked *flight plan*, Model A2; the sinusoid with a 90° rotation (Figure 3.6a). However, the most northerly and western cells in the *flight plan* were too close to the coast and would bring the glider to a shallow bathymetry which is inoperable for the glider. Therefore prior to the deployment, the launch location of the *flight plan* was shifted to the right and down by one grid cell (Figure 3.8), lowering the $\sum P(encounter)$ to 0.931.

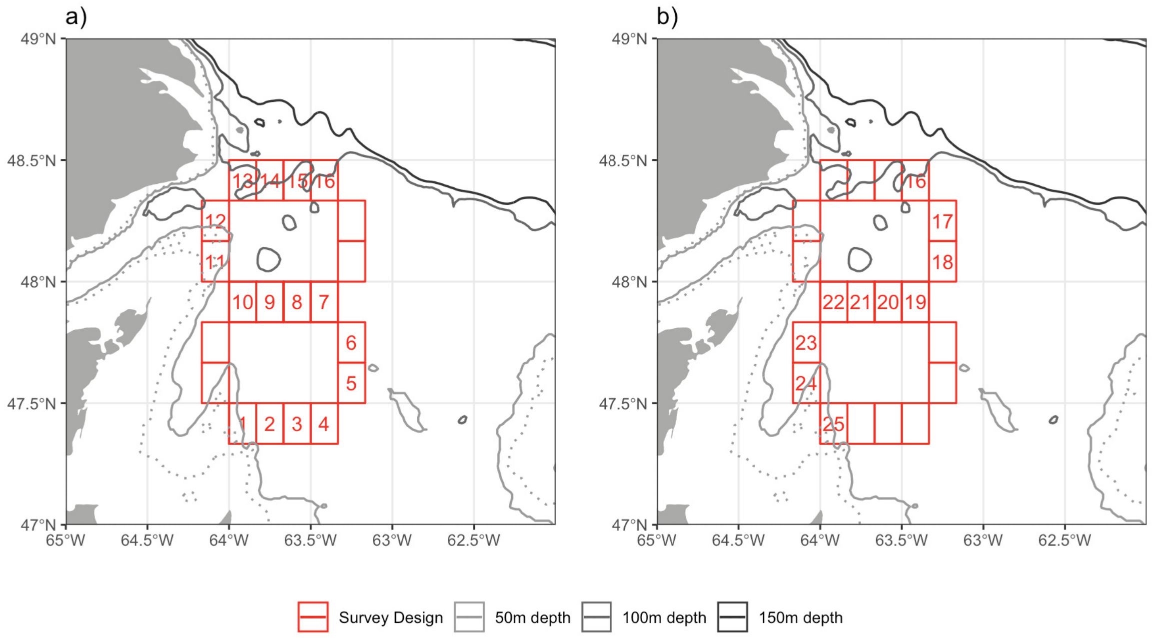


Figure 3.8 The flight plan tested during the glider pilot study mission from Step 1-3; Model A2, the sinusoid with no corners (rotated at 90º) starting at grid cell HB37. a) Leg 1 of the deployment flight plan showing waypoints 1-16, b) Leg 2 of the deployment flight plan in reverse order showing waypoints 17-25.

During the 42-day deployment, the glider flew the *flight plan* approximately 1.5 times. The survey plan was divided into two legs: waypoints 1 through 16 on leg 1, and waypoints 16 through 25 on leg 2 (Figure 3.8). The actual path flown is shown in Figure 3.9. Strong winds and currents impeded the path of the glider near waypoints 11 and 12 in real-time. To minimize the northerly movement of the glider in those waters, waypoints 11 and 12 were shifted east by one *grid cell*, aligning the waypoints with waypoints 10. Waypoint 13 was omitted in the glider's path to allow the glider to continue the planned survey. Near the end of the deployment, waypoints 23 and 24 were also shifted east by one grid cell to avoid the currents that were similar in magnitude and direction as those observed at waypoints 11 and 12. This was done to position the glider in a retrievable location.

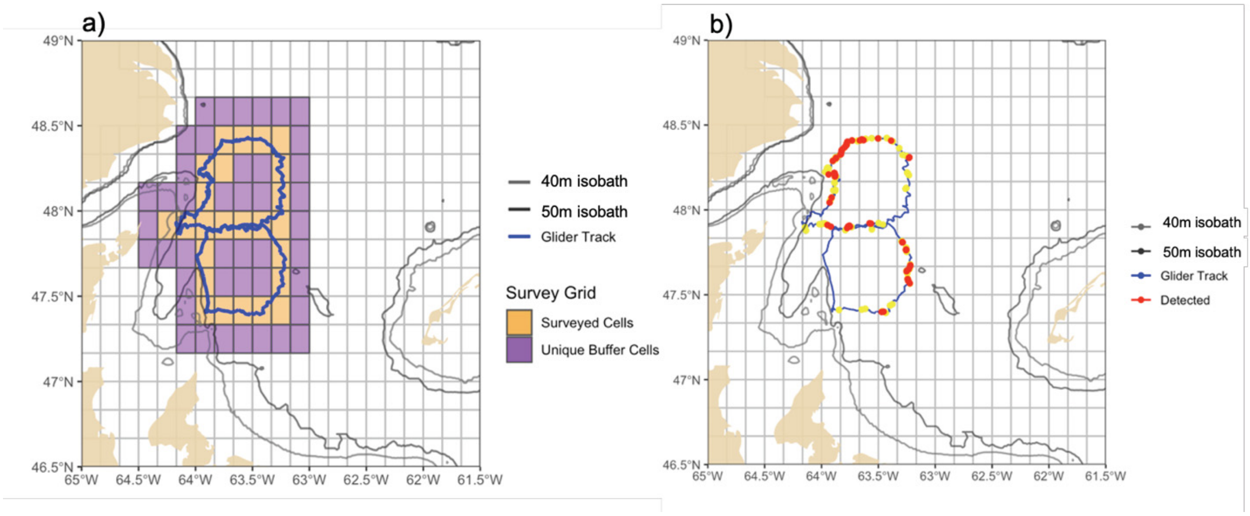


Figure 3.9 a) The path transited by the glider during the pilot mission from July 17th – August 28th, showing the associated survey grid. Surveyed cells are illustrated in orange and unique buffer cells are illustrated in purple. b) The glider tracks (blue track) with associated NARW detections (red dots) and possible detections (yellow dots).

The glider's final survey grid included 25 *surveyed cells* and 43 *unique buffer cells* and the glider made 68 NARW detections on 20 of the 42 deployment days (Figure 3.9). The glider revisited ten of these cells twice and one cell three times throughout the deployment (Figure 3.10a). Many *grid cells* in the *survey grid* had already been closed by visual survey platforms that had been monitoring the region in advance of the glider deployments. However, detections made by the glider closed in total 8 *grid cells* that had not been closed by other platforms, 4 of which were seasonal closures. In a hypothetical scenario where all cells would have been open at the start of the deployment (*i.e.,* if no other *monitoring platforms* had been surveying in advance of the glider), a total of 51 *grid cells* would have been closed by the glider, 40 of which would have been seasonal closures (Figure 3.11). Only once was a seasonal closure triggered from a detection made within the same *surveyed cell* as the initial detection. The majority of the triggered closures occurred by day 30 of the deployment. In fact, almost all 25 *surveyed cell*s would have been closed at least as temporary closures, with the exception of 4 cells within which the glider spent less than 24 hours. Of the 11 cells that were triggered for a temporary closure, only one of them was within triggering range of the glider after its temporary closure expired. In further hypothetical scenarios, wherein seasonal closures would be triggered due to a detection made in a cell two or three days following the initial detection, seasonal closures would have been triggered 37 and 29 times respectively.

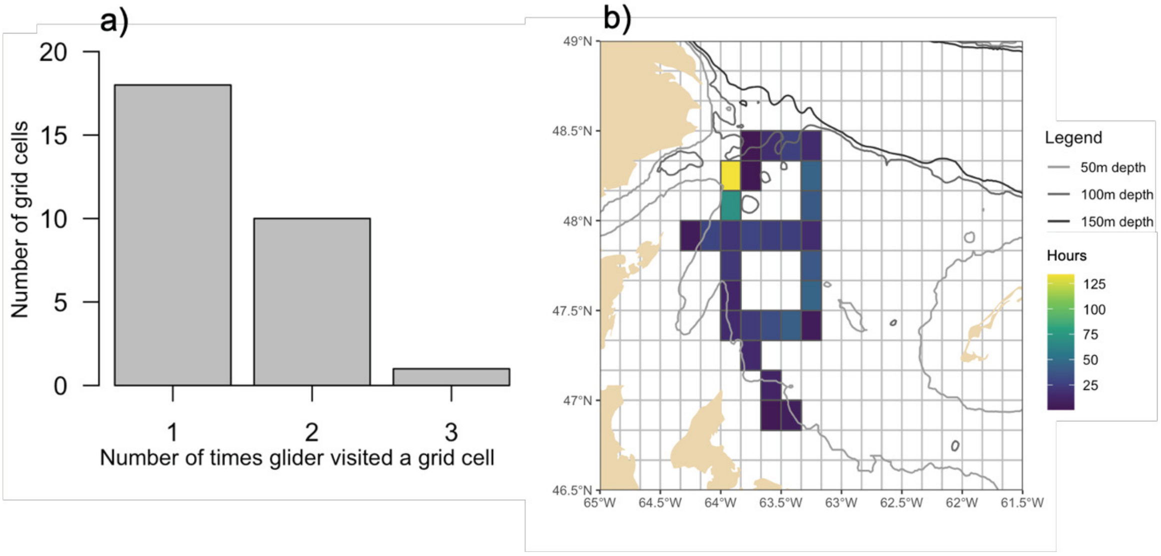


Figure 3.10 a) Number of times the glider visited each grid cell during the pilot mission from July 17th – August 28th. b) Amount of time (hours) the glider spent in each grid cell during the pilot mission.

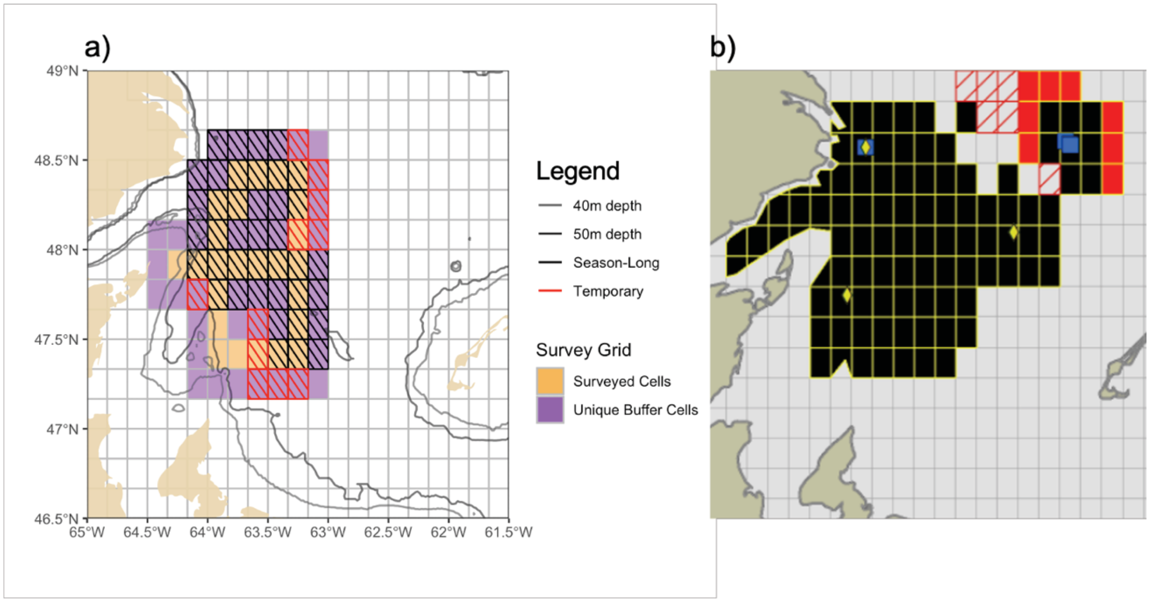


Figure 3.11 a) The hypothetical DFM closures (temporary in red and seasonal in black hatched layer) triggered throughout the glider pilot mission from July 17th – August 28th, overlaid with the survey grid. Surveyed cells are illustrated in orange and unique buffer cells are illustrated in purple. b) The DFO (2020) DFM closures that were triggered as of August 28th, the last day of the pilot mission. Temporary closures are illustrated by red cells and seasonal closures are illustrated by black cells.

The glider was generally slower than expected during the pilot deployment, with a mean horizontal speed of 0.28 knots. The glider transited a minimum and maximum six and 16 *grid cells* every 15 days over the full deployment (Median = 11.00, Mean = 11.03, std = 2.47; Table B.2.2). The minimum and maximum amount of time the glider spent within a cell during a single transit was 0.5 and 133.8 hours respectively; median = 21.6 hours and mean = 25.1 hours (Figure 3.10b, 3.12b). The period during which the glider spent the highest amount of time in a cell coincides with strong winds and currents at waypoints 11 and 12 (Figure 3.10b). An increased amount of time spent in a cell did not appear to correlate with increased NARW detections (Spearman $\rho = 0.26$, $p > 0.1$; Figure 3.12a). Compared to the P(encounter) based on the climatology of NARW distribution between 2015 - 2019, the glider made more detections where the probability was low and fewer detections where the probability was high (Figure 3.13).

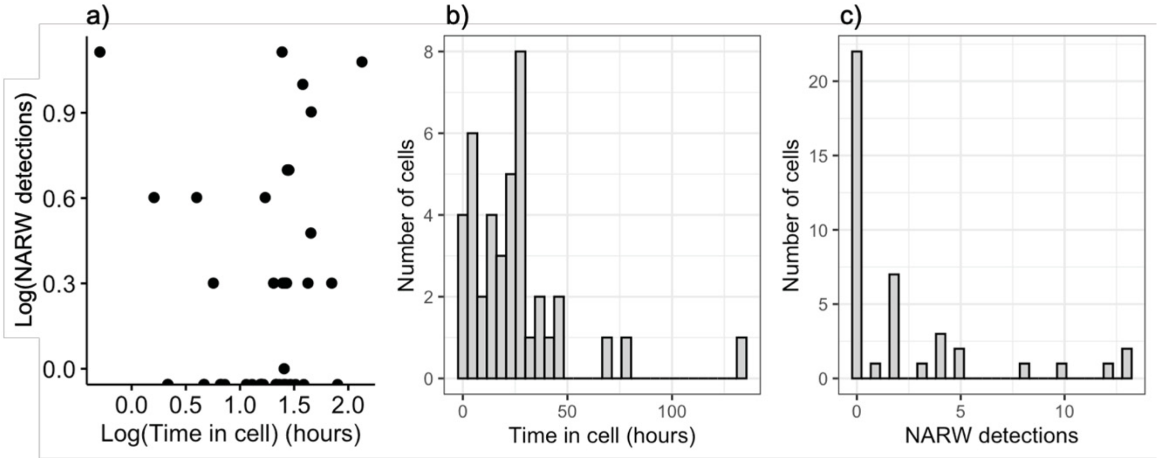


Figure 3.12 a) The Spearman correlation between the time (hours) spent by the glider in one cell at a time and associated number of NARW detected during this time. Data were log transformed. b) The amount of time (hours) spent by the glider in one cell at a time, c) The number of NARW detections made by the glider during time spent in one cell at a time in b).

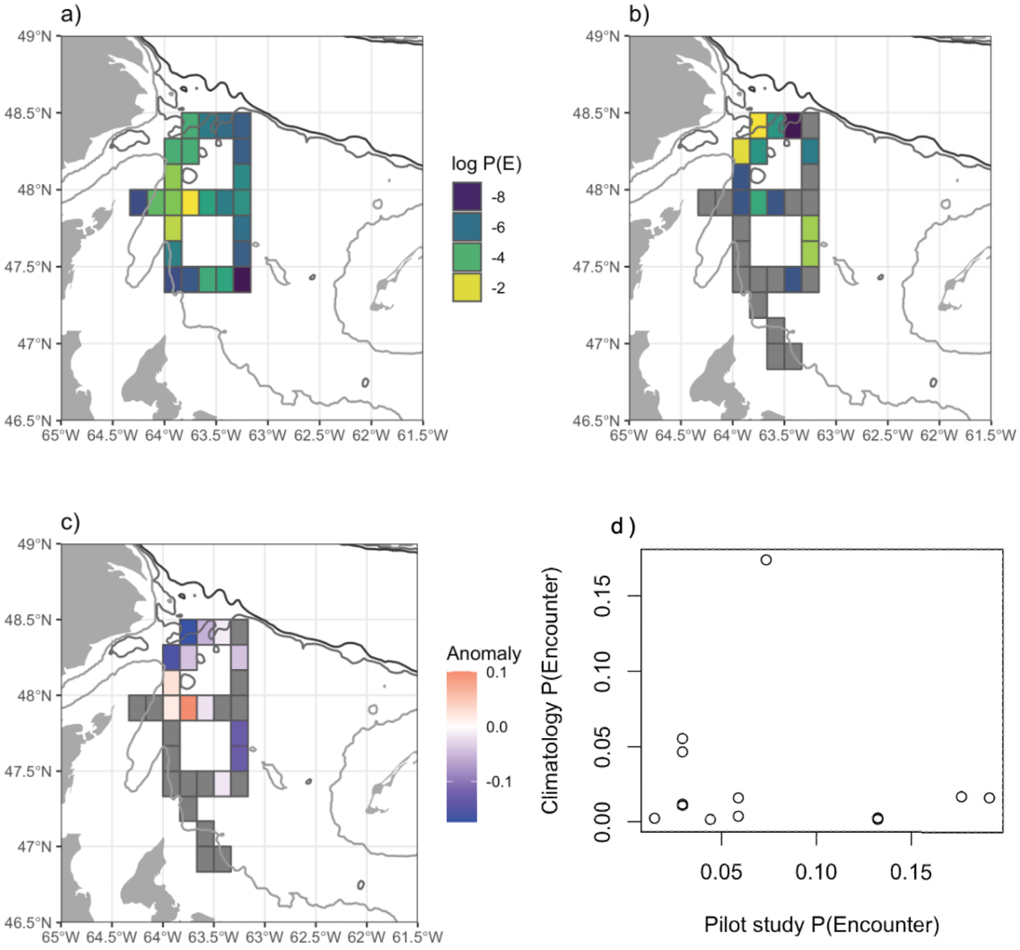


Figure 3.13 a) Log scale of NARW encounter probabilities, taken from the climatology NARW distribution layer from Figure 3.5, within each fishery grid cell of the survey grid of the glider pilot mission, b) Log scale of NARW encounter probabilities within each grid cell, of the survey grid of the glider pilot mission. These probability values were calculated from the number of glider NARW detections in each grid cell divided by all glider NARW detections during pilot mission. c) Anomaly between probabilities of encountering a NARW in a cell between the climatology data and that from the pilot study. d) Scatterplot of NARW encounter probabilities from the climatology against the pilot mission, wherein each point is a different surveyed cell in the deployment.

3.5 Discussion

This study demonstrates how an autonomous *monitoring platform* can strategically be integrated into existing DOM strategies, even if the strategy was not originally planned with gliders as a *monitoring platform*. The measures of success of this study were based on two performance metrics that were established to fit most conservatively the DFM protocols implemented by the DFO in 2020. The aim of this performance study was to design a glider *flight plan* to most efficiently monitor an area for the presence of NARW. I define an efficient flight plan as one that maximizes the glider's potential to survey as many fishery-areas as possible in areas where whales are likely present. This was done to provide a conservative yet maximal protection to the whales. Not only was this the first documented instance of an *acoustic glider* triggering DOM for conservation purposes, this study demonstrates that an autonomous *monitoring platform* can rapidly trigger the fishery-area closure of a large area. Though this highlights the efficiency of the platform to monitor for NARW presence, the glider's speed may have important implications in how this platform can be used to inform DFM in the future.

The *flight plan* models were designed on the assumption that the glider would travel at a speed over ground of approximately 0.5 knots and would therefore travel through one *grid cell* per day and complete a *survey grid* within ~15 days. However, the glider generally moved slower than expected throughout the pilot deployment. Glider speed over ground is variable depending on a number of factors, notably the strength and direction of the ocean currents, how well ballasted the glider is relative to the local vertical density gradient in the water, and the buoyancy engine with which it is equipped. In this study, the glider moved especially slow in areas with stronger currents, which usually occurred in waters that were 40 m depth or less. As a consequence, the glider spent significantly more time in some cells than others and occasionally remained in a single cell for several days. This speed issue might be resolved by incorporating modeled hydrodynamic flow fields into the flight model (*e.g.,* the CANOPA model described by Brickman and Drozdowski, 2012). Flights could be planned so that the glider moves with the currents as opposed to against them, potentially increasing the gliders speed over ground. The glider *flight plan*s could also be designed to avoid some repeatedly problematic areas where the flow fields are not well modeled. However, this could reduce the efficiency of the survey if they correspond with areas within which the glider detected NARWs.

Although an increased amount of time spent in a cell by the glider was not correlated with a higher probability of detecting NARWs, the slower speed of the glider contributed to the higher proportion of seasonal compared to temporary fishery-area closures. For a seasonal closure to be triggered NARWs must be detected by the glider within a cell or in a cell adjacent to it, during two separate 24-hour periods within 15 days of one another. The fact that the glider spent on average over 24 hours in a single cell increased the chance of seasonal closures in most cells, relative to the *flight plan* model. To illustrate this point, consider three adjacent cells. If the glider makes a NARW detection in any of these three cells, the cell with the detection and the associated buffer cells will be closed to fishing. If the glider spends 24 hours in each of the three cells, the cell in the center and the buffer cells above and below are eligible for closure during 72 consecutive hours. If the first detection is made on the first day, there are two additional consecutive days during which a seasonal closure could be triggered. Therefore, each shared buffer cell along the glider *flight plan* is surveyed and available to be closed for three days. In this study, almost all *grid cells* could have been triggered by the glider for seasonal closures and all seasonal closures, except one, would have been triggered due to detections made in *shared buffer cells*. This is driven by the frequency of whale calls, which is likely related to the very dense aggregation of whales that was resident in the area during the time (as confirmed by visual surveillance; whalemap.org, Johnson, 2018; Durette-Morin *et al.*, 2019).

There is a consequence to going too slow in times and places when whale calls may not be prevalent enough to trigger a seasonal closure. The temporal period of 15 days for the *flight plans* was chosen on the basis that the cells would be resurveyed every 15 days to allow continual re-triggering of temporary closures. However, of the 11 cells that reopened upon the expiration of the temporary closure, only one of them was within the detection range of the glider upon its re-opening. In fact, without counting the *buffer cell*s, the majority of the *surveyed cell*s were only surveyed once during the deployment, with the exception of the cells in the center of the *flight plan*. This is because the glider only conducted two legs. If the deployment had been longer, more cells would have been resurveyed more than once during the deployment. Given the slower than anticipated speed of the glider, the targeted survey area could be made smaller to achieve better repeat coverage of the survey area at slower speeds. The trade off to this is that only a portion of the known NARW habitat area would be surveyed by the glider. A solution to this would be to simultaneously use two (or more) *acoustic gliders*.

Alternately, an additional performance metric could be included in the *flight plan* model which would aim to maximise re-*survey effort* among the cells in the *survey grid*. Though the *flight plan* model used in the pilot study scored relatively high in both performance metrics assessed, the *survey effort* was uneven in space and highest at the center arm of the sinusoid (waypoints 7 - 10 and 19 - 22). A different *flight plan* configuration, such as the Rectangle (Figure 3.4 Model D), would promote a more even distribution of effort through time and space. Though this model had a smaller *survey grid*, it scored similarly high on the probability of NARW encounter metric compared to the one used in the pilot study. In fact, there was little difference in the probability of NARW encounter among the majority of the models. Therefore, it is possible that the *flight plan* configuration is less important when it comes to the probability of NARW encounter metric, as long as the glider moves through the climatology layer.

In the present study, glider flight plans were chosen from a "library" of possible geometric configurations (*e.g.,* line, rectangle, saw tooth). An alternative approach would be to design the glider *flight plans* using a dynamic algorithm (*e.g.,* Appendix B.3) which considers the *grid cells* in the immediate proximity of the glider to determine its next trajectory. An algorithmic approach has a number of important advantages: it is dynamic, like the DFM protocol it is informing; it will create more complex flight plan configurations that take into account logistics, climatology, and possibly new observations as they become available in real-time, *e.g.,* PAM detections from the glider or aerial sightings from DFO planes. Future work should further explore this dynamic approach.

Considering the majority of the cells along the glider path in the pilot study were triggered for a seasonal closure, for the purpose of DFM these cells no longer need to be revisited by the monitoring efforts. In an ideal scenario, the most efficient use of the monitoring effort would be re-allocating it to the *grid cells* that remain open. This would require changing the *flight plan* dynamically in real-time in response to the closures, similar to the algorithmic approach proposed above. Logistically speaking this may not be possible due to the glider's slow speed, as it may take numerous days for the glider to travel to the open cells, or if the remaining open cells are spread throughout the *flight plan* after the first transit. Furthermore, this approach may impede the glider's ability to systematically collect oceanographic data for scientific purposes. The latter may not be problematic if the sole purpose of the surveys were for DFM monitoring. At the extreme, the glider could be programmed to remain in one cell until it is closed for the season, then move to the adjacent cell until it is closed, *etc.*, until the whole *survey grid* was closed. However, this could lead to limited spatial survey effort as the glider could survey a single grid cell for numerous days.

The NARW encounter probability climatology seems to be a good predictor of NARW distribution when designing a monitoring plan in the GSL. There were slight anomalies between the probability of NARW encounter, based on the climatology of NARW distribution between 2015-2019, and the glider detections. However, the fishery-area closures that were triggered throughout the 2020 fishing season covered a similar area compared to that highlighted by the climatology layer. This suggests that using climatology is more useful for glider planning than for year-to-year predictions on the NARW distribution within a habitat or region. Had the NARW occurrence data from only the previous year (2019) been used in the pre-flight modeling exercise, the *flight plan* may not have been as successful at triggering dynamic fishery-area closures.

Although the pilot mission was designed to most conservatively fit the current DFM and thus maximize the glider's potential for surveying as many fishery-areas as possible where whales were determined to be present, and successfully did so, this may have greater implications relative to the DFM plan. The current pilot study would have successfully closed most of the *survey grid* within a month of the launch date and the majority of those cells would have been closed for the remainder of the season. For conservation purposes, the higher number of seasonal closures triggered translates to a larger area with lower entanglement risk. However, by definition, DOM opens and closes areas as necessary as the distribution of the target species shift through the managed area and the pilot study does not promote the re-opening of *grid cells*. This raises the questions whether the high occurrence of seasonal closures triggered by the glider were justified or was the glider biased due to an over-sampling of the *grid cells*? Seasonal closures aim to protect areas with persistent NARW presence while the 15-day closure period accounts for short term residency of whales in an area and whale movement therein. Future work should determine whether NARW acoustic presence over three or more days is correlated with persistent NARW presence beyond a 15-day period. Because the NARW distribution is known to shift within a season (*e.g.,* 2017 as shown on whalemap.org, Johnson, 2018; Pettis *et al.*, 2018), it seems important to discuss whether a less conservative condition should trigger seasonal closure (*e.g.,* two non-consecutive days with glider NARW detections) to ensure that the restrictions are only in areas where the whales are consistently present. This could be further assessed with a risk reduction analysis between the use of seasonal closures versus 15-day temporary closures given the known NARW distribution (or a simulated distribution). A similar study should also be conducted on the visual monitoring component of the DFM. Further work should define and assess the success of a DFM relative to whale conservation and the industry.

Although DOM remains a recent conservation approach, many studies use species distribution predictability models, relying on proper characterisation between the target species and their environment (Hobday and Hartmann, 2006; Hobday *et al.*, 2011; Howell *et al.*, 2015; Hazen *et al.*, 2017). This poses a challenge for species with limited distribution data. Though there have been efforts by research and government groups to study whale habitat conditions and develop habitat suitability models (*e.g.,* Pendleton *et al.*, 2012; Plourde *et al.*, 2019; Sorochan *et al.*, 2019), much research remains to be conducted prior to obtaining a model that could inform DFM to protect NARWs. The approach used in this study is different in that it uses real-time occurrence data of the target species, rather than a prediction of where the species might occur. In doing so, the current method provides the means to collect and transmit information on NARW spatial patterns in real-time and dynamically manage human resources at scales that are practical to managers in the GSL, all the while collecting data for habitat suitability models.

Chapter 4 CONCLUSION

This thesis addresses some of the knowledge gaps about the distribution of NARW and provides some information that is needed to find an optimal balance between human activities in Atlantic Canadian waters and protecting whales from human induced injury and mortality. Until recently (since 2015), much of what was known of NARW occurrence in Canadian waters was limited to regular surveys within two small Critical Habitats, opportunistic sightings and historical whaling records. This thesis uses passive acoustic monitoring (PAM) technologies over the spatial scales needed to measure the shelf-scale distribution and seasonal occurrence of the North Atlantic right whale (NARW) population (Chapter 2), and intensive near real-time monitoring at sub-regional scales (Chapter 3), to generate the data needed to advance conservation measures for of NARWs in Canadian waters.

The objectives of Chapter 2 were to define the contemporary northern extent of the species distribution, identify the primary NARW migratory corridor into the GSL, and explore potential previously unidentified high use habitats within Atlantic Canadian waters. To accomplish this, NARW occurrence was measured across Atlantic Canadian waters from the Bay of Fundy to the Labrador Sea using a comprehensive network of fixed (bottom mounted) and mobile (glider-mounted) PAM hydrophone platforms. The results presented in Chapter 2 identified areas of NARW presence off eastern Canada in the 2015 - 2017 period, providing valuable information on NARW distribution and northern range. The greatest year-round NARW occurrence was on the Scotian Shelf, and in the central regions of eastern Canadian waters (such as around the Cabot Strait and in the GSL) between May and December.

NARW occupancy was rare north of the Cabot Strait, highlighting the importance of the Cabot Strait as the primary migratory corridor used by NARWs into the GSL compared to Strait of Belle Isle. These results indicate that likely most of NARWs identified in the sGSL habitat have used this corridor each year since 2015. This finding emphasizes that this is an area with high risk of vessel strike because four shipping lanes and a ferry route intersect in the region and migrating NARWs must transit through at least one lane to enter the GSL. This result was published and used in a federal Canadian Science Advisory Secretariat (CSAS) Science Advisory Report (SAR) used to advise federal government decision makers in the 2019 and 2020 management regulations in Canadian waters to protect NARWs (DFO, 2019a; Durette-Morin *et al.* in review). Thereafter, Transport Canada implemented a voluntary slow-down zone covering the Cabot Strait area in the spring and fall. Although this regulation is not in effect during the entire NARW occupancy period estimated in this study (May through December), it is a landmark event because it is the first voluntary speed reduction zone to be implemented for NARWs in Canada. The results from this study highlight the importance of the Cabot Strait for conservation efforts for the protection of the NARWs species, as well as other whale species.

Overall, Chapter 2 indicates that the increase of NARW occurrence into the GSL (DFO, 2019a; Simard *et al.*, 2019) does not appear to constitute a range shift, but rather a movement of the species into the northern region of their historical range. The broad-scale distribution of NARWs in Canadian waters prior to this study is unknown due to a lack of monitoring effort. However, evidence suggests that prior to the 2010 range shift, the population primarily occurred south of Halifax, in the Bay of Fundy and on Roseway Basin during summer, but that individuals also occasionally used the GSL (Kraus and Rolland, 2007). This work shows that, between 2015 – 2017, the population occurred as far north as the GSL, but not further on the continental shelf to any great extent. This is true even during the summertime 'peak' NARW occupancy period in Canadian waters when subarctic waters are ice-free and can produce high abundances of NARW prey (Environment Canada, 2011; Head *et al.*, 2013; Pepin *et al.*, 2013).

The lack of definite acoustic presence in subarctic waters around Newfoundland and Labrador indicates that the contemporary northern range of the geographic distribution of the species is primarily constrained to the temperate-subarctic latitudinal range. The result highlights that the species does not currently extend as far north as the estimated distribution of their preferred prey, *Calanus finmarchicus* (Conover, 1988; Melle *et al.*, 2014; Record *et al.*, 2018). NARW occurrence in their feeding range is influenced by food abundance and distribution (Pendleton *et al.*, 2009; Record *et al.*, 2019). The reason why

NARWs are not found in larger numbers in more northern waters remains unknown and suggests other factors may be at play. It is possible that NARWs remain a highly sensitive ecological species whose future is dependent on oceanographic process effecting its prey (Baumgartner *et al.*, 2007). Copepods of the genus *Calanus* are sensitive to changes in ocean circulation, temperature, and productivity (Melle *et al.*, 2014; Grieve *et al.*, 2017). Climate change is altering these processes dramatically in the North Atlantic, which is changing the spatial and temporal availability of NARW food (Richardson, 2008; Grieve *et al.*, 2017; Record *et al.*, 2019; Pershing and Stamieszkin, 2020). If the declining trend in *C. finmarchicus* abundance that has been occurring in the Gulf of Maine, Scotian Shelf and GSL since 2010 (DFO, 2016; Sorochan *et al.*, 2019) continues into future decades, NARWs may well migrate further north in search of additional prey resources, which would represent a significant shift in the ecological niche for this species.

Given that only a portion of the NARW population has been sighted in the GSL (L. Crowe, personal communication, NMFS, Woods Hole, MA; Crowe, 2020), a question of great importance to the conservation of the species is where the remaining portion of the population goes during the summer period if not in the contemporary core regions in Chapter 2. New summertime aggregations have been found south of the Gulf of Maine in the Nantucket Shoals region, suggesting the population could be spread out both north and south of the Gulf of Maine (RWSAS, n.d.; Johnson, 2018). Continued research is crucial to locate as yet unidentified habitats where whales may be aggregating in large numbers (Meyer-Gutbrod *et al.*, 2018). Furthermore, in the event that the species' distribution does change and shifts north of the Cabot Strait, the distribution would overlap with different types of human risks, including seismic activity, which is known to have broad impacts on baleen species (Castellote *et al.*, 2012; Blackwell *et al.*, 2013; Cerchio *et al.*, 2014) but unknown effects on this particular population. Continued and improved monitoring techniques for efficient risk mitigations in these waters will be critical, despite their current (apparently) low occurrence in these areas. Mitigation of human risk can only occur if we know where the whales and their threats overlap. Alternatively, there is a possibility that the remainder of the population does not aggregate in specific areas in large numbers; these whales may be dispersed. This would be problematic for conservation purposes but would explain why the whereabouts of a large portion of the population remains consistently unknown at all times.

The objective of Chapter 3 was to design a survey flight plan for a real-time monitoring acoustic glider platform to optimally inform a given set of DOM protocol parameters in the GSL. To accomplish this, a performance study was presented wherein metrics were defined to characterize the efficiency of glider monitoring assets for triggering the NARW DOM protocol in the GSL. Glider flight plans were then modeled with variable efficiency in relation to the known NARW distribution. Finally, one of my modeled survey plans was tested during a pilot mission in the GSL where the NARW detections were used to trigger fishery-area closures.

To my knowledge, this pilot study was the first use of an acoustic glider to trigger dynamic fishery closure protocols for marine mammal conservation purposes. This approach provides the means to collect and transmit information on NARW spatial patterns in real time and dynamically manage human resources at scales that are practical to managers in the GSL, all the while collecting data for habitat suitability models. This is a unique approach compared to many DOM tools that use modeled predictions as proxy for distribution data of target species (*e.g.,* Hazen *et al.*, 2018). While it is not possible to make direct comparisons of efficiency among these different tools, it is important to highlight that this pilot study uses a purely empirical approach predicated on 100% accurate real-time distribution data. This means that industry restrictions are only activated when the target species is present as opposed to modeled with a level of uncertainty. This tool is thus designed for the coexistence among the industry and conservation. Furthermore, the near real-time data obtained with this tool could be assimilated into models to improve their distribution prediction output.

Advancements in our ability to deploy and conduct surveys to optimally inform how to allocate human activities for minimization of the risks to whales is crucial for the development of a balance between the pursuit of NARW conservation and the continuation of industries needed for the livelihood of many Canadians in coastal communities. As NARW distribution appears to be constrained to what is defined as the contemporary core regions (Chapter 2), the areas where NARWs are known to occur are currently of great importance for conservation. This highlights the importance of optimizing tools to monitor the species for the purpose of risk mitigation (Chapter 3), because most of the waters in these core regions overlap with extensive human activity which can be detrimental to the species. The performance study and pilot study conducted in Chapter 3 of this thesis are but the first steps in this optimization, which should be conducted for all monitoring platforms used to monitor the species, especially for the purpose of risk mitigation.

The application of such an optimization process is not limited to NARW conservation in Canadian waters; unprecedented shifts in the distribution of species have been observed around the world (Perry *et al.*, 2005; Pinsky *et al.*, 2013). Tools that can rapidly assess regional distributional shifts are critical for scientists and managers to quickly adapt to these changes. These tools must be mobile, fit within a variety of management frameworks, and allow monitoring offshore and in remote locations. Ocean gliders can be useful for many marine conservation situations that fit the above requirements; scientists can monitor in offshore MPAs, whale conservation zones, shipping lanes, international fishing areas, and as remote as the Arctic and Antarctic. Although gliders are flexible in their use, it is important to tailor their deployments to particular circumstances and application. For example, develop sensors that can monitor species of interest, develop software that can process and disseminate data onboard the glider, and design flight plans that can adapt to a particular problem, region, or species. Chapter 3 is an example of the importance of such a process. In fact, though simple at its core, this study identified the strengths and weaknesses of gliders as a DOM tool and determined how gliders can best be used in future years to mitigate harm to NARW from fisheries in the GSL.

The development and use of these PAM technologies for the conservation of NARW in Canadian waters was largely in response to a mortality crisis that drastically reduced the population size of this endangered species. Five years passed between the time NARWs began abandoning their known summer habitats and the discovery of large aggregations in the GSL (Davies and Brillant, 2019). Over this same period, gliders and real-time PAM have been developed as a tool for rapid NARW presence assessment to help prevent further multi-year gaps in the knowledge of NARW distribution and help prevent future mortality crises. This thesis is a significant contribution to this effort.

Appendix A CHAPTER 2

A.1 Recorder information

Table A.1.1 Recorder information of the 2015-2017 PAM recording system deployments analysed in this study.

Data Providing Agency	Platform	Instrument Type	Deployment Location	Deployment Location	Water Depth (m)	Instrument Depth (m)	Latitude	Longitude	Deployment Date (DD/MM/YY)	Recovery Date (DD/MM/YY)	Sampling Rate (kHz)	Duty Cycle (seconds on /seconds off)
Dalhousie	Mooring	AMAR	RB	Roseway Basin	NA	165	42.948	-65.225	30/06/15	30/11/15	32	678/522
DFO-Mar	Mooring	AMAR	EB	Emerald Basin	205	185	43.608	-62.869	24/05/15	19/04/16	8	678/522
DFO-Mar	Mooring	AMAR	SF	Stone Fence	487.5	424.5	44.463	-57.183	22/09/15	21/09/16	8	678/522
DFO-Mar	Mooring	AMAR	SABS	St. Ann's Bank	94	74	46.195	-59.155	16/06/15	01/05/16	8	678/525
DFO-Mar	Mooring	AMAR	SABD	St. Ann's Bank	371	308	46.355	-58.728	17/06/15	01/05/16	8	678/522
DFO-Mar	Mooring	AMAR	EB	Emerald Basin	201	181	43.608	-62.869	16/09/16	01/12/17	8	678/522
DFO-Mar	Mooring	AMAR	SF	Stone Fence	468	449	44.463	-57.183	11/11/16	01/12/17	8	678/522
DFO-Mar	Mooring	AMAR	SABS	St. Ann's Bank	100	80	46.195	-59.155	24/09/16	01/12/17	8	678/522
DFO-Mar	Mooring	AMAR	SABD	St. Ann's Bank	375	355	46.355	-58.728	23/09/16	01/12/17	8	678/522
DFO-NFLD	Mooring	AURAL	SPB	St. Pierre Bank - Shallow	60	110.3	46.482	-57.378	08/12/15	18/07/16	32	600/3000
DFO-NFLD	Mooring	AURAL	SPB	St. Pierre Bank - Deep	50	347.5	45.881	-56.998	12/08/15	18/07/16	32	1200/2400

Data Providing Agency	Platform	Instrument Type	Deployment Location	Deployment Location	Water Depth (m)	Instrument Depth (m)	Latitude	Longitude	Deployment Date (DD/MM/YY)	Recovery Date (DD/MM/YY)	Sampling Rate (kHz)	Duty Cycle (seconds on /seconds off)
DFO-NFLD	Mooring	AURAL	BB	Burgeo Bank (Offshore)	59	109	46.970	-57.973	10/08/15	19/07/16	32	1200/2400
DFO-NFLD	Mooring	µAURAL	RBBNear	Rose Blanche Bank (Nearshore)	84	95	47.567	-58.780	25/03/16	15/11/16	32	2040/1560
DFO-NFLD	Mooring	AURAL	SPB	St. Pierre Bank West	75	100	46.484	-57.369	25/07/16	20/08/17	32	2040/1560
DFO-NFLD	Mooring	AURAL	RBB OFF	Offshore - Rose Blanche Bank	128	154	47.472	-58.776	15/11/16	20/08/17	32	2040/1560
DFO-NFLD	Mooring	AURAL	RBB Near	Nearshore - Rose Blanche Bank	72	72	47.571	-58.778	15/11/16	21/08/17	32	2040/1560
DFO-NFLD	Mooring	AURAL	PBAC	Placentia Bay Arnold's Cove	96	100	47.771	-54.043	27/06/17	28/08/17	32	2040/1560
DFO-NFLD	Mooring	AURAL	PBRI	Placentia Bay Red Island	96	100	47.342	-54.167	26/06/17	28/07/17	32	2040/1560
DFO-NFLD	Mooring	AURAL	PrtBsq	Port aux Basques	124	128	47.520	-59.025	20/08/17	01/12/17	32	2040/1560
DFO-NFLD	Mooring	AURAL	RBB Near	Rose Blanche Nearshore	72	72	47.571	-58.778	21/08/17	01/12/17	32	1200/2400
JASCO	Mooring	AMAR	BOF01	Bay of Fundy	151	151	44.558	-66.334	27/08/15	01/12/15	16	700/500
JASCO	Mooring	AMAR	BOF02	Bay of Fundy	140	140	44.769	-66.254	26/08/15	01/12/15	16	700/500

Data Providing Agency	Platform	Instrument Type	Deployment Location	Deployment Location	Water Depth (m)	Instrument Depth (m)	Latitude	Longitude	Deployment Date (DD/MM/YY)	Recovery Date (DD/MM/YY)	Sampling Rate (kHz)	Duty Cycle (seconds on /seconds off)
JASCO	Mooring	AMAR	BOF03	Bay of Fundy	123	123	44.759	-66.155	26/08/15	01/12/15	16	700/500
JASCO	Mooring	AMAR	BOF04	Bay of Fundy	90	90	44.560	-66.584	27/08/15	01/12/15	16	700/500
JASCO	Mooring	AMAR	BOF01	Bay of Fundy	148	148	44.558	-66.334	01/12/15	28/04/16	16	700/500
JASCO	Mooring	AMAR	BOF02	Bay of Fundy	139	139	44.769	-66.254	01/12/15	28/04/16	16	700/500
JASCO	Mooring	AMAR	BOF03	Bay of Fundy	119	119	44.759	-66.155	01/12/15	28/04/16	16	700/500
JASCO	Mooring	AMAR	BOF04	Bay of Fundy	82	82	44.560	-66.584	01/12/15	28/04/16	16	700/500
JASCO	Mooring	AMAR	ESRF1	ESRF-15-16	186	161	46.991	-60.024	17/08/15	15/07/16	8	678/522
JASCO	Mooring	AMAR	ESRF2	ESRF-15-16	126	101	45.426	-59.764	17/08/15	15/07/16	8	678/522
JASCO	Mooring	AMAR	ESRF4	ESRF-15-16	1830	1805	43.217	-60.499	19/08/15	15/07/16	8	678/522
JASCO	Mooring	AMAR	ESRF5	ESRF-15-16	2002	1977	42.548	-62.176	19/08/15	15/07/16	8	678/522
JASCO	Mooring	AMAR	ESRF6	ESRF-15-16	1802	1777	44.853	-55.271	22/08/15	15/07/16	8	678/522
JASCO	Mooring	AMAR	ESRF7	ESRF-15-16	78	53	45.701	-51.233	23/08/15	15/07/16	8	678/522
JASCO	Mooring	AMAR	ESRF8	ESRF-15-16	428	403	47.493	-59.413	16/08/15	15/07/16	8	678/522
JASCO	Mooring	AMAR	ESRF9	ESRF-15-16	44	44	48.927	-58.878	16/08/15	15/07/16	8	678/522
JASCO	Mooring	AMAR	ESRF10	ESRF-15-16	121	96	51.269	-57.538	03/08/15	15/07/16	8	678/522
JASCO	Mooring	AMAR	ESRF11	ESRF-15-16	158	133	55.603	-57.750	09/08/15	15/07/16	8	678/522
JASCO	Mooring	AMAR	ESRF12	ESRF-15-16	143	118	57.253	-60.002	10/08/15	15/07/16	8	678/522
JASCO	Mooring	AMAR	ESRF13	ESRF-15-16	1750	1725	55.228	-54.190	08/08/15	15/07/16	8	678/522
JASCO	Mooring	AMAR	ESRF14	ESRF-15-16	582	557	53.016	-53.460	04/08/15	15/07/16	8	678/522
JASCO	Mooring	AMAR	ESRF15	ESRF-15-16	2000	1975	50.413	-49.196	14/08/ 15	15/07/16	8	678/522

Data Providing Agency	Platform	Instrument Type	Deployment Location	Deployment Location	Water Depth (m)	Instrument Depth (m)	Latitude	Longitude	Deployment Date (DD/MM/YY)	Recovery Date (DD/MM/YY)	Sampling Rate (kHz)	Duty Cycle (seconds on /seconds off)
JASCO	Mooring	AMAR	ESRF16	ESRF-15-16	1602	1577	44.192	-53.274	23/08/15	15/07/16	8	678/522
JASCO	Mooring	AMAR	ESRF17	ESRF-15-16	1282	1257	44.971	-48.734	24/08/15	15/07/16	8	678/522
JASCO	Mooring	AMAR	ESRF18	ESRF-15-16	111	86	46.909	-48.504	24/08/15	15/07/16	8	678/522
JASCO	Mooring	AMAR	ESRF19	ESRF-15-16	1282	1257	48.729	-49.381	25/08/15	15/07/16	8	678/522
JASCO	Mooring	AMAR	ESRF20	ESRF-15-16	237	212	50.752	-52.336	13/08/15	15/07/16	8	678/522
JASCO	Mooring	AMAR	ESRF1	ESRF-16-17	175	161	46.991	-60.024	15/07/16	15/07/17	8	678/522
JASCO	Mooring	AMAR	ESRF2	ESRF-16-17	120	101	45.426	-59.764	15/07/16	15/07/17	8	678/522
JASCO	Mooring	AMAR	ESRF3	ESRF-16-17	72	72	44.048	-60.595	15/07/16	15/07/17	8	678/522
JASCO	Mooring	AMAR	ESRF4	ESRF-16-17	1558	1805	43.217	-60.499	15/07/16	15/07/17	8	678/522
JASCO	Mooring	AMAR	ESRF5	ESRF-16-17	1831	1831	42.548	-62.176	15/07/16	15/07/17	8	678/522
JASCO	Mooring	AMAR	ESRF6	ESRF-16-17	1790	1777	44.853	-55.271	15/07/16	15/07/17	8	678/522
JASCO	Mooring	AMAR	ESRF8	ESRF-16-17	420	403	47.493	-59.413	15/07/16	15/07/17	8	678/522
JASCO	Mooring	AMAR	ESRF9	ESRF-16-17	43	43	48.927	-58.878	15/07/16	15/07/17	8	678/522
JASCO	Mooring	AMAR	ESRF10	ESRF-16-17	110	96	51.269	-57.538	15/07/16	15/07/17	8	678/522
JASCO	Mooring	AMAR	ESRF11	ESRF-16-17	150	133	55.603	-57.750	15/07/16	15/07/17	8	678/522
JASCO	Mooring	AMAR	ESRF12	ESRF-16-17	142	118	57.253	-60.002	15/07/16	15/07/17	8	678/522
JASCO	Mooring	AMAR	ESRF13	ESRF-16-17	1700	1700	55.228	-54.190	15/07/16	15/07/17	8	678/522
JASCO	Mooring	AMAR	ESRF14	ESRF-16-17	551	551	53.016	-53.460	15/07/16	15/07/17	8	678/522
JASCO	Mooring	AMAR	ESRF15	ESRF-16-17	1993	1975	50.413	-49.196	15/07/16	15/07/17	8	678/522
JASCO	Mooring	AMAR	ESRF16	ESRF-16-17	1608	1577	44.192	-53.274	15/07/16	15/07/17	8	678/522

Data Providing Agency	Platform	Instrument Type	Deployment Location	Deployment Location	Water Depth (m)	Instrument Depth (m)	Latitude	Longitude	Deployment Date (DD/MM/YY)	Recovery Date (DD/MM/YY)	Sampling Rate (kHz)	Duty Cycle (seconds on /seconds off)
JASCO	Mooring	AMAR	ESRF17	ESRF-16-17	1273	1257	44.971	-48.734	15/07/16	15/07/17	8	678/522
JASCO	Mooring	AMAR	ESRF18	ESRF-16-17	214	86	46.909	-48.504	15/07/16	15/07/17	8	678/522
JASCO	Mooring	AMAR	ESRF19	ESRF-16-17	1547	1522	48.374	-46.518	15/07/16	15/07/17	8	678/522
JASCO	Mooring	AMAR	ESRF20	ESRF-16-17	236	212	50.752	-52.336	15/07/16	15/07/17	8	678/522
JASCO/DFO	Mooring	AMAR	DFO-ST	Grand Bank	117	117	45.446	-48.764	24/08/15	09/10/15	64	480/720
JASCO/DFO	Mooring	AMAR	DFO-CT	Grand Bank	155	155	44.903	-49.272	24/08/15	11/10/15	64	480/720
Dalhousie	Slocum	DMON	EB	halifaxline	NA	NA	NA	NA	27/07/15	23/08/15	2	1800 /1800
Dalhousie	Slocum	DMON	RB	roseway	NA	NA	NA	NA	28/07/15	04/09/15	2	1800 /1800
Dalhousie	Slocum	DMON	EB	halifaxline	NA	NA	NA	NA	10/09/15	04/10/15	2	1800 /1800
Dalhousie	Slocum	DMON	EB	halifaxline	NA	NA	NA	NA	27/10/15	17/11/15	2	1800 /1800
Dalhousie	Slocum	DMON	EB	halifaxline	NA	NA	NA	NA	22/01/16	11/02/16	2	1800 /1800
Dalhousie	Slocum	DMON	WS	westshelf	NA	NA	NA	NA	24/06/16	13/10/16	2	1800 /1800
Dalhousie	Slocum	DMON	RB	roseway	NA	NA	NA	NA	06/10/16	30/10/16	2	1800 /1800
Dalhousie	Slocum	DMON	RB	roseway	NA	NA	NA	NA	02/11/16	24/11/16	2	1800 /1800
Dalhousie	Slocum	DMON	GSL	GoSL	NA	NA	NA	NA	05/06/17	19/09/17	2	1800 /1800

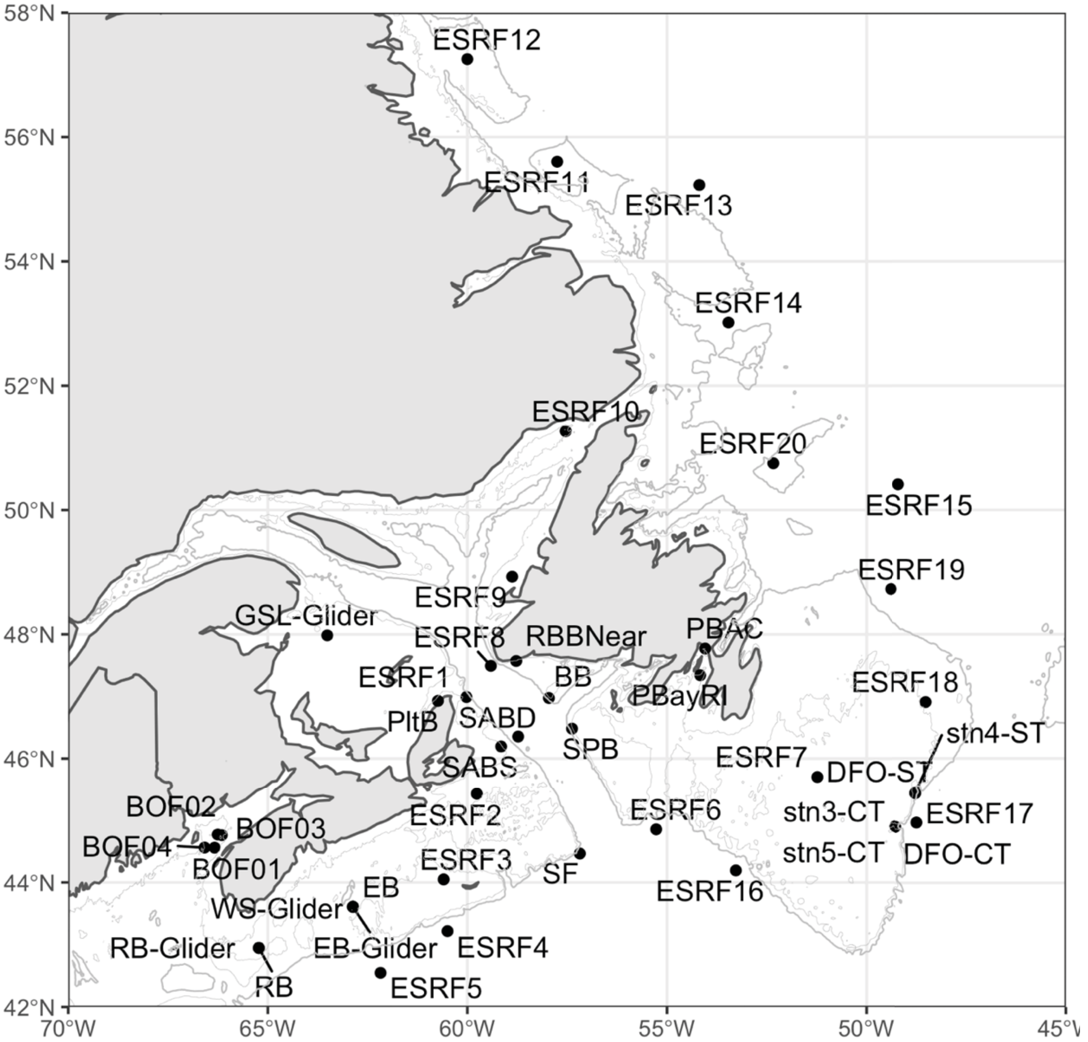


Figure A.1.1 Deployment locations of the 2015-2017 PAM recording system analysed in this study. Line-tracks are shown for the PAM Slocum gliders and closed circles for the PAM moorings. The 400m isobath is shown in light grey.

A.2 Sensitivity analysis

To test the sensitivity of effort variation of the seasonal acoustic presence signal observed in Figure 2.3a, the daily presence data for each region (Figure 2.4) was randomly permutated within the bounds of recording effort (n = 1000). Figure 2.3a was then regenerated using the means of weekly presence obtained from the permutation (Figure A.2.1a). This analysis suggests the seasonal signal is sensitive to the effort collection.

However, the peak of the signal coincides temporally with the recording effort in the sGSL region (Jun though Sep; Figure 2.4). When the data were permutated while omitting the recorder in the sGSL region, the signal is not as strong (Figure A.2.1b). This suggests that the seasonal signal was highly sensitive to the limited recording effort in the sGSL region rather than the effort variation across all regions; the seasonal signal was not strongly affected by the way the data was collected, except for the effort in the sGSL. The seasonal signal observed in Figure 2.3a remains even when the sGSL data is omitted (Figure A.2.2).

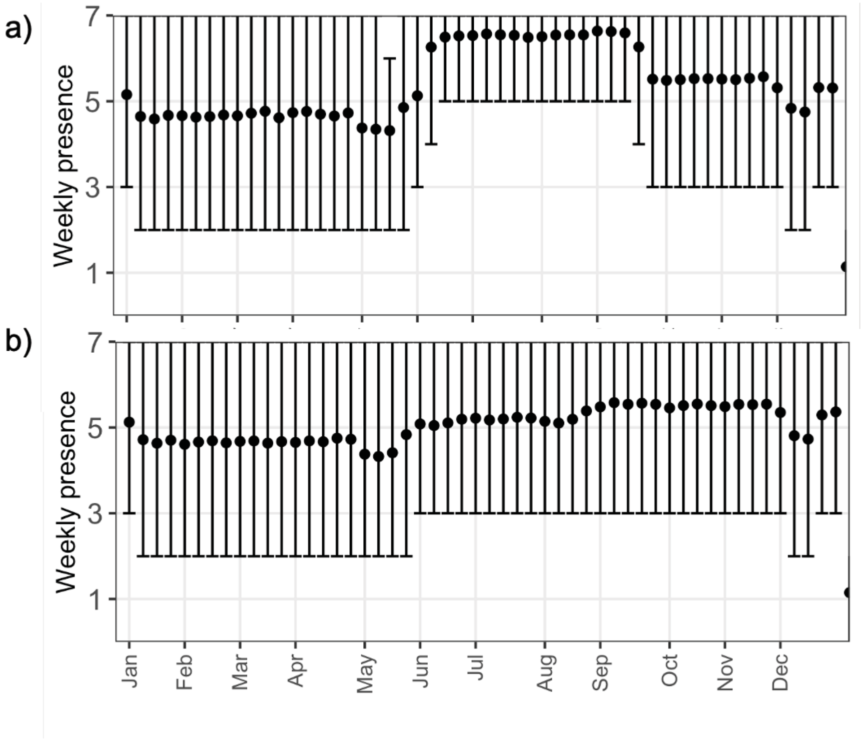


Figure A.2.1 Mean weekly acoustic presence from the random permutation of daily presence data. a) Presence data from all regions were permutated, and b) Presence data from all regions except for the sGSL were permutated. Data were permutated within the bounds of recording effort. The error bars depict the 95% confidence intervals of the permutated data (n = 1000).

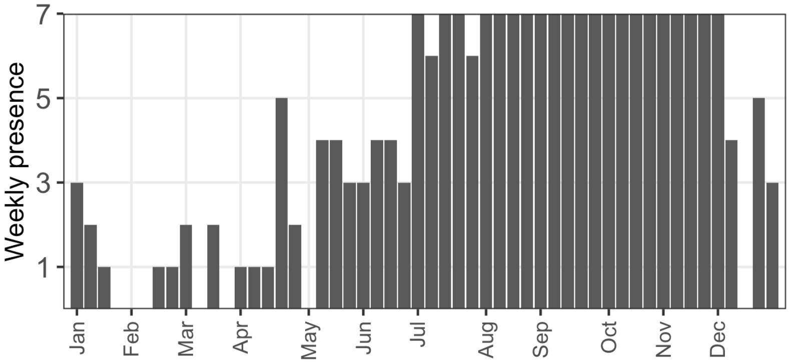
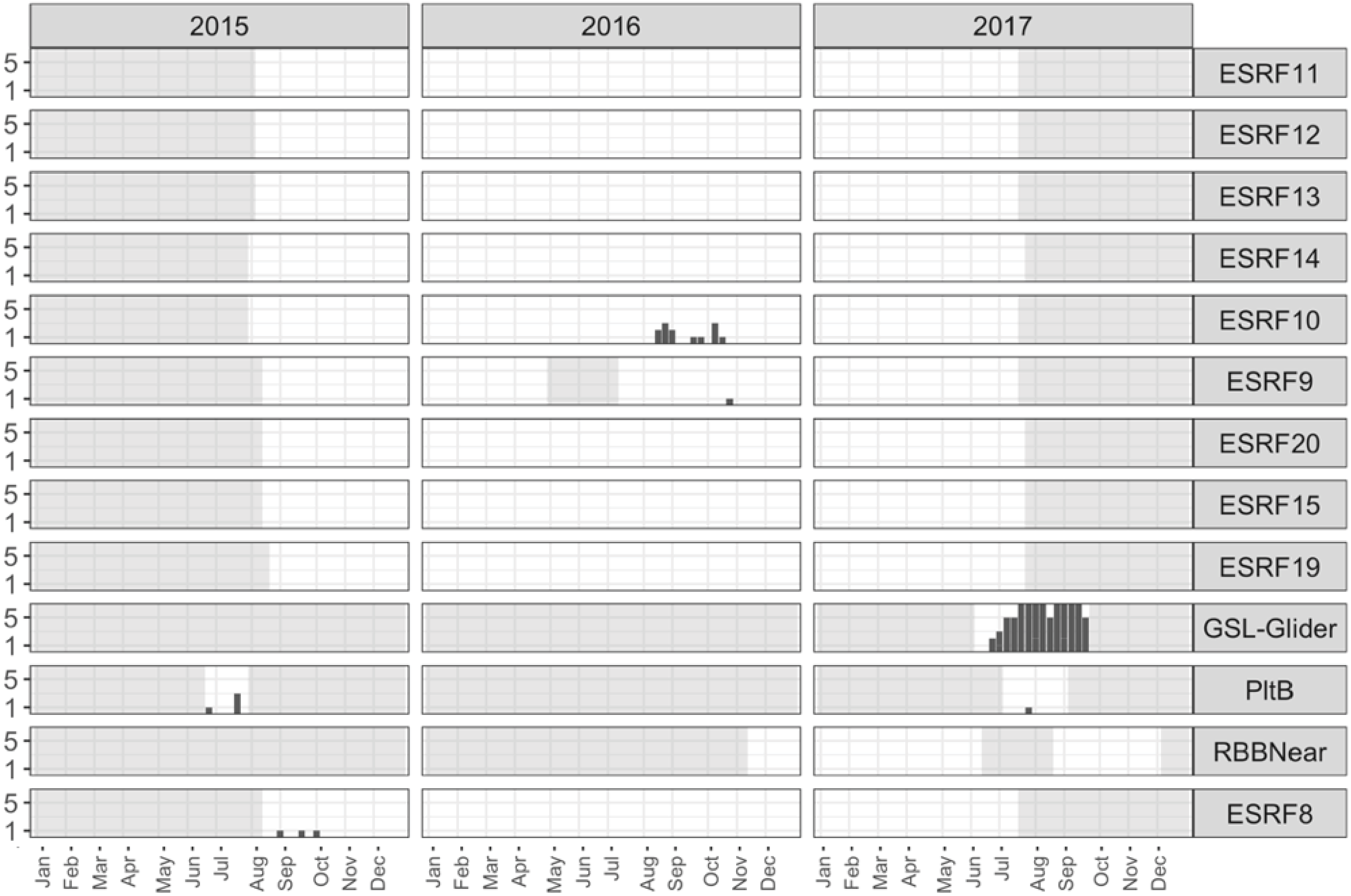
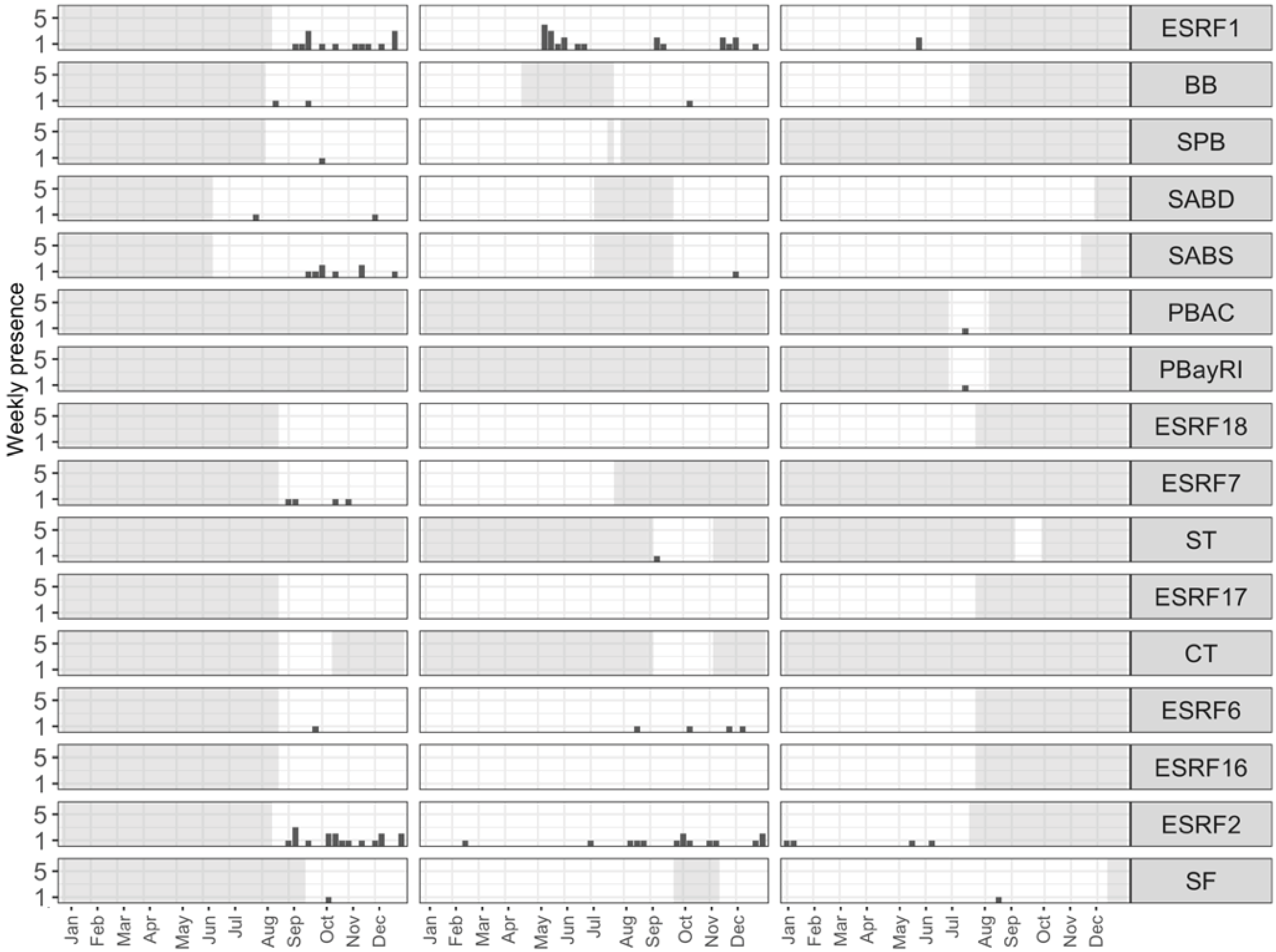


Figure A.2.2 The number of days per week with at least one NARW upcall detection per day across all recorders analysed for this study in Canadian waters aggregated overall years analysed. The sGSL region recorder was omitted in this analysis.

A.3 Deployment location acoustic presence




Weekly presence
5
1
ESRF1
BB
SPB
SABD
SABS
PBAC
PBayRI
ESRF18
ESRF7
ST
ESRF17
CT
ESRF6
ESRF16
ESRF2
SF
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec

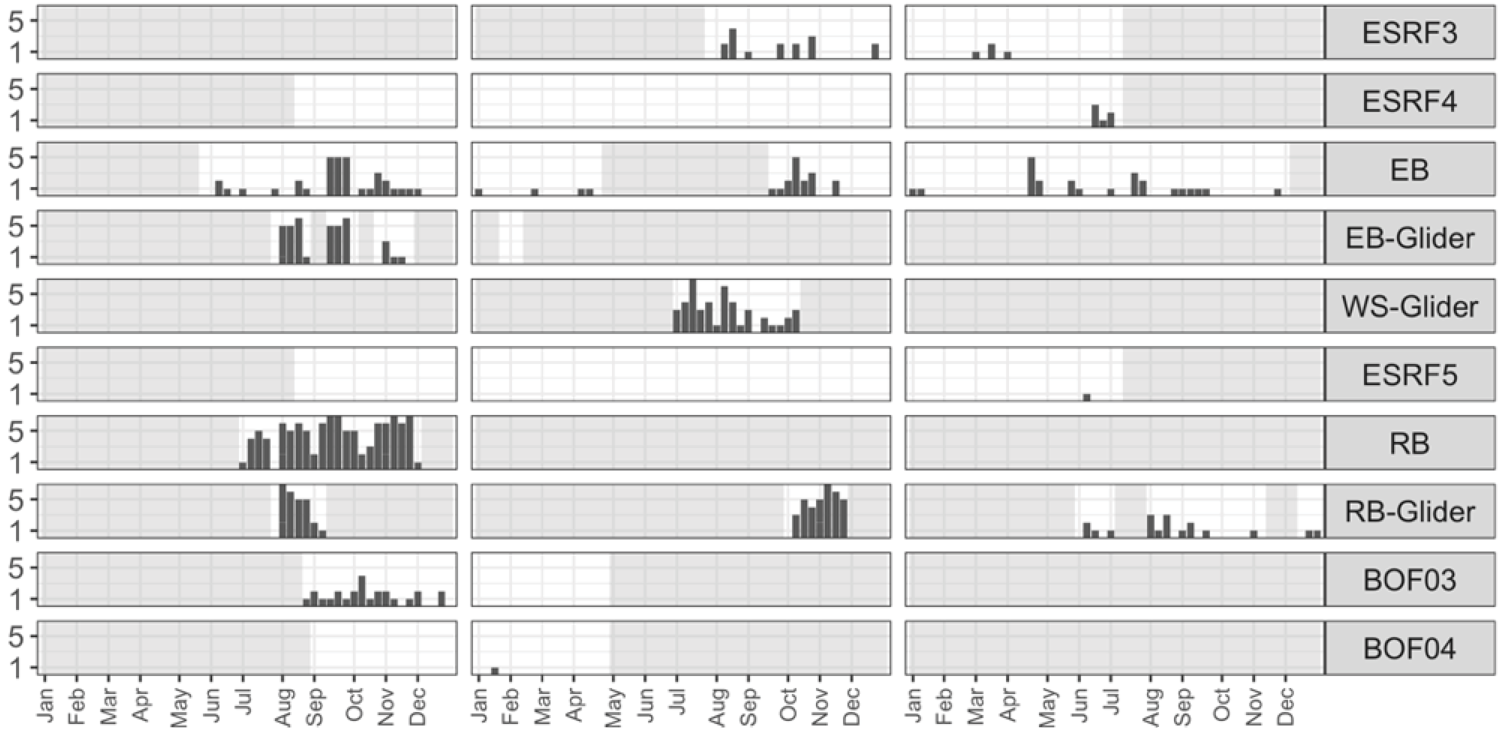


Figure A.3.1 The number of days per week with at least one NARW upcall detection per day at each deployment location. Light grey polygons indicate periods with no recording effort in that deployment location. Refer to Figure A.1.1 for the locations.

Appendix B CHAPTER 3

B.1 Glider flight plan models

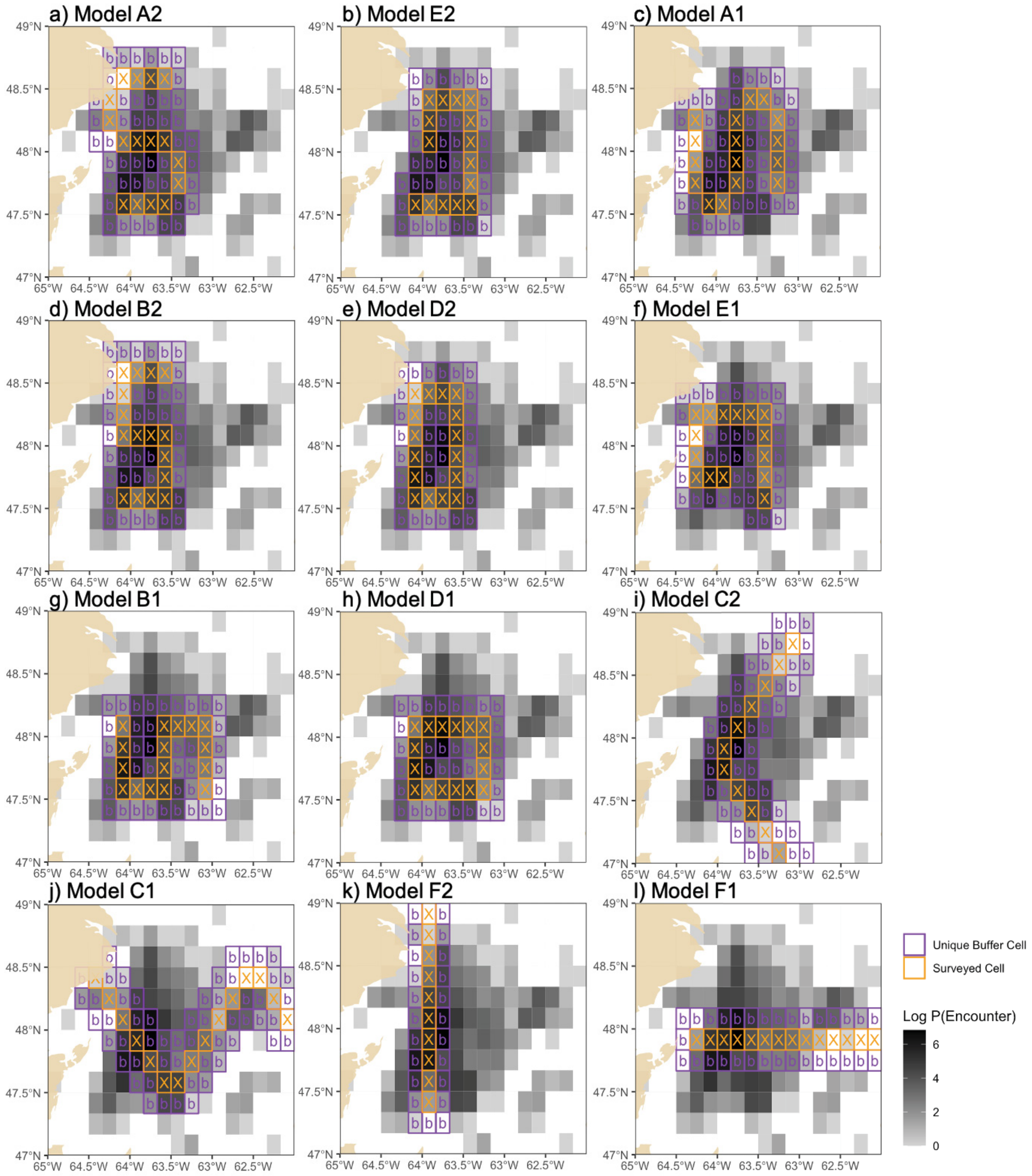


Figure B.1 a-l) Glider flight plan models designed to optimize the second performance metric; NARW detection probability $\sum P(encounter)$; Table 3.2). Models A) sinusoid, B) five, C) sawtooth, D) rectangle, E) spiral, F) line. Models 1) non-rotated and 2) rotated at 90º. Flight plans are shown ranked from highest to lowest $\sum P(encounter)$ and are overlaid with NARW P(encounter) climatology (gray scale). Surveyed cells are illustrated with the orange x and unique buffer cells are illustrated with the purple b.

B.2 Pilot study additional results

Table B.2.1 The amount of time (hours; Delta(t)) spent by the glider during each transit through a cell, the grid index of each cell, the time at which the glider entered the grid cells (time in), the time at which the glider exited the grid cells (time out), and the number of NARW detections made by the glider during each time interval.

Transit Through a Grid Cell	Delta(t)	Grid Index	Time In	Time Out	Number of Detections
1	21.486	HB37	2020-07-17 15:13	2020-07-18 12:42	0
2	23.099	HB38	2020-07-18 12:42	2020-07-19 11:48	0
3	32.605	HB39	2020-07-19 11:48	2020-07-20 20:25	0
4	42.453	HB40	2020-07-20 20:25	2020-07-22 14:52	2
5	4.672	HB41	2020-07-22 14:52	2020-07-22 19:32	0
6	45.467	HA41	2020-07-22 19:32	2020-07-24 17:00	8
7	38.002	GZ41	2020-07-24 17:00	2020-07-26 7:00	10
8	2.157	GY41	2020-07-26 7:00	2020-07-26 9:10	0
9	26.330	GY40	2020-07-26 9:10	2020-07-27 11:30	0
10	25.958	GY39	2020-07-27 11:30	2020-07-28 13:27	2
11	27.362	GY38	2020-07-28 13:27	2020-07-29 16:49	5
12	26.940	GY37	2020-07-29 16:49	2020-07-30 19:45	2
13	79.688	GY36	2020-07-30 19:45	2020-08-03 3:26	0
14	4.652	GY35	2020-08-03 3:26	2020-08-03 8:06	0
15	29.249	GY36	2020-08-03 8:06	2020-08-04 13:20	0

Transit Through a Grid Cell	Delta(t)	Grid Index	Time In	Time Out	Number of Detections
	5.683	GY37	2020-08-04 13:20	2020-08-04 19:01	2
17	70.362	GX37	2020-08-04 19:01	2020-08-07 17:23	2
18	133.770	GW37	2020-08-07 17:23	2020-08-13 7:09	12
19	1.612	GW38	2020-08-13 7:09	2020-08-13 8:46	4
20	24.492	GV38	2020-08-13 8:46	2020-08-14 9:16	13
21	3.986	GV39	2020-08-14 9:16	2020-08-14 13:15	4
22	0.510	GV38	2020-08-14 13:15	2020-08-14 13:45	13
23	17.104	GV39	2020-08-14 13:45	2020-08-15 6:52	4
24	25.571	GV40	2020-08-15 6:52	2020-08-16 8:26	1
25	15.814	GV41	2020-08-16 8:26	2020-08-17 0:15	0
26	45.177	GW41	2020-08-17 0:15	2020-08-18 21:25	3
27	38.816	GX41	2020-08-18 21:25	2020-08-20 12:14	0
28	16.452	GY41	2020-08-20 12:14	2020-08-21 4:41	0
29	25.311	GY40	2020-08-21 4:41	2020-08-22 6:00	0
30	24.766	GY39	2020-08-22 6:00	2020-08-23 6:46	2
31	28.272	GY38	2020-08-23 6:46	2020-08-24 11:02	5
32	20.443	GY37	2020-08-24 11:02	2020-08-25 7:29	2
33	21.639	GZ37	2020-08-25 7:29	2020-08-26 5:07	0
34	12.963	HA37	2020-08-26 5:07	2020-08-26 18:05	0

Transit Through a Grid Cell	Delta(t)	Grid Index	Time In	Time Out	Number of Detections
35	15.710	HB37	2020-08-26 18:05	2020-08-27 9:47	0
36	15.373	HC38	2020-08-27 9:47	2020-08-28 1:10	0
37	11.435	HD39	2020-08-28 1:10	2020-08-28 12:36	0
38	7.245	HE39	2020-08-28 12:36	2020-08-28 19:51	0
39	6.735	HE40	2020-08-28 19:51	2020-08-29 2:35	0
40	2.165	HE39	2020-08-29 2:35	2020-08-29 4:45	0
41	6.594	HE40	2020-08-29 4:45	2020-08-29 11:20	0

Table B.2.2 The number of grid cells the glider traveled through within every possible 15-day interval over the full deployment.

1st day of interval	15th day of interval	Number of *grid cells*
2020-07-17	2020-07-31	13
2020-07-18	2020-08-01	13
2020-07-19	2020-08-02	12
2020-07-20	2020-08-03	12
2020-07-21	2020-08-04	12
2020-07-22	2020-08-05	12
2020-07-23	2020-08-06	10
2020-07-24	2020-08-07	11
2020-07-25	2020-08-08	10
2020-07-26	2020-08-09	10
2020-07-27	2020-08-10	8
2020-07-28	2020-08-11	7
2020-07-29	2020-08-12	6
2020-07-30	2020-08-13	7
2020-07-31	2020-08-14	8
2020-08-01	2020-08-15	9
2020-08-02	2020-08-16	10
2020-08-03	2020-08-17	11
2020-08-04	2020-08-18	11
2020-08-05	2020-08-19	9
2020-08-06	2020-08-20	10
2020-08-07	2020-08-21	11
2020-08-08	2020-08-22	11
2020-08-09	2020-08-23	12
2020-08-10	2020-08-24	13
2020-08-11	2020-08-25	14
2020-08-12	2020-08-26	16
2020-08-13	2020-08-27	16

1st day of interval	15th day of interval	Number of *grid cells*
2020-08-14	2020-08-28	14
2020-08-15	2020-08-29	13
		Min: 6.00 Median: 11.00 Mean: 11.03 Max: 16.00 Std: 2.47

B.3 Example of simple algorithm for dynamic glider flight planning

In Chapter 3, the flight plans were chosen from a "library" of possible geometric configurations (*e.g.,* line, saw tooth). An alternative approach would be to design the glider *flight plans* using a dynamic algorithm which considers the grid cells in the glider's immediate proximity to determine the next trajectory. An algorithmic approach has a number of important advantages: it is dynamic, like the DFM protocol it is informing; it will create more complex flight configurations taking into account logistics, climatology, and possibly new observations as they become available in real-time, *e.g.,* glider PAM detections or aerial sightings from DFO planes. An example of such an approach may involve the following steps:

1) *Specify glider's initial position.* This position is arbitrary and could be based on deployment logistics, taking into account how the glider is deployed (*e.g.,* from land or offshore by via vessel). If logistics are not a factor, a sensible starting position would be the location with the maximum whale encounter probability.
2) *Find all legitimate buffer cells centered on the current position.* The maximum number of buffer cells is eight (excluding the current position). This number could be lower if some of the buffer cells are outside the study area, over land, or coincide with buffer cells identified in the recent past.
3) *For each buffer cell that have yet to be surveyed, calculate encounter probability and the overlap of its buffer cells with buffer cell from previous time steps.* The next position will be chosen taking into account encounter probabilities and buffer overlap.
4) *Choose the next position of the glider based on a weighted sum of encounter probability and number of non-overlapping buffer cells*. The weights are set by the user. They can depend on the application of the survey plan, cost, *etc.*. In practice, if the overlap weight is set to 0, the glider will move up the gradient to the position of maximum encounter probability.
5) *Reset glider's initial position and go back to Step 2.* Looping the algorithm leads to a glider path or flight plan.

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