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Occurrence of Blue Whales (*Balaenoptera musculus*) off Nova Scotia, Newfoundland, and Labrador

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Foreword

This series documents the scientific basis for the evaluation of aquatic resources and ecosystems in Canada. As such, it addresses the issues of the day in the time frames required and the documents it contains are not intended as definitive statements on the subjects addressed but rather as progress reports on ongoing investigations.

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TABLE OF CONTENTS

ABSTRACT

This study presents a summary of multiple sources of information to assess the spatial and seasonal distribution of Blue Whales in areas off eastern Canada outside the Gulf of St. Lawrence. Aerial and vessel-based systematic surveys, opportunistic sightings, acoustic monitoring, and species distribution modelling (SDM) identified five potentially important areas for Blue Whales off Nova Scotia, Newfoundland and Labrador: (1) deep water areas along the continental slope of the Scotian Shelf, (2) deep water areas along the continental slope of the Grand Banks south of Newfoundland, (3) deep water areas of the Laurentian Channel, (4) shallower water areas off the southwest coast of Newfoundland, and (5) shallower areas on the western Scotian Shelf. While Blue Whales were detected visually and/or acoustically in these areas, and their importance is further highlighted by the SDM results, there has been little Blue Whale focused research in these areas and therefore exactly how, and why, Blue Whales use these areas remains unknown. There is some suggestion in the acoustic data of a difference in use of these areas in summer (when the majority of arch calls are detected, which are made by both sexes and are thought to be related to foraging) and winter (when male-specific songs thought to be related to reproductive activities are detected). Sightings and acoustic detections indicate that Blue Whales occur year-round outside the Gulf of St. Lawrence with some seasonal peaks in call presence observed in July-August and December-January that appear to correspond to inward/outward movements of Blue Whales through the Cabot Strait. Photo-identification studies suggest that some individuals that occur off Nova Scotia and Newfoundland also occur in the Gulf of St. Lawrence, but also that some Blue Whales appear to remain outside the Gulf. Future research can be informed by the results of this and other recent studies. Suitable habitat for Blue Whales predicted by the SDM represent priority areas where monitoring efforts for Blue Whales (including passive acoustic monitoring and aerial and/or vessel-based surveys) should be focused in the future. Future monitoring efforts should also include expanded monitoring of Blue Whales and their prey in offshore areas where little survey effort has occurred. Additional photo identification effort outside the Gulf of St. Lawrence is warranted as a means to collect information on Blue Whale movements and activities, especially in deeper offshore waters. The potential impact of ice entrapment mortality should also be better studied given the number of mortalities that have occurred in the past few decades.

INTRODUCTION

While most effort to collect information on Blue Whale (*Balaenoptera musculus*) off eastern Canada has occurred in the Gulf of St. Lawrence, there is a growing body of information to assess how Blue Whales use other areas in the Canadian Northwest Atlantic. Using multiple types of available data, this document synthesizes the current state of knowledge on Blue Whale occurrence off Nova Scotia, Newfoundland, and Labrador.

Blue Whales are the largest migratory marine mammals in the world, inhabiting all oceans. Relatively little is known about their seasonal distribution off Nova Scotia, Newfoundland, and Labrador as they are only occasionally sighted in these areas in relation to other large baleen whales such as Humpback (*Megaptera novaeangliae*) and Fin whales (*Balaenoptera physalus*). Following decades of whaling and a significant population decline, it is thought that their distribution off eastern Canada has changed from its pre-whaling state (Beauchamp et al. 2009; COSEWIC 2002). For example, Blue Whales were sighted regularly by whalers on the western Scotian Shelf from June to November in the 1960s (Sutcliffe Jr. and Brodie 1977); however, few sightings have been reported in this area since (e.g., CETAP 1982; Gosselin and Lawson 2005; Lawson and Gosselin 2009). Most recent sightings off Nova Scotia are reported on the eastern Scotian Shelf (e.g., Whitehead 2013). Whalers operating out of Newfoundland and Labrador caught Blue Whales predominantly along the south and west coasts of Newfoundland, in the northern Gulf of St. Lawrence, and in the Strait of Belle Isle, but rarely east of Newfoundland or Labrador (Sergeant 1966). Though sightings are rare in these areas today, the regular presence of Blue Whales off southwestern Newfoundland is confirmed by ice entrapment events in late winter and early spring (see below), and Blue Whales have also been occasionally reported near St. Pierre & Miquelon, just south of Newfoundland (Desbrosse and Etcheberry 1987). Blue Whales have been sighted only sporadically off the Labrador coast (Boles 1980; Sergeant 1966).

Due to a small population size (unknown but likely in the low hundreds), low calving and recruitment rates, and threats posed by an increasing number of human activities in areas where the whales occur, the Northwest Atlantic Blue Whale population is listed as Endangered under the *Species at Risk Act* (SARA) (Beauchamp et al. 2009). Determining the potential impacts of human activities on endangered populations is difficult, particularly for species such as the Blue Whale where there is little information on population trends and distribution. It is crucial to determine areas of occurrence and important habitats of such at-risk species to better inform and direct efforts to mitigate threats that may be impeding their recovery. Critical habitat for the Northwest Atlantic Blue Whale population has not yet been identified, and the SARA Recovery Strategy for the population recommends investigating seasonal distribution including in areas where there has been less study effort in the past as an important activity for identifying important habitat (Beauchamp et al. 2009).

The objectives of this document are to: (1) describe the available information on Blue Whale occurrence off Nova Scotia, Newfoundland, and Labrador; (2) use species distribution modelling (SDM) techniques to predict potentially suitable Blue Whale habitat and identify areas in which to focus future monitoring efforts; and (3) based on these data, describe areas of likely importance to Blue Whales in the Northwest Atlantic to identify potential critical habitat and areas on which to focus future research efforts for this species.

HISTORICAL WHALING DATA

Whaling activities have been estimated to have killed 6,699 Blue Whales in the North Atlantic (Rocha Jr. et al. 2014). Approximately 1,500 Blue Whales were taken off eastern Canada during whaling operations from 1898 to 1951, which included 1,368 Blues whales captured off Newfoundland and Labrador (Mitchell 1974; Sergeant 1966). In the 1960s, whaling activities off eastern Canada were conducted primarily by one whaling station in Nova Scotia and two stations in Newfoundland. During this period, no Blue Whales were captured off Newfoundland and Labrador (Sergeant 1966), but at least one Blue Whale was captured off Nova Scotia (Sutcliffe Jr. and Brodie 1977). Figure 1 shows available Blue Whale catch locations recorded during whaling operations; these records document kills that occurred primarily along the northern coast of Newfoundland and represent only a subset of catches known to have occurred in the area. These catch records were obtained from the International Whaling Commission (IWC) database and include data from 1927-1958 between the months of April-November (with the majority of kills in June, July and August). Note that these 103 records represent available information that has been previously gathered by Fisheries and Oceans Canada (DFO) (see Abgrall 2009), but are only a portion (<10%) of the catches known to have occurred in the area. Many Canadian catch records have been lost or do not have associated kill locations but rather just the station where the whale was landed. The one Blue Whale kill recorded on the Scotian Shelf was reported by the Blandford whaling station operating in Nova Scotia in 1966 (Sutcliffe Jr. and Brodie 1977, Figure 2).

Abgrall (2009) compiled the available catch data to estimate catch per unit of whaling effort (CPUE) from stations in Eastern Canada (Figure 2). Note that Figure 1 only shows the catches for which DFO had exact location information, whereas the CPUE estimates in Figure 2 include all kills, such as those off the south coast of Newfoundland, where only the general location is known. Highest CPUE occurred along the south and west coasts of Newfoundland, in the northern Gulf of St. Lawrence, and in the Strait of Belle Isle; much lower CPUE occurred east of Newfoundland or Labrador.

In addition to capture data, some whaling operators also recorded sightings data. Blue Whale sightings recorded by the Blandford whaling station in Nova Scotia between 1966 and 1969 indicate that most sightings occurred during June-November, and were concentrated off southwestern Nova Scotia - particularly on Emerald Bank (Sutcliffe Jr. and Brodie 1977, Figure 3). Note that the sightings presented in Figure 3 were collected opportunistically during operations not targeting Blue Whales and therefore their pattern is at least partially driven by whaling efforts focused on other species, as well as operating range from the shore-based whaling stations.

Blue Whale hunting was banned in 1966 by the IWC, and only a few individuals (<3) were taken illegally from eastern Canadian waters after this date (Sears and Calambokidis 2002). All commercial whaling operations ceased in Canada in 1972.

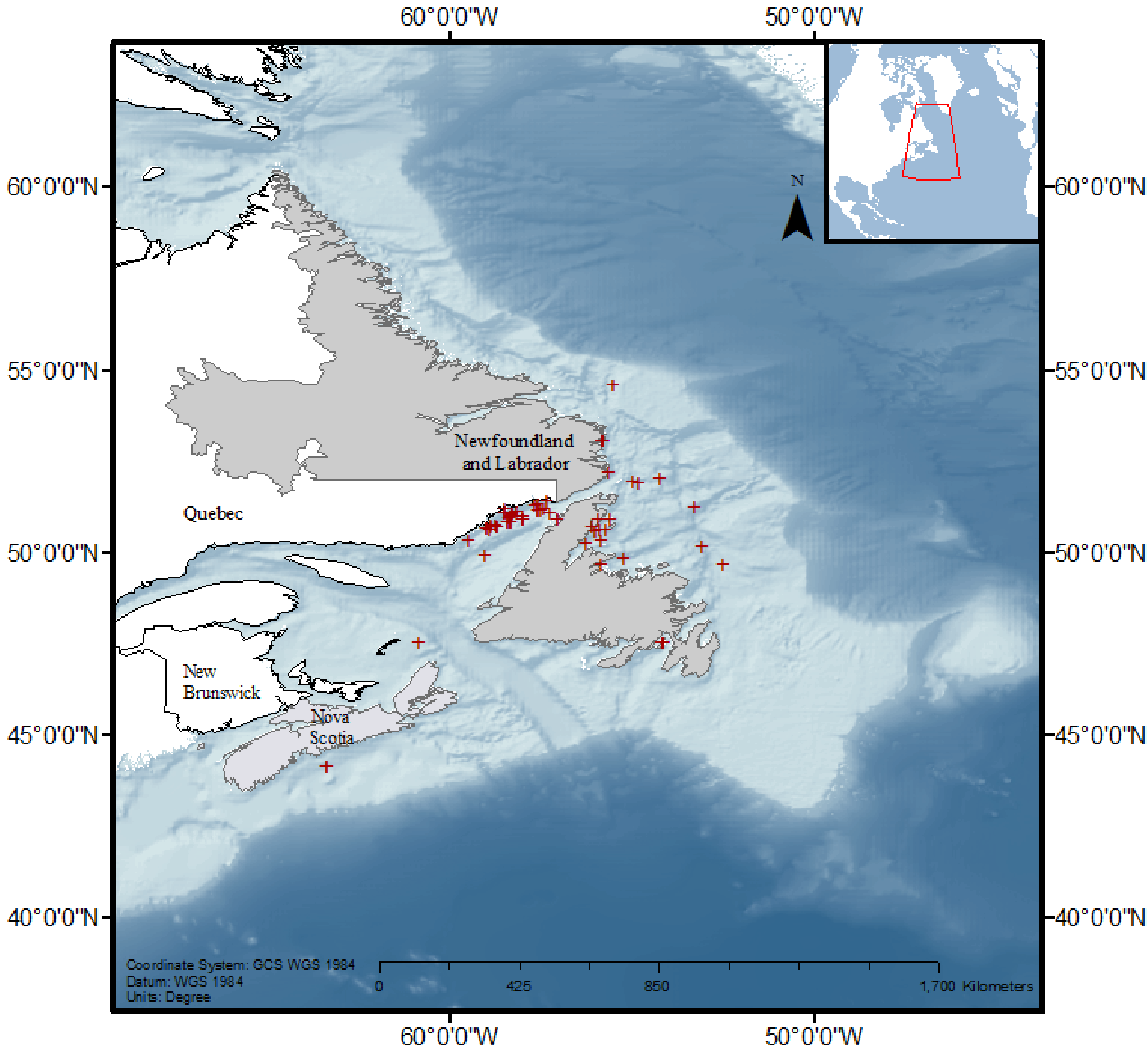

Figure 1. Available Blue Whale catch records (red crosses) reported by whaling operations based out of Newfoundland and Labrador (N=103), and Nova Scotia (N=1). Newfoundland and Labrador records were obtained from the International Whaling Commission database and represent a small portion of the whale catches/kills between 1927-1958 for which DFO could obtain exact catch locations; most catch records have been lost or do not have associated kill locations but rather just the station where the whale was landed. For example, there are few georeferenced kill records for the Newfoundland south coast though it is known that many more catches occurred in that region. The single record off Nova Scotia was obtained from Blandford whaling station logs as compiled in Sutcliffe and Brodie (1977), and occurred in 1966.

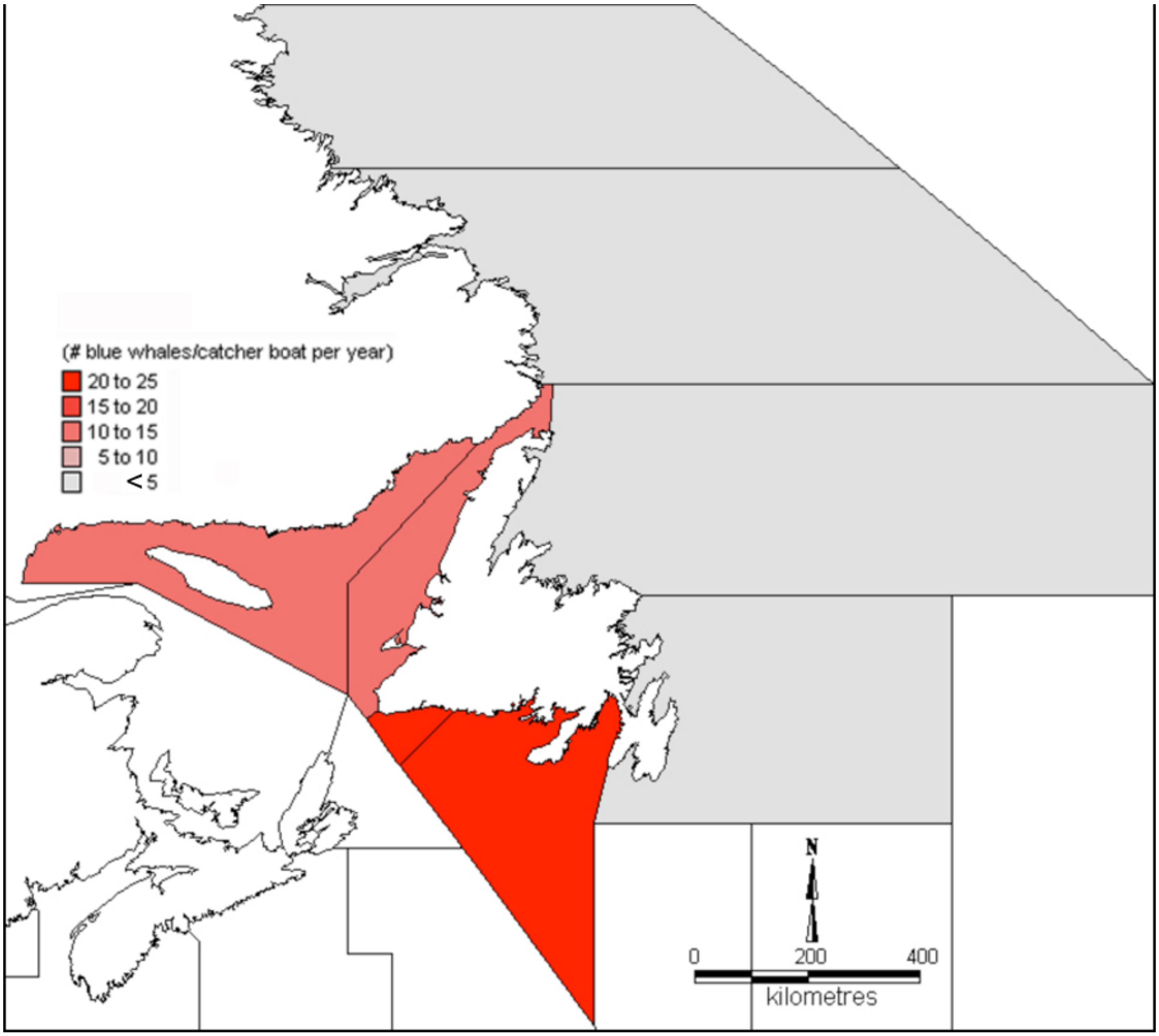

Figure 2. Blue Whale catch per unit effort (number of killed Blue Whales/catcher boat/year), calculated from shore-based whaling data from 1898-1966 (figure from Abgrall 2009). Note that while Figure 1 only shows the catches for which DFO had more detailed location information, the CPUE estimates presented here incorporate data from all known kills within an area, such as those off the south coast of Newfoundland.

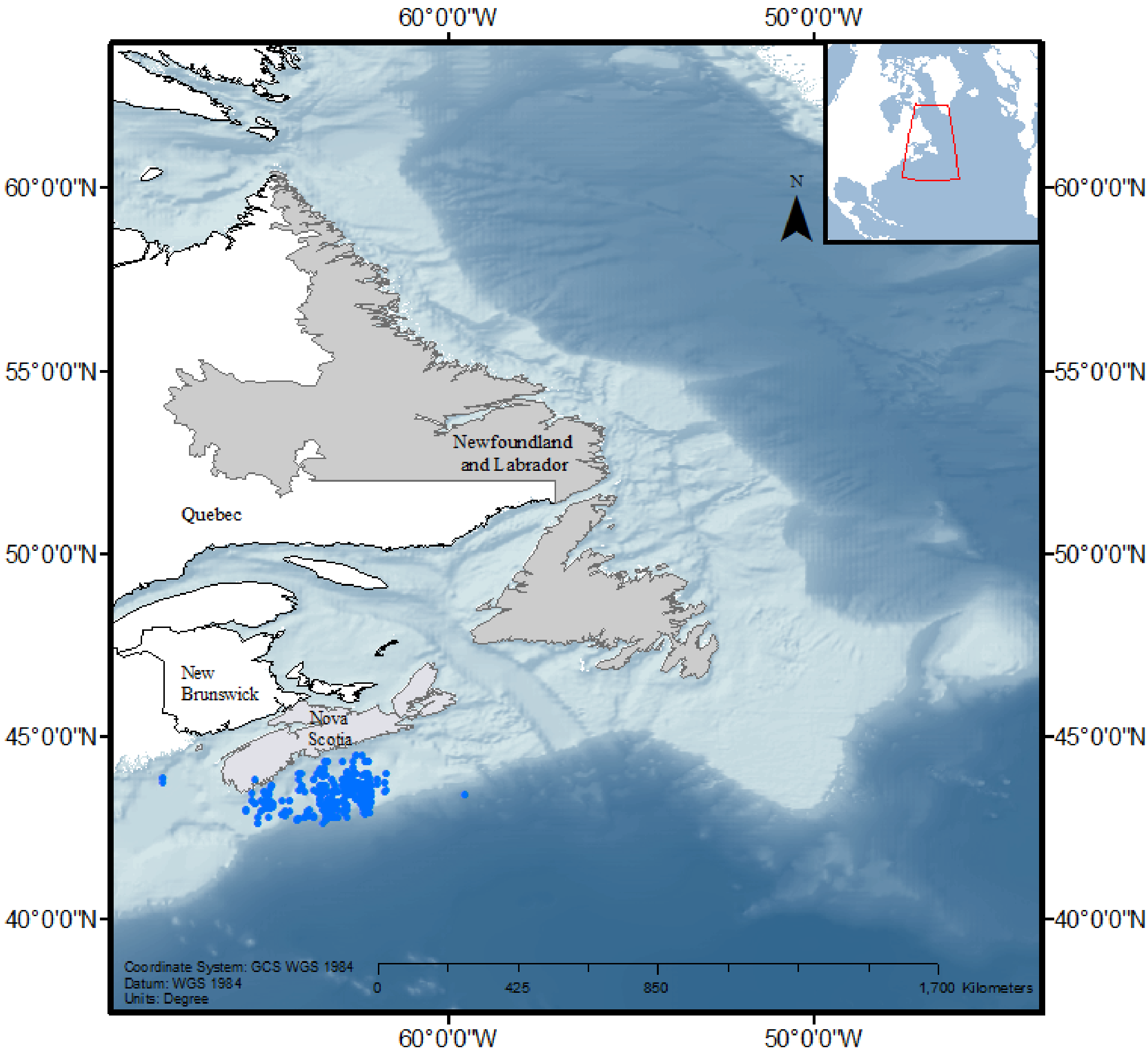

Figure 3. Blue Whale sighting records (Blue circles) recorded during whaling operations occurring off Nova Scotia from 1966-1969 (N=139), obtained from Blandford whaling station logs, compiled in Sutcliffe and Brodie (1977).

SYSTEMATIC AERIAL SURVEYS

This section describes data collected on Blue Whale occurrence during four systematic aerial surveys conducted by DFO associated with known levels of search effort.

No Blue Whales were sighted during more than 20,000 nm of survey effort off eastern Newfoundland and southern Labrador conducted in the 1980s. These surveys included a survey conducted in coastal and offshore waters of eastern Newfoundland and southeastern Labrador during 1-22 August 1980 (Hay 1982) and two broad-coverage aerial surveys conducted in the southern Labrador Sea between April 1981 to April 1982 (McLaren et al. 1982) (Figure 4). During these efforts many other large whales such as Humpback, Fin, and Pilot whales (*Globicephala melas*) were observed (Hay 1982). However, observers on board systematic surveys conducted in earlier time frames had reported Blue Whales present in this area (Boles 1980).

In late summer and early fall of 2002 and 2003, aerial surveys were conducted around Newfoundland and in the Gulf of St. Lawrence (Lawson and Gosselin 2003). Observers recorded a total of 4,399 animals from 541 sighting events over these two years. These included three Blue Whales sighted during two encounters from the 6,500 nm of survey effort, and only in 2003. Two Blue Whales were sighted off the central south coast of Newfoundland and one Blue Whale was offshore of the northeast coast of Newfoundland (Figure 5).

The most extensive survey of the Northwest Atlantic was the DFO component of the multinational Trans North Atlantic Sightings Survey (TNASS) in 2007. This was the first complete, systematic survey coverage for the entire eastern Canadian seaboard, and included the Labrador Shelf, Grand Banks, Gulf of St. Lawrence, and Scotian Shelf (Lawson and Gosselin 2009). Three aircraft were used to fly >25,000 nm of survey effort during which many baleen and toothed whales were sighted (1,801 sightings including 11,494 individuals). Seventeen Blue Whales, counted during 14 sighting events, were recorded (Figure 6). The majority of Blue Whales observed during this survey were in deep waters >55 km from shore, with half being sighted at or near the shelf breaks of the Scotian Shelf and southwest Newfoundland. A single Blue Whale was seen off the northeast coast of Newfoundland and four animals were sighted in the Gulf of St. Lawrence. Note that in an effort to increase the likelihood of sighting Blue Whales, TNASS apportioned higher effort to areas where more Blue Whales had been sighted previously (Lawson and Gosselin 2009). Despite this, there were too few sightings to derive a reliable estimate of abundance, but the low number of sightings is consistent with there likely being only a few hundred individuals occurring off eastern Canada. This large-scale aerial survey was repeated in summer 2016, but the sighting data were not available for this analysis.

An additional source of aerial survey data off eastern Canada is from the National Marine Fisheries Services (NMFS), who have periodically extended their northeastern U.S. surveys into Canadian waters primarily in the Bay of Fundy and western Scotian Shelf region (e.g., NMFS 2002; Palka 2012). Sightings from these surveys have been reported to DFO and are captured in DFO regional cetacean sightings databases (see below); however, associated survey effort was not readily available for incorporation into this analysis. Nonetheless, relatively few Blue Whale sightings over multiple years (approximately 6 between 1998 and 2015) have been reported from these survey efforts. These are included in the opportunistic sightings described below.

Only 20 sightings from over 50,000 km of survey effort off eastern Canada demonstrates the relative rarity of Blue Whale sightings in the region (Table 1). The areas of potential importance for Blue Whales highlighted by these data are the slope region along the eastern Scotian Shelf, the southwest coast of Newfoundland, and the Gulf of St. Lawrence (Figures 5 and 6).

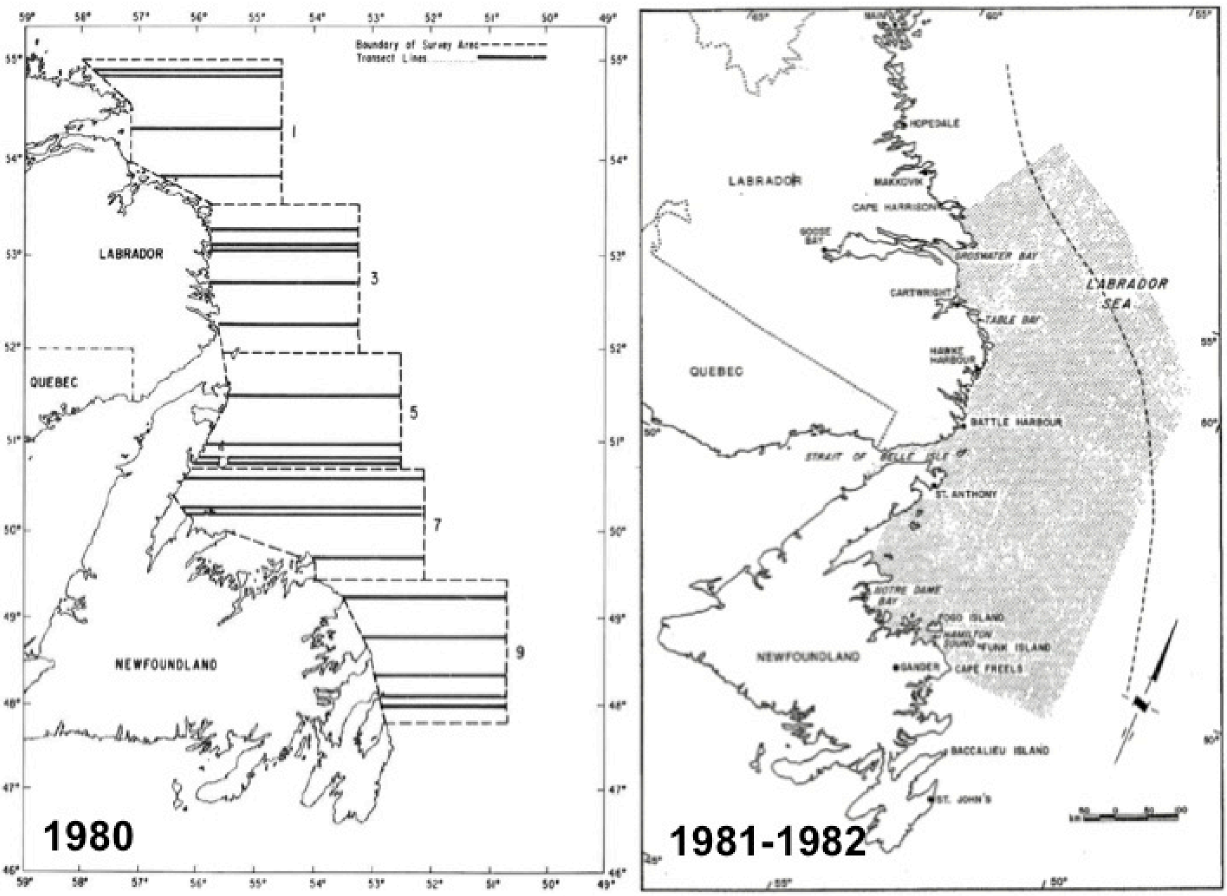

Figure 4. Systematic aerial survey transects (black lines) covered in August 1980 {left; from Hay (1982)} and area covered by aerial surveys (grey shading) in April 1981 to April 1982 {right; from McLaren et al. (1982)}. No Blue Whale sightings were reported during these surveys.

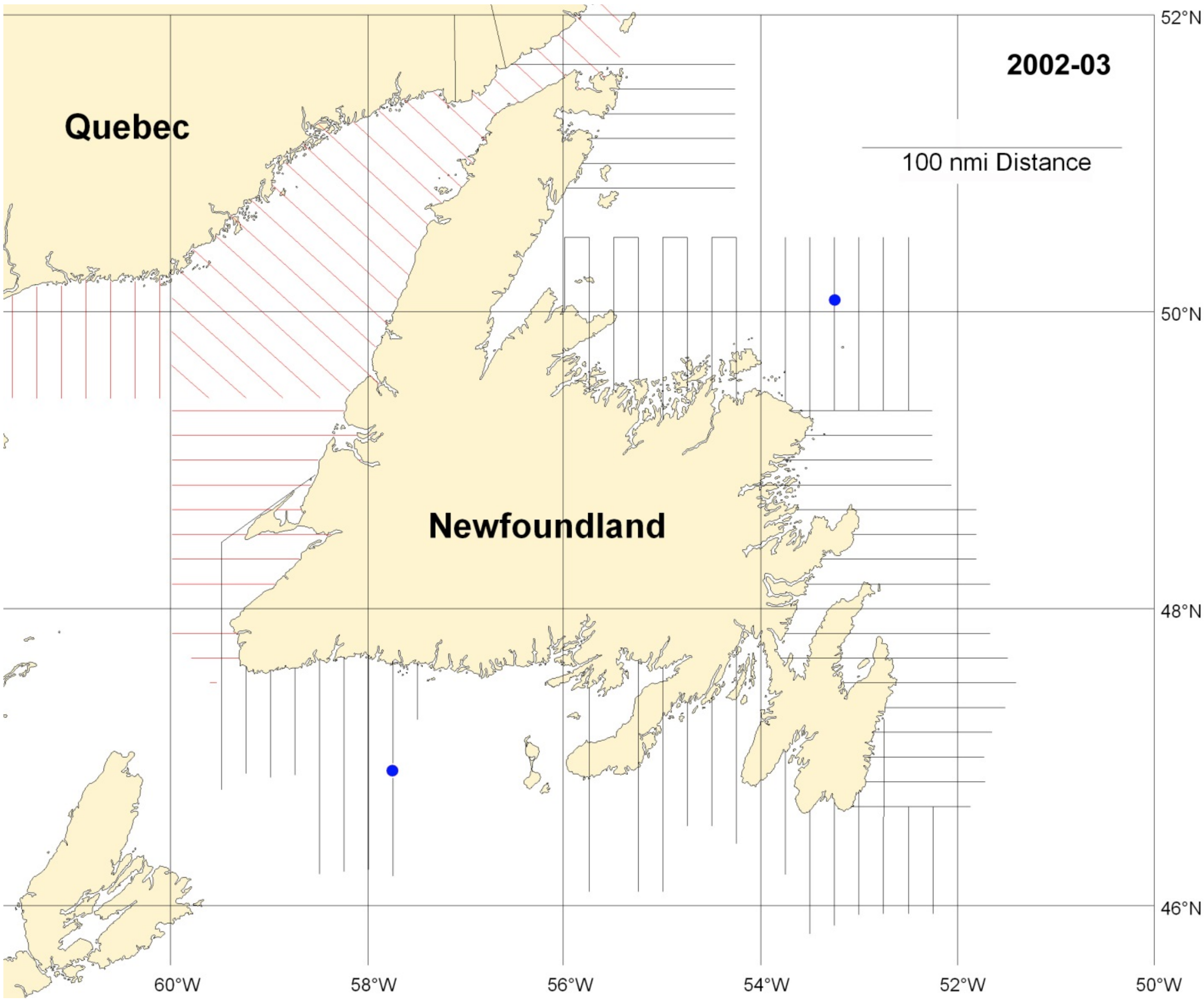

Figure 5. Blue Whale sightings (Blue circles; N=2) during systematic aerial survey transects (red and black lines) covered in summer and early fall of 2002 and 2003 {figure from Lawson and Gosselin (2003)}. The gap in survey coverage off the south coast of Newfoundland was a function of poor weather and international flying restrictions in 2003.

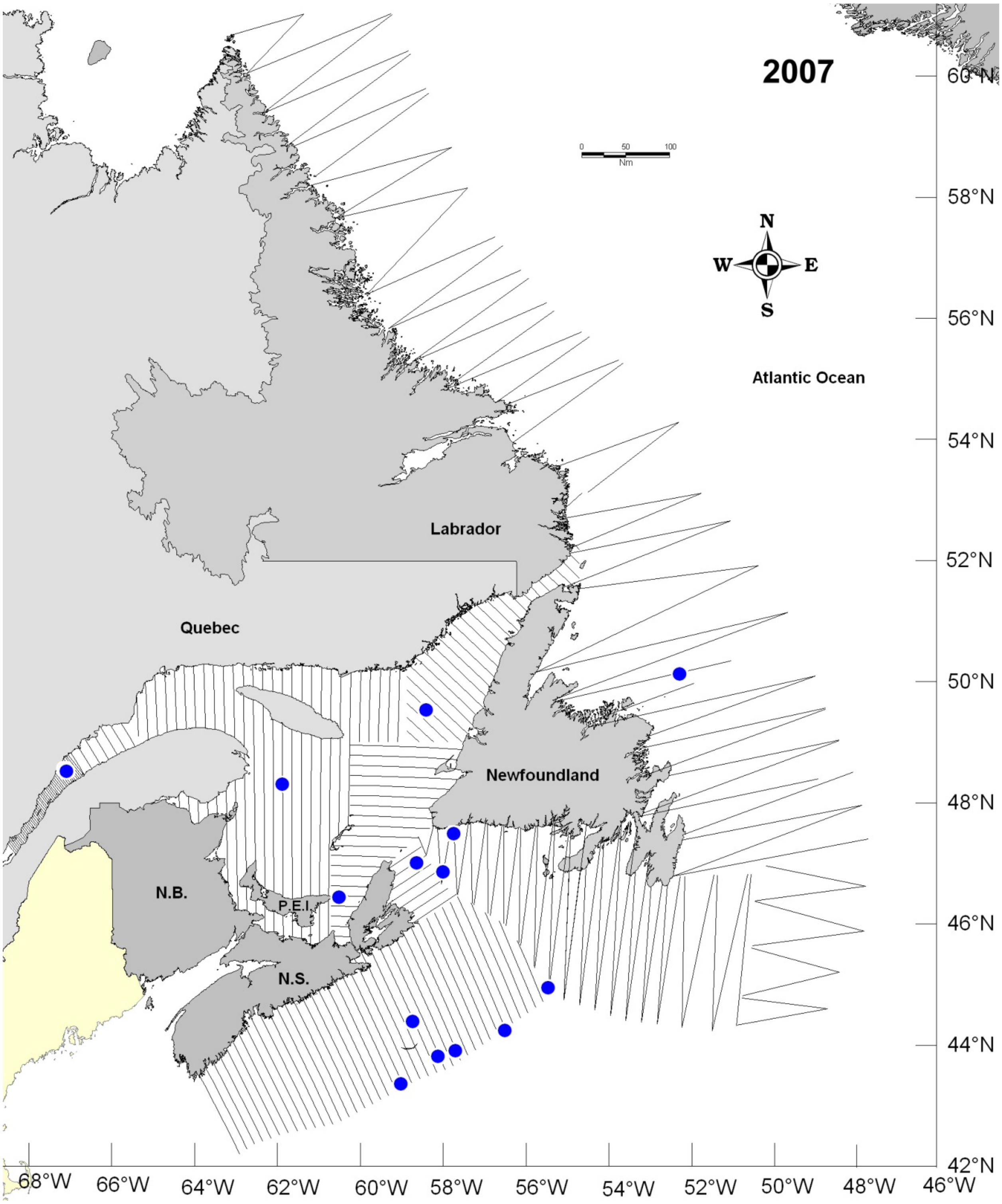

Figure 6. Blue Whale sightings (Blue circles, N=14) near systematic aerial survey transects (black lines) covered during the DFO component of the multinational Trans North Atlantic Sightings Survey (TNASS) conducted in 2007 (Lawson and Gosselin 2009).

Table 1. Summary of systematic aerial surveys conducted in the Northwest Atlantic. Data includes the total number of Blue Whale sightings in each survey as well as the total number of all cetacean encounters (when known), shown in parenthesis.

Systematic Aerial Survey	General Location	Date Range	Distance Surveyed (nm)	Survey Platform	Blue Whales Sighted (Cetacean Encounters)	Reference
DFO systematic surveys	Eastern Newfoundland, southeastern Labrador	1-22 August 1980	3,554	Beechcraft AT-11	0 (125)	Hay (1982)
Offshore Labrador Biological Studies (OLABS)	Southern Labrador Sea	April 1981 to April 1982	17,138	Twin Otter & Aerocom-mander	0 (496)	McLaren et al. (1982)
DFO systematic SARA surveys	Newfoundland, northern Gulf of St. Lawrence	Summer and early fall 2002 and 2003	6,530	Single Skymaster	3 (541)	Lawson and Gosselin (2003)
DFO component of the multi-national Trans North Atlantic Sightings Survey (TNASS)	Northwest Atlantic	July and August 2007	25,272	Multiple aircraft (Twin Otter & Skymaster)	17 (1,801)	Lawson and Gosselin (2009)
National Marine Fisheries Service systematic surveys into Canadian waters	Scotian Shelf, including the Bay of Fundy	Multiple years	Unk.	Multiple aircraft (Twin Otter)	~ 6 (Unk.)	NMFS (2002), Palka (2012)

SYSTEMATIC VESSEL-BASED SURVEYS

Deep-water vessel-based surveys off the eastern United States, Nova Scotia, and Labrador were conducted by the Whitehead Lab of Dalhousie University in 2001 (Wimmer and Whitehead 2004) and 2003. These surveys followed the 1,000 m contour along the continental slope using a 12.5 m auxiliary sailing vessel. The first set of surveys were conducted May-August 2001 between 54° and 72° W for a total survey effort of 2,061 km of track line over 257 search hours. Three Blue Whale sightings of one individual each were recorded during these efforts; one near Emerald Bank and two off southern Newfoundland (Figure 7). A similar survey including 1,982 km of track line surveyed over 214 search hours (H. Whitehead, pers. comm.) was conducted off Labrador in July and August 2003 during which no Blue Whale sightings were recorded (Figure 7).

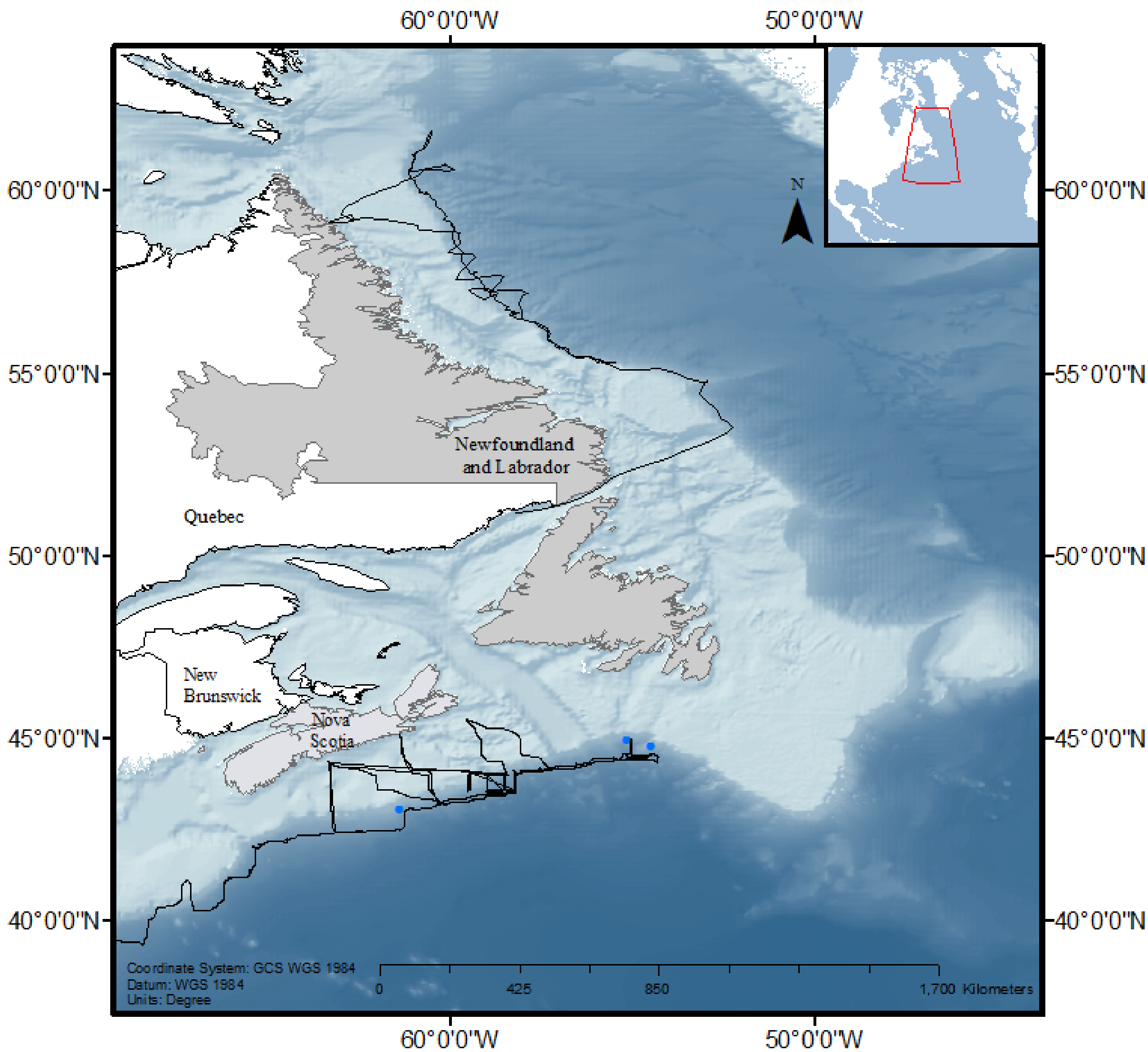

Figure 7. Blue Whale sightings (Blue circles, N=3) during vessel-based survey transects (black lines) and along the 1,000 m contour off eastern United States, Nova Scotia, and southern Newfoundland in 2001, and off Labrador in 2003 (data from the Whitehead Lab of Dalhousie University).

NON-SYSTEMATIC VESSEL-BASED ENCOUNTER RATES

The Whitehead Lab of Dalhousie University has been conducting cetacean studies in slope waters of the eastern Scotian Shelf since the 1980s, primarily in the Gully, Shortland and Haldimand canyons (e.g., Hooker et al. 1999; Whitehead et al. 1997; Whitehead and Wimmer 2005). These studies were focused on Northern Bottlenose and Sperm whales, and were generally conducted during June-Sept from 10 m or 12.5 m auxiliary sailing vessels. A constant watch for marine mammals was kept during daylight hours and sightings of all cetaceans were recorded. Whitehead (2013) examined trends in sighting rates of non-target cetacean species, including Blue Whales, from 1988-2011. This analysis included 2,938 hours of search effort in good conditions. No Blue Whales were recorded prior to 1995, while 57 sightings were recorded during 1995-2011 (47 of which were included in the Whitehead (2013) analysis). An additional three Blue Whales were recorded in 2015 (Table 2). Sightings were distributed throughout the canyons (Figure 8). Although most sightings (70%) occurred in the Gully, sighting rates were highest in the other canyons (Gully = 0.012 whales/hr, Shortland = 0.068 whales/hr, Haldimand = 0.049 whales/hr) (Whitehead 2013). It should be noted that most of the search effort took place in the Gully with almost no search effort in the additional canyons prior to the 2000s, and very little search effort between canyons (thus non-canyon areas were not included in this analysis). Sighting rates within the core region of the Gully also varied by month, with no sightings in June or September, <0.01 whales/hr in July, and just over 0.02 whales/hr in August. Overall, the sighting rate of Blue Whales in the core region of the Gully increased over the 23-year study period at a rate of 11%/year (SE = 8%) (Whitehead 2013).

Table 2. Number of Blue Whales sighted in the Eastern Scotian Shelf area during each month of each year when field studies were conducted (data from the Whitehead Lab of Dalhousie University). "-" indicates no field studies were conducted in the study area during a particular month.

Year	June	July	August	September	All Months
1988-1994	0	0	0	0	0
1995	-	-	3	-	3
1996	0	0	5	-	5
1997	0	0	2	-	2
1998	-	0	4	-	4
1999	-	1	5	-	6
2001	-	-	0	-	0
2002	0	2	14	-	16
2003	0	0	1	0	1
2006	-	0	0	-	0
2007	-	-	2	-	2
2010	-	6	11	-	17
2011	-	0	1	-	1
2015	-	-	3	-	3
Total	**0**	**9**	**51**	**0**	**60**

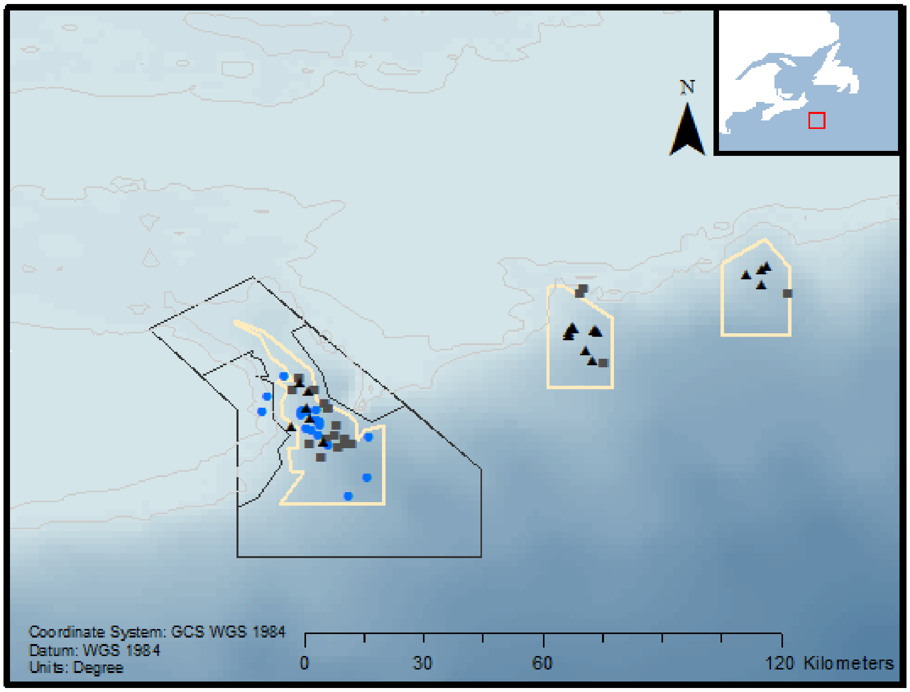

Figure 8. Blue Whale sightings in the Gully, Shortland, and Haldimand canyon study areas between 1995-1999 (Blue circles, N=20), 2000-2009 (black triangles, N=19), and 2010-2015 (grey squares, N=21) (data from the Whitehead Lab of Dalhousie University). Note that almost all search effort occurred in these three canyons thus the lack of sightings outside the canyons does not necessarily indicate a lack of Blue Whales in these areas.

COMBINED OPPORTUNISTIC AND EFFORT-BASED SIGHTINGS

While some of the Blue Whale sightings from Nova Scotia, Newfoundland, and Labrador are associated with a measure of search effort, the majority of reported sightings are opportunistic in nature. These include sightings collected from research vessels not conducting cetacean surveys, whale-watch vessels, oil and gas platforms, fishing boats, and various other sources. These sightings are generally reported without a level of search effort associated with them and can provide information on Blue Whale spatial and temporal presence, but not absence. In other words, it is not known if areas with many sightings are areas of higher importance, or simply areas where more search effort has occurred; alternately, opportunistic sightings data in areas with no or few sightings are either areas where Blue Whales do not occur or are areas where little search effort has occurred.

DFO Maritimes Region, and Newfoundland and Labrador Region, maintain cetacean sightings databases for storing cetacean sightings data collected from various sources. These databases contain both opportunistic sightings and sightings collected during more systematic surveys (including the aerial and vessel-based survey sightings reported above). Capitalizing on these and other long-term cetacean sightings datasets, a total of 346 Blue Whale sightings from the Gulf of St. Lawrence, Nova Scotia, Newfoundland and Labrador between 1975 and 2015 (the post-whaling period) were obtained (Figure 9). The majority of these sightings (63%) occurred during summer, followed by fall (19%), spring (16%), and then winter (2%); however, this is likely a reflection of more search effort occurring in summer and does not necessarily represent a seasonal trend in occurrence. Although there are fewer sightings during non-summer months, there does not appear to be any significant difference in the locations of the sightings collected from each season. The majority of the sightings occur along the slope of the Scotian Shelf with far fewer sightings reported off eastern Newfoundland and Labrador (Figure 9).

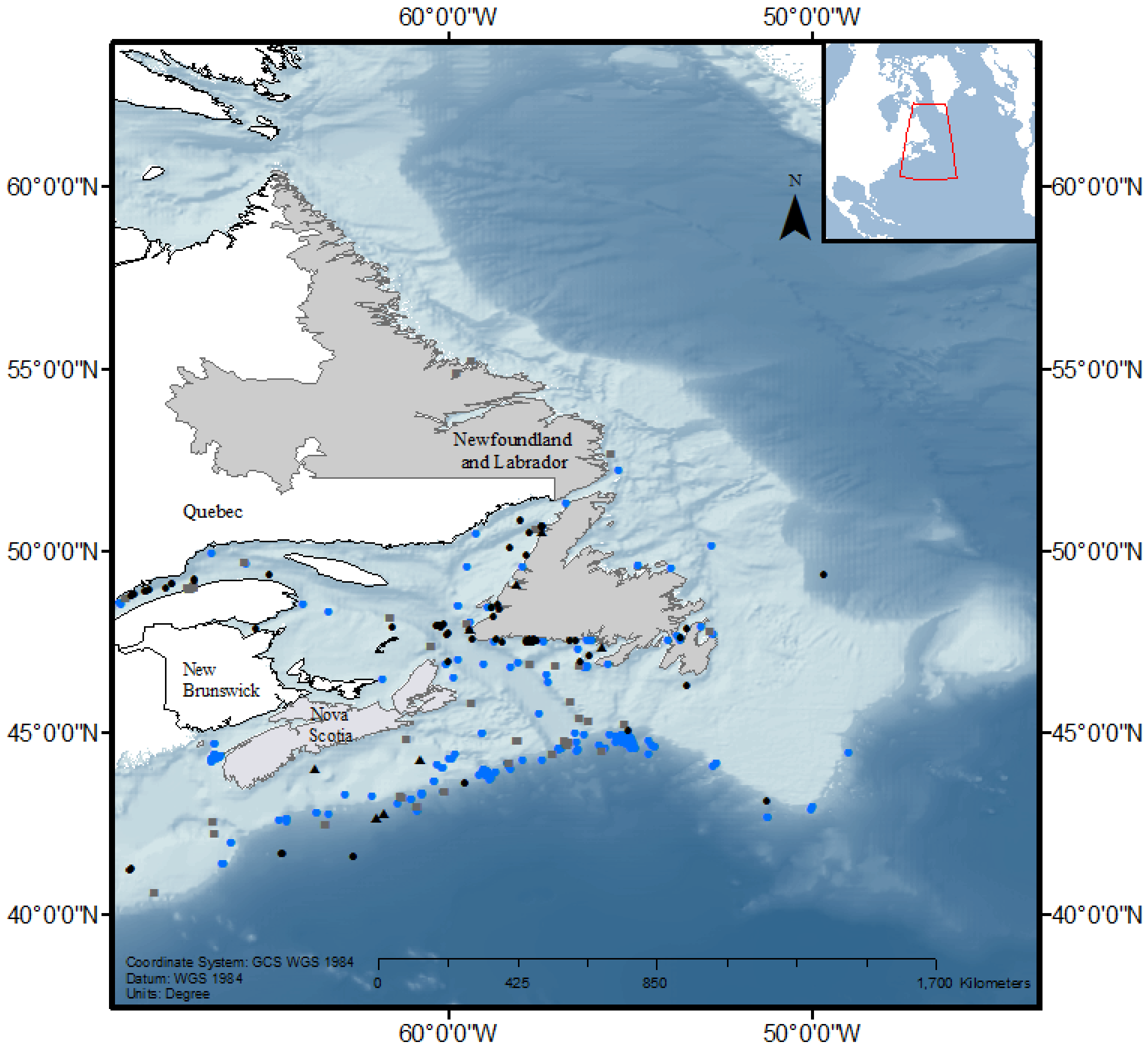

Figure 9. Locations of live Blue Whale sightings in the Gulf of St. Lawrence, Nova Scotia, Newfoundland, and Labrador between 1975-2015 in spring (black circles; N=55), summer (Blue circles; N=218), fall (grey squares; N=65) and winter (black triangles; N=8). These sightings were obtained from: (1) DFO Maritimes and DFO Newfoundland and Labrador regions' cetacean sightings databases, (2) the Ocean Biogeographic Information System (OBIS), (3) the Whitehead Lab at Dalhousie University, (4) the Environment Canada (Canadian Wildlife Service) Eastern Canada Seabirds at Sea (ECSAS) programme database, and (5) the "Song of the Whale" initiative (R/V Song of the Whale 1993-2013, International Fund for Animal Welfare c/o MCR International, OBIS Seamap) and include the effort-based sightings presented in the previous figures as well as additional opportunistic sightings.

PHOTOGRAPHIC IDENTIFICATION CATALOGUE

A Blue Whale photographic identification (photo ID) catalogue has been maintained by the Mingan Island Cetacean Study (MICS) since the 1980s that contains approximately 483 individually-identified whales primarily from the Gulf of St. Lawrence, where most of the effort to collect photographs for individual identification purposes has taken place (Ramp and Sears 2012). Between 1980 and 2015, 34 Blue Whales photographed off Nova Scotia (primarily by the

Whitehead Lab of Dalhousie University during studies in the Gully area, but also some individuals from Cape Breton and one individual from the Bay of Fundy area) were identified, 15 of which had been sighted previously in the Gulf of St. Lawrence and 19 of which were sighted exclusively off Nova Scotia. Three of ten individuals photographically identified from waters east and south of Newfoundland during this same time period were previously sighted in the Gulf of St. Lawrence, all three of which were photographed near St. Pierre & Miquelon (Ramp and Sears 2012).

ICE ENTRAPMENTS

Since 1974, 26 Blue Whale ice entrapment events involving at least 48 animals have been reported in the Northwest Atlantic (Stenson and Lawson, unpubl. data; Table 3, Figure 10). This is likely an underestimate of the actual number of events due to the difficulty in detecting entrapped whales and limited search effort prior to 1974. Reported entrapments occurred in the southern Gulf of St. Lawrence and off the southwest coast of Newfoundland (Figure 11) mainly during March and April and involving 1-9 animals, mostly adults. In most cases the entrapment resulted in death of the individuals (Table 3, Figure 10). With over 700 reports of ice-entrapped cetaceans off Newfoundland and Labrador, Blue Whales are a small fraction of the animals reported. Overall, there has been no consistent pattern in the location of entrapped cetaceans with the exception of Blue Whales, which appear to be concentrated off the southwest coast of Newfoundland (Figure 11). This highlights the southwest coast of Newfoundland as both a consistent area of spring occupancy by Blue Whales, and an area of significant mortality risk for the endangered Northwest Atlantic population.

Outside of ice entrapments, no stranded Blue Whales have been reported in Nova Scotia, or elsewhere in Newfoundland and Labrador (e.g., Nemiroff et al. 2010).

Table 3. Numbers and fates of Blue Whales entrapped in ice since 1974 near southwest Newfoundland (Stenson and Lawson, unpubl. data).

Year	Escaped	Killed	Total
1974	1	2	3
1975	0	1	1
1976	2	2	4
1977	2	2	4
1978	0	1	1
1980	4	3	7
1982	1	3	4
1985	0	1	1
1986	1	5	6
1988	0	3	3
1989	0	2	2
1992	0	3	3
2011	0	2	2
2014	0	9	9
2015	0	1	1
Total	**11**	**40**	**51**

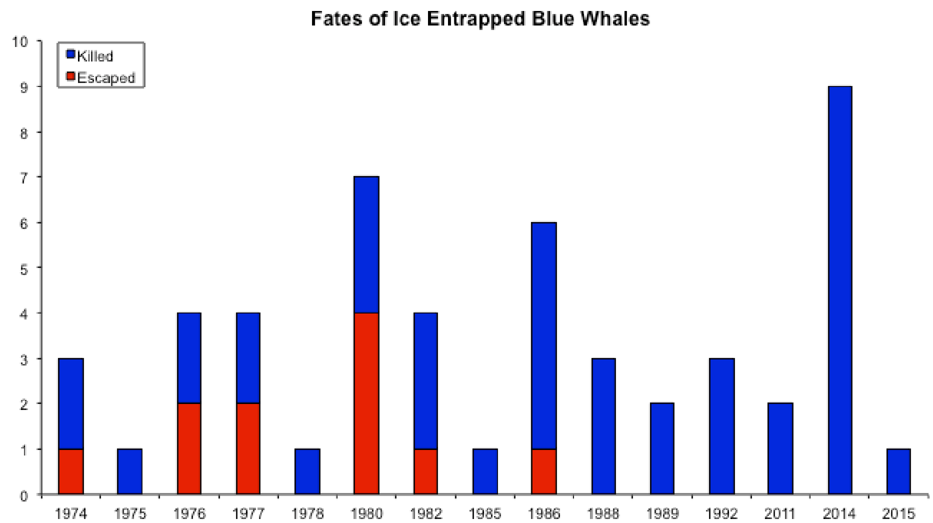

Figure 10. Fates of Blue Whales entrapped in ice since 1974 near southwest Newfoundland (Stenson and Lawson, unpubl. data).

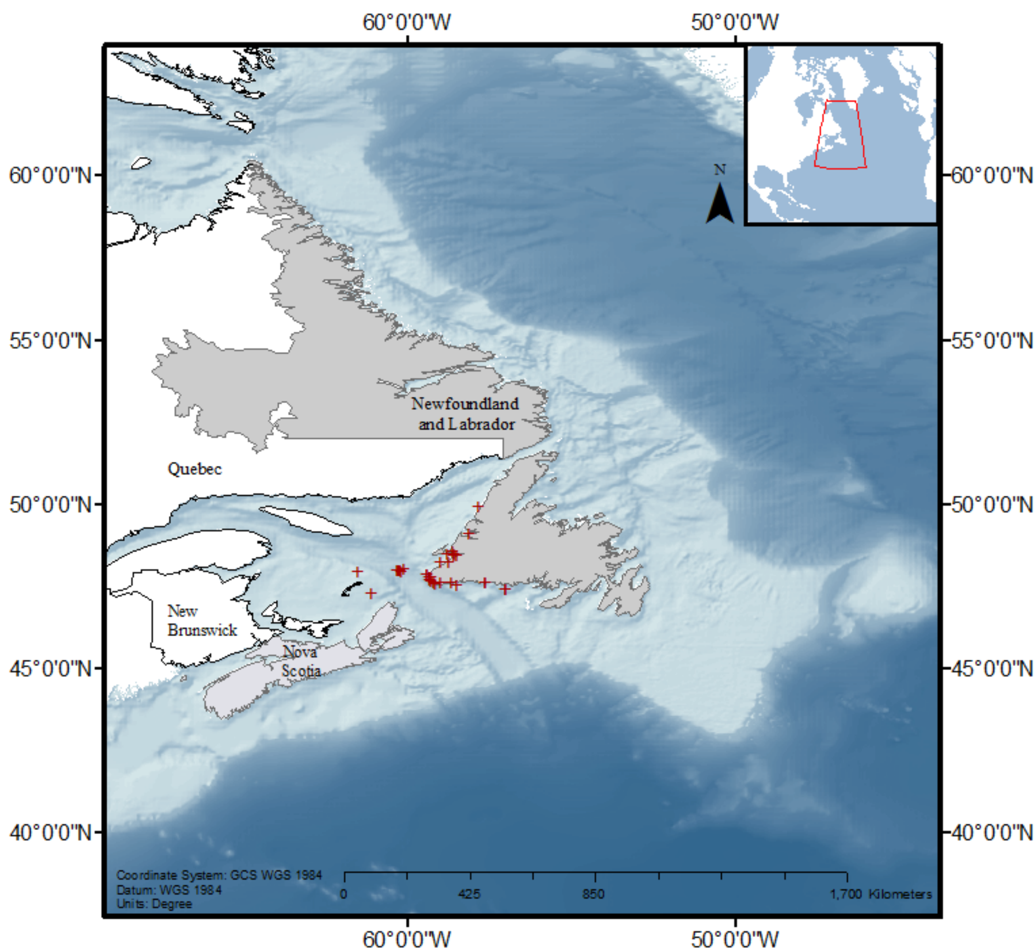

Figure 11. Reported Blue Whale ice entrapment records (red crosses) off Newfoundland from 1974 to 2015. The black box surrounds the location where DFO located the corpses of Blue Whales (N=9) entrapped in 2014 that had drifted southwest with the sea ice for multiple days.

PASSIVE ACOUSTIC DETECTIONS

Passive Acoustic Monitoring (PAM) offers a non-invasive and relatively inexpensive approach for monitoring vocalizing cetaceans throughout the year that is not limited by adverse weather conditions and poor visibility (Mellinger et al. 2007). Advancements in acoustic recording and detection systems make it possible to detect and in some cases track vocalizing marine mammals. While there are some limitations to PAM, such as for non-vocal species, it can be used to gain valuable information on the occurrence of many cetacean species, including Blue Whales (e.g., Berchok et al. 2006; Di Iorio and Clark 2010). For example, (Clark 1995) used the U.S. Navy's SOSUS underwater listening system to detect and track Blue Whale calls over much of the North Atlantic. Clark reported that most of the Blue Whale acoustic detections were from the Newfoundland Grand Banks and in offshore waters west of the British Isles (Figure 12).

The Blue Whale's calls are thought to be the loudest sounds produced by any animal (e.g., Sirović et al. 2007). They produce distinctive long, low frequency calls that have been described in both the Pacific and the Atlantic (e.g., Mellinger and Clark 2003; Oleson et al. 2007). Blue Whale calls are generally classified into three or four distinct call types, though terminology tends to vary between regions. For the North Atlantic, there are four consistent call types reported. The "A" call consists of an 8-14 s constant-frequency tone around 18 Hz; the "B" call is similar in duration but characterized by an 18-15 Hz downsweep at the end of the call; the "AB" (or "hybrid") call is a longer 17-24 s call consisting of an A part followed by a B part; and the "D" (also "arch" or "audible") call is a shorter 2-7 s call that begins around 50 Hz, increases to about 70 Hz, then declines to 30-35 Hz (Berchok et al. 2006; Mellinger and Clark 2003; Nieukirk et al. 2004). The A, B, and AB calls are collectively referred to as "tonal" calls and can occur sporadically or in stereotypical patterns with distinct repetition of the call separated by regular intervals. These repeated tonal calls are thought to be produced only by males (McDonald et al. 2006). The low frequency characteristics of the Blue Whale tonal calls allow them to propagate for many kilometres and thus these songs are thought to serve a long-range communication function related to reproduction. D calls tend to occur as multiples in rapid succession (Mellinger and Clark 2003; Nieukirk et al. 2004) and are produced by both males and females (Oleson et al. 2007). These quieter, shorter-range calls appear to play a different function than tonal calls. Studies based in the Pacific have suggested that D calls are a contact call used to communicate with nearby conspecifics (McDonald et al. 2001; Melcón et al. 2012; Oleson et al. 2007; Wiggins et al. 2005), and may serve a function related to foraging (Oleson et al. 2007).

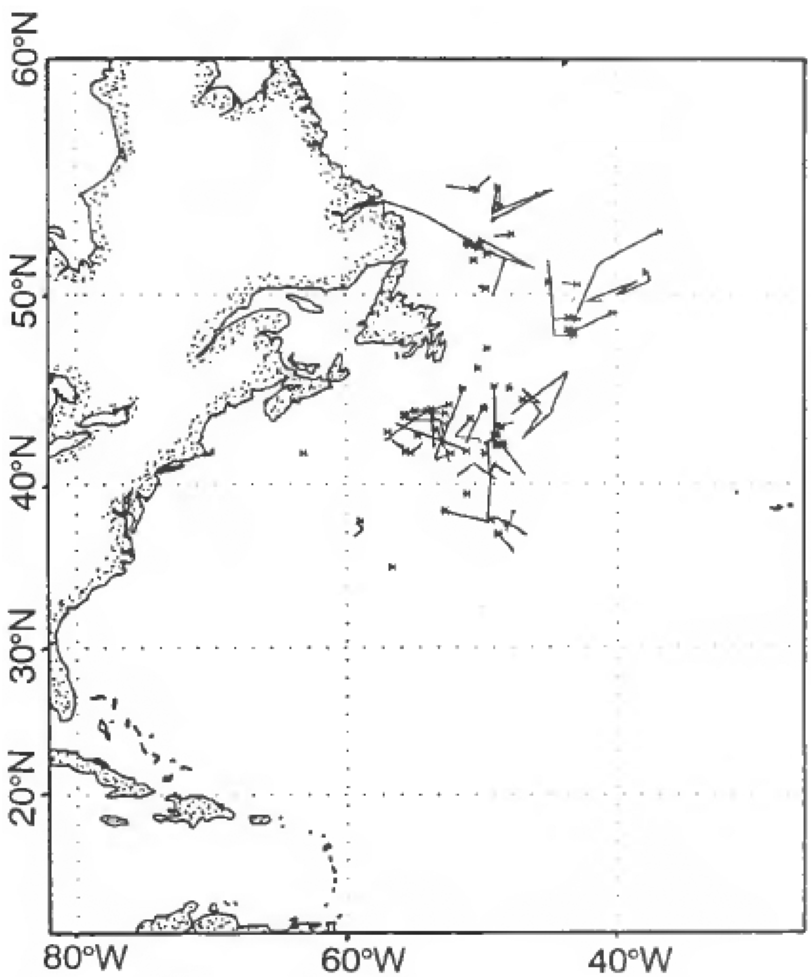

Figure 12. Tracks and detection locations of calling Blue Whales collected by the U.S. Navy SOSUS acoustic system in September, 1993 (Figure 2 in Clark 1995). Note that acoustic locations cannot be compared to one another as location estimates are not corrected for recording range.

OVERVIEW OF DATA

Several acoustic datasets obtained from bottom-moored recording systems have been collected from waters off Nova Scotia, Newfoundland, and Labrador over the past ten years. These include Marine Autonomous Recording Units (MARU; Cornell Lab of Ornithology, Bioacoustics Research Program) deployed by the Whitehead Lab of Dalhousie University in the eastern Scotian Slope area in the 2006-2009 period, Autonomous Multichannel Acoustic Recorders (AMARs; JASCO Applied Sciences Ltd.) deployed by DFO in the same area in the 2012-2014 period, and Autonomous Underwater Recorders for Acoustic Listening (AURALs; Multi-Électronique (MTE) Inc.) deployed by DFO at several locations off Newfoundland and Labrador in the 2009-2015 period. These datasets include almost 50,000 hours of recordings (Table 4). The following sections describe analyses conducted on these datasets to detect and assess the seasonal occurrence of Blue Whale calls.

Table 4. Description of acoustic datasets analysed for Blue Whale calls.

Parameter	MARUs	AMARs	AURALs	All
Area	Eastern Scotian Slope	Eastern Scotian Slope	Newfoundland and Labrador	
Period	2006-2009	2012-2014	2009-2015	
Number of files	12,700	154,990	19,600	187,290
Number of hours of recordings	1,682	37,743	9,022	48,447
Number of files with Blue Whale detections	1,385	19,012	3,335	23,732
Number of files with verified Blue Whale detections	905	5,092	156	6,153

MARU DATASET

MARUs were deployed by the Whitehead Lab of Dalhousie University in several locations along the slope of the eastern Scotian Shelf from 2006-2009 (Moors 2012). Deployment depths varied between 1,250-1,950 m and the recorders were suspended about one meter above the seabed. These systems were moored to the sea bottom for months at a time (Table 5). The MARUs recorded sound by passing an analogue acoustic signal acquired by an omni-directional HTI-9-MIN series hydrophone (frequency response ± dB re 1 V/µPa from 0.002-30 kHz) through a low-pass anti-aliasing filter connected to a signal microprocessing board which converted and saved the signal into a digital format. Data were collected at a sampling rate of 50 kHz, thus frequencies up to 25 kHz were recoverable. A regular duty cycle (one 7- or 10-min recording collected each hour) allowed the MARUs to record data over several months (Moors 2012).

Data from four recording locations from the MARU dataset were analysed for the presence of Blue Whale calls; the head (GULH) and mouth (GULM) of the Gully canyon, and Shortland (SHORT) and Haldimand canyons (HALD) (Figure 13). Data collected from one summer/fall (June-October) and one winter (December-March) deployment at each of these locations was included in the analysis. In total, over 12,600 files (1,682 hours) of acoustic data were analysed for the presence of Blue Whale calls ((Marotte and Moors-Murphy 2015); Table 5).

Automated contour-based Blue Whale call detectors developed by JASCO Applied Sciences Ltd. (Martin et al. 2014) were used to identify possible Blue Whale calls on the recordings. The detectors were configured to detect low frequency Blue Whale tonal (A, B, and AB calls) and higher frequency arch calls (D calls). The data were processed using the detectors set at a relatively low threshold to increase the probability that any sound matching the parameters for these call types were detected. The detectors were therefore less likely to miss even very quiet Blue Whale calls (i.e., the false negative rate was minimized), but more likely to detect sounds that were not Blue Whale calls (i.e., had a high false alarm/false positive rate). Such trade-offs exist when configuring any type of automatic acoustic signal detector and for the purposes of this and the analyses of the AMAR and AURAL datasets described in the following sections, it was more advantageous to minimize the number of Blue Whale calls missed by the detectors at the expense of increased false detections, and data processing time.

Due to the known high false positive rate, all recordings that had at least one detection were manually (aurally and visually) inspected using Raven Pro 1.4 sound analysis software (Cornell Laboratory of Ornithology, Bioacoustics Research Program) to verify the presence of Blue Whale calls. Additionally, 100 recordings on which Blue Whale calls were not detected were sampled randomly from each deployment to verify and estimate the rate of false negative detections.

Blue Whale calls were detected on 1,385 (11.0%) of the 12,606 recordings analysed. Manual analysis verified that 905 of these (7.2% of all recordings) contained Blue Whale calls (i.e., were true positive detections) resulting in an overall false positive rate of 34.7%. Of the 800 recordings with no Blue Whale calls detected on them, 69 were found to have Blue Whale calls present, resulting in an overall false negative rate of 8.6%. Although only a small percentage of recordings with Blue Whale calls on them were missed, this further emphasizes that the number of recordings with verified Blue Whale calls present is an indication of minimum Blue Whale call presence only.

The number of hours with confirmed Blue Whale calls varied by location and season (Table 6). Haldimand Canyon had the most hours with calls present while Shortland Canyon had the least. All locations except Shortland Canyon had more hours with calls present in summer/fall period. Overall, there was more than three times as many hours with Blue Whale calls present in summer/fall as compared to winter and this seasonal trend was most strongly observed at the Haldimand Canyon and mouth of the Gully locations. For all three summer/fall periods from which recordings were obtained, August had the most hours with calls present (Figure 14). However, Blue Whale calls were also present during December, January, and February of each winter from which recordings were obtained.

The types of Blue Whale calls present on the recordings were examined more closely for the GULM dataset. The 258 hours with detections at this location contained 953 individual Blue Whale calls. All three tonal call types previously described in the Atlantic (A, B, and AB calls), as well as arch calls (D calls) were identified. The most common call type was the A call, followed by the AB call, while the B and D call types were less common and not found on the winter datasets (Table 7). However, D calls were identified on some of the winter recordings from other locations (Marotte and Moors-Murphy 2015).

Further details on this dataset and analysis are provided by Marotte (2015).

Table 5. Description of eight MARU deployments included in the Blue Whale analysis.

Location	Deployment	Recorder Depth (m)	Date of First Recording	Date of Last Recording	Duty Cycle	Num. Files
GULM	Summer/Fall	1,950	25 Jul 2006	16 Sep 2006	10 min on/ 50 min off	1,267
GULM	Winter	1,950	9 Dec 2006	30 Jan 2006	10 min on/ 50 min off	1,248
GULH	Summer/Fall	1,250	25 Jul 2006	16 Sep 2006	10 min on/ 50 min off	1,266
GULH	Winter	1,500	7 Dec 2007	25 Feb 2008	7 min on/ 53 min off	1,914
SHORT	Summer/Fall	1,650	23 Jun 2008	11 Sep 2008	7 min on/ 53 min off	1,911
SHORT	Winter	1,500	13 Dec 2008	3 Mar 2009	7 min on/ 53 min off	1,907
HALD	Summer/Fall	1,500	4 Aug 2007	1 Oct 2007	7 min on/ 53 min off	1,379
HALD	Winter	1,500	13 Dec 2008	2 Mar 2009	7 min on/ 53 min off	1,714
All						**12,606**

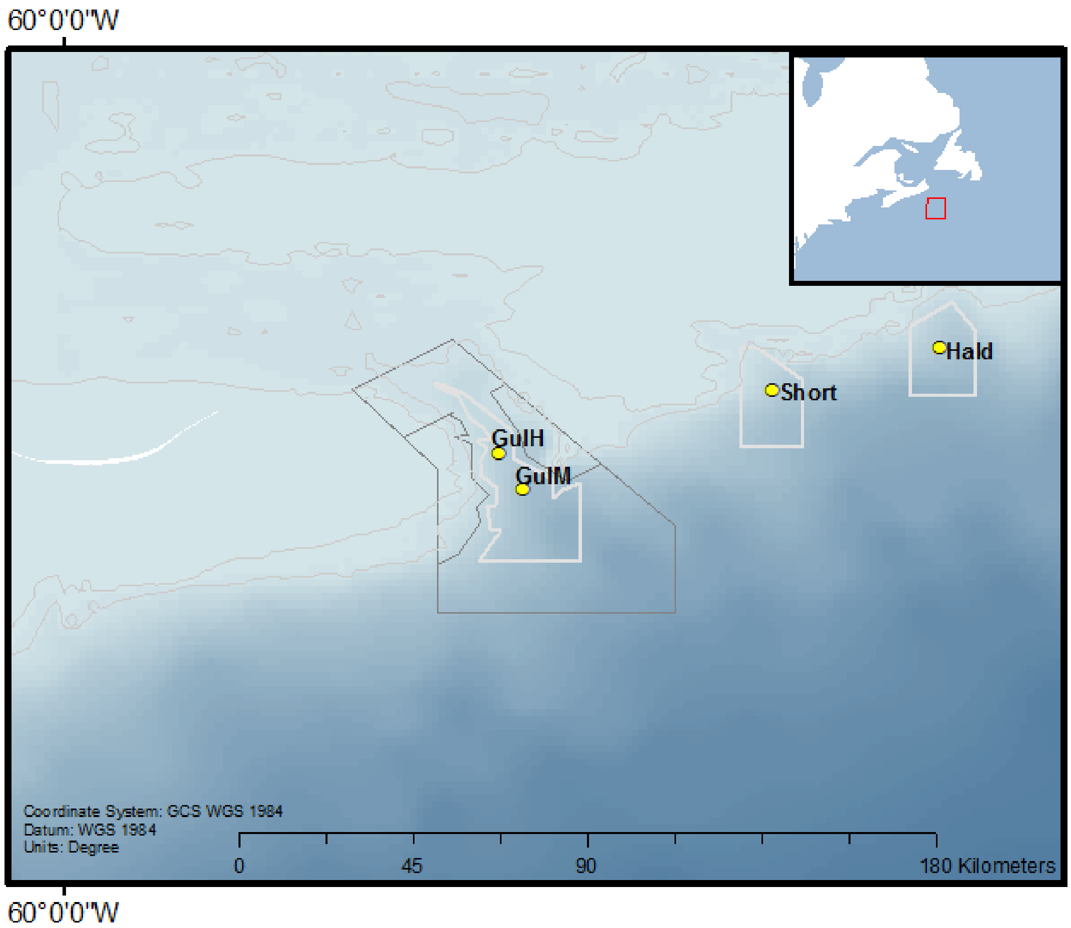

Figure 13. The MARU acoustic recorder locations along the slope of the eastern Scotian Shelf.

Table 6. Number and proportion of hours with confirmed Blue Whale calls present from each MARU recording location during each season, and for each season in total.

Location	Deployment	Hours with Calls	Prop. of Hours with Calls
GULM	Summer/Fall	214	0.169
	Winter	44	0.035
	Total	258	0.103
GULH	Summer/Fall	94	0.074
	Winter	80	0.042
	Total	174	0.055
SHORT	Summer/Fall	56	0.029
	Winter	66	0.035
	Total	122	0.032
HALD	Summer/Fall	315	0.228
	Winter	36	0.021
	Total	351	0.113
All	**Summer/Fall**	**679**	**0.117**
	Winter	**226**	**0.033**
	Total	**905**	**0.072**

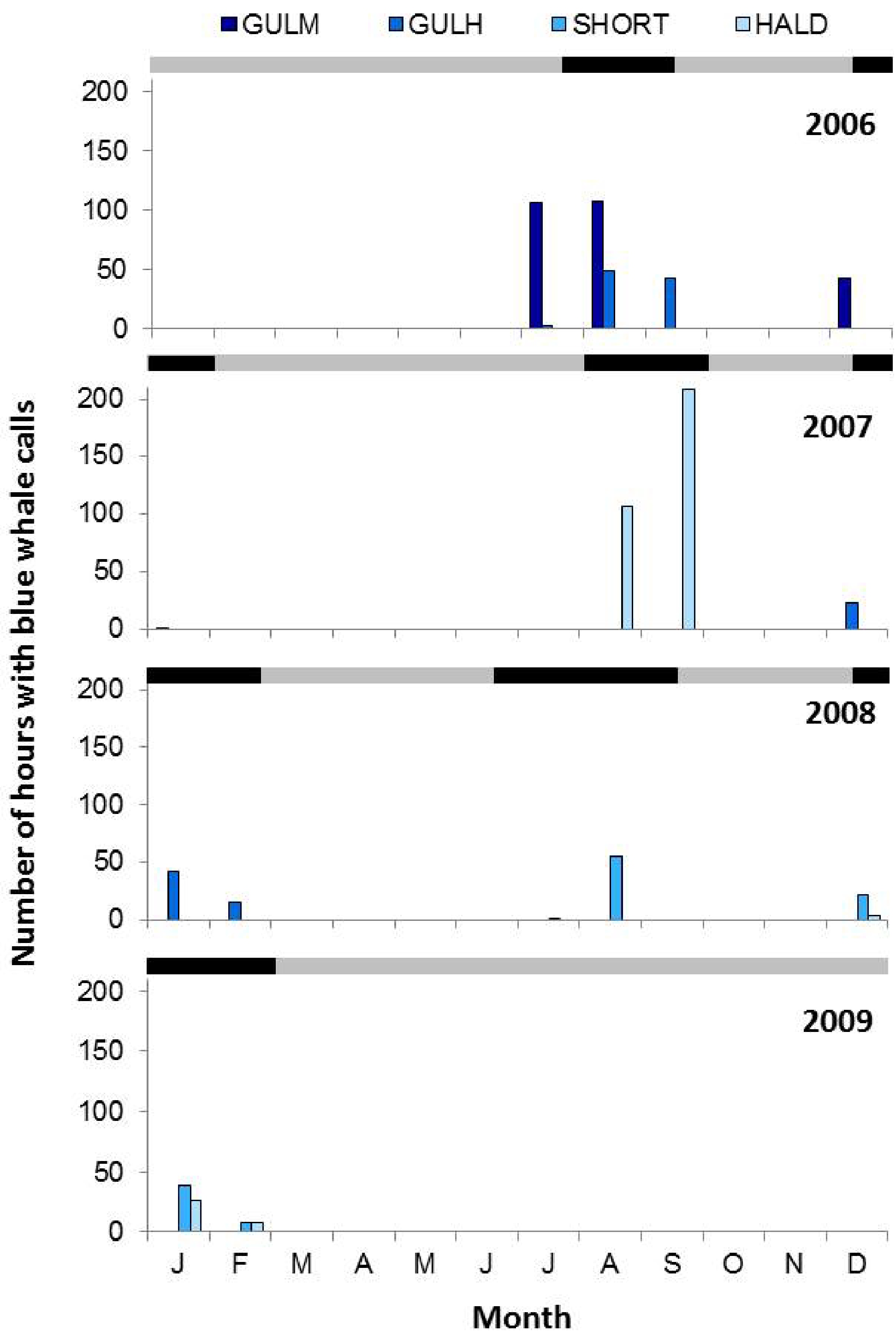

Figure 14. The number of hours with confirmed Blue Whale calls present for each month of each year, for the four MARU recording locations. Black bars indicate months for which there were acoustic recordings available, while grey bars indicate months from which no recordings were collected. Note that the sampling schedule was incomplete (recordings were not collected from every location during each recording period).

Table 7. Number and proportion of each Blue Whale call type counted on the GULM recordings with Blue Whale calls present.

Call Type	Summer		Winter		All	
	Number of Calls	**Proportion of Calls**	**Number of Calls**	**Proportion of all Calls**	**Number of Calls**	**Proportion of all Calls**
A	546	0.698	104	0.608	650	0.682
B	17	0.022	0	0.0	17	0.018
AB	211	0.270	67	0.392	278	0.292
D	8	0.010	0	0.0	8	0.008
Total	**782**	**1.000**	**171**	**1.000**	**953**	**1.000**

AMAR DATASET

AMARs were deployed by DFO at six locations along the slope of the eastern Scotian Shelf in the 2012-2014 period; in the middle of the Gully (MIDGUL), halfway between the Gully and Shortland Canyon (GULSHO), halfway between Shortland and Haldimand Canyons (SHOHALD), in shallow water just to the east of the Gully (SHALLOWGUL), between the Gully and Logan Canyon (INTERCANDEEP) and in Logan Canyon (LOGAN) (Figure 15). The AMARs were moored at approximately 1,400-1,900 m depth, with the exception of the SHALLOWGUL recorder which was moored at a depth just over 200 m deep, and were suspended approximately 60 m off bottom at MIDGUL, GULSHO and SHOHALD, and 20 m off bottom at SHALLOWGUL, INTERCANDEEP and LOGAN (Table 8). Each system was equipped with a broadband M8 omnidirectional hydrophone with a nominal frequency response of -165 dBV/µPa from 20 Hz-170 kHz (Geospectrum Technologies Inc.). Recordings were made using a 24-bit analogue-to-digital converter with a built-in anti-aliasing filter. The AMARs at MIDGUL, GULSHO and SHOHALD collected data continuously using a duty cycle which sampled at a rate of 16 kHz for 13 min then 128 kHz for 2 min during the first year of the study, and 16 kHz for 17.8 min then 250 kHz for 2.2 min during the second year. The AMARs at SHALLOWGUL, INTERCANDEEP and LOGAN had a duty cycle of 11.3 min at 16 kHz, 250 kHz for 3.3 min, then 0.3 min of sleep (Table 8).

Two years of near-continuous recordings were collected from MIDGUL, GULSHO and SHOHALD, from October 2012 through September 2014, with AMARs retrieved and redeployed approximately every six months (Table 8). October 2013 was the only month during this two-year period from which no data was collected. In total, 154,990 recordings (37,743 hours) made at the 16 kHz sampling rate (four files from each hour of recording during the first year, and three files from each hour of recording during the second year) were analysed for the presence of Blue Whale calls from this dataset. Data was only collected from July-September 2014 at the SHALLOWGUL, INTERCANDEEP and LOGAN locations. In total, 23,378 recordings (4,403 hours) made at the 16 kHz sampling rate (four files from each hour of recording) were analysed for the presence of Blue Whale calls from this dataset. Automated spectrogram correlation-based Blue Whale call detectors developed by JASCO Applied Sciences Ltd. (see Martin et al., 2014) were used to detect possible Blue Whale calls (A, B, AB, and D calls) on these recordings.

Blue Whale vocalizations were detected on 15,153 (9.8%) of the 154,990 recordings analysed from the MIDGUL, GULSHO and SHOHALD. A total of 4,614 files (3.0%) were confirmed to contain Blue Whale calls and the overall false positive rate was 69.6%. Based on an analysis of 480 files with no Blue Whale detections on them (sampled from all deployments), 28 files were found to contain Blue Whale calls resulting in a false negative rate similar to that calculated for the MARU data of 5.8%.

The number of hours with confirmed Blue Whale calls at MIDGUL, GULSHO and SHOHALD varied by location, season and year (Tables 9 and 10). The location halfway between Shortland and Haldimand canyons had the most hours with calls present while the Gully had the least. The Gully had the most hours with calls present in summer, followed by winter, with relatively few calls present during spring and fall. At the non-canyon locations a different trend was observed: winter had the most hours with calls present, followed by fall and then summer with few detections in spring. In contrast to what was observed from the MARU dataset, overall there were approximately twice as many hours with Blue Whale calls present in winter as compared to summer (Table 9). There was also interannual variability observed in the dataset with almost twice as many hours with Blue Whale calls present in the second year of the study as compared to the first year, primarily due to more calls being present in summer months (Table 10). At all three recording locations the number of hours with calls present peaked between November and January and decreased to almost no detections throughout the summer of the first year of the study, peaked again in the November-January period, fell to few detections throughout the spring and then peaked in July and August in the second year of the study (Figure 16). Figure 17 shows the day-to-day variation in call presence at each site. Throughout much of the year, there were only one or two hours with calls present within a day, and several to numerous days between detected calls, suggesting that animals were not remaining in these areas for significant periods of time. During the peak calling times in winter and summer, often calls were heard for several hours each day over consecutive days. It is unclear if this is due to animals remaining in an area for days at a time, or due to multiple animals transiting through; however, an analysis of the average consecutive hours with calls present suggests the latter. When Blue Whale calls were present, the average number of consecutive hours in which they were heard varied between 0.25-3.61 hours, with the greatest amount of consecutive hours with calls during both years occurring in November and December. During peak calling periods, calls were typically only heard for 1-2 consecutive hours, suggesting that whales were generally not remaining in the area for more than a couple of hours, though calls were heard over three consecutive hours on average in November 2013 and over two consecutive hours on average in December 2013 (Table 11).

The Blue Whale call types present on the MIDGUL recordings were examined more closely. The 684 hours with calls present consisted of 342 hours (50%) with tonal calls and 353 hours (52%) with arch calls. There was a difference in the seasonal call repertoire, with the majority of calls occurring in fall and winter of each year being tonal calls, while the majority of calls in summer of each year were arch calls (a mixture of both call types occurred in the spring). While there were more hours with calls present in the second year for both call types (76 hours with tonal calls in year 1 as compared to 266 hours with tonal calls in year 2; 11 hours with arch calls in year 1 as compared to 342 hours with arch calls in year 2), the most distinct difference was the substantial increase in hours with arch calls present throughout the May-August 2014 period (Figure 18).

Blue Whale vocalizations were detected on 3,859 (16.5%) of the 23,378 recordings analysed from SHALLOWGUL, INTERCANDEEP, and LOGAN. A total of 478 files (2.0% of all recordings collected from these locations) were confirmed to contain Blue Whale calls. The overall false positive rate was thus 87.6%. The false negative rate has not yet been determined for this dataset, but is expected to be similar to that determined for the other AMAR recorders.

The number of hours with confirmed Blue Whale calls varied by location, with SHALLOWGUL having significantly more hours with calls than INTERCANDEEP or LOGAN (Table 12, Figure 19). LOGAN had the least number of hours with calls; however, there was a wide-azimuth seismic survey being conducted close to Logan Canyon during summer 2014 that resulted in the recordings from this location being inundated with seismic airgun sounds, which overlap the frequency of Blue Whale calls. This compromised the efficacy of the detectors and made determining the presence of Blue Whale calls impossible in some cases; therefore, the LOGAN dataset in particular may be an underestimate of the Blue Whale calling rates in the area. This issue was not encountered in the more eastern locations where seismic signals were not as loud.

Table 8. Description of 15 AMAR deployments included in the Blue Whale analysis. "LF" denotes the low-frequency (16 kHz) recording duty cycle and "HF" denotes the high-frequency recording duty cycle.

Location	Deployment	Recorder Depth (m)	Date of First Recording	Date of Last Recording	Duty Cycle	Num. Files
MIDGUL	Fall/Winter	1,850	12 Oct 2012	10 Apr 2013	13 min LF/ 2 min HF	17,262
MIDGUL	Spring/ Summer	1,520	7 May 2013	26 Sep 2013	13 min LF/ 2 min HF	13,553
MIDGUL	Fall/Winter	1,470	15 Nov 2013	6 Apr 2014	17.2 min LF/ 2.2 min HF	10,228
MIDGUL	Spring/ Summer	1,470	3 May 2014	26 Sep 2014	17.2 min LF/ 2.2 min HF	10,603
GULSHO	Fall/Winter	1,370	12 Oct 2012	10 Apr 2013	13 min LF/ 2 min HF	17,271
GULSHO	Spring/ Summer	1,520	8 May 2013	26 Sep 2013	13 min LF/ 2 min HF	13,564
GULSHO	Fall/Winter	1,470	15 Nov 2013	6 Apr 2014	17.2 min LF/ 2.2 min HF	10,233
GULSHO	Spring/ Summer	1,560	3 May 2014	26 Sep 2014	17.2 min LF/ 2.2 min HF	10,573
SHOHALD	Fall/Winter	1,720	12 Oct 2012	10 Apr 2013	13 min LF/ 2 min HF	17,263
SHOHALD	Spring/ Summer	1,490	8 May 2013	25 Sep 2013	13 min LF/ 2 min HF	13,606
SHOHALD	Fall/Winter	1,490	15 Nov 2013	7 Apr 2014	17.2 min LF/ 2.2 min HF	10,295
SHOHALD	Spring/ Summer	1,500	3 May 2014	26 Sep 2014	17.2 min LF/ 2.2 min HF	10,529
SHALLOWG UL	Summer	200	13 Jul 2014	27 Sep 2014	11.3 min on/ 3.6 min off	7,805
INTER-CANDEEP	Summer	1,400	13 Jul 2014	27 Sep 2014	11.3 min on/ 3.6 min off	7,798
LOGAN	Summer	1,430	13 Jul 2014	27 Sep 2014	11.3 min on/ 3.6 min off	7,775
All						**178,368**

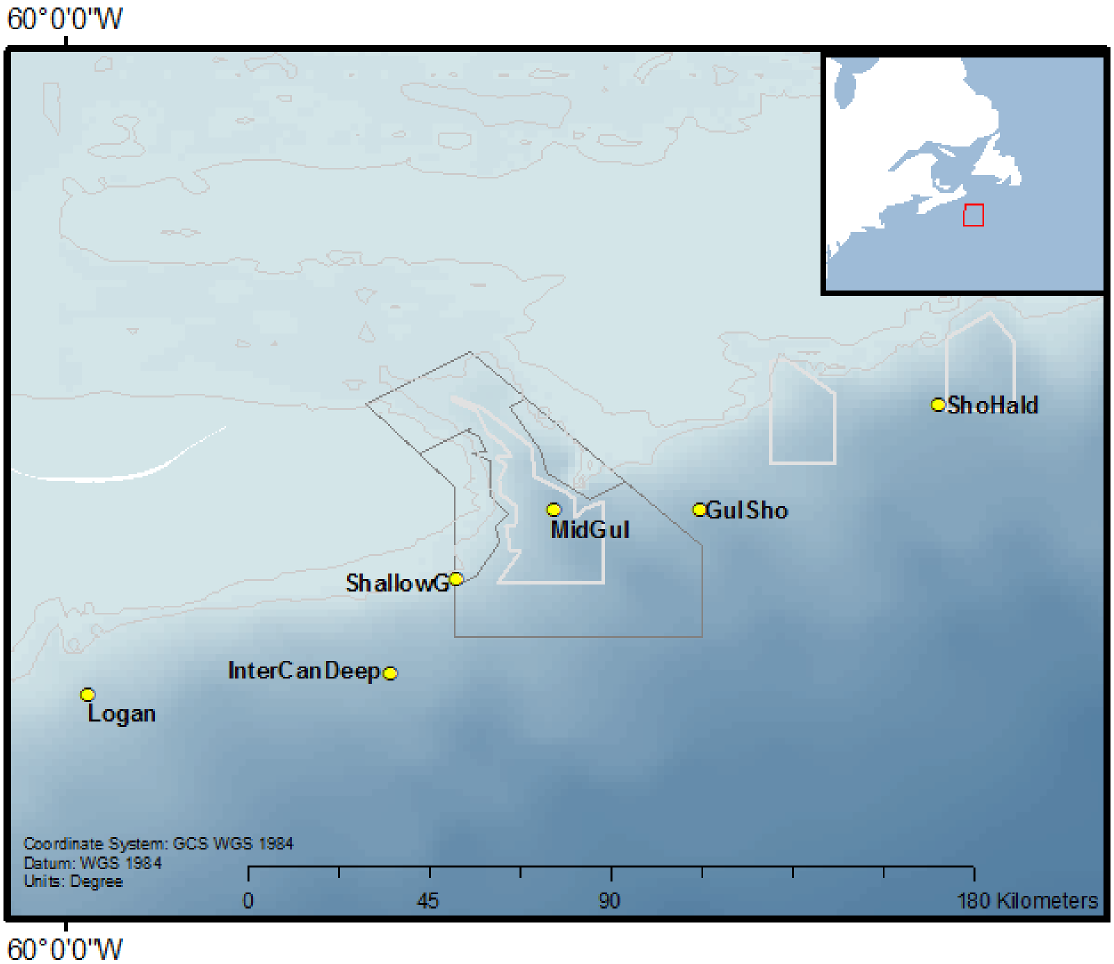

Figure 15. The AMAR acoustic recorder locations along the slope of the eastern Scotian Shelf.

Table 9. Number and proportion of hours with confirmed Blue Whale calls present from MIDGUL, GULSHO, and SHOHALD during each season, and for each season in total.

Location	Deployment	Hours with Calls	Prop. of Hours with Calls
MIDGUL	Spring	26	0.012
	Summer	317	0.144
	Fall	64	0.035
	Winter	277	0.128
	Total	684	0.082
GULSHO	Spring	6	0.003
	Summer	172	0.078
	Fall	198	0.109
	Winter	376	0.174
	Total	752	0.090
SHOHALD	Spring	39	0.018
	Summer	147	0.067
	Fall	222	0.123
	Winter	602	0.279
	Total	1,010	0.120
All	**Spring**	**71**	**0.016**
	Summer	**636**	**0.144**
	Fall	**484**	**0.134**
	Winter	**1,255**	**0.291**
	Total	**2,446**	**0.146**

Table 10. Number of hours per month with confirmed Blue Whale calls present per year of deployment at MIDGUL, GULSHO, and SHOHALD. "-" indicates no recordings available for that particular month.

Month	Number Hours with Calls Year 1	Number Hours with Calls Year 2
October	35	-
November	157	159
December	380	412
January	221	180
February	7	55
March	0	46
April	1	0
May	1	23
June	1	60
July	7	219
August	5	344
September	47	86
Total	**862**	**1,584**

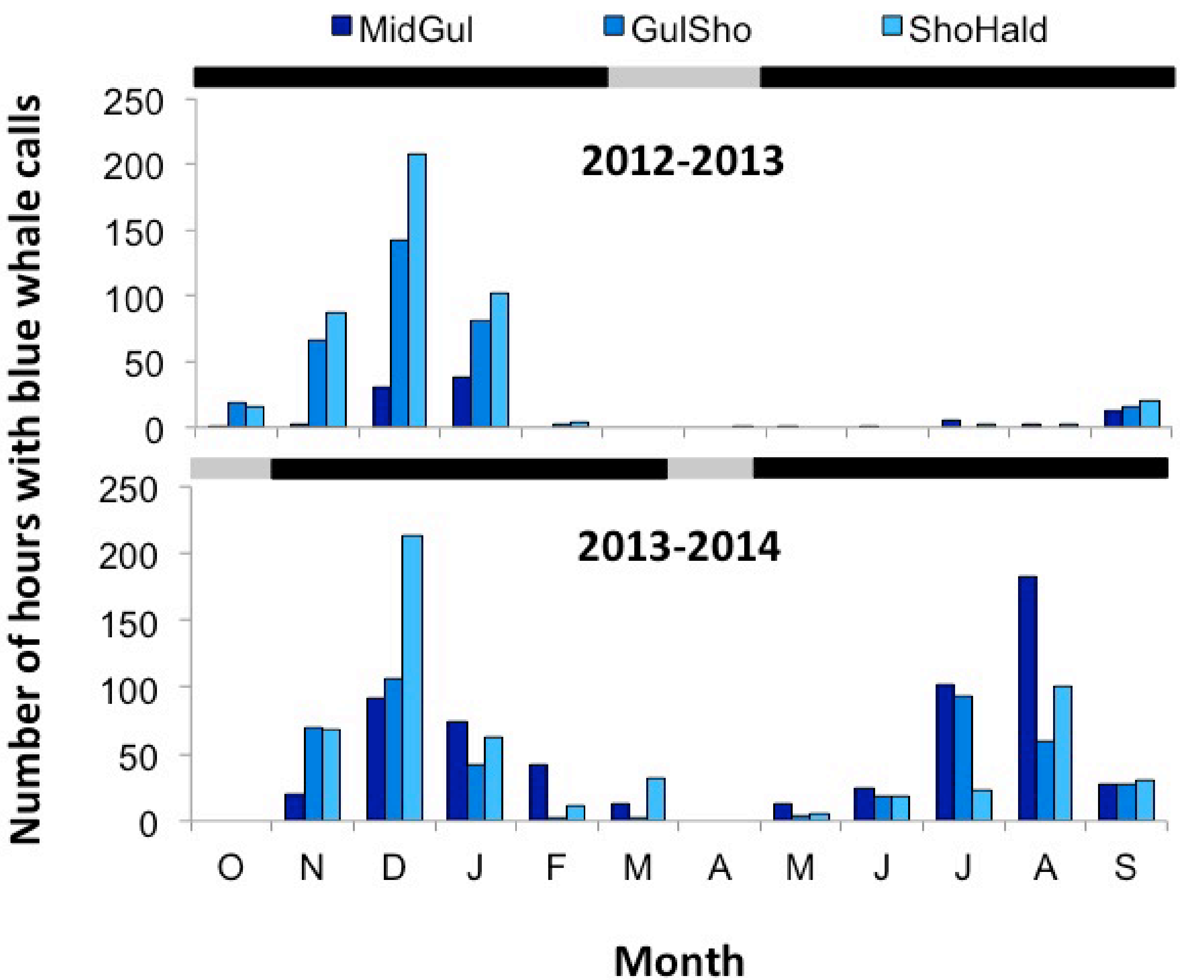

Figure 16. The number of hours with confirmed Blue Whale calls for each month of each year, for MIDGUL, GULSHO, and SHOHALD. Black bars indicate times for which there were recordings while grey bars indicate times when no recordings were detected. No recordings were obtained from October 2013.

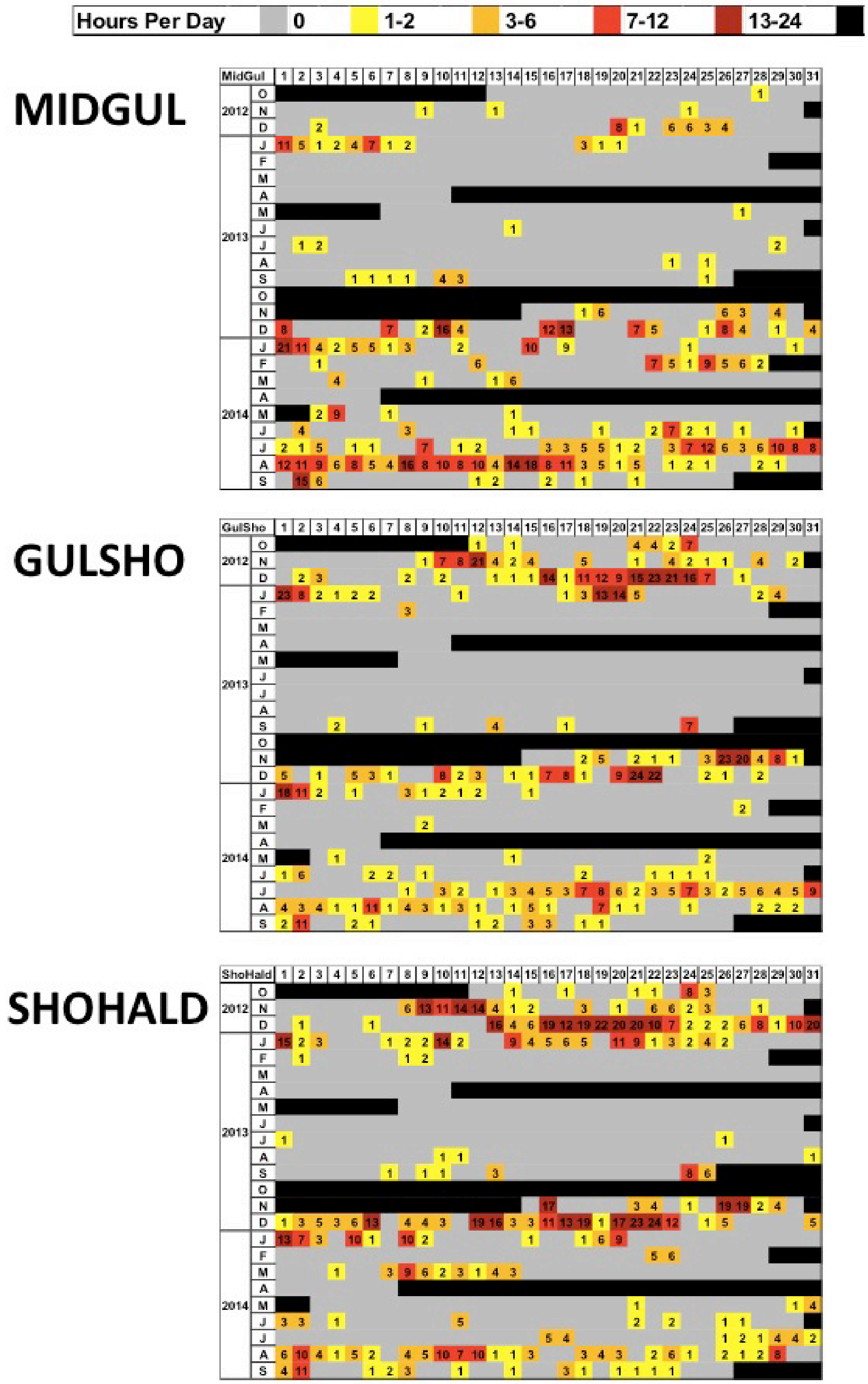

Figure 17. Number of hours each day (x-axis) of each month (y-axis) with confirmed Blue Whale calls present at MIDGUL, GULSHO, and SHOHALD.

Table 11. Average time (in hours) with Blue Whale calls present for each month per year of deployment at MIDGUL, GULSHO, and SHOHALD, calculated by determining the average number of consecutive recordings with Blue Whale calls present on them (files with no confirmed Blue Whale call detections were not included in this calculation). "-" indicates no recordings available for that particular month. Asterix (*) indicates that the value is based on only one recording with confirmed Blue Whale calls present.

Month	Av. Consecutive Hours with Calls Year 1	Av. Consecutive Hours with Calls Year 2
October	0.90	-
November	1.25	3.61
December	1.85	2.85
January	1.07	1.23
February	1.13	1.06
March	0.00	1.25
April	0.25*	0.00
May	0.25*	1.10
June	0.25*	1.06
July	0.50	1.07
August	0.50	0.98
September	1.21	1.87

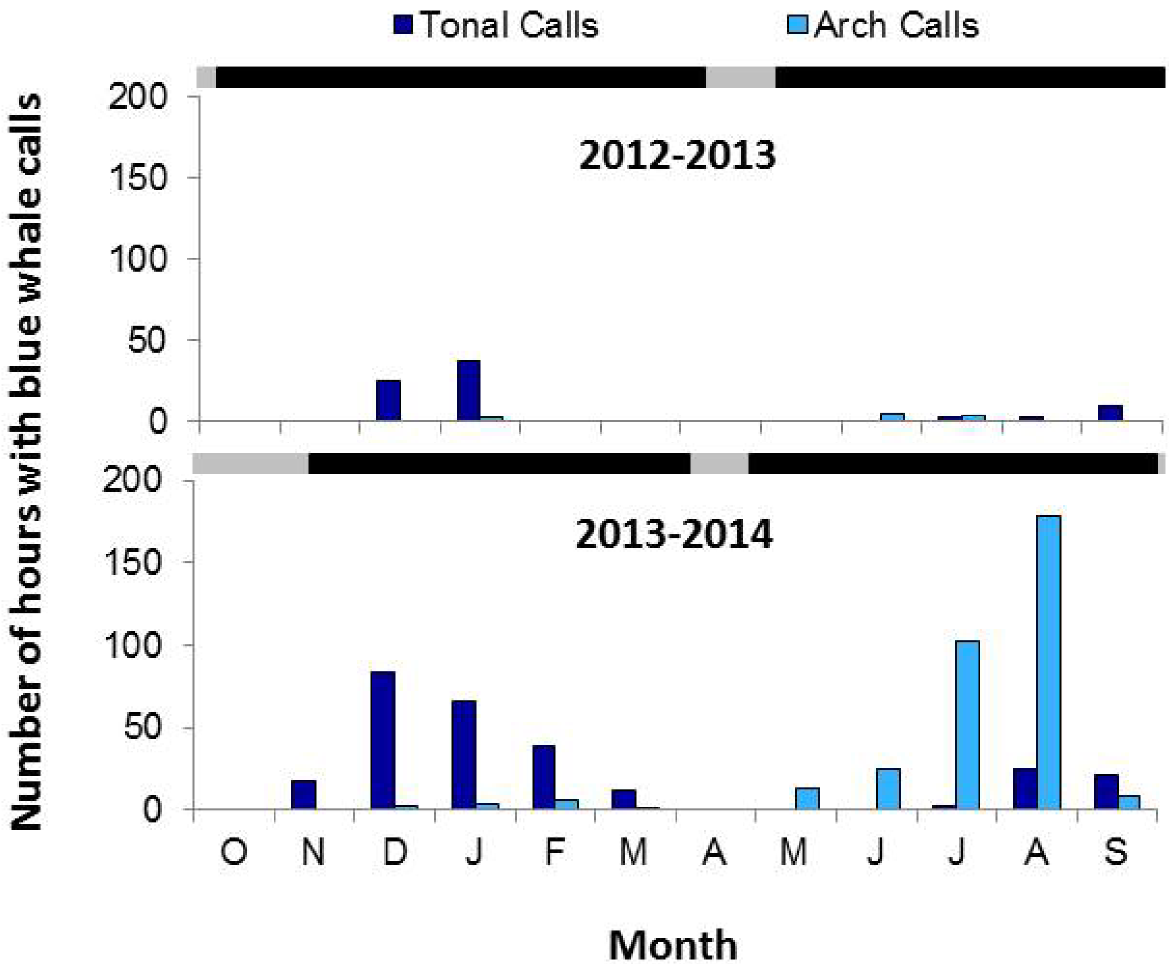

Figure 18. Number of hours with each Blue Whale call type present on the MIDGUL recordings.

Table 12. Number and proportion of hours with confirmed Blue Whale calls present from each recording location during summer 2014.

Location	Deployment	Hours with Calls	Prop. of Hours with Calls
SHALLOWGUL	Summer	183	0.101
INTERCANDEEP	Summer	45	0.025
LOGAN	Summer	66	0.036
All	**Total**	**294**	**0.054**

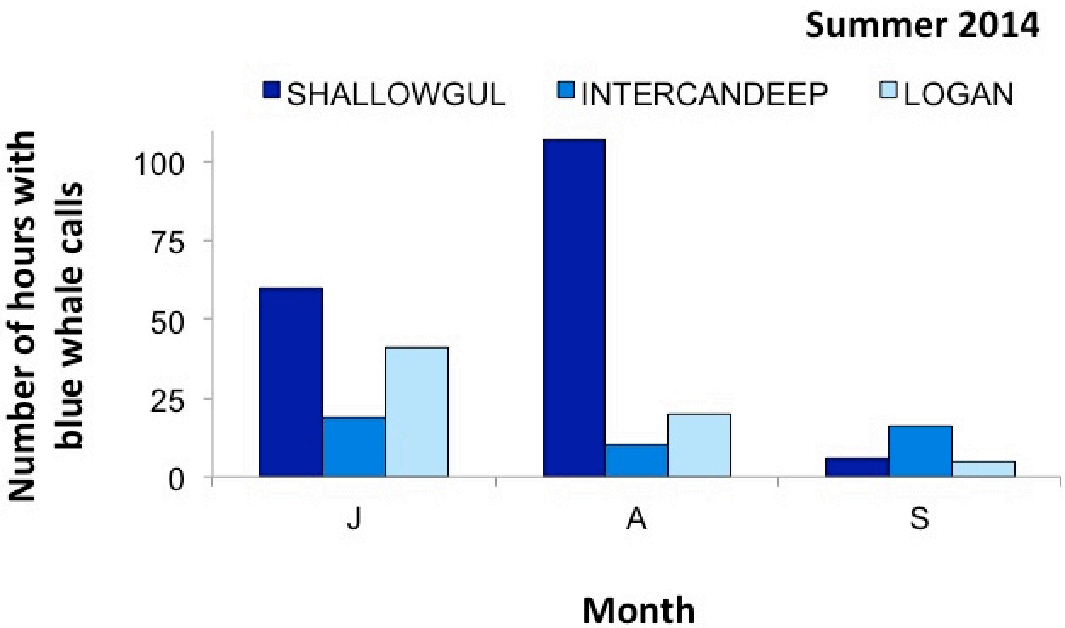

Figure 19. The number of hours with confirmed Blue Whale calls present for each month for which recordings were obtained for SHALLOWGUL, GULSHO, and SHOHALD.

AURAL DATASET

DFO deployed AURALs at a number of locations off Newfoundland and Labrador between 2009 and 2015 (Figure 19). The systems were moored at water depths ranging between 29-207 m, with the AURALs positioned 42-157 m off the sea bottom (Table 13). The recorders had a HTI-96-MIN hydrophone, and the 16-bit digital recording system had an adjustable amplifier with 22 dB gain chosen for this study. The resulting analogue signal was passed through an anti-aliasing filter where it was recorded into 128 MB WAV format files. The recordings were collected at a 32 kHz sampling rate, providing usable frequencies of 10 to 16,384 Hz, at a duty cycle which varied between 20-34 min on and 26-40 min off, with the exception of one recorder which collected data for 32.5 min and then turned off for only 2.5 min (Table 13).

Data from six recording locations; Burgeo Bank (BB) and Placentia Bay (PB) off southern Newfoundland, two locations (on the margins of the Carson and Lily Canyons) on the Grand Banks (GBW and GBE), and two locations off southern Labrador (LABS and LABN) (Figure 20), were analysed for the presence of Blue Whale calls. Recording coverage varied between the 6 locations, but recordings were generally obtained during the summer, fall, and winter. Acoustic data were recorded in the LABN and LABS locations in summer-fall of 2014 as well, but these have not yet been analysed. In total, 19,658 recordings (9,022 hours) were analysed for the presence of Blue Whale calls (Table 13).

The automated FFT-based Blue Whale call detectors developed by JASCO Applied Sciences Ltd., described above, were used to detect possible Blue Whale calls (A, B, AB, and D calls) on the AURAL recordings.

Blue Whale calls were detected on 3,335 (16.9%) of the 19,658 recordings analysed. Analysis verified that 156 of these (0.7% of all recordings) contained Blue Whale calls (i.e., were true positives) resulting in an overall false positive rate of 95.3%. This high false positive rate was likely a function of both high levels of anthropogenic noise (mainly vessel and seismic airgun sounds), and self-noise from the moorings present on the recordings in the Blue Whale vocalization frequency band. This compromised the efficacy of the detectors and made determining the presence of Blue Whale calls difficult in some cases. This dataset thus likely underestimates Blue Whale calling rates in these recorder locations.

The number of hours with confirmed Blue Whale calls again varied by location and season, though data was not collected from all seasons at all locations (Table 14). Burgeo Bank summer recordings had the most hours with Blue Whale calls present, while there were few confirmed calls from any of the seasons at the Grand Banks locations and almost no confirmed calls from the Placentia Bay recordings during any seasons and the fall and winter Labrador datasets (the summer Labrador recordings have yet to be analysed). Confirmed Blue Whale calls occurred in July, August, October, November, December, and January (Figure 21). Arch calls were detected during 41 hours of the Burgeo Bank summer recordings and during one hour of the LABS recordings (in October).

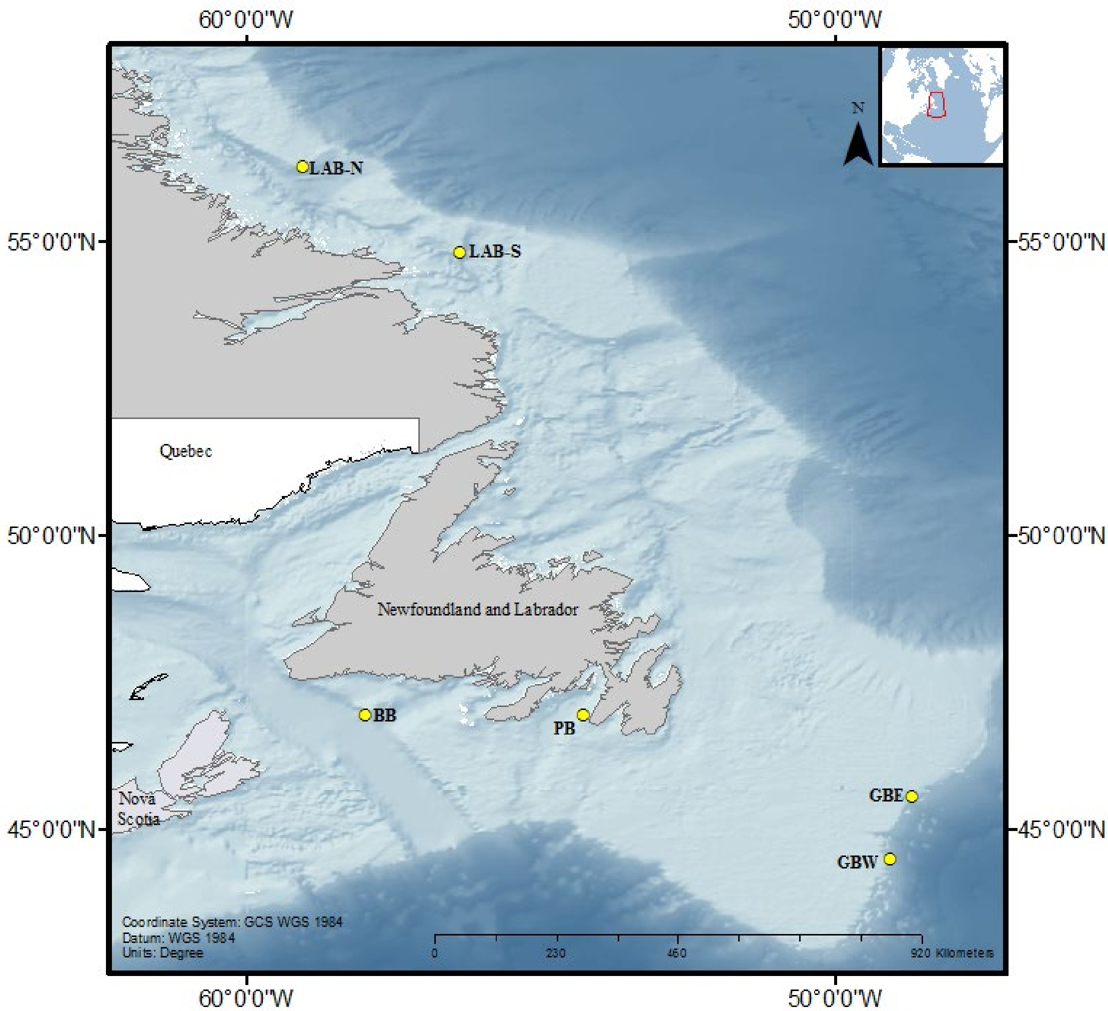

Figure 20. The AURAL acoustic recorder locations off Newfoundland and Labrador.

Table 13. Description of eight AURAL acoustic recorder deployments included in the Blue Whale analysis.

Location	Deployment	Recorder Depth (m)	Date of First Recording	Date of Last Recording	Duty Cycle	Num. Files
GBW	Summer-Winter	76	25 Aug 2009	10 Feb 2010	20 min on/ 40 min off	4,063
GBE	Summer-Winter	81	25 Aug 2009	10 Feb 2010	30 min on/ 30 min off	2,383
PB	Summer-Winter	63	13 Aug 2009	29 Jan 2010	20 min on/ 40 min off	4,062
BB	Summer	157	21 June 2010	20 Aug 2010	32.5 min on /2.5 min off	2,500
LABS	Fall-Winter	42	20 Oct 2013	27 Jan 2014	34 min on/ 26 min off	2,385
LABN	Fall-Winter	42	19 Oct 2013	25 Jan 2014	34 min on/ 26 min off	2,358
LABN	Winter	60	27 Jan 2014	13 Mar 2014	34 min on/ 26 min off	1,077
LABS	Winter	80	25 Jan 2014	1 Mar 2014	34 min on/ 26 min off	830
All						**19,658**

Table 14. Number and proportion of hours with Blue Whale call detections from each AURAL recording location during each season. Number and proportion of hours with detections from each recording location during each season, and from each season in total.

Location	Deployment	Hours with Detections	Prop. of Hours with Detections
GBW	Fall	4	0.002
	Winter	3	0.002
GBE	Summer	2	0.013
	Fall	17	0.015
	Winter	14	0.012
PB	Summer	1	0.016
	Fall	0	0.0
	Winter	0	0.0
	Spring	1	0.002
BB	Summer	114	0.046
LABS	Fall	0	0.0
	Winter	1	<0.001
LABN	Fall	0	00
	Winter	0	0.0
All	**Fall**	**21**	**0.004**
	Winter	**18**	**0.003**
	Summer	**118**	**0.037**
	Total	**157**	**0.011**

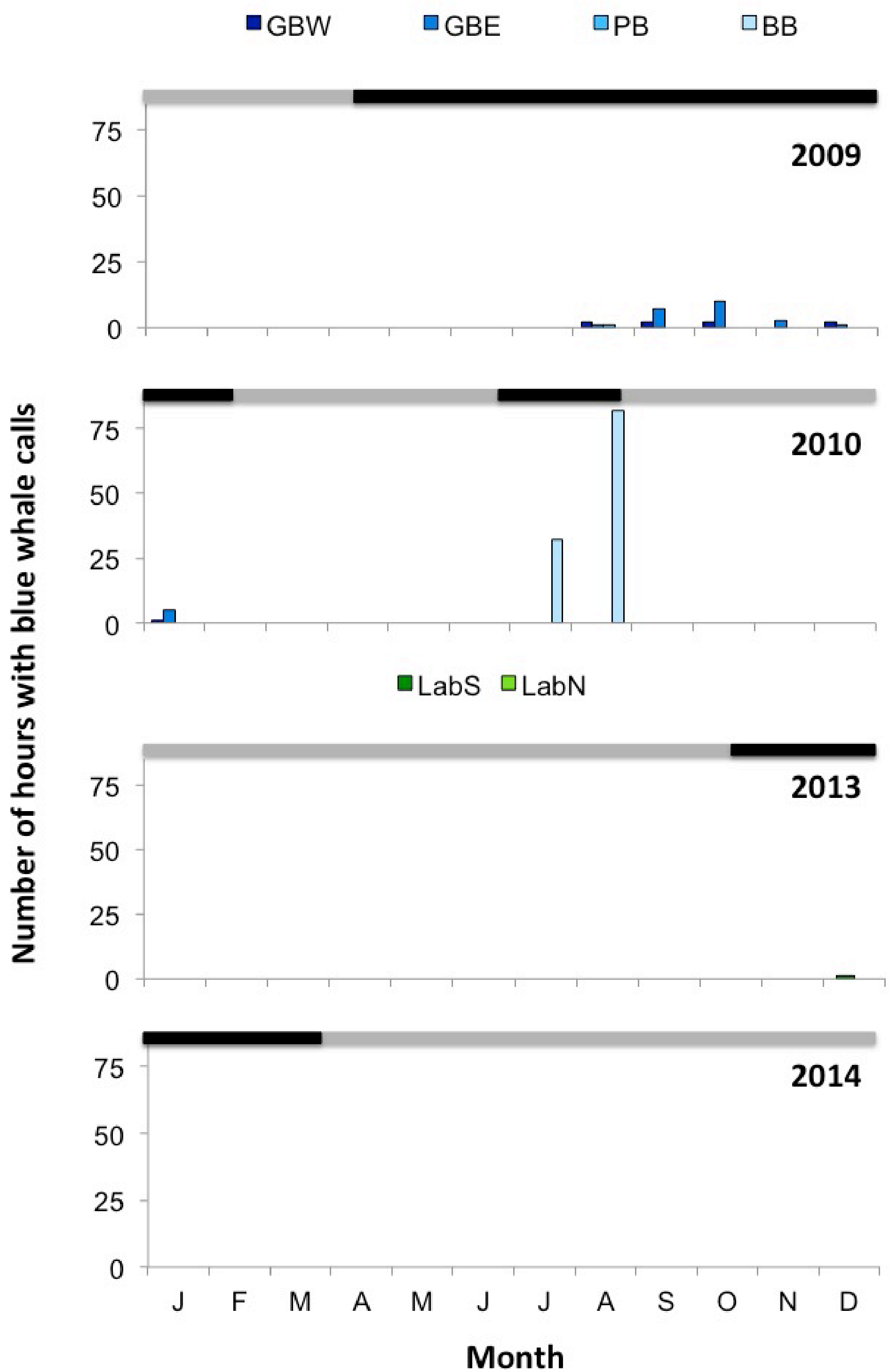

Figure 21. The number of hours with confirmed Blue Whale calls present for each month of each year, for the five recording locations. Black bars indicate times for which there were recordings, while grey bars indicate times when no recordings were collected. Acoustic data were collected in the LabN and LabS locations in summer-fall of 2014 as well, but these are not indicated here, and have not been analysed.

SUMMARY AND CONCLUSIONS

Results are not directly comparable between the various datasets presented, and in some cases even between different recorders within a dataset, due to differences in the sensitivity of the various recorders used and the local environmental conditions at each recording site, which means that there are likely different detection ranges associated with each recording site. For example, a recorder would detect more Blue Whale calls in an area where sound propagation conditions are better, or background noise levels are lower, than a recorder in an area with poorer sound propagation conditions or louder background noise levels, even if the relative densities of calling Blue Whales were equal. Additionally, given that under some conditions Blue Whale calls may be detected over very large ranges (tens of kilometres to even a hundred kilometres), it is possible that in some cases multiple recorders recorded the same calling individual. Caution is thus warranted when comparing results between nearby recording sites.

These datasets demonstrate that both tonal and arch calls are present, and while Blue Whale vocalizations are recorded throughout the year, peaks in call occurrence generally occur in July/August and December/January. There is also some degree of interannual variability in seasonal trends observed at the recording locations that have been most extensively monitored. In particular, there is a substantial increase in the number of hours with Blue Whale arch calls observed in summer 2014. It is not known if this difference is a result of environmental conditions or some other factor, but it is interesting that during summer 2014 a wide-azimuth seismic survey was occurring within 150 km of the AMAR recorders during the same time frame (May-August). Such interannual variation requires further investigation.

Sightings data (see above) and SDM results (see next section) suggest that northeastern Newfoundland and Labrador are not areas of importance for Blue Whales. In contrast, an acoustic monitoring study by Clark (1995) did detect and track Blue Whales on Newfoundland's northeast coast (Figure 12), and there were some Blue Whale calls on the eastern edge of the Grand Banks (Figure 20). Further analysis of summer acoustic records from the mid-shelf area off central Labrador may confirm this earlier result, but more offshore acoustic monitoring is merited in eastern Newfoundland, and Labrador to gain a better understanding of Blue Whale seasonal call occurrence in these areas.

SPECIES DISTRIBUTION MODELS

Species Distribution Models (SDM) models were used to predict potentially suitable habitat for Blue Whales off Nova Scotia, Newfoundland, and Labrador during summer. Areas predicted as highly or moderately suitable habitat are interpreted as potentially important for this species, and should be considered priority areas for future monitoring efforts. A summary of the SDM is presented below. The methods are described in greater detail in Gomez et al. (2017).

MODELLING METHODS

Long-term cetacean sightings data from waters off Nova Scotia, Newfoundland, and Labrador available from DFO, the Ocean Biogeographic Information System (OBIS), the Whitehead Lab at Dalhousie University, and the Environment Canada (Canadian Wildlife Service) Eastern Canada Seabirds at Sea (ECSAS) programme were used for this analysis. These data included sightings observed during systematic surveys as well as sightings obtained from platforms of opportunity. Records of Blue Whales from the summer months during the post-whaling period of 1975-2015 (N=196; Figure 22 [left panel]) were used to build the SDM.

SDM requires selection of environmental variables expected to exhibit a spatial relationship with the geographic location of a species and thus are appropriate for predicting suitable habitat. For cetaceans, prey distribution is an ideal predictor variable (e.g., Pendleton et al. 2012); however, information on the spatial and temporal distribution of krill (the primary prey of Blue Whales) is lacking for the Northwest Atlantic outside the Gulf of St. Lawrence. As an alternative, five environmental variables likely related to the physical and biological conditions required for the occurrence of Blue Whale prey, were selected (Gomez et al. 2017; Table 15, Figures 23 and 24).

MaxEnt software (version 3.3.3k; www.cs.princeton.edu/~schapire/maxent, Phillips et al. 2006) was used to build the SDM. This tool performs well compared to other conventional approaches that use species presence-only data when sample size is relatively small (Elith et al. 2011; Phillips et al. 2006; Tittensor 2013). MaxEnt incorporates the geographic location of each sighting of the species of interest (i.e., presence-only data for the target group species [TGS]; Blue Whales) and the environmental data predictors across the area of study (landscape). MaxEnt then extracts a sample of locations of species presence and a sample of point locations within the landscape and contrasts them to explore the relative occurrence rate (ROR, Fithian et al. 2015), or the relative probability of presence of individuals in the landscape (Merow et al. 2013; Phillips et al. 2006). The raw ROR output was rescaled to range between 0-100 and used to generate maps predicting suitable habitat for Blue Whales (Merow et al. 2013). These maps present the rescaled ROR in four arbitrary categories: high (100-60%), moderate (60-40%), low (40-10%), and very low (<10%). The Area Under the Curve (AUC) metrics of the receiver operating characteristic (ROC) plot were used to evaluate the ability of the SDMs to correctly distinguish between sites associated with Blue Whale presence and the sample of points from the landscape (Phillips et al. 2006).

One potential source of sampling bias in the SDM is that Blue Whale records in potential suitable habitat may be absent due to lack of survey effort in the area. A bias file correction was applied to partially account for this potential sampling bias (Bystriakova et al. 2012; Fourcade et al. 2014). A sampling distribution map was created by plotting sightings of cetaceans other than Blue Whales (i.e., non-target group species [non-TGS]) within the study area during summer. Cells within a specified radius of non-TGS records were considered surveyed and were used to generate a bias file representing ‘sampled’ areas within the study area (Merow et al. 2013; Phillips et al. 2006); Figure 22 [right panel]). Note that this correction does not account for areas where no cetaceans are sighted or no effort at all occurs. A sensitivity analysis was then conducted to explore the effect on the resulting SDM of not including the bias file, and of adjusting the radius of surveyed cells included in the bias file to 1, 2.5, and 5 km (Bystriakova et al. 2012; Fourcade et al. 2014).

An additional potential source of bias is that Blue Whale sightings may be overrepresented in regions with high sampling effort (e.g., the Gully Marine Projected Area [MPA]). Systematic subsampling of Blue Whale sightings was used to account for this potential bias (Bystriakova et al. 2012; Fourcade et al. 2014). For this correction, only one Blue Whale sighting within a specified grid was sampled and included in the SDM. A sensitivity analysis was conducted to explore the result on the SDM of not subsampling, and of adjusting the subsampling grid size to 1, 2.5, and 5 km (Bystriakova et al. 2012; Fourcade et al. 2014).

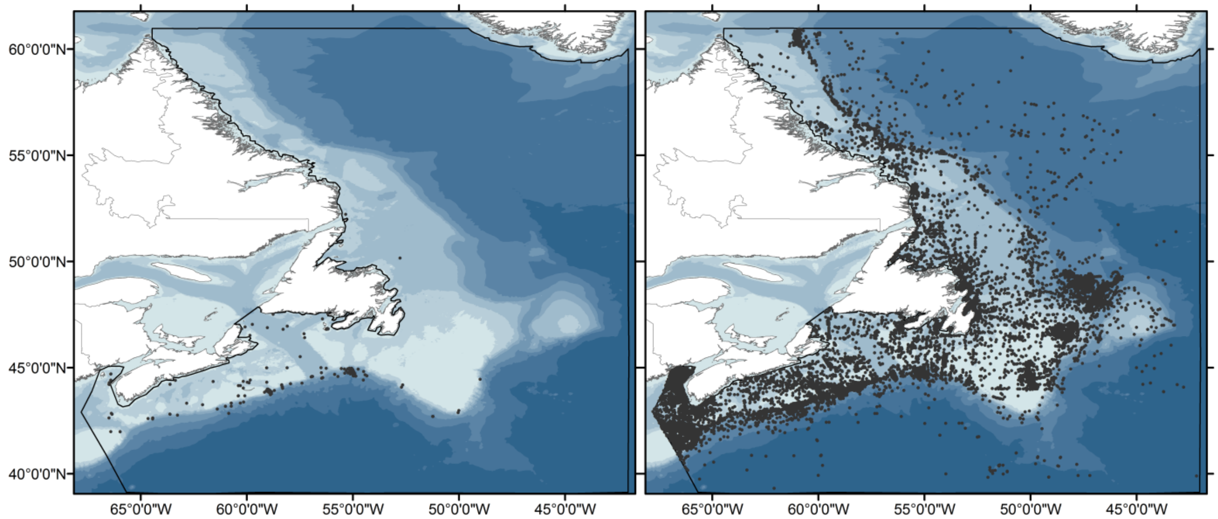

Figure 22. [left panel] Blue Whale (TGS) sightings collected within the boundaries of our study area indicated by the black line (N=196 records); and, [right panel] sightings of cetacean species other than Blue Whales (non-TGS records; N=40,929) used to create a bias file. This map highlights the relative lack of survey effort on the Northeast Newfoundland and Labrador shelves, and in deeper waters of the Northwest Atlantic. Cetacean sightings data from DFO, OBIS, the Whitehead lab at Dalhousie University, and the ECSAS programme were included.

Table 15. Environmental layers selected to predict the distribution of Blue Whales. Seasons were defined as spring (March to May) and summer (June to August). Table from Gomez et al. (2017).

Variable	Units	Temporal Resolution	Spatial Resolution	Source
Ocean Depth	metres	Static variable	1 km	Oceans and Coastal Management Division, Maritimes Region, DFO, Bedford Institute of Oceanography
Compound Topographic Index (CTI)	not applicable	Static variable	1 km	Calculated using the Geomorphometry and Gradient Metrics Toolbox version 2.0 in ArcGIS (Evans et al. 2014)
Sea Surface Temperature (SST)	degrees Celsius	Seasonal (used in SDM: summer)	1.5 km pixel	Derived from remotely-sensed images from the Moderate Resolution Imaging Spectroradiometer (MODIS) instrument on the Aqua satellite. The seasonal climatologies (2003-2014) were derived from semi-monthly composites (2003-2014). (Available on the Ocean Research and Monitoring Section website.)
Areas of persistent high chlorophyll-a concentration ($CHL_{persistence}$)	%	Seasonal (used in SDM: spring & summer)	1.5 km pixel	Derived from images obtained from MODIS Aqua satellite (Fuentes-Yaco et al. 2015).
Regional concentrations of chlorophyll-a ($CHL_{magnitude}$)	mg/m^3	Seasonal (used in SDM: spring & summer)	1.5 km pixel	Derived from images obtained from MODIS Aqua satellite (Fuentes-Yaco et al. 2015).

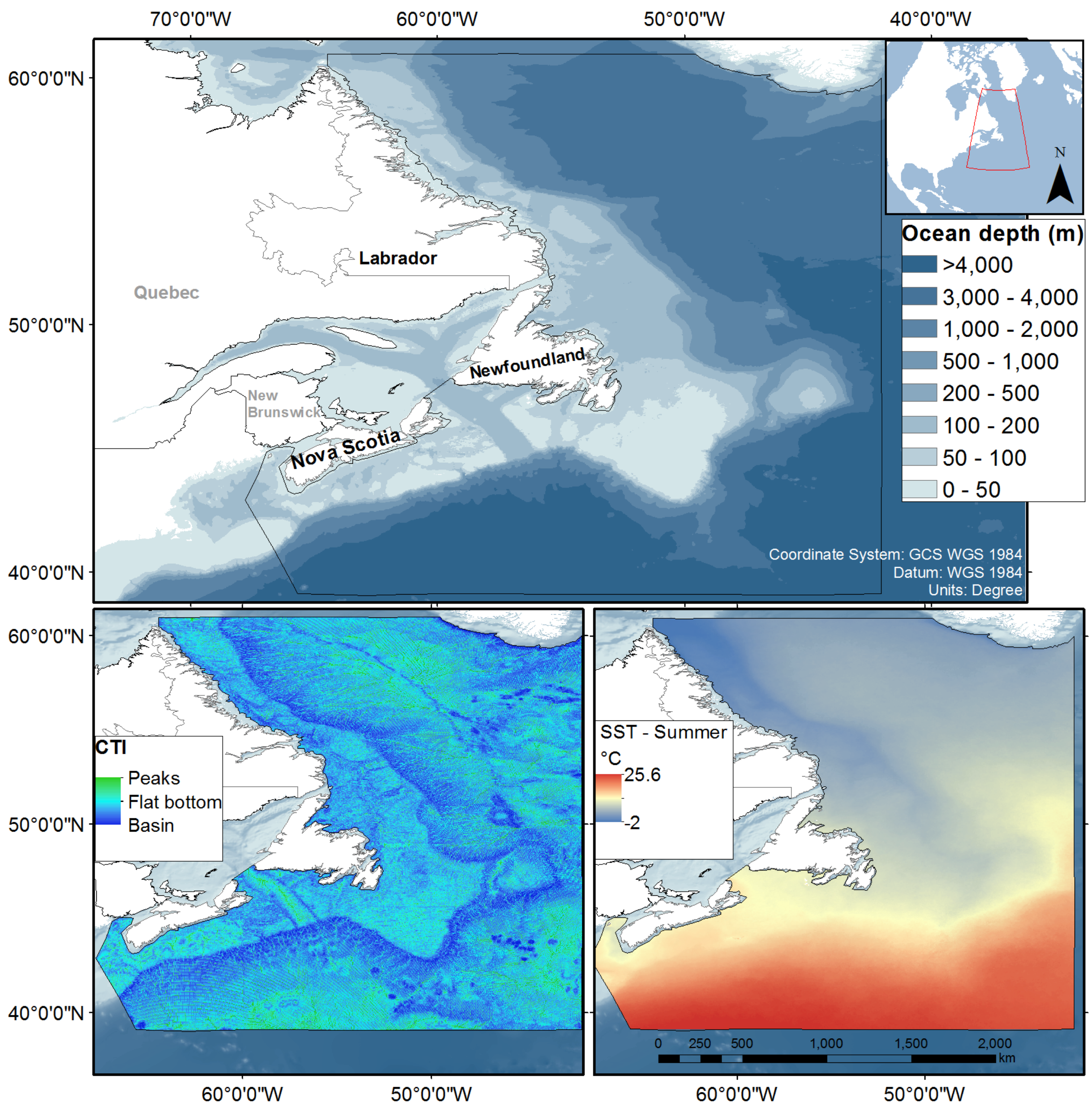

Figure 23. Physical environmental data used to predict the distribution of Blue Whales in the Northwest Atlantic Ocean: (upper panel) ocean depth (metres), (bottom left panel) Compound Topographic Index (CTI), and (bottom right panel) Sea Surface Temperature (SST) (°C) during the summer (June to August). CTI, derived from ocean depth, is a continuous variable that ranged from 9.57 to 27.8 (low values represent basins, high values represent peaks and intermediate values around 18.7 represent flat surfaces). Seasonal climatologies for SST were derived from semi-monthly composites for the 2003-2014 period. Figure from Gomez et al. (2017).

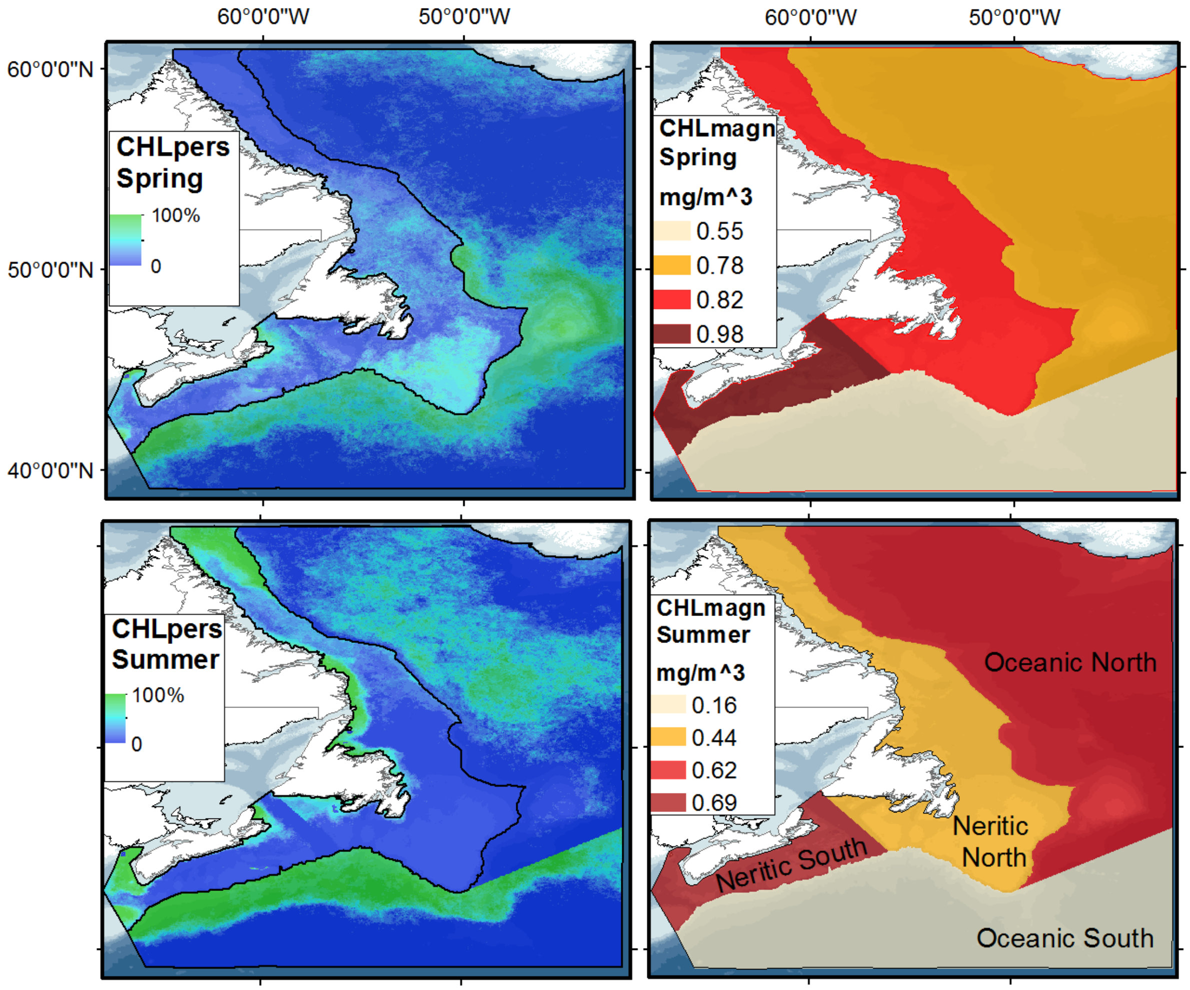

Figure 24. Biological environmental data used to predict the distribution of whales in the Northwest Atlantic Ocean: (left panels) areas of persistently high chlorophyll-a concentration (CHLpers) and (right panels) average regional chlorophyll-a magnitude (CHLmagn). Seasonal climatologies (for spring, March to May, and summer, June to August) were derived from weekly composites for the 2003-2014 period (Table 1, Fuentes-Yaco et al. 2015). Black line shows the subdivision of the study area into neritic (between 50 m and 600 m depth) and oceanic (>600 m depth). Neritic and oceanic regions were further divided into North and South (see left panel). The procedures to compute each of those maps are presented in detail in Fuentes-Yaco et al. (2015). Figure from Gomez et al. (2017).

MAXENT MODELLING RESULTS

Visual inspection of the SDMs produced for the sensitivity analysis, which included 16 model runs (no bias file, bias file with a sampling cell radius of 1, 2.5, and 5 km; no subsampling, subsampling using a grid size of 1, 2.5, and 5 km), indicate that while there was some similarities between the various SDMs generated, the SDM results were sensitive to the size of the bias file radius and to a lesser extent the resolution of the subsampling grid size used (Figure 25). The slopes of the Scotian Shelf and Grand Banks were consistently identified as highly suitable in all model runs, though the extent of these identified areas varied. The Laurentian Channel and large areas of the western and central Scotian Shelf, as well as the southern Newfoundland shelf were also moderately to highly suitable in all model runs when a bias file was applied; when no bias file was applied primarily just the western and eastern slopes of the Laurentian Channel, and much smaller areas of the Scotian Shelf and southern Newfoundland shelf, were moderately or highly suitable. When no bias file was applied, a large portion of the Bay of Fundy area was moderately to highly suitable, while only very small areas within the Bay of Fundy were moderately or highly suitable during some of the model runs with a bias file applied. Waters off Labrador, and north and eastern Newfoundland consistently remained of very low to low suitability for all model runs.

The SDM that included the bias file generated by plotting non-TGS records on a sampling cell radius of 1 km and Blue Whale sightings sub-sampled on a 1 km grid (N = 176) is presented in Figure 26. One kilometre is considered to be a reasonable distance at which observers from vessel-based platforms can detect and identify Blue Whales, justifying a 1 km distance chosen for the bias file (Gomez et al. 2017). A 1 km grid for subsampling of Blue Whale sightings was chosen to approximate the scale of the model environmental layers (Table 15). The five environmental variables included in this study were not correlated and thus were all used in the SDM (Variance Inflation Factor <3, Zuur et al. 2010). SST (56.4%), ocean depth (15.1%) and $CHL_{magnitude}$ during spring (13.3%) provided the greatest contributions to the Blue Whale SDM. This model had high AUC values (0. 851 +/- 0.130) indicating good model performance. Although AUC provides an adequate evaluation of model performance (see Phillips et al. 2006), caution is warranted because it is not a perfect measure of model accuracy due in part to lack of true species absence data (Lobo et al. 2008, Fourcade et al. 2014). There are no alternatives for evaluating model performance for this type of presence-only SDM (Merow et al. 2013).

The SDM predicts areas of suitable Blue Whale habitat that should be considered as priority areas for future Blue Whale monitoring efforts. Importantly, the results of the SDM are not interpreted as the most accurate distribution of Blue Whales in the Northwest Atlantic because this is beyond the scope of the model’s evaluation capabilities. Caution is warranted when interpreting the SDM results as the majority of cetacean sightings were located on the Scotian Shelf and there is a lack of survey effort in large portions of the study area, particularly in deep water beyond the shelf break. Results are likely to vary as new data become available, as evidenced by Gomez et al. (2017). Furthermore, many cetacean sightings were collected through platforms of opportunity rather than systematically. As well, the SDMs were sensitive to the model parameters used such as the bias file sampling cell radius. For these reasons, the SDM results provide an indication of potentially suitable habitat and represent interim maps pending new information and model validation. Results can be used as a hypothesis to test once additional updated and relevant data is taken into consideration (Gomez et al. 2017). To improve and validate the SDMs produced for this study, efforts should focus on using cetacean sightings derived from systematic surveys where true zeros are available (e.g., Lawson and Gosselin 2009) as well as potentially reconstructing the effort associated with sightings gathered from platforms of opportunity.

Highly and moderately suitable habitat for Blue Whales corresponded to deep-water areas along the continental slopes of the Scotian Shelf and the Grand Banks, the Laurentian Channel, as well as shallower areas on the western Scotian Shelf and the shelf off southern Newfoundland (Figure 25). Deep-water regions beyond the shelf break correspond to areas of very low Blue Whale habitat suitability (Figure 25), which are areas that have poor or non-existent survey effort (Figures 3, 4, 5, 6, and 22). It is not clear whether this is due to the lack of sightings data in these areas, since Blue Whale vocalizations have been recorded in the offshore northern region by Clark (1995).

Abgrall (2009) used an Ecological Niche Factor Analysis (ENFA) approach to define the Blue Whale habitat off Newfoundland and Labrador using four predictor environmental layers: water depth, seabed slope, sea surface temperature, and chlorophyll concentration. The most suitable habitat for Blue Whales around Newfoundland and Labrador was mainly found in the Gulf of

St. Lawrence and off the southern coast of Newfoundland (Abgrall 2009). Suitable habitat was also identified along the coastlines of northeast Newfoundland and southern Labrador. There are some differences between Abgrall's (2009) results and the MaxEnt results presented above, in part because the Blue Whale sighting records used by Abgrall (2009) included sightings from the Gulf of St. Lawrence as well as whaling records prior to 1974, which includes more sightings off the northwest coast of Newfoundland and south coast of Labrador (Figure 1) compared to the sighting pattern after 1975 (Figure 9). Abgrall (2009) also used a different model algorithm and different predictor layers.

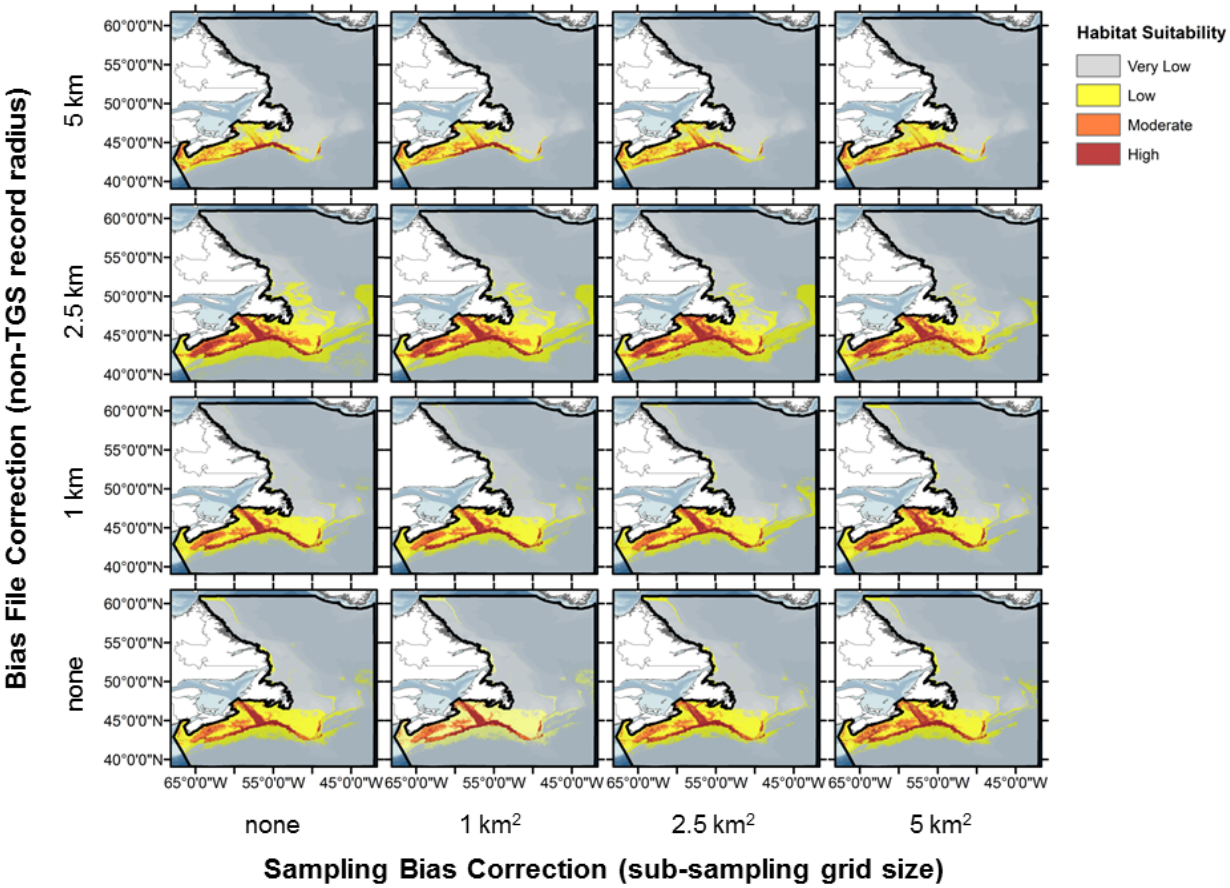

Figure 25. Averaged MaxEnt SDM results for Blue Whales during summer (June-August) using five predictor environmental variables: ocean depth, CTI, SST in the summer, areas of persistently high chlorophyll-a concentration in the spring and summer, and regional chlorophyll-a magnitude in the spring and summer for each scenario of sampling bias correction (columns from left to right show no subsampling applied, Blue Whale sightings sub-sampled on a 1.0 km² grid, 2.5 km² grid and 5.0 km² grid) and bias file correction (rows from top to bottom show no bias file correction applied, bias file corrections using non-TGS records for a 1 km radius, 2.5 km radius and 5 km radius). The black lines indicate the boundaries of the study area (3,251,342 km²); the analysis did not include the Gulf of St. Lawrence or shallow coastal waters.

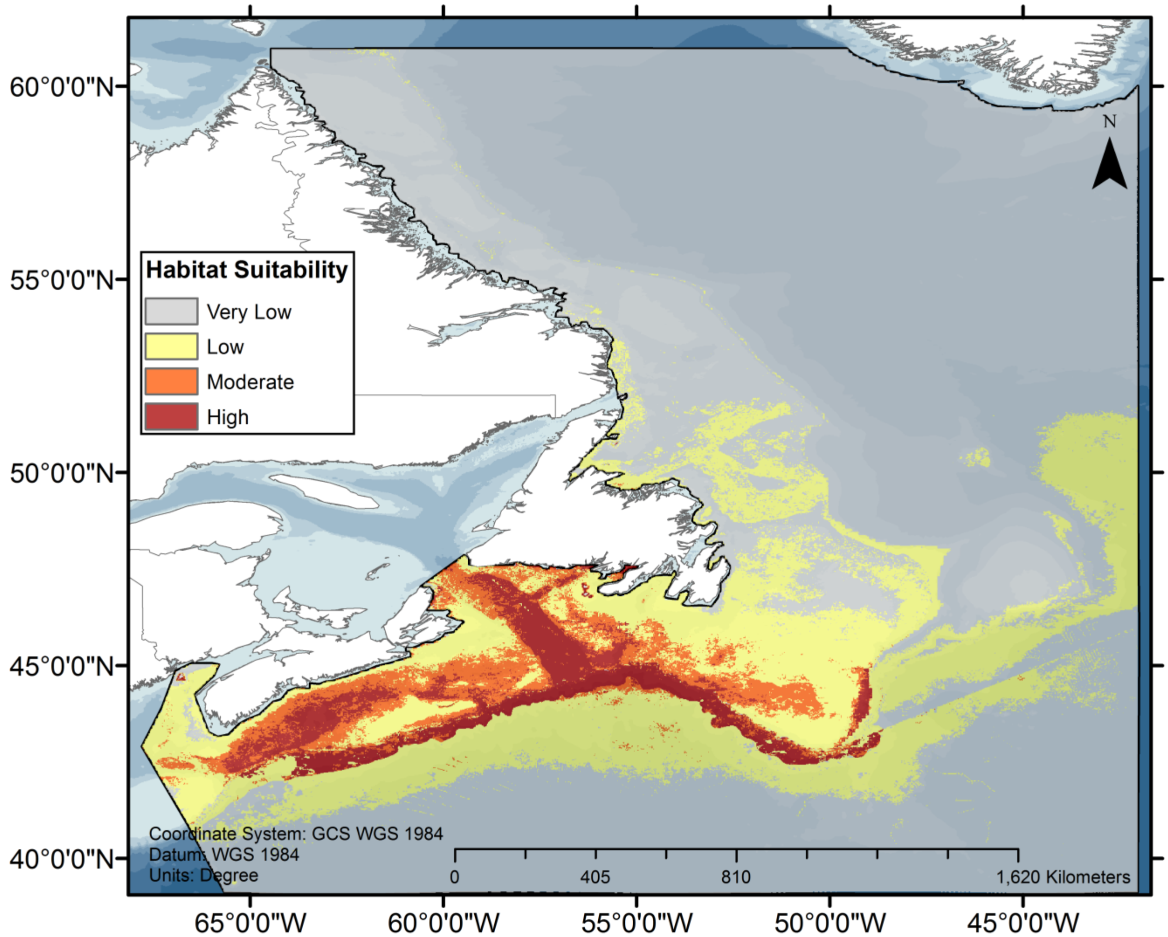

Figure 26. Averaged MaxEnt SDM for Blue Whales during summer (June-August; AUCBlue Whales = 0.85 (+/- 0.130)) using Blue Whale sightings sub-sampled on a 1x1 km grid (N=176), bias maps of non-TGS records using a radius of 1 km, and five predictor environmental variables: ocean depth, CTI, SST in the summer, areas of persistently high chlorophyll-a concentration in the spring and summer, and regional chlorophyll-a magnitude in the spring and summer. The black line indicates the boundaries of the study area (3,251,342 km^2); the analysis did not include the Gulf of St. Lawrence or shallow coastal waters.

DISCUSSION

AREAS OF POTENTIAL IMPORTANCE FOR BLUE WHALES

Based on the data collated from systematic surveys, opportunistic sighting platforms, acoustic monitoring and SDM efforts, the following potentially important areas for Blue Whales in the Northwest Atlantic outside the Gulf of St. Lawrence have been identified:

1. Deep water areas along the continental slope of the Scotian Shelf, especially the eastern Scotian Shelf near several submarine canyons (supported by sightings, acoustic detections, and SDM results).
2. Deep water areas along the continental slope of the Grand Banks south of Newfoundland (supported by sightings and SDM results).
3. Deep water areas of the Laurentian Channel (supported by sightings and SDM results).

4. Shallower areas off the southwest coast of Newfoundland (supported by historical whaling data, ice entrapment data, sightings, acoustic detections, and SDM results).
5. Shallower areas on the western Scotian Shelf (supported by historical whaling data and SDM results).

While Blue Whales were detected visually and/or acoustically in these areas and their potential importance is further highlighted by the SDM results, there has generally been little research effort targeting Blue Whales in these areas. Exactly how and why Blue Whales use these areas thus remains unknown. However, the acoustic data suggests a difference in use of these areas in summer (when the majority of arch calls are detected, which are made by both sexes and are thought to be related to foraging) and winter (when male-specific songs thought to be related to reproductive activities are detected).

COMPARISON TO HISTORICAL DISTRIBUTION

There has been a relatively large amount of opportunistic search effort for whales on the Scotian Shelf (Figure 22); however, post-whaling sightings data does not highlight Emerald Bank of the western Scotian Shelf as being particularly important for Blue Whales. This is different than the pattern observed during the whaling period when most sightings occurred around the Emerald Bank area (Figure 3). This could suggest a possible alteration of distribution over time. Interestingly, despite the lack of sightings in the area, the SDM shows the western Scotian Shelf region as a priority area for monitoring (Figure 25). Similarly, post-whaling sightings data and the SDM results do not align with historic Blue Whale harvests off northern Newfoundland, but do align with whaling data off southern Newfoundland.

SEASONALITY OF BLUE WHALE OCCURRENCE

Blue Whales are migratory species known to frequent the Gulf of St. Lawrence and eastern Scotian Shelf primarily during summer months (Hooker et al. 1999; Reeves et al. 1998; Sears et al. 1990). However, sightings and acoustic detections indicate that Blue Whales do occur year-round in areas outside the Gulf of St. Lawrence. Records of Blue Whales vocalizing during the fall and winter on the eastern edge of the Scotian Shelf, occasional sightings, as well as data derived from satellite tagged animals (Lesage et al. 2016), has revealed their presence in this area during the spring, fall and winter months suggesting that at least some individuals occur in the area throughout the year. Persistently high chlorophyll-a (a proxy for primary productivity and potentially related to prey availability) does occur year-round on the Scotian Shelf (Fuentes-Yaco et al. 2015).

There are seasonal peaks in call presence in the eastern Scotian Slope area observed in winter (December-January) and summer (July-August). These peaks correspond well with movement patterns observed in the St. Lawrence Estuary and the Gulf of St. Lawrence, suggestive of inward/outward movements of Blue Whales through the Cabot Strait. Photo-identification studies suggest that some individuals that occur off Nova Scotia and Newfoundland also occur in the Gulf of St. Lawrence, but also that some Blue Whales appear to remain outside the Gulf of St. Lawrence. Future studies should continue to incorporate a seasonal component to increase understanding of seasonal movements and habitat use.

MANAGEMENT IMPLICATIONS

Our SDM results showed highly- and moderately-suitable habitat for Blue Whales in areas that overlapped with the Gully Marine Protected Area (MPA), and designated critical habitat for Northern Bottlenose Whales including the Gully, Shortland, and Haldimand canyons. This was expected as a significant portion of whale sighting records were collected in these conservation areas (e.g., Figure 8). High- and moderately-suitable habitat for Blue Whales was also predicted within the boundaries of a proposed MPA in the Laurentian Channel. While these areas, particularly the Gully MPA, are afforded some level of protection that will benefit Blue Whales, Blue Whales are distributed widely throughout Atlantic Canada and much of their habitat is not currently protected.

The SDM results only highlighted a proportion of the southwest coast of Newfoundland as highly- or moderately-suitable habitat for Blue Whales. However, there must be an important reason why Blue Whales enter this area in the spring, despite the entrapment risk (Figure 11). In 2014, at least nine adult Blue Whales were entrapped and killed by moving sea ice, which represented a significant loss to the small population of adults. Enhanced monitoring efforts in this area may help better understand its significance to the population and the magnitude of risk posed by ice entrapment events to the population.

Oil and gas lease areas off Eastern Canada are concentrated in the same regions as highly and moderately suitable habitat for Blue Whales: along the deep water of the continental slope. Frequent and large-scale seismic survey efforts occur in these areas. Consequently, up-to-date information on the presence of Blue Whales and potential overlap with human activities in the Northwest Atlantic is necessary for informing marine spatial planning processes and evaluating potential threats and impacts on Blue Whales (for example, Pirotta et al. 2014; Thompson et al. 2013)(for example, Pirotta et al. 2014; Thompson et al. 2013) (for example, Pirotta et al. 2014; Thompson et al. 2013)(for example, Pirotta et al. 2014; Thompson et al. 2013)(for example, Pirotta et al. 2014; Thompson et al. 2013). Anthropogenic noise has been identified as an important threat to Blue Whales (Beauchamp et al. 2009) and assessing the temporal and spatial overlap of sounds from anthropogenic activities and Blue whale occurrence is an important step towards assessing potential impacts on the population. Blue Whales are known to produce longer calls in the presence of noise from seismic airguns (Di Iorio and Clark 2010). Such changes in vocalization behaviour can carry an energetic cost, and there are physiological limits on how much individuals can cope (Holt et al. 2015). Acoustic recorders are already in place in many of the suitable habitat areas highlighted in this study; these recorders will not only provide information on the presence of Blue Whales but will also facilitate investigation of the magnitude of potential noise exposure (such as in Di Iorio and Clark 2010; Melcón et al. 2012). Studies of the spatial and temporal overlap of Blue Whale occurrence and shipping activities (e.g., Laist et al. 2001; Simard et al. 2014; Vanderlaan and Taggart 2007) would facilitate similar impact assessments.

RECOMMENDATIONS FOR FUTURE RESEARCH EFFORTS

Suitable habitat for Blue Whales predicted by the SDM is interpreted as regions where Blue Whales have been and are most likely to be found, and represent priority areas where monitoring efforts for Blue Whales (including passive acoustic monitoring and aerial and/or vessel-based surveys) should be focused in the future. Future monitoring efforts should also include expanded monitoring of Blue Whales and their prey in offshore areas where little survey effort has occurred. Targeting areas of predicted highly-suitable habitat, as well as areas with currently low monitoring efforts, in future visual or acoustic surveys would allow the accuracy of current and any revised SDM predictions to be assessed.

To further refine the SDM, data on the relative concentration of the Blue Whale’s prey (krill) at fine temporal and spatial scales is needed. Outside the Gulf of St. Lawrence, information on

Blue Whale prey such as that described in (McQuinn et al. 2016[1]) and (Plourde et al. 2016) could provide an additional indicator of potential Blue Whale hotspots and development of krill data layers could be used to better describe suitable Blue Whale habitat. Additionally, potential scenarios of future changes in the spatial indices of krill concentration are desirable to quantify how different scenarios of prey distribution may alter the suitable habitat of Blue Whales.

The value of knowledge arising from year-round acoustic monitoring of calling Blue Whales to better describe seasonal occurrence and use of an area is evidenced in this study and emphasizes the need for more acoustic monitoring effort for assessing species presence and residency patterns, as well as anthropogenic threats. The location for this effort could be informed by SDM results and satellite tagging studies (Lesage et al. 2016). This work could be accomplished by fixed moorings, or more ambitiously, by using underwater gliders that have large geographic and temporal operating scope that can collect multibeam sonar data on krill features in addition to detecting Blue Whale calls and other calling marine mammals (e.g., Baumgartner and Fratantoni 2008; Moore et al. 2008).

Given the small population size and results owing to previous photo ID catalogue research (Sears et al. 1990), an enhanced Blue Whale photo ID effort outside the Gulf of St. Lawrence is warranted as a means to collect information on Blue Whale movements and activities, especially in deeper offshore waters. Again, SDM results could be used to identify areas in which to target future research efforts.

The potential impact of ice entrapment mortality on the small Northwest Atlantic Blue Whale population could be significant, and it is recommended that efforts be made to conduct regular patrols to detect entrapment events. Currently, it is unlikely that DFO could develop or employ means to prevent such entrapments (e.g., by scaring Blue Whales away from these high-risk areas with pingers, etc.), but detection of such events when they do occur is important for understanding their potential impact on the population. In addition, there must be an important reason why Blue Whales enter this area off southwest Newfoundland in the spring, despite the entrapment risk, and prey studies in the area could enhance understanding of the drivers behind Blue Whale occurrence in the area.

Finally, a quantitative assessment of the temporal and spatial overlap between anthropogenic activities (e.g., seismic surveys, shipping) and Blue Whale occurrence is needed to better gauge the potential impacts of these activities, especially as such data and modelling are required in the context of cumulative risk assessment (see for example Farcas et al. 2016; DFO 2017; O et al. 2015). While the SDM can provide a starting point for evaluating the relative level of risk of such threats, ideally Blue Whale density itself would be used for a more accurate assessment of overlap with human activities and risk. Greater systematic survey effort would be required to build Blue Whale density maps.

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