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Acoustic occurrence of beaked whales off eastern Canada, 2015–2017

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ABSTRACT: Several beaked whale species occur off eastern Canada. However, except for the northern bottlenose whale (NBW; *Hyperoodon ampullatus*), their distribution and annual occurrence remain largely unknown, which complicates management efforts to assess the status of poorly known species and effectively protect those species considered at risk. The main objective of this paper is to provide a year-round and pluriannual description of the minimum acoustic occurrence of the NBW, Sowerby's (SBW; *Mesoplodon bidens*), Cuvier's (CBW; *Ziphius cavirostris*), True's (TBW; *M. mirus*) and Gervais' (GBW; *M. europaeus*) beaked whales. Twenty-five acoustic recorders were deployed off eastern Canada between May 2015 and November 2017. Beaked whale echolocation clicks were detected using a combination of automated detectors and manual validation at 12 of these stations. Detections were generally restricted to deep continental slope waters. All detected species occurred in the southern part of the study area (off the Scotian Shelf and southern Grand Banks), while only NBWs were detected at the northern edge, off southern Labrador. Clicks identified as TBW or GBW were restricted to, but occurred annually in, the southern areas. All other species were present, at least seasonally, east and north of the Grand Banks. NBWs occurred every day in the Gully Canyon, where SBWs also occurred regularly. While these results should be interpreted as minimum species presence and considered with regards to detector performance, they provide important information regarding beaked whales' use of areas off eastern Canada where these species have generally received no or very limited monitoring effort.

KEY WORDS: Acoustic occurrence · Northern bottlenose whale · Cuvier's beaked whale · Sowerby's beaked whale · True's beaked whale · Gervais' beaked whale · Eastern Canada

1. INTRODUCTION

Beaked whales are a family of cetaceans (Ziphiidae) that occur in deep offshore waters along continental slopes and sometimes aggregate around deep-sea bottom features such as submarine canyons and seamounts (Moors-Murphy 2014, Hooker et al. 2019). The distribution, abundance, and habitat use of most beaked whale species in eastern Canadian waters remain poorly documented, with records of presence for some species largely limited to strandings, acoustic detections in a limited number of areas, and/or sparse or localized sightings (Stanistreet et al. 2017, Gomez et al. 2020). The lack of information on the spatio—temporal occurrence of beaked whales in this region hinders assessments of species' status and the anthropogenic threats they face, including acoustic disturbance, fisheries interactions, ship strikes, pollution, and increasingly urgent concerns regarding the impacts of climate change on ocean ecosystems. The Canadian federal Species at Risk Act (SARA) aims to prevent endangered or threatened wildlife from be-

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coming extinct and to manage species of special concern to prevent them from becoming endangered or threatened. The Committee on the Status of Endangered Wildlife in Canada (COSEWIC) is a committee of government and non-government experts that assesses the status of species using the best available knowledge, and it makes recommendations for listing under the SARA. Species listed under SARA by the federal Cabinet are granted federal protection, which, in the case of marine species such as beaked whales, is administered and enforced by the Department of Fisheries and Oceans (DFO).

The main factors limiting data collection on beaked whales are their remote offshore location and their cryptic surfacing behavior, which reduces detectability by visual observers (Barlow et al. 2005). All species are deep-divers that remain submerged for long periods and spend little time at the surface (MacLeod & D'Amico 2006, Hooker et al. 2019). They do not produce tall, visible blows like baleen whales nor perform regular surface displays that may improve detectability (MacLeod & D'Amico 2006). Visual observations are generally restricted to calm weather and good visibility conditions. While some species are morphologically distinct (e.g. northern bottlenose whales [NBW]), most species of the genus *Mesoplodon* are difficult to visually distinguish at sea, especially for inexperienced observers, unless approached at close range where species-specific features can be observed. Conducting beaked whale field studies or surveys off eastern Canada can be logistically challenging, as the continental slope is located 150–450 km from land. Appropriate survey conditions are generally limited to summer month, when sea state and weather conditions tend to be calmer and waters are clear of pack ice, though the common occurrence of fog during this time of year hampers research efforts.

Passive acoustic monitoring (PAM) provides an alternative method to visual surveys for studying the spatio–temporal occurrence of marine mammals in general and beaked whales in particular (Van Parijs et al. 2009). Most beaked whale species regularly produce distinctive echolocation clicks which can be used to assess their occurrence in the vicinity of acoustic recorders (e.g. Baumann-Pickering et al. 2013, 2014, Stanistreet et al. 2017). Though detection ranges for the high frequency clicks produced by beaked whales are generally short (<5 km; e.g. Hildebrand et al. 2015), PAM is not constrained by daylight or visibility and can operate over extended periods of time. Further, automated algorithms can be used to detect and classify the distinct beaked whale signals (clicks) to the species level which can vastly decrease data processing time (Stanistreet et al. 2022).

There are 6 species of beaked whales known to occur in the western North Atlantic: NBW (*Hyperoodon ampullatus*), Cuvier's (CBW; *Ziphius cavirostris*), Sowerby's (SBW; *Mesoplodon bidens*), True's (TBW; *M. mirus*), Gervais' (GBW; *M. europaeus*), and Blainville's (BBW; *M. densirostris*) beaked whale.

NBWs off eastern Canada are managed as 2 populations: the Scotian Shelf (SS) population and the Davis Strait–Baffin Bay–Labrador Sea (DSBBLS) population (COSEWIC 2011). Consisting of around 170 individuals (Feyrer 2021), the SS population has been assessed by the COSEWIC and is listed under SARA as endangered (COSEWIC 2011, Fisheries and Oceans Canada 2016). This is the most well-known beaked whale species in eastern Canadian waters due to the long-term dedicated vessel-based studies that have been conducted on the SS population since 1988, primarily in the Gully submarine canyon (Whitehead et al. 1997, Hooker & Baird 1999b, Gowans et al. 2000, Hooker et al. 2002a, Wimmer & Whitehead 2004, Feyrer 2021). The Gully (see Fig. 1) is recognized as a cetacean 'hotspot' off eastern Canada and is a designated marine protected area (MPA) (Moors-Murphy 2014). The Gully, Shortland and Haldimand canyons along the edge of the eastern SS have been designated as 'critical habitat' (Fisheries and Oceans Canada 2010), and the areas between these canyons have been identified as additional important habitat for the SS population of NBW (Fisheries and Oceans Canada 2020). Acoustic detections of this species in the Gully and the adjacent areas have shown NBWs to occur year-round, (Moors 2012, Stanistreet et al. 2017, 2021), though it is known NBWs regularly occur throughout slope waters off Nova Scotia and Newfoundland with sightings extending from the edges of Georges Bank to the Grand Banks and beyond (Stanistreet et al. 2021). Few NBW sightings or acoustic detections have been reported in waters off the USA (Waring et al. 2015). The SS population of NBWs is genetically isolated from other more northern populations (Dalebout et al. 2001, Feyrer et al. 2019).

The DSBBLS population was assessed by the COSEWIC as 'special concern' (COSEWIC 2011) and under consideration for SARA listing. This larger population is found primarily in the Davis Strait and extends down off Labrador and into northern Newfoundland waters but likely also extends into the central and eastern North Atlantic (Feyrer et al. 2019). There is uncertainty about the population structure of NBWs in the North Atlantic (Whitehead & Hooker 2012). It has been suggested that core areas of historical whaling catches could reflect population structure, with potential subdivisions between whales living off the SS, in a broad area encompassing the Labrador Sea, Davis Strait and Baffin Bay, off Iceland, Norway, and Svalbard (Benjaminsen 1972, Whitehead & Hooker 2012). However, a very low level of genetic diversity continues to hinder confirmation of these presumed population boundaries. For this same reason, a recently discovered NBW aggregation area along the southern margin of Orphan Basin (southeast of Newfoundland) could not be unambiguously assigned to 1 of the 2 known Canadian populations (Feyrer et al. 2019). The current size of the DSBBLS population is unknown, although substantial catches (n = 818) were made in this area during a short period of whaling (1969—1971), and relatively low sighting rates, albeit under low survey effort, suggest that they may not have recovered from whaling (Whitehead & Hooker 2012).

SBWs have been assessed by the COSEWIC and listed under the SARA as a species of special concern (COSEWIC 2006, Fisheries and Oceans Canada 2017a). SBWs were first documented off eastern Canada in the Gully in the late 1990s (Hooker & Baird 1999a). They are regularly sighted during beaked whale-dedicated research cruises off the SS (Clarke et al. 2019), particularly in the Gully and adjacent areas where their presence was documented to be increasing between the years of 1988—2011 (Whitehead 2013). SBWs are the most common beaked whales to strand off eastern Canada, with at least 15 strandings recorded since 2013 in Newfoundland, Nova Scotia, and Quebec, about half of which occurred in the Gulf of St. Lawrence (Wimmer & Maclean 2021), although these are considered to be vagrant individuals well outside of their typical deep-water habitat. Prior to 2016, stranding locations were biased towards northern Newfoundland (Fisheries and Oceans Canada 2017a). Their presence has also been confirmed acoustically off the SS, with SBWs detected nearly daily over the course of a 2 yr PAM study in the Gully (Stanistreet et al. 2017). SBWs have been regularly detected both visually and acoustically off the eastern USA (e.g. Stanistreet et al. 2017, Hayes et al. 2020, Cohen et al. 2022), but there are only a few sightings records north of the SS (Gomez et al. 2020). There is currently no abundance estimate for this species due to low sighting rates and a lack of understanding of their range in eastern Canadian waters (Fisheries and Oceans Canada 2017a). Animals frequenting eastern Canadian waters are presumably part of a larger North Atlantic population, although the potential level of population structuring among North Atlantic SBW is unknown (COSEWIC 2006).

The other species have either not been assessed by the COSEWIC (GBW), or their last assessment dates back to 1989—1990 (CBW, TBW, BBW), and their presumed rarity has not warranted any updates. None of them are considered species at risk in Canada.

Sightings and acoustic detections of CBWs are common off the eastern USA and southwestern Nova Scotia (Stanistreet et al. 2017, Hayes et al. 2020, Cohen et al. 2022), and they were detected acoustically throughout the year in the Gully between October 2012 and September 2014 (Stanistreet et al. 2017) and off the southern SS in September 2015 and 2016 (Stanistreet et al. 2022). There are only a few sightings reported in the SS area (Gomez et al. 2020) including a sighting reported in Haldimand Canyon, east of the Gully (Whitehead 2013). Three strandings have been reported since 2016 in eastern Canada, 2 in Nova Scotia and 1 vagrant animal in the Gulf of St. Lawrence (Wimmer & Maclean 2021, T. Wimmer pers. comm.). Beyond this sparse information, little is known about the presence of this species off eastern Canada.

TBW have been sighted and acoustically detected in waters off the eastern USA and southwestern Nova Scotia (DeAngelis et al. 2018, Hayes et al. 2020, NOAA 2023). Three strandings have been reported in eastern Canada since 2015: 1 in southern Newfoundland, and 2 in the Gulf of St. Lawrence (the Magdalen Islands and in the northern Gulf) (Wimmer & Maclean 2021, T. Wimmer pers. comm.). These strandings extend the known or inferred range of the species in the western North Atlantic (Macleod 2000, Macleod et al. 2005) but must nevertheless be interpreted with caution as these may represent vagrant individuals outside their normal habitat. The range of the TBW in the North Atlantic remains ultimately very poorly understood. Clicks resembling those attributed to the TBW (DeAngelis et al. 2018) were also detected acoustically in deep waters off Nova Scotia in September 2015 and 2016 (Stanistreet et al. 2022). These records are too sparse to assess the occurrence of TBWs in eastern Canadian waters but suggest some habitat suitability for this species in at least the southern parts thereof.

Evidence of the presence of BBWs in eastern Canadian waters consists of 3 documented strandings in Nova Scotia and New Brunswick (MacKenzie 1940, Houston 1990, McAlpine & Rae 1999), all dating back more than 5 decades. One author acknowledged that the northernmost records of this species, including off eastern Canada, could be vagrants carried north by the Gulf Stream (Macleod 2000). There is only one sighting recorded off eastern Canada, near the mouth of the Gully (Gomez et al. 2020). This species was not detected acoustically further north than Cape Hatteras by multi-year PAM studies (Stanistreet et al. 2017, Cohen et al. 2022) despite a handful of sightings off the northeastern USA, including one in deep waters south of Georges Bank. The combined evidence suggests that BBWs do not commonly occur in eastern Canadian waters, even though areas influenced by the Gulf Stream may provide suitable habitat for this species, which shows a wide, although tropically biased, distribution (Macleod 2000, Macleod et al. 2005).

GBWs are endemic to the Atlantic Ocean and generally found in tropical to warm–temperate areas (Macleod 2000, Macleod et al. 2005) but have never been positively documented in Canada. This species is regularly observed and acoustically detected off the US east coast (Hayes et al. 2020, Cohen et al. 2022, NOAA 2023). The northernmost stranding record in the western North Atlantic is in Cape Cod (Hayes et al. 2021). Therefore, there is currently little evidence to suggest that this species may be present in eastern Canadian waters.

Here, we provide a year-round, pluri-annual description of the occurrence of beaked whales in temperate and subarctic eastern Canadian waters using PAM data collected at 25 recording stations over a 2 yr period from 2015 to 2017.

2. MATERIALS AND METHODS

2.1. Data collection

Acoustic data were collected from 25 recorders deployed between 2015 and 2017 (Fig. 1, Table 1) (these are the same recorders described in Delarue et al. 2022) during 2 successive deployments. Twenty recorders (Stns 1–20) were deployed throughout the Scotian, Newfoundland, and southern Labrador shelf and slope areas (recorder depth range: 44–2002 m). They were part of a study supported by the Environmental Studies Research Fund (ESRF; Delarue et al. 2018) focused on characterizing marine mammal occurrence and the underwater soundscape in areas where anthropogenic activities were concentrated or planned and where marine mammal occurrence remained poorly described. Stns 21–25 were deployed as part of an ongoing PAM program by the DFO Maritimes Region aimed at monitoring marine protected areas off Nova Scotia and/or filling in knowledge gaps for species at risk (including NBW and SBW). Monitoring locations were separated by 40 to 260 km.

Acoustic data were acquired using autonomous multichannel acoustic recorders (AMAR; JASCO Applied Sciences). The recordings consisted of 1 min of data sampled at 250 kHz with a 16-bit resolution for every 20 min (5% duty cycle). Acoustic data were recorded using M36-V35-100, M8Q-51 (GeoSpectrum Technologies, GTI) or HTI-99-HF hydrophones (High Tech), all with a flat frequency response (±3 dB) between 10 and 100 000 Hz. The nominal sensitivity level was −165 and −164 dB re 1 V/μPa for GTI and HTI hydrophones, respectively. Both hydrophone models had maximum received signal level of 165 dB re 1 μPa. Calibration was performed using a pistonphone producing a reference tone at 250 Hz (GRAS Sound & Vibration, model 42AC) before and after each deployment. Except for Stn 19, all deployment locations were the same in both years (Table 1). Among deep stations that were the focus of this study, there was no interruption in recording effort between both years in the ESRF study, while pauses in recording effort (~3–4 mo) between successive deployments occurred at Stns 21–25 (see Table 1).

2.2. Automated click detection

This study is based on the detection of echolocation clicks produced by beaked whales. Information on the species-specific characteristics of beaked whale clicks has come from various studies including tagging programs, concurrent visual and acoustic surveys, and opportunistic encounters at sea. Beaked whale echolocation clicks can generally be distinguished from the echolocation clicks of other odontocetes that occur in the same frequency range (such as sperm whale and delphinid clicks) by their frequency-modulated upsweep structure. Previously reported spectral features of the clicks of each species are summarized in Table 2. Spectrograms showing examples of clicks from all species detected in our data are presented in Fig. 2.

A zero-crossing-based automated click detector-classifier (referred to as 'click detector') was applied to the data and used to identify the clicks of NBW, SBW, CBW, TBW/GBW and BBW. Zero-crossings are the rapid oscillations of a click's pressure waveform above and below the signal's normal level. Clicks were first detected using a split-window detector (Struzinski & Lowe 1984). Once potential click events were identified, 3 classification parameters were extracted: the number of zero crossings within the click, the median time separation between zero crossings, and the slope of the change in time separation between zero-crossings (Table S1 in the Supplement; www.int-res.com/articles/suppl/n053p439_supp.pdf).

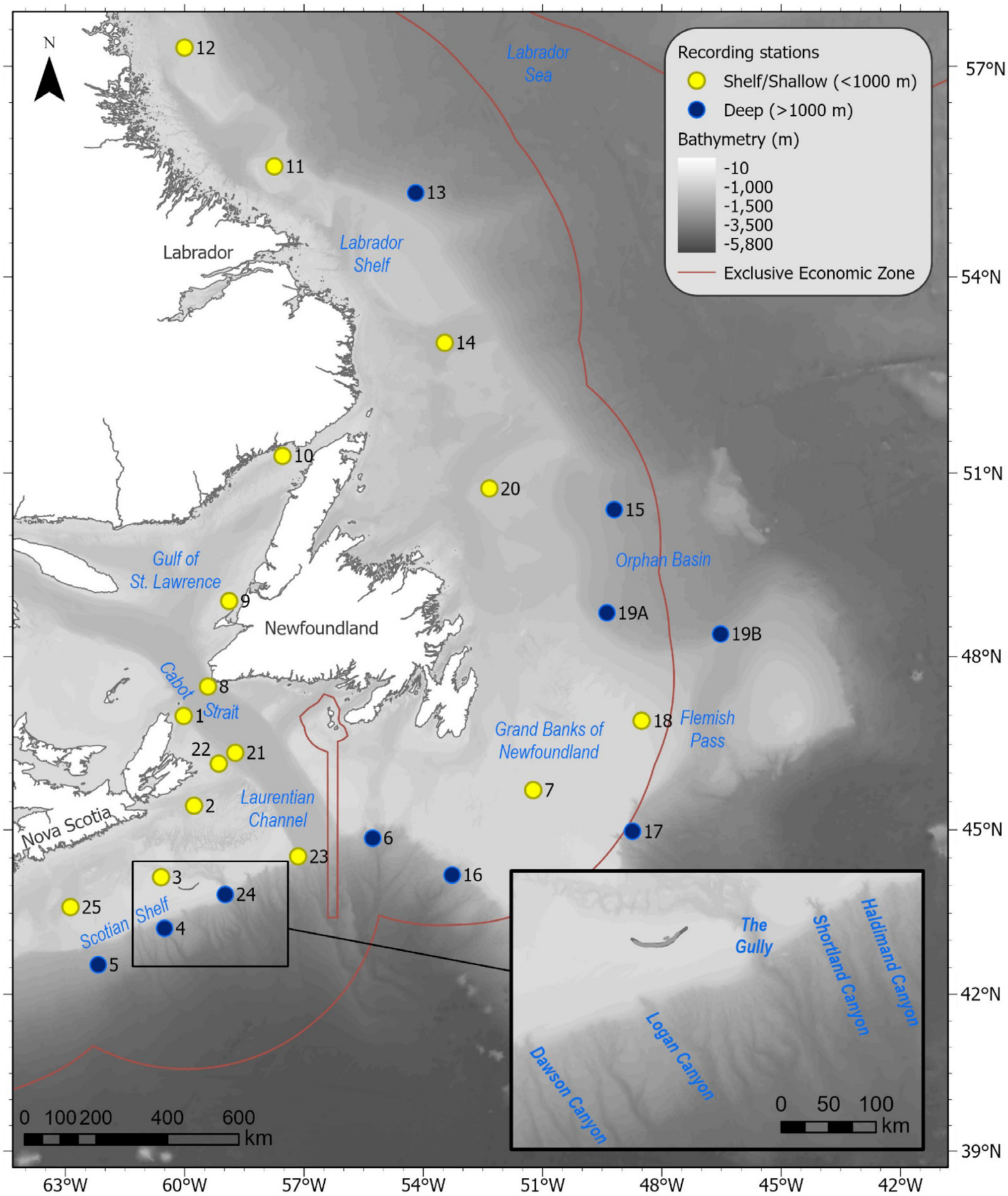

Fig. 1. Study area and locations of the 25 acoustic recording stations deployed between May 2015 and November 2017 to monitor beaked whale occurrence off eastern Canada. Yellow points: recorders deployed on the shelf and in shallower (less than 1000 m) waters; blue points: recorders deployed in deeper (>1000 m), off shelf waters. Bathymetry layer provided by GEBCO Bathymetric Compilation Group (2020)

Covariance matrices of the 3 parameters were computed from thousands of manually identified clicks for each species and stored in the external template files. These matrices described the distributions of the parameters for each species. Each click was classified by computing the Mahalanobis distance (Baumgartner & Mussoline 2011) between the detected clicks and the species-specific distributions. The Mahalanobis distance is normalized by the variances and co-variances of the parameters and yields a value that can be compared to the chi-squared distribution with n degrees of freedom, where n is the number of parameters. The species with the lowest distance is assigned as the detected species, unless none of them were less than a distance of 4.1, which is further from the center of the distributions than 75% of the training data, in which case the detected 'click' was classified as 'unidentified' and not included in further analysis. The same click detector has been successfully applied for the detection of beaked whale species in other PAM projects

Table 1. Location, recorder depth, and deployment time frame for the 25 recording stations (see Fig. 1). Recorders at Stns 3, 7 and 9 were deployed on bottom. All others were suspended approximately 25 m above the seafloor. For continuous recording periods, the service date refers to the date when the recorder deployed during the first year was retrieved and a new recorder was deployed for the second year of monitoring. na: not applicable, either because data were recorded during 1 yr only or because there was a delay between retrieval and deployment for the second year of data collection. nd: no data. The location of Stn 19 was different in both years and is referred to as 19A and 19B. Republished from Delarue et al. (2022)

Stn	Latitude	Longitude	Recorder depth (m)	Deployment	Service date	Retrieval/ record end
1	46.99134	−60.02403	186	17-Aug-2015	8-Jul-2016	10-Jul-2017
2	45.42599	−59.76398	126	18-Aug-2015	21-Jul-2016	9-Jul-2017
3	44.14955	−60.59600	72	22-Jul-2016	na	8-Jul-2017
4	43.21702	−60.49943	1830	19-Aug-2015	22-Jul-2016	8-Jul-2017
5	42.54760	−62.17624	2002	19-Aug-2015	23-Jul-2016	8-Jul-2017
6	44.85309	−55.27108	1802	22-Aug-2015	20-Jul-2016	23-Jul-2017
7	45.70082	−51.23315	78	23-Aug-2015	19-Jul-2016	19-Jul-2016
8	47.49307	−59.41325	428	16-Aug-2015	8-Jul-2016	10-Jul-2017
9	48.92733	−58.87786	44	16-Aug-2015 9-Jul-2016	na na	26-Apr-2016 10-Jul-2017
10	51.26912	−57.53759	121	3-Aug-2015 10-Jul-2016	na na	5-Jul-2016 11-Jul-2017
11	55.60300	−57.75040	158	9-Aug-2015	13-Jul-2016	14-Jul-2017
12	57.25273	−60.00175	143	10-Aug-2015	13-Jul-2016	14-Jul-2017
13	55.22797	−54.19047	1750	8-Aug-2015	11-Jul-2016	15-Jul-2017
14	53.01567	−53.46022	582	4-Aug-2015	14-Jul-2016	16-Jul-2017
15	50.41327	−49.19638	2000	14-Aug-2015	16-Jul-2016	18-Jul-2017
16	44.19230	−53.27441	1602	23-Aug-2015	20-Jul-2016	22-Jul-2017
17	44.97141	−48.73373	1282	24-Aug-2015	18-Jul-2016	21-Jul-2017
18	46.90877	−48.50418	111	25-Aug-2015	18-Jul-2016	20-Jul-2017
19A	48.72873	−49.38087	1282	25-Aug-2015	na	17-Jul-2016
19B	48.38020	−46.52540	1547	17-Jul-2016	na	19-Jul-2017
20	50.75232	−52.33602	237	13-Aug-2015	15-Jul-2016	18-Jul-2017
21	46.35540	−58.72768	341	17-Jun-2015 23-Sep-2016	na na	1-May-2016 23-Nov-2017
22	46.16837	−59.14563	87	16-Jun-2015 24-Sep-2016	na na	1-May-2016 29-Oct-2017
23	44.52339	−57.14949	478	22-Sep-2015 nd	na	13-Jan-2016
24	43.85879	−58.90974	1610	23-May-2015 20-Sep-2016	na na	23-Apr-2016 30-Nov -2017
25	43.60871	−62.86832	200	24-May-2015 16-Sep-2016	na na	20-Apr-2016 25-Nov-2017

including the waters off Ireland (Kowarski et al. 2018) and off the US eastern seaboard (Kowarski et al. 2022).

2.3. Manual validation

To assess detector performance, beaked whale clicks were verified by experienced analysts (J.J.-Y. Delarue, K.A. Kowarski, E. E. Maxner) for a subset (0.5%) of the data. The analysts have over a decade of experience identifying beaked whale clicks in North Atlantic recordings. The process of selecting the subset of files for review is described below. During manual review, beaked whale clicks were distinguished from other odontocete clicks by their ascending, frequency-modulated contours (see Fig. 2). Analysts relied on a combination of features to identify the species producing a given click, pri-

Table 2. Summary of descriptive metrics for clicks produced by beaked whale species targeted in this study, presented as median (10^{th}–90^{th} percentile). ICI: inter-click interval. NBW: northern bottlenose whale; SBW: Sowerby's beaked whale; CBW: Cuvier's beaked whale; TBW: True's beaked whale; GBW: Gervais' beaked whale; BBW: Blainville's beaked whale. –: metric not reported

Species	Peak frequency (kHz)	Center frequency (kHz)	−10 dB bandwidth (kHz)	−10 dB lower endpoint (kHz)	Duration (µs)	ICI (ms)	Recording platform	Study area	Reference
NBW	25.9 (22.9–29.3)	27.4 (23.5–31.8)	13.5 (9.4–22.1)	20.3 (15.8–23.6)	–	402 (290–524)	Towed array	Eastern Canada	Clarke et al. (2019)
SBW	65.8 (61.5–76.5)	65.8 (61.4–71.3)	25.1 (9.8–30.8	55.1 (52.6–71.9)	–	237 (130–315)	Towed array	Eastern Canada	Clarke et al. (2019)
CBW	40.2 (20.3, 49.2)	35.9 (28.7, 42.5)	10.9 (5.1, 21.9)	–	585 (306, 976)	337 (94, 491)	Bottom-mounted recorder	Pacific Ocean	Zimmer et al. (2005), Baumann-Pickering et al. (2013)
TBW	43.5 (37.5, 49.5)	– (9.4, 32.3)	20.6 (30.4, 40.5)	34.5 (198, 390)	271 (130, 380)	190	Towed array	Northeast USA	DeAngelis et al. (2018)
GBW	43.8 (35.9, 55.9)	45.2 (37.5, 55.0)	18.8 (7.8, 34.8)	–	450 (260, 765)	275 (114, 353)	Bottom-mounted recorder	Pacific Ocean	Gillespie et al. (2009), Baumann-Pickering et al. (2013)
BBW	34.4 (31.3, 44.1)	37.3 (32.3, 44.0)	11.7 (5.5, 23.0)	–	581 (299, 950)	280 (111, 427)	Bottom-mounted recorder	Pacific Ocean	Johnson et al. (2006), Baumann-Pickering et al. (2013)

marily peak frequency and inter-click-interval (ICI). NBW and SBW clicks exhibit less frequency range overlap than other beaked whale species and had a low risk of misclassification by analysts. CBW clicks stand out due to their distinct shape, narrow bandwidth and long ICI. BBWs produce clicks that are lower in frequency than the other *Mesoplodon* species (Baumann-Pickering et al. 2013). The main difficulty encountered was distinguishing between GBW and TBW clicks. Clicks of these 2 species have similar peak frequency and bandwidth, the most promising distinguishing feature (also least affected by the recording equipment or environment) being ICI (Baumann-Pickering et al. 2013, DeAngelis et al. 2018). The initial descriptions of the clicks of these 2 species were based on a low number of acoustic encounters recorded from near-surface towed arrays in the vicinity of visually observed groups (Gillespie et al. 2009, DeAngelis et al. 2018). The GBW click characteristics presented by Baumann-Pickering et al. (2013) rely on a large sample of detections from bottom-mounted recorders without concurrent visual observations, the clicks being identified based on their resemblance to those in Gillespie et al. (2009). In the present study, clicks resembling TBW or GBW clicks were considered a single category (i.e TBW/GBW) during the analysis.

Manual validation of automated detector results was completed using the methodology described in Kowarski et al. (2021) and Delarue et al. (2022). This method relies on the automatic data selection for validation (ADSV) algorithm to select a subset of sound files from each station and deployment that are then manually validated by experienced analysts to evaluate automated detector performance (see Section 2.4). In this study, the size of the validation subset was 0.5% of 1 min sound files for each station and deployment. While all 25 stations were subjected to the same level of review effort, here we report only on the analysis of data from stations where the clicks of at least one beaked whale species were detected, representing a combined total of 2790 files across 12 stations. The validation effort was constrained by time and funding allocated to the research programs from which these data are derived. For each deployment at each station, the ADSV algorithm selected files for manual validation such that the resulting sample matches the corresponding full dataset in terms of number of detectors triggered per file and number of detected clicks, and files were not temporally clustered. Additionally, the ADSV forced the inclusion of 3 files with the highest detection counts for each beaked whale species, which in-

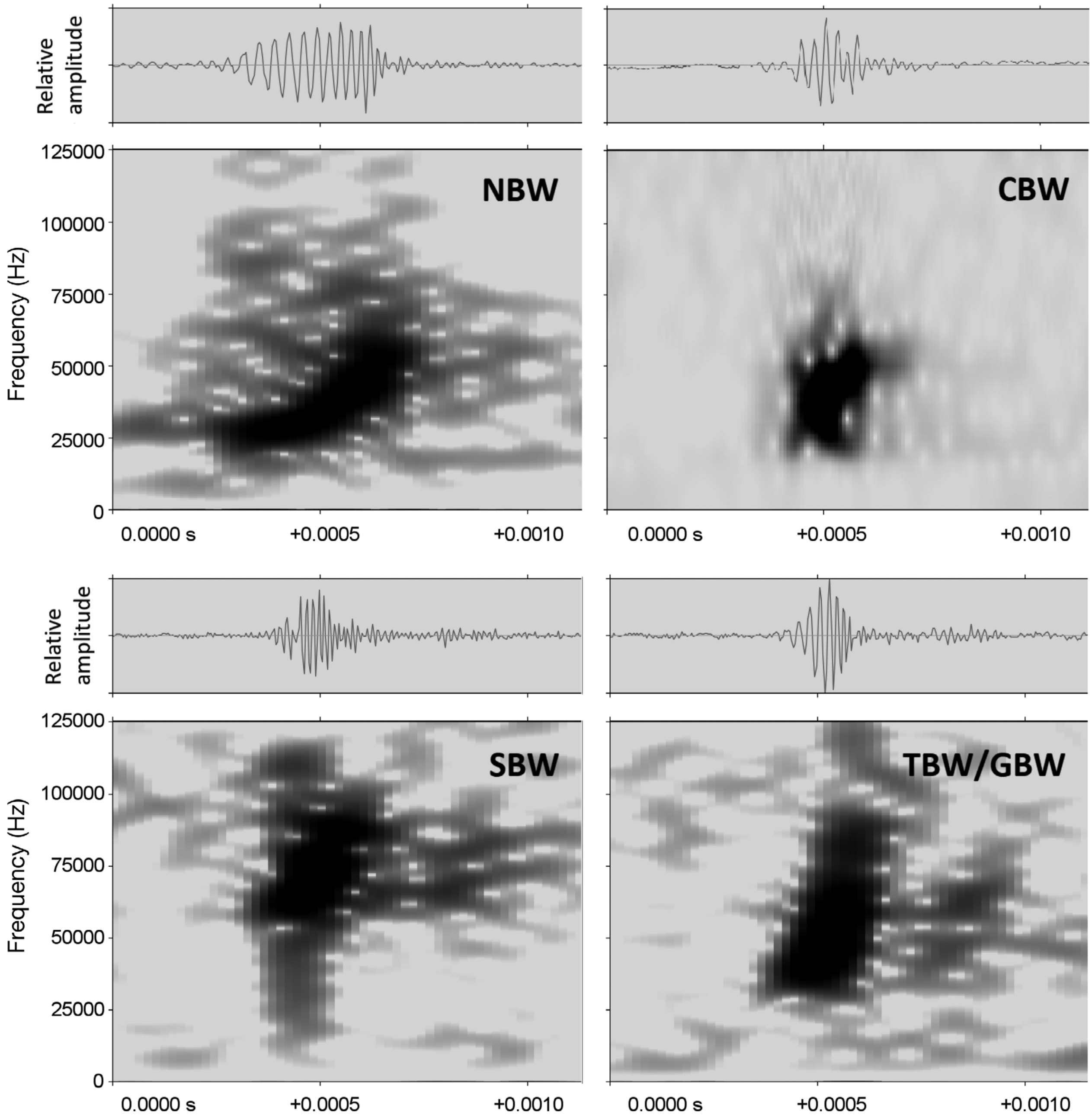

Fig. 2. Spectrograms and waveforms of clicks targeted for automated and manual detections. NBW: northern bottlenose whale; CBW: Cuvier's beaked whale; SBW: Sowerby's beaked whale; TBW/GBW: True's/Gervais' beaked whale. Spectogram settings: 512 Hz discrete Fourier transform (DFT) frequency step, 0.000266 s DFT time window, 0.00002 s DFT time advance, Hann window, 75% overlap

creases the probability that isolated detection events of rare species are reviewed.

This multi-species approach is expected to capture a significant portion of the range of background noise conditions in which each automated detector had to operate, thereby improving the representativeness of the performance indices derived from the ADSV samples. The occurrence of species was validated by file (1 min duration), even though the automated detectors classify individual signals. The outputs of this manual validation process (i.e. the presence of confirmed clicks characterized to species level) are referred to as 'manual detections' hereafter.

2.4. Automated detector performance assessment

Before assessing the performance of the click detector, the following restrictions were applied to the automated detector results, as applicable. If a species was automatically detected at a station, but no clicks of the target species were found by analysts during the manual validation process, the species was considered absent from that station. If manual detections of a given species were absent during a prolonged (>1.5 mo) period within a data set, an exclusion period was defined, and all potential automated detections for that species during that period were deemed false positives (FPs) and excluded from further processing. The start and end days of an exclusion period were defined as the dates following and preceding the manual detections bounding the period of absence. Exclusion periods ensured that automated detection results were only used when there was sufficient overlap between manual, and automated detections and detector performance could be reliably estimated (see Tables S2–S5 and Figs. 4, 6, 8 & 10). Because of the low manual review effort, exclusion periods may be overly restrictive but ensure conservative results.

The performance of the automated detectors based on presence/absence within a 1 min file was described using precision (P), recall (R) and the Matthews correlation coefficient (MCC) score combining both (see Eqs. 1 & 2). The metrics were determined for each species, station, and deployment combination using a maximum likelihood estimation algorithm. This algorithm compares the automated detections and manual validation results and finds the minimum number of automated detections per 1 min sound file (hereafter threshold) that maximizes the MCC.

$$\mathrm{MCC} = \frac{\mathrm{TP} \times \mathrm{TN} \quad \mathrm{FP} \times \mathrm{FN}}{(\mathrm{TP}+\mathrm{FP})(\mathrm{TP}+\mathrm{FN})(\mathrm{TN}+\mathrm{FP})(\mathrm{TN}+\mathrm{FN})} \tag{1}$$

$$P = \frac{\mathrm{TP}}{\mathrm{TP}+\mathrm{FP}};\ R = \frac{\mathrm{TP}}{\mathrm{TP}+\mathrm{FN}} \tag{2}$$

where TP (true positive) is the number of files that had both an automated detection and a manual detection of the same species, FP is the number of files with false detections, FN (false negative) is the number of files with missed detections and TN (true negative) is the number of files in which there were no automated and manual detections.

If P (after application of threshold) was <0.75, only manual detections were used to describe the acoustic occurrence of a species. The 0.75 precision cut-off value is an informed choice that represents a compromise between displaying potentially incorrect detections and ignoring all automated detections for a given deployment, which overall provide more information than manual detections. When P was $\geqslant 0.75$, all sound files with an automated detection count greater than or equal to the threshold value were deemed to contain valid signals and used to characterize species' presence, in addition to manual detections.

A recording day (RD) was considered any day from which data were collected from a given site, including partial days of recording (such as those at the start or end of a deployment). The minimum acoustic occurrence of beaked whales is based on detection days (full or partial days with a minimum of one automated or manual detections) and presented as in Delarue et al. (2022).

Where shown, automated detections were filtered to apply exclusion periods (shown in pink on relevant figures) and detection count threshold, if any. Deployments when automated detections were excluded ($p < 0.75$) are also highlighted (shown in yellow on relevant figures). Combined manual and automated detections are summarized using weekly number of detection days by station and species. In addition, spatial plots present the seasonal proportion of detection days (%RD, calculated by dividing the number of detection days by the total number of RD to account for recording effort) at each station.

2.5. Click measurements

In an attempt to resolve ambiguity regarding the species producing clicks identified as TBW/GBW, a sample of these clicks was analyzed to characterize ICI, peak frequency, 10 dB bandwidth and the 10 dB bandwidth lower endpoint such that these metrics can be compared to published description of TBW and GBW clicks (Baumann-Pickering et al. 2013, DeAngelis et al. 2018). Consecutive clicks within distinct click trains were annotated in a selected subset of 23 sound files (3 per station and deployment except 2 at Stn 6 in the 2015–2016 dataset) using the acoustic analysis software PAMLAB (JASCO). The click measurement methodology is described in Text S1 in the Supplement and includes a detailed description of the metrics used to characterize these clicks (Table S1). Linear regression was used to characterize the relationship between SNR and the selected clicks' descriptive metrics.

3. RESULTS

3.1. Automated detector performance

The evaluation of automated detector performance was based on the manual review of 0.5% (n = 2790) 1 min sound files, distributed across two 1 yr deployments at 12 stations. The automated detector performance metrics are presented in Tables S2–S5 and summarized in Fig. 3. Automated detector performance varied between species, stations, and years, highlighting the need to evaluate automated detector results on a deployment basis as location, season, and background noise influence the performance of detectors differently (Kowarski & Moors-Murphy 2021). The automated detectors for NBW and SBW clicks performed best overall, followed by those for CBW and TBW/GBW clicks. For all deployments where *P* exceeded 0.75, the average *P* was higher than 0.86 for CBW and 0.94 for NBW and SBW, indicating the automated detections provide a good representation of the acoustic occurrence of these species. TBW/GBW automated click detections showed more variability in performance metrics across stations with lower *P* and *R* scores. This may be due to the greater overlap in spectral features between these clicks and those from delphinid species, which were also commonly detected throughout the study area. In general, stations with few manual detections had low automated detector performance metrics. This points, partly, to the inability of the algorithm to assess automated detector performance metrics when the number of manual detections is low, which led to the necessity of applying exclusion periods. *R* values indicated that the occurrence of target species per 1 min file was, on average, not underestimated by more than 21% (TBW/GBW), 15% (CBW), 12% (SBW) and 7.5% (NBW). However, this applies only to stations or periods for which automated detections were used. Occurrence was likely to be underestimated by a greater amount when automated detections were excluded, since click presence was assessed based on a small, albeit detector-guided, sample of manually analyzed files. The proportion of recording periods for which acoustic occurrence was assessed using only manual detections is shown in Table 3. TBW/GBW was the click type with the highest proportion of data assessed manually to characterize occurrence, while the occurrence of NBW and SBW was assessed almost entirely using automated detections.

3.2. NBW minimum presence

NBW was the most commonly detected beaked whale species, with detections at 10 stations and on 43.7% RD across all deployments with at least one detection. They were broadly distributed in deep continental slope waters from the central SS (Stn 4) to the northernmost deep station off southern Labrador (Stn 13) (Figs. 4 & 5, Table 3). Click presence was highest in the Gully (Stn 24), with clicks detected on 99.9% RD, and was also relatively high off Labrador (Stn 13; 88.2% RD) and south of Orphan Basin (Stns 19A and B; 72 and 53.3% RD, respectively). NBW clicks were detected once at Stn 4, west of the Gully. They were not detected at Stn 5, about 150 km southeast from Stn 4, but located further offshore from the continental shelf break and in deeper water. Similarly, click detections were substantially lower at the northeastern corner of

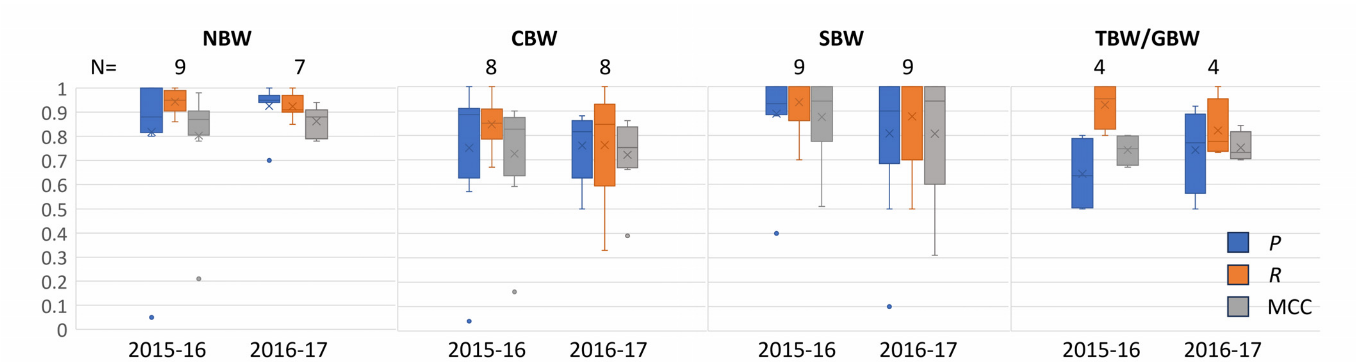

Fig. 3. Boxplots of the precision (*P*), recall (*R*) and Matthews correlation coefficient (MCC) scores for the Northern bottlenose whale (NBW), Cuvier's beaked whale (CBW), Sowerby's beaked whale (SBW) and True's/Gervais' beaked whale (TBW/GBW) click automated detectors across the stations where they were detected for both recording years (2015–2016 and 2016–2017). The top and bottom edges of each box show the 25th and 75th percentiles. The black line and cross inside each box show the median and mean, respectively. The top and bottom whiskers show the 5th and 95th percentiles. The dots show outliers

Table 3. Proportion of recording days (RD) per deployment with click detections (manual or automated) and proportion of the recording period (RP) for which acoustic occurrence was assessed only with manual detections (MD; based on 0.5% manual review effort) for all stations where northern bottlenose whale (NBW), Cuvier's beaked whale (CBW), Sowerby's beaked whale (SBW) and True's (TBW) or Gervais' beaked whale (GBW) were detected at least once. Values shown for each recording year. na: not applicable

Station	Recording year	RD	NBW		CBW		SBW		TBW/GBW	
			% RD with detections	% RP evaluated with MD only	% RD with detections	% RP evaluated with MD only	% RD with detections	% RP evaluated with MD only	% RD with detections	% RP evaluated with MD only
4	2015–2016	339	0.3	100	23.9	25.4	18.6	0	4.7	100
	2016–2017	352	0	na	14.5	100	17.3	0	11.9	44.4
5	2015–2016	340	0	na	49.7	0	1.2	0	20.6	0
	2016–2017	351	0	na	33.6	0	0.6	100	17.3	15.3
6	2015–2016	334	21.3	0	24.6	0	13.5	0	0.6	100
	2016–2017	369	16.3	0	24.1	0	12.5	0	2.4	100
8	2015–2016	328	0	na	0	na	0	na	0	na
	2016–2017	368	0	na	0	na	0.3	100	0	na
13	2015–2016	339	92.0	0	0	na	0	na	0	na
	2016–2017	370	84.3	0	0	na	0	na	0	na
15	2015–2016	338	36.4	0	13.0	0	2.1	0	0	na
	2016–2017	368	31.8	0	34.8	0	3.5	0	0	na
16	2015–2016	333	24.3	0	36.3	0	25.5	0	4.2	57.5
	2016–2017	368	19.8	0	38.6	0	34.8	0	5.4	58.9
17	2015–2016	330	21.2	0	7.0	61.7	6.7	0	0	na
	2016–2017	369	11.4	100	15.4	76.9	19.0	0	0	na
18	2015–2016	329	0	na	0	na	0.3	100	0	na
	2016–2017	368	0	na	0	na	0	na	0	na
19A	2015–2016	328	72.0	0	1.5	100	0	na	0	na
19B	2016–2017	368	53.3	0	1.4	100	11.7	0	0	na
23	2015–2016	115	14.8	0	0	na	83.5	0	0	na
	2016–2017					No data				
24	2015–2016	337	100	0	0.9	100	94.1	0	0	na
	2016–2017	437	99.8	0	7.3	25.8	78.3	0	0	na

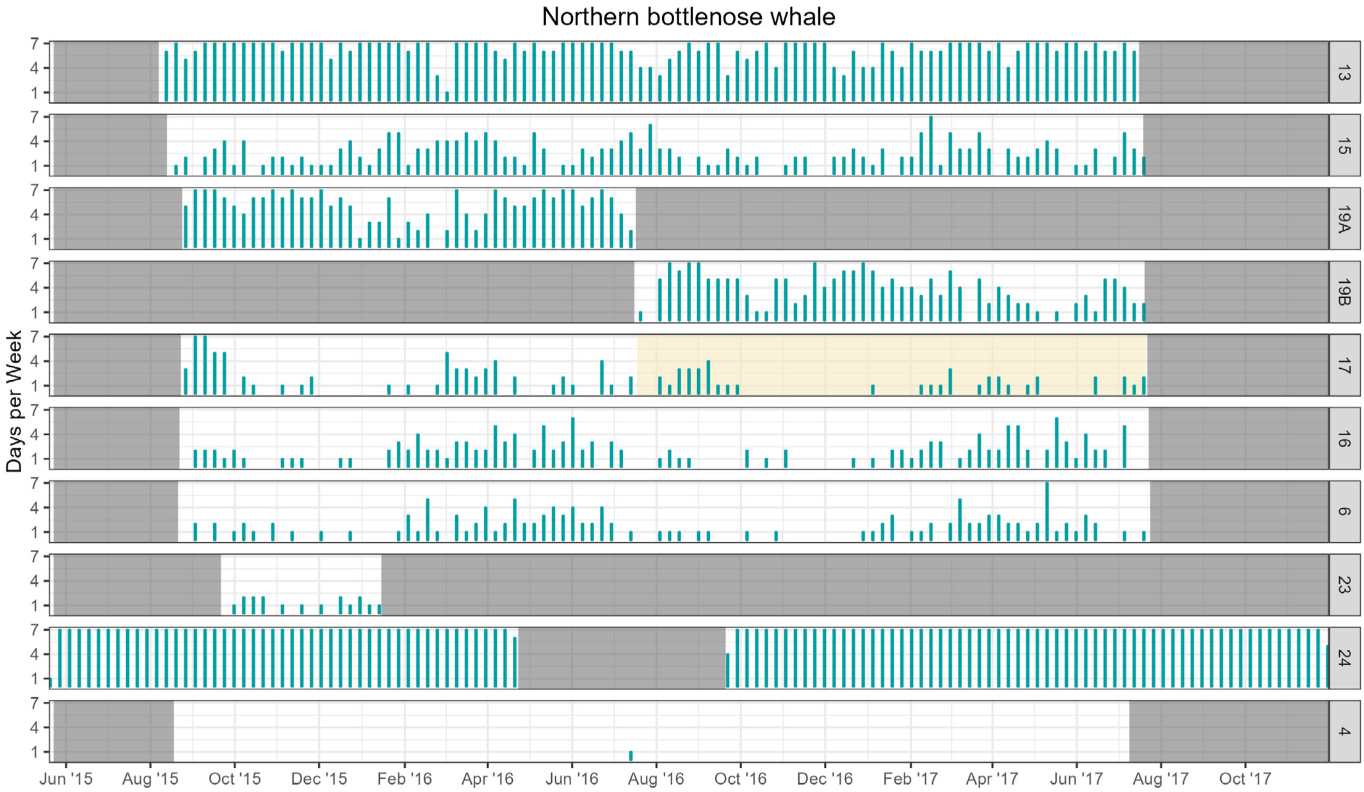

Fig. 4. Number of detection days (days with automated or manual detections) per calendar week for all stations where northern bottlenose whales were detected at least once between May 2015 and November 2017. Stations (numbers on right) are arranged north to south. Grey blocks: weeks with no available data. Yellow shaded areas: deployments for which the automated detector's precision was below 0.75; manual detection results shown instead

the SS (Stn 23; 14.8% RD) than at the Gully, but it should be noted that Stn 23 was deployed in shallower water (478 m). NBWs were not detected on any of the on-shelf (shallower) stations.

NBWs were detected year-round at all deep stations north of the Flemish Pass (Stns 13, 15, 19A and 19B) and in the Gully (Stn 24). Stations along the southern and southeastern edge of the Grand Banks (Stns 6, 16 and 17) displayed a different pattern. Several periods of regular detections were separated by periods characterized by a lack of, or scarce, detections. In both monitoring years, these periods with lower click presence occurred in fall and early winter. Detections resumed in late January or February. In early 2017, and to a lesser extent in 2016, a slight delay in the onset of detections from west to east is apparent at these 3 stations (Fig. 4).

3.3. SBW minimum presence

SBWs were detected at the largest number of stations (11) (Figs. 6 & 7, Table 3), with detections occurring on 26.3% RD across all deployments with at least one detection. SBWs were most commonly detected at the Gully (Stn 24; 86.2% RD). They occurred as far north as Orphan Basin (Stn 15) and as far south as Stn 5. Detections were sporadic in Orphan Basin (2.8% RD). At Stn 19, the species was absent during the first deployment (Stn 19A) and occurred sporadically in all months except February and March during the second year, when the recorder was relocated next to the northern edge of the Flemish Pass (Stn 19B). Near the southeastern corner of the Grand Banks (Stn 17), SBWs appeared to be more common during the second year, though there were few detections in December and January. In general, seasonal variations in acoustic occurrence were more pronounced with increasing latitude.

Stations off the eastern SS (Stns 23 and 24) had near-daily detections during the first year. During the second year in the Gully (Stn 24), detections occurred in all weeks but were less sustained from March to August. Stn16 had the most sustained detections (30.2% RD) outside of Stns 23 and 24. Stn 6 had spora-

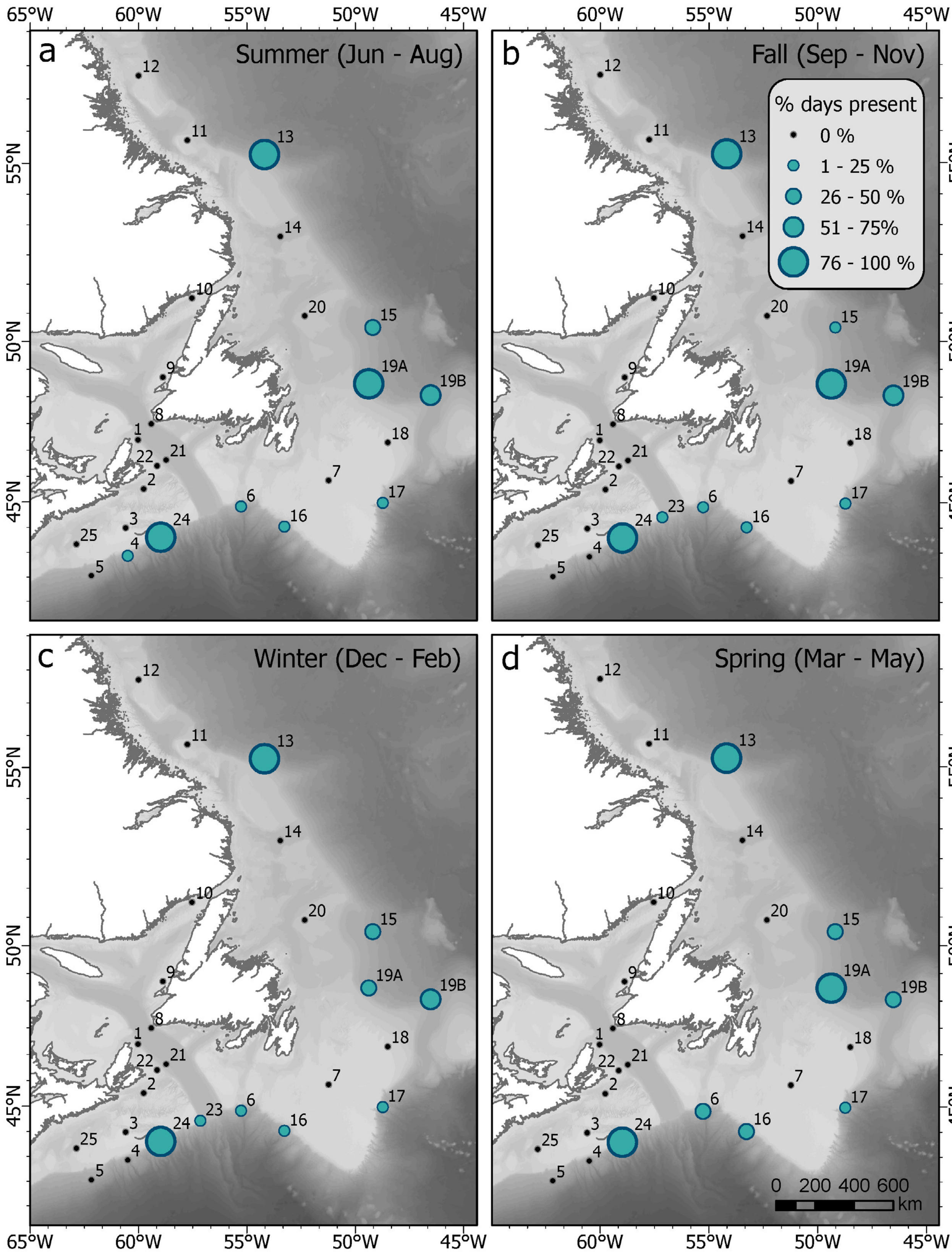

Fig. 5. Proportion of recording days per season with northern bottlenose whale automated or manual detections (detection days) for all 25 recording stations between May 2015 and November 2017. Bathymetry layer provided by the GEBCO Bathymetric Compilation Group (2020)

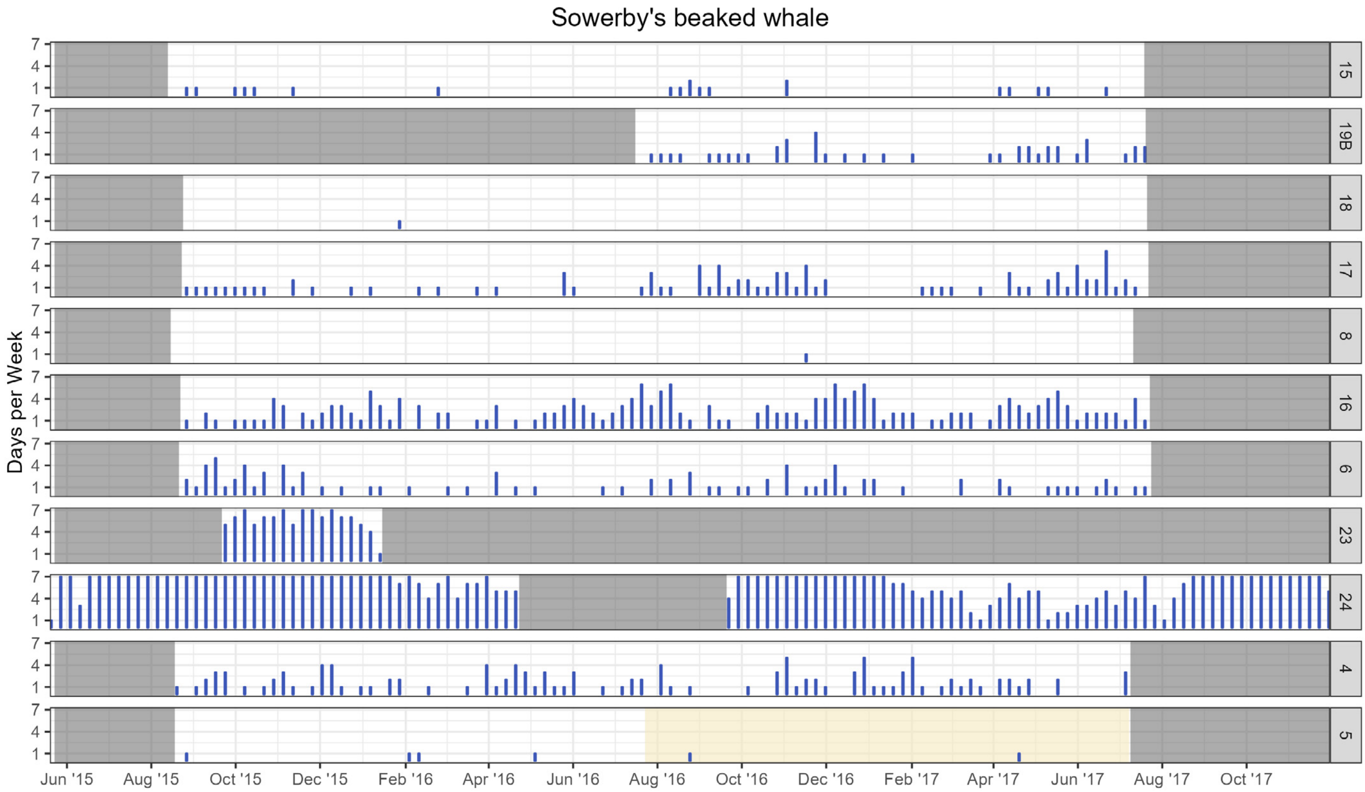

Fig. 6. Number of detection days (days with automated or manual detections) per calendar week for all stations where Sowerby's beaked whales were detected at least once between May 2015 and November 2017. Stations (numbers on right) are arranged north to south. Grey blocks: weeks with no available data. Pink blocks: exclusion periods when automated detections were ignored. Yellow shaded area: deployments for which the automated detector's precision was below 0.75; manual detection results shown instead

dic detections throughout the year. West of the Gully, detections occurred sporadically throughout the year at Stn 4. SBW were only detected on 6 occasions at Stn 5. Besides deep stations, SBW were detected once at Stn 18, located on the eastern Grand Banks and once at Stn 8 at the northern edge of the Cabot Strait. SBW were not detected at any of the other shallow on-shelf sites.

3.4. CBW minimum presence

CBW was the third most commonly detected beaked whale species, with detections occurring at 9 stations and on 20.4% RD across all stations with at least one detection (Figs. 8 & 9, Table 3). CBWs had a similar spatial distribution as did SBWs, except for the shallow sites, but the occurrence of these 2 species differed at most stations, possibly reflecting different habitat preference. The northernmost detections occurred in Orphan Basin (Stn15), where their presence was highest between May and September, although they were sporadically detected in winter months. Detections at Stns 19A and 19B were limited to manual detections due to poor detector performance and are therefore underestimated but presumably low. At Stn 17, CBWs appeared to occur primarily in spring and summer, but it is not possible to indicate whether the lack of detections in winter is real or simply reflects the limited amount of manual review and the exclusion of automated detections resulting from a lack of manual detections.

Along the southern edge of the Grand Banks (Stns 6 and 16) and off the SS (Stns 4 and 5), detections occurred throughout the year. Stns 5 and 16 had the highest proportion of RD with detections (41.7 and 37.5%, respectively). Worth noting is the lack of detections at Stn 6 from August until October–November in both years, while detections continued at Stn16, 170 km further east. Detections followed a similar temporal trend at Stns 4 and 5 but were higher at the deeper Stn 5 in all seasons except spring. CBWs were detected only sporadically in the Gully (Stn 24, 4.1% RD across both years) but are

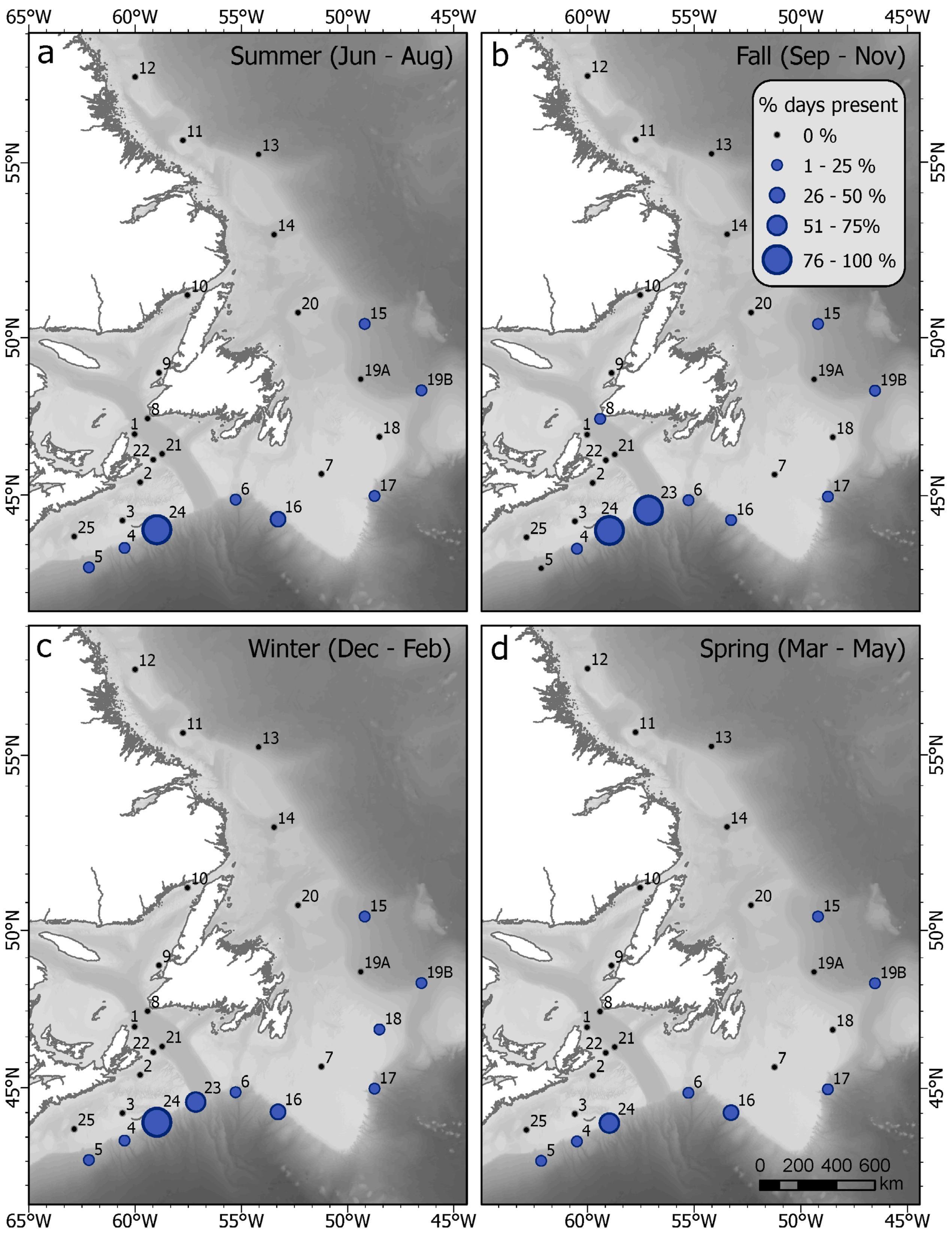

Fig. 7. Same as Fig. 5, but for Sowerby's beaked whales

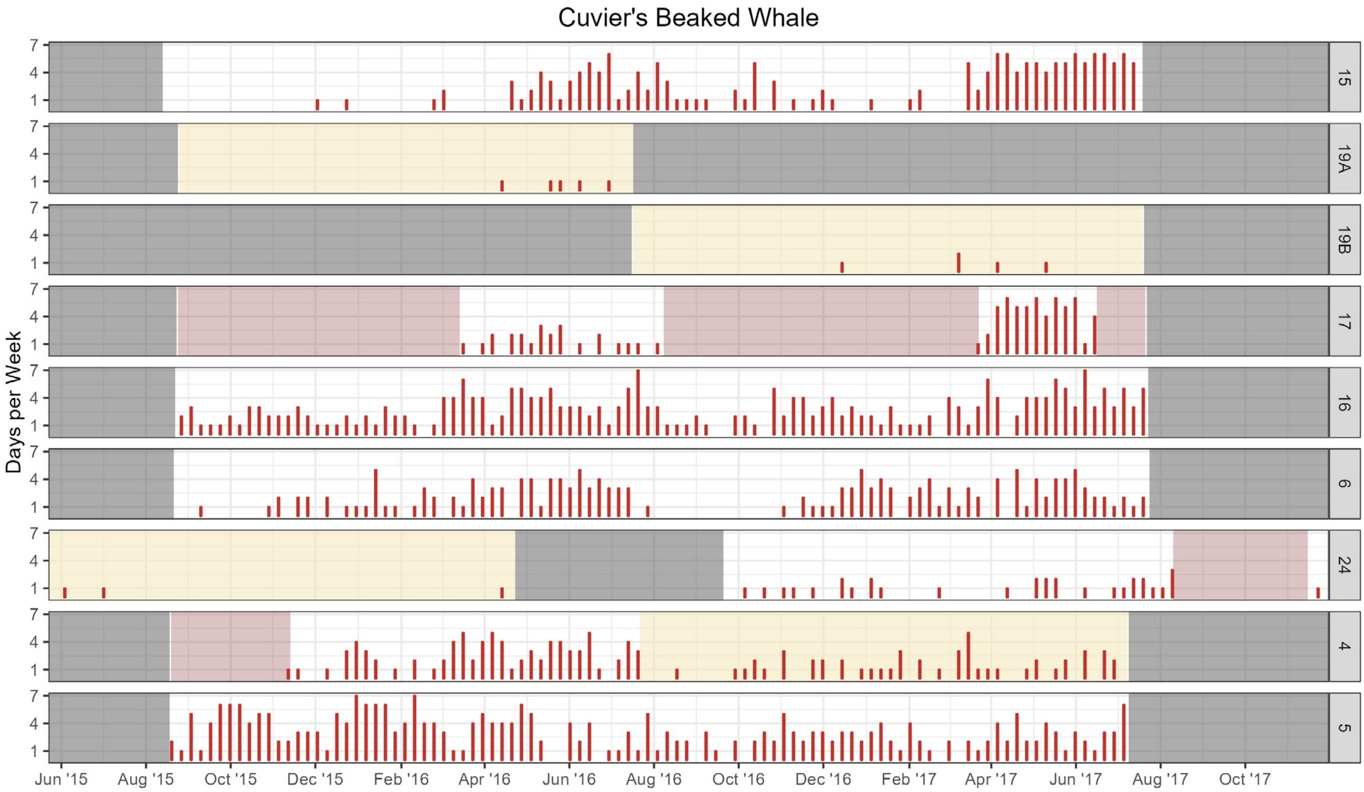

Fig. 8. Number of detection days (days with automated or manual detections) per calendar week for all stations where Cuvier's beaked whales were detected at least once between May 2015 and November 2017. Stations (numbers on right) are arranged north to south. Grey blocks: weeks with no available data. Pink blocks: exclusion periods when automated detections were ignored. Yellow shaded areas: deployments for which the automated detector's precision was below 0.75; manual detection results shown instead

likely highly underestimated due to the limitations of the manual analysis.

3.5. TBW/GBW minimum presence

TBW/GBWs had the most restricted distribution and occurred only at 4 stations off the SS and southern Grand Banks (Figs. 10 & 11, Table 3). The proportion of recording periods for which presence was assessed using only manual detections was highest for this species, ranging between 39.4 and 100% of RDs. Stn 5 in 2015–2016 was the only deployment for which presence was assessed entirely based on automated detections. These detections suggest year-round presence of TBW/GBWs off the southern SS. At Stns 6 and 16, detections were restricted to a few weeks between May and October. The few manual detections recorded for Stn 6 occurred at the same time as the combined automated and manual detections at Stn16. Off the SS, detections occurred in most weeks at Stn 5 and followed a similar pattern at Stn 4. Lower presence during the first year at Stn 4 are attributed to the use of manual detections only to characterize occurrence.

In an attempt to resolve species identity for these clicks, an analysis of ICI and spectral characteristics was performed on a sample of 1610 clicks with high SNR clicks (>10 dB; mean: 22.8 dB) from 23 distinct detection events distributed across all 4 stations and both years. The mean ICI was 0.199 s (10^{th}–90^{th} percentiles: 0.167–0.232 s; n = 1484; Fig. S1). Peak frequency (48.9 ± 9.5 kHz) and 10 dB bandwidth (33 ± 16.6 kHz) were positively correlated with SNR (Pearson's r = 0.626 and 0.783, respectively). There was no correlation between the 10 dB bandwidth lower endpoint with SNR (35.9 ± 9.5 kHz; Pearson's r = 0.068).

3.6. Other species

No clicks matching the description of BBW clicks were found. The automated click detectors applied to

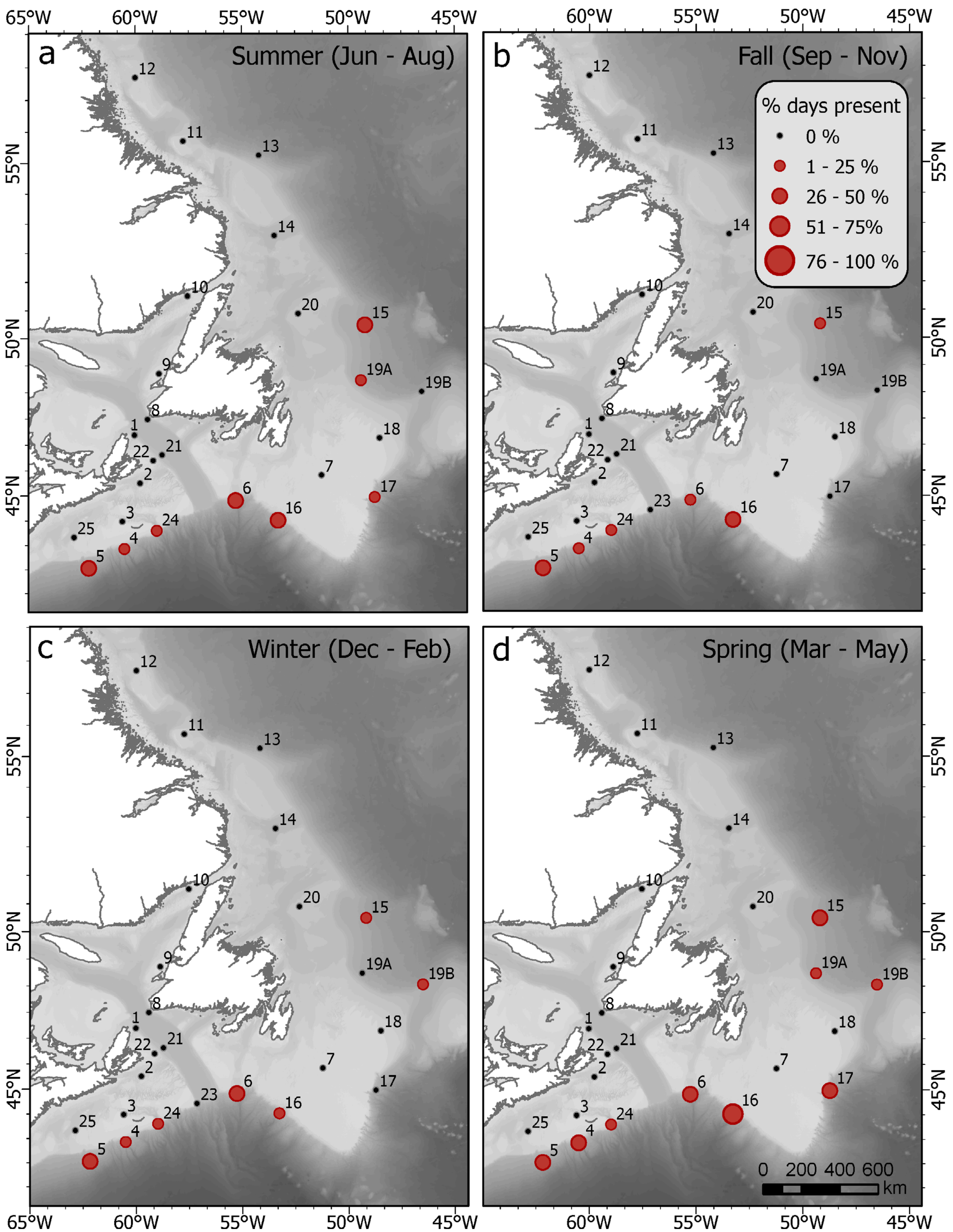

Fig. 9. Same as Fig. 5, but for Cuvier's beaked whales

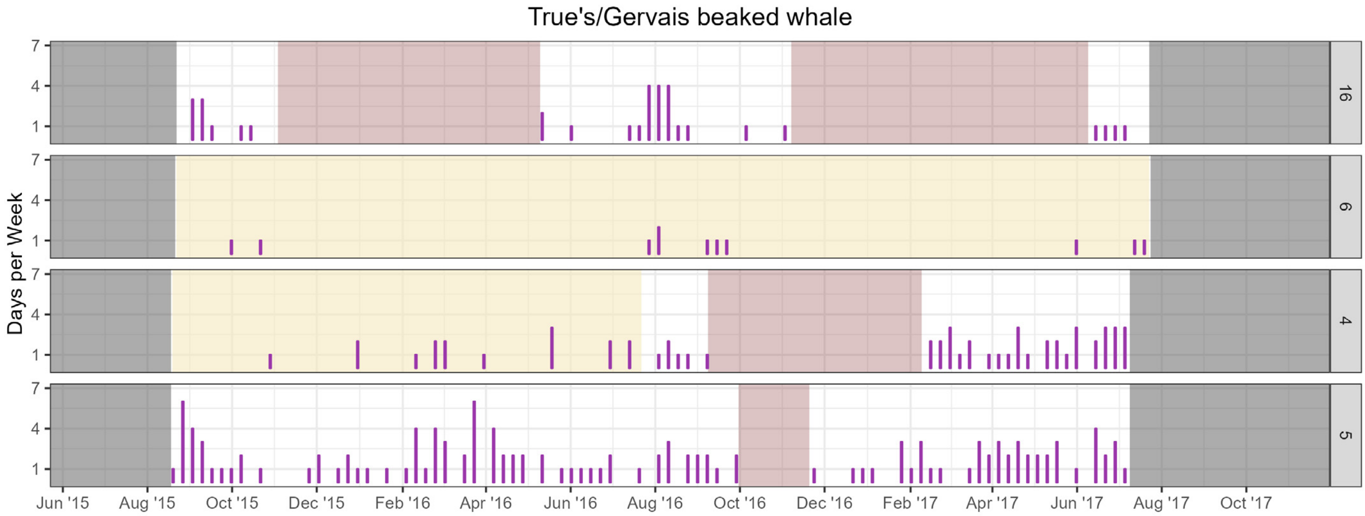

Fig. 10. Number of detection days (days with automated or manual detections) per calendar week for all stations where True's or Gervais' beaked whales were detected at least once between May 2015 and November 2017. Stations (numbers on right) are arranged north to south. Grey blocks: weeks with no available data. Pink blocks: exclusion periods when automated detections were ignored. Yellow shaded areas: deployments for which the automated detector's precision was below 0.75; manual detection results are shown instead

the data also included a template for clicks matching the description of a beaked whale click recorded in the Gulf of Mexico, which remains unassigned to a species. These clicks were labelled BWG when first described by Baumann-Pickering et al. (2013) (see Table S1), and their occurrence throughout the Atlantic Ocean is unknown. These clicks were not detected at any of the stations in this study.

4. DISCUSSION AND CONCLUSIONS

4.1. Overview and caveats

The acoustic detections presented here represent the minimum occurrence of beaked whales off eastern Canada. All detected species were found to be present year-round in at least some of the monitored areas. Worth highlighting is the potential co-occurrence of all detected species in some areas, particularly south of the Grand Banks and off the Scotian shelf. Species diversity was generally consistent across sites, with 3–4 species detected at all stations but Stn 13, where NBW was the only detected species, and the shallow sites where only SBW were detected (Fig. 12). However, species diversity showed more seasonal variation at the northern stations (Stns 15, 17, and 19) due to the lower occurrence of SBW and CBW in these areas, particularly in winter. These results establish the regular occurrence of a click type assigned to TBW/GBW, which increases the number of species now known to be present in this area to 4 (Stanistreet et al. 2022). TBW/GBWs were restricted to deep slope waters south of the Grand Banks, while CBWs and SBWs extended north into the Orphan Basin. Except for the southernmost station, NBW was the only species encountered at all the deep stations of the monitoring area.

It is possible that some of the differences in species occurrence presented here were driven by the depth of each recorder, ranging from about 500 to 2000 m at stations where beaked whales were regularly detected, and reflect habitat preferences of each species. However, the placement of recorders was such that it would be difficult to tease apart a potential depth effect on detections from other environmental or geographic (e.g. latitude) factors. In addition, the clicks of these species can be detected a few km out, and depth can vary by a few hundred meters over these ranges such that the depth at the actual locations of detected whales could vary by up to 500 m for a given station. Therefore, the potential influence of depth on the results is only discussed in general terms.

Several caveats must be considered when evaluating these results to assess the occurrence of beaked whales. Detection distances depend primarily on the source level of the signal of interest, propagation losses between the source and the receiver driven by environmental factors such as temperature and salinity, and background noise levels in the frequency band

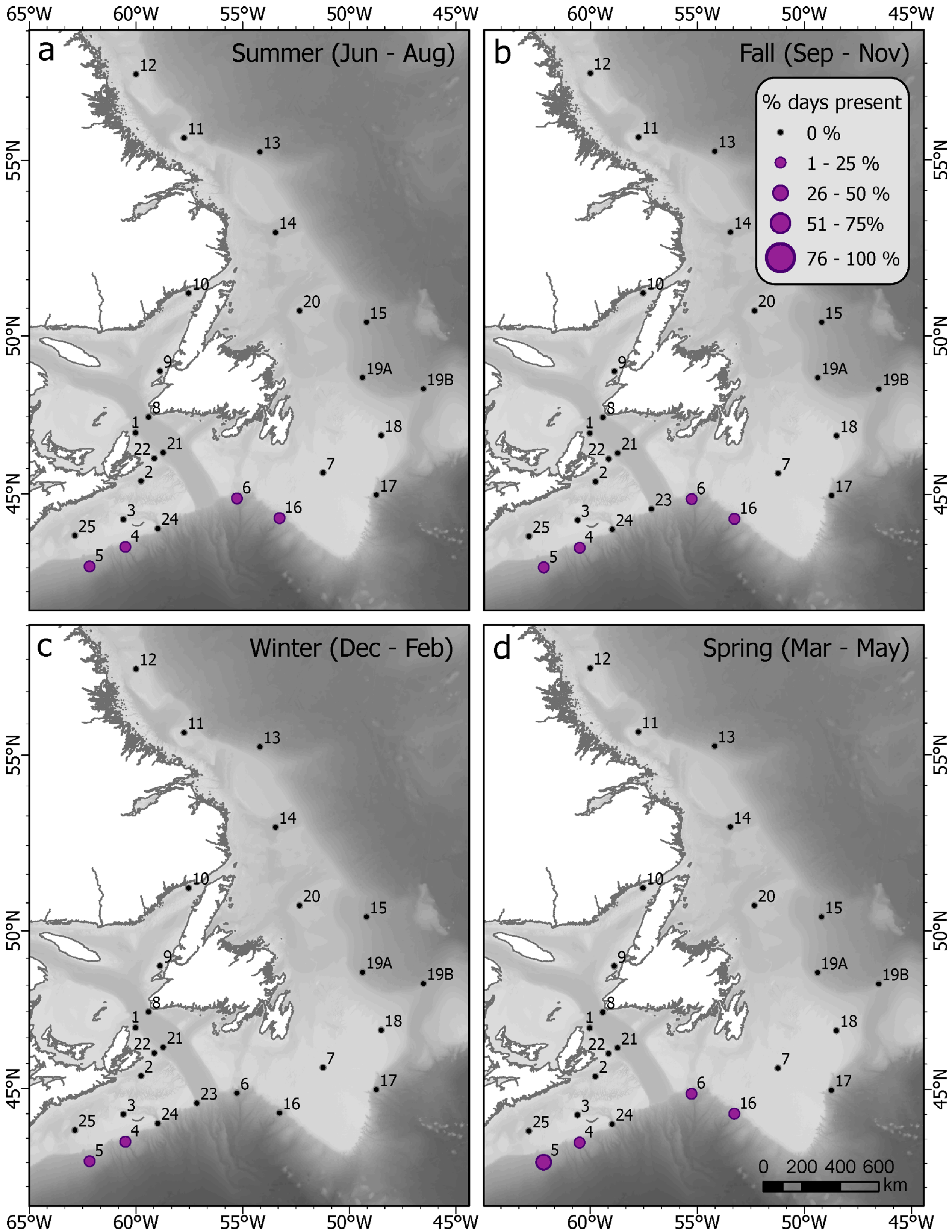

Fig. 11. Same as Fig. 5, but for True's/Gervais' beaked whales

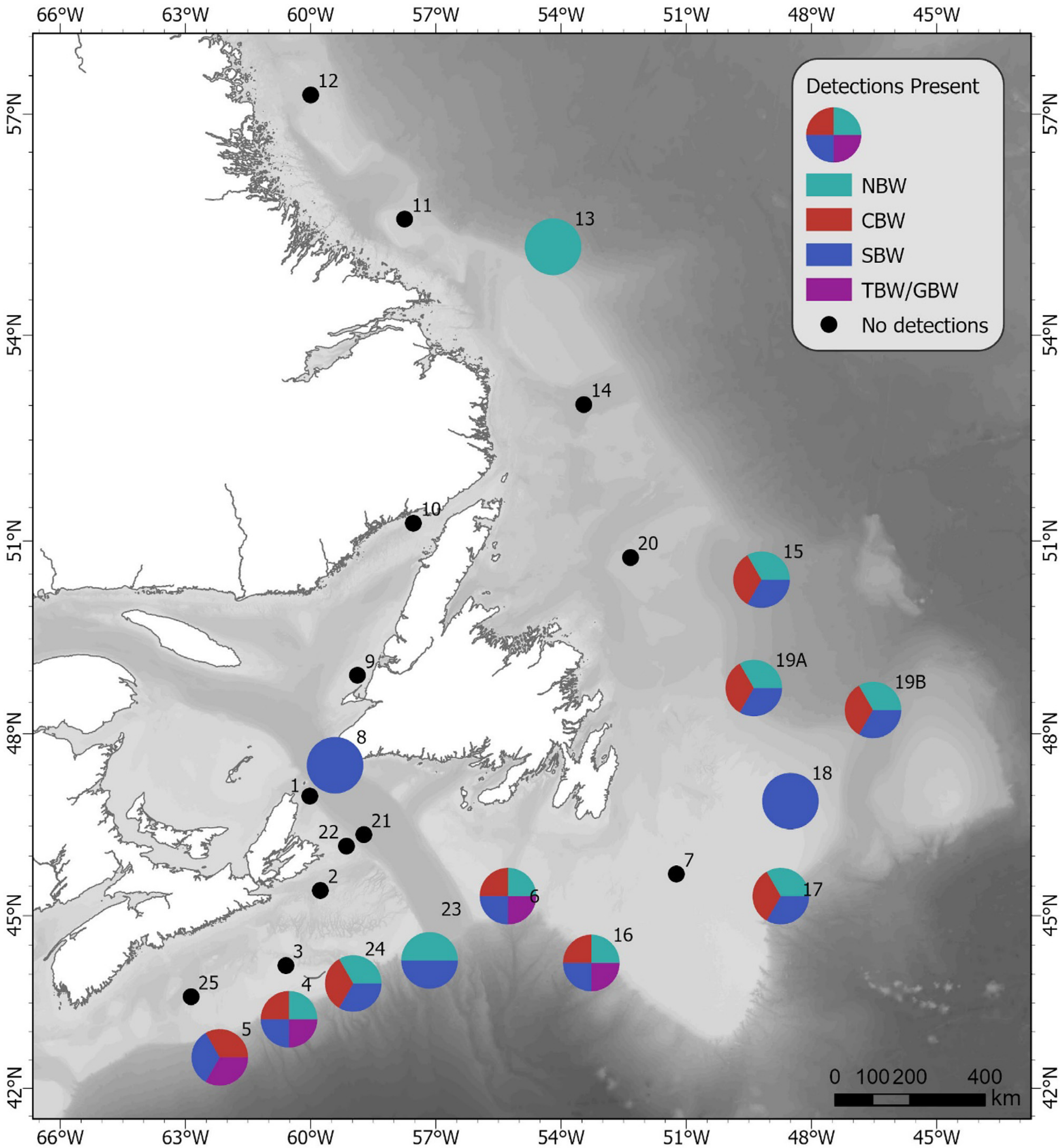

Fig. 12. Beaked whale species diversity observed at 25 acoustic recorders deployed between May 2015 and Nov 2017. A minimum of one acoustic detection (manual or automated) was required to determine a species as present. NBW: northern bottlenose whale; CBW: Cuvier's beaked whale; SBW: Sowerby's beaked whale; TBW/GBW: True's/Gervais' beaked whale. Bathymetry layer provided by GEBCO Compilation Group (2020)

of the signal (Zimmer et al. 2008). While detection ranges were not computed in this study, they have been estimated at 3–4 km for CBWs and NBWs (maxima of 5–6 km) and 1.5–2.5 km for SBWs in slope waters off eastern Canada (JASCO unpubl. data). However, these estimated detection ranges apply only for on-axis clicks (i.e. clicks produced with the sound beam of the animal directed at the recorder). These clicks have more energy and better match the click characteristics used for the automated detector parameters than off-axis clicks because of the strong horizontal and vertical directivity of the sound beam of beaked whale clicks (Zimmer et al. 2005, Wahlberg et al. 2011). In practice, the actual proportion of clicks available for detection is a fraction of all the clicks produced within the detection range of a recorder (Hildebrand et al. 2015), and detection probability decreases with increasing distance from the recorder, with only on-axis clicks being detectable at long ranges.

Click rate and acoustic and diving behavior also influence the likelihood of detecting beaked whale clicks in an area. Beaked whales echolocate primarily during the descent and bottom part of their deep foraging dives (Johnson et al. 2006, Arranz et al. 2011, Miller et al. 2015, Warren et al. 2017). While echolocating, clicks are produced at sustained rates of several clicks per second (see Table 2). Foraging dives occupy only a portion of the activity budget of beaked whales. They are typically separated by longer periods spent performing shallow dives (Baird et al. 2006) during which clicks, if any, are unlikely to be detected by near-bottom sensors (as in this study). Beaked whales perform numerous deep dives each day, but detection opportunities may be separated by 30 min to several hours (Miller et al. 2015, Shearer et al. 2019, Visser et al. 2022). However, studies have shown restricted home ranges (Hooker et al. 2002b, Foley et al. 2021, Stanistreet et al. 2021) and low horizontal travel speed (Falcone et al. 2009, Schorr et al. 2009) for several beaked whale species. Despite the restricted detection range of their clicks, these observations suggest that beaked whales are most likely detectable by a fixed recorder over several dives in a day. Because a single minute out of 72 recorded each day is required to contain detections to confirm daily presence, this suggests that daily R may be higher than R calculated on a per-file basis (Kowarski et al. 2020), as presented here (Tables S2–S5). The effects of detection range and probability on R are ultimately constrained by the effect of the recording duty cycle, i.e. the temporal overlap between actual click events and active recording periods. Stanistreet et al. (2016) found that short but frequent recordings were more effective than longer, less frequent recordings to assess the daily presence of beaked whales. In addition, they found that the acoustic occurrence of *Mesoplodon* species was more likely to be underestimated than that of NBWs or CBWs at short duty cycles and increasingly so for longer duty cycles, which was tentatively attributed to longer mean detection durations of CBWs and NBWs than *Mesoplodon* species. The low duty cycle in this study (5%) suggests that we may be more likely to miss SBW and TBW/GBW clicks compared to NBW and CBW clicks.

Beaked whales forage daily throughout the year. Any seasonal variations observed in this study are therefore likely representative of real trends in the presence of beaked whales at a given site over time and not a reflection of a seasonal change in clicking (foraging) behavior (though any seasonal variation in detector performance must also be considered when interpreting results).

Ultimately, one can expect that a beaked whale foraging within 3–4 km (~2 km for SBW) of our recorders has a reasonable probability of being detected on a daily basis, as presented here, but that occurrence at finer time scales (e.g. hours) is more likely to be underestimated. The relatively low number of files reviewed by analysts, despite their distribution across the duration each recording period, may result in a failure to detected isolated vocalization events from rare species (e.g. TBW/GBW, BBW) or outside a species' main period of occurrence. The occurrence of beaked whales is expected to be more greatly underestimated with increasing reliance on manual detections (see Table 3). This effect varied between species and across stations within species. While these results should be interpreted as minimum species presence, and the relative occurrence may be influenced by the fluctuating reliance on automated and manual detections, the patterns in click occurrence presented here still provide important information regarding the relative habitat use over space and time of each species in areas off eastern Canada which have generally received no or very limited monitoring effort for beaked whales.

4.2. NBW

NBWs had the highest number of detection days across the study area among all species. They were present within the Gully on all but one (partial) recording day, confirming the importance of this area as critical habitat for the NBW. Stanistreet et al. (2021) reported that SS NBW move to and from areas beyond the eastern SS canyons currently designated as critical habitat, suggesting that this endangered population is not closed to immigration or emigration and that low level of exchanges may occur with NBWs from more northern areas. Our detections suggest that NBWs do not commonly occur west of the Gully area, as clicks were only detected once at Stn 4 and never at Stn 5. Similarly, few visual and acoustic detections have been documented west of the Gully in other studies (Stanistreet et. al. 2021).

NBWs prefer areas greater than 500 m deep, in particular the continental slope where depth is between 800 and 1500 m (Hooker et al. 2002b, Wimmer & Whitehead 2004), with currently designated critical habitat encompassing depths up to 2200 m (Fisheries and Oceans Canada 2010). The deep-water extent of NBW habitat remains unknown, largely due to a lack of monitoring effort beyond the continental slope. In this study, NBWs were common at stations in depths of ~2000 m in Orphan Basin and off the southern Labrador shelf, but not west of the Gully. Four months of recording at Stn 23 at the eastern edge of the SS (Sep 2015–Jan 2016) showed a much lower frequentation of this area compared to the Gully, though detection rates may have been affected by depth of this recorder (480 m) being shallower than the preferred depth range of this species. In general, the occurrence of NBWs at the monitored stations was likely more influenced by location and proximity to areas of aggregation, such as the Gully or northern Flemish Pass, than depth itself.

Stanistreet et al. (2021) observed a peak in acoustic detection at recorders deployed between the eastern SS canyons between February and July in 2013 and 2014. It is worth noting that a period of increased acoustic activity occurred during the same months in 2016 and 2017 at Stns 6 and 16, and to a lesser extent Stn 17, along the southern edge of the Grand Banks. Low or no detections were observed on either side of that period (late January to early July). More effort is required to assess whether this represents a seasonal shift in distribution of SS NBWs (noting that the Gully remains heavily used during these months), a southerly range shift by the DSBBLS population, or other factors. These results contribute to some of the recovery objectives and measures listed in the Recovery Strategy (Fisheries and Oceans Canada 2010) and Action Plan for the SS NBW (Fisheries and Oceans Canada 2017b), specifically those aimed at increasing our understanding of the spatial and temporal distribution and habitat use of this population. In particular, we highlight regular use of deep-water areas along the Grand Banks that may be part of the range of this population. These areas are outside the critical and important habitat areas that have been identified around the Gully, Shortland, and Haldimand canyons, and warrant further investigation as potentially important habitat for the SS NBW.

There appears to be a discontinuity in acoustic detections between areas north and south of the Flemish Pass. In particular, the seasonality in detections observed south of the Flemish Pass was absent to the north where detections occurred regularly throughout the year. Detections in areas of steep bathymetric contours (Stns 19A, 19B, and 13) had higher acoustic occurrence than Stn 15, an area of lower slope, which is consistent with previous habitat modeling showing depth and steep topography to be the main predictive variables of NBW distribution (Gomez et al. 2020). The change in location of Stn 19 after the first year resulted in a decrease in the proportion of detection days from 68 to 54%. It is unclear if this represents habitat preference and is possibly an indication that the northern Flemish Pass may be the southern edge of the DDBBLS population. Stn 19B was deployed in the area where NBWs were sampled by Feyrer et al. (2019). The genetic affiliation of these individuals is unresolved, suggesting that this area could be one of mixing among individuals from both the SS and DSBBLS populations.

Considering the relatively short detection range of NBW clicks, the high NBW detection rates at Stn 13 off the southern Labrador Shelf (86% of days with NBW detections) show consistent presence of this species in the area, approaching that observed in the Gully, and suggest it may be an important foraging area. While NBW sightings have been reported throughout deep slope waters from northern Newfoundland to the Davis Strait (Harris et al. 2013), visual monitoring effort in these areas remains extremely limited. Additional long-term PAM efforts at several locations along the slope of the Labrador shelf would help assess use of these areas by the NBW throughout the year.

4.3. SBW

The results herein contribute to addressing some of the objectives and conservation measures outlined in the management plan for the SBW in Canadian waters (Fisheries and Oceans Canada 2017a), by providing a new understanding of the extent of the species' range and distribution off eastern Canada. The northern extent of SBWs appears to be around the Orphan Basin, with no detections occurring at stations north of Stn 15. The difference in detections between Stn 19A and 19B, along the southern edge of Orphan Basin, could be connected to the proximity of Stn 19B to the northern edge of the Flemish Pass in 2016–2017, where this species is also regularly acoustically detected (JASCO unpubl. data). North of the Flemish Pass, presence of SBW was previously only known from 3 sightings, including 1 in Orphan Basin and 2 on the outer southern Labrador Shelf (Gomez et al. 2020).

Little is known about the specific habitat preferences of the SBW. Like other beaked whales, this species is believed to favor deep water habitats such as those encountered in submarine canyons and along the continental slope (Fisheries and Oceans Canada 2017a). There were relatively consistent detections of SBWs at all stations along the SS and south of Newfoundland, except for Stn 5 off the central SS. The primary difference between Stn 5 and the other stations lining the edge of the SS and southern Grand Banks is the distance to the shelf break (defined as the 200 m isobath; <32 km for Stns 4, 6, and 16 and 55 km for Stn 5). This observation is consistent with other acoustic records which show detections more closely associated with the shelf break in SBWs compared to other beaked whale species in the Northwest Atlantic (NOAA 2023). Whether this reflects potential habitat preference needs to be further investigated. Depth, slope and other abiotic and biotic factors also presumably influence the occurrence of the SBW and other beaked whales.

These results confirm the importance of the Gully and nearby areas off the eastern SS for SBWs. The southern edge of the Grand Banks and northern edge of the Flemish Pass are other areas used consistently by SBWs. It is interesting to note the difference in frequentation at both edges of the entrance to the Laurentian Channel (Stns 23 and 6) in the first months of the study, where presence was greater at Stn 23 despite its relatively shallow depth (<500 m depth). However, SBWs were also detected at 2 other shallow stations in the Cabot Strait, the main entrance to the GSL, and on the Grand Banks. These records may be related to the relatively elevated numbers of strandings in the GSL and off northern Newfoundland. The North Sea is another shallow area that concentrates abnormally high number of SBW strandings despite no recorded sightings, leading to conclusions that it is an area of occasional occurrence where many animals that enter subsequently die (Macleod 2000).

4.4. CBW

This study indicates the year-round presence of CBWs in Orphan Basin and waters south and west of the Grand Banks as well as all along the edge of the SS. This is the first documentation of CBWs east of the Laurentian Channel, with the exception of a single stranding recorded on the central part of the eastern Newfoundland coast (Wimmer & Maclean 2021). It expands the confirmed range of this species for the western North Atlantic (MacLeod et al. 2005). CBWs were commonly detected in Orphan Basin from spring to fall. The lack of, or reduced, CBW detections from December to April may represent seasonal movement away from the area when SST are lowest and sea ice may be near or present.

While CBWs are commonly detected throughout the year at most SS stations, there is a relatively low number of acoustic detections in the Gully. This is due to poor detector performance likely caused by a consistently high number of odontocete click detections in the Gully (delphinids and NBWs, in particular) resulting in a high reliance on manual detections only at this station (Table 3). Despite dedicated visual monitoring in this area since 1988 (Gowans et al. 2000, Moors 2012, Whitehead 2013), only a single CBW sighting has been reported in this area. However, Stanistreet et al. (2017) acoustically detected CBWs in the Gully on ~30% of recording days in 2012–2014 (Stanistreet et al. 2017) via manual validation of all automated beaked whale detection events. This results in a higher probability of finding CBW clicks amongst clicks produced by other odontocetes, though the authors noted that even with this more in-depth analysis approach, CBW presence was likely underestimated at the Gully site due to the high number of NBW clicks present. Further manual validation effort would be needed to provide a more thorough assessment of CBW click presence in the Gully.

The population size of CBW frequenting the waters of eastern Canada is unknown. It is unclear whether the more common recent (since 2012) detections of this species in this region via PAM and stranding events reflects a range expansion into Canadian waters over the past decade or reflects low sighting probability during visual survey efforts and a lack of PAM effort prior to 2012.

4.5. TBW/GBW

In this study, TBW/GBW detections were restricted to the edges of the SS and southern Grand Banks. Their absence further north could reflect the limits of their range and habitat preferences of this generally more southern species. For instance, stations north of the Grand Banks are under the influence of the cold Labrador current, while deep water areas south of the Grand Banks are influenced by the warmer Gulf Stream (see e.g. Jutras et al. (2023)). There are few prior references to the presence of TBWs or GBWs in Canadian waters, but Stanistreet et al. (2022) detected this click type, referred to as 'unidentified Mesoplodont beaked whale', in September and October 2016 at a PAM station located east of the Gully in 2000 m water depth.

Our inability to confidently assign clicks resembling those of TBW and GBW lies in the similarities between the clicks produced by these 2 species (DeAngelis et al. 2018, Cohen et al. 2022). However, several factors suggest a greater probability of presence of TBWs rather than GBWs off eastern Canada. First, GBWs have never stranded in Canada, and the northernmost recorded stranding is in Cape Cod (Hayes et al. 2020). In contrast, there are 4 records of TBWs stranding (all since 2015) in the Gulf of St Lawrence and in Newfoundland (Wimmer & Maclean 2021, T. Wimmer pers. comm.). Second, acoustic records of GBWs along the US eastern seaboard are biased towards the central and southeastern USA, while TBW detections are more common from Virginia to the Canadian border (Cohen et al. 2022, NOAA 2023). Third, sighting records, although limited, indicate that the GBW can occur all along the US eastern seaboard, while TBWs were seen exclusively northeast of Cape Hatteras (Cohen et al. 2022). Finally, in a sample of TBW/GBW clicks analyzed to measure spectral features and ICI, ICI was found to be close to those reported for TBW (DeAngelis et al. 2018), and none of the detection events had ICIs close to those associated with GBW (see Table 2). The lower 10 dB bandwidth endpoint (which was unaffected by SNR) was similar to that of TBW, but this metric has yet to be reported for GBW. The click descriptions of GBW and TBW remain relatively limited in comparison to other species. ICIs are to date the least overlapping descriptor of clicks for these 2 species. ICIs have been used to identify GBWs in a multi-species study in the Gulf of Mexico (Hildebrand et al. 2015). The combined evidence therefore indicates that TBWs are the most likely source of the TBW/GBW clicks.

4.6. Final remarks

There are a number of threats common to all beaked whales in eastern Canadian waters (Feyrer et al. 2024). Considering protection for deep water areas including the continental slope of the SS and southern Grand Banks would benefit several beaked whale species. These 2 broad areas in particular have year-round presence of at least 4 beaked whale species and are also known to be important for several species of baleen whales, including endangered blue whales (Lesage et al. 2018, Delarue et al. 2022).

Large naval exercises involving use of military sonars are known to take place off Nova Scotia (e.g. see Stanistreet et al. 2022). Military sonar is of particular concern for beaked whales due to the occurrence of fatal strandings that have been linked to military sonar activities in various parts of the world (e.g. Balcomb & Claridge 2001, D'Amico et al. 2009, Filadelfo et al. 2009, Simonis et al. 2020). Military sonar was assessed as having an extreme and high risk of individual and population level effect, respectively, for SS NBWs (Fisheries and Oceans Canada 2022). CBWs and TBW/GBWs have been shown to react to sonar exposures off the SS, as demonstrated by a cessation of acoustic detections, indicating an interruption of foraging or avoidance of the area (Stanistreet et al. 2022). Similar reactions have been documented for several species in other parts of the world (Tyack et al. 2011, DeRuiter et al. 2013, Falcone et al. 2017).

Renewed interest in oil and gas exploration and production in deep offshore areas of Newfoundland and Labrador raises questions about the long-term effects of underwater noise on beaked whales in these areas. This is particularly relevant for the NBWs present in these areas year-round. Although the waters east and north of Newfoundland and Labrador include several federally designated sensitive areas, such as Ecologically and Biologically Sensitive Areas (EBSA) or Marine Refuges, these allow oil and gas activities to proceed and offer little protection to beaked whales and other marine mammals from long-term underwater noise exposures and other impacts.

Protection from other risks to beaked whales in these areas should also be considered. Entanglements of NBWs and SBWs in fishing gear have been documented off eastern Canada (Harris et al. 2013, Fisheries and Oceans Canada 2017a, Feyrer et al. 2021), as have NBW depredation events (when whales remove or damage fish from fishing gear; COSEWIC 2011), which increases risk of entanglements (Feyrer et al. 2024). Some individuals from the SS NBW population were documented to have scars consistent with vessel strike injuries (Feyrer et al. 2021). Pollution and chemical contaminants also pose a threat to beaked whales off eastern Canada; for example, Desforges et al. (2021) suggest that the levels of persistent organic pollutants in SS NBWs have increased since the 1990s, while Kelly et al. (2023) provide evidence that SS NBWs are exposed to and ingesting plastic.

This study provides the first long-term documentation of the occurrence of 4 species of beaked whales over a substantial portion of suitable habitat eastern Canadian waters. A systematic understanding of the spatio–temporal distribution of beaked whales is a first step to quantifying and mitigating the risks associated with the anthropogenic activities discussed above. Though PAM has greatly expanded our knowledge of beaked whale habitat use in these areas, there remain many knowledge gaps around their occurrence, such as habitat preference and partitioning among species, that have yet to be addressed. Under the expectation of accelerating climate-driven changes in the marine environment, this work will serve as a baseline for the long-term assessment of changes in the occurrence of these species off eastern Canada. PAM efforts are continuing and will help build upon these results.

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