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# Variation in glider-detected North Atlantic right, blue, and fin whale calls in proximity to high-traffic shipping lanes

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ABSTRACT: Passive acoustic monitoring has become an integral tool for determining the presence, distribution, and behavior of vocally active cetacean species. Acoustically equipped underwater gliders are becoming a routine monitoring platform, because they can cover large spatial scales during a single deployment and have the capability to relay data to shore in near real-time. Yet, more research is needed to determine what information can be derived from glider-recorded cetacean detections. Here, a Slocum glider that monitored continuously for low frequency (<1 kHz) baleen whale vocalizations was deployed across the Honguedo Strait and the associated traffic separation scheme in the Gulf of St. Lawrence, Canada, during September and October 2019. We conducted a manual analysis of the archived audio to examine spatial and temporal variation in acoustic detection rates of North Atlantic right whales (NARWs), blue whales, and fin whales. Call detections of blue and fin whales demonstrated that both species were acoustically active throughout the deployment. Environmental association models suggested their preferential use of foraging areas along the southern slopes of the Laurentian Channel. Results also indicate that elevated background noise levels in the shipping lanes from vessel traffic only minimally influenced the likelihood of detecting blue whale acoustic presence, while they did not affect fin whale detectability. NARWs were definitively detected on less than 20% of deployment days, so only qualitative assessments of their presence were described. Nevertheless, detections of all 3 species highlight that their movements throughout this seasonally important region overlap with a high volume of vessel traffic, increasing their risk of ship strike.

KEY WORDS: Acoustic detections · Blue whales · Fin whales · North Atlantic right whales · Remote sensing · Shipping lanes · Underwater gliders · Whale calls

## 1. INTRODUCTION

Commercial and recreational shipping traffic represents a significant conservation concern for cetacean species worldwide, with evidence of 11 mysticete species (baleen whales) being struck by vessels, including fin whales *Balaenoptera physalus*, blue whales *B. musculus*, North Pacific *Eubalaena japonica*, North Atlantic *E. glacialis* and southern *E. australis* right whales, and humpback whales *Megaptera novaeangliae* (Laist et al. 2001, Van der Hoop et al. 2013). Between the 1970s to the early 2000s, a tripling of the global shipping fleet led to a 3- to 4-fold increase in the number of whales reportedly struck by vessels annually (Vanderlaan et al. 2009). During this same period, a 3- to 6-fold increase of ship strikes occurred

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along the east coast of the USA (Vanderlaan et al. 2009). This threat has become particularly apparent in Canadian waters, where an unusual mortality event (UME) of the Critically Endangered North Atlantic right whale (NARW) (Cooke 2020) has been unfolding. The ongoing UME began in 2017 with the injury or death of at least 17 right whales in the Gulf of St. Lawrence (GoSL), 4 of which were directly attributed to blunt force trauma from ship strike (Daoust et al. 2018, Davies & Brillant 2019).

The GoSL is a large semi-enclosed sea in the western North Atlantic Ocean of considerable oceanographic, biological, and socioeconomic importance. It has become a summertime foraging hotspot for NARWs in recent years, following an oceanographic regime shift that led to precipitous declines in the abundance of their primary copepod food source, late-stage *Calanus finmarchicus*, in previously important feeding areas (Davies et al. 2019, Record et al. 2019, Meyer-Gutbrod et al. 2021, 2022). This range shift has resulted in migratory movements that directly overlap with busy shipping lanes in the GoSL. Running through the GoSL, the Laurentian Channel and the associated traffic separation scheme (TSS), a maritime traffic-management route system, links the Lower St. Lawrence Estuary (LSLE) to the Scotian Shelf via the Cabot Strait, which connects the GoSL to the Atlantic Ocean. This route is both the main conduit for the commercial shipping industry between ports in the Great Lakes (including Canada's largest cities, Toronto and Montréal) and the rest of the world, as well as a migratory corridor for several baleen whale species that move into and out of high latitude foraging areas in the region, including the southern GoSL, Honguedo Strait, Jacques Cartier Passage, and LSLE (Lesage et al. 2017, Schleimer et al. 2019, Delarue et al. 2022, Durette-Morin et al. 2022, Meyer-Gutbrod et al. 2022) (Fig. 1).

Krill (Order Euphausiacea), one of the primary prey of rorqual whales, is known to aggregate along the sloped bathymetry of the Laurentian Channel (McQuinn et al. 2016). As such, the TSS not only co-occurs with the migratory pathway of these whales into the GoSL, but intersects important feeding habitat, from the Gaspé Peninsula to the Saguenay-St. Lawrence Marine Park (SSLMP) (Fig. 1). This means that several species spend a significant amount of time in and/or near the shipping lanes for substantial portions of each year. While the plight of the NARW has drawn attention to the risks posed by this overlap, other large whales common to the area are also susceptible to ship strike (Van der Hoop et al. 2013, Wimmer & Maclean 2021). This includes minke *B. acutorostrata*, humpback, sei *B. borealis*, and fin whales, and also the region's population of blue whales, which is thought unlikely to exceed 250 mature individuals and is classified as endangered (Sears & Calambokidis 2002, Beauchamp et al. 2009, COSEWIC 2012).

For mysticetes like NARWs and blue whales, the morbidity and mortality resulting from ship strikes is a threat to population growth and recovery (e.g. Stewart et al. 2021, 2022). Consequently, cetacean monitoring and mitigation strategies have become a priority in the GoSL, to mitigate interactions between whales and vessels in Canadian waters (Davies & Brillant 2019, Fisheries and Oceans Canada 2021, Pettis et al. 2022). Consistent monitoring efforts are crucial to balance the needs of industry and conservation by establishing the occurrence and distribution of species across space and time throughout the region. Visual surveys are a frequently used monitoring method conducted via boat-based observations, aerial surveillance, and use of remotely piloted aircraft systems (RPAS, i.e. drones). Although visual surveys often allow for positive species identification and estimates of abundance, they are commonly limited by daylight, weather and visibility (e.g. wind, rain, fog), season, surfacing behavior, funding constraints, and field trip durations. Passive acoustic monitoring (PAM) provides an effective complement to visual observation efforts, as it can be used for long-term, continuous recordings of nearby marine mammals across periods unsuitable for visual monitoring (e.g. at night, during winter months or inclement weather, and without prolonged need for the physical presence of field personnel) (Clark et al. 2010, Smith et al. 2020, Ceballos et al. 2023).

While PAM traditionally relied on moored archival recorders, untethered mobile autonomous platforms such as surface drifters, wave gliders, profiling floats, and electric gliders are becoming widespread as their recording capabilities continue to advance (Moore et al. 2007, Baumgartner & Fratantoni 2008, Matsumoto et al. 2013, Griffiths & Barlow 2016, Bittencourt et al. 2018, Fregosi et al. 2020, 2022). For example, electric gliders equipped with hydrophones and programmed with automated detection software have been used successfully for near real-time marine mammal acoustic monitoring, while providing continuous archival recordings post-deployment (Baumgartner et al. 2013, 2020). These technologies have the advantage of covering large horizontal (10s to 100s of kilometers) and vertical (10s to 100s of meters) spatial scales over long deployment periods (weeks to months) (Webb et al. 2001, Baumgartner et al. 2020, Fregosi et al. 2020).

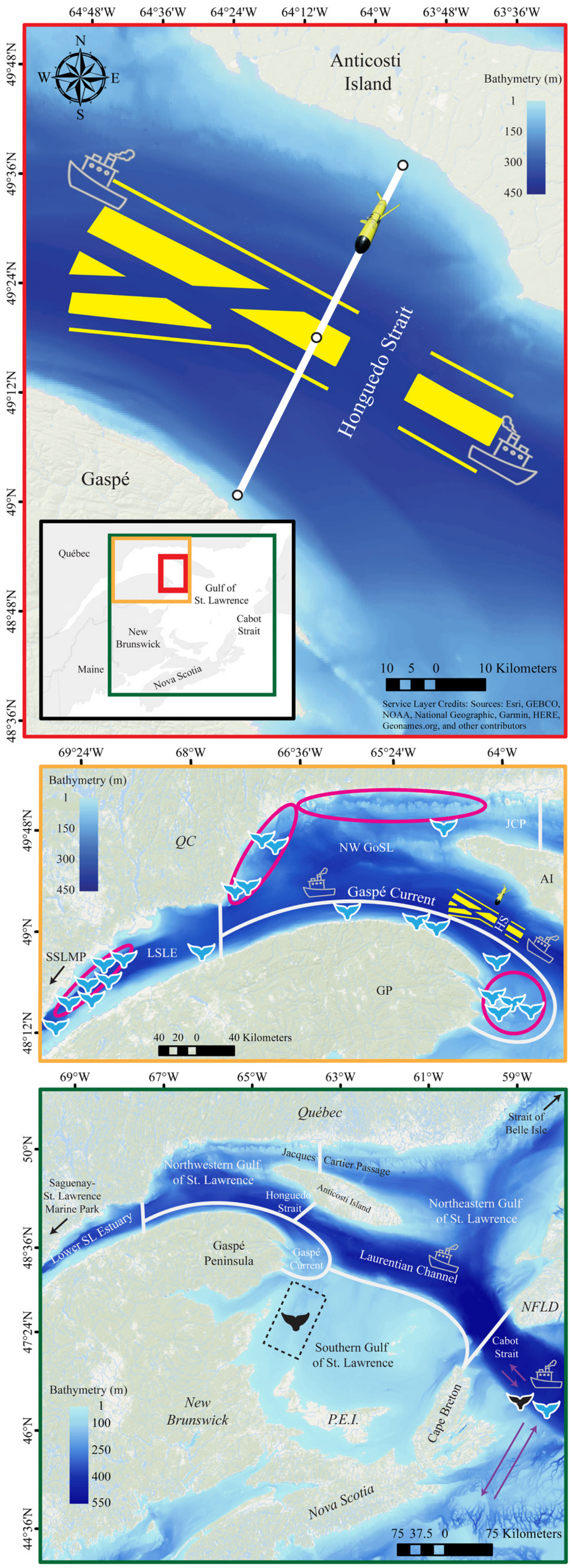

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Fig. 1. Shipping routes and whale foraging grounds in the Gulf of St. Lawrence (GoSL). Red panel: glider transect line (center point 0, endpoint 34.4 km to the northeast, endpoint −32.4 km to the southwest) and boundaries of the traffic separation scheme in- and outbound shipping lanes (in yellow). Orange panel: historical krill hotspots (pink circle and ovals) and areas of previously observed blue whale (blue tails) presence and foraging activity (see Fig. 2 in McQuinn et al. 2016 and Figs. 1 & 3 in Lesage et al. 2017 for fine-scale details). Green panel: all major regional features, including pathways of migratory whales and vessel traffic into and out of the GoSL via the Cabot Strait, as well as the general aggregation area of North Atlantic right whales (black tails) in the foraging grounds of the southern GoSL (dashed black box). White lines in the 2 bottom panels: major subregions of the GoSL: northeastern GoSL, southern GoSL, northwestern GoSL, Lower St. Lawrence Estuary (LSLE), and Gaspé Current. SSLMP: Saguenay-St. Lawrence Marine Park

This enables the detection of species-identifiable calls and, therefore, acoustic occurrence can be assessed in relation to variations in spatial, temporal, environmental, and acoustic variables (e.g. Baumgartner et al. 2014, 2020, Fregosi et al. 2020, 2022). Establishing baseline information such as this can contribute to a better understanding of species' distributions across any given region that, when considered in proximity to areas of heightened anthropogenic risk such as shipping lanes, is important for informing the implementation of future mitigation measures.

Since the start of the UME, ship strikes have resulted in 11 observed NARW mortalities in the USA and Canada, 2 documented incidents of serious injury (a designation indicating that a whale is likely to die from its injuries), and 2 documented incidents of sublethal morbidity (National Marine Fisheries Service 2023). Additionally, evidence suggests that observed mortality, which is already at unsustainable levels, accounts for only a third of actual NARW deaths (Pace et al. 2021). As such, this species has been the primary focus of Gulf-wide marine mammal monitoring efforts to inform shipping and fishing industry operations. Approximately 40% of the NARW population now uses the southern GoSL foraging ground every summer, migrating adjacent to or in the shipping lanes through the Cabot Strait and up the Laurentian Channel (Crowe et al. 2021). And although the main feeding aggregation tends to remain in the southern GoSL, individuals are known to range further north into the Honguedo Strait and Jacques Cartier Passage (Crowe et al. 2021) (Fig. 1). Therefore, acoustic monitoring is crucial for documenting daily occurrence, as well as spatial and seasonal shifts in distribution.

For NARWs, 'upcalls', which are approximately 1 s upsweeps from 50–200 Hz, are the call type normally used for detecting whales in acoustic records for several reasons; they are produced by both sexes and all age classes, their stereotypy lends itself well to automated detectors, and they are believed to function as contact calls, used during periods of rest and travel and commonly heard throughout the GoSL (Parks et al. 2011, Matthews & Parks 2021, Durette-Morin et al. 2022).

Like the NARW, the northwest Atlantic population of blue whales may benefit from similar conservation actions, as they are listed as endangered under the Canadian Species at Risk Act (SARA) and face similar threats (Fisheries and Oceans Canada 2020). However, quantifying the causes of blue whale mortality is difficult, as their carcasses tend to sink when they die, meaning that many instances of ship strike go undocumented (e.g. Redfern et al. 2013 assumed a generous 17% carcass-detection rate). To preempt potentially harmful interactions, dynamic management measures are being used in areas with a high degree of overlap between blue whale hotspots and heavy vessel traffic (e.g. to protect eastern North Pacific blue whales off the California coast; Hazen et al. 2017). Northwest Atlantic blue whales frequent the SSLMP, LSLE, and GoSL during the summer foraging season, with extended use of this area lasting into the fall, including evidence that some individuals are present year-round (Sears & Calambokidis 2002, Beauchamp et al. 2009, Simard et al. 2016). During this time, these whales actively feed along the coast of the Gaspé Peninsula and into the northwestern GoSL, before migrating through the Cabot Strait to winter calving grounds (Simard et al. 2016, Lesage et al. 2017) (Fig. 1). This means that the seasonal movements of these whales are commonly in proximity to or overlapping with the Laurentian Channel TSS that bisects the region. Therefore, acoustic monitoring would be particularly helpful in determining blue whale acoustic occurrence on a daily time scale in relation to the shipping lanes. While blue whale calling behavior in the western North Atlantic is better understood along the outer continental shelf of the USA and Canada (Davis et al. 2020, Delarue et al. 2022, Wingfield et al. 2022, Kowarski et al. 2023), comparatively few comprehensive acoustic analyses have been conducted in the GoSL, particularly in recent years (Mellinger & Clark 2003, Berchok et al. 2006, Simard et al. 2016).

Male blue whales produce population-specific songs comprised of 1 to 5 stereotyped, low frequency (15–18 Hz) tonal units (including 'A', 'B', and 'AB' calls), which are generally 8–20 s long, repeated every 1–2 min, and thought to function as a breeding display (McDonald et al. 2001, 2006, Mellinger & Clark 2003, Širović & Oleson 2022). Alternatively, non-song calls tend to dominate foraging grounds like the GoSL and include 'arch' calls (arcing from 65–70–30 Hz over approximately 5–12 s) and highly variable downswept 'D' calls (lasting 1–4 s and typically descending within a range of 120 to 25 Hz), as well as singular A and B calls (Mellinger & Clark 2003, Berchok et al. 2006, Boisseau et al. 2008). Non-song calls are produced by both sexes and have been associated with both social and foraging contexts, leading to hypotheses that these calls either function as a contact call between individuals or as a means of locating and/or advertising the presence of food (McDonald et al. 2001, Oleson et al. 2007a, Saddler et al. 2017, Lewis et al. 2018). Nevertheless, the variability in the spectral and temporal characteristics of D calls has historically made them difficult to detect reliably and efficiently using automated algorithms, resulting in relatively few studies that have explored their presence in long-term datasets (although with the advent of deep learning methods, this is beginning to change, e.g. Miller et al. 2023). Furthermore, most studies consider arch and D calls as one broad 'downsweeping' category, despite consistency across the relatively stereotyped arch calls compared to the widely varying D call (Wingfield et al. 2022). As such, there is a critical gap in our understanding of blue whale call occurrence, differential non-song call type use, and communication behavior on their GoSL foraging grounds.

In addition to these 2 endangered species, there are several other large whale species that frequent the same waterways (e.g. fin, humpback, minke, and possibly the occasional sei whale). Under SARA, North Atlantic fin whales are designated as special concern (COSEWIC 2019). Fin whales are the most commonly struck whale species globally, and collisions with vessels are known to have contributed to some of the 26 dead fin whales that were reported in the GoSL between 2004 and 2016 (Laist et al. 2001, Van der Hoop et al. 2013, Schleimer et al. 2019). While fin whales are known to range across the entire Atlantic Ocean basin, there are several lines of evidence suggesting that those with high site fidelity to GoSL foraging grounds may form a separate management stock of 'core regulars' with limited interchange with the rest of the North Atlantic (Delarue et al. 2009, Ramp et al. 2014, Schleimer et al. 2019). Recent data revealed a marked decline in apparent survival rates of GoSL fin whales from 1990–2015, punctuated by a significant decline in estimated stock size from 335 animals (2004–2010) to 291 (2010–2016), as well as a substantial decrease in the number of reported calves since 2008 (Ramp et al. 2014, Schleimer et al. 2019). While one explanation for this may be a shift to more favorable feeding areas if recent ecosystem changes have affected prey availability in the GoSL, another reason could be the incidence of ship strike.

While fin whales are not currently considered to be at imminent risk of irreparable decline, preventable morbidity and mortality may prove unsustainable in the long term for the core stock of fin whales in the GoSL. Therefore, their inclusion in acoustic monitoring efforts will provide continued awareness of seasonal occurrence in a region with heightened anthropogenic risk. Although fin whales do irregularly produce non-song calls similar to the downswept D calls of blue whales (Boisseau et al. 2008), the 20 Hz pulses of fin whale song (produced exclusively by males) are their most frequently recorded calls in the GoSL (Mouy et al. 2009). These 1 s calls are high amplitude frequency-modulated downsweeps from 25–17 Hz, often centered around 20 Hz (Boisseau et al. 2008, Mouy et al. 2009, Delarue et al. 2022). In the western North Atlantic, fin whales sing from approximately September through June, with song bouts that can last from hours to days (Delarue et al. 2009, Morano et al. 2012). Because of its temporal prevalence and stereotyped units, song is detected effectively by automated algorithms, making it a reliable tool with which to monitor fin whale acoustic occurrence (Mouy et al. 2009, Schall & Parcerisas 2022).

Ship strike risk in the GoSL has manifested with obvious consequence in recent years. As a result, the collection of foundational data detailing the acoustic occurrence of species common to the region (e.g. fin whales), particularly those that are reduced or in active decline (i.e. blue whales and NARWs), both in and around the GoSL TSS has become a priority across academic, government, and industry partnerships (Pettis et al. 2022, Transport Canada 2022). However, ship noise is effective at masking low frequency baleen whale calls, which might affect the ability to detect whales and derive spatiotemporal information about whale distribution from those acoustic detections. Spatial information is one of the advantages of using mobile whale detection platforms such as gliders, but sources of bias caused by spatial variation in environmental noise must be quantified. Therefore, this study aims to establish baseline information about the spatial, temporal, and acoustic distributions of NARW, blue whale, and fin whale calls detected by a glider in the Gulf of St. Lawrence, particularly considering proximity to the noisy Laurentian Channel shipping lanes. The goal is that these data will serve as a catalyst for investigating how well glider-recorded call detections of the lowest frequency vocalizers (i.e. blue and fin whales) provide insight into whale distribution and behavior in a region where dynamic management of ship traffic in response to whale presence is already being implemented for the NARW (Transport Canada 2022) and will likely be necessary for the future conservation of additional baleen whale species.

## 2. MATERIALS AND METHODS

### 2.1. Data collection

Data were collected in the Honguedo Strait, Gulf of St. Lawrence, Canada, from September 4 to October 30, 2019 (Fig. 1). A Slocum G3 electric glider (Teledyne Webb Research) was programmed to transit back and forth along a 67 km-long transect that spanned the Laurentian Channel and its associated TSS (Fig. 1). This repetition was designed to measure spatial and temporal variations in whale call detections across expected variability in background noise levels due to vessel traffic (i.e. inside versus outside the shipping lanes) as well as between sloped regions where krill aggregate along the edges of the Laurentian Channel and deep regions where large ships transit (Fig. 1).

The glider conducted V-shaped dives between approximately 25 and 210 m. The minimum profiling depth was intended to avoid the draught of large vessels that transit this region, while the maximum depth was constrained by the electric glider's 200 m buoyancy pump. During each dive, the glider recorded flight, temperature, salinity (converted from electric conductivity), depth (converted from pressure), and acoustic data. It was programmed to surface every 4 h when outside of the shipping lanes to obtain a GPS fix, transmit data, and receive commands from shore via an onboard Iridium satellite modem. When transiting beneath the shipping lanes, the glider switched to 9 h dive intervals and would only surface to obtain a GPS fix ('no-comms' mode), otherwise remaining underwater to minimize the risk of vessel collision.

Acoustic data were collected using an omnidirectional digital acoustic monitoring (DMON) instrument (Johnson & Hurst 2007), externally affixed to the glider (Baumgartner et al. 2013, 2020). The DMON's low-frequency hydrophone has a flat response between 10 and 7500 Hz, a sensitivity of −203 dB re 1 V $\mu$Pa$^{-1}$, and a total system gain of 33.2 dB. The DMON continuously recorded 16-bit audio at a sampling rate of 2 kHz with an effective recording bandwidth of 1 kHz, which was sufficient for capturing the low frequency repertoire of the 3 baleen whale species of interest (NARWs, blue whales, and fin whales). All acoustic recordings were archived and accessible for analysis post-deployment.

### 2.2. Acoustic data processing

The background ambient noise analysis consisted of 4 steps, conducted in MATLAB (The MathWorks Inc. 2022) and as described in Gehrmann et al. 2023: (1) calculating the power spectral density (PSD) for the acoustic time series in millidecade frequency intervals between 0 and 1000 Hz; (2) calculating the statistical mean of the PSD for 20 s long intervals; (3) associating the mean PSD with glider flight parameters such as depth, location, and glider vertical velocity; (4) extracting the mean PSD for frequencies relevant to the underwater communication of blue whales, fin whales, and NARWs. The mean PSD values are referred to as 'background noise levels' within this manuscript and include ambient noise levels, glider self-noise, and glider flow noise.

### 2.3. Acoustic data annotations

The DMON recorded continuously throughout the deployment. Every other hour of archived audio data was manually reviewed by 2 experienced analysts (K. L. Indeck and A. L. Richardson). Manual review was chosen because of the scarcity of detailed data on blue whale call production and communication behavior in the GoSL, precluding the use of regional automated detectors. Therefore, all low frequency baleen whale calls (including those from non-target species, i.e. humpback whales) were identified from the acoustic recordings aurally and by visual inspection of the audio spectrograms. These were produced in Raven Pro 1.6 (Cornell Lab of Ornithology) using a 1024-point fast Fourier transform (FFT), a Hann window, 2.81 Hz resolution, 90% overlap, and a playback rate of 5 times normal speed to make the lowest frequency calls (< 30 Hz) readily audible to the human ear.

Calls were then qualitatively classified based on their visual and aural similarities to previously described call types for each species including A calls, D calls, and arch calls for blue whales; 20 Hz pulses for fin whales; upcalls and 'other' tonal calls for NARWs (Fig. 2). However, calls of blue whales and NARWs occur across the same frequency ranges and often have structural characteristics common to those of fin and humpback whales, respectively. Therefore, calls that could not confidently be attributed to a single species using contextual information (e.g. ambiguous calls of similar amplitude to species-identifiable calls during periods of simultaneous acoustic presence) were marked as 'unidentified' and omitted from analyses.

Call detectability was affected by noise generated from interactions of the glider with the surface (e.g.

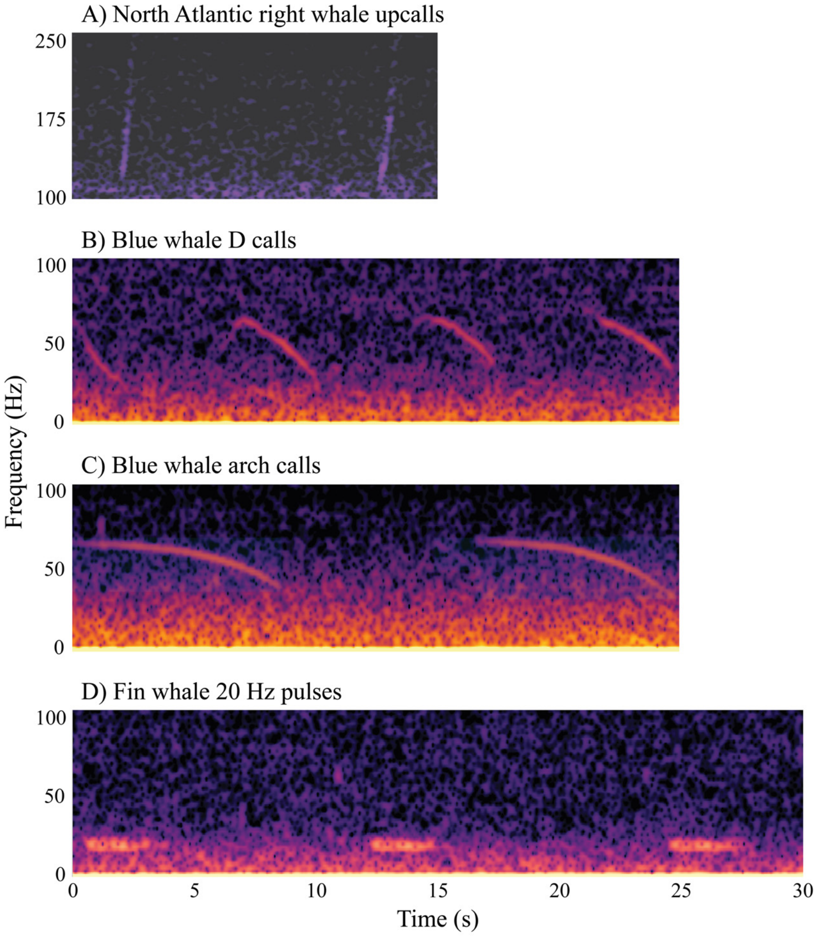

Fig. 2. Spectrograms of the 4 main baleen whale call types detected in the Honguedo Strait, including (A) North Atlantic right whale upcalls, (B) blue whale D calls, (C) blue whale arch calls, and (D) fin whale 20 Hz pulses. Note that the spectrogram in (A) has a different frequency scale than the others; all 4 spectrograms share a common time scale. This figure also illustrates flow noise as the main contributor to total noise levels below 50 Hz (the warmer colors, particularly below 30 Hz, represent higher amplitude noise)

waves, wind, and oscillations between the air and water) and broadband glider self-noise during inflections (which cumulatively corresponded to a monitoring loss of 17% across the deployment), flow noise (the magnitude of which was dependent upon the glider's vertical velocity), and vessel noise from the shipping lanes (Gehrmann et al. 2023). At shallow depths (i.e. within roughly the top 20 m of the water column), the recorded audio was affected most significantly by glider surfacings and self-noise, although these were only secondary contributors to overall noise levels throughout the deployment. Flow noise was the main contributor to total noise levels below 50 Hz and was particularly prevalent below 30 Hz (Fig. 2B—D).

Near-constant baseline flow noise, as well as brief increases due to variations in glider vertical velocity (see Gehrmann et al. 2023) and occasional thruster use to counteract the effects of currents, made distinguishing all but the highest amplitude fin whale 20 Hz pulses (and to a lesser extent, the occasional blue whale A call) difficult throughout the entirety of the deployment. Because of this, it is likely that a considerable number of individual calls were missed in the acoustic record. Additionally, as the deployment progressed through the fall season, fin whale singing intensified, frequently leading to overlapping calls from concurrently vocalizing animals. For these reasons, it was impossible to identify every single 20 Hz pulse. Instead, fin whale acoustic presence/absence was determined in 15 min periods, as this provided more opportunity to observe at least one call, given that this call type had a high probability of being masked by flow noise. Therefore, we assumed that 15 min was sufficient for acoustic detection, if whales were calling, even if flow noise was high. Additionally, it is important to note that the magnitude of flow noise was rarely observed to vary noticeably within any given 15 min period.

Blue whale D and arch calls typically occurred between 30 and 100 Hz and were less affected by flow noise. The main source of masking for these calls was acute high level ship noise caused by the transit of a nearby vessel and influenced by the glider's proximity to the shipping lanes. As such periods were brief and irregular, it is presumed that all blue whale D and arch calls outside of these intervals were successfully captured by the acoustic analysts, making it feasible to investigate quantitative differences in detection rates within and between call types. Alternatively, as A calls (~18 Hz) represented only a small fraction of blue whale call production (Table 1), and because their detectability was heavily constrained by flow noise, 15 min blue whale acoustic presence/absence was also determined and used for inter-species comparisons of acoustic occurrence with fin whales. In contrast, NARW upcalls normally occur between 100 and 300 Hz. As the noise levels of distant ships typically have a maximum between 50 and 200 Hz (Wenz 1962, Gehrmann et al. 2023), NARW detection was most affected by the irregular and infrequent acute broadband noise of closely passing vessels. Nevertheless, there was minimal right whale acoustic activity within detection range of the glider (Table 1), and therefore, upcalls were only assessed qualitatively.

### 2.4. Spatial and temporal distribution of detections

The glider recorded flight data approximately every 4 s. The glider's internal clock and that of the DMON were initially unsynchronized and drifted further apart (about 2.2 s $d^{-1}$) during the deployment (e.g. the initial offset was 1 min and 46 s during the first acoustic file). This was corrected for post-deployment (see Gehrmann et al. 2023), which allowed flight data to be accurately associated with each individual call or 15 min presence/absence bin using custom-written MATLAB scripts (The MathWorks Inc. 2022). Variables of interest derived from the flight and acoustic data included the glider's estimated latitude and longitude (horizontal spatial movement), depth (vertical spatial movement), and background noise levels (acoustic environment). Latitude and longitude were converted to rotated UTM easting and northing coordinates relative to a central point in the TSS, from which it was possible to calculate the distance along the transect in either direction (−35 km to the southwest of center, 35 km to the northeast of center; Fig. 1).

Table 1. Summary of the total call/presence counts for each target species. Acoustic presence was the number of 15 min time periods with at least 1 species-identifiable call. North Atlantic right whale (NARW) 'other' included all tonal calls that were not upcalls (e.g. moans)

| Species | Call type | Total count |
|---|---|---|
| Blue whale | A call | 438 |
| | D call | 10708 |
| | Arch | 2831 |
| | Acoustic presence | 1832 |
| NARW | Upcall | 216 |
| | Other | 15 |
| Fin whale | Acoustic presence | 1295 |

This variable was used as a proxy for the glider's geographic location. Latitude and longitude were also used to determine the glider's proximity to the shipping lanes, which resulted in a binary categorical variable (0 = outside the shipping lanes, 1 = inside the shipping lanes), as well as the light regime at any given date and local time (EDT). Light regimes (i.e. dawn, day, dusk, and night) at each time step were calculated in R version 4.1.2 (R Development Core Team 2021), using the function 'getSunlightTimes' from the package 'suncalc' (Thieurmel & Elmarhraoui 2022). Background noise levels were averaged across the octave or one-third octave band corresponding to the main frequencies of each species' calls (i.e. the one-third octave band centered at 20 Hz for fin whale presence/absence, the one-third octave band centered at 63 Hz for blue whale presence/absence, the octave band centered at 63 Hz for blue whale D and arch calls, and the octave band centered at 125 Hz for NARW upcalls).

To determine whether the observed distributions of blue whale D and arch call detections varied significantly across these spatial, temporal, and acoustic variables, call counts of each call type were binned into 5 km distance, 10 m depth, and 5 dB noise level bins; count data for light regime (categorical) and proximity to the shipping lanes (binary) were inherently binned. Each bin for each variable was then corrected for listening effort by dividing its call counts by the amount of time the glider spent in that bin during deployment. This resulted in binned detection rates (calls $h^{-1}$) that accounted for variation in monitoring effort across space and time. Detection rates within call types were then examined for significant deviations from a uniform distribution across a given variable by performing pairwise comparisons of observed versus expected call counts following a global chi-squared test for given probabilities using the 'rstatix' package in R (Kassambara 2022). Statistical significance was set to $p < 0.05$ for these and all following statistical tests and models.

To determine whether the observed distributions of blue and fin whale acoustic presence/absence varied significantly across variables, the same variable binning approach was used as described above. In this case, each 15 min presence/absence period was placed into discrete bins by calculating the average of each continuous variable (i.e. distance, depth, and noise level) and finding the mode of each categorical variable (i.e. light regime and proximity to the shipping lanes) over the 15 min period. Each bin for each variable was effort-adjusted by dividing its presence and absence counts by the total number of periods that fell into that bin. This resulted in acoustic presence/absence percentages that accounted for variation in monitoring effort. Counts of periods with acoustic presence were then examined for significant deviations from an effort-weighted probabilistic distribution across a given variable, by performing pairwise comparisons of observed versus expected numbers of 15 min periods following a global chi-squared test for given probabilities. Additionally, notched boxplots were produced to identify any significant differences in median noise levels between periods with and without acoustic presence, both inside and outside the Laurentian Channel shipping lanes, for each species.

An exploratory full-subsets analysis of a binomial (absence = 0, presence = 1 based on 15 min periods) generalized additive mixed model (GAMMs) was run for each species using the 'FSSgam' package in R (Fisher 2022) to explore the predictive power and overall importance of our spatial and temporal variables in determining where/when blue and/or fin whale acoustic detections were made during glider deployment. The models implemented a logit link, thus giving the log-odds (or the odds of success) of the response variable as a function of any given explanatory variable. The 'FSSgam' package was used to construct, fit, and compare a complete set of candidate GAMMs that considered all possible combinations of predictor variables (outlined below) by building upon the 'dredge' function in the 'MuMIn' package, which automates the model selection process (Barton 2022). This approach has been optimized for GAMMs, as it properly evaluates interactions between factor (i.e. categorical) and continuous predictors (smoothed using a cubic regression spline that interpolates between the observed data points and guarantees smoothness across those points) and automatically removes models containing correlated predictor variables from the candidate model set (Fisher et al. 2018). GAMMs rather than generalized linear mixed models (GLMMs) were deemed appropriate for our analyses, as few spatially varying ecological or acoustic processes are linear, and we had no hypothesis related to linearity nor any reason to assume linearity.

Candidate model sets for blue and fin whale call detections considered glider depth, distance along the transect, background noise levels, and light regime as predictor variables, as well as bathymetry (i.e. seafloor depth) and $\log_{10}$ of the bathymetric slope (calculated as the centered 3-point sliding standard deviation of bathymetric depth) (Table 2). The models also considered 2 interactions: distance by light regime

Table 2. List of spatial, temporal, and environmental variables used as predictors in the full-subsets analyses of blue and fin whale acoustic presence/absence. All continuous variables were averaged across each 15 min time bin; the modal result of light regime (i.e. the most common observation for every 15 min increment) was assigned to each time bin

| Variable | Type | Description |
|---|---|---|
| Distance | Continuous | Distance (km) along the glider's cross-strait transect from a mid-point of 0; a measure to represent its combined latitude/longitude |
| Depth | Continuous | Glider dive depth (m) |
| Bathymetry | Continuous | Seafloor depth (m) |
| $\text{Log}_{10}$Slope | Continuous | Logarithm of the bathymetric slope (i.e. the centered 3-point sliding standard deviation of seafloor depth) |
| Noise level | Continuous | Background ambient noise level (dB re 1 µPa$^2$ Hz$^{-1}$) |
| Light regime | Factor | Time of day: dawn, day, dusk, or night (local time, EDT) |
| $\text{DateHr}_4$, $\text{DateHr}_8$ | Factor | Date and time at the start of each 15 min presence/absence bin, grouped into 4 and 8 h bins beginning at midnight for blue and fin whales, respectively; used as a random effect to account for the temporal autocorrelation of acoustic detections |
| Interactions: Distance × Light regime; $\log_{10}$Slope × Light regime | | |

and $\log_{10}$ of the bathymetric slope by light regime. Additionally, they included date-time as a random effect to account for the temporal autocorrelation of acoustic detections; this was a factor variable that represented the date and time at the start of each 15 min presence/absence bin, with time grouped into 4 and 8 h bins beginning at midnight for blue and fin whales, respectively (e.g. 20190905_00, 20190905_04, 20190905_08, etc. for blue whales; 20190905_00, 20190905_08, 20190905_16 for fin whales).

After each candidate model set was generated, we evaluated the constituent models' corrected Akaike information criterion ($\text{AIC}_\text{C}$), which is an estimator of prediction error and, therefore, the relative quality of statistical models for a given set of data. $\text{AIC}_\text{C}$ was used rather than AIC, as both estimators are asymptotically equivalent at large sample sizes, but $\text{AIC}_\text{C}$ is more appropriate for small sample sizes. We then created a confidence set of models that contained only those models with a $\Delta\text{AIC}_\text{C}$ value of less than 2 (Burnham & Anderson 2002) (Table 3). While multiple models within a confidence set indicates selection uncertainty between the top models, it also identifies the variables most likely to influence trends in call detections for each species. Results from the top model with the lowest $\text{AIC}_\text{C}$ were plotted and discussed below. Model estimates (±SE) and *z* values for factor predictors and chi-squared statistics for smoothed predictors, as well as associated p-values, are presented in Tables S1 & S2 in the Supplement at www.int-res.com/articles/suppl/n054p191_supp.pdf). Finally, to determine that the chosen date-time variables were the most appropriate temporal scales to use as random effects, we ran an autocorrelation function on the residuals of each species' top model using the 'acf' function from the 'stats' package in R (R Development Core Team 2021). This confirmed that autocorrelation was accounted for in the model and negligible in the results (Fig. S1).

Table 3. Top model fits from full-subsets analyses of blue and fin whale acoustic presence/absence, showing all models within 2 corrected Akaike information criterion ($\text{AIC}_\text{C}$) of the best model. Shown are $\text{AIC}_\text{C}$, $\Delta\text{AIC}_\text{C}$, $\text{AIC}_\text{C}$ weights (ω), and the total model estimated degrees of freedom (edf)

| | $\text{AIC}_\text{C}$ | $\Delta$ $\text{AIC}_\text{C}$ | ω $\text{AIC}_\text{C}$ | edf |
|---|---|---|---|---|
| **Blue whale top model** | | | | |
| Depth + Noise level + Distance | 2488.84 | 0.00 | 0.50 | 266.65 |
| Depth + Noise level + Distance + Light regime | 2489.88 | 1.04 | 0.30 | 268.78 |
| **Fin whale top models** | | | | |
| Depth + Noise level + Distance by light regime + Light regime | 2435.18 | 0.00 | 0.52 | 171.32 |
| Depth + Noise level + $\log_{10}$slope + Distance by light regime + Light regime | 2436.88 | 1.70 | 0.22 | 168.86 |

## 3. RESULTS

### 3.1. Overview

The glider completed 14 (7 northbound and 7 southbound) transits of its 67 km cross-channel transect between Anticosti Island and the Gaspé Peninsula during its 56 d deployment. The total distance travelled was 1437 km, and the mean transit time across the entire transect was 4.0 d (range = 2.3–5.9 d). Course deviations from the programmed trackline were within normal expectations for the G3 glider model. Specifically, 50 and 75% of course deviations were less than 1.3 and 2.3 km from the programmed trackline, respectively, while the largest deviation was 12.78 km. Course deviations were higher near the Gaspé Peninsula (50th percentile = 1.9 km, 75th percentile = 3.1 km) than in the center of the Strait where the shipping lanes are located (50th percentile = 1.2 km, 75th percentile = 2.0 km), which was expected because currents are known to be stronger near the coast. There was no obvious consistent directionality to these deviations, suggesting that they were primarily driven by tidal currents.

The vertical velocity of the glider changes as the glider moves between denser water at depth and less dense water near the surface, while the glider's density stays the same. Here, during descent, the glider's vertical velocity decreased from ~15.4 to ~12.8 cm $s^{-1}$ between 60 and 180 m. This resulted in a decrease in mean relative PSD with increasing depth by up to 5 dB re 1 $\mu Pa^2$ $Hz^{-1}$ at 25 Hz. The opposite was true during ascent, as the glider's vertical velocity decreased from ~19.5 to ~ 16.5 cm $s^{-1}$ between 180 and 60 m, resulting in a decrease in mean relative PSD with decreasing depth by up to 5 dB re 1 $\mu Pa^2$ $Hz^{-1}$ at 25 Hz (Gehrmann et al. 2023). This was consistent throughout the mission and is expected behavior for other similarly designed deployments, although precise ballasting can help minimize vertical velocity discrepancies. It is the goal of any acoustic mission to keep glider vertical velocity as consistent as possible below a predefined threshold to maximize detection capability; here, maximum vertical velocity barely exceeded 0.2 m $s^{-1}$. Nevertheless, due to the depth-dependence of flow noise, we evaluated noise profiles for ascent and descent independently (see Gehrmann et al. 2023 for details).

The glider acoustic data were affected by broadband self-noise, e.g. from the buoyancy pump during inflection and surfacing, which inhibited the detection of whale calls for 17% of the deployment period. During other times, flow noise, ship noise, and wind-generated noise were the main contributors to background noise levels in frequency bands below ~50 Hz, between about 50 and 200 Hz, and above ~200 Hz, respectively (Gehrmann et al. 2023). Of the 1348 h of acoustic recordings, 665 were manually reviewed for calls from NARWs, blue whales, and fin whales, but due to missing pressure sensor data, only 662 of those hours were included in analyses. In total, 13 977 blue whale and 231 NARW calls were identified; fin whales were acoustically present in 49% (1295 of 2648) of 15 min periods, while blue whales were present in 69% of those periods (Table 1).

### 3.2. Spatial and temporal distribution of detections

#### 3.2.1. North Atlantic right whales

NARW upcalls were detected sporadically across time and space on 24 d throughout the deployment. However, the majority of upcalls (155 of the 231 total calls) were recorded within one brief period on September 10 and 11 between 20:00 and 00:30 local time (EDT) (Fig. 3A,B). These detections were made when the glider was at the northeastern end of its transect, near Anticosti Island (64 to 64.05°W). Even if we were to assume the greatest maximum detection distance reported in the literature for upcalls (~30 km; Laurinolli et al. 2003, Thode et al. 2017, Johnson et al. 2022), this suggests that, at the very least, one whale was within very close (i.e. <5 km) proximity to the Laurentian Channel shipping lanes; there is a strong likelihood that the calling animal was either within the boundaries of the shipping lanes or fully crossed them to ultimately end up on the northern side of the TSS in the Honguedo Strait (Fig. 3C).

It is also interesting to note that the background noise levels at which 100% of the upcalls were detected were below 70 dB re 1 $\mu Pa^2$ $Hz^{-1}$ in the 125 Hz octave band (i.e. the same range as typical upcall fundamental frequencies). By comparison, only ~25% of 15 min periods with blue whale acoustic presence had noise levels below the same threshold, while none of the periods with fin whale acoustic presence were characterized by such quiet conditions (Figs. 3C, 4C, & see Fig. 7C). This was because average noise levels across the deployment at 125 Hz were approximately 45 dB lower than those at 20 Hz and 15 dB lower than those at 63 Hz, indicating that NARW call detection was not affected by the low frequency flow noise that reduced the probability of detection for fin whale calls and were less influenced by diffuse low level vessel noise than blue whale calls, respectively (Fig. 5).

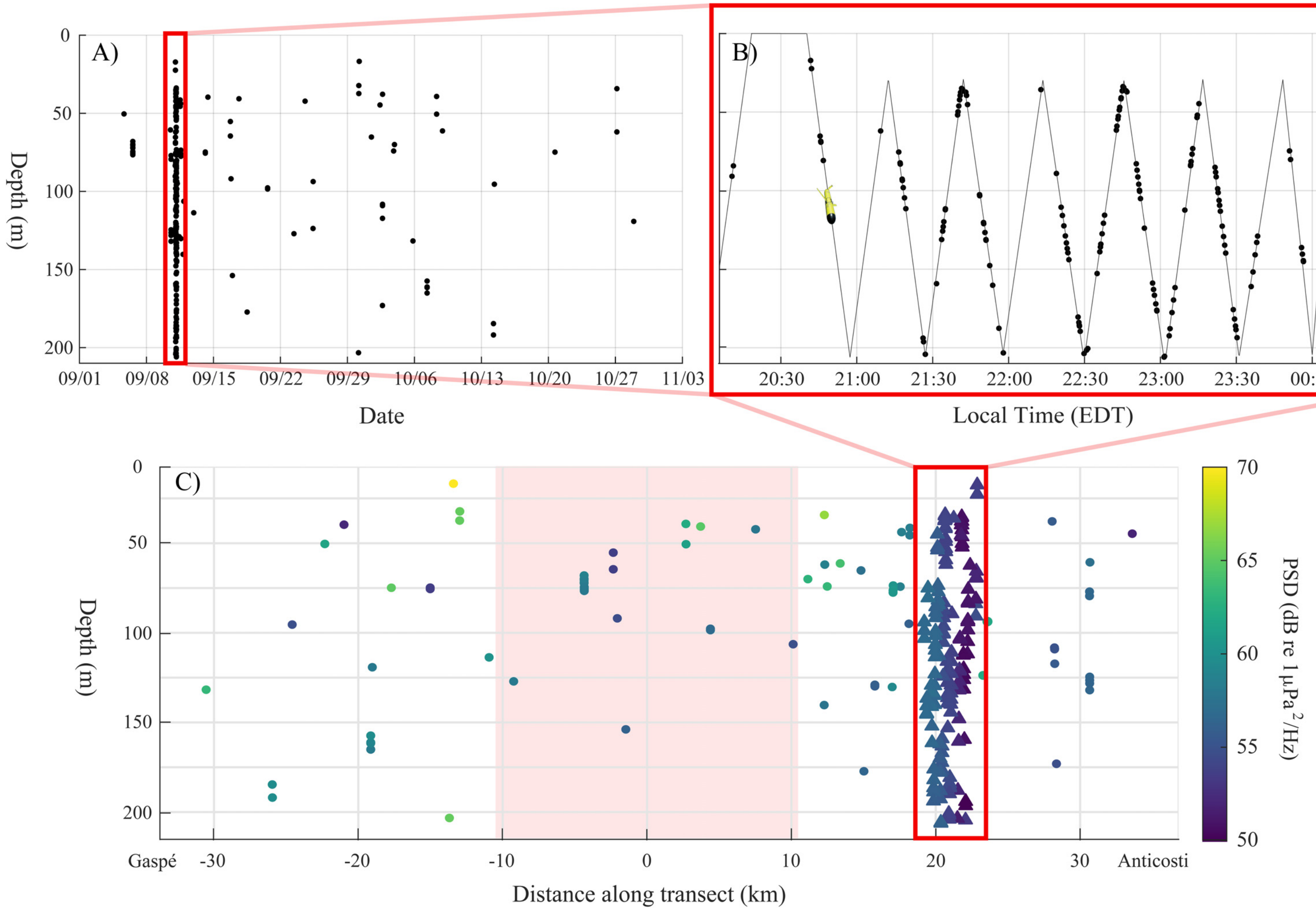

Fig. 3. Distribution of North Atlantic right whale upcall detections. The majority of upcalls were detected early in the deployment over a roughly 4 h period (20:00—00:30 EDT) on September 10 and 11, 2019 (A & B; triangle symbols in C), when the glider was northeast of the shipping lanes (pink shading, C). (B) Sawtooth dive pattern of the glider (thin black lines). (C) Power spectral density (PSD) of the ambient noise in the octave band centered at 125 Hz at the time of each upcall detection

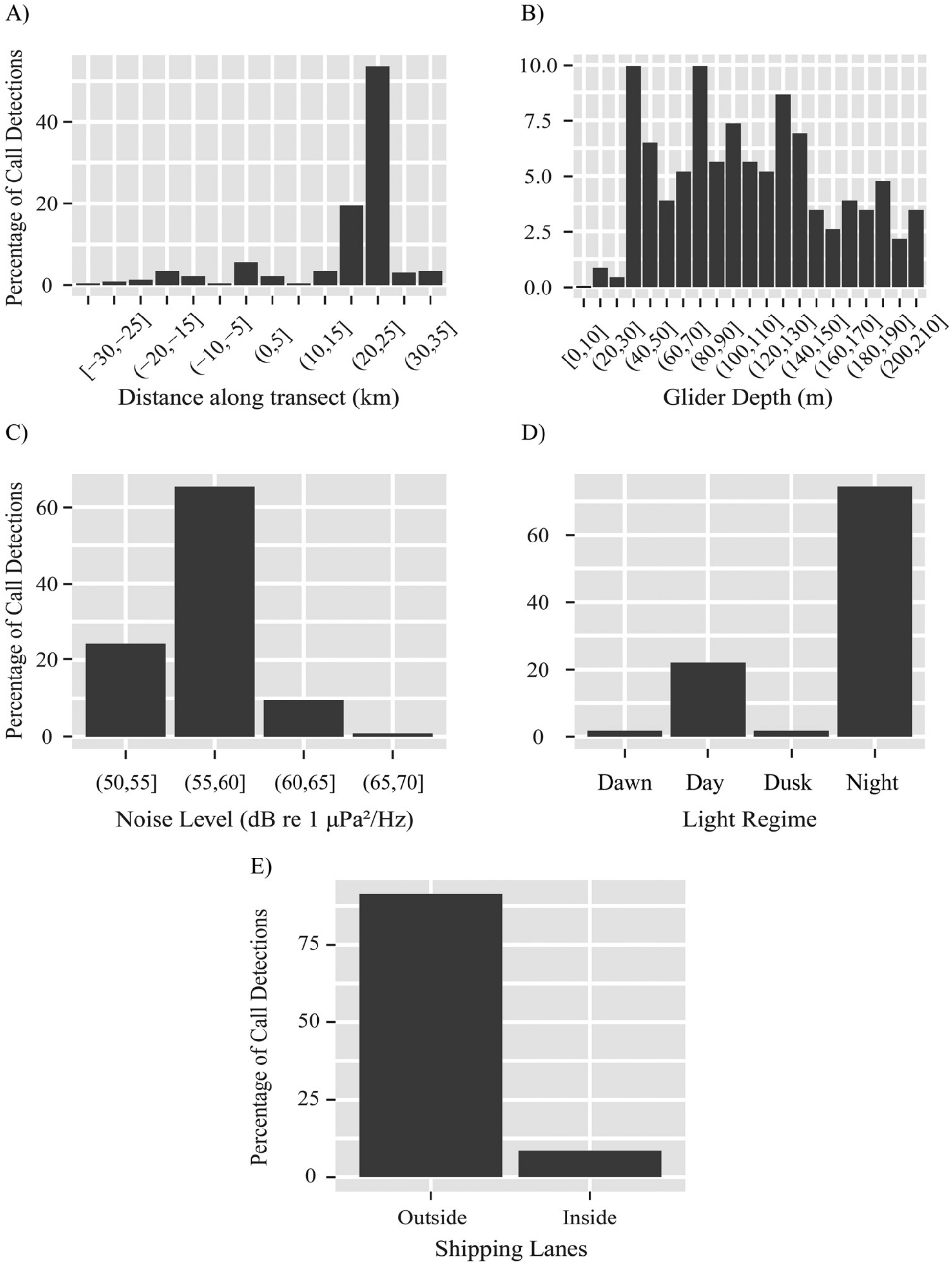

Fig. 4. Raw percentage of total North Atlantic right whale call detections across (A) geographic location, (B) glider depth, (C) background noise level, (D) light regime, and (E) proximity to the shipping lanes. Distributions are skewed by a single prolonged period of calling (i.e. 155 of 231 total calls detected during the deployment)

Specifically, average noise levels at 125 Hz across depths were consistently around 60 dB re 1 μPa$^2$ Hz$^{-1}$, and outlying noise levels above 70 dB re 1 μPa$^2$ Hz$^{-1}$ (with maximum noise levels around 95 dB re 1 μPa$^2$ Hz$^{-1}$; Fig. 5) occurred only 1% of the deployment period (only ~6.8 of 661.4 h). This suggests that acute noise level increases from nearby transiting vessels that may negatively affect NARW detection probability are rarely problematic despite the glider's proximity to the shipping lanes.

The remaining NARW calls were detected across nearly all glider depths, distances along the transect, and both inside and out of the shipping lanes (Figs. 3 & 4). Due to the constraints of an extremely small sample size (skewed by a single productive vocal bout), we did not calculate effort-adjusted call rates,

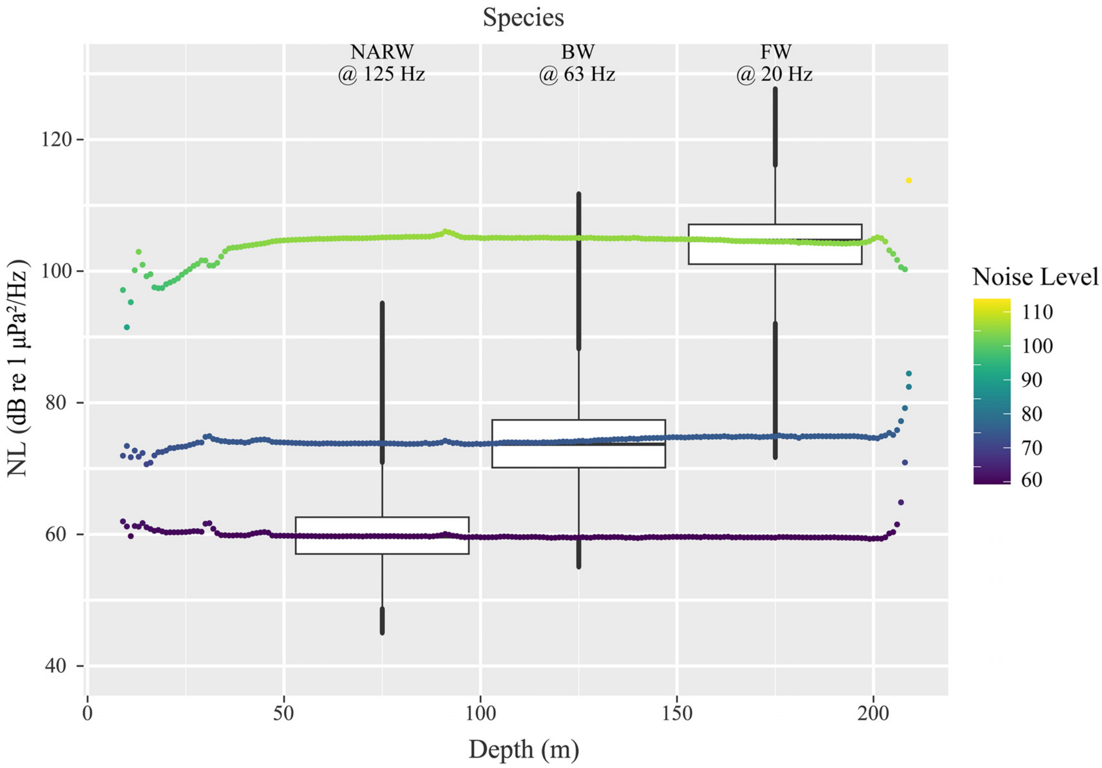

Fig. 5. Depth-stratified (dots corresponding to the bottom *x*-axis) and depth-integrated (boxplots corresponding to the top *x*-axis) background noise levels across the glider deployment in the frequency bands corresponding to the predominant frequency range of each species' calls. Depth-stratified results display noise levels (NL) within the 20 Hz one-third octave band around fin whale (FW) calls (green dots), the 63 Hz one-third octave band around blue whale (BW) calls (blue dots), and the 125 Hz octave band around North Atlantic right whale (NARW) calls (purple dots), averaged across every reviewed second of the deployment at each depth. Boxplots show the median, 1st quartile (i.e. 25th percentile), and 3rd quartile (i.e. 75th percentile), as well as whiskers (equivalent to 1.5 × IQR) and outliers (black dots adjacent to each upper and lower whisker), for overall NL integrated across depths

investigate statistical significance, or conduct GAMM modeling with the NARW call dataset. However, we do provide the raw percentages of call detections across variables in Fig. 4.

### 3.2.2. Blue whales

Blue whale calls were ubiquitous across the study area for the duration of the glider deployment (i.e. no single, call-heavy event influenced results), although D calls were detected nearly 4 times more than arch calls (Table 1, Fig. 6). A calls accounted for only a small fraction of blue whale call detections, occurring nearly 25 times less often than D calls and 6.5 times less often than arch calls (Table 1).

Acoustic detection rates and presence were significantly less than expected when the glider was in the top 20 (Fig. 6A) to 60 m (Fig. 7A) of the water column. These low detection rates occurred even after accounting for listening effort and considering background noise levels in the upper water column. Average noise levels (Fig. 5) were slightly reduced above 120 m compared to deeper depths (by about 2 dB), and near the surface (above 30 m), they dropped another ~3 dB, presumably due to the glider's reduced vertical velocity and consequently, flow noise, immediately preceding and following surfacings (Gehrmann et al. 2023). Therefore, the reduced acoustic detection rates above 60 m (Fig. 7A) were likely due to increased transmission loss, as calls propagate poorly in the upper water column due to surface reflection, which reduces their probability of detection at shallow depths. Interestingly, D call detection rates were greatest (i.e. around 25 calls $h^{-1}$) when the glider was between 70 and 100 m (Fig. 6A). These depths coincided with the minimum sound speed velocity at the center of the regional sound channel (Fig. S2; Gehrmann et al. 2023), and average noise levels corresponding to individual calls were slightly lower (1.6 dB re 1 $\mu Pa^2\ Hz^{-1}$) at these depths than in the upper water column. This indicates that enhanced propagation conditions, as well as slight differences in background noise levels,

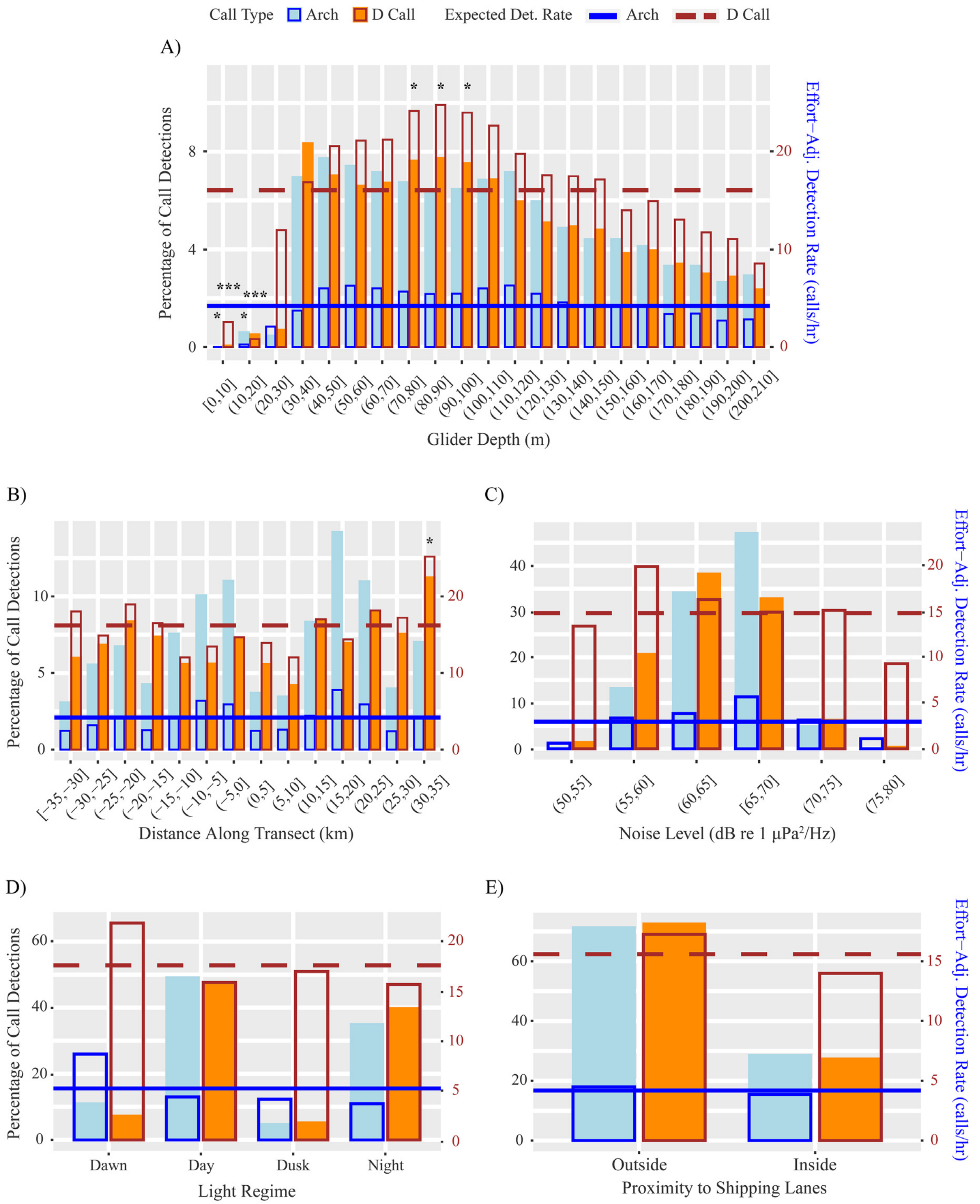

Fig. 6. Raw percentage of total call detections (light blue shading for blue whale arch calls, dark orange shading for blue whale D calls) and effort-adjusted detection rates (calls h$^{-1}$; dark blue boxes for arch calls, brown boxes for D calls) across (A) glider depth, (B) geographic location, (C) background noise level, (D) light regime, and (E) proximity to the shipping lanes. Expected detection rates are represented by the dark blue solid lines for arch calls and the brown dashed lines for D calls; observed detection rates that were significantly different from the expected uniform distribution are noted (*$p < 0.05$; **$p < 0.01$; ***$p < 0.001$)

may improve the detection probability of the shorter, highly variable, frequency-modulated D call at deeper depths.

The observed distributions of detections by call type, as well as overall blue whale acoustic presence, exhibited few significant deviations from expectation

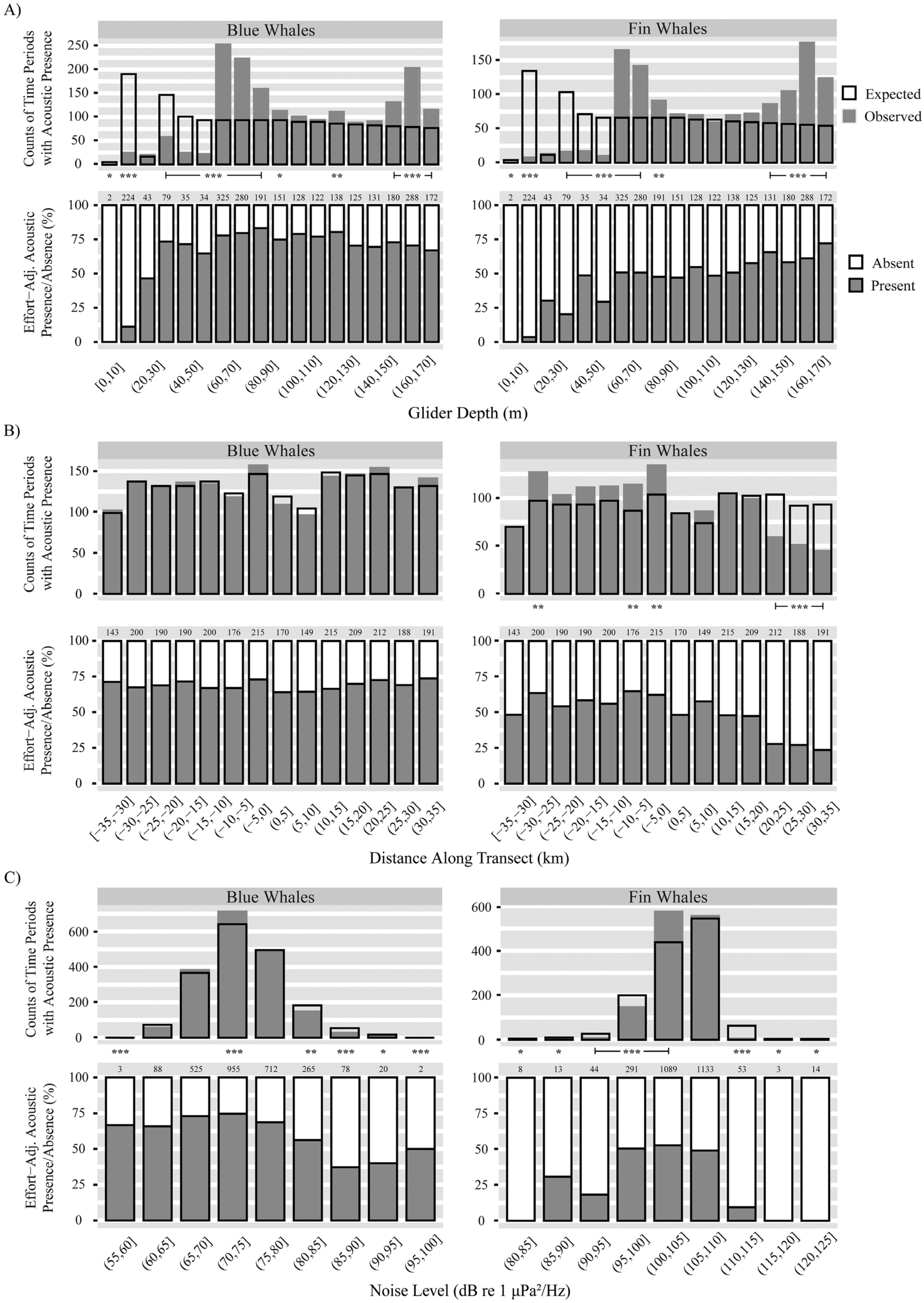

Fig. 7 continued on next page

Fig. 7. Observed counts of time periods with acoustic presence (gray shading) compared to effort-weighted expected counts (black outlines) (top panels), and the effort-adjusted acoustic presence/absence (bottom panels) of blue and fin whales across and within (A) glider depth, (B) geographic location, (C) background noise level, (D) light regime, and (E) proximity to the shipping lanes. The number of 15 min bins whose averaged/modal values occurred and were accounted for within each binned range is shown above the bars in the bottom panels. Observed counts that were significantly different from expected are noted (*$p < 0.05$; **$p < 0.01$; ***$p < 0.001$)

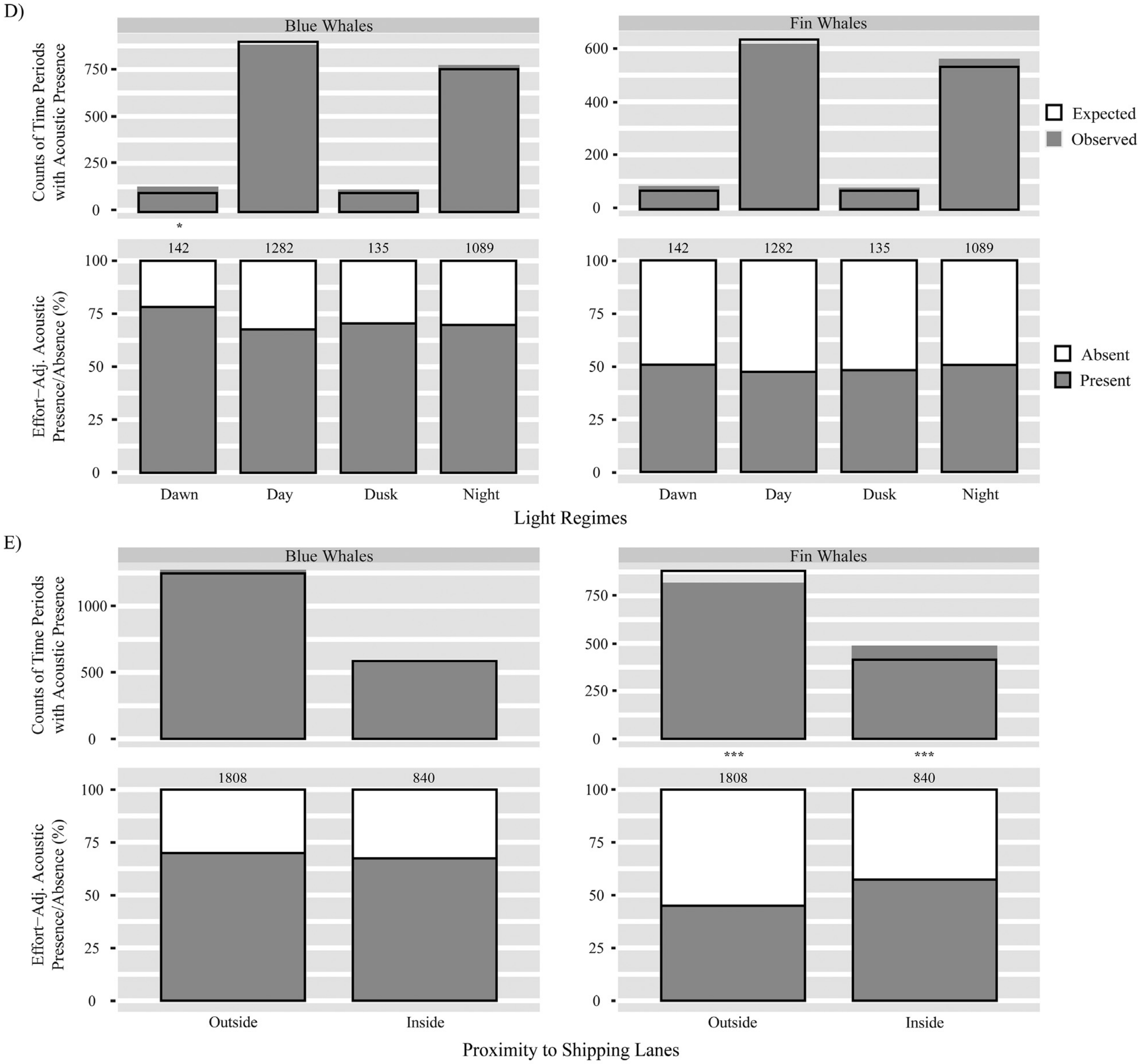

Fig. 7 (continued)

across glider transect (Figs. 6B & 7B), background noise levels (Figs. 6C), time of day (Figs. 6D & 7D), and proximity to the shipping lanes (Figs. 6E & 7E). Only the D call detection rate at the northeast extreme of the glider transect (i.e. 25 calls h$^{-1}$ between 30 and 35 km) differed significantly from an expected rate of ~16 calls h$^{-1}$ (Fig. 6B), while there were no significant departures from rates of 3–5 calls h$^{-1}$ for arch calls across these 4 variables (Fig. 6B–E). Additionally, acoustic presence varied most substantially at the highest background noise levels (i.e. decreasing significantly below expected above 80 dB re 1 µPa$^2$ Hz$^{-1}$) (Fig. 7C). Noise levels in the blue whale frequency band (i.e. 63 Hz) were most heavily influenced by vessel noise and, as such, exhibited a noticeable increase in the middle of the glider transect (i.e. inside the shipping lanes) (Fig. 8A). While median noise levels outside the shipping lanes were comparable between periods of acoustic presence (72.3 dB re 1 µPa$^2$ Hz$^{-1}$) and absence (73.0 dB re 1 µPa$^2$ Hz$^{-1}$), elevated background noise levels within the shipping lanes were higher during periods of acoustic absence (median = 77.7 dB re 1 µPa$^2$ Hz$^{-1}$) than during periods of acoustic presence (median = 75.3 dB re 1 µPa$^2$ Hz$^{-1}$) (Fig. 8B). This indicates that higher noise levels in the shipping lanes may contribute to a reduced probability of detection for blue whale audible calls along this portion of transect, although this effect is thought to

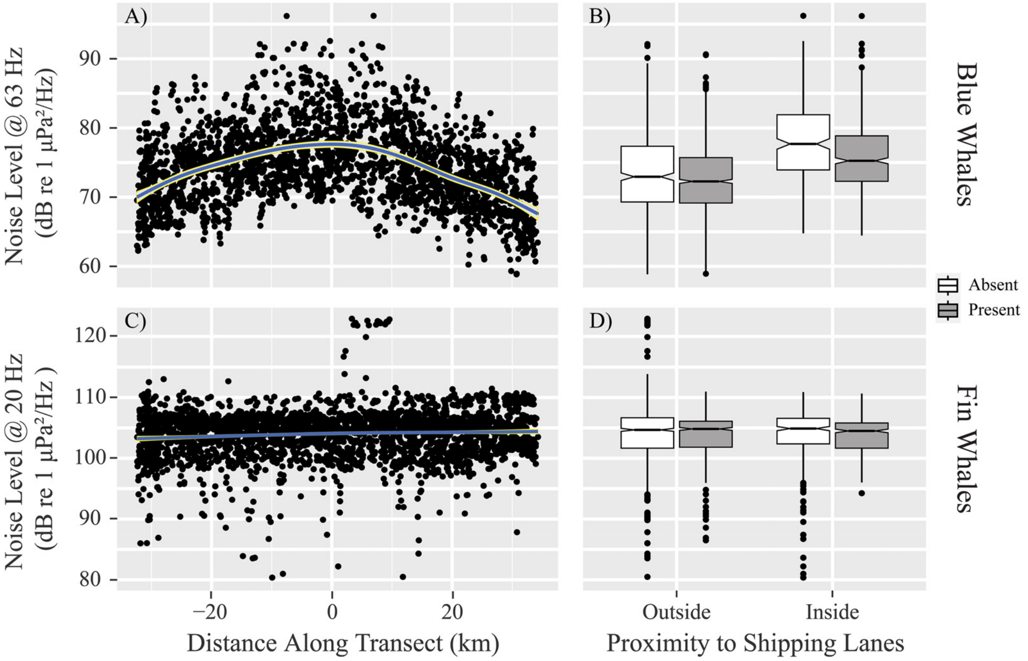

Fig. 8. Distributions of the average noise levels from each 15 min time bin (including smoothed trendlines) in the (A) 63 Hz and (C) 20 Hz one-third octave bands across the glider's transect. Boxplots in (B) and (D) display the median, 25th and 75th percentiles, 95% confidence intervals (the 'whiskers'), and outliers of each noise level band for periods with and without acoustic presence, both inside and outside the Laurentian Channel shipping lanes, for (B) blue and (D) fin whales. Notches extend 1.58 × IQR / sqrt(n), which gives a roughly 95% confidence interval for comparing medians; if the notches of 2 boxes do not overlap, this suggests that the medians are significantly different

be minimal given all other observations (e.g. acoustic presence still accounted for over 50% of periods with average noise levels up to 85 dB re 1 $\mu Pa^2 Hz^{-1}$; Fig. 7C, bottom panel).

The most parsimonious GAMM suggests that blue whale acoustic presence is related to the distance along the glider's transect (Fig. 9A), as well as background noise level (Fig. 9B) and glider depth (Fig. 9C) (n = 2648 15 min periods; Table 3, Table S1). For example, the model indicates detections are more likely in the middle 20 km of the glider transect, although this result is not statistically significant ($p = 0.15$) (Fig. 9A, Table S1). (Fig. 9A, Table S1). Intuitively, acoustic presence is predicted to negatively correlate with background noise levels ($p < 0.001$) — the likelihood of detection decreasing with increasing noise (Fig. 9B) — although this trend is not as well defined for noise levels <65 and >85 dB re 1 $\mu Pa^2 Hz^{-1}$ because of a lack of samples. Furthermore, detections of blue whale acoustic activity are predicted to peak between 50 and 100 m glider depth, before decreasing slowly ($p < 0.001$), suggesting that detectability may be enhanced when the glider is at depths corresponding to the regional sound channel, where transmission loss is at its minimum (Fig. 9C, Fig. S2).

### 3.2.3. Fin whales

Fin whale calls were detected in roughly 50% of 15 min periods during the deployment (Table 1, Fig. 7). Similar to blue whales, fin whale acoustic detections were significantly less frequent in the top 60 m of the water column (Fig. 7A), presumably due to a decreased probability of detection as transmission loss increased near the surface, which outweighed any potential positive effects from decreased glider vertical velocity and associated reductions in flow noise before and after surfacings (Fig. 5). However, compared to blue whale acoustic detections, which had a primary peak between 50 and 100 m, fin whale call detections increased with increasing depth beyond 100 m (Fig. 7A), which was likely due to favorable propagation conditions in the sound channel and middle water column between 100 and 200 m (in ~400 m water depth) for such low frequency calls. Acoustic presence was significantly less than expected when the glider was at the northeastern end of its transect (near Anticosti Island), with acoustic activity being detected in 25% or less of 15 min periods across the last three 5 km distance bins (i.e. 20–35 km) (Fig. 7B), and decreased significantly at the highest background

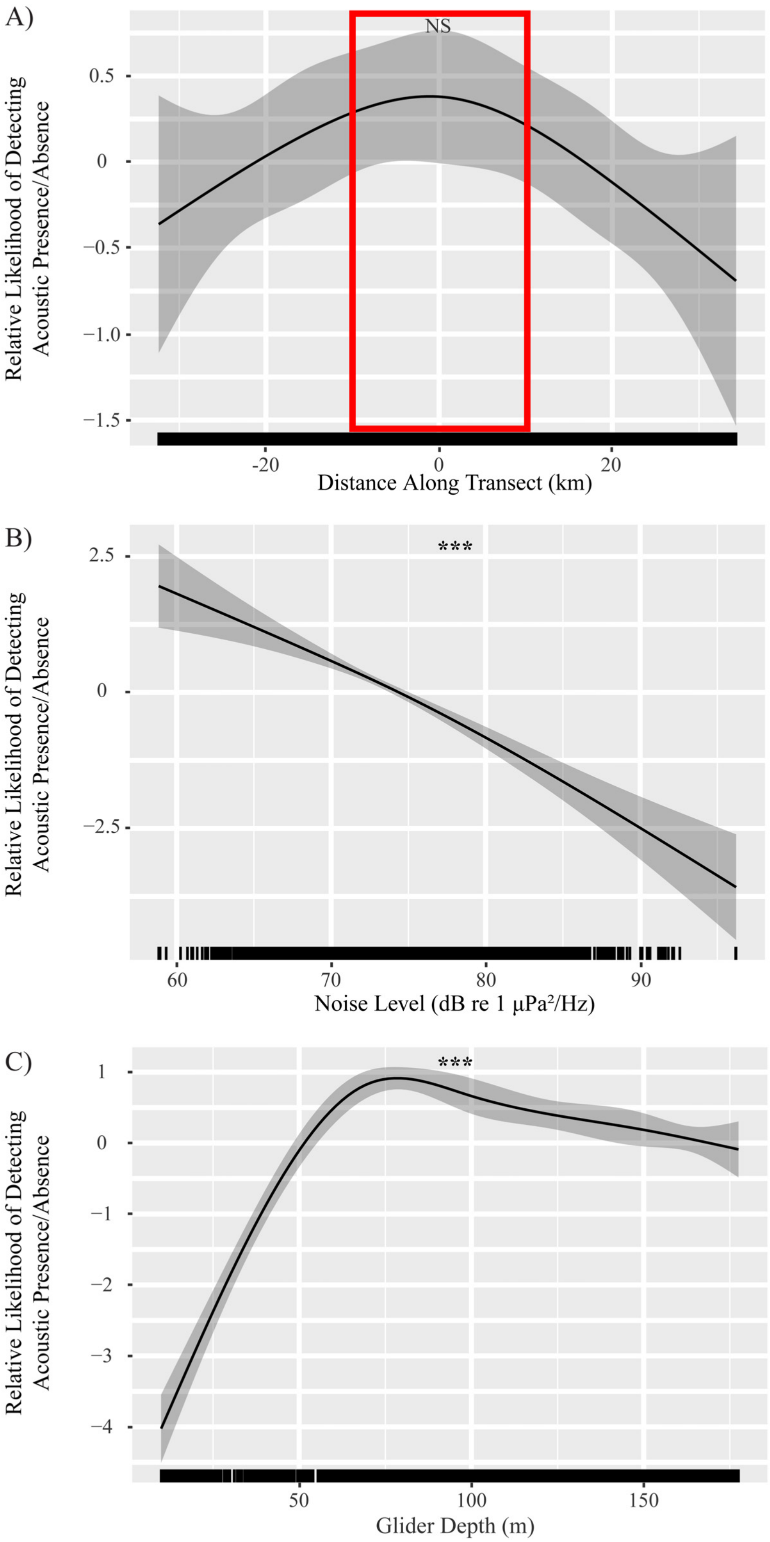

Fig. 9. Plots of the most parsimonious model, as ranked by corrected Akaike information criterion ($AIC_C$), for predicting the likelihood of blue whale acoustic presence (>0) or absence (<0) in relation to (A) the distance of the glider along its transect, (B) the background noise level, and (C) the glider's dive depth. Solid lines: fitted generalized additive mixed model (GAMM) curves; gray shading: SE 95% confidence bands. Rug at the bottom of each panel shows distribution of raw observations; red box in (A) indicates location of the shipping lanes. Blue whale calls most likely to be detected in the middle of the glider transect, at noise levels below 75 dB, and at glider depths below 50 but above 150 m. NS: not significant, *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$

noise levels (i.e. between 110 and 125 dB re 1 $\mu Pa^2 Hz^{-1}$) (Fig. 7C). However, as noise levels in the fin whale frequency band (i.e. 20 Hz) were predominantly affected by flow noise, they were consistent across the glider's transect. Therefore, fin whale acoustic detections were unaffected by noise level variations in the shipping lanes (Fig. 8C,D) and were in fact significantly higher than expected within the lanes than outside of them (Fig. 7E). Finally, the distribution of observed fin whale acoustic presence was as expected across time of day (Fig. 7D).

The most parsimonious GAMM suggests that fin whale acoustic presence is related to the distance along the glider's transect in relation to time of day (Fig. 10A), as well as background noise level (Fig. 10B) and glider depth (Fig. 10C) ($n = 2648$ 15 min periods; Table 3, Table S2). For example, acoustic presence is predicted to be more likely at the southwestern end (near the Gaspé Peninsula), particularly during dusk ($p < 0.01$) and nighttime ($p < 0.001$) hours, while it decreases significantly in the easternmost 25 km (Fig. 10A). The reason for this is presumably due to preferential use of the southern Honguedo Strait as a foraging area. As with blue whales, fin whale acoustic presence is predicted to negatively correlate with background noise levels ($p < 0.001$) — the likelihood of detection decreasing with increasing noise (Fig. 10B) — although this trend is not well defined for noise levels <90 and >115 dB re 1 $\mu Pa^2$ $Hz^{-1}$ because of a lack of samples. Furthermore, the likelihood of detecting fin whale acoustic activity peaks between 150 and 200 m glider depth, with a secondary peak between 50 and 100 m ($p < 0.001$), suggesting that their low frequency calls encounter optimal propagation conditions in the sound channel and middle water column (where the vertical distribution of transmission loss is at its minimum) (Fig. 10C, Fig. S2).

## 4. DISCUSSION

Low frequency NARW, blue whale, and fin whale vocalizations were detected during a glider deployment in the Honguedo Strait in the GoSL. The GoSL encompasses seasonally important foraging habitats for these species, with increased numbers of NARWs using the area annually and strong site fidelity exhibited by the region's populations of blue and fin whales. However, the migratory corridors and local movements of these whales often overlap with heavily trafficked commercial vessel routes, putting them at risk of morbidity and/or mortality due to inadvertent ship strikes. To minimize this potential outcome, near real-time PAM is becoming an effective supplement to visual observations made from research vessels and aerial surveillance platforms. Nevertheless, to better inform dynamic management decisions (e.g. mandatory slowdowns in shipping lanes) based on glider-detected acoustic activity, it is crucial to understand the target species' acoustic occurrence and what influences the recording platform's ability to detect their calls. As such, this study contributes detailed information about the temporal and spatial distribution of acoustic detections in relation to a portion of the Laurentian Channel TSS, for multiple species of conservation concern in the GoSL.

### 4.1. North Atlantic right whales

A relatively small number of upcalls were distributed across 43% of deployment days in the Honguedo Strait. Of these days, 10 had 3 or more calls, which has been used as the conservative minimum threshold required in a 24 h period to be confident that a NARW is definitively present (Davis et al. 2017). Therefore, despite low raw detection rates compared to those of blue and fin whales, NARWs were deemed to be in or near the Honguedo Strait on nearly 20% of survey days. This is particularly important when considering the likelihood of call detection by the glider in relation to its position along the transect.

Although detection distances are environmentally dependent and particularly influenced by water depth, maximum detection range estimates of NARW upcalls are fairly consistent across locations. Laurinolli et al. (2003) localized tonal NARW calls to a maximum distance of approximately 29 km in the Bay of Fundy, Canada, using sonobuoys over bottom depths ranging from 120–200 m. Likewise, Thode et al. (2017) estimated that North Pacific right whale upcalls were detected out to 30 km (with an average of 14.1 km) in the Bering Sea, Alaska, using moorings over bottom depths between 20 and 70 m. Additionally, off the coast of Massachusetts in depths of 30–50 m, Johnson (2022) found the maximum range of a localized call using a hydrophone array to be roughly 30 km but reported an observed detection distance (defined as the range at which the probability of detection was 0.10) of 23–28 km for a glider-mounted DMON hydrophone. Furthermore, Tennessen & Parks (2016) found upcall detection ranges were limited to 16 km or less at the quietest levels (85 dB re 1 $\mu Pa^2$ $Hz^{-1}$) of point-source noise modeled (i.e. a container ship 25 km away) but were only able to achieve this distance when accounting for vocal com-

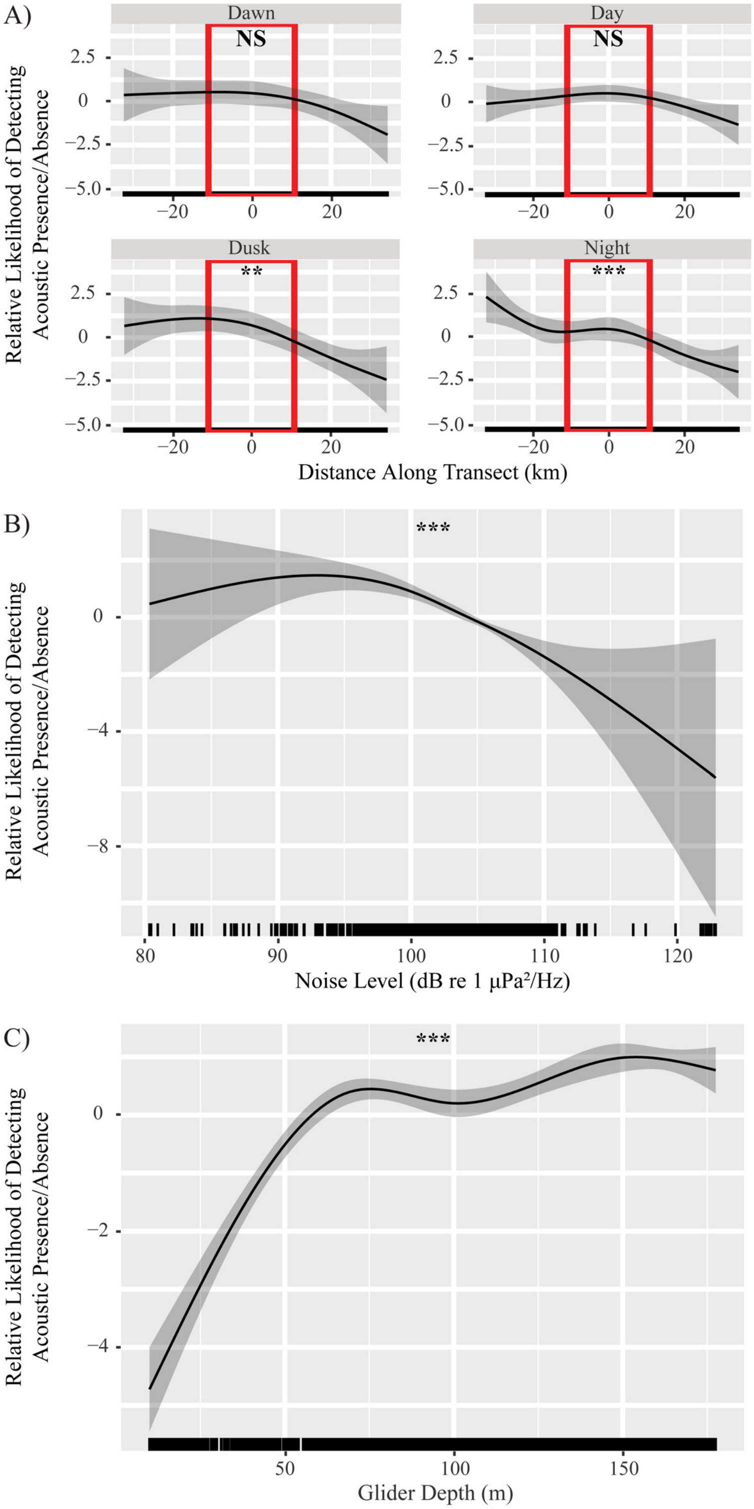

Fig. 10. Plots of the most parsimonious model, as ranked by corrected Akaike information criterion ($AIC_C$), for predicting the likelihood of fin whale acoustic presence (>0) or absence (<0) in relation to (A) the distance of the glider along its transect by light regime, (B) the background noise level, and (C) the glider's dive depth. Solid lines: fitted generalized additive mixed model (GAMM) curves; gray shading: SE 95% confidence bands. Rug at the bottom of each panel shows distribution of raw observations; red boxes in (A) indicate location of the shipping lanes. Fin whale calls most likely to be detected when the glider is at the southwestern edge of its transect, at noise levels below 105 dB, and at depths below 100 m. NS: not significant, $*p < 0.05$, $**p < 0.01$, $***p < 0.001$

pensation (in this case, a 20 dB increase in upcall source level). Here, despite being in a major shipping corridor, observed background noise levels (at 125 Hz) measured concurrently with upcall detections (<70 dB re 1 $\mu Pa^2 Hz^{-1}$) were well below the scenario in Tennessen & Parks (2016), suggesting that in the absence of an acute increase in background noise levels due to the close passing of a ship or glider self-noise, there were likely few constraints to detecting right whale calls other than their distance to the glider. Nevertheless, considering the many factors that influence detection distance estimates (e.g. environmental conditions, bathymetric features, regional depth, platform recording depth and location, calling whale depth and location, and the acoustic properties of a call), it is reasonable to assume that most upcalls recorded in this study were not detected at their maximum possible distance. Although a glider-mounted DMON in the Honguedo Strait, a deep-water environment with depths greater than 400 m, could ostensibly detect upcalls from greater distances than those reported for the comparatively shallow-water environments aforementioned, the probability of doing so is likely quite low. Therefore, even if we take a precautionary approach and assume that calls were detected at a maximal distance like that established in the literature (~30 km), our results highlight important implications for this species in relation to the area's shipping lanes.

The majority of upcall detections occurred during a roughly 4 h period when the glider was 20 km to the northeast of the transect midpoint (i.e. the middle of the shipping lanes). Therefore, if these calls were detected 30 km from the whale(s) producing them, this would still indicate a high probability that at least one NARW was either within the GoSL Laurentian Channel shipping lanes or had, at some point, traveled through them from the whale's shelf habitat south of the lanes (Fig. 1), to end up in the northern Honguedo Strait (Fig. 3). The same can be said of the handful of other detections that also occurred when the glider was northeast of the shipping lanes — it is likely that many of these calls were produced by individuals that had either crossed the lanes, were within the TSS boundaries, or near its southern edge. To validate these assumptions, future work will evaluate transmission loss in the Honguedo Strait and analyze the detection of these same calls on a stationary acoustic recording platform in the center of the shipping lanes.

By comparison, the majority of NARW definite visual detections from 2017 to 2019 were to the southwest of the TSS, in the southern GoSL; despite extensive survey effort, only 3 visual sightings of NARWs occurred in the southeast of the Laurentian Channel during this period, while there were no confirmed visual observations of NARWs in either the Honguedo Strait or northeast of the TSS boundary (Whale Insight 2022). However, there were 162 visual sighting events of NARWs off the northwest tip of Anticosti Island in the Jacques Cartier Passage during the same period, meaning that many of these whales likely crossed the shipping lanes to get there, but were not visually detected while in transit. Therefore, the acoustic detection of NARW calls near the TSS versus the breadth of visual detections well outside of it exemplifies the importance of acoustic recording platforms, as the presence of many NARWs detected in this study, the movements of which were likely in proximity to or directly overlapping the shipping lanes for prolonged periods of time, would have otherwise gone undetected in this high threat area. Indeed, recognizing this threat spurred Transport Canada to initiate a glider program aimed at detecting NARW presence in near real-time to subsequently implement dynamic 15 d slowdowns of vessels transiting different zones of the TSS (Transport Canada 2022). This mitigation method has proven successful thus far, with no documented right whale mortalities due to ship strike reported in Canadian waters since the 3 cases in 2019 (Bourque et al. 2020, Pettis et al. 2022). However, the feasibility of developing a similar management program for other endangered or vulnerable species (e.g. blue whales) still needs to be assessed.

### 4.2. Blue whales

Blue whales were the cetacean species detected most frequently throughout the deployment, with acoustic presence observed in nearly 70% of manually reviewed 15 min periods. D calls were the predominant call type detected throughout the study area, while arch calls represented the second most common call. Both non-song calls (which are typically categorized together) are produced on foraging grounds, primarily during shallow dives (<35 m) between lunge-feeding at greater depths (Oleson et al. 2007a,b, Lewis et al. 2018). Blue whales feed almost exclusively on diel-migrating euphausiids (i.e. krill), which tend to form dense aggregations at depth during daylight hours, before dispersing across shallow surface waters at night to feed on phytoplankton (Sourisseau et al. 2008). Because foraging efficiency is reduced when prey patches are less concentrated, blue whales usually forage during the daytime (Oleson et al. 2007a), especially along the slopes of the Laurentian Channel and within shelf habitats (<100 m) of the lower St. Lawrence Estuary and the GoSL (McQuinn et al. 2016, Lesage et al. 2017). Observed blue whale acoustic presence was higher than expected during dawn hours, likely reflecting the foraging context of audible call production at a time of day when euphausiids descend back to aggregations in deeper waters.

During non-song calling periods, whales have been found in loosely associated pairs or within close proximity (~1 km) of other conspecifics, with some evidence to suggest counter-calling between individuals (McDonald et al. 2001, Oleson et al. 2007a). Therefore, these calls are believed to facilitate social interactions (e.g. the splitting and joining of nearby individuals) and to mediate contact over short distances (McDonald et al. 2001, Oleson et al. 2007a, Lewis et al. 2018). And much like NARW upcalls, distance from the signaler to the receiver was the main limiting factor of D and arch call detectability. Here, mean background noise levels were at or below 80 dB re 1 $\mu Pa^2$ $Hz^{-1}$ for 86% of 15 min periods, despite the glider recording in and around busy shipping lanes (in the 63 Hz frequency band the average = 74 dB re 1 $\mu Pa^2$ $Hz^{-1}$, while the range = 55–112 dB re 1 $\mu Pa^2$ $Hz^{-1}$). These relatively quiet and consistent conditions corresponded to model results that predicted an increased likelihood of detecting blue whales at levels below 75 dB re 1 $\mu Pa^2$ $Hz^{-1}$; coupled with the fact that D and arch calls occur across frequencies that are minimally affected by flow noise, this means that these calls could be reliably detected during most of the survey, as long as the glider was within 'hearing' range of the calling whale(s). However, as these calls are shorter in duration, higher in frequency, and lower in source level than infrasonic A and B calls, they are thought to have a considerably reduced propagation range by comparison.

Few studies have discussed the possible detection range of D calls, although Torterotot et al. (2023) estimated that it was likely little more than 30 km for calls recorded on hydrophones in the SOFAR channel of the Indian Ocean, compared to the 100–200 km range potential of lower frequency, higher source level blue whale song (Sirović et al. 2007, Samaran et al. 2010, Delarue et al. 2022). Assuming similar propagation maxima in other regions, acute noise level increases (e.g. during nearby vessel transit) would further reduce an already restricted range of detection. This is demonstrated by the observed differences in background noise levels for periods of acoustic absence versus presence within the Laurentian Channel shipping lanes (Fig. 8), as well as the significant decrease in the predicted likelihood of detecting blue whale acoustic activity with increasing noise levels in this study, especially as levels rise above 75 dB re 1 $\mu Pa^2$ $Hz^{-1}$ (Fig. 9B). This means it is possible that blue whale D and arch calls have a comparable detection range limit to that of NARWs; although average NARW upcall source levels (150 dB; Parks & Tyack 2005) are estimated to be 15 dB lower than blue whale arch/D calls (~165 dB; Akamatsu et al. 2014), these blue whale calls are produced in a frequency band that is approximately 15 dB noisier than that of upcalls (i.e. average levels of ~75 dB compared to ~60 dB). Therefore, blue whale audible calls could have similar range limits to NARW calls and may be just as susceptible to vocal masking at increased noise levels. Ultimately, this could indicate that the whales whose calls were detected by the glider may have been in proximity to the shipping lanes.

We chose to analyze D calls and arch calls separately, as qualitative differences in their temporal and frequency characteristics suggest there is potential that they serve slightly different functions in the blue whale repertoire. While D calls were detected at much higher rates than arch calls overall, the arch call detection rate was relatively stable across depths below 30 m, while that of D calls was greatest when the glider was between 70 and 100 m deep. Noise levels corresponding to individual call detections were slightly higher between 30 and 50 m than those at 70 and 100 m, suggesting that the longer duration, less frequency-modulated arch call, which is often produced in minutes-long bouts, may be more detectable as background noise levels increase. If D calls are more susceptible to transmission loss and decreased probability of detection in noisier conditions, it makes sense that their detection rates were highest at depths that correspond to the local sound channel (~50–150 m). This channel would function as a waveguide, propagating these calls farther than they might otherwise travel at shallower depths, which are increasingly affected by transmission loss nearer to the surface.

Considering our results in the context of these calls' hypothesized function of maintaining contact over short distances, perhaps arch call production is directed towards specific individuals while D calls are intended for any conspecific within range. Not only do calling animals spend a significantly greater proportion of time near the surface than quietly feeding whales (Oleson et al. 2007a), but the average depth of a calling blue whale is between 20 and 30 m (Oleson et al. 2007a, Lewis et al. 2018). Therefore, as arch calls appear to have stable detection rates across depths, it is possible that they are targeted at other calling whales. Alternatively, D calls may be particularly effective at enabling actively foraging individuals to passively maintain contact with nearby conspecifics, as the depths at which we observed a peak in detection of these calls overlap with typical depths of vertical lunge feeding. Nevertheless, there is still very little that is known regarding these calls and whether contact, food advertisement, and/or cooperative hunting is their main purpose. As such future research should explore the quantitative differences of these call types and continue to expand our knowledge of their production as it relates to these whales' social environment and behavioral context.

What we do know is that the results presented here emphasize that the movements of blue whales in the Honguedo Strait have a very high likelihood of overlapping with regional vessel traffic. Non-song vocal activity indicates that where there is one calling animal there are likely to be other whales present and that at least some of those individuals are spending a significant amount of time near the surface. Together with what is suspected to be a modest detection range for both D and arch calls, this means that call detection, especially when the recording platform is in the shipping lanes, signals that there are whales in the vicinity at heightened risk of being struck. This is compounded by the fact that blue whales have been documented to double their proportion of time at the surface at night (spending 73 and 90% of time within 15 and 30 m of the surface, respectively), significantly increasing their vulnerability to ship strike (Calambokidis et al. 2019). Therefore, these whales are as susceptible to vessel-related morbidity and mortality in this region as NARWs and may be good candidates to consider as a targeted species in a similar management program that relies on passive acoustics for future mitigation decisions.

### 4.3. Fin whales

Like blue whales, fin whales were also prevalent across the deployment, as they were detected in approximately 50% of 15 min periods that were reviewed. Although fin whale 20 Hz pulses are the constituent notes of song, which is believed to be a male breeding display, they are detected year-round in the northwest Atlantic, including on foraging grounds that are temporally and geographically separate from presumed breeding grounds in low latitudes (Morano et al. 2012, Davis et al. 2020, Delarue et al. 2022). Like blue whales, fin whales are lunge feeders that ingest large volumes of prey-filled water and, therefore, forage predominantly during the day, when prey are concentrated at depth (Simon et al. 2010). However, unlike blue whale non-song (i.e. arch and D) calls, which are closely associated with foraging dives, baleen whale songs and feeding are believed to be temporally mutually exclusive behaviors because of the energetic expenditure required for both (Oleson et al. 2007a). Lunge feeding typically occurs significantly deeper than calling, with quiet animals exhibiting longer duration dives at greater maximum depths than their vocally active counterparts (Stimpert et al. 2015). Alternatively, Stimpert et al. (2015) documented the average depth of fin whale calling to be between 10 and 15 m, while calling animals had low overall body movement, which can indicate either stationary behavior or slow, directed travel. As suggested by Oleson et al. (2007a) for blue whales, the use of travel time between foraging areas for singing to attract potential mates while looking for food may also be a strategy for fin whales, to maximize their energetic expenditure across behavioral states.

In the GoSL, krill is a main component of the fin whale diet. McQuinn et al. (2015) found substantial krill biomass from the head of the Laurentian Channel in the LSLE, around the Gaspé coast, and along the Laurentian Channel's southern slope, extending to the southeast. These areas are particularly productive, because strong, tidally induced upwelling promotes krill to aggregate along the slopes of the Laurentian Channel. Therefore, they represent favorable foraging areas for fin whales in the region. This is likely why the detection of fin whale acoustic activity is predicted to be strongly linked to distance along the glider transect (Fig. 10A). The marked increase in the likelihood of detecting acoustic presence near the southwestern edge of the glider transect parallels the krill hotspots reported by McQuinn et al. (2015) and indicates that areas along the southern slope of the Laurentian Channel are preferentially frequented by the region's fin whales. Additionally, the higher probability of detecting calls during dusk and nighttime hours is likely reflective of the inverse relationship between fin whale singing and foraging. As discussed above, krill concentrate at depth during the day, suggesting this would be the most energetically efficient time to feed, while singing may take priority at night when prey is dispersed.

Fin whale 20 Hz pulses have been estimated to have detection distances ranging from 56 km off the western Antarctic Peninsula (Sirović et al. 2007), to no more than 85 km off western Greenland (Simon et al. 2010), and anywhere between 10 and 100 km in the Gulf of Alaska (Stafford et al. 2007). In the GoSL, detections of fin whale acoustic presence are predicted to peak at depths corresponding to the local sound channel, but also at the deepest depths of the glider dive path (in the middle of the water column). Detection distances in the middle of the sound channel/water column could ostensibly correspond to the largest possible range estimates for these calls (due to maximal propagation conditions). However, near-constant glider flow noise in the 20 Hz frequency band across depths considerably reduced fin whale probability of detection throughout the deployment and, presumably, the range at which these whales were recorded, by masking faint calls from distant animals. Although song bouts can last for several hours and are comprised of many 10s of calls in consecutive 15 min periods, enhancing the calling whale's detectability (i.e. even if the probability of detecting any individual call is small, the probability of missing all calls is even smaller), it is no surprise that the likelihood of the glider detecting acoustic presence decreases significantly with increasing noise levels (the average background noise level in the 20 Hz frequency band across the deployment was 104 dB re 1 $\mu$Pa$^2$ Hz$^{-1}$, with a range of 72–128 dB re 1 $\mu$Pa$^2$ Hz$^{-1}$; Fig. 5). This means that few calls were likely detected at their maximum distance from the calling animal; most were presumably detected at greatly reduced ranges. Therefore, it is likely that glider-recorded fin whale calls have relatively modest detection distances, akin to those of NARWs and blue whales (e.g. see Fig. 9 in Fregosi et al. 2020).

The results discussed here imply that fin whales migrating to foraging hotspots around the Gaspé Peninsula are just as susceptible to ship strike in the study area as the other 2 species considered, if/when they cross the TSS. Not only do other studies suggest that calling animals spend more time at shallow depths than do those that are actively foraging (Stimpert et al. 2015), but like blue whales, fin whales have been documented to significantly increase their proportion of time spent at the surface at night (spending 76 and 90% of time within 15 and 30 m of the surface, respectively) (Calambokidis et al. 2019). Therefore, these whales are at a heightened risk from the pervasive vessel traffic across the region. Although fin whales are not currently considered endangered, precautionary management actions to mitigate the effects of ship strike could prevent this from becoming a reality for the small core group of individuals that exhibit dedicated site fidelity in the GoSL.

### 4.4. Conclusions

This study demonstrates that underwater gliders are an effective PAM platform for detecting calls from NARWs, blue whales, and fin whales in the northwestern Gulf of St. Lawrence. Glider-recorded detections have the potential to elucidate whale distribution and behavior in near real-time across a seasonally important region, where whale presence co-occurs with a high volume of vessel traffic that poses a risk to multiple species of conservation concern. The observed effect of elevated background noise generated by vessel traffic in the shipping lanes was minimal, as it did not noticeably mask more calls than in quieter nearby regions, and it was not deemed an important explanatory variable for predicting either blue or fin whale acoustic presence/absence in our models. This means that glider platforms are a useful tool for conducting passive acoustic monitoring surveys within and near shipping lanes. Indeed, a glider-supported near real-time dynamic management program has already been implemented for NARWs in the Laurentian Channel region (since 2020) (Transport Canada 2022). Nevertheless, planned research that establishes detection distance estimates of low frequency calls from blue and fin whales will enable managers and policymakers to determine whether these species are viable candidates for similar mitigation efforts and inform future species-specific monitoring protocols. Gliders represent an integral component of modern PAM programs that may prove irreplaceable in Canada's efforts to minimize vessel-related morbidity and mortality of cetaceans throughout the Laurentian Channel in the Gulf of St. Lawrence.

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