Final Report for New York Bight Whale Monitoring Passive Acoustic Surveys: October 2017– October 2020

Contract C009925

Prepared for:
Division of Marine Resources
New York State Department of Environmental Conservation
625 Broadway
Albany, NY 12233

Prepared by:
K. Lisa Yang Center for Conservation Bioacoustics
Cornell Lab of Ornithology
Cornell University
159 Sapsucker Woods Road
Ithaca, NY 14850

TheCornellLab of Ornithology

Cornell University

Suggested Citation:

Estabrook, B. J., K. B. Hodge, D. P. Salisbury, A. Rahaman, D. Ponirakis, D. V. Harris, J. M. Zeh, S. E. Parks, A. N. Rice. 2021. Final Report for New York Bight Whale Monitoring Passive Acoustic Surveys October 2017- October 2020. Contract C009925. New York State Department of Environmental Conservation. East Setauket, NY.

Table of Contents

List of Figures

List of Tables

Acronyms and Abbreviations

AMAR	Autonomous Multichannel Acoustic Recorder, JASCO Applied Sciences
AURAL	Autonomous Underwater Recorder for Acoustic Listening, Multi-Électronique Inc.
BRP	Bioacoustics Research Program, Cornell University
CCB	K. Lisa Yang Center for Conservation Bioacoustics, Cornell University
CV	Coefficient of Variation
dB	Decibel (referenced to 1 μPa)
EEZ	Exclusive Economic Zone
FLAC	Free Lossless Audio Codec
FDR	False Discovery Rate
FNR	False Negative Rate
FPR	False Positive Rate
L_{eq}	Sound Level Equivalent
LF	Low Frequency (<100 Hz)
LTSA	Long Term Spectral Average
MARU	Marine Autonomous Recording Unit
NY Bight	New York Bight
NYS	New York State
NYSDEC	New York State Department of Environmental Conservation
NYSERDA	New York State Energy Research and Development Authority
PAM	Passive Acoustic Monitoring
RMS	Root-Mean-Square
SL	Source Level (dB re: 1 μPa @ 1m)
TB	Terabyte
TPR	True Positive Rate
TSS	Traffic Separation Scheme
UTC	Universal Time Coordinated
WNA	Western North Atlantic

Executive Summary

The K. Lisa Yang Center for Conservation Bioacoustics (CCB; formerly the Bioacoustics Research Program) at Cornell University's Lab of Ornithology was contracted by the NYSDEC, Division of Marine Resources to conduct a three-year passive acoustic monitoring survey within New York Bight (NY Bight) to assess marine mammal occurrence and patterns of ambient noise in this region. Six large whale species known to occur within NY Bight are the focus of this passive acoustic monitoring effort: North Atlantic right whales (*Eubalaena glacialis*), humpback whales (*Megaptera novaeangliae*), fin whales (*Balaenoptera physalus*), sei whales (*B. borealis*), blue whales (*B. musculus*), and sperm whales (*Physeter macrocephalus*). This report describes the results from Year-3 of this passive acoustic survey and provides a summary of results from the 3-year data collected.

The objectives for this project are to:

> 1) Describe the daily, monthly, and seasonal patterns of acoustic detections of the six species of large whales found in NY Bight.
>
> 2) Describe the spatial distribution of acoustic detections of six large whale species across NY Bight.
>
> 3) Describe spatial and temporal patterns of ambient noise across NY Bight.
>
> 4) Describe acoustic masking potential that the different whale species encounter as they move through NY Bight.

Fifteen archival recording devices were deployed along two transect lines spanning the NY Bight to record whale sounds and noise levels in the study area. These transects parallel the two major shipping lanes entering and leaving NY Harbor (Nantucket-Ambrose and Ambrose-Hudson Canyon Lanes). Of these 15 recording devices, 10 were Cornell University's Marine Autonomous Recording Units (MARUs); and 5 were JASCO's third generation Autonomous Multichannel Acoustic Recorders (AMARs), which were later replaced with Autonomous Underwater Recorder for Acoustic Listening units (AURAL M-2s, Multi-Électronique, Inc.). Each deployment of MARUs recorded continuously for approximately 3 months at a 5 kHz sampling frequency, while AMARs recorded continuously for approximately 6 months at an 8 kHz sampling frequency, and AURALs recorded for approximately 4 months at an 8 kHz sampling frequency. Sounds from focal whale species were identified using a combination of human visual analysis and species-specific automated detection algorithms with human review.

All of the focal baleen whale species were detected in the NY Bight throughout the 3-year passive acoustic survey. In all three years, North Atlantic right whales, fin whales, and humpback whales were detected during nearly every month of the recording period. Right whales showed peak presence during fall at sites that were closer to New York Harbor, and during spring months at sites farthest from the Harbor. Overall, right whales were detected less during the Year-3 survey than Year-1 and Year-2. Humpback whales had the highest presence during fall and summer months, and were detected at all recording site locations; there was little difference in the number of days of humpback whale detections between survey years. Fin whale presence was nearly continuous throughout Year-3, as was the case in Year-1 and Year-2. Fin whales had higher presence during winter and summer months, but persisted with at daily detections on at least 50% of the days recorded in spring and fall. Fin whales were detected at all sites, however, most detections occurred at sites furthest from New York Harbor, suggesting that some of the long-range 20-Hz pulses may have originated beyond NY Bight. Fin whales calls were, however, definitively recorded within the bight as well. Sei whales were primarily detected during the winter and spring months, and most often occurred at sites farther from New York Harbor during Year-3, similar to spatial trends that were observed during the Year-2 survey. Blue whales were rarely detected (<10% of the total recording days), and were only detected at sites farther from New York Harbor between December and February, with peak daily acoustic presence in February. Sperm whales were not detected in the Year-3 survey. This is likely due to the missing data for the 8 kHz AMAR sites. Data are missing for sites 8A, 9A, and 13A for 99% of the Year-3 survey dates, and site 11A only recorded for 87 days (October 2019 – January 2020, 24% of days) during Year-3.

Year-3 of the survey coincided with the COVID-19 global pandemic, raising the question of whether there were concomitant changes in noise levels in NY Bight due to changes in human activities. Year-3 median ambient noise levels in NY Bight were consistent with noise levels during Year-2, however, there was a significant decrease in the 95th percentile noise levels in 2020 compared to 2019. The decrease in the highest noise levels during 2020 is likely due to a decrease in shipping activity during the pandemic.

This 3- year passive acoustic survey demonstrated that all of the large whale species regularly occur in NY Bight at different times of the year, and many species are detected across the Bight. However, it remains unclear how these large whale species are using NY Bight as a habitat; whether it serves an important life history function (e.g., feeding, mating), or whether animals are largely transient and use NY Bight as a migratory corridor. Because of the extensive shipping activity in NY Bight, whales are exposed to high levels of ambient and anthropogenic noise as they occur in this area, and may be vulnerable to not only noise exposure but also ship strikes. While this passive acoustic survey documented the daily acoustic detections of whales, it is unclear exactly how many individuals within each species are found within the Bight at any given time. Given the advances in sophistication of passive acoustic monitoring, future surveys can go beyond just presence/absence of detections (as was the requirement here) and be designed to more detailed information, including location, density/abundance, different calling activities and behaviors. Knowing that whales are in the Bight, and there remain high degrees of shipping activity, increases in ocean temperatures, and likely a major increase in offshore wind development, future survey efforts can be designed to help support monitoring and mitigation efforts associated with the management and conservation of these species. Continued passive acoustic monitoring surveys should remain a priority to continue to improve our understanding of these charismatic species within this dynamic and important marine ecosystem.

.

Introduction

The K. Lisa Yang Center for Conservation Bioacoustics (CCB; formerly the Bioacoustics Research Program) at Cornell University's Lab of Ornithology was contracted by the New York State Department of Environmental Conservation (NYSDEC), Division of Marine Resources to conduct a three-year passive acoustic monitoring survey to understand the occurrence of large whale species in NY Bight. For this project, Cornell collaborated with Dr. Susan Parks and the Bioacoustics and Behavioral Ecology Laboratory at Syracuse University, and JASCO Applied Sciences, Inc. (JASCO). This report presents species' acoustic occurrence data for the Year-3 survey, collected from October 2019-October 2020, and summarizes results from the 3-year data collection period (October 2017 – October 2020).

Background

New York Bight is an ecologically important marine region within the U.S. Atlantic Coast, and has significant environmental and economic value to New York State (NYS) and the United States. Beginning in the 1960s and 1970s, there have been numerous ecological surveys and assessments to characterize the habitats and biota (NOAA 1974, 1976, Grosslein and Azarovitz 1981, Pearce et al. 1981, Mayer 1982, USACE 1994, Menza et al. 2012). However, despite this history of intense study, the vast majority of efforts have focused on fishes (e.g., Grosslein and Azarovitz 1981), benthic habitats (e.g., Pearce et al. 1981, Menza et al. 2012), and human impacts to the ecosystem (Mayer 1982); there had been no systematic surveys for marine mammals in NY Bight (NOAA 1974, 1976, Mayer 1982, USACE 1994). The Bight is approximately 17,000 mi^2, and includes a wide diversity of habitat and taxa. Through an extensive spatial planning process, in anticipation of future development activities and the need for continued characterization of the NY Bight natural resources, the NY Offshore Planning Area was designated as a recognized boundary for assessments and planning activities (Menza et al. 2012).

The size of this immense marine area imposes significant logistical challenges for conducting surveys and assessing the diversity and abundance of its natural resources. Consequently, while scientists and state and federal natural resource managers know that marine mammals regularly traverse NY Bight waters, and these species are identified in the New York State Comprehensive Wildlife Conservation Strategy (NYSDEC 2005) and Ocean Action Plan (NYSDEC and NYSDOS 2015), the temporal and spatial extent of when marine mammals inhabit NY waters, and how they are using this habitat are unclear. In light of NYS conservation efforts, increasing human use of NY Bight, and possible impacts of climate change on NYS marine natural resources, the current state of scientific knowledge on marine mammals is not sufficient for management needs.

To address the current needs for more detailed information on the spatial and temporal occurrence of whale species in NY Bight, the New York State DEC has funded two baseline monitoring programs – aerial surveys and passive acoustic monitoring – to systematically document the presence of large whales within NY Bight and the NY Offshore Planning Area. The concurrent aerial surveys in the region, funded by both the New York State Department of Environmental Conservation (NYSDEC) and New York State Energy Research and

Development Authority (Normandeau and APEM 2018, Tetra Tech and Smultea Sciences 2018, Tetra Tech and LGL 2019, 2020) have also demonstrated extensive occurrence of marine mammals and other protected species in the area. However, passive acoustic monitoring has been established as an increasingly used survey methodology for marine mammals, as it has a high probability of detection for vocally active species, overcomes some of the logistical constraints of visual surveys, and provides a data-rich time-series and spatial record of detections (Mellinger et al. 2007, Van Parijs et al. 2009). Passive acoustic monitoring can also provide a useful complement to visual surveys to address survey biases and provide a more complete understanding of animal occurrence and behavior (Kraus et al. 2016). A number of state and federal agencies, including New York State, have been employing passive acoustic surveys for cetacean assessments in the coastal and marine spatial planning process (e.g., Hodge et al. 2015, Kraus et al. 2016, Bailey et al. 2018, Muirhead et al. 2018, Salisbury et al. 2019).

The six large whale species that are the focus of this passive acoustic monitoring survey include: North Atlantic right whales (*Eubalaena glacialis*), humpback whales (*Megaptera novaeangliae*), fin whales (*Balaenoptera physalus*), sei whales (*B. borealis*), blue whales (*B. musculus*), and sperm whales (*Physeter macrocephalus*). These species are all protected under the U.S. Marine Mammal Protection Act, and five of these species (North Atlantic right, fin, sei, blue, and sperm whales) are listed under the U.S. Endangered Species Act. With the recent mortalities and risk of injury or mortality from ship strikes, North Atlantic right whales are a particular concern.

North Atlantic right whales occur along nearly the entire expanse of the U.S. Western North Atlantic (WNA) coastline (Kraus and Rolland 2007, Davis et al. 2017, Hayes et al. 2019). The Gulf of Maine, Bay of Fundy, Gulf of St. Lawrence, and other northern sites serve as feeding grounds in warmer months, and females migrate to southern waters in the fall and winter to give birth (Hayes et al. 2021). To protect animals in these regions, the feeding and calving grounds have been established and spatially expanded as federally protected right whale critical habitats (NOAA 2016). As right whales move between these areas, they have been acoustically detected for large portions of the year in the Gulf of Maine (Christian and Hendrick 2007, Morano et al. 2012a, Bort et al. 2015), the Mid-Atlantic Bight (Whitt et al. 2013, Hodge et al. 2015, Salisbury et al. 2016, Leiter et al. 2017, Muirhead et al. 2018), and South Atlantic Bight (Soldevilla et al. 2014, Hodge et al. 2015). However, right whale movement timing between these regions remains uncertain (Hayes et al. 2021). A meta-analysis of right whale occurrence revealed that right whale migratory phenology has changed in recent years (Davis et al. 2017), possibly as a function of changes in ocean temperatures or prey availability (Pendleton et al. 2012, Meyer-Gutbrod et al. 2015, Record et al. 2019). As right whales move across their range, they cross the NY Bight (Muirhead et al. 2018), though it is unclear how long they spend in this region or how they are using this habitat. Previously, it was thought that right whales primarily fed in the Gulf of Maine, though recent aerial surveys observed right whales feeding near Nantucket and Block Island Sound (Leiter et al. 2017) raising the possibility that NY Bight may serve as a foraging area for right whales.

Because right whale habitat overlaps with significant human activity along the U.S. Atlantic coast (Kraus and Rolland 2007), right whales face a combination of anthropogenic threats (Kraus

1990, Knowlton and Kraus 2001), including noise (Hatch et al. 2008, Parks et al. 2009, Parks et al. 2011, Rolland et al. 2012, Rice et al. 2014, Cholewiak et al. 2018), entanglement with fishing gear (Clapham and Pace 2001, Johnson et al. 2005), and vessel strikes (Ward-Geiger et al. 2005, Knowlton and Brown 2007, Campbell-Malone et al. 2008, Parks et al. 2012, Conn and Silber 2013). With a small population size of less than 500 individuals (Pace et al. 2017, Hayes et al. 2019), and recent increases in mortality (Davies and Brillant 2019), the long-term recovery or survivorship of this species is perilous (Kraus et al. 2005, Corkeron and Kraus 2018, Meyer-Gutbrod and Greene 2018). Consequently, addressing data gaps in right whale ecology to improve effectiveness of management efforts is paramount. NOAA's median best population estimate of right whales is 412 individuals (CV=0) (Hayes et al. 2021), and in their 2020 report card, the North Atlantic Right Whale Consortium estimates that 356 individuals remain in the population (Pettis et al. 2021). Both population estimates indicate that the species is currently experiencing a significant population decline after years of growth (Pace et al. 2017, Hayes et al. 2019). This decline in species number raises profound concerns about the future viability of the right whales (Taylor and Walker 2017, Meyer-Gutbrod and Greene 2018), particularly in light of ecosystem shifts due to climate change in the WNA that are concomitant with other possible impacts and stressors to right whales (Corkeron and Kraus 2018, Meyer-Gutbrod et al. 2021).

Humpback whales are widely distributed across the WNA Ocean, primarily using the Mid-Atlantic and Gulf of Maine as feeding grounds (Hayes et al. 2019). Humpbacks have been acoustically detected in these higher latitude regions throughout the year (Vu et al. 2012, Murray et al. 2014) and it is possible that the Mid-Atlantic may represent an additional winter feeding ground for humpback whales (Barco et al. 2002). A portion of the population migrates down to lower latitudes for mating and calving (Hayes et al. 2019), however, humpback song – produced by males likely in an advertisement context – has been widely recorded in the Mid-Atlantic and Gulf of Maine throughout much of the year (Clark and Clapham 2004, Vu et al. 2012, Murray et al. 2014). Humpbacks have been readily observed within NY Bight (Tetra Tech and Smultea Sciences 2018, Tetra Tech and LGL 2019, Zeh et al. 2020), with some individuals venturing well into the New York Lower Harbor Estuary (Brown et al. 2018). The latest NOAA population estimates for the Gulf of Maine Stock range is 1,396 individuals occurring between central Virginia and the Bay of Fundy (CV=0) (Hayes et al. 2021).

Fin whales are regularly detected along most of the U.S. Atlantic Coast, north of Cape Hatteras (Hayes et al. 2019), and are present nearly year round north of 35°N latitude (Edwards et al. 2015). Acoustic and aerial surveys in NY Bight observed fin whales throughout the year in NY Bight and the NY Offshore Planning Area (Morano et al. 2012b, Muirhead et al. 2018, Tetra Tech and Smultea Sciences 2018, Tetra Tech and LGL 2019). Fin whales have a repertoire of low-frequency calls with high source levels, and consequently have a large acoustic detection range up to hundreds of kilometers (Širović et al. 2007); thus, fin whale acoustic detections at individual acoustic sensors do not necessarily indicate that the calling individual was calling from within or near the acoustic survey area. Fin whales occur across both shelf and pelagic habitats, but they have also been observed extremely close to shore in the Mid-Atlantic (Ambler 2011). The current NOAA population estimate of fin whales in the North Atlantic Ocean is 6,802 (CV=0.24) (Hayes et al. 2021).

Compared to other large whale species in the WNA, sei whales have not received extensive study, and consequently, many aspects of their biology and ecology are unclear. The Nova Scotia sei whale stock inhabits the area around NY Bight, with the highest abundance occurring in the spring (Hayes et al. 2017). NY Bight represents the southernmost observations of sei whales in the WNA (Hayes et al. 2017), with the majority of sightings occurring in deeper waters along the shelf edge, though they have been periodically observed in shallower waters (Hayes et al. 2017). In the WNA, it has been suggested that sei whales migrate to and from more northerly waters, as there are increased observations in the summer and fall (Mitchell 1975). Only recently have Atlantic sei whales been acoustically monitored (Baumgartner et al. 2008, Tremblay et al. 2019), and a more complete understanding of their seasonal distribution in the U.S. Exclusive Economic Zone (EEZ) has not yet emerged. The best population estimate of sei whales for the Nova Scotia sei whale stock is 6,292 (CV=1.015), with a minimum population estimate of 3,098 (CV=0.52), though there are currently insufficient data to establish population trends (Hayes et al. 2021).

Blue whales have been infrequently documented within the U.S. Atlantic waters, and this region may represent the southern limit of the species' feeding range (Waring et al. 2010). Blue whales occur primarily offshore in deep waters, though Muirhead et al. (2018) acoustically tracked a blue whale in the NY Bight on the shelf edge. Previous surveys have observed blue whales within the U.S. Atlantic EEZ in August (CETAP 1982, Wenzel et al. 1988), and recent aerial surveys observed blue whales in January and February within the NY Offshore Planning Area (Tetra Tech and Smultea Sciences 2018). Due to their high source level and low frequency calls, blue whale songs propagate over very large distances, and are thus detectable at ranges of hundreds of kilometers (Payne and Webb 1971, Širović et al. 2007); consequently, acoustic detections of blue whales at single acoustic sensors do not necessarily indicate that the animals are in immediate proximity of the instruments. It is currently unclear how many blue whales are found within the WNA, though the minimum number is estimated to be 402 with an unknown CV (Hayes et al. 2021). While they are federally listed as an endangered species, their population trend is uncertain (Waring et al. 2010).

Sperm whales in NY Bight have been primarily documented along the continental shelf edge (NEFSC and SEFSC 2016, Tetra Tech and Smultea Sciences 2018, Tetra Tech and LGL 2019), consistent with their observed (Stanistreet et al. 2018) and modeled (Roberts et al. 2016) occurrence elsewhere across the WNA. Few sightings have been documented in depths less than 180 m (Scott and Sadove 1997). The geographical distribution of sperm whales in the Atlantic appears to be socially structured, with males primarily occurring at higher latitudes and juveniles and females at lower latitudes; females have rarely been observed north of New England (Waring et al. 2015). It is unclear how connected the U.S. Atlantic EEZ and other Atlantic habitat areas are for sperm whales (Waring et al. 2015). Sperm whale occurrence in the WNA appears to be south of New England in the fall, with the center of distribution in the Mid-Atlantic (between Virginia and northeast of Delaware) highest in the spring (Waring et al. 2015). In the New York Offshore Planning area, there has been a location with persistent sperm whale observations in shallower waters (depths ranging from 41-67 m), centered around the 50 m isobath, 27 km SSE off of Montauk (Scott and Sadove 1997). With the last population estimate from 2016, the best estimate of the number of sperm whales in the Western North Atlantic is

4,349 (CV=0.28) (Hayes et al. 2021), though it is unclear what proportion of this population occurs in the NY Bight.

The NY Bight represents an ecologically important area for these large whale species, though these taxa are also exposed to high anthropogenic noise levels in the region (Rice et al. 2014). Whales in the NY Bight have faced a rapidly changing ocean soundscape in recent decades, including increasing vessel traffic. In particular, vessel traffic has been increasing over time. The noise produced by ships overlaps in the frequency ranges that baleen whales utilize for communication (Richardson et al. 1995, Erbe et al. 2016), making acoustic "masking" a concern for heavily trafficked areas (Hatch et al. 2008, Clark et al. 2009, Hatch et al. 2012, Cholewiak et al. 2018), such as the Ambrose Traffic Separation Schemes. Acoustic masking occurs when the presence of one sound (or combination of sounds) impedes the detection and recognition of another signal. When ambient noise levels are high, the auditory detection threshold is raised and often the range over which a communication signal can be detected is decreased member of the same species (Erbe et al. 2016). It is important to understand the potential impacts of ambient noise in the NY Bight on acoustically communicating taxa, and how noise conditions may impact their acoustic ecologies (Clark et al. 2009, Hatch et al. 2012, Cholewiak et al. 2018).

To provide a more detailed understanding of the temporal and spatial dynamics of large whales in the NY Offshore Planning Area and possible influences of noise conditions, Cornell, Syracuse, JASCO and NYSDEC conducted a passive acoustic survey for marine mammals from October 2017 to October 2020. Specifically, the passive acoustic survey objectives for this project are to:

1) Describe the daily, monthly, and seasonal patterns of acoustic detections of the six species of large whales found in NY Bight.

2) Describe the spatial distribution of acoustic detections of six large whale species across NY Bight.

3) Describe spatial and temporal patterns of ambient noise across NY Bight.

4) Describe acoustic masking potential that the different whale species encounter as they move through NY Bight.

Methods

Data Collection: Instrumentation and Survey Design

Passive acoustic monitoring (PAM) methods were utilized to describe spatiotemporal acoustic occurrence patterns of six large whale species and to characterize ambient noise levels across two transect lines along the Nantucket-Ambrose and the Ambrose-Hudson Traffic Separation Schemes (TSS). PAM has several advantages over other survey methods, such as visual surveys, since passive acoustic recording provides stationary, continuous coverage across multiple locations, and is independent of inclement weather events (e.g., poor visibility or high sea states) which make visual detection of marine mammals challenging. The acoustic detection of these focal species, however, is dependent on their acoustic behavior, the source levels and frequency band of their acoustic signals, and the ambient noise conditions in the survey area. In high noise environments, acoustic masking can reduce detectability of target species' signals whose received levels are below the background ambient noise levels (Hatch et al. 2008, Clark et al. 2009, Hatch et al. 2012, Erbe 2015, Cholewiak et al. 2018). In addition, as a form of acoustic interference, acoustic masking drastically reduces a whales' ability to hear the sounds of conspecifics, and may have profound behavioral or social consequences (Clark et al. 2009).

Acoustic data were collected using three different archival digital acoustic recording devices: Cornell's Marine Autonomous Recording Units (MARUs), JASCO Applied Sciences' Autonomous Multichannel Acoustic Recorders (AMARs, http://www.jasco.com/amar) and the Autonomous Underwater Recorder for Acoustic Listening M-2s (AURALs) produced by Multi-Électronique, Inc. to replace the AMARs in the second half of Year-3. The different sensor types were used in the survey to balance the recording schedule, the sample rates for target species (i.e., baleen whale species versus sperm whales), coverage over time, and cost.

MARUs are contained in a positively buoyant 43 cm glass sphere that is deployed on the bottom of the ocean for periods of weeks to months (Calupca et al. 2000). A hydrophone (HTI-94-SSQ, High Tech, Inc.) mounted outside the sphere is the mechanism for acquiring sounds that are recorded and stored in a binary digital audio format on internal electronic storage media. The MARU can be programmed to record continuously or on a schedule, and deployed in a remote environment, where it is held in place by an anchor, suspended approximately 2 m above the seafloor. Upon retrieval, the MARU is sent an acoustic command to release itself from its anchor and float to the surface for recovery. After the recovery, the MARU data are extracted, converted into lossless audio files, and stored on a server for analysis. The unit is then refurbished (batteries and hard drive replaced, etc.) in preparation for a subsequent deployment. Data recorded by a MARU are thus accessible only after the device is retrieved, cleaned of biofouling (e.g., microorganisms, animals, algae) and saltwater, and unsealed and depressurized in the CCB fabrication facility in Ithaca, NY. For the NY Bight acoustic survey, the MARUs recorded continuously at a 5 kHz sample rate, with a high-pass filter set at 10 Hz to reduce electrical interference produced by the MARU, and a low-pass filter set at 2500 Hz to reduce aliasing. Aliasing is the distortion of sound signals that occur in frequencies above the Nyquist frequency (half the sampling rate) which appear as artifacts in the sound file. Audio data were recorded at a bit depth (number of recorded bits per sample) of 12 bits. The effective recording bandwidth of 10 Hz to 2500 Hz had a sensitivity of -168 dB ± 3.0 dB re 1 µPa (re: 1V/µPa) with a flat frequency response between 15-585 Hz. Sound files were down-sampled (or decimated) to a 400 Hz sample-rate for the fin whale, sei whale, and blue whale analyses, increasing computational efficiency for the analysis of these lower-frequency calling species. Each MARU was equipped with a Xeos satellite tag for tracking units at the surface.

AMARs function similarly to MARUs, but have increased capacity for battery storage, which allows for collecting data over longer periods of time or at higher sampling rates. AMARs are contained in a PVC, anodized aluminum and stainless-steel tube measuring 16.5 cm in diameter and 57.2 cm in length. AMARs are attached to floatable moorings and are anchored on the seafloor. The AMARs were equipped with acoustic release mechanisms, which release the unit from its anchor upon receiving an acoustic release signal, after which the unit floats to the surface. An external mounted hydrophone sits approximately 1 m above the seafloor and records wav sound files to storage media. AMARs recorded continuously at 8 kHz with a bit depth of 24 bits. The AMAR hydrophones were calibrated with a sensitivity of -164 dB re 1V/µPa at 1 kHz. The combination of hydrophone calibration and high bit-depth allows for collection of high-resolution ambient noise data. While the MARUs and AMARs recorded at different sample rates, they both covered the low frequency range needed for baleen whales and ambient noise analysis, and the AMARs recordings covered the lower frequency range of sperm whale clicks.

AURAL-M2s replaced AMARs in August 2020 due to the repeated loss of AMAR units, and served as a lower-cost alternative. AURALs have a similar high-frequency sampling capability to the AMARs, but a shorter deployment duration. The AURAL electronics are housed in a stainless steel body and utilize a HTI-96-MIN hydrophone with a sensitivity of -165 dB re 1V/µPa. The AURAL units were programmed to record continuously at an 8 kHz sample rate with a bit-depth of 16 bits. AURALs were equipped with acoustic releases for recovery, similar to the AMAR units.

Fifteen sites were configured in two transects along the Nantucket-Ambrose and Ambrose-Hudson Traffic Separation Schemes (Figure *1*).**Error! Reference source not found.** During the 3 year survey (October 2017 – October 2020), recording devices were deployed for 16,680 site-days, with sound data collected on 10,795 of those days. Year-1 data were collected from 16 October 2017 through 15 October 2018 (Table 1, Table 2, Table 5, Figure 2), totaling 3,654 days of sound data across all sites (referred to here as *site-days*). Year-2 data were collected from 16 October 2018 through 15 October 2019 (Table 1, Table 3, Table 6, Figure 2), totaling 3,747 site-days of sound data. Year-3 survey, data were collected between 16 October 2019 through 15 October 2020 (Table 1, Table 4, Table *5*, Figure 2), totaling 2,952 site-days (~8 years) of sound data. Data gaps in the recordings are described in detail below. The time from which a recording device is deployed in the water to when it is retrieved is referred to as the deployment period. During the 3-year survey, MARUs were deployed in nine deployment periods (hereafter denoted as “M-D#”) and AMARs and AURALs were deployed in five deployment periods (hereafter denoted as “A-D#”).

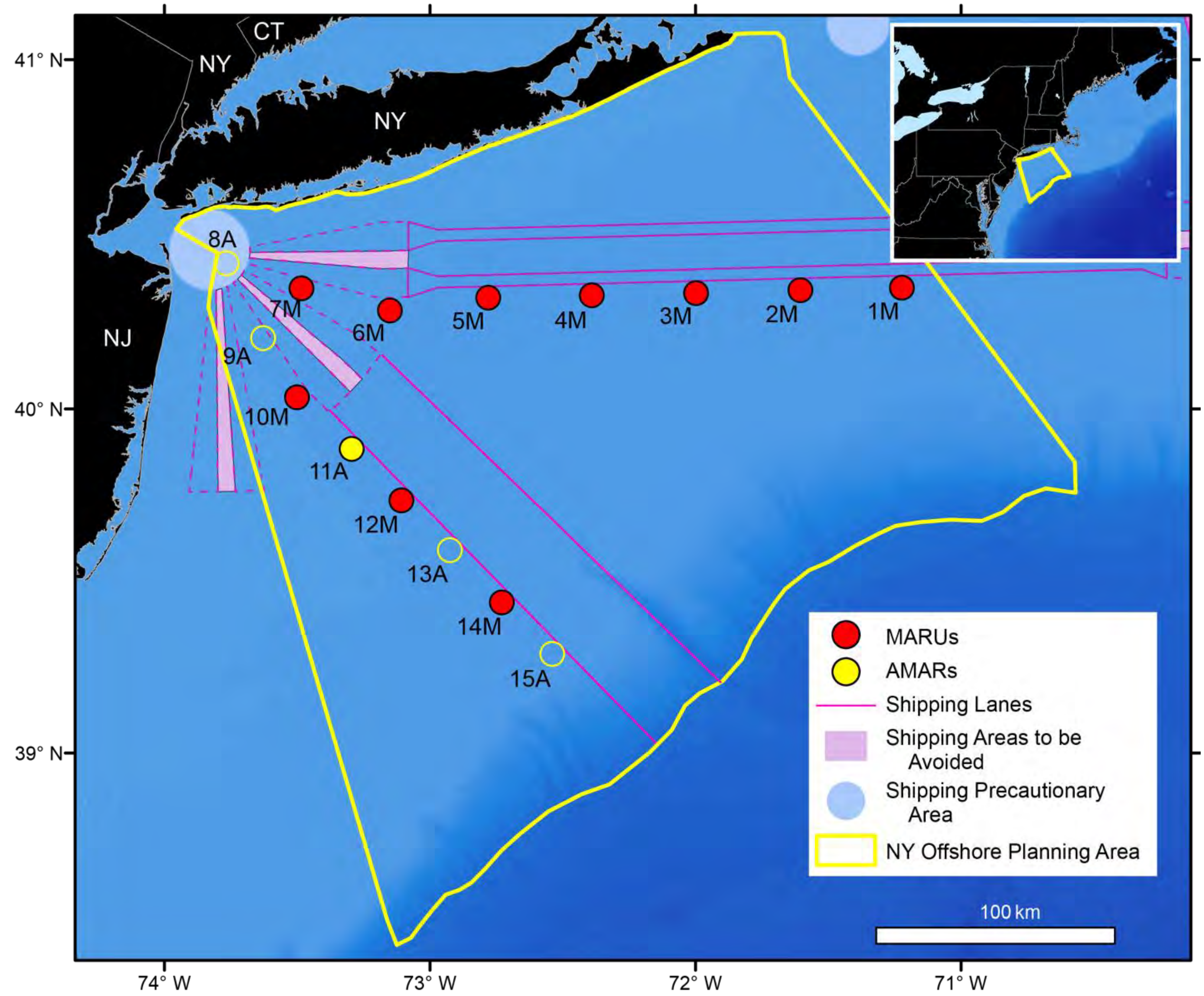


Figure 1. Map of the acoustic recording locations within New York Bight for all survey years, with sensor location numbers. “M” denotes MARUs (red), and “A” denotes AMARs/AURALs (yellow). The hollow circle indicates that data were not recovered during the entire Year-3 survey at that site. Inset shows the NY Bight at a larger spatial scale for geographical context.

Data loss occurred during the 3-year acoustic survey, and is attributed to four primary causes: 1) units dragged by bottom trawling fishing vessels (hereafter referred to as trawling or trawled) and prematurely surfacing, 2) damage to units when trawled, 3) units failing to surface, and 4) system malfunction of the MARUs. A unit that failed to surface may have experienced system malfunction, relocation of the unit by trawling, or was weighed down by significant biofouling. In most cases, it was impossible to determine why the unit did not surface because the unit was inaccessible to inspect. In some cases, units surfaced days after the attempted recovery. Occasionally, surface-delayed units were recovered and returned to the fabrication facility in Ithaca, NY and inspected for issues. System malfunctions include MARUs with corrupted media cards, water intrusion damage, and units with internal noise. Many of the corrupted media cards were caused by power loss from battery depletion, due to delayed recovery of the MARU. Long delays in recovery efforts were largely due to turbulent weather and limited opportunities to safely conduct field operations.

During the Year-1 survey, there were several equipment issues resulting in data loss at a number of sites from different deployments (Table 2, Table 5). During deployment M-D1, 8 sites had 100% data coverage, 4 sites had 85-99% coverage, 1 site had less than 50% coverage, and 2 sites had a complete loss of data. In M-D2, 9 sites had 100% data coverage, 1 site had ~80% data coverage, and 5 sites had 3% or less data coverage. In M-D3, for the 10 MARUs that had been recovered, 4 sites had 100% coverage, 2 sites had 30-40% data coverage, and 4 sites suffered complete data loss. Further details regarding data loss for Year-1 can be found in the Year-1 report (Estabrook et al. 2019).

The Year-2 survey experienced data loss due to delayed recovery, trawling, system malfunction, and lack of unit response during retrieval attempts (Table 3, Table 6). During the Year-2 M-D3 recording period (16 October 2018 – 23 December 2018), 6 MARU sites had complete data loss due to system malfunctions, and 4 MARU sites recorded approximately 75% of the recording period due to battery depletion when retrieval efforts were delayed by weather. During M-D4, M-D5 and M-D6, all MARUs recorded 100% of the deployment, except site 14M (PU 131) of M-D6 which did not surface during the retrieval effort. Site 6M (PU 304) in M-D5 recorded internal noise that interfered with recording quality and prevented species analysis. The AMARs at site 8A of A-D2, and at sites 11A and 15A of A-D-3 did not surface during retrieval attempts and therefore, were not recovered. All other AMARs recorded 100% of the Year-2 deployment periods. Additional details regarding data loss for Year-2 can be found in the Year-2 report (Estabrook et al. 2020).

During the Year-3 survey, several equipment issues lead to data loss at multiple sites (Table 4, Table 7). MARU data loss was due to three primary causes: 1) units were trawled (site 4M of deployment M-D8; 4M of M-D9), 2) units were lost or did not surface (14M of M-D6; 3M of M-D7; 5M, 6M and 7M of M-D9), and 3) system malfunction on the MARUs. The system malfunctions were caused by a corruption of the recording media (7M of M-D8) and hydrophone assembly failure (2M of M-D9). Additionally, nearly all of the AMARs had missing data during the Year-3 survey, where AMARs at all five sites did not surface. The AMAR at site 11A from the Year-2 deployment A-D3 surfaced unexpectedly in February 2020, and is therefore the only AMAR site with data from Year-3. Site 11A recorded 87 days in Year-3. Site 15A was not successfully recovered during the entirety of the 3-year survey.

The swap of MARUs from M-D6 to M-D7 (see Table 1 and Table 4) were carried out as planned, however the MARU at site 14M (unit # PU313) did not surface, resulting in lost data for the duration of M-D6 at that site location. The swap of MARUs from M-D7 to M-D8 also went as expected, with the exception of the MARU at site 3M (PU310), which did not surface. This resulted in missing data at site 3M for the entirety of the M-D7 recording period (October 2019 – January 2020). The M-D7 deployment units recorded a total of 803 days across all sites, and for 94 calendar days. In May 2020, we observed that the MARU at site 4M (PU306) had surfaced prematurely, due to trawling. The unit was recovered and returned to Cornell, resulting in approximately 74% recording coverage at site 4M for the M-D8 recording period (January 2020 – June 2020). The recovery of MARUs from M-D8 and the deployment of MARUs for M-D9 went as planned. Upon inspection of data quality for MARUs from M-D8, we discovered that the media storage card for site 7M (PU316) data was corrupted, resulting in complete data loss at site 7M for the duration of M-D8. The media card corruption was determined to be caused by power draw on the MARU system, resulting in unit power failure. We were unable to recover the corrupted data from the media card. During the M-D9 recording period, the MARU from site 4M (PU147) was trawled on 5 October 2020. The unit was recovered and returned to Cornell, resulting in 72% recording coverage for the M-D9 recording period. The recovery of MARUs from M-D9 occurred in mid-November 2020. The crew were able to recover MARUs from sites 1M, 2M, 3M, 10M, 12M, and 14M. The recovery effort was interrupted by unsafe weather conditions, so the crew returned to Cornell with the recovered MARUs and planned to make a second recovery attempt for MARUs at sites 5M, 6M, and 7M during the next period of safe weather conditions. Of the recovered MARUs, PU311 from site 2M experienced a system failure, caused by a malfunction in the hydrophone assembly, resulting in 99% data loss for site 2M during M-D9 (July – October 2020). In November 2020, the remaining MARUs at site 5M, 6M, and 7M automatically surfaced, and we monitored their locations with the intent of tracking and recovering the units. However, after a few weeks, the tracking device on the MARUs lost power. Unfortunately, during that time, the weather was not safe for the crew to attempt recovery, resulting in complete data loss for sites 5M, 6M, and 7M during M-D9 (June – October 2020).

In October 2019, AMARs for sites 8A, 9A, 11A, 13A, and 15A were deployed (A-D4). The AMAR at site 13A was trawled and surfaced prematurely on 10 December 2019. The recovered unit was received by JASCO, where it was discovered that the unit was damaged and the data were not recoverable, resulting in complete data loss for A-D4 (October 2019 – August 2020) at site 13A. In February 2020, the AMAR at site 9A surfaced and was tracked by JASCO, however the location data for the unit were intermittent and did not produce reliable tracking information. It is believed that the unit was submerged just under the surface of the water during this time. The unit was not recoverable before the tracking device lost power, resulting in complete data loss for site 9A during A-D4. We attempted to recover the remaining 3 AMARs in August 2020, however, none of them surfaced during the attempt. During the recovery attempt, AURAL recording devices from JASCO were deployed at the 5 AMAR locations (deployment A-D5). In October 2020, during the M-D9 MARU deployment, the crew made another attempt to recover the AMARs from A-D4, however they were unsuccessful. It is possible that these three units were dragged off location by fishing vessels.

As of September 2021, AURALs have not been recovered. Between October 2020 and February 2021, our crew monitored weather conditions to recover the AURALs and attempt, again, to recover the AMARs if they are still at their site locations. However, the persistent and sustained unsafe weather conditions during the winter season had prevented the crew from recovering the units. The large moorings used for AURAL deployments make recovery of instruments dangerous and difficult when seas are greater than 6 ft. The final attempt to recover AURAL units was in June 2021. By this time, the batteries for the AMAR acoustic release mechanisms were depleted, therefore units would not have responded to acoustic release signals. The AURAL at site 8A responded to the release signal and was tracked to within 10 m from the Jaeger, however, the unit was not observed by the crew during their search, and therefore not recovered. It is likely that the biofoul accumulation on the AURAL prevented the unit from breaking through the surface, and therefore was never within view to be sighted. The AURAL at site 9A did not respond to the release signal, despite attempts by the crew to ping it from several locations around the site. It is possible that the AURAL deployed at that location was trawled and dragged off site, beyond the range of the release signal. Prior to the Jaeger's arrival to site 13A, the weather conditions began to rapidly deteriorate, becoming unsafe and prevented recovery attempts at sites 11A, 13A, and 15A. The batteries of the acoustic release mechanisms for AURALs at sites 11A and 15A were estimated to have been depleted by that time, in which case it was highly unlikely that recovery the AURALs at those sites would have been successful, even in safe weather conditions.

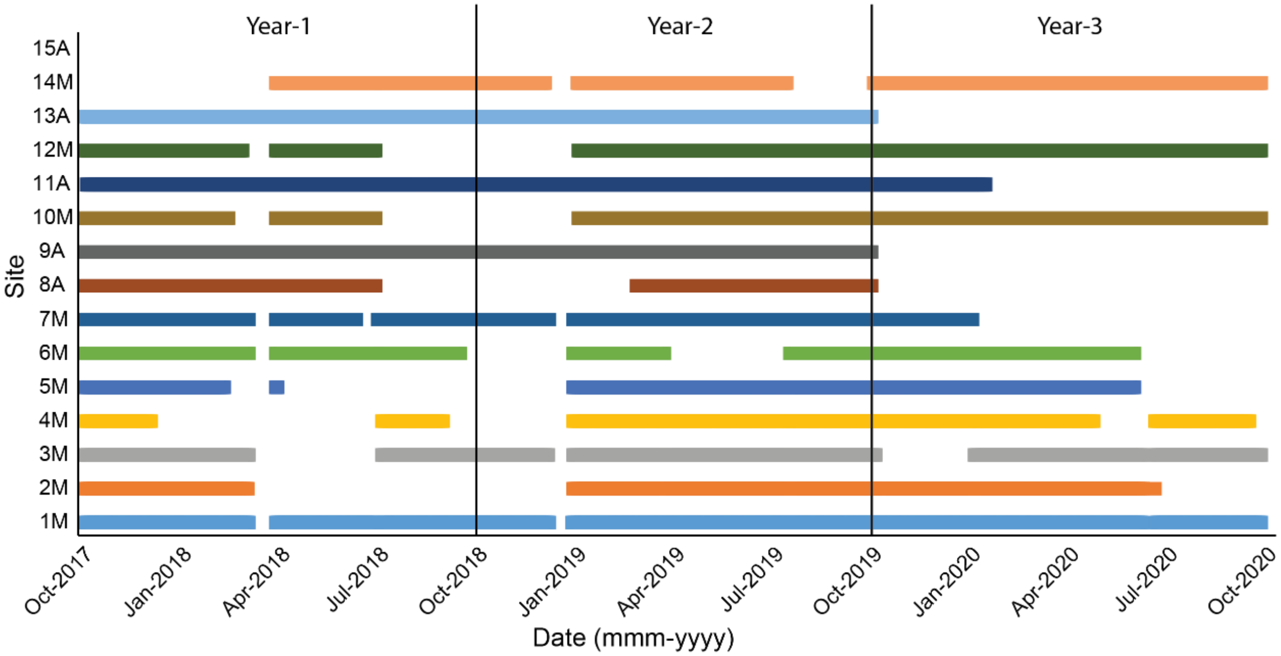


Figure 2. Recording effort for each MARU, AMAR, and AURAL site during the 3-year passive acoustic survey (16 October 2017 - 15 October 2020). The multi-colored horizontal bars indicate time periods in which the site recorded acoustic data. The white gaps indicate times in which there were no acoustic recordings. AMARs at site 15A were not successfully recovered throughout the survey.

Table 1. Deployment and recovery dates for MARUs and AMARs/AURALs of each deployment for Year-1, Year-2, and Year-3 (MARUs=M, AMARs/AURALs=A, Deployment=D).

Survey Year	Deployment	Deployment Date	Recovery Date	Total Calendar-Days	Total Site-Days
1	M-D1	10-Oct-17	11-Apr-18	154	1233
1	M-D2	10-Apr-18	19-Jul-18	94	542
1-2	M-D3	15-Jul-18	18-Jan-19	157	770
2	M-D4	12-Jan-19	25-Apr-19	101	887
2	M-D5	10-Apr-19	4-Aug-19	115	970
2-3	M-D6	2-Aug-19	25-Oct-19	83	712
3	M-D7	20-Oct-19	23-Jan-20	94	803
3	M-D8	21-Jan-20	9-Jul-20	157	1319
3	M-D9	20-Jun-20	10-Nov-20	133	711
1	A-D1	10-Oct-17	15-Jul-18	272	1084
1-2	A-D2	15-Jul-18	14-Mar-19	241	720
2-3	A-D3	13-Mar-19	20-Oct-19	220	874
3	A-D4	19-Oct-19	Not Recovered	0	0
3	A-D5	8-Aug-20	Not Recovered	0	0

Table 2. Deployment information for MARUs for Year-1.

Deployment	Site	Unit Number	Latitude (°N)	Longitude (°W)	Depth (m)	Deploy Date	Retrieval Date	Analysis Start Date	Analysis End Date	Total Analysis Days	Percent Coverage	Notes
M-D1	1M	309	40.347982	71.224167	90	15-Oct-17	11-Apr-18	16-Oct-17	18-Mar-18	154	87%	
M-D1	2M	303	40.34219	71.606067	84	14-Oct-17	11-Apr-18	16-Oct-17	17-Mar-18	153	86%	Battery died
M-D1	3M	306	40.333845	71.999408	65	14-Oct-17	11-Apr-18	16-Oct-17	18-Mar-18	154	87%	
M-D1	4M	311	40.327372	72.408	54	14-Oct-17	11-Apr-18	16-Oct-17	17-Dec-17	63	35%	Trawled 2017-12-18
M-D1	5M	310	40.319978	72.781935	50	14-Oct-17	11-Apr-18	16-Oct-17	23-Feb-18	131	74%	Trawled 2018-02-24
M-D1	6M	304	40.284352	73.152112	40	14-Oct-17	11-Apr-18	16-Oct-17	18-Mar-18	154	87%	Bad sound quality
M-D1	7M	308	40.347333	73.484445	30	14-Oct-17	11-Apr-18	16-Oct-17	18-Mar-18	154	87%	
M-D1	10M	301	40.032333	73.499988	49	11-Oct-17	10-Apr-18	16-Oct-17	23-Feb-18	131	73%	Trawled 2018-02-24
M-D1	12M	300	39.734522	73.106817	51	11-Oct-17	10-Apr-18	16-Oct-17	12-Mar-18	148	82%	
M-D1	14M	302	39.438865	72.72855	80	10-Oct-17	10-Apr-18	No Data	No Data	0	0%	Corrupt Flash Drive
M-D2	1M	312	40.348321	71.225644	90	11-Apr-18	19-Jul-18	12-Apr-18	14-Jul-18	94	0%	No Response Surfaced July 2020 – corrupt CF Card
M-D2	2M	316	40.342242	71.607933	84	11-Apr-18	18-Jul-18	No Data	No Data	0	3%	Trawled
M-D2	3M	321	40.333843	72.000828	65	11-Apr-18	18-Jul-18	No Data	No Data	0	100%	
M-D2	4M	315	40.327631	72.408339	54	11-Apr-18	Not Recovered	No Data	No Data	0	78%	Stopped recording on 2018-06-27
M-D2	5M	313	40.319907	72.782415	50	11-Apr-18	18-Jul-18	12-Apr-18	14-Apr-18	3		
M-D2	6M	320	40.284681	73.153109	40	11-Apr-18	18-Jul-18	12-Apr-18	14-Jul-18	94		
M-D2	7M	317	40.34779	73.486217	30	11-Apr-18	18-Jul-18	12-Apr-18	26-Jun-18	76		
M-D2	10M	318	40.031789	73.500126	49	10-Apr-18	15-Jul-18	12-Apr-18	14-Jul-18	94	100%	
M-D2	12M	314	39.73377	72.105267	51	10-Apr-18	15-Jul-18	12-Apr-18	14-Jul-18	94	0%	Corrupt CF Card - Water intrusion
M-D2	14M	319	39.438872	72.729047	80	10-Apr-18	15-Jul-18	12-Apr-18	14-Jul-18	94	0%	Trawled - corrupt CF card

Table 2 (continued). Deployment information for MARUs for Year-1.

Deployment	Site	Unit Number	Latitude (°N)	Longitude (°W)	Depth (m)	Deploy Date	Retrieval Date	Analysis Start Date	Analysis End Date	Total Analysis Days	Percent Coverage	Notes
M-D3	1M	310	40.34884	71.22556	88	19-Jul-18	12-Jan-19	20-Jul-18	23-Dec-18	157	89%	
M-D3	2M	304	40.34263	71.60848	84	19-Jul-18	13-Jan-19	No Data	No Data	0	0%	Internal noise - malfunctioning hydrophone assembly
M-D3	3M	307	40.33393	72.0013	64	19-Jul-18	13-Jan-19	20-Jul-18	22-Dec-18	156	88%	
M-D3	4M	303	40.32781	72.40787	53	18-Jul-18	13-Jan-19	20-Jul-18	15-Sep-18	58	33%	Stopped recording on 2018-09-16, - 33% deployment data
M-D3	5M	301	40.31991	72.7825	50	18-Jul-18	13-Jan-19	No Data	No Data	0	0%	Corrupt CF card (power pin corrosion) - no data
M-D3	6M	311	40.28409	73.1523	40	18-Jul-18	13-Jan-19	20-Jul-18	30-Sep-18	73	41%	Trawled around 3 Oct - partial data
M-D3	7M	308	40.34806	73.48566	30	18-Jul-18	13-Jan-19	20-Jul-18	23-Dec-18	157	88%	
M-D3	10M	300	40.03231	73.49923	49	15-Jul-18	18-Jan-19	No Data	No Data	0	0%	CF card failed to mount - no data
M-D3	12M	302	39.73353	73.10452	51	15-Jul-18	18-Jan-19	16-Jul-18	7-Aug-18	23	12%	CF card corrupt - only 15% data extracted
M-D3	14M	309	39.43877	72.72832	80	15-Jul-18	17-Jan-19	20-Jul-18	19-Dec-18	153	83%	

Table 3. Deployment information for MARUs for Year-2.

Deployment	Site	Unit Number	Latitude (°N)	Longitude (°W)	Depth (m)	Deploy Date	Retrieval Date	Analysis Start Date	Analysis End Date	Total Analysis Days	Percent Coverage	Notes
M-D3	1M	310	40.34884	71.22556	88	19-Jul-18	12-Jan-19	16-Oct-18	23-Dec-18	69	79%	
M-D3	2M	304	40.34263	71.60848	84	19-Jul-18	13-Jan-19	No Data	No Data	0	0%	Internal noise
M-D3	3M	307	40.33393	72.00130	64	19-Jul-18	13-Jan-19	16-Oct-18	22-Dec-18	68	77%	
M-D3	4M	303	40.32781	72.40787	53	18-Jul-18	13-Jan-19	No Data	No Data	0	0%	Stopped recording on 2018-09-16
M-D3	5M	301	40.31991	72.78250	50	18-Jul-18	13-Jan-19	No Data	No Data	0	0%	CF card corrupt
M-D3	6M	311	40.28409	73.15230	40	18-Jul-18	1-Oct-18	No Data	No Data	0	0%	Trawled around 3 Oct 2018
M-D3	7M	308	40.34806	73.48566	30	18-Jul-18	13-Jan-19	16-Oct-18	23-Dec-18	69	78%	
M-D3	10M	300	40.03231	73.49923	49	15-Jul-18	18-Jan-19	No Data	No Data	0	0%	CF card corrupt
M-D3	12M	302	39.73353	73.10452	51	15-Jul-18	18-Jan-19	No Data	No Data	0	0%	CF card corrupt
M-D3	14M	309	39.43877	72.72832	80	15-Jul-18	17-Jan-19	16-Oct-18	19-Dec-18	65	71%	
M-D4	1M	314	40.34938	71.22603	88.0	12-Jan-19	11-Apr-19	13-Jan-19	10-Apr-19	88	100%	
M-D4	2M	306	40.34231	71.60760	83.0	13-Jan-19	11-Apr-19	14-Jan-19	10-Apr-19	87	100%	
M-D4	3M	321	40.33381	72.00063	65.0	13-Jan-19	11-Apr-19	14-Jan-19	10-Apr-19	87	100%	
M-D4	4M	316	40.32791	72.40718	54.0	13-Jan-19	11-Apr-19	14-Jan-19	10-Apr-19	87	100%	
M-D4	5M	313	40.31928	72.78249	50.4	13-Jan-19	21-Apr-19	14-Jan-19	10-Apr-19	87	100%	
M-D4	6M	318	40.28386	73.15194	40.0	13-Jan-19	10-Apr-19	14-Jan-19	9-Apr-19	86	100%	
M-D4	7M	319	40.34806	73.48566	36.0	13-Jan-19	10-Apr-19	14-Jan-19	9-Apr-19	86	100%	
M-D4	10M	305	40.03189	73.49901	48	18-Jan-19	25-Apr-19	19-Jan-19	24-Apr-19	96	100%	
M-D4	12M	317	39.73312	73.10454	50	18-Jan-19	25-Apr-19	19-Jan-19	24-Apr-19	96	100%	
M-D4	14M	320	39.43941	72.72879	81	17-Jan-19	25-Apr-19	18-Jan-19	24-Apr-19	97	100%	

Table 3 (continued). Deployment information for MARUs for Year-2.

Deployment	Site	Unit Number	Latitude (°N)	Longitude (°W)	Depth (m)	Deploy Date	Retrieval Date	Analysis Start Date	Analysis End Date	Total Analysis Days	% Coverage	Notes
M-D5	1M	301	40.34756	71.22794	88.9	11-Apr-19	4-Aug-19	12-Apr-19	3-Aug-19	114	100%	
M-D5	2M	303	40.34307	71.60787	84.6	11-Apr-19	4-Aug-19	12-Apr-19	3-Aug-19	114	100%	
M-D5	3M	300	40.33433	72.00121	65.3	11-Apr-19	4-Aug-19	12-Apr-19	3-Aug-19	114	100%	
M-D5	4M	307	40.32778	72.40862	54.1	10-Apr-19	4-Aug-19	11-Apr-19	3-Aug-19	115	100%	
M-D5	5M	311	40.31922	72.78351	50.7	10-Apr-19	3-Aug-19	11-Apr-19	2-Aug-19	114	100%	
M-D5	6M	304	40.28400	73.15348	39.8	10-Apr-19	3-Aug-19	No Data	No Data	0	0%	Internal noise
M-D5	7M	312	40.34836	73.48706	30.2	10-Apr-19	3-Aug-19	11-Apr-19	2-Aug-19	114	100%	
M-D5	10M	309	40.03275	73.50000	48	25-Apr-19	2-Aug-19	26-Apr-19	1-Aug-19	98	100%	
M-D5	12M	310	39.73422	73.10571	51	25-Apr-19	2-Aug-19	26-Apr-19	1-Aug-19	98	100%	
M-D5	14M	302	39.44002	72.72978	81	25-Apr-19	2-Aug-19	26-Apr-19	1-Aug-19	98	100%	
M-D6	1M	319	40.34755	71.22902	86.5	4-Aug-19	25-Oct-19	5-Aug-19	15-Oct-19	72	100%	
M-D6	2M	314	40.34304	71.60850	82.6	4-Aug-19	25-Oct-19	5-Aug-19	15-Oct-19	72	100%	
M-D6	3M	321	40.33471	72.00192	65.3	4-Aug-19	24-Oct-19	5-Aug-19	15-Oct-19	72	100%	
M-D6	4M	320	40.32823	72.40906	54.1	4-Aug-19	24-Oct-19	5-Aug-19	15-Oct-19	72	100%	
M-D6	5M	318	40.31896	72.78440	50.5	3-Aug-19	24-Oct-19	4-Aug-19	15-Oct-19	73	100%	
M-D6	6M	317	40.28438	73.15464	39.0	3-Aug-19	24-Oct-19	4-Aug-19	15-Oct-19	73	100%	
M-D6	7M	316	40.34891	73.48807	27.6	3-Aug-19	24-Oct-19	4-Aug-19	15-Oct-19	73	100%	
M-D6	10M	305	40.03372	73.49926	47.4	2-Aug-19	20-Oct-19	3-Aug-19	15-Oct-19	74	100%	
M-D6	12M	306	39.73487	73.10667	48.9	2-Aug-19	20-Oct-19	3-Aug-19	15-Oct-19	74	100%	
M-D6	14M	313	39.44064	72.73072	79.6	2-Aug-19	Not Recovered	3-Aug-19	No Data	0	0%	Did not surface

Table 4. Deployment information for MARUs for Year-3.

Deployment	Site	Unit Number	Latitude (°N)	Longitude (°W)	Depth (m)	Deploy Date	Retrieval Date	Analysis Start Date	Analysis End Date	Total Analysis Days	Percent Coverage	Notes
M-D6	1M	319	40.347553	-71.229020	86.5	4-Aug-19	25-Oct-19	5-Aug-19	24-Oct-19	81	100%	
M-D6	2M	314	40.343041	-71.608501	82.6	4-Aug-19	25-Oct-19	5-Aug-19	24-Oct-19	81	100%	
M-D6	3M	321	40.334706	-72.001923	65.3	4-Aug-19	24-Oct-19	5-Aug-19	23-Oct-19	80	100%	
M-D6	4M	320	40.328230	-72.409055	54.1	4-Aug-19	24-Oct-19	5-Aug-19	23-Oct-19	80	100%	
M-D6	5M	318	40.318961	-72.784396	50.5	3-Aug-19	24-Oct-19	4-Aug-19	23-Oct-19	81	100%	
M-D6	6M	317	40.284382	-73.154640	39.0	3-Aug-19	24-Oct-19	4-Aug-19	23-Oct-19	81	100%	
M-D6	7M	316	40.348906	-73.488074	27.6	3-Aug-19	24-Oct-19	4-Aug-19	23-Oct-19	81	100%	
M-D6	10M	305	40.033720	-73.499260	47.4	2-Aug-19	20-Oct-19	3-Aug-19	19-Oct-19	78	100%	
M-D6	12M	306	39.734870	-73.106670	48.9	2-Aug-19	20-Oct-19	3-Aug-19	19-Oct-19	78	100%	
M-D6	14M	313	39.440640	-72.730720	79.6	2-Aug-19	Not Recovered	No Data	No Data	0	0%	Did not surface
M-D7	1M	309	40.347891	-71.229810	85.5	25-Oct-19	23-Jan-20	26-Oct-19	22-Jan-20	89	100%	
M-D7	2M	311	40.342957	-71.609415	81.3	25-Oct-19	23-Jan-20	26-Oct-19	22-Jan-20	89	100%	
M-D7	3M	310	40.334684	-72.002578	63.8	24-Oct-19	Not Recovered	No Data	No Data	0	0%	Responded, but did not surface
M-D7	4M	308	40.328341	-72.409856	53.3	24-Oct-19	22-Jan-20	25-Oct-19	21-Jan-20	89	100%	
M-D7	5M	301	40.319107	-72.784496	50.2	24-Oct-19	22-Jan-20	25-Oct-19	21-Jan-20	89	100%	
M-D7	6M	238	40.284842	-73.155409	39.5	24-Oct-19	22-Jan-20	25-Oct-19	21-Jan-20	89	100%	
M-D7	7M	312	40.349921	-73.488591	27.6	24-Oct-19	22-Jan-20	25-Oct-19	21-Jan-20	89	100%	
M-D7	10M	302	40.034733	-73.499356	46.0	20-Oct-19	21-Jan-20	21-Oct-19	20-Jan-20	92	100%	
M-D7	12M	300	39.735634	-73.106751	50.0	20-Oct-19	22-Jan-20	21-Oct-19	21-Jan-20	93	100%	
M-D7	14M	303	39.441003	-72.730863	79.0	20-Oct-19	22-Jan-20	21-Oct-19	21-Jan-20	93	100%	

Table 4 (continued). Deployment information for MARUs for Year-3.

Deployment	Site	Unit Number	Latitude (°N)	Longitude (°W)	Depth (m)	Deploy Date	Retrieval Date	Analysis Start Date	Analysis End Date	Total Analysis Days	Percent Coverage	Notes
M-D8	1M	321	40.347786	71.230618	87.8	23-Jan-20	9-Jul-20	24-Jan-20	27-Jun-20	156	93%	
M-D8	2M	318	40.342794	71.610601	83.3	23-Jan-20	8-Jul-20	24-Jan-20	25-Jun-20	154	92%	
M-D8	3M	317	40.334158	72.000763	64.8	22-Jan-20	8-Jul-20	23-Jan-20	28-Jun-20	158	94%	
M-D8	4M	306	40.328529	72.410882	53.7	22-Jan-20	21-Jun-20	23-Jan-20	13-May-20	112	74%	Trawled 2020-05-14
M-D8	5M	319	40.319013	72.785293	50.4	22-Jan-20	21-Jun-20	23-Jan-20	20-Jun-20	150	100%	
M-D8	6M	320	40.285197	73.156822	39.7	22-Jan-20	21-Jun-20	23-Jan-20	20-Jun-20	150	100%	
M-D8	7M	316	40.350122	73.488815	28.2	22-Jan-20	21-Jun-20	No Data	No Data	0	0%	Corrupt CF card
M-D8	10M	305	40.035185	73.499680	47.7	21-Jan-20	20-Jun-20	22-Jan-20	19-Jun-20	150	100%	
M-D8	12M	307	40.736100	73.106361	50.1	22-Jan-20	20-Jun-20	23-Jan-20	19-Jun-20	149	100%	
M-D8	14M	314	39.440391	72.730293	80.1	22-Jan-20	20-Jun-20	23-Jan-20	19-Jun-20	149	100%	
M-D9	1M	300	40.347852	71.231932	88.7	9-Jul-20	8-Nov-20	10-Jul-20	15-Oct-20	114	100%	
M-D9	2M	311	40.342827	71.610971	82.5	8-Jul-20	8-Nov-20	9-Jul-20	9-Jul-20	1	0%	Hydrophone assembly failure
M-D9	3M	238	40.334159	72.002521	64.1	8-Jul-20	10-Nov-20	9-Jul-20	15-Oct-20	115	100%	
M-D9	4M	147	40.382664	72.411243	52.9	8-Jul-20	10-Nov-20	9-Jul-20	5-Oct-20	89	90%	Trawled 2020-10-06
M-D9	5M	304	40.318051	72.786949	49.5	21-Jun-20	Not Recovered	No Data	No Data	0	0%	Not Recovered
M-D9	6M	309	40.285505	73.158954	38.9	21-Jun-20	Not Recovered	No Data	No Data	0	0%	Not Recovered
M-D9	7M	312	40.350430	73.489172	28.2	21-Jun-20	Not Recovered	No Data	No Data	0	0%	Not Recovered
M-D9	10M	308	40.035483	73.499426	46.7	20-Jun-20	7-Nov-20	21-Jun-20	15-Oct-20	133	100%	
M-D9	12M	302	39.736350	73.136457	49.5	20-Jun-20	10-Nov-20	21-Jun-20	15-Oct-20	133	100%	
M-D9	14M	303	39.441048	72.730799	79.7	20-Jun-20	10-Nov-20	21-Jun-20	15-Oct-20	133	100%	

Table 5. Deployment information for AMARs for Year-1.

Deployment	Site	Unit Number	Latitude (°N)	Longitude (°W)	Depth (m)	Deploy Date	Retrieval Date	Analysis Start Date	Analysis End Date	Total Analysis Days	Percent Coverage	Notes
A-D1	8A	421	39.88428	73.293273	28	11-Oct-17	15-Jul-18	16-Oct-17	14-Jul-18	272	100%	
A-D1	9A	436	40.20305	73.628742	38	11-Oct-17	15-Jul-18	16-Oct-17	14-Jul-18	272	100%	
A-D1	11A	430	40.41723	73.766032	49	11-Oct-17	15-Jul-18	16-Oct-17	14-Jul-18	272	100%	
A-D1	13A	437	39.591833	72.923667	63	10-Oct-17	15-Jul-18	16-Oct-17	14-Jul-18	272	100%	
A-D1	15A	NA	39.289855	72.539843	NA	10-Oct-17	Not Recovered	No Date	No Data	0	0%	No response during recovery
A-D2	8A	395	39.88345	73.763080	28	16-Jul-18	Not Recovered	No Data	No Data	0	0%	No response during recovery
A-D2	9A	399	39.59182	73.628470	38	15-Jul-18	14-Mar-19	16-Jul-18	13-Mar-19	241	100%	
A-D2	11A	401	40.41739	73.291870	49	15-Jul-18	14-Mar-19	16-Jul-18	13-Mar-19	241	100%	
A-D2	13A	397	40.20318	72.922080	63	15-Jul-18	14-Mar-19	16-Jul-18	13-Mar-19	241	100%	

Table 6. Deployment information for AMARs for Year-2.

Deployment	Site	Unit Number	Latitude (°N)	Longitude (°W)	Depth (m)	Deploy Date	Retrieval Date	Analysis Start Date	Analysis End Date	Total Analysis Days	Percent Coverage	Notes
A-D2	8A	395	40.41739	73.76308	28	16-Jul-18	Not Recovered	No Data	No Data	0	0%	Not recovered
A-D2	9A	399	40.20318	73.62847	38	15-Jul-18	14-Mar-19	16-Oct-18	13-Mar-19	149	100%	
A-D2	13A	397	39.59182	72.92208	63	15-Jul-18	14-Mar-19	16-Oct-18	13-Mar-19	149	100%	
A-D2	15A	NA				Not Deployed	NA	No Data	No Data	0	0%	Not Deployed
A-D3	8A	447	40.41367	73.76214	32	13-Mar-19	20-Oct-19	14-Mar-19	15-Oct-19	216	100%	
A-D3	9A	427	40.19968	73.62833	37	13-Mar-19	20-Oct-19	14-Mar-19	15-Oct-19	216	100%	
A-D3	11A	431	39.88142	73.28865	49	14-Mar-19	Not Recovered	15-Mar-19	No Data	0	0%	Did not surface
A-D3	13A	394	39.58882	72.92199	63	14-Mar-19	20-Oct-19	15-Mar-19	15-Oct-19	215	100%	
A-D3	15A	446	39.28598	72.53463	141	14-Mar-19	Not Recovered	No Data	No Data	0	0%	Did not surface

Table 7. Deployment information for AMARs and AURALs for Year-3.

Deployment	Site	Unit Number	Latitude (°N)	Longitude (°W)	Depth (m)	Deploy Date	Retrieval Date	Analysis Start Date	Analysis End Date	Total Analysis Days	Percent Coverage	Notes
A-D3	8A	447	40.413670	-73.762140	32	13-Mar-19	20-Oct-19	14-Mar-19	19-Oct-19	220	100%	
A-D3	9A	427	40.199680	-73.628330	37	13-Mar-19	20-Oct-19	14-Mar-19	19-Oct-19	220	100%	
A-D3	11A	431	39.881420	-73.288650	49	14-Mar-19	20-Oct-19	15-Mar-19	10-Jan-20	302	100%	Surfaced 15 May; redeployed 17 May; Delayed surface (Feb 2020), battery depleted 11-Jan-2020
A-D3	13A	394	39.588820	-72.921994	63	14-Mar-19	20-Oct-19	15-Mar-19	19-Oct-19	219	100%	
A-D3	15A	446	39.285980	-72.534630	141	14-Mar-19	Not Recovered	No Data	No Data	0	0%	Did not surface
A-D4	8A	399	40.414579	-73.758602	30.0	19-Oct-19	Not Recovered	No Data	No Data	0	0%	Did not surface
A-D4	9A	401	40.201540	-73.629489	36.0	19-Oct-19	Not Recovered	No Data	No Data	0	0%	Did not surface
A-D4	11A	425	39.888638	-73.292945	50.0	20-Oct-19	Not Recovered	No Data	No Data	0	0%	Did not surface
A-D4	13A	430	39.590675	-72.923145	61.0	20-Oct-19	Not Recovered	No Data	No Data	0	0%	Trawled. Surfaced 10 Dec. Replaced with AURAL #15
A-D4	15A	393	39.283581	-72.532101	140.0	20-Oct-19	Not Recovered	No Data	No Data	0	0%	Did not surface
A-D5	8A	17	40.415150	-73.757630	26.0	8-Aug-20	Not Recovered	No Data	No Data	0	0%	AURALS - No data
A-D5	9A	11	40.203054	-73.630477	36.5	9-Aug-20	Not Recovered	No Data	No Data	0	0%	AURALS - No data
A-D5	11A	10	39.889740	-73.294121	54.0	9-Aug-20	Not Recovered	No Data	No Data	0	0%	AURALS - No data
A-D5	13A	22	39.590111	-72.922941	62.4	9-Aug-20	Not Recovered	No Data	No Data	0	0%	AURALS - No data

Data Analysis for Focal Species Detection

To evaluate temporal patterns of whale acoustic presence, we used a combination of automated detection algorithms and human visual and aural analysis to establish daily acoustic presence of North Atlantic right whales, fin whales, humpback whales, blue whales, sei whales, and sperm whales across the recording sites. "Daily acoustic presence" is the human-validated positive detection of one or more species-specific acoustic signals on a particular sensor during each day of the survey, and shown as presence or non-presence; the number of detections on a particular day is not reflected in this metric. Sperm whales were analyzed only for the AMAR data, as the AMARs' higher sampling rate (and thus larger operational frequency bandwidth) were better suited to sperm whale detection than the MARUs' lower sampling rate. Sound files were browsed using Raven Pro 2.0 Sound Analysis Software (Bioacoustics Research Program 2017). All automatically detected or human-identified signals used to determine presence were subject to a second verification process to ensure data accuracy to eliminate the inclusion of false positive signals or misidentifications in detection results.

North Atlantic Right Whales

Daily acoustic presence of right whales at each site was determined by identifying contact calls (referred to as upcalls, see Figure 3). Upcalls are the most common sound produced by migrating right whales (Parks and Tyack 2005, Parks and Clark 2007, Urazghildiiev et al. 2009), and are frequently used to determine acoustic presence of right whales (e.g., Morano et al. 2012a, Hodge et al. 2015, Salisbury et al. 2016, Muirhead et al. 2018). The following quantitative criteria help to distinguish upcalls from other biological and anthropogenic sounds: 1) starting frequency occurs between 65-170 Hz; 2) minimum and maximum frequencies differ by 75-200 Hz; 3) duration ranges from 0.3-1.3 s; 4) energy is concentrated in the lower portion of the signal; and 5) signal contour slopes upward. In this analysis, a custom MATLAB-based automated detector algorithm was used to detect upcalls (Dugan et al. 2013) and was applied to all sound data. Spectrogram settings for reviewing detections included a 60 s page duration, a frequency range of 10 – 450 Hz, and a Fast Fourier Transform (FFT) window size of 512 points. Each detection was reviewed by an analyst until a true positive (TP) detection was identified for each day and site. Automated detection of right whale upcalls can falsely detect humpback whale signals with similar acoustic properties in geographic regions where the two species overlap (Mellinger et al. 2011, Mussoline et al. 2012). Detection events with concurrent bioacoustic activity suggestive of humpback whale song were not included in the right whale presence analysis if the event could not be clearly distinguished from humpback song.

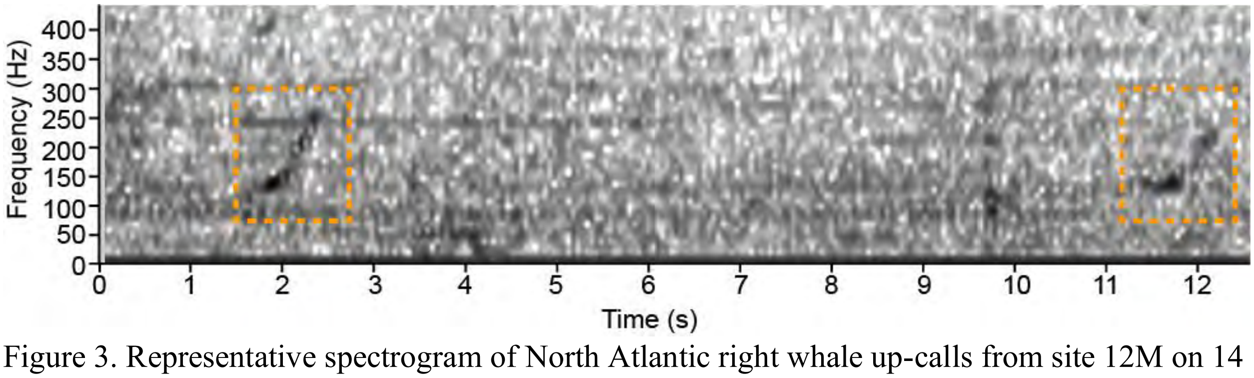


Figure 3. Representative spectrogram of North Atlantic right whale up-calls from site 12M on 14 April 2018. The two calls shown here are indicated by dashed orange boxes.

Humpback Whales

Both humpback whale songs and social sounds were used to determine their acoustic presence in NY Bight (Payne and McVay 1971, Silber 1986, Chabot 1988). Analysts used Raven Pro 2.0 to visually review spectrograms in search of humpback whale sounds. During the Year-3 analysis, every 4th sound file was manually reviewed for humpback whale presence, resulting in a 25% subsample of the data. (MARU file durations are 15 min, AMAR file durations are 30 min). When tested with a subset of 50 days, the 25% subsample analysis for humpback whale daily presence per site yielded the same presence results as manually reviewing 100% of the sound files. Spectrogram settings included a 5 min page duration, frequency range of 10–600 Hz, and a FFT window size of 512 points. Humpback vocalizations (Figure 4) were marked on a daily basis per site.

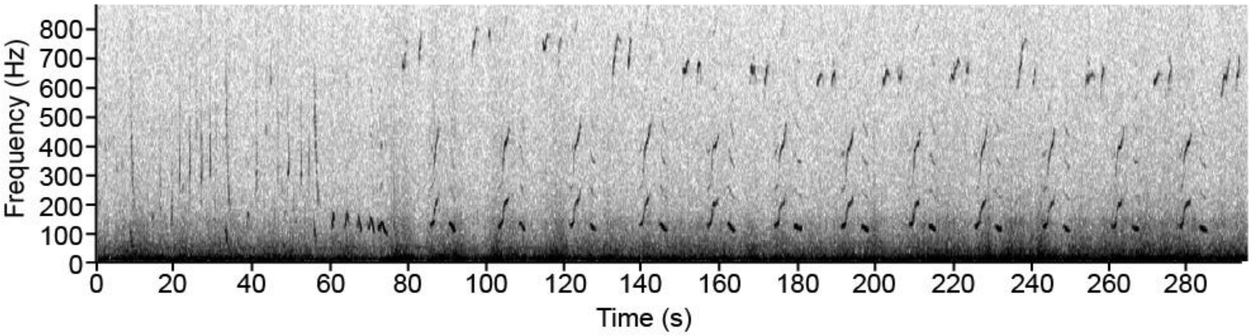


Figure 4. Spectrogram of representative humpback whale song, recorded from site 1M on 6 March 2018.

Fin Whales

Fin whale song is comprised of long sequences of individual 20-Hz notes (Figure 5) (Watkins et al. 1987, McDonald et al. 1995, Clark et al. 2002). We used a matched-filter data-template detection algorithm to automatically detect 20-Hz notes in the acoustic data (Mellinger and Clark 1997, 2000, Dugan et al. 2016). The detector is trained using multiple exemplars of 20-Hz fin whale notes and is able to cross-correlate sounds with similar characteristics, yielding detections with an associated correlation score. Exemplars comprised fin whale 20-Hz pulses with a high signal-to-noise ratio. Each detection was reviewed by analysts until a true positive (TP) detection was identified for each day and site. Down-sampled 400 Hz sound data were used for this analysis, with spectrogram settings that comprised a 90 s page duration, 10–60 Hz frequency band, and an FFT window size of 512 points.

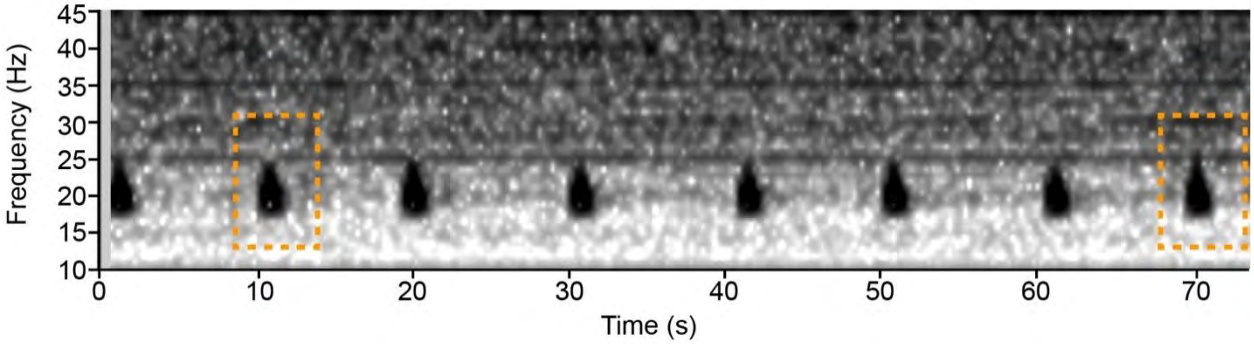


Figure 5. Spectrogram of representative fin whale 20-Hz pulse song, recorded at site 7M on 26 December 2017. Two of the pulses are indicated by dashed orange boxes.

Sei Whales

Sei whales produce low-frequency (34–82 Hz) downsweeps (Figure 6) that last approximately 1.4 s (Baumgartner et al. 2008). The downsweeps can occur singularly, or in doublets and triplets. To determine the daily presence of sei whales, we used the template detector in Raven Pro 2.0 to detect sei whale downsweeps. To develop the detector, six examples of sei whale downsweeps with high signal-to-noise ratio from this dataset were used as templates. Those templates were then cross-correlated against the continuous sound data to find instances of sei whale downsweeps with an associated correlation value, or score. The correlation scores were subsequently used in the detector performance evaluation (see below) to determine the threshold correlation cutoff that would maximize the true positive rate. Detection events were reviewed by analysts until a true positive (TP) detection was identified for each day and site. Spectrogram settings comprised a 60 s page duration, 0–200 Hz frequency band, and an FFT window size of 512 points.

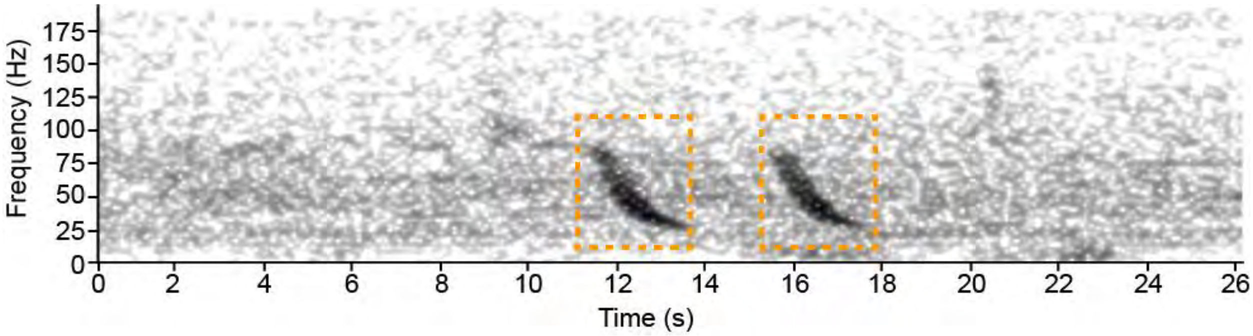


Figure 6. Spectrogram of representative sei whale downsweeps, recorded at site 1M on 26 April 2018. The two calls are indicated by a dashed orange box.

Blue Whales

Blue whales in the North Atlantic produce song that is characterized by a sequence of phrases, commonly comprising phrase part A and part B (referred to as the A-B phrase), between 15 and 20 Hz (Mellinger and Clark 2003). To determine daily acoustic presence of blue whale song at each site, we first down-sampled the sound files to 400 Hz to improve computational efficiency for long-term spectrogram analysis. Analysts then manually browsed through the down-sampled sound files using spectrogram visualization in Raven Pro 2.0 and searched for characteristic patterns of 14–22 Hz blue whale sounds (Figure 7) and marked positive events on a daily basis per site. Spectrogram settings included a page length of 60 min and a frequency range of 10–25 Hz. The FFT window size was set to 512 points.

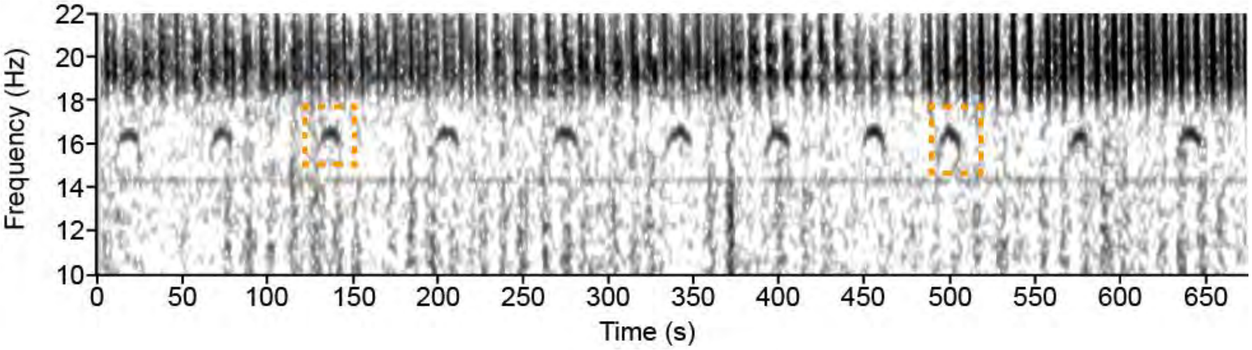


Figure 7. Spectrogram of a representative sequence of A-B phrases of a blue whale song from site 1M on 1 November 2017. Two of the phrases are marked by dashed orange boxes.

Sperm Whales

When foraging, sperm whales produce clicks, called "usual clicks" or "regular clicks" which are impulsive, broadband sounds, are the most common click type produced by sperm whales, and are hypothesized to be associated with foraging (Goold and Jones 1995, Jaquet et al. 2001, Madsen et al. 2002). Sperm whales spend 72% of their time in dive cycles (Watwood et al. 2006, Jochens et al. 2008) and produce usual clicks in 80-91% of the dive (Watwood et al. 2006, Teloni et al. 2008). Previous research suggests that the number of hours per day that sperm whales are vocally active is relatively constant (Whitehead and Weilgart 1991, Aoki et al. 2007). Usual clicks are broadband (200 Hz – 13 kHz) with an omnidirectional component between 1-3 kHz (Diogou et al. 2019). Clicks associated with feeding events ("buzzes") are higher in frequency and highly directional (Madsen et al. 2002). While sperm whales also produce buzzes and "codas" in social contexts (Watkins and Schevill 1977, Schulz et al. 2011, Oliveira et al. 2016), the amount of time in a day that sperm whales produce usual clicks make these types of clicks well-suited as target signals for passive acoustic monitoring of sperm whales in this area. To determine daily sperm whale acoustic presence per site (site-day presence), every 4th sound file (25% subsample) was manually reviewed by an analyst for usual clicks using a spectrogram (Hann window, window size = 1024, hop size = 25.5 ms, frequency grid = 7.81 Hz) and filtered waveform (1 – 4 kHz) in Raven Pro 2.0. Every 4th sound file for the AMAR data represented 15 min of each recorded hour. Since sperm whales spend most of their time in dive cycles, which can last an average of 45 min (Watwood et al. 2006), and they produce usual clicks during most of their dive time (including the decent, while foraging at the bottom, and beginning of the ascent), there is a high chance that the sampled 15-min sound file overlapped with the sperm whale dive time, assuming they were foraging within the detection area of an AMAR. Sequences of five or more broadband pulses that had a regular inter-click-interval between 0.5 s and 1.5 s were annotated as sperm whale clicks within a click train, and used to establish daily acoustic presence (Figure 8). These conservative criteria were developed to exclude individual broadband pulses that resemble clicks but were produced by other sound sources (non-target signals, either anthropogenic or biological). While there is significant acoustic energy in sperm whale clicks between 1000-4000 Hz (Diogou et al. 2019), the majority of the acoustic energy (including center frequency) is above the Nyquist frequency of the AMARs in this study. Consequently, in some cases, the limited information in the operational frequency bandwidth (due to the sample-rate of 8 kHz) constrained the ability for positive inference of sperm whales from individual clicks, and it is possible that lower SNR clicks that were not included in our analysis may be false negatives leading to a slight underestimate of sperm whale occurrence.

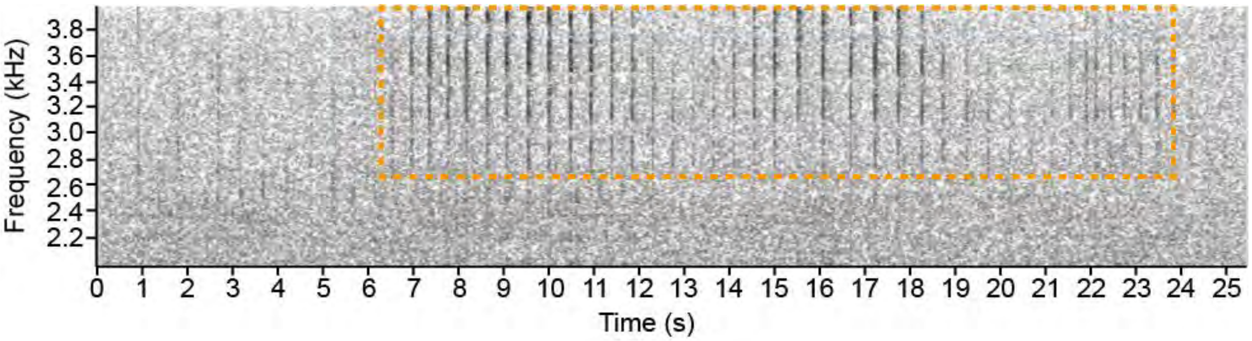


Figure 8. Spectrogram of representative sperm whale usual clicks, recorded at site 13A on 6 February 2018. A "usual click" sequence is indicated by a dashed orange box.

Evaluation of Whale Call Automated Detector Performance

For analysis of right whale, sei whale, and fin whale daily presence-absence, we used automated detection algorithms to find the target signals. After the first deployment of sound data was recovered, we quantified the performance of the automated detectors on MARU recordings (units at AMAR sites were still in the water) by manually reviewing a subset of the sound data from M-D1 and marking every occurrence of the target signals for which an automated detector applied (fin whale 20-Hz pulse, right whale upcalls, and sei whale downsweeps). These manually marked target signals for each species from M-D1 are referred to as the M-D1 'ground-truth' datasets. The M-D1 ground-truth dataset consisted of manually reviewed data from every 20th day of sound from the M-D1 deployment (between October 2017 and April 2018), resulting in 9 calendar-days. From those days, data from a subset of sites were reviewed (sites were rotated through the subset of days; see Table 8

Table 9. Subsampled dates and sites used for the full 20th-day ground-truth dataset to evaluate the detector performance of fin, right, and sei whale detectors. “NA” represents a date when the selected site does not have data, and blank cells mark dates when a third site was not sampled.). This process resulted in a total of 33 site-days of ground-truth data across different sites for all three species.

The manually annotated target signals were compared against the detector output of the corresponding automated detectors to determine true positive rates (TPR) and false discovery rates (FDR), which were the key metrics used for the detector performance evaluation. For each species, if a detection event overlapped by >1% in time and frequency with a ground-truth event, it was considered a true positive (TP) event. If a detection event did not overlap with a ground-truth event, it was considered a false positive (FP) event, and if a ground-truth event did not have an overlapping detector event by at least 1%, it was considered a false negative (FN) event. From there, we calculate the TPR as the number of TP events divided by the total number of ground-truth events, and FDR as the total FP events divided by the total number of detector events. An optimal detector score threshold is one that strikes a balance between TPR and FDR, where TPR represents the total true target signals detected and FDR represents the number of false detections of the detector output. A ‘reasonable’ balance between the two metrics aims to achieve the highest TPR possible with an FDR low enough to allow analyst review of the detector output. While we don’t directly present the false negative rate (FNR) in these results, the FNR reflects the proportion of target signals the detector missed to the number of target signals available to be detected (FN/FN+TP), and can easily be calculated by subtracting the TPR from 1 (1 – TPR).

To better understand detector performance at a resolution that is more comparable to the monitoring scale and acoustic presence results that we report for each species, we also looked at the detector performance on a daily scale. Days in which any automated detection overlapped in time and frequency by at least 1% of a ground-truth event were considered true positive days (TP_{day}). Days that contained automated detections that did not overlap with a ground-truth event were defined as false positive days (FP_{day}). Days in which there was at least one ground-truth event, but no overlapping detection are defined as false negative days (FN_{day}). We then calculated the TPR and FDR for daily performance. For daily-basis detector performance, a true positive rate (TPR_{daily}) is defined as the number of TP_{day} divided by the total number of days with ground-truth event days. False discovery rate (FDR_{daily}) is the number of FP_{day} divided by the sum of TP_{day} and FP_{day}. The scores of the detections were then used to determine a score threshold at which there was a reasonable balance of TPR and FDR, meaning that enough target signals were detected, while maintaining a low FDR to keep the number of detections that need to be reviewed manageable. Relying on a score threshold significantly reduces the volume of detections (mostly FPs) that need to be reviewed. The score threshold that was determined from the M-D1 subset was used for the remainder of the survey, for which only scores above the determined threshold were reviewed.

After the three years of data were collected, the performance of each detector was evaluated again with the new subset of ground-truth data that spanned the three years. Starting with a random date within the first 20 survey days (24 October, 2017), we manually searched for target signals on every 20th sound day for 1 - 3 sites (Table 9), yielding a new ground-truth dataset (hereafter referred to as the ‘full 20th-day’ dataset) consisting of 58 calendar-days and 117 site-days that span the duration of the survey period (October 2017 – October 2020). Since fin whale daily presence had been identified during the initial analysis, and since the detector performed well on a daily basis for the M-D1 dataset, we did not manually review days in the 20th-day subset for which presence was previously identified. This approach saved valuable analysis time to evaluate signal-to-detection and daily detector performance for the full 20th-day ground-truth dataset. However, due to this method, we did not evaluate daily performance per score threshold, rather we present performance for a score threshold of 0.75, which was the determined threshold from the M-D1 analysis. We do present detector performance on a signal-to-detection basis for the dates which were analyzed, and note that TPR_{daily} tends to be higher than signal-to-detection TPR for other evaluations. Right whale presence was sparse in the full 20th-day ground-truth dataset, therefore we added dates that occurred every 10th day after a subset day, from months during which right whales were commonly detected (November through May). These additional dates, hereafter referred to as the ‘full 10th-day’ ground-truth dataset, resulted in a total of 80 calendar-days and 171 site-days (Table 10).

Table 8. Subsampled dates and sites used for the M-D1 ground-truth dataset to evaluate the detector performance of the fin, right, and sei whale detectors.

Date	**Site**			
16-Oct-17	1M	4M	7M	12M
04-Nov-17	2M	5M	10M	1M
23-Nov-17	3M	6M	12M	2M
12-Dec-17	4M	7M	1M	3M
31-Dec-17	5M	10M	2M	
19-Jan-18	6M	12M	3M	5M
07-Feb-18	7M	1M	4M	6M
26-Feb-18	10M	2M	5M	7M
17-Mar-18	3M	6M		

Table 9. Subsampled dates and sites used for the full 20th-day ground-truth dataset to evaluate the detector performance of fin, right, and sei whale detectors. “NA” represents a date when the selected site does not have data, and blank cells mark dates when a third site was not sampled.

Date	**Site**		
24-Oct-17	4M	9A	NA
12-Nov-17	1M	6M	11A
1-Dec-17	3M	8A	13A
20-Dec-17	5M	10M	
8-Jan-18	2M	7M	12M
27-Jan-18	NA	9A	NA
15-Feb-18	1M	6M	11A
6-Mar-18	3M	8A	13A
25-Mar-18	NA	NA	
13-Apr-18	NA	7M	12M
2-May-18	NA	9A	14M
21-May-18	1M	6M	11A
9-Jun-18	NA	8A	13A
28-Jun-18	NA	10M	
17-Jul-18	NA	NA	12M
5-Aug-18	4M	9A	14M
24-Aug-18	1M	6M	11A
12-Sep-18	3M	NA	13A
1-Oct-18	NA	NA	
20-Oct-18	NA	7M	NA
8-Nov-18	NA	9A	14M
27-Nov-18	1M	NA	11A
16-Dec-18	3M	NA	13A
4-Jan-19	NA	NA	
23-Jan-19	2M	7M	12M
11-Feb-19	4M	9A	14M
2-Mar-19	1M	6M	11A
21-Mar-19	3M	8A	13A
9-Apr-19	5M	10M	
28-Apr-19	2M	7M	12M
17-May-19	4M	9A	14M
5-Jun-19	1M	NA	11A
24-Jun-19	3M	8A	13A
13-Jul-19	5M	10M	
1-Aug-19	2M	7M	12M

Table 9 (continued). Subsampled dates and sites used for the full 20th-day ground-truth dataset to evaluate the detector performance of the fin, right, and sei whale detectors. “NA” represents a date when the selected site does not have sound data, and the blank cells mark dates when a third site was not sampled.

Date	Site		
20-Aug-19	4M	9A	NA
8-Sep-19	1M	6M	11A
27-Sep-19	3M	8A	13A
16-Oct-19	5M	10M	
4-Nov-19	2M	7M	12M
23-Nov-19	4M	NA	14M
12-Dec-19	1M	6M	11A
31-Dec-19	NA	NA	NA
19-Jan-20	5M	10M	
7-Feb-20	2M	NA	12M
26-Feb-20	4M	NA	14M
16-Mar-20	1M	6M	NA
4-Apr-20	3M	NA	NA
23-Apr-20	5M	10M	
12-May-20	2M	NA	12M
31-May-20	NA	NA	14M
19-Jun-20	1M	6M	NA
8-Jul-20	NA	NA	NA
27-Jul-20	NA	10M	
15-Aug-20	NA	NA	12M
3-Sep-20	4M	NA	14M
22-Sep-20	1M	NA	NA
11-Oct-20	3M	NA	NA

Table 10. Subsampled dates and sites used for the full 10th-day ground-truth dataset to evaluate the detector performance the right whale detector. “NA” represents a date when the selected site does not have sound data, and the blank cells mark dates when a third site was not sampled. These additional dates supplemented the full 20th-day ground-truth dataset for right whale detector performance evaluation.

Date	**Site**		
30-Dec-17	1M	6M	11A
04-Apr-18	NA	NA	11A
14-Jan-19	1M	6M	11A
19-Apr-19	NA	NA	11A
29-Jan-20	1M	6M	NA
03-May-20	1M	6M	NA
22-Nov-17	2M	7M	12M
31-May-18	NA	7M	12M
07-Dec-18	NA	7M	NA
12-Mar-19	2M	7M	12M
22-Dec-19	2M	7M	12M
26-Mar-20	2M	NA	12M
18-Jan-18	3M	8A	13A
23-Apr-18	NA	8A	13A
08-May-19	3M	8A	13A
14-Nov-19	NA	NA	NA
22-May-20	3M	NA	NA
11-Dec-17	4M	9A	NA
16-Mar-18	NA	9A	NA
26-Dec-18	NA	9A	NA
31-Mar-19	4M	9A	14M
10-Jan-20	4M	NA	14M
14-Apr-20	4M	NA	14M
03-Nov-17	5M	10M	
12-May-18	NA	10M	
18-Nov-18	NA	NA	
27-May-19	5M	10M	
03-Dec-19	5M	10M	
07-Mar-20	5M	10M	

Occurrence Analysis of Focal Whale Species

For each target species, daily acoustic presence was annotated at each recording site. We report daily presence using *calendar-days* and *site-days*. The term "*calendar-days*" is defined by the number of days during the calendar month, regardless of site location. If a detection occurred on the first day of the month on 2 sites, it is considered to occur on 1 calendar-day. In contrast, the term "*site-days*" is defined by the collective number of calendar days (either days with acoustic recordings or days with acoustic detection of the target signal) for all sites. In the previous example, the detection would have occurred on 2 site-days. From these daily occurrence data, we were able to compute the percentage of calendar-days or site-days per week, month, and season, in which a target species was present. The resulting percentage of time with presence is hereafter referred to as the "*percent presence*". Only days in which acoustic data were available were factored into the percent presence metric in order to normalize the relative presence across sites, months, and seasons. For seasonal presence, we defined seasons as Fall: October – December, Winter: January – March, Spring: April – June, and Summer: July-September.

Noise Analysis

Ambient Noise Levels

Acoustic data were processed using the Raven-X toolbox (Dugan et al. 2016) in MATLAB using a Hann window with zero overlap, a fast Fourier transform (FFT) size where Δ *time* = 1 s and Δ *frequency* = 1 Hz. We used the metric of equivalent continuous sound pressure level or L_{eq} (dB_{rms} re: 1 μPa) to represent the average unweighted sound level of a continuous time-varying pressure signal (Morfey 2001) over specified time intervals. The resulting root-mean-square pressure is expressed by:

$$L_{eq} = 10log_{10}\frac{1}{T}\int_{0}^{T}\left(\frac{P_m^2(t)}{P_{ref}^2}\right)dt \qquad (1)$$

where T is the time interval, P_m is the measured sound pressure, t refers to time, and P_{ref} is the reference pressure of 1 μPa. Percentiles of the resulting L_{eq} values were used to quantify ambient noise levels. To reflect noise levels that could represent a period of time in which ships would pass by the sensors, we used a time average of 10-min, consistent with other studies (Hatch et al. 2012).

To illustrate the overall variation in ambient noise levels between sites, we calculated the cumulative percent distribution of L_{eq} values at each recording site and frequency band, which illustrate the percentage of time that sound pressure levels reached a particular L_{eq} value. The cumulative percent distribution allows for a comparison of noise values across sites within a particular frequency band. Species-specific frequency bands (Table 11) were used to represent the range in which each baleen whale species' hearing is likely most sensitive, and the bandwidth in which each whale species target signals occur (Dunlop et al. 2007; Hatch et al. 2012; Weirathmueller et al. 2013; Risch et al. 2014). We also included a "full band" in which noise levels within the full frequency band of the MARUs (10 – 2500 Hz) were measured for each site. For additional ambient noise measurements, see Appendix A.

Table 11. Referenced signal type, frequency band, and source levels of the target species used for detection range estimation and masking potential.

Species	Target Signal	Frequency Band	1/3rd Octave Band (lower - upper)	Source Level (dB re: 1µPa @ 1m RMS)
North Atlantic Right Whale	Upcall	71-224 Hz (Hatch et al. 2012)	70.8 – 224 Hz	172 (Parks and Tyack 2005, Hatch et al. 2012)
Humpback Whale	Song	29-2480 Hz (Dunlop et al. 2007)	17.8 – 708 Hz	169 (Au et al. 2006)
Fin Whale	20-Hz pulse	15-25 Hz (Weirathmueller et al. 2013)	17.8 – 28.2 Hz	189 (Weirathmueller et al. 2013)
Sei Whale	Downsweep	34 – 82 Hz (Baumgartner et al. 2008)	44.7 – 112 Hz	177 (Romagosa et al. 2015)
Blue Whale	Song	15 – 19 Hz (Mellinger and Clark 2003)	14.1 – 22.4 Hz	194 (McDonald et al. 2009)
Sperm Whale	Usual clicks	1000-4000 Hz (Diogou et al. 2019)	891 – 3550 Hz	155 (Diogou et al. 2019)

Whale Acoustic Masking

Because ship noise in this area is so extensive (Rice et al. 2014), this pervasive noise source poses limitations for both our ability to detect whales and the ability of whales to communicate. The influence of ship noise is a major issue for species whose vocalizations have significant overlap with low-frequency ship noise in the time and frequency domain, such as right whales or humpback whales. The signals of fin whales, sei whales, and blue whales typically occur in frequencies below the majority of ship noise (i.e. <50 Hz), and sperm whale clicks occur in higher frequencies than ship noise (>1000-2000 Hz).

Since ambient noise levels can dramatically affect the range in which a target signal from a sender can be received by a "listener", we estimated the detection range of signals from each target species given their respective source level estimates (see Table 11) as a function of measured ambient noise level percentiles at the sites with the highest and lowest median noise levels during the survey period. Detection range was estimated to be the distance from the receiver at which the receive level (RL) is exceeded by the ambient noise level. Detection range estimates were derived from the transmission loss model below:

$$TL = 20log_{10}(H) + 17log_{10}\left(\frac{R}{H}\right) \tag{2}$$

where *TL* is the transmission loss, *H* is the depth of the source to the sea floor (considered to be the transmission range from spherical to intermediate spherical/cylindrical spreading), and *R* represents the direct distance of the source to the receiver. The modeled detection range estimation is based on the distance from the sensor (using the TL model) for which the receive level (RL) exceeds the ambient noise level, based on a source level (SL), following a simplified passive sonar equation (Urick 1983):

$$RL = SL - TL \tag{3}$$

The intermediate $17\log_{10}R$ spreading loss model was used in a custom Matlab package to estimate sound propagation and transmission loss (Dugan et al. 2011). The model incorporates bathymetry in its calculation of propagation (e.g., Siderius and Porter 2008, Porter 2019) by using spherical radiation to depth and the intermediate spreading beyond that. We estimated the detection range of the six whale species at specific range steps for eight different bearings (0°, 45°, 90°, 135°, 180°, 225°, 270°, 315°) from each site location to account for varying bathymetry around each sensor, during high (95th percentile), median (50th percentile), and low (5th percentile) noise conditions.

Results

Evaluation of Whale Call Automated Detector Performance

True positive rate (TPR) and false discovery rate (FDR) were calculated for right whale, sei whale and fin whale detections. Of the 33-day M-D1 ground-truth dataset, target signals were manually confirmed in 9, 27, and 5 days for right, fin, and sei whales, respectively. Within the full 20th-day ground-truth dataset, fin and sei whales were found on 86 and 19 of the 116 site-days, respectively. In the full 10th-day ground-truth dataset, right whales were found on 29 of the 171 site-days.

North Atlantic Right Whale Upcall Detector Performance

To determine an appropriate score threshold for the right whale upcall detector, we assessed the TPR and FDR at different detection thresholds. From the M-D1 ground-truth dataset, the North Atlantic right whale upcall detector had a TPR ranging from 0.12 (threshold = 0.95) to 0.65 (threshold = 0.1). At a threshold of 0.55, the TPR was low (0.40), however, compared to lower threshold, the number of false positives per hour (0.86) and the FDR (0.86) showed a relatively manageable number of detections to review (n = 797 detections, 26% fewer detections than threshold 0.5, and 46% fewer detections than threshold of 0.45) within the time constraints of the survey, therefore we decided to use a score threshold of 0.55 (Table 12). To provide context to the number of detections at different score thresholds, note the Total Test column of Table 12.

On a daily basis, the right whale upcall detector found presence on 9 days with a score threshold of 0.1, however, the FDR_{daily} was high (0.73), resulting in a prohibitively high number of detections to manually review, when scaled to the full 3-year survey. The right whale detector began to miss days with presence if the score threshold was set above 0.1 (Table 13; Figure 9A, Figure 10A). In Table 13, the increase in FDR_{daily} as a function of increasing score is a statistical artifact of converting the number of detections to TPR and FPR on a daily scale. With the score threshold of 0.55, the TPR_{daily} for right whale presence was 0.5; however, from our inspection and analysis of visually identified right whale signals, we believe the low TPR_{daily} from the performance evaluation is overly biased for low SNR events, and the actual TPR_{daily} for the survey data is significantly higher than 0.5. We chose to use the score threshold of 0.55 as the threshold for running the right whale upcall detector throughout the 3-year survey, which resulted in approximately 391,000 detections.

Performance from the full 10th-day ground-truth dataset showed that the score of 0.55 yielded a TPR of 0.53 (391 TP upcalls and 344 FN upcalls) on a signal-to-detection basis (e.g., when a detection aligns in time and frequency with a target signal), and a TPR_{daily} of 0.69, where 20 days had at least one TP detection and 9 days had FN. Tables for the full 10th-day detector performance results can be found in Appendix B (Table 31, Table 32, Figure 72, Figure 73).

Table 12. Performance metrics of the right whale upcall detector for the M-D1 ground-truth dataset. Score Threshold is the sensitivity level of the algorithm, TPR is the true positive rate, FDR is false discovery rate, FP/hr represents the number of false positives (FP) per hour, TP Truth represents the number of target signals the detector found, FN Truth represents the number of target signals the detector missed, Total Truth represents the number target signals in the ground-truth data, TP Test represents the number of detector events that detected a target signal (which may contain more than one detection event per true call), FP Test represents the number of FP detections, and Total Test represents the total number of detections by the automated detector.

Score Threshold	TPR	FDR	FP/hr	TP Truth	FN Truth	Total Truth	TP Test	FP Test	Total Test
0.1	0.65	0.99	39.24	185	101	286	186	31076	31262
0.15	0.59	0.99	20.13	170	116	286	171	15941	16112
0.2	0.58	0.98	11.69	166	120	286	167	9256	9423
0.25	0.55	0.97	7.42	157	129	286	158	5873	6031
0.3	0.52	0.96	4.89	150	136	286	150	3871	4021
0.35	0.49	0.95	3.41	140	146	286	140	2698	2838
0.4	0.46	0.94	2.41	131	155	286	131	1911	2042
0.45	0.46	0.91	1.71	130	156	286	130	1358	1488
0.5	0.42	0.89	1.21	119	167	286	119	960	1079
0.55	0.40	0.86	0.86	114	172	286	114	683	797
0.6	0.38	0.82	0.62	108	178	286	108	493	601
0.65	0.36	0.77	0.44	103	183	286	103	349	452
0.7	0.34	0.72	0.31	96	190	286	96	247	343
0.75	0.32	0.65	0.22	92	194	286	92	173	265
0.8	0.29	0.59	0.15	84	202	286	84	120	204
0.85	0.25	0.54	0.11	72	214	286	72	84	156
0.9	0.21	0.50	0.07	60	226	286	60	59	119
0.95	0.12	0.51	0.04	33	253	286	33	34	67

Table 13. Summary of the right whale automated detector algorithm evaluation for the M-D1 ground-truth dataset on daily scale. Score Threshold is the sensitivity level of the algorithm, Total True Days represents days with upcalls, Total Days with Detections represents days that had automated detections, Total TP Days are days with true positives (TP), Total FP Days are days with false positives (FP) and no TPs, true positive rate (TPR), and false discovery rate (FDR).

Score Threshold	Total True Days	Total Days with Detections	Total TP Days	Total FP Days	TPR	FDR
0.1	9	33	9	24	1.0	0.73
0.2	9	33	8	25	0.89	0.76
0.3	9	33	7	26	0.78	0.79
0.4	9	33	6	27	0.67	0.82
0.5	9	33	5	28	0.56	0.85
0.6	9	32	4	28	0.44	0.88
0.7	9	31	4	27	0.44	0.87
0.8	9	21	4	17	0.44	0.81
0.9	9	9	3	6	0.33	0.67

Fin Whale 20-Hz Pulse Detector Performance

For the M-D1 ground-truth dataset, the signal-to-detection fin whale detector performance (Table 14) yielded TPRs that ranged from 0.11 (score threshold = 0.95) to 0.98 (score threshold = 0.25). At a score threshold of 0.75, the TPR was 0.48 and the FDR was 0.003, and the total number of detections for the M-D1 subset equaled 59,461. Considering the relatively higher number of false positives at lower score thresholds (see Total Test column in Table 14), it was reasonable to use a score threshold of 0.75 for the 3-year dataset, which resulted in approximately 13,454,000 detections. On a daily scale, the fin whale detector did not miss any of the manually verified days (TPR_{daily} = 1) below a score threshold of 0.5 (Table 15; Figure 9B, Figure 10B). At scores greater than 0.5, the TPR_{daily} gradually decreased. The daily FDR_{daily} with a score threshold of 0.5 was 0.16, in other words 5 of the 33 sampled days had detections in which there were no 20-Hz fin whale pulses. At a score threshold of 0.75 the TPR_{daily} remained high (0.96) and the FDR_{daily} was low (0.07), where the detector missed 1 of 27 days with presence, illustrating that fin whale pulses were rarely missed by the detector on a daily scale.

Using the full 20th-day ground-truth dataset, the fin whale detector had a TPR of 0.81 on a detector-to-signal basis (363 TP and 85 FN), and a TPR_{daily} of 0.99 (TP_{day} = 85 and FN_{day} = 1) with the score threshold of 0.75. The detector performance summary table for the full 20th-day detector performance results can be found in Appendix B (Table 33, Figure 74).

Table 14. Performance metrics of the fin whale 20-Hz pulse detector for the M-D1 ground-truth dataset. Score Threshold is the sensitivity level of the algorithm, TPR is the true positive rate, FDR is false discovery rate, FP/hr represents the number of false positives (FP) per hour, TP Truth represents the number of target signals the detector found, FN Truth represents the number of target signals the detector missed, Total Truth represents the number target signals in the ground-truth data, TP Test represents the number of detector events that detected a target signal (which may contain more than one detection event per true call), FP Test represents the number of FP detections, and Total Test represents the total number of detections by the automated detector.

Score Threshold	TPR	FDR	FP/hr	TP Truth	FN Truth	Total Truth	TP Test	FP Test	Total Test
0.25	0.98	0.40	186.13	1695	35	1730	119182	78456	197638
0.3	0.97	0.36	156.56	1677	53	1730	115829	65994	181823
0.35	0.95	0.32	126.96	1648	82	1730	112000	53517	165517
0.4	0.92	0.16	46.6	1596	134	1730	103143	19642	122785
0.45	0.81	0.07	18.21	1401	329	1730	96225	7678	103903
0.5	0.75	0.04	8.82	1294	436	1730	90909	3719	94628
0.55	0.70	0.02	4.52	1210	520	1730	85699	1907	87606
0.6	0.65	0.01	2.37	1115	615	1730	80195	1000	81195
0.65	0.60	0.01	1.29	1036	694	1730	74099	543	74642
0.7	0.54	0.00	0.69	937	793	1730	67238	290	67528
0.75	0.48	0.00	0.44	836	894	1730	59277	184	59461
0.8	0.43	0.00	0.33	749	981	1730	49090	141	49231
0.85	0.36	0.00	0.22	627	1103	1730	35877	91	35968
0.9	0.25	0.00	0.13	427	1303	1730	19137	54	19191
0.95	0.11	0.00	0.03	195	1535	1730	5699	11	5710

Table 15. Summary of fin whale automated detection algorithm evaluation for the M-D1 ground-truth dataset on a daily scale. Score Threshold is the sensitivity level of the algorithm, Total True Days represents days with upcalls, Total Days with Detections represents days that had detections, Total TP Days are days with true positives (TP), Total FP Days are days with false positives (FP), true positive rate (TPR), and false discovery rate (FDR).

Score Threshold	Total True Days	Total Days with Detections	Total TP Days	Total FP days	TPR	FDR
0.4	27	33	27	6	1	0.18
0.5	27	32	27	5	1	0.16
0.6	27	30	26	4	0.96	0.13
0.7	27	28	26	2	0.96	0.07
0.8	27	24	24	0	0.89	0
0.9	27	20	20	0	0.74	0

Sei Whale Downsweep Detector Performance

Of the 33 sampled days in M-D1, sei whale downsweeps were found on 5 days. An evaluation of the sei whale signal-to-detector performance for the M-D1 ground-truth dataset (Table 16) showed a sharp decrease in the TPR from a score of 0.65 (TPR = 0.52) to a score of 0.7 (TPR = 0.26), for which there was also a strong decrease in the total number of false positive detections (n = 5,465 and 456 detections, respectively). To maintain a reasonable TPR while limiting the number of FPs, we selected a score threshold of 0.68 (TPR = 0.36, FDR = 0.88) to use for the detector. On a daily scale, the sei whale detector correctly identified 4 of the 5 days with sei whale downsweeps with a score of 0.68 in the M-D1 dataset, resulting in a $\text{TPR}_{\text{daily}}$ of 0.7 (Table 16, Table 17; Figure 9C, Figure 10C). We selected a score threshold of 0.68 to apply to the 3-year detector output, resulting in approximately 360,000 detections.

Using the full 20th-day ground-truth dataset, the sei whale detector had a TPR of 0.33 on a detector-to-signal basis (558 TP and 1,122 FN), and a TPR of 0.33 on a daily scale (7 days with at least one TP and 12 days with FN) for the score threshold of 0.68. The detector-to-signal TPR and $\text{TPR}_{\text{daily}}$ for the M-D1 dataset are notably higher than those of the 20th-day dataset. The difference in TPR may be caused by several factors: 1) the TPR from the M-D1 dataset was based on a small sample size (5 days with presence out of 33 sampled days) and may not be representative of the variation in sei whale signals or the ambient noise environment of NY Bight, 2) we observed many distorted sei whale downsweeps (Figure 11) that could be due to signal propagation and reflection of the signal off the seafloor and water surface (Wiggins et al. 2004, Munger et al. 2011, Newhall et al. 2012), which the detector was not trained to detect, and 3) and signals with a low signal-to-noise ratio (SNR) were not detected as well as signals with a higher SNR. Detector performance tables for the full 20th-day detector performance results can be found in Appendix B (Table 34, Table 35, Figure 75, Figure 76).

To test the influence that SNR had on an event being detected (TP) or missed (FN) by the detector, a random set of 100 TP and 100 FN events were selected from the full 20th-day ground-truth dataset. Event boxes were adjusted around the signal to exclude non-target signals from the SNR measurement and to ensure that at least 25% of the time-frequency bins in the event box contained background noise. We calculated the signal-to-noise ratio in which *noise* is the 25th percentile time-frequency bin within the event box, and the *signal* is the 100th percentile bin (Mellinger and Bradbury 2007). Event boxes that could not be resized to exclude noise from signal were removed from this analysis, leaving 191 usable sei whale downsweeps for this analysis. A one-way ANOVA showed a statistically significant difference ($F_{1,189} = 6.48$, $p = .0117$) in SNR between TP (n = 24, mean SNR = 9.28 dB ± 0.37 SE) and FN (n = 167, mean SNR dB = 8.27 ± 0.14 SE) for events that had a score of 0.68 or higher. This suggests that lower SNR events were more likely to be missed by the detector at a score of 0.68 or higher.

To investigate the influence that the distorted sei whale downsweep signal (Figure 11) may have on the detector, we marked all 20th-day ground-truth sei whale events as a) a signal in which the downsweep frequency contour appears to be split into multiple bands (n = 666) or b) signals that were a single band (n = 433). Events for which distortion of the signal was difficult to determine (e.g., due to low SNR) were excluded from this analysis. When distorted downsweeps were excluded, detections with a score of 0.68 or more yielded a TPR of 0.51, suggesting that the distorted sei whale signals influenced the detector performance at a score threshold of 0.68. Additionally, a Fisher's exact test shows that the probability of a TP detection is significantly higher for signals that were not distorted than for signals that are ($p < .0001$).

Table 16. Performance of the sei whale downsweep template detector for the M-D1 ground-truth dataset. Score Threshold is the score, TPR is the true positive rate, FDR is the false discovery rate, FP/hr represents the rate of false positives (FP) per hour, TP Truth represents the number of downsweeps the detector found, FN Truth represents the number of downsweeps the detector missed, Total Truth represents the number of downsweeps in the ground-truth data, TP Test represents the number of detector events that detected a downsweep (which may contain more than one detection event per true call), FP Test represents the number of false positive (FP) detections, and Total Test represents the total number of detection events.

Score Threshold	TPR	FDR	FP/hr	TP Truth	FN Truth	Total Truth	TP Test	FP Test	Total Test
0.6	0.80	1.00	59.58	78	19	97	244	47102	47346
0.65	0.52	0.97	6.91	50	47	97	163	5465	5628
0.7	0.26	0.79	0.58	25	72	97	118	456	574
0.75	0.12	0.37	0.06	12	85	97	75	44	119
0.8	0.05	1.00	0	5	92	97	25	0	25
0.85	0.03	1.00	0	3	94	97	5	0	5
0.9	0.00	NA	0	0	97	97	0	0	0
0.95	0.00	NA	0	0	97	97	0	0	0

Table 17. Summary of the sei whale automated detector algorithm evaluation for the M-D1 ground-truth dataset on a daily scale. Score Threshold is the sensitivity level of the algorithm, Total True Days represents days with upcalls, Total Days with Detections represents days that had detections by the detector algorithm, Total TP days are days with true positives (TP), Total FP days are days with false positives (FP), true positive rate (TPR), and false discovery rate (FDR).

Score Threshold	Total True Days	Total Days with Detections	Total TP Days	Total FP Days	TPR	FPR
0.6	5	33	4	29	0.8	0.88
0.7	5	22	3	19	0.6	0.86
0.8	5	1	1	0	0.2	0
0.9	5	0	0	0	0	NA

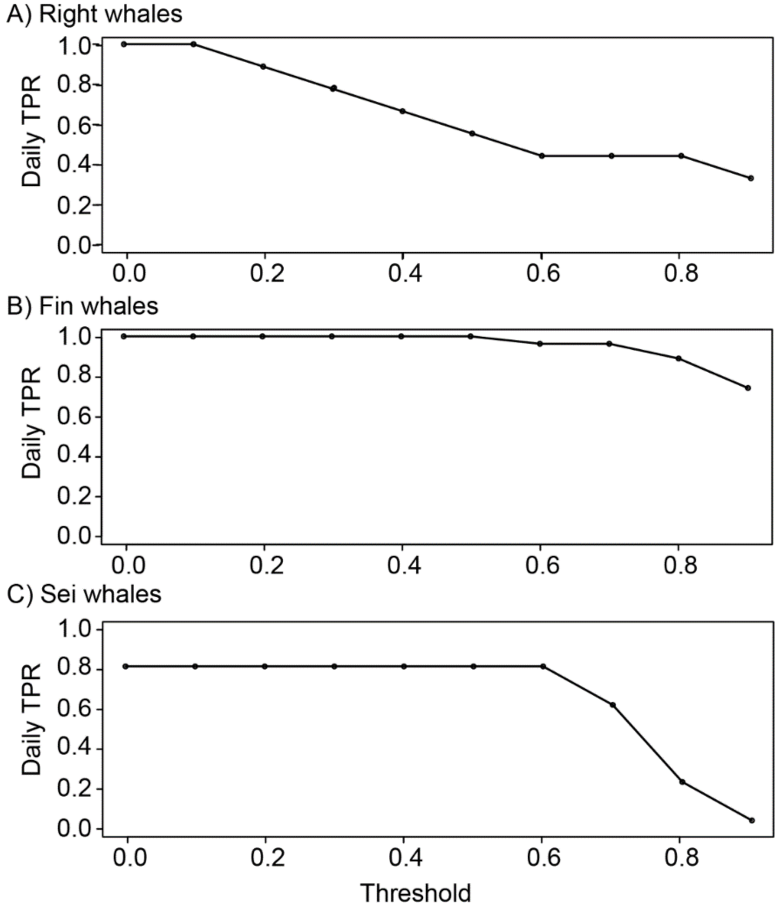


Figure 9. Daily true positive rates (TPR) of detection algorithms for three target species at varying sensitivity thresholds based on the M-D1 ground-truth dataset: A) right whales, B) fin whales, C) sei whales.

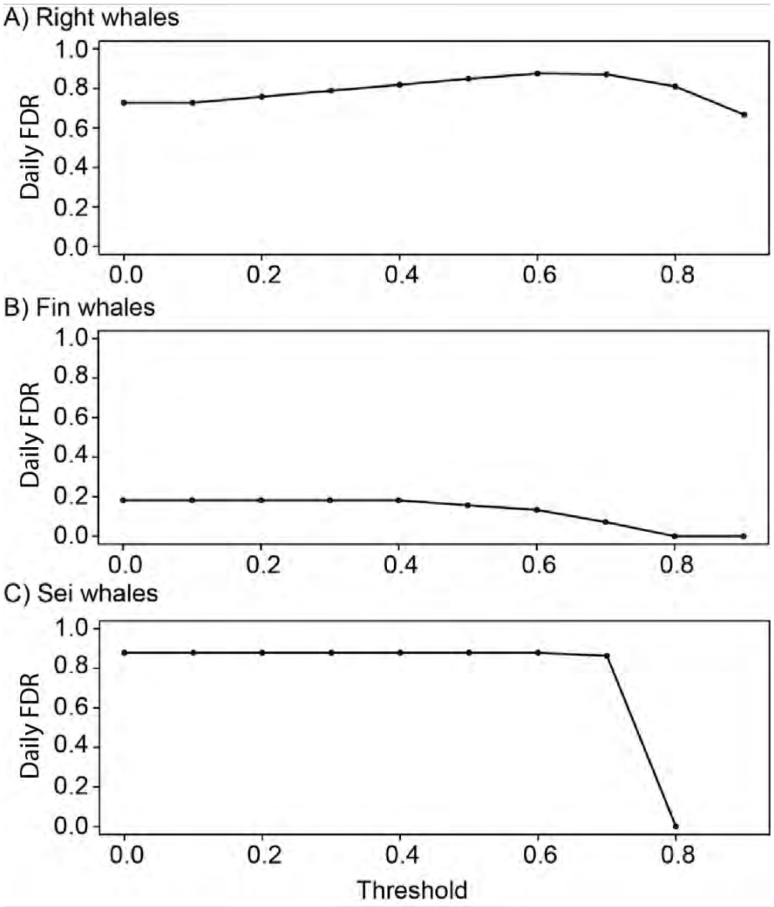


Figure 10. Daily false discovery rates (FDR) of detection algorithms for three target species at varying sensitivity thresholds based on the M-D1 ground-truth dataset: A) right whales, B) fin whales, C) sei Whales.

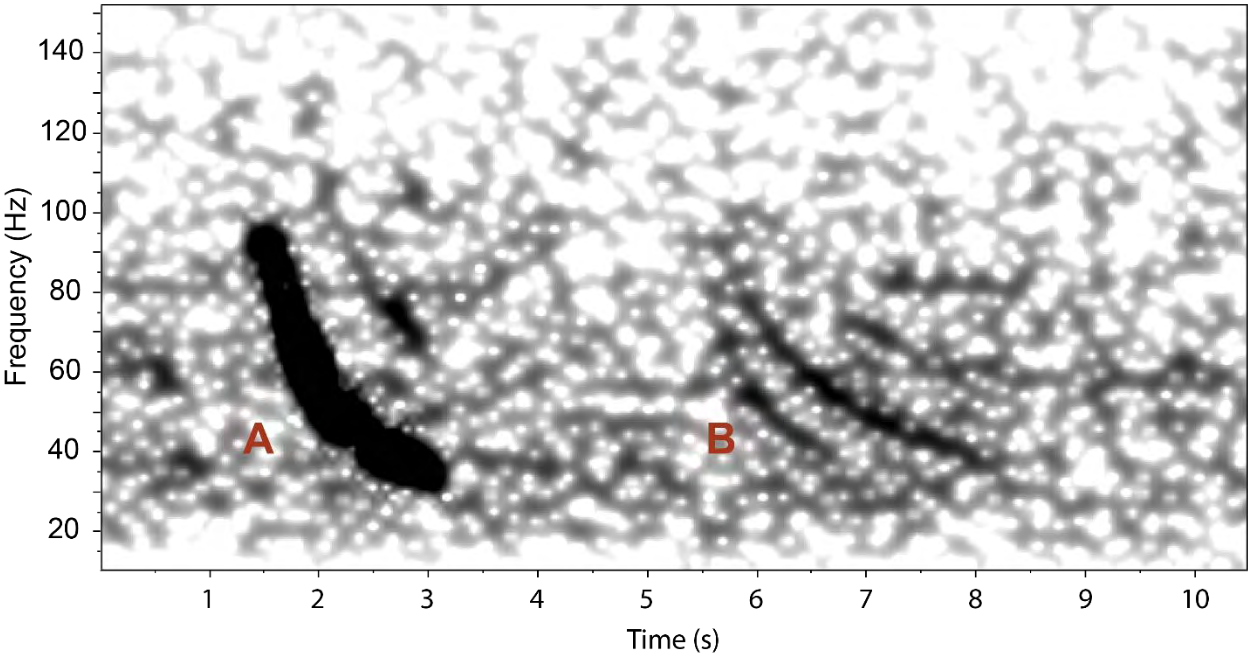


Figure 11. Spectrogram of sei whale downsweeps exhibiting frequency dispersion: A) an exemplar representative sei whale downsweep, which is similar to the templates used for the template detector, B) a multi-path (distorted) sei whale downsweep, which was often not detected by the template detector. Spectrogram was created with a window size = 2048, DFT = 4096, with frequency and time bins of 1.22 Hz and 0.0614 s, respectively.

Occurrence of Focal Whale Species

Whale Acoustic Occurrence per Deployment

Target species were acoustically detected throughout the 3-year study, with many species occurring during each deployment period (Table 18 and Table 19, also see Year-1 and Year-2 reports; Estabrook et al. 2019, 2020). Year-3 data collection began during the end of M-D6 (August 2019 – October 2019), which contained approximately 10 calendar days within the Year-3 survey period (16 – 25 October 2019). M-D7 (October 2019 – January 2020) recorded across approximately 94 calendar-days at each site, during which 44% of those days recorded right whales, 82% of the days recorded humpback whales, 93% recorded fin whales, and 7% recorded sei whales (Table 18). Blue whales were not recorded during the deployment period. Sperm whale presence was not annotated on MARUs due to the low sample-rate (5 kHz). Deployment M-D8 (January – July 2020) recorded 157 calendar-days. Of those days, right whales were detected on 15%, humpback whales were detected on 38%, fin whales were detected on 100% and sei whales were detected on 80% of the days. In contrast to M-D7, blue whales were detected on 11% of the recorded calendar-days. Deployment M-D9 (June – November 2020) recorded a total of 133 calendar-days, however, 16 of those days occurred beyond the Year-3 end date (15 October 2020) and were not analyzed, resulting in 117 survey days for M-D9. Of those 117 calendar-days, 16% had right whale presence, 86% had humpback whale presence, 100% had fin whale presence, and less than 1% had blue whale presence. Sei whales were not detected during M-D9.

Since the A-D4 and A-D5 AMARs and AURALs were not recovered for the Year-3 recording period. the only available AMAR data for Year-3 came from the site 11A AMAR from A-D3 that surfaced in February 2020. The AMAR recorded from 14 March 2019 through 10 January 2020, comprising 87 days of usable sound data during the Year-3 survey period (Table 7). Of those 87 days, right whales were detected on 15% of days, humpback whales were detected on 36% of days, and fin whales were detected on 89% of days. Sei whales, blue whales, and sperm whales were not detected at site 11A during that period. Species' presence data from site 11A deployment A-D3 are included in the results for each species below.

Table 18. Summary of the days that were recorded at each site per deployment, calendar-day presence for focal baleen whale species for the 3-year survey (October 2017 – 2020), and the corresponding percentage of calendar-days in which each species was detected.

		Right		**Humpback**		**Fin**		**Sei**		**Blue**	
Deployment	**Total Recording-Days**	**Days with presence**	**% Days**	**Days with presence**	**% Days**	**Days with presence**	**% Days**	**Days with presence**	**% Days**	**Days with presence**	**% Days**
M-D1	154	91	59	100	65	141	92	47	31	26	17
M-D2	94	33	35	85	90	91	97	45	48	0	0
M-D3	157	14	9	110	70	155	99	4	3	0	0
M-D4	101	69	68	52	51	100	99	49	49	7	7
M-D5	115	64	56	105	91	112	97	59	51	0	0
M-D6	83	8	10	66	80	75	90	17	20	0	0
M-D7	94	41	44	77	82	87	93	7	7	0	0
M-D8	157	24	15	59	38	157	100	125	80	17	11
M-D9	117	19	16	101	86	117	100	0	0	1	0
A-D1	272	106	39	171	63	264	97	74	27	1	0
A-D2	241	77	32	194	80	241	100	14	6	0	0
A-D3	220	43	20	167	76	288	131	41	19	0	0
A-D4	0	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
A-D5	0	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Total	**1821**	**589**	**32**	**1287**	**71**	**1842**	**101**	**482**	**26**	**52**	**3**

Table 19. Summary of total days and percent of time in which sperm whale*s* were detected per deployment during the 3-year survey (October 2017 – October 2020).

Deployment	**Total Recording-Days**	**Days with presence**	**% Days**
A-D1	272	113	42
A-D2	241	64	27
A-D3	220	44	20
A-D4	0	NA	NA
A-D5	0	NA	NA
Total	**733**	**221**	**30**

Table 20. Daily presence for each focal whale species by month across all sites (MARUs and AMARs), and the corresponding percentage of total calendar-days in which the species was detected.

Month-Year	**Total Days Recorded**	**Right**		**Humpback**		**Fin**		**Sei**		**Blue**	
		# Days Detected	**% Days Detected**	**# Days Detected**	**% Days Detected**	**# Days Detected**	**% Days Detected**	**# Days Detected**	**% Days Detected**	**# Days Detected**	**% Days Detected**
17-Oct	16	2	13	3	19	16	100	8	50	0	0
17-Nov	30	25	83	11	37	30	100	9	30	3	10
17-Dec	31	31	100	28	90	31	100	7	23	7	23
18-Jan	31	24	77	26	84	31	100	10	32	8	26
18-Feb	28	11	39	28	100	28	100	5	18	8	29
18-Mar	31	22	71	25	81	31	100	24	77	0	0
18-Apr	30	19	63	25	83	30	100	30	100	0	0
18-May	31	14	45	29	94	29	94	27	87	0	0
18-Jun	30	7	23	29	97	30	100	7	23	0	0
18-Jul	30	3	10	28	93	30	100	6	20	0	0
18-Aug	31	4	13	31	100	31	100	2	6	0	0
18-Sep	30	3	10	29	97	30	100	0	0	0	0
18-Oct	31	4	13	29	94	31	100	3	10	0	0
18-Nov	30	19	63	27	90	30	100	5	17	0	0
18-Dec	31	28	90	24	77	31	100	1	3	0	0
19-Jan	31	24	77	26	84	31	100	0	0	6	19
19-Feb	28	16	57	22	79	28	100	1	4	1	4
19-Mar	31	24	77	30	97	31	100	27	87	0	0
19-Apr	30	28	93	27	90	30	100	30	100	0	0
19-May	31	25	81	31	100	31	100	31	100	0	0

Table 20 (continued). Daily presence for each focal whale species by month across all sites (MARUs and AMARs), and the corresponding percentage of total calendar-days in which the species was detected.

Month-Year	**Total Days Recorded**	**Right**		**Humpback**		**Fin**		**Sei**		**Blue**	
		# Days Detected	**% Days Detected**	**# Days Detected**	**% Days Detected**	**# Days Detected**	**% Days Detected**	**# Days Detected**	**% Days Detected**	**# Days Detected**	**% Days Detected**
19-Jun	30	23	77	30	100	30	100	10	33	0	0
19-Jul	31	2	6	31	100	31	100	0	0	0	0
19-Aug	31	7	23	25	81	31	100	14	45	0	0
19-Sep	30	2	7	29	97	30	100	4	13	0	0
19-Oct	31	3	10	23	74	31	100	0	0	0	0
19-Nov	30	12	40	26	87	30	100	3	10	0	0
19-Dec	31	19	61	31	100	31	100	2	6	0	0
20-Jan	31	14	45	18	58	28	90	4	13	6	19
20-Feb	29	0	0	15	52	29	100	25	86	11	38
20-Mar	31	0	0	10	32	31	100	26	84	0	0
20-Apr	30	16	53	5	17	30	100	26	87	0	0
20-May	31	7	23	21	68	31	100	30	97	0	0
20-Jun	30	1	3	5	17	28	93	16	53	0	0
20-Jul	31	9	29	14	45	31	100	0	0	1	3
20-Aug	31	5	16	31	100	31	100	0	0	0	0
20-Sep	30	5	17	28	93	30	100	0	0	0	0
20-Oct	31	0	0	28	90	31	100	0	0	0	0

Table 21. Daily presence for sperm whales by month across all AMAR sites and corresponding percentage of total calendar-days in which sperm whale usual clicks were detected.

Month-Year	Total Days Recorded	Sperm Whale	
		# Days Detected	% Days Detected
17-Oct	16	1	6
17-Nov	30	8	27
17-Dec	31	5	16
18-Jan	31	15	48
18-Feb	28	19	68
18-Mar	31	13	42
18-Apr	30	10	33
18-May	31	23	74
18-Jun	30	16	53
18-Jul	30	15	50
18-Aug	31	26	84
18-Sep	30	21	70
18-Oct	31	5	16
18-Nov	30	0	0
18-Dec	31	0	0
19-Jan	31	0	0
19-Feb	28	0	0
19-Mar	31	1	3

Table 21 (continued). Daily presence for sperm whales by month across all AMAR sites and corresponding percentage of total calendar-days in which sperm whale usual clicks were detected.

Month-Year	Total Days Recorded	Sperm Whale	
		# Days Detected	% Days Detected
19-Apr	30	5	17
19-May	31	8	26
19-Jun	30	6	20
19-Jul	31	8	26
19-Aug	31	10	32
19-Sep	30	7	23
19-Oct	31	1	3
19-Nov	30	0	0
19-Dec	31	0	0
20-Jan	10	0	0
20-Feb	0	NA	NA
20-Mar	0	NA	NA
20-Apr	0	NA	NA
20-May	0	NA	NA
20-Jun	0	NA	NA
20-Jul	0	NA	NA
20-Aug	0	NA	NA
20-Sep	0	NA	NA
20-Oct	0	NA	NA

Table 22. Seasonal number of days with detections for each focal baleen whale species among all recording sites: Fall (October – December), Winter (January – March), Spring (April – June), and Summer (July - September).

Season		**Right**		**Humpback**		**Sei**		**Fin**		**Blue**	
	Total Site-Days Recorded	**# Site-Days Detected**	**% Site-Days Detected**	**# Site-Days Detected**	**% Site-Days Detected**	**# Site-Days Detected**	**% Site-Days Detected**	**# Site-Days Detected**	**% Site-Days Detected**	**# Site-Days Detected**	**% Site-Days Detected**
Fall 2017	987	207	21	186	19	49	5	690	70	18	2
Winter 2018	923	138	15	400	43	73	8	704	76	34	4
Spring 2018	843	74	9	405	48	152	18	378	45	0	0
Summer 2018	803	14	2	223	28	8	1	564	70	0	0
Fall 2018	607	81	13	196	32	9	1	432	71	0	0
Winter 2019	1043	124	12	301	29	135	13	833	80	14	1
Spring 2019	1184	155	13	391	33	266	22	754	64	0	0
Summer 2019	1186	13	1	270	23	50	4	852	72	0	0
Fall 2019	972	58	6	333	34	6	1	758	78	0	0
Winter 2020	820	33	4	125	15	194	24	754	92	63	8
Spring 2020	738	46	6	133	18	243	33	381	52	0	0
Summer 2020	528	21	4	187	35	0	0	481	91	2	0

Table 23. Seasonal number of site-days with detections of sperm whale whales among AMAR sites: Fall (October – December), Winter (January – March), Spring (April – June), and Summer (July - September).

Season	**Total Days Recorded**	**Sperm**	
		# Days Detected	**% Days Detected**
Fall 2017	308	14	5
Winter 2018	360	62	17
Spring 2018	364	59	16
Summer 2018	287	88	31
Fall 2018	276	5	2
Winter 2019	286	2	1
Spring 2019	363	19	5
Summer 2019	368	25	7
Fall 2019	149	1	1
Winter 2020	10	0	0
Spring 2020	0	NA	NA
Summer 2020	0	NA	NA

Table 24. Summary of daily presence for each focal species during the Year-3 survey (October 2019 – October 2020). Total Calendar Days represents the number of days recorded per site (maximum possible = 365), Days Presence represents the total number of days in which the species was detected, and % Days represents the percentage of recorded days on which the species was detected. Percent Days was not calculated for sites with fewer than 5 Total Calendar-Days in Year-3, as the percentages based on a low number of days would be uninformative.

Site	**Total Calendar -Days**	**Right**		**Humpback**		**Fin**		**Sei**		**Blue**		**Sperm**	
		Days Presence	**% Days**	**Days Presence**	**% Days**	**Days Presence**	**% Days**	**Days Presence**	**% Days**	**Days Presence**	**% Days**	**Days Presence**	**% Days**
1M	352	18	5	78	22	312	89	88	25	14	4	NA	NA
2M	253	19	8	46	18	230	91	87	34	14	6	NA	NA
3M	265	13	5	100	38	245	92	60	23	11	4	NA	NA
4M	298	11	4	106	36	262	88	51	17	8	3	NA	NA
5M	247	7	3	66	27	136	55	9	4	0	0	NA	NA
6M	247	15	6	78	32	141	57	14	6	0	0	NA	NA
7M	97	9	9	54	56	65	67	1	1	0	0	NA	NA
8A	4	0	NA	0	NA	1	NA	0	NA	0	NA	0	NA
9A	4	1	NA	1	NA	4	NA	0	NA	0	NA	0	NA
10M	363	9	2	61	17	224	62	9	2	0	0	NA	NA
11A	87	13	15	31	36	77	89	0	0	0	0	0	0
12M	363	17	5	63	17	274	75	45	12	5	1	NA	NA
13A	4	0	NA	1	NA	4	NA	0	NA	0	NA	0	NA
14M	359	24	7	68	19	333	93	79	22	13	4	NA	NA
15A	0	No Data	NA	No Data	NA	No Data	NA	No Data	NA	No Data	NA	No Data	NA

Table 25. Summary of site-day detections for each baleen whale species during the Year-1, Year-2, and Year-3 surveys (October 2017 – October 2020). Maximum possible Total Calendar Days refers to the number of calendar days that were sampled during the 3-year survey.

Site	Total Calendar Days	Right		Humpback		Fin		Sei		Blue	
		# Days presence	% Days	# Days presence	% Days	# Days presence	% Days	# Days presence	% Days	# Days presence	% Days
1M	1047	85	8	245	23	849	81	193	18	42	4
2M	679	77	11	140	21	599	88	176	26	36	5
3M	864	52	6	297	34	789	91	134	16	20	2
4M	693	44	6	277	40	610	88	107	15	10	1
5M	655	56	9	172	26	403	62	34	5	0	0
6M	727	69	9	251	35	404	56	33	5	0	0
7M	757	56	7	197	26	266	35	4	1	0	0
8A	492	15	3	43	9	125	25	5	1	0	0
9A	733	99	14	188	26	344	47	35	5	0	0
10M	872	76	9	213	24	601	69	27	3	0	0
11A	814	121	15	300	37	726	89	49	6	0	0
12M	912	76	8	291	32	731	80	93	10	5	1
13A	732	81	11	386	53	689	94	113	15	1	0
14M	817	57	7	207	25	604	74	182	22	17	2
15A	0	0	NA	0	NA	0	NA	0	NA	0	NA
Total	10794	964	9	3207	30	7740	72	1185	11	131	1

Table 26. Summary of site-day presence of sperm whales during the Year-1, Year-2, and Year-3 surveys (October 2017 – October 2020). Note that 103 site-days were sampled in Year-3. Total Calendar Days refers to the number of calendar days that were sampled during the 3-year survey.

Site	Total Calendar Days	Sperm	
		# Days presence	% Days
8A	492	16	3
9A	733	83	11
11A	814	79	10
13A	732	97	13
15A	0	NA	NA
Total	2771	275	10

North Atlantic Right Whale Occurrence

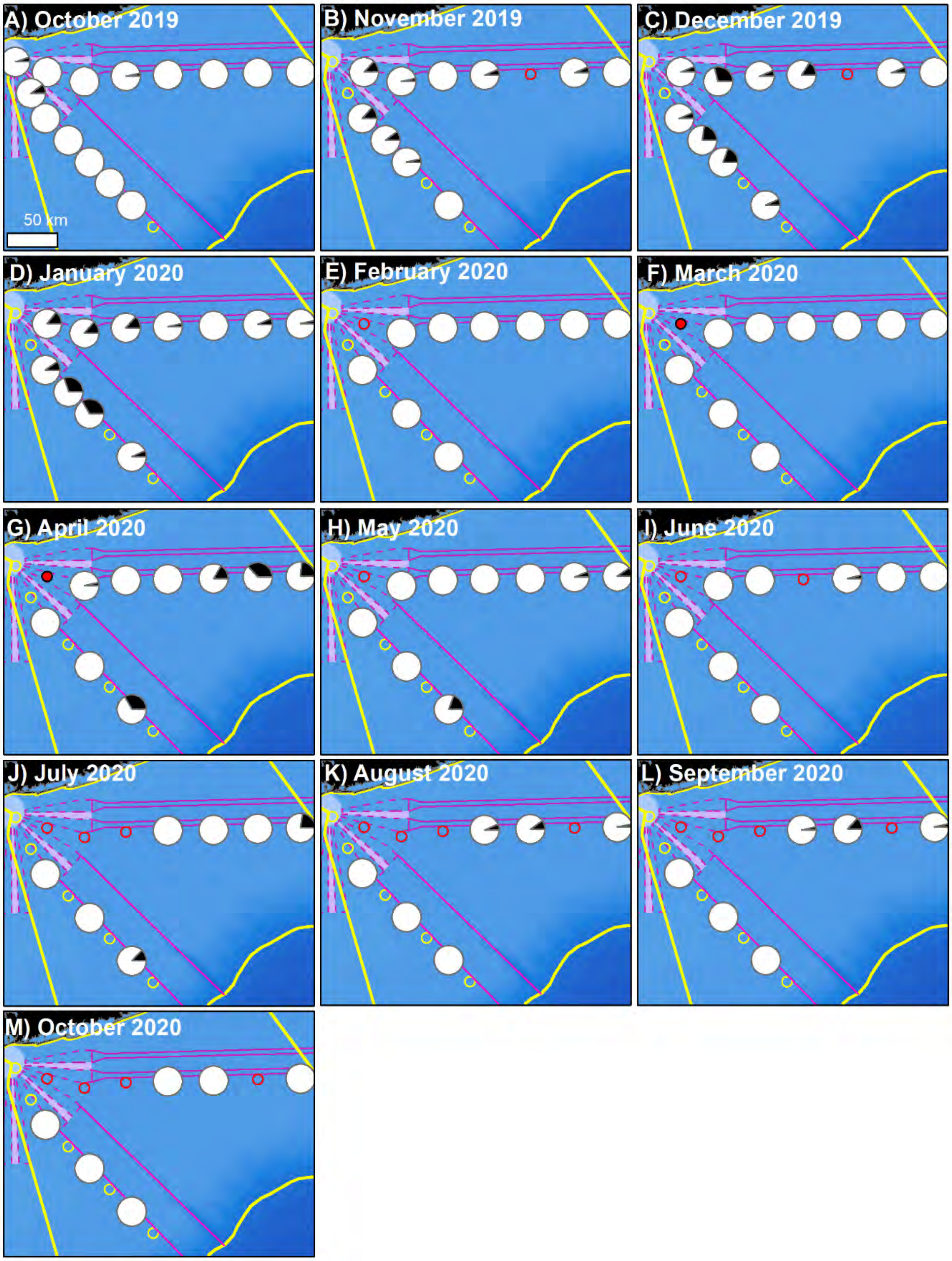
Year-3

Temporal Presence

During the Year-3 survey period, North Atlantic right whales were detected at all sites and in each month, except in February, March, and October 2020 (Figure 12, Figure 13, Table 20), with the most detections occurring in late fall through early spring. The highest monthly presence in Year-3 occurred in December 2019, when 19 (61%) of the recorded calendar-days (n = 31 days) had right whale upcall detections. During that month, there were detections on 37 site-days (12%). The month with the second highest number of detections was April 2020, when 16 (53%) of the recorded calendar-days (n = 30 days) and 34 site-days (13%) had right whale upcall detections and there were 34 site-days with right whale detections (Figure 13). Of the months when right whales were detected, June had the lowest monthly presence (3% calendar-days), with 1 calendar-day of presence that month. The reduction in detections around June was seen in Year-1 and Year-2 monthly data (Figure 49), as well. More details on the interannual presence trends are described below.

On a seasonal scale, North Atlantic right whale presence was highest during the fall season (36% calendar-days, 6% site-days), followed by spring (26% calendar-days, 6% site-days), and fewer detections during summer with detections on 21% of the calendar-days (4% site-days, Figure 15). Winter had right whale detections on 15% of calendar-days (4% site-days, Table 20).

Spatial Presence



Right whales were detected at each of the recording site locations during Year-3 (Figure 14, Figure 16). Sites further from New York Harbor (4M, 5M, 6M, 7M, 10M, 11A, and 12M) had higher detections of right whales between October and January. Conversely, between April and September, right whales were rarely, if at all, detected at those sites, but were detected at sites furthest from the Harbor (1M, 2M, 3M, and 14M). Monthly spatial presence data (Figure 14) illustrates that right whales occurred at northwest sites during their peak months between November and January. During a second peak in presence between March and June, right whales were detected more on sites at the east and southerly edges of the NY Offshore Planning Area.

3 Year Presence Summary (2017 – 2020)
Year-3 had a decrease in number of overall right whale site-day detections (n = 156) compared to Year-1 (n = 436) and Year-2 (n = 372), however, there were also fewer site-days recorded during Year-3 (n = 2943) compared to Year-1 (n = 3661) and Year-2 (n = 4110), due to the loss of the AMARs and MARUs in Year-3. When accounting for survey effort in terms of recorded site-days, right whales site-day percent presence for Year-1, Year-2, and Year-3 were 12%, 9% and 5%, respectively, which could suggest a possible decrease in presence over the 3-year survey. It is important to consider that right whales had higher numbers of detections at sites 9A, 11A, and 13A during Year-1 and Year-2 surveys, comprising approximately 27% and 31% of all site-day upcall detections at those sites during each year, respectively (Table 25).

To test if there was a decrease in right whale acoustic presence during Year-3, or if the fewer upcall site-day detections were due to missing data from sites 9A, 11A, and 13A, we conducted a one-way analysis of variance (ANOVA) to compare the proportion of days of presence per week between the three survey years. To do this, we excluded time periods between the three years in which there were no sound data (data gaps) for one of the years, and calculated the proportion of surveyed days per week with right whale detections. We also excluded AMAR sites from the analysis since few days of survey data were recovered from AMAR sites during Year-3. The ANOVA showed that right whale weekly presence was significantly different between survey years ($F_{2,149}$ = 3.781, p = .025). A post hoc Tukey HSD test showed that Year-3 was different from Year-1 (p = .0376), and marginally different from Year-2 (p = .0663), suggesting that right whale presence was different in Year-3.

Overall, right whales exhibited similar presence trends across the survey areas between survey years (Figure 17, Figure 18), with upcall detections occurring first at the sites near New York Harbor (4M, 5M, 6M, 7M, 10M, 11A, and 12M) during fall and winter seasons, followed by detections at sites farther from the Harbor (1M, 2M, 3M, 13A, 14M). Year-1 recorded more summer detections than the other survey years. The onset of right whale acoustic presence in the fall remained consistent over time. Seasonal trends show higher right whale acoustic presence during Year-2 in spring than the other years, particularly at sites 1M, 2M, 3M, 13A, and 14M. In contrast, Year-1 showed generally higher right whale presence during fall and winter seasons. Cumulative detection data show right whales were present somewhat consistently across recording sites over the 3 years (

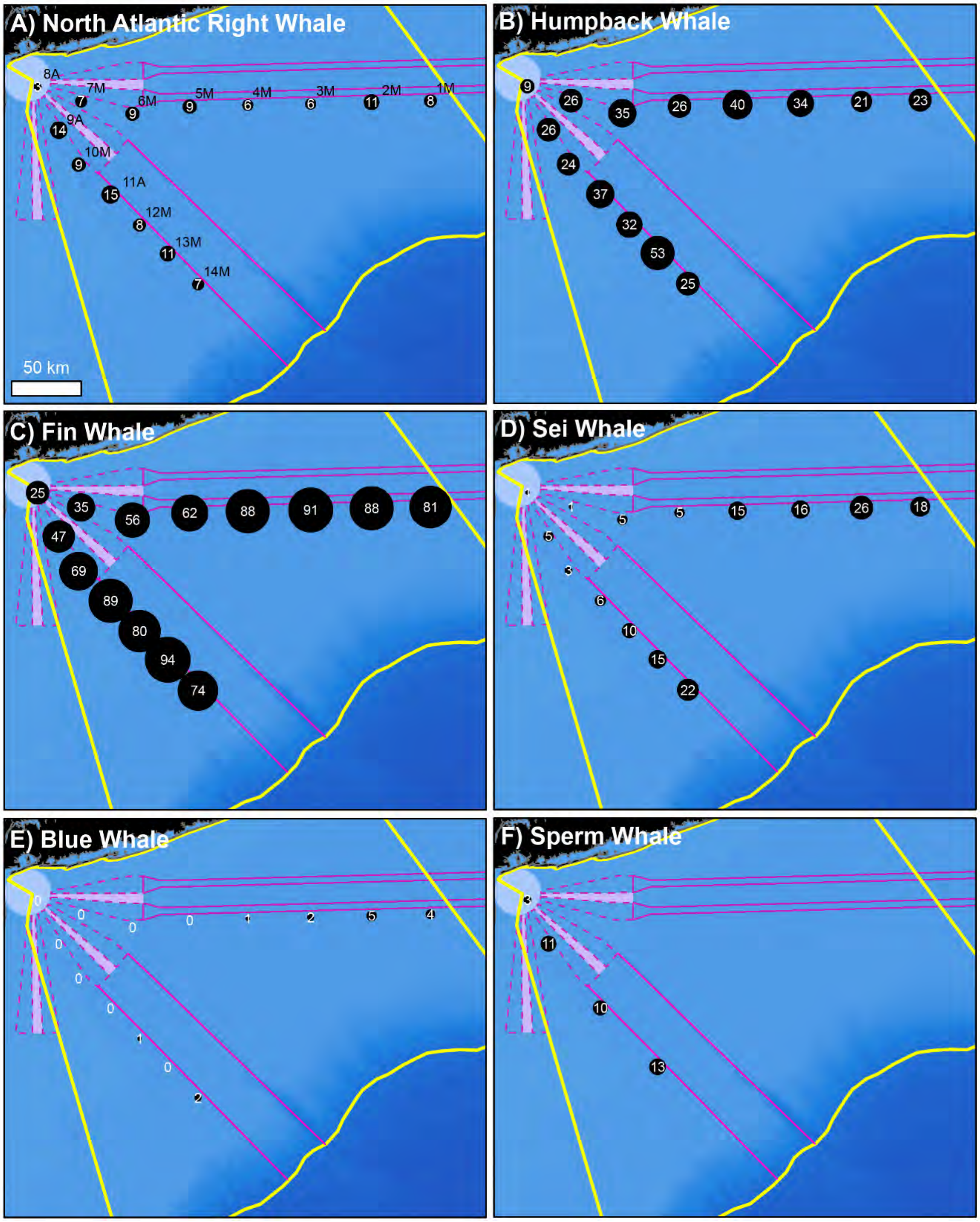


Figure 50A).

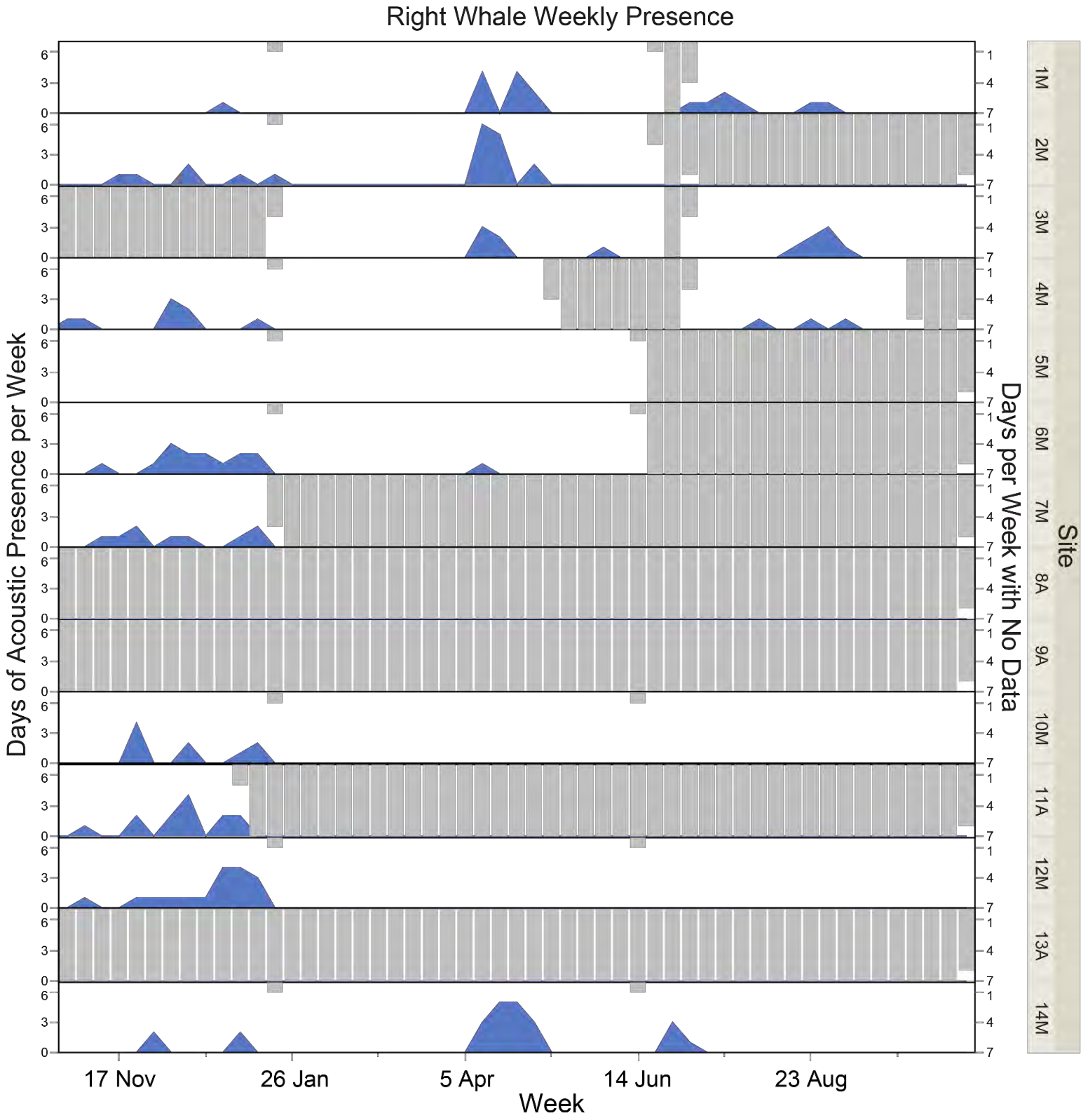


Figure 12. Year-3 weekly acoustic presence of North Atlantic right whales in New York Bight between October 2019-October 2020, shown as number of days per week with confirmed right whale upcall detections across all sensors (blue area). The inverse secondary y-axis indicates the number of days for each week during which there are no sound data (grey bars).

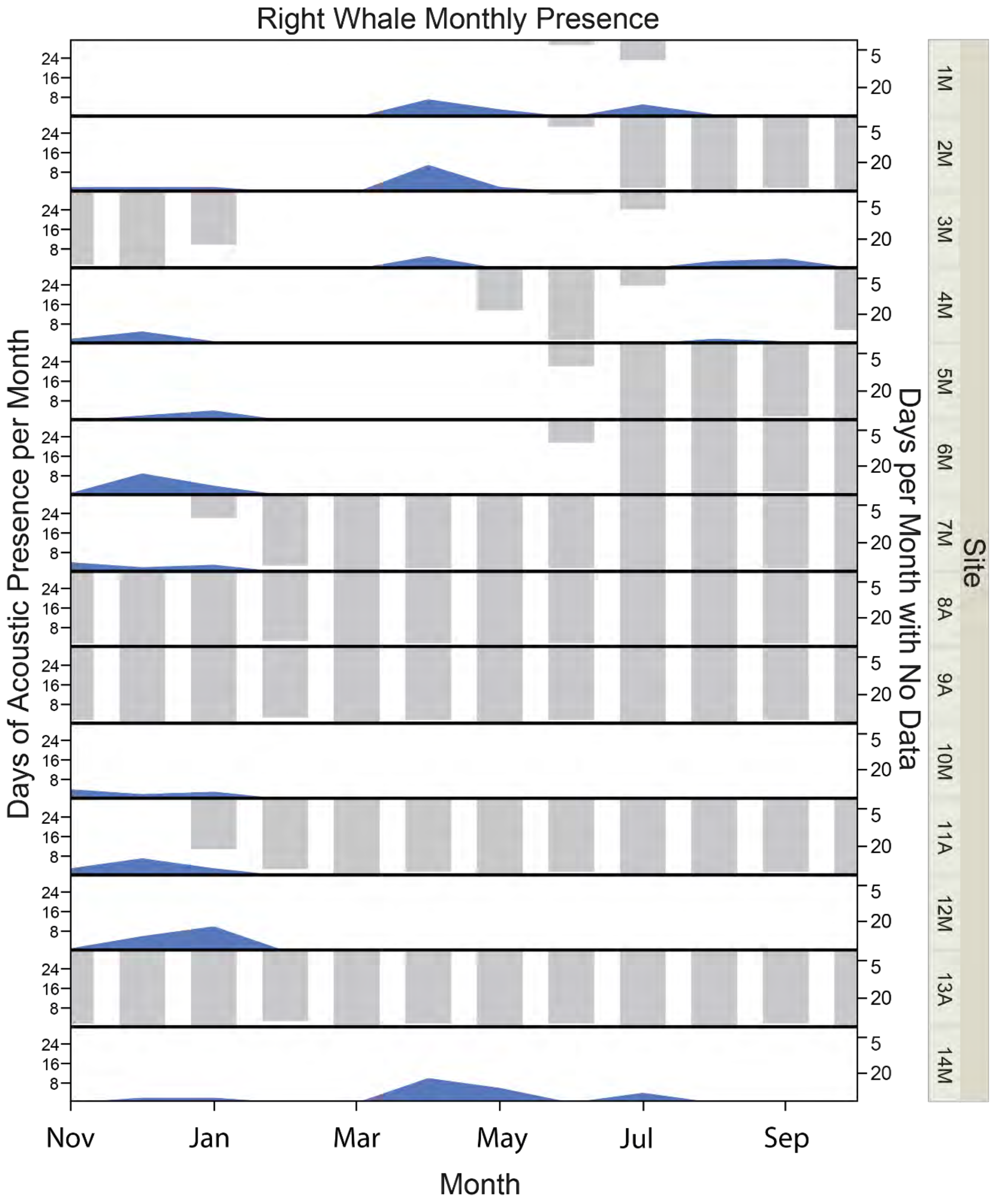


Figure 13. Year-3 monthly acoustic presence of North Atlantic right whales in New York Bight between October 2019-October 2020, shown as number of days per week with confirmed right whale upcall acoustic detections across all sensors (blue area). The inverse secondary y-axis indicates the number of days for each month during which there are no sound data (grey bars).

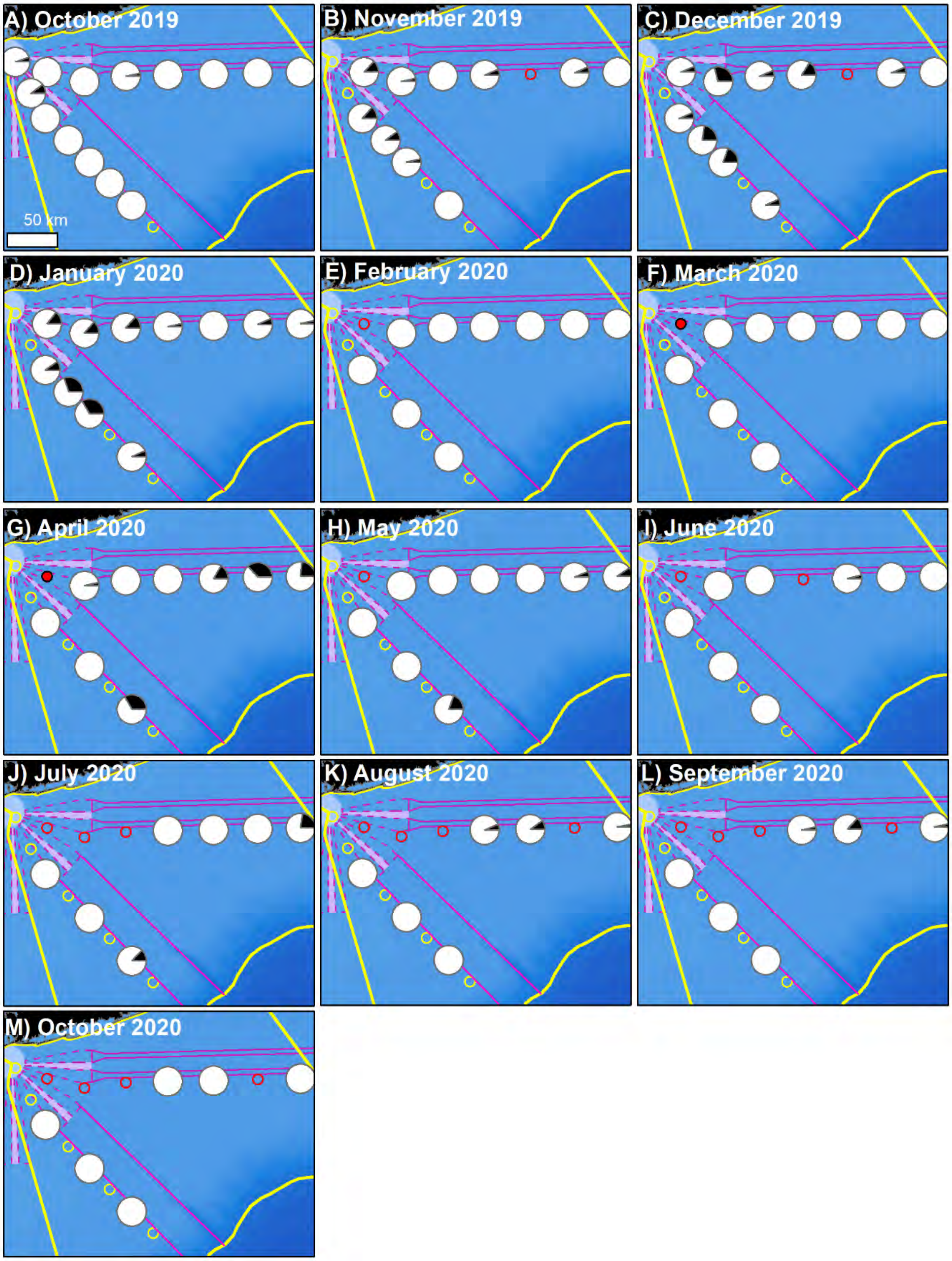


Figure 14. Year-3 spatial patterns of monthly acoustic presence of North Atlantic right whales in New York Bight, shown as percentage of days per month on each recording unit. Black indicates the proportion of days per month with acoustic detections; white indicates no detections. Hollow circles denote AMAR/AURAL (in yellow) and MARU (in red) site locations in which there are no data for that month.

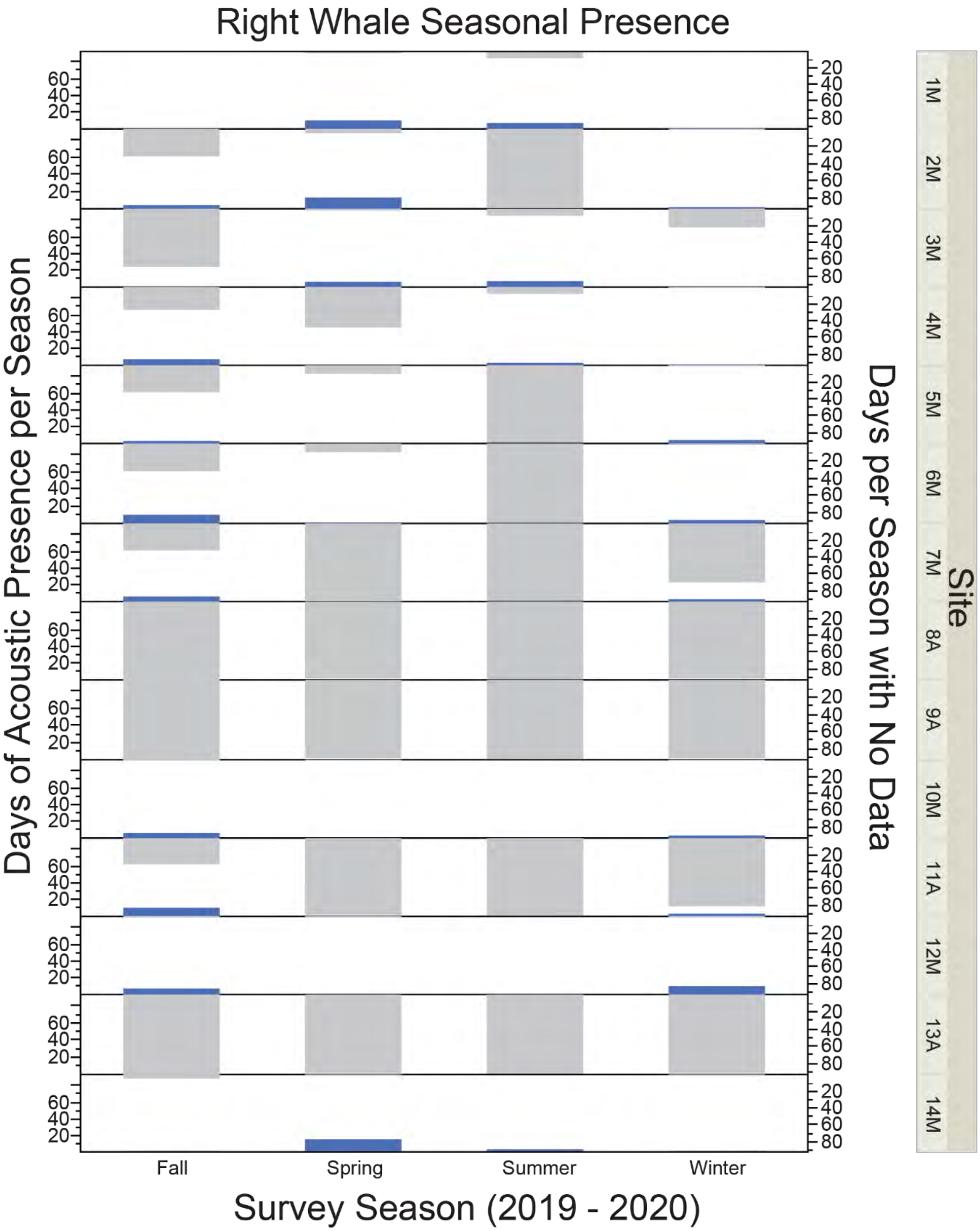


Figure 15. Year-3 seasonal acoustic presence of North Atlantic right whales in New York Bight from Fall 2019 through Fall 2020, shown as number of days per month with confirmed right whale upcall detections across all sensors (blue area) for Fall (October – December), Winter (January – March), Spring (April – June), and Summer (July - September). Gray bars (inverse secondary y-axis) indicate the number of days for each season during which there are no sound data.

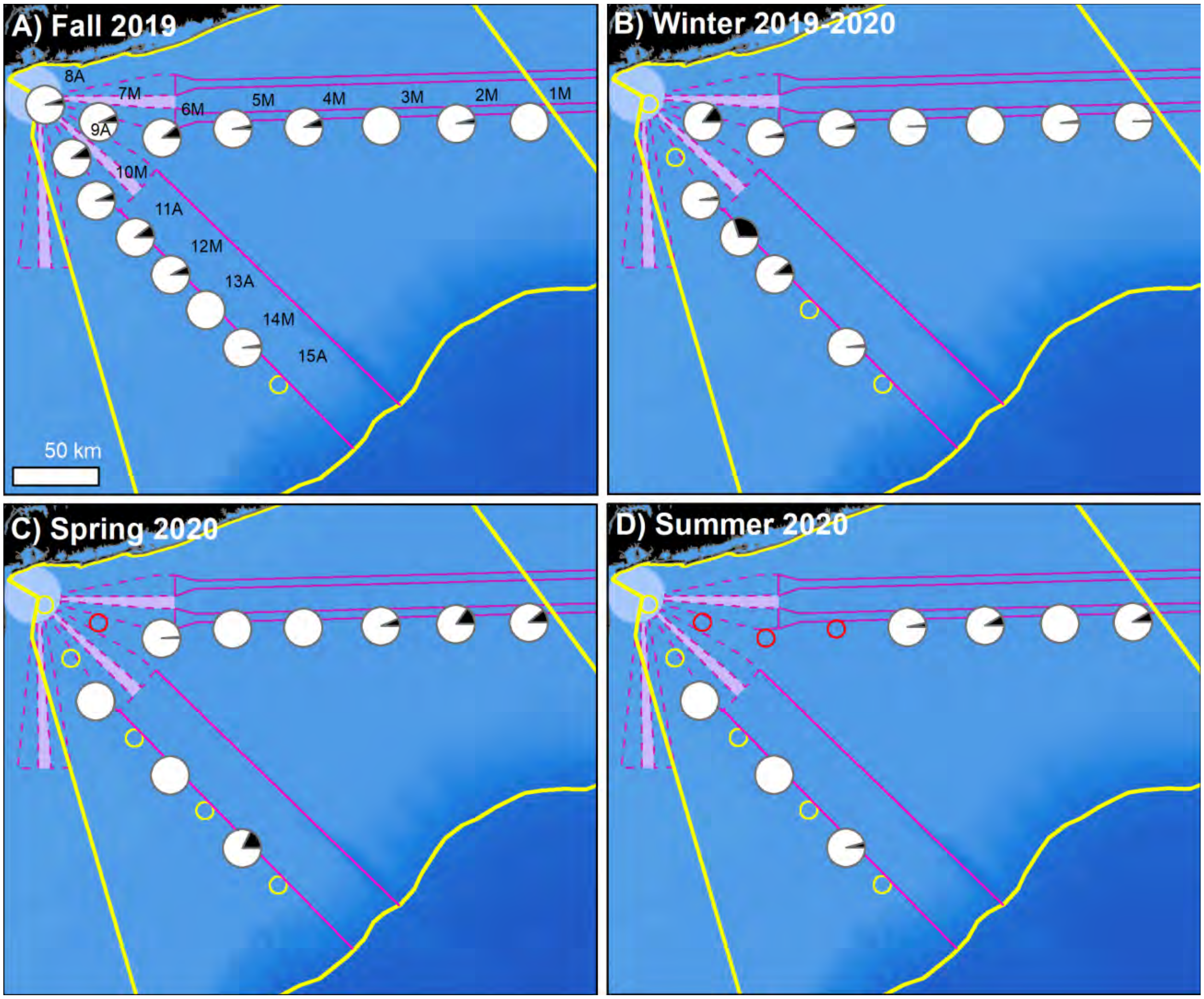


Figure 16. Year-3 spatial patterns of seasonal acoustic presence of North Atlantic right whale upcalls in New York Bight, shown as percentage of days per season on each recording unit. Black indicates the proportion of days per month with acoustic detections; white indicates no detections. A) Fall (October – December), B) Winter (January – March), C) Spring (April – June), and D) Summer (July-September). Hollow circles denote AMAR/AURAL (in yellow) and MARU (in red) site locations in which there are no data for that season.

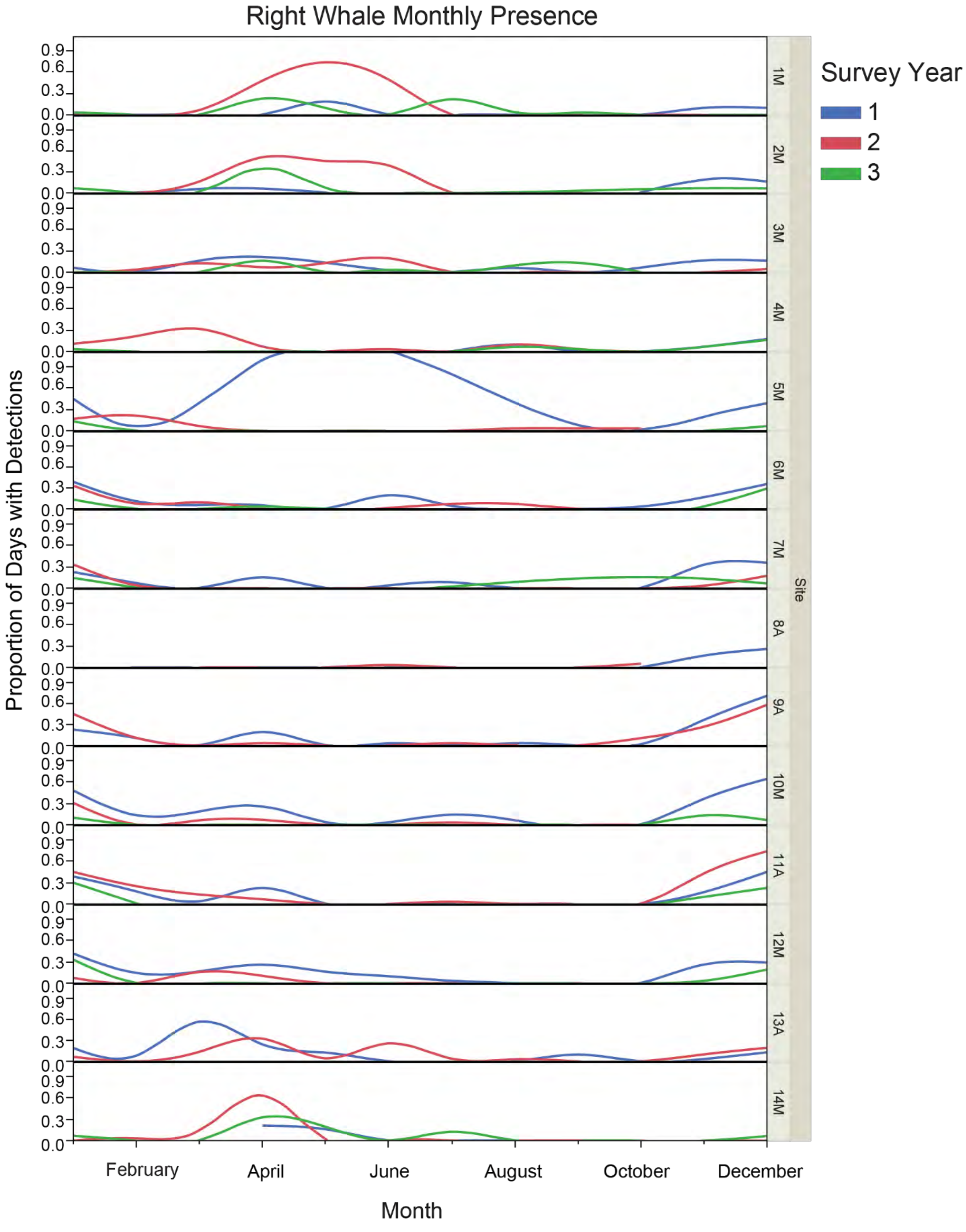


Figure 17. Internannual proportions of surveyed days with North Atlantic right whale detections in New York Bight, for survey Year-1 (blue), Year-2 (red), Year-3 (green) as a function of days per month with acoustic presence. Each line is a smooth cubic spline (lambda = 1e^{-07}).

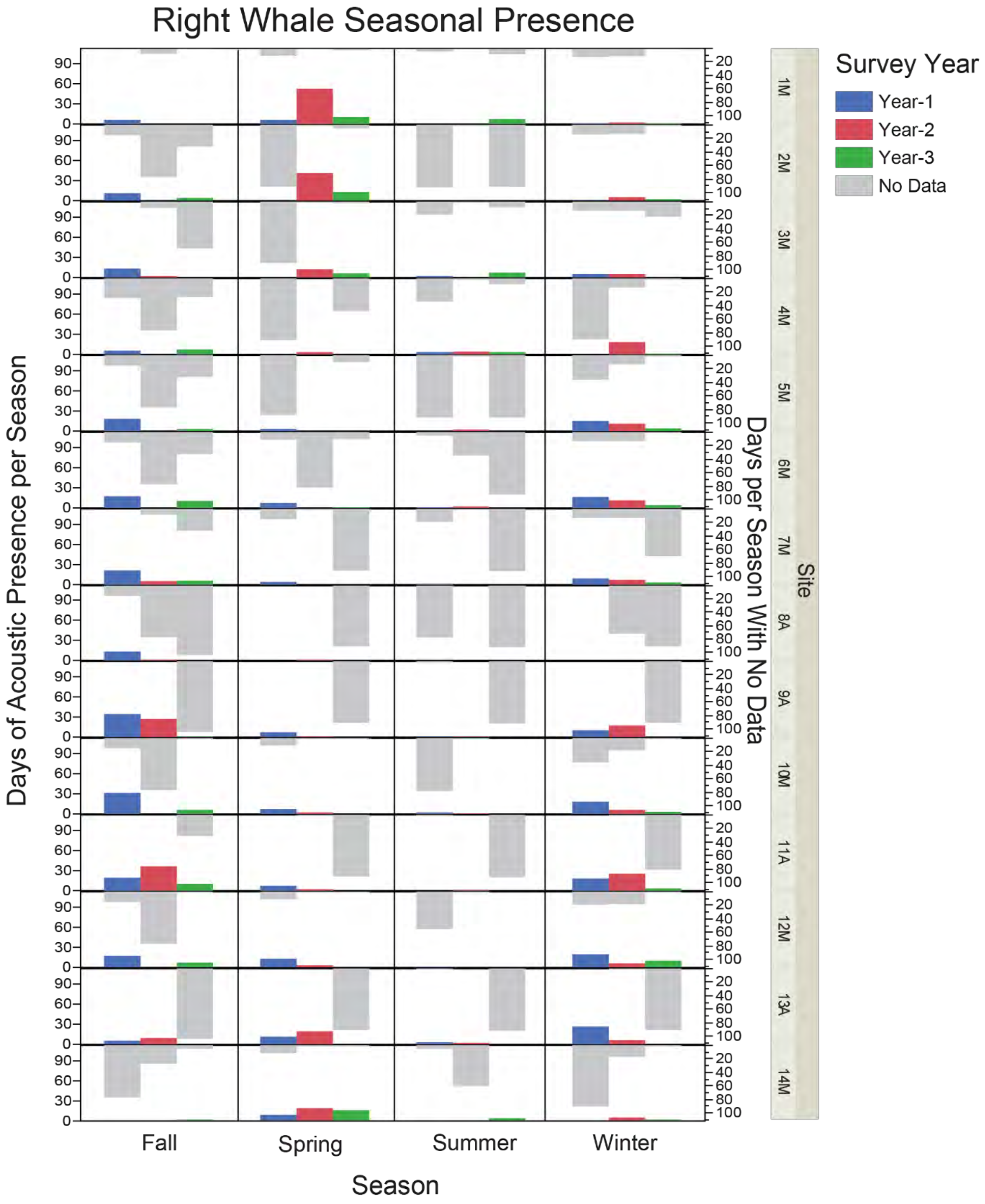


Figure 18. Internannual North Atlantic right whale seasonal acoustic presence in New York Bight for survey Year-1 (blue), Year-2 (red), and Year-3 (green) as a function of days with acoustic presence per month. Data gaps years 1-3 are shown in grey (inverse secondary y-axis) as the number of missing days per month.

Humpback Whale Occurrence

Year-3

Temporal Presence

Humpback whales were detected during most weeks (Figure 19) and during every month (Figure 20) of the Year-3 survey period. Humpback whales were detected at the start of the Year-3 survey period, with persistent high (>50%) percent monthly acoustic presence from November through February. Humpback whale detections were highest in December, where 31 calendar-days (100% of the recorded calendar-days) and 176 site-days had detections (57% of the recorded site-days). For comparison, the month with the next highest site-day presence was May, with 97 site-days (37%). Acoustic presence in May exhibited a second, brief peak in occurrence, after low monthly presence in March and April (32% and 17%, respectively). In May, 21 of the calendar-days (68%) had humpback whale detections, followed by slight decrease in monthly presence from June through July (17% and 45% calendar-days, respectively). In August, monthly percent presence increased to 100% of the calendar-days (n = 31) and 87 site-days (47%), and persisted through the end of the survey, with September recording 28 calendar-days of presence (93%) and October 2020 recording presence during all 15 survey days of that month (100%).

On a seasonal scale, humpback acoustic presence was highest during fall and summer, with 58% and 35% of all recorded site-days (Figure 22, Figure 23). Detections at sites 1M, 3M, and 4M account for the relatively high presence in summer, during which those three sites experienced the most humpback detections, in contrast to other sites, for which presence was highest during winter months.

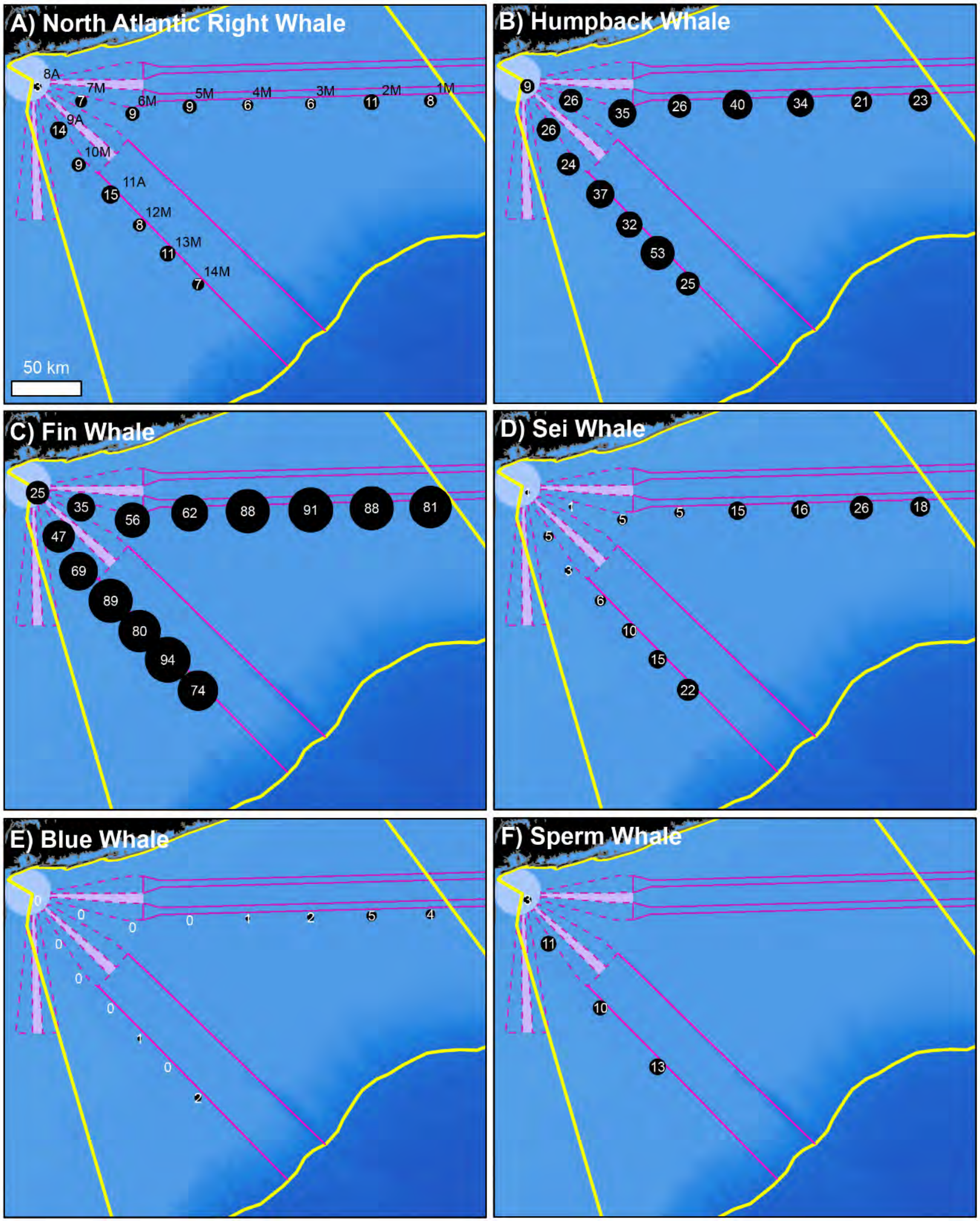
Spatial Presence

Humpback whales were detected at all sensors throughout the Year-3 survey (Table 23, Figure 21). Between November and March, humpbacks occurred mostly on sites towards the center of the offshore planning area (4M, 5M, 6M, 7M, and 10M, 11A, and 12M), and least on the eastern- (1M, 2M), and southern-most (14M) sites. From July – October 2020, presence occurred most on sites 1M, 3M, 4M, 12M, and 14M, and least on site 10M. Given the data gaps at the end of the Year-3 survey, it is difficult to identify if this indicates humpback whale seasonal movement through the survey area, however this trend appears in Year-1 and Year-2 (Figure 24, Figure 25). Overall, sites 3M and 4M recorded the most humpback whale acoustic presence, with detections on 99 (39%) and 103 (36%) calendar-days, respectively. Considering the survey effort, the sites with the highest percent acoustic presence were 7M (62%) and 11A (44%), however, those two sites only recorded from October through January, which were months of peak humpback whale acoustic presence. During the Year-2 survey, humpback whale presence exhibited a similar spatial trend across seasons, which again suggests that humpback whales are moving through certain areas of NY Bight by season.

3-Year Presence Summary (2017 – 2020)

There were fewer overall humpback whale daily detections in Year-3 (n = 751) compared to Year-1 (n = 1245) and Year-2 (n = 1184). To test if there was a decrease in humpback whale acoustic presence during Year-3, or if the fewer days of humpback detections is due to missing data from sites 9A, 11A, and 13A, we conducted a one-way analysis of variance (ANOVA) to compare the proportion of days per week with detections between the three survey years, following the method described in the right whale 3-year presence result section. The ANOVA showed that there was no significant difference in humpback whale weekly presence between survey years ($F_{2,149} = 2.305$, $p = .103$), indicating that humpback whale presence was not less in Year-3 than the previous survey years.

Overall, seasonal spatial trends for humpback whale acoustic presence (Figure 24, Figure 25) appear fairly consistent across the three survey years, where summer presence is relatively higher at sites 1M, 3M, 4M, 12M, 13A, and 14M, while sites 5M – 9A have relatively low presence. Site 8A recorded the lowest humpback whale presence (9%) during the 3-Year survey (Table 25). It is important to note, however, that ambient noise levels within the humpback whale frequency band were highest at site 8A (located nearest to New York Harbor) compared to all other sites, therefore, it is possible that some humpback whale vocalizations could have been masked at this location. Cumulative presence for humpback whales across the three survey years show higher number of daily detections at sites near the middle of both acoustic sensor transect lines (Figure 50B).



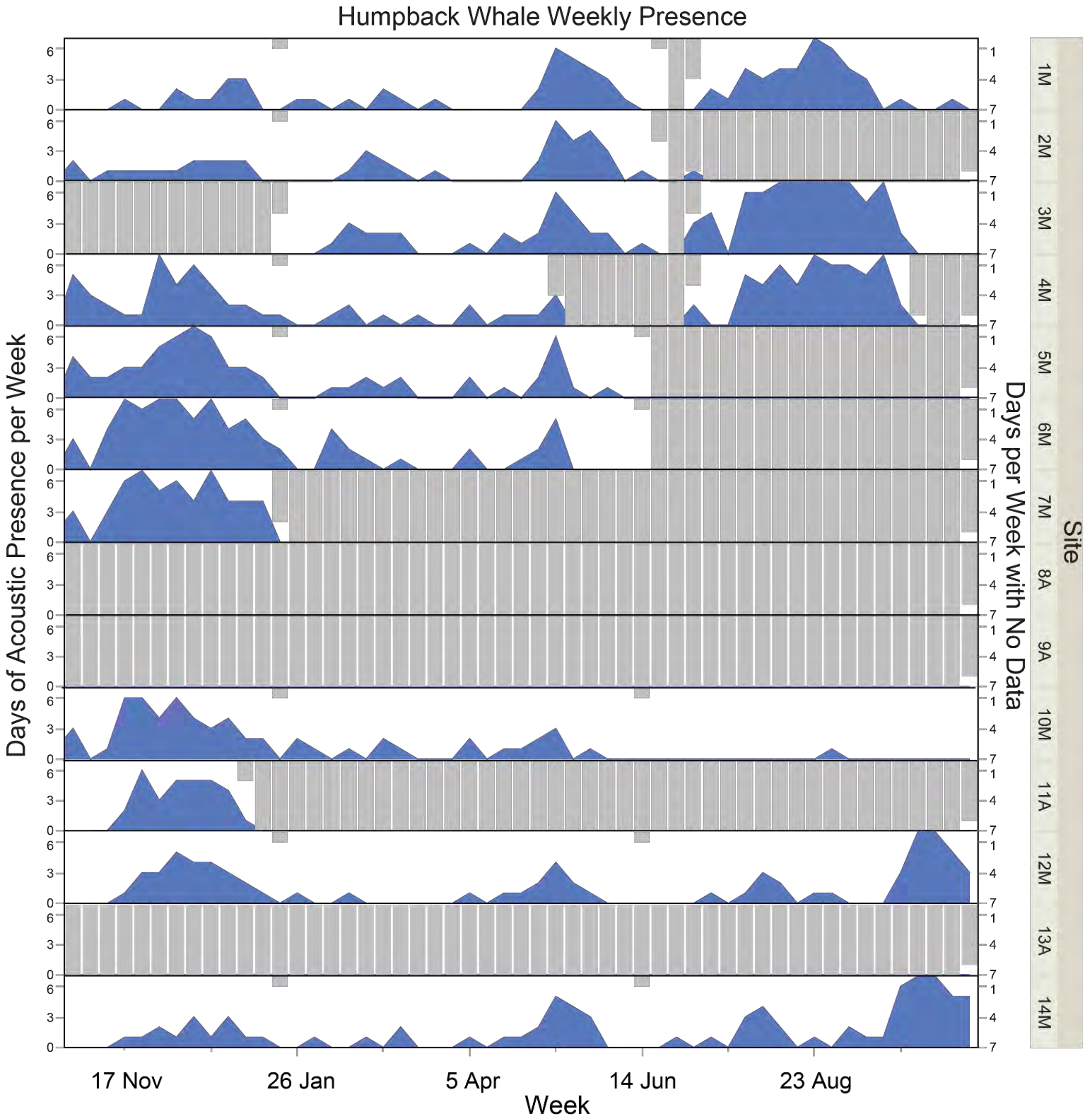


Figure 19. Year-3 weekly acoustic presence of humpback whales detected in New York Bight between October 2019-October 2020, shown as number of days per week with confirmed humpback whale acoustic detections across all sensors (blue area). The inverse secondary y-axis indicates the number of days for each week during which there are no sound data (grey bars).

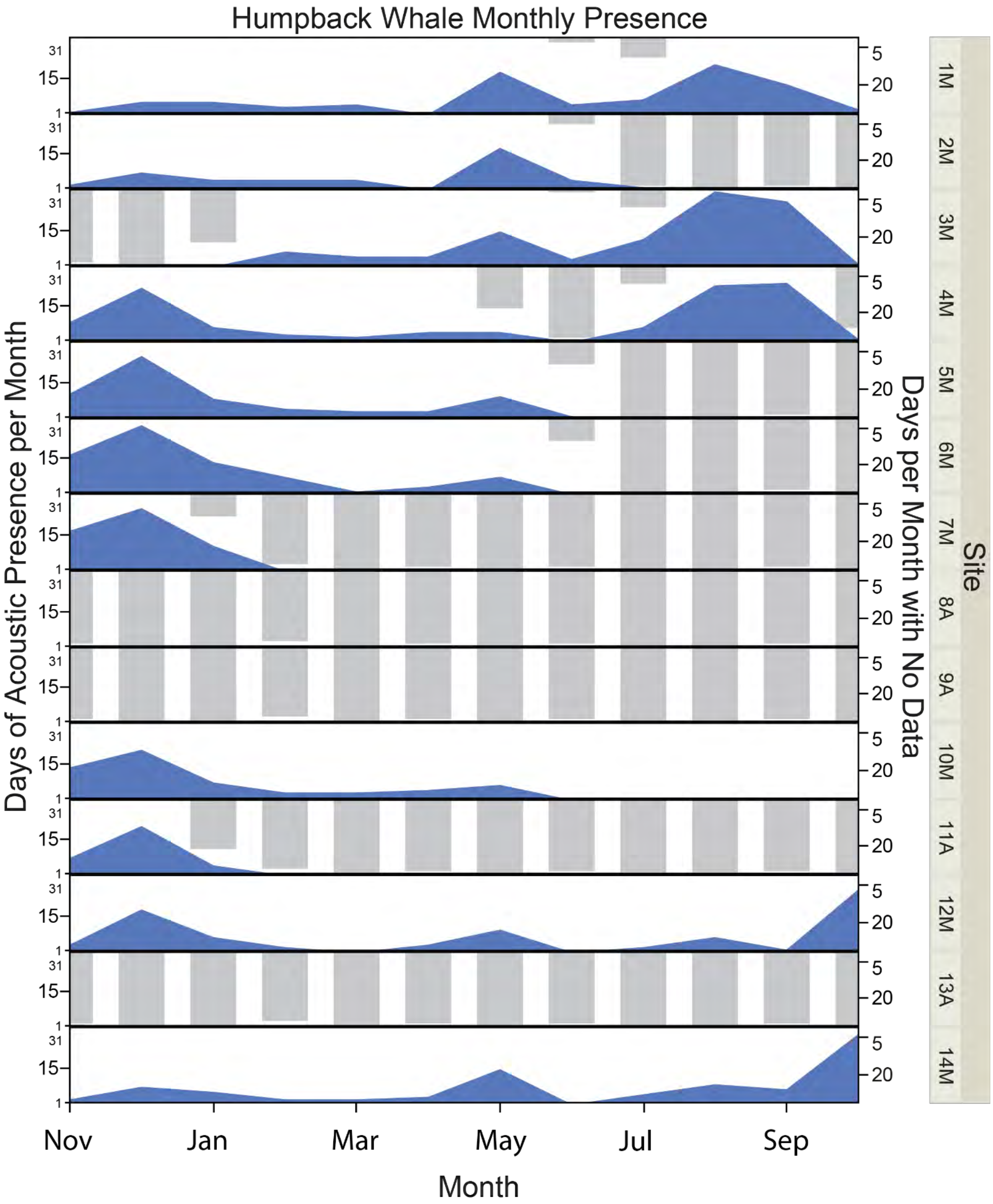


Figure 20. Year-3 monthly acoustic presence of humpback whales detected in New York Bight between October 2019-October 2020, shown as number of days per week with confirmed humpback whale acoustic detections across all sensors (blue line). The inverse secondary y-axis indicates the number of days for each month during which there are no sound data (grey bars).

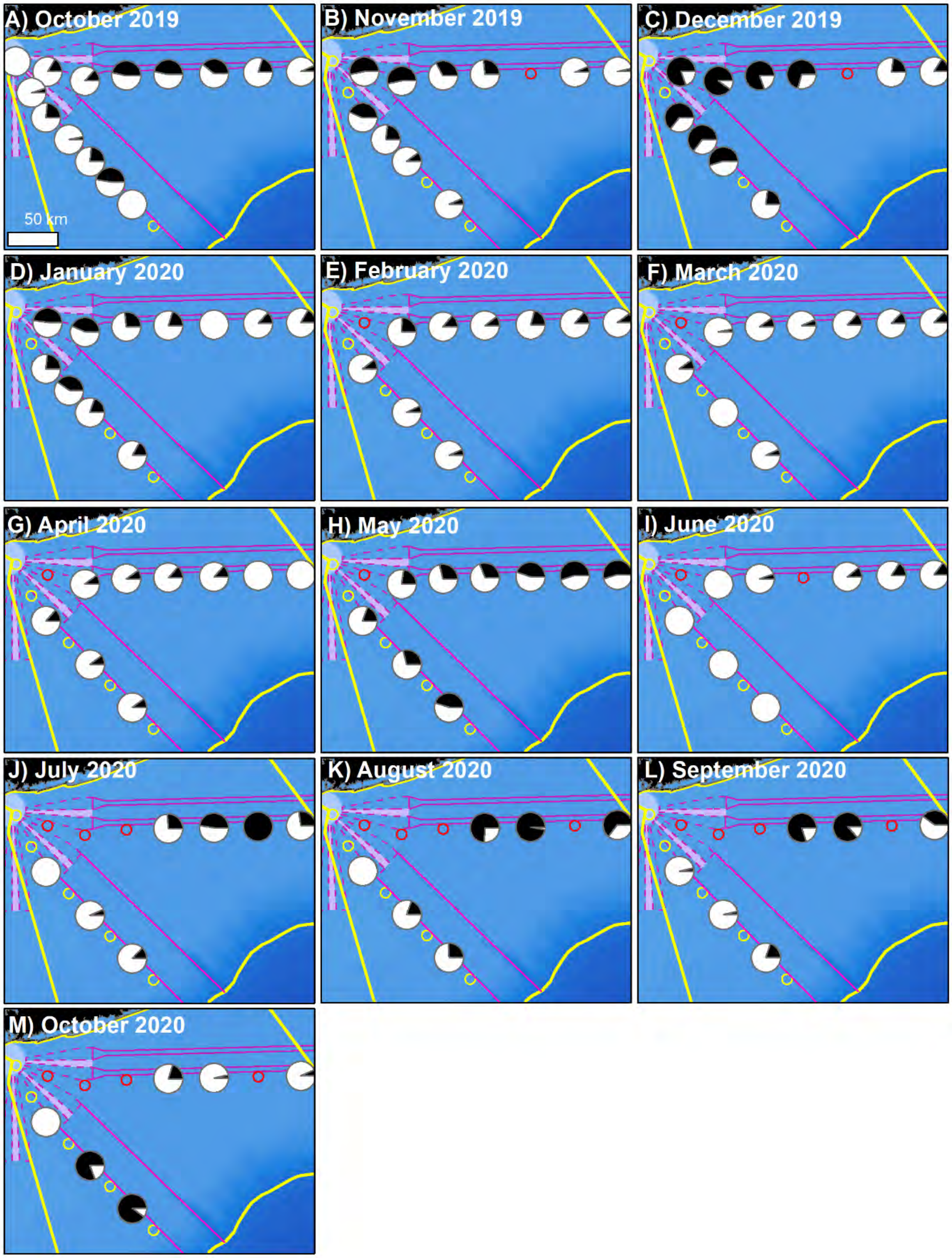


Figure 21. Year-3 spatial patterns of monthly presence of humpback whales in New York Bight, shown as percentage of days per month on each recording unit, . Black indicates the proportion of days per month with acoustic detections; white indicates no detections. Hollow circles denote AMAR/AURAL (in yellow) and MARU (in red) site locations in which there are no data for that season.

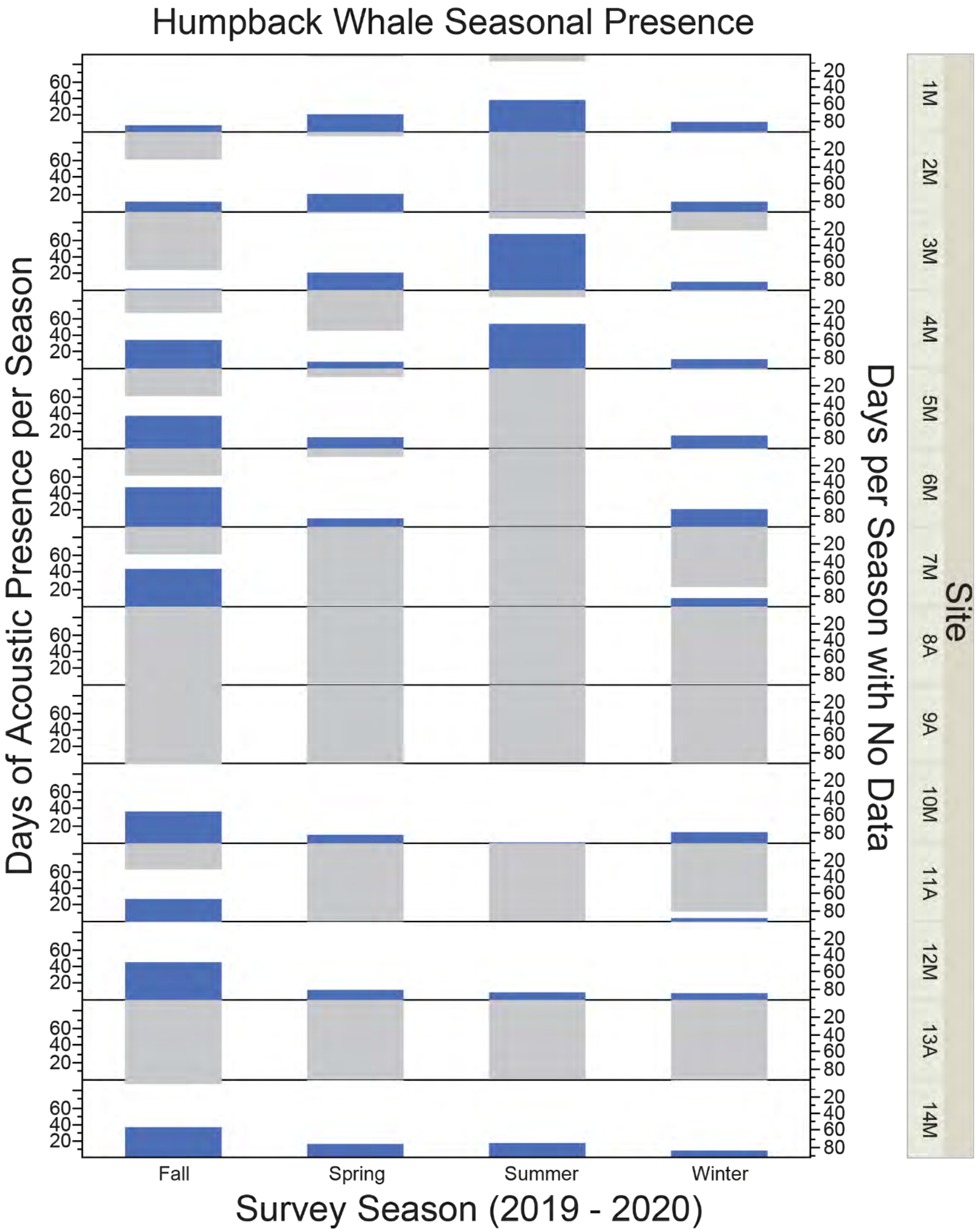


Figure 22. Year-3 seasonal acoustic presence of humpback whales detected in New York Bight from Fall 2019 through Summer 2020, shown as number of days per month with confirmed humpback whale acoustic detections across all sensors for Fall (October – December), Winter (January – March), Spring (April – June), and Summer (July - September). Grey bars (inverse secondary y-axis) indicate the number of days for each season during which there are no sound data.

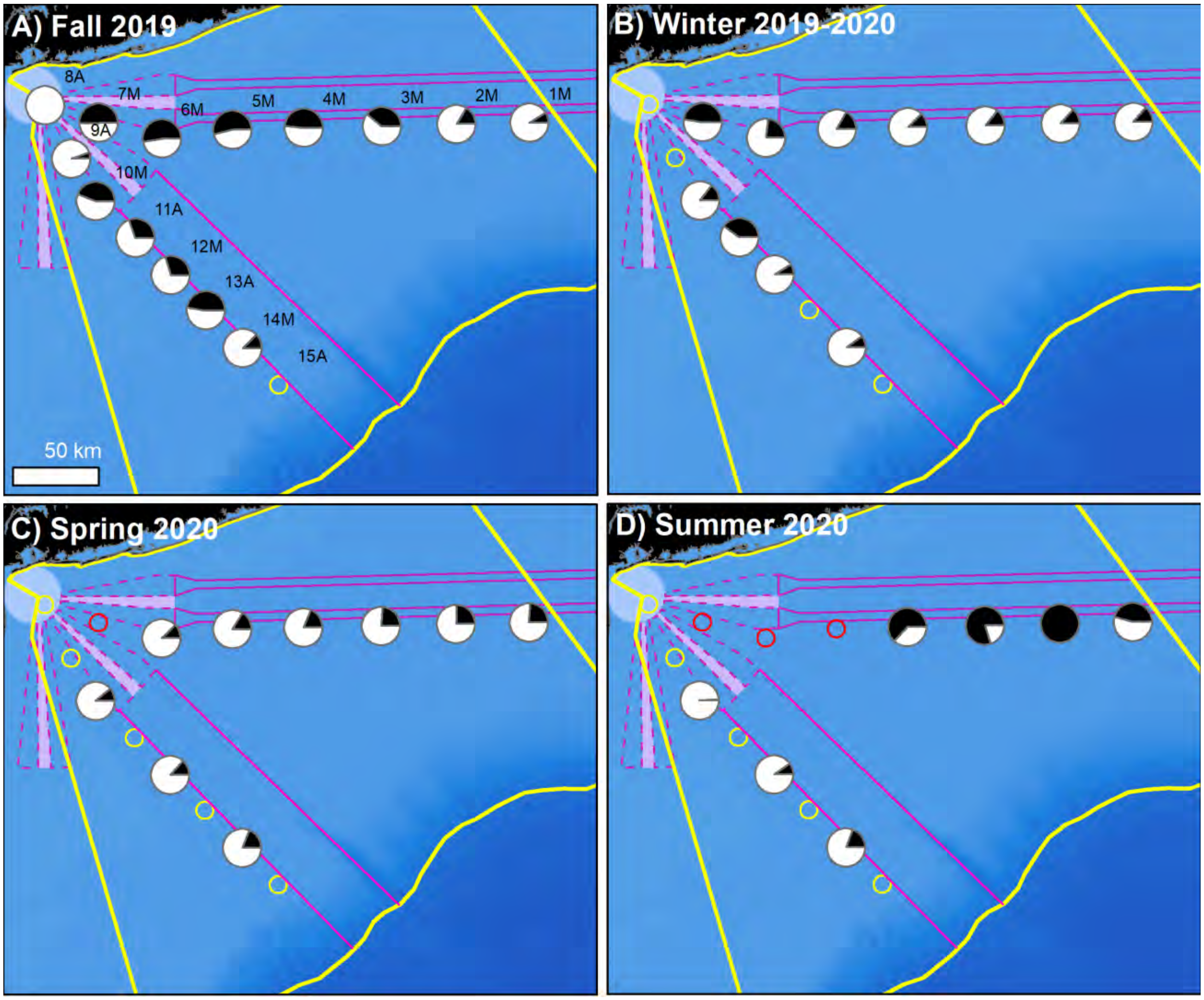


Figure 23. Year-3 spatial patterns of seasonal acoustic presence of humpback whales in New York Bight, shown as percentage of days per season on each recording unit . Black indicates the proportion of days per month with acoustic detections; white indicates no detections. A) Fall (October – December), B) Winter (January – March), C) Spring (April – June), and D) Summer (July-September). Hollow circles denote AMAR/AURAL (in yellow) and MARU (in red) site locations in which there are no data for that season.

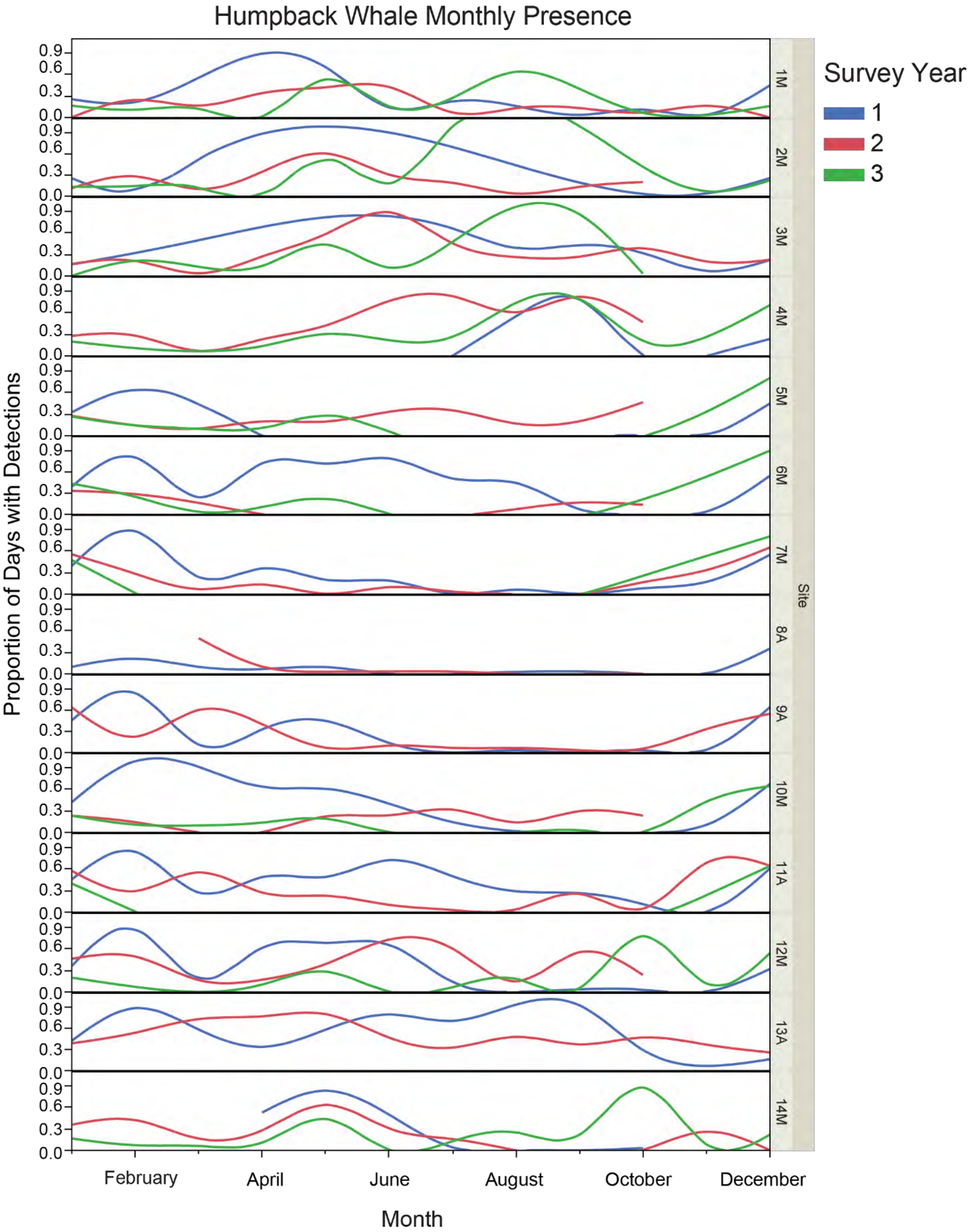


Figure 24. Internannual proportion of surveyed days with humpback whale detections in New York Bight for survey Year-1 (blue), Year-2 (red), Year-3 (green) as a function of days per month with acoustic presence. Each line is a smooth cubic spline (lambda = 1e^{-07}).

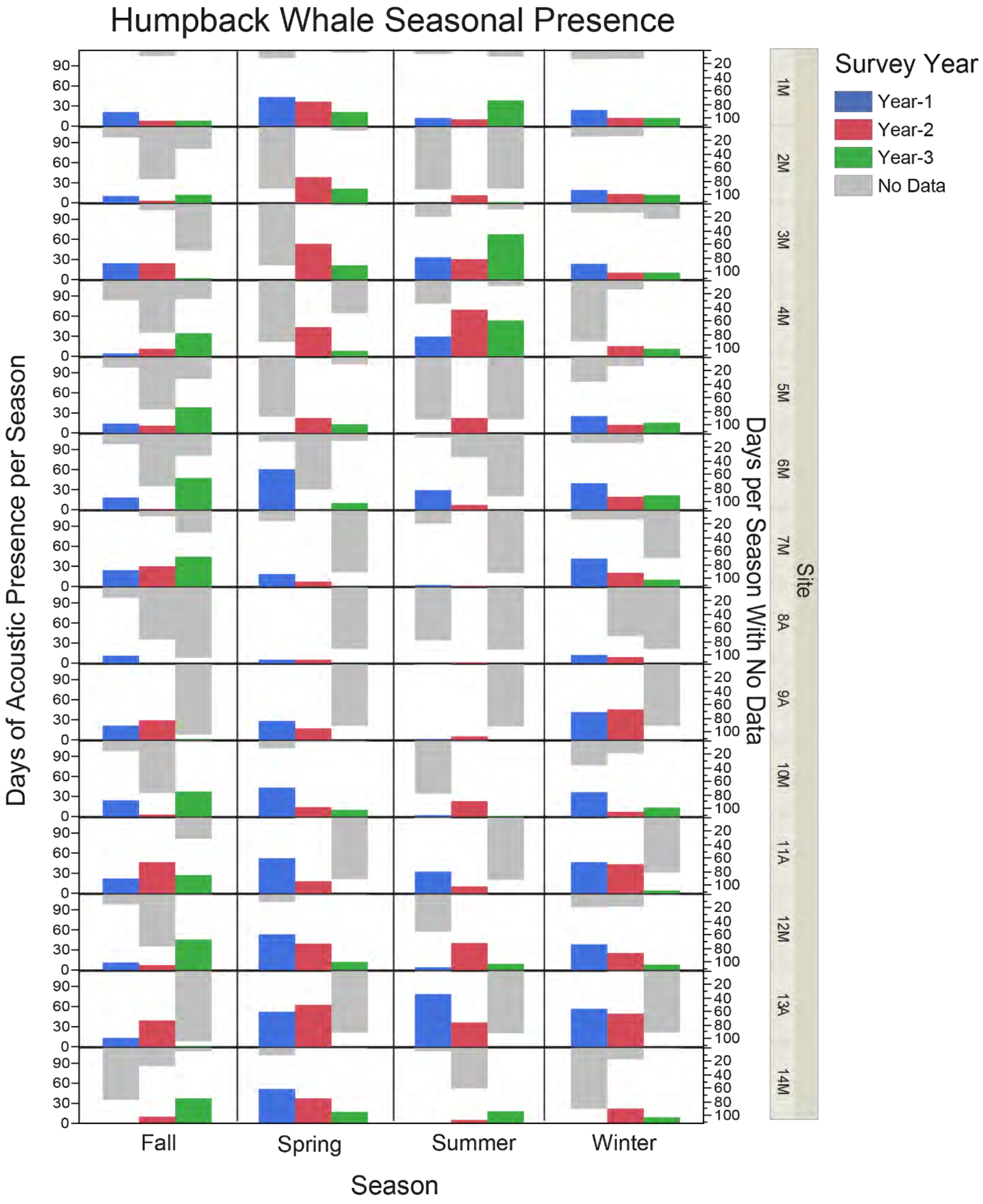


Figure 25. Internannual humpback whale seasonal acoustic presence in New York Bightfor survey Year-1 (blue),Year-2 (red), and Year-3 (green) as a function of days with acoustic presence per month. Data gaps in years 1-3 are shown in grey (inverse secondary y-axis) as the number of missing days per month.

Fin Whale Occurrence

Year-3

Temporal Presence

Fin whales were the most regularly detected whale species in NY Bight. Across all of the NY Bight sensors, fin whales were detected during every week (Figure 26), and in every month of the Year-3 survey (Table 20, Figure 26, Figure 27). Fin whales were detected on 100% of the recorded calendar-days in Year-3 for all months except January (90%) and June (93%). Daily acoustic detections of fin whales were highest in February, when 100% of the recorded calendar-days at each site except site 6M (27 days, 93% calendar-days of that month) had fin whale detections. November through March had consistently high site-day acoustic presence, with 247 or more site-days of presence for each month. April, May, and June had the lowest monthly acoustic presence, with 63%, 47%, and 40% of the recorded site-days having detections. An increase in acoustic presence then began in July (86% site-day presence) and steadily increased through the end of the survey.

Seasonally, fin whale presence was lowest in the spring (52% site-days; Table 22, Figure 29, Figure 30), with most detections occurring at sites further from New York Harbor. The highest seasonal presence occurred during winter (92%) and summer (91%) months.

Spatial Presence

Sites 1M, 2M, 3M, 4M, 11A, and 14M recorded the highest number of daily detections in Year-3, with between 88% and 93% calendar-days of presence. Sites 5M, 6M, 7M, and 10M recorded the lowest presence throughout the area, with 55% - 67% calendar-days of presence. Spatial examination of monthly trends of fin whale presence across the array suggests some small-scale spatial variability, but for the most part, spatial detection patterns appear similar across sites (Figure 28, Figure 30).The higher detection rates of fin whales at sites farther from the New York Harbor may be a function of the long-range propagation distance of fin whale song, which can still be detected at distances greater than 50 km from the source. The observed spatial pattern in fin whale detections suggests that the detected fin whale vocalizations could originate from both inside, and outside of the survey area. During our analyses, it was often observed that the arrival pattern of a fin whale song at multiple sensors suggested the song originated within NY Bight.

3-Year Presence Summary (2017 – 2020)

Overall, there were fewer fin whale detections during Year-3 (n = 2299), compared to Year-1 (n = 2407) and Year-2 (n = 2945). Again, this may be due to the data loss at AMAR sites for the entire Year-3 survey period. To test if there was a decrease in fin whale acoustic presence during Year-3, or if the fewer days with fin whale detections is due to missing data from sites 9A, 11A, and 13A, we conducted a one-way analysis of variance (ANOVA) to compare the proportion of days of presence per week between the three survey years, following the same methods described in the right whale results section. The ANOVA showed that there was no statistically significant difference in fin whale weekly presence between survey years ($F_{2,149} = 0.783$, p = .459), indicating that fin whale presence was not less in Year-3 than the previous survey years.

Year-3 recorded the highest site-day detections, where 78% of the recorded site-days in Year-3 (recorded site-days = 2943) had fin whale detections, compared to 66% (recorded site-days = 3661) and 72% (recorded site-days = 4110) for Year-1 and Year-2, respectively. All three survey years exhibit similar seasonal trends in fin whale presence, with peak occurrence in winter and the lowest presence during spring months (Figure 32, Table 22). Cumulative detections across the 3-year survey illustrates that fin whales were often detected >50% of the recording time at many sites (

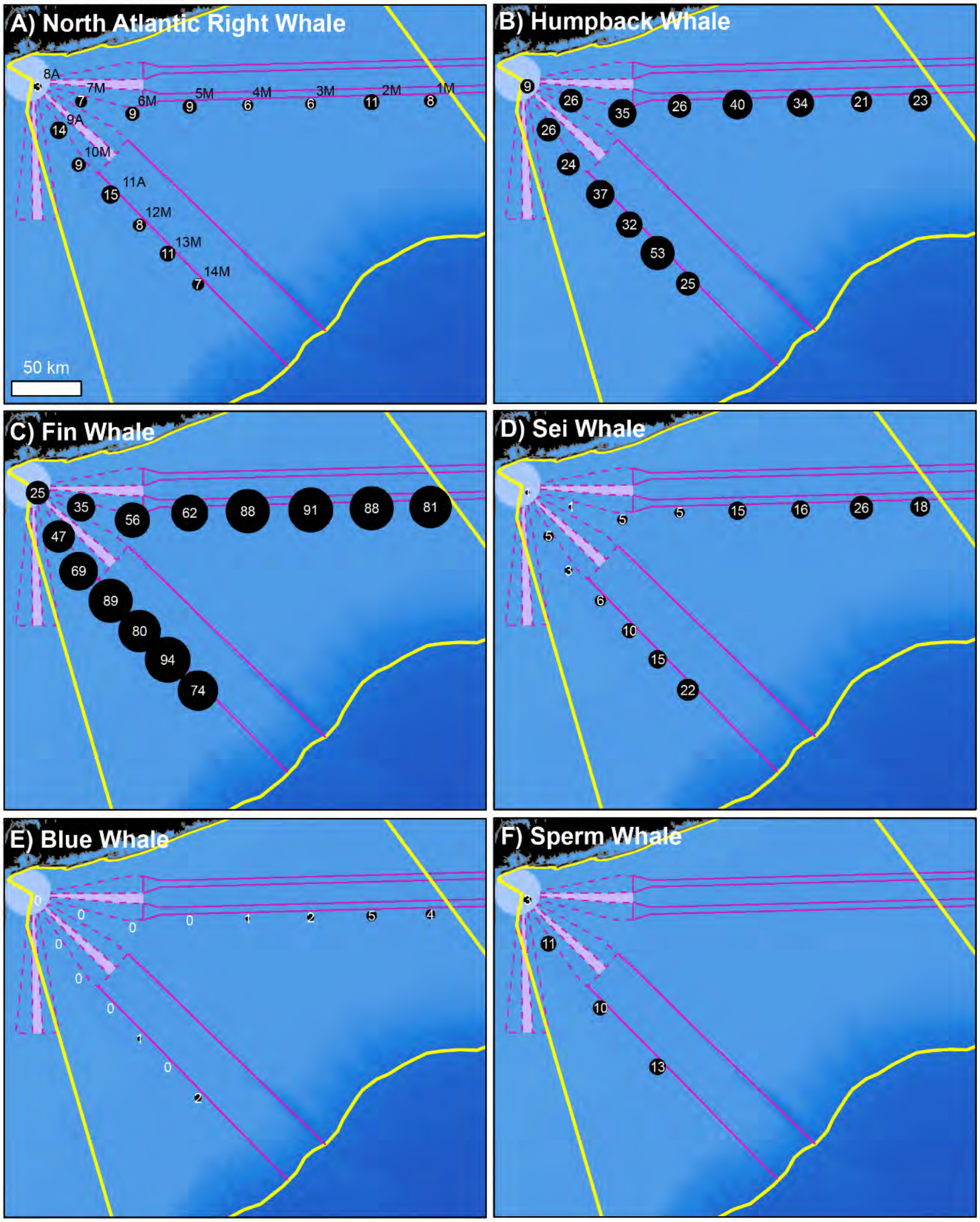


Figure 50C), and were more often detected closer to the shelf edge.

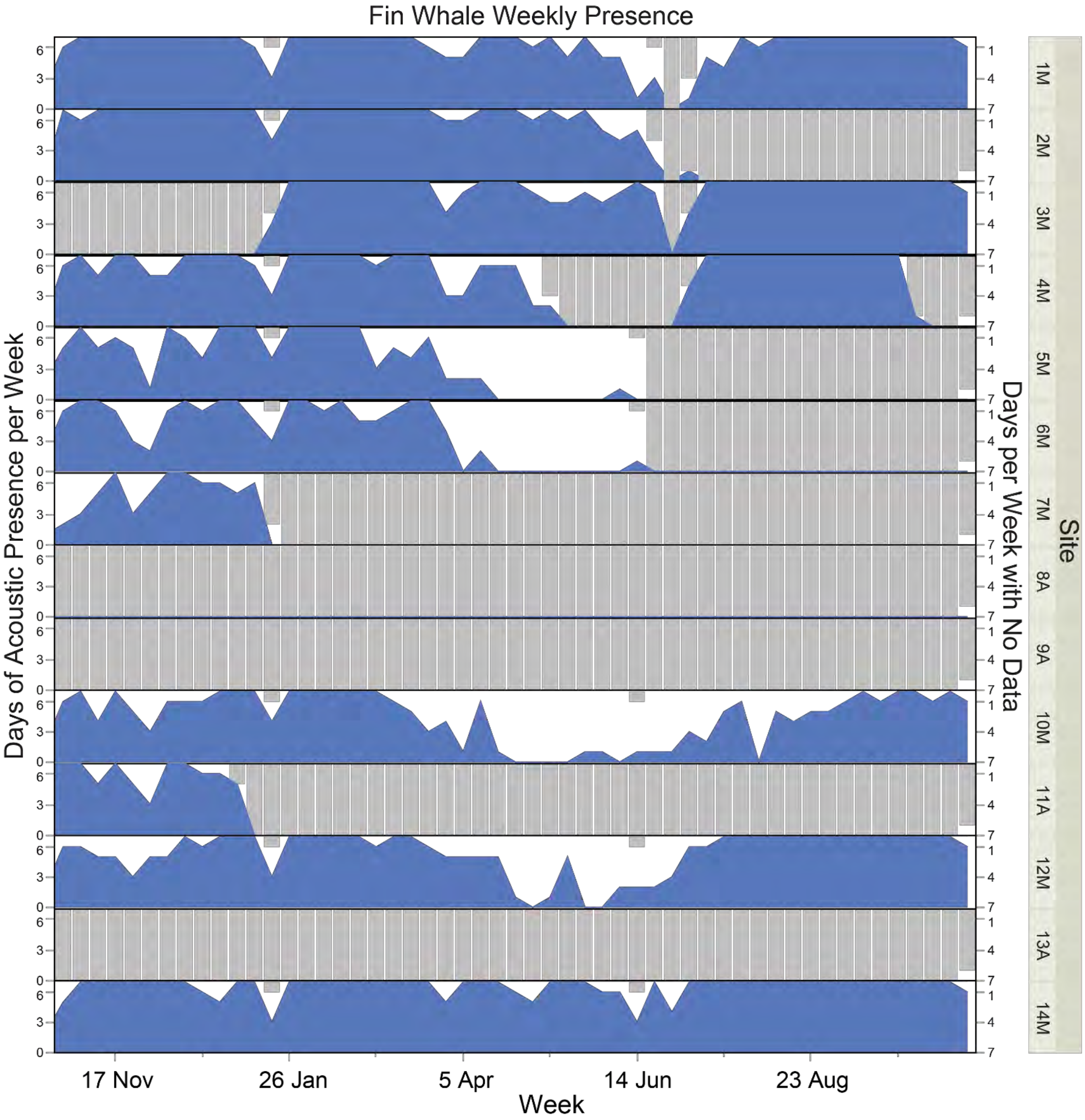


Figure 26. Year-3 weekly acoustic presence of fin whales detected in New York Bight between October 2019-October 2020, shown as number of days per week with confirmed fin whale acoustic detections across all sensors (blue line). The inverse secondary y-axis indicates the number of days for each week during which there are no sound data (grey bars).

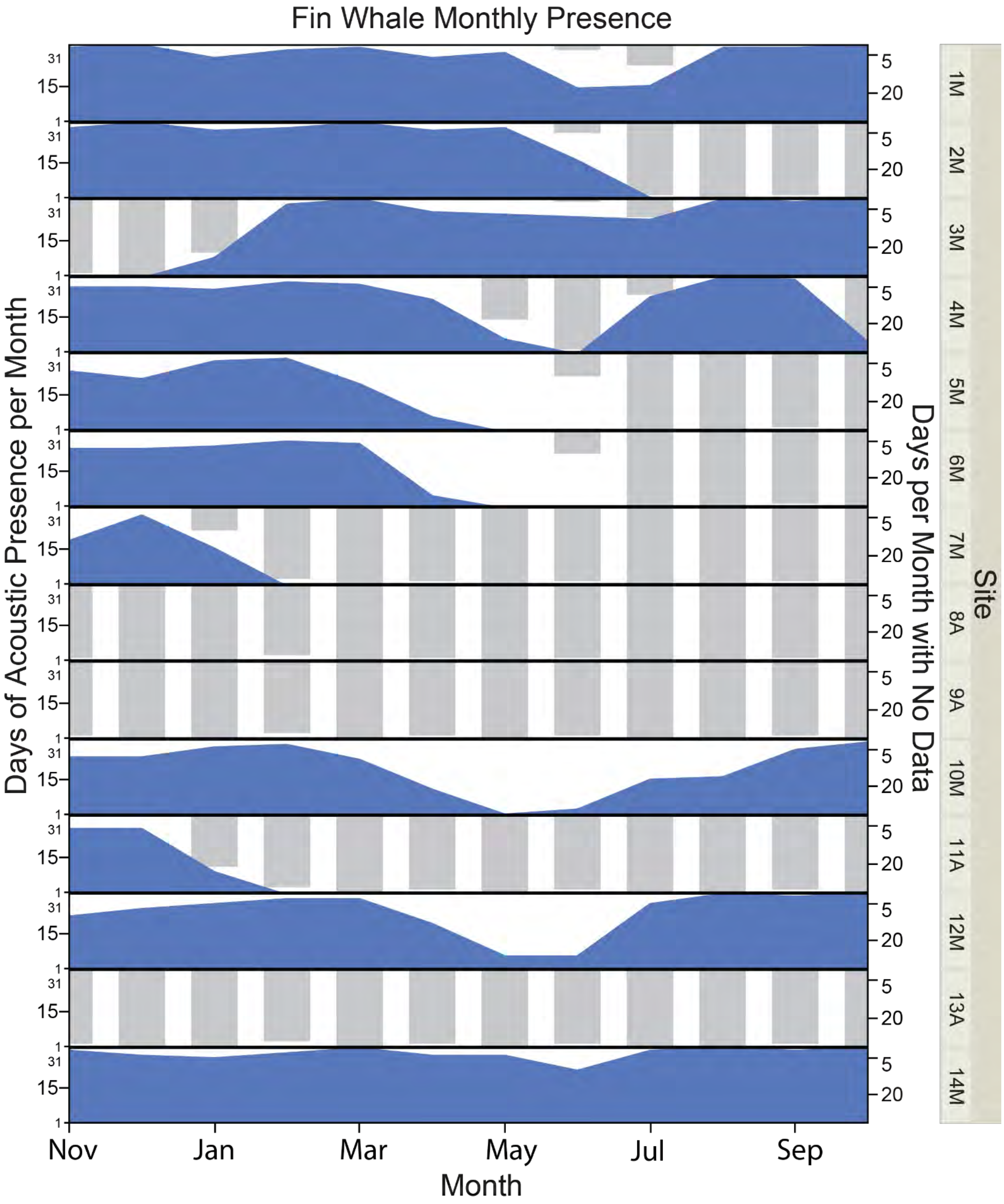


Figure 27. Year-3 monthly acoustic presence of fin whales detected in New York Bight between October 2019-October 2020, shown as number of days per week with confirmed fin whale acoustic detections across all sensors (blue line). The inverse secondary y-axis indicates the number of days for each month during which there are no sound data (grey bars).

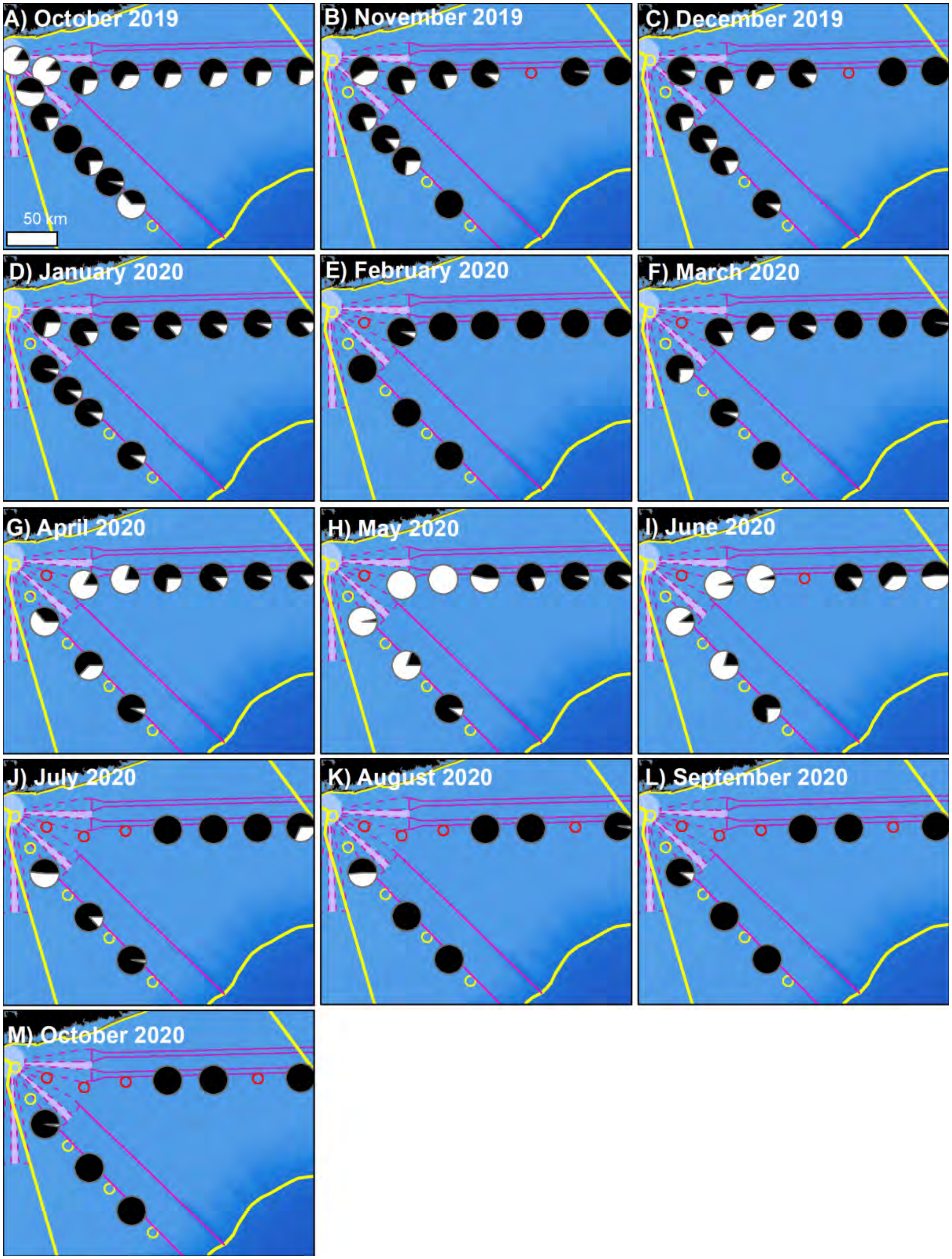


Figure 28. Year-3 spatial patterns of monthly presence of fin whales in New York Bight, shown as percentage of days per month on each recording unit. Black indicates the proportion days per month with acoustic detections; white indicates no detections. Hollow circles denote AMAR/AURAL (in yellow) and MARU (in red) site locations in which there are no data for that season.

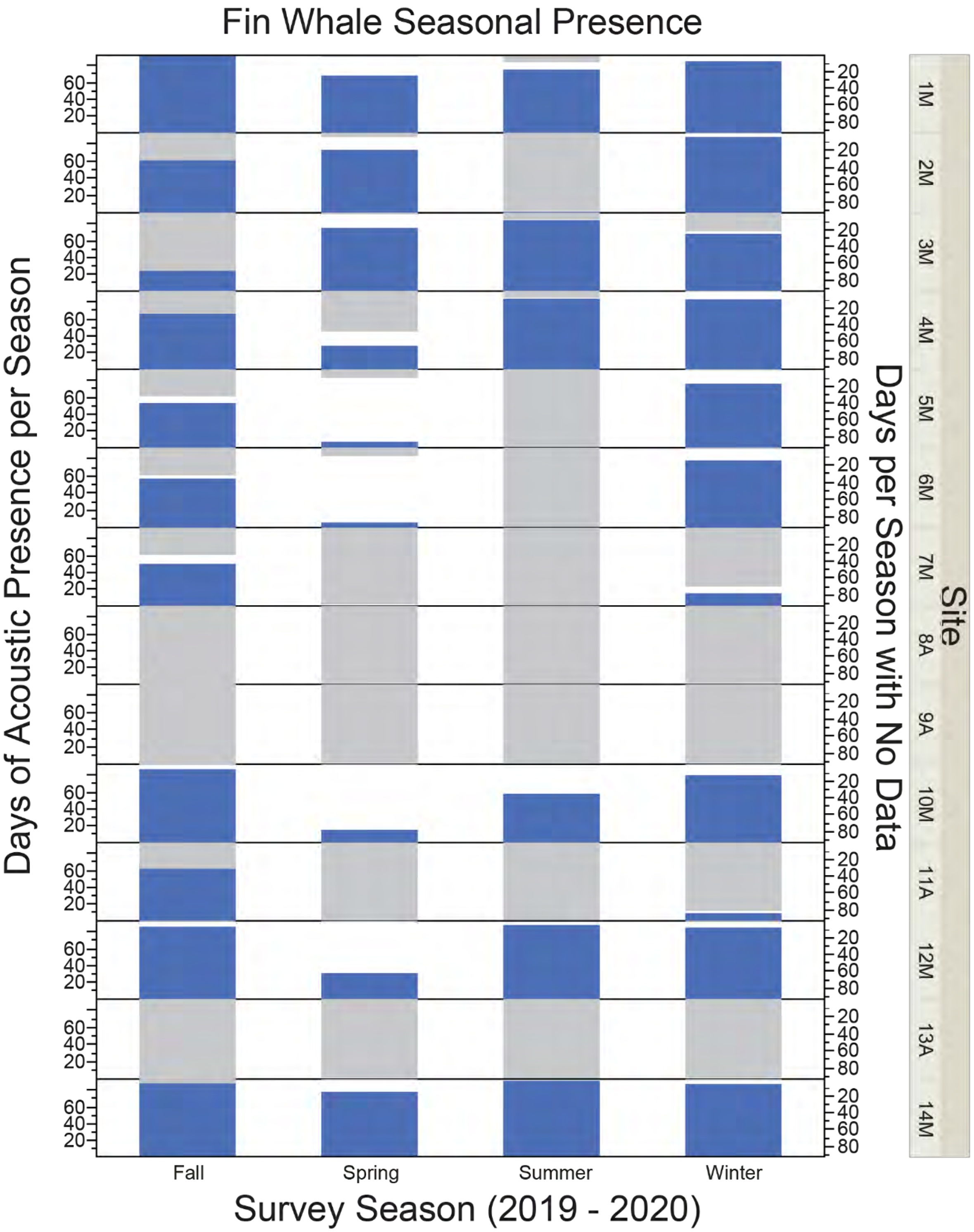


Figure 29. Year-3 seasonal acoustic presence of fin whales detected in New York Bight from Fall 2018 through Summer 2019, shown as number of days per month with confirmed right whale acoustic detections across all sensors for Fall (October – December), Winter (January – March), Spring (April – June), and Summer (July - September). Gray bars indicate the number of days for each season during which there are no sound data.

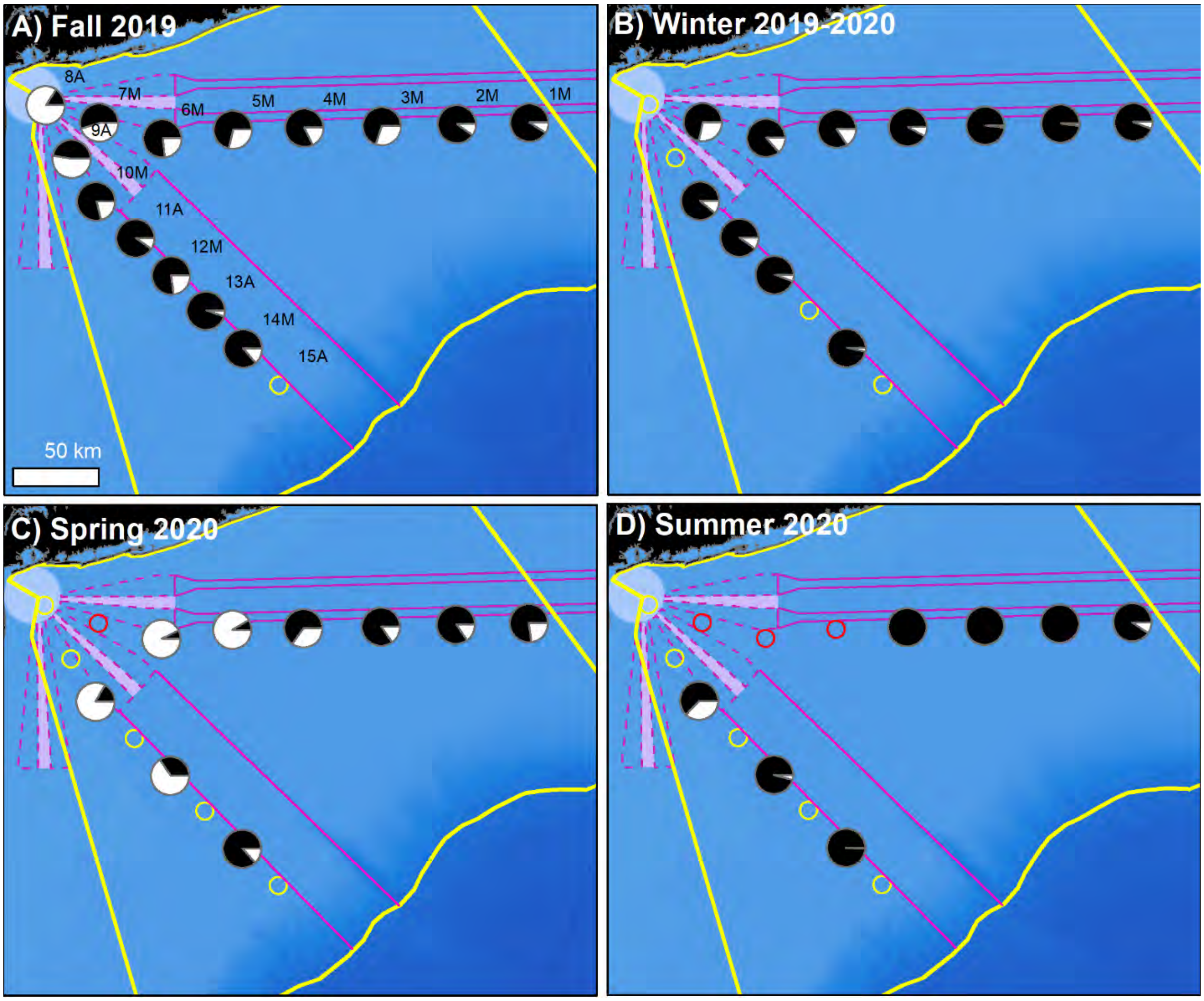


Figure 30. Year-3 spatial patterns of seasonal acoustic presence of fin whales in New York Bight, shown as percentage of days per season on each recording unit. Black indicates the proportion of days per month with acoustic detections; white indicates no detections. A) Fall (October – December), B) Winter (January – March), C) Spring (April – June), and D) Summer (July-September). Hollow circles denote AMAR/AURAL (in yellow) and MARU (in red) site locations in which there are no data for that season.

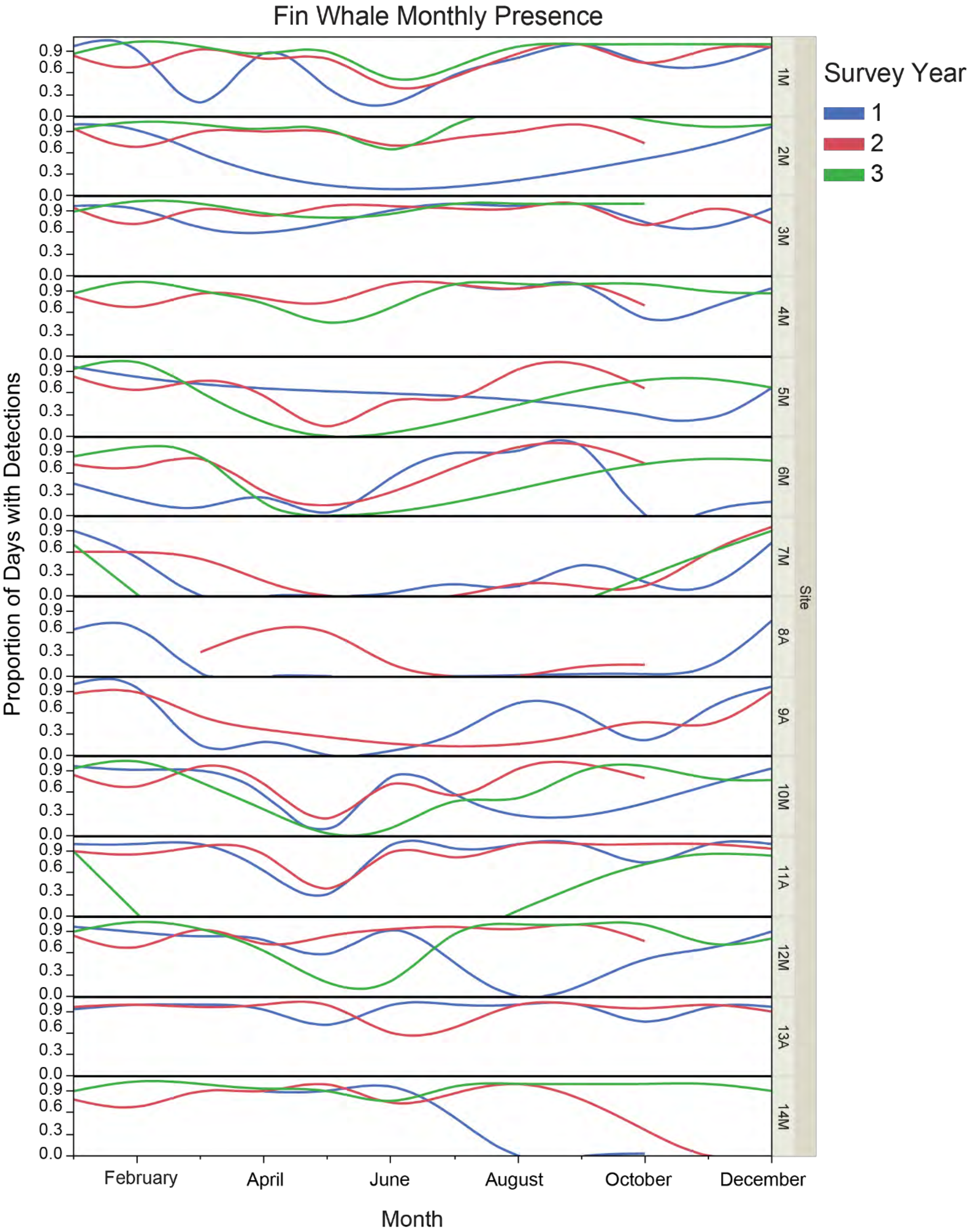


Figure 31. Internannual proportion of surveyed days with fin whale detections in New York Bight for survey Year-1 (blue), Year-2 (red), and Year-3 (green) as a function of days per month with acoustic presence. Each line is smooth a cubic spline (lambda = $1e^{-07}$).

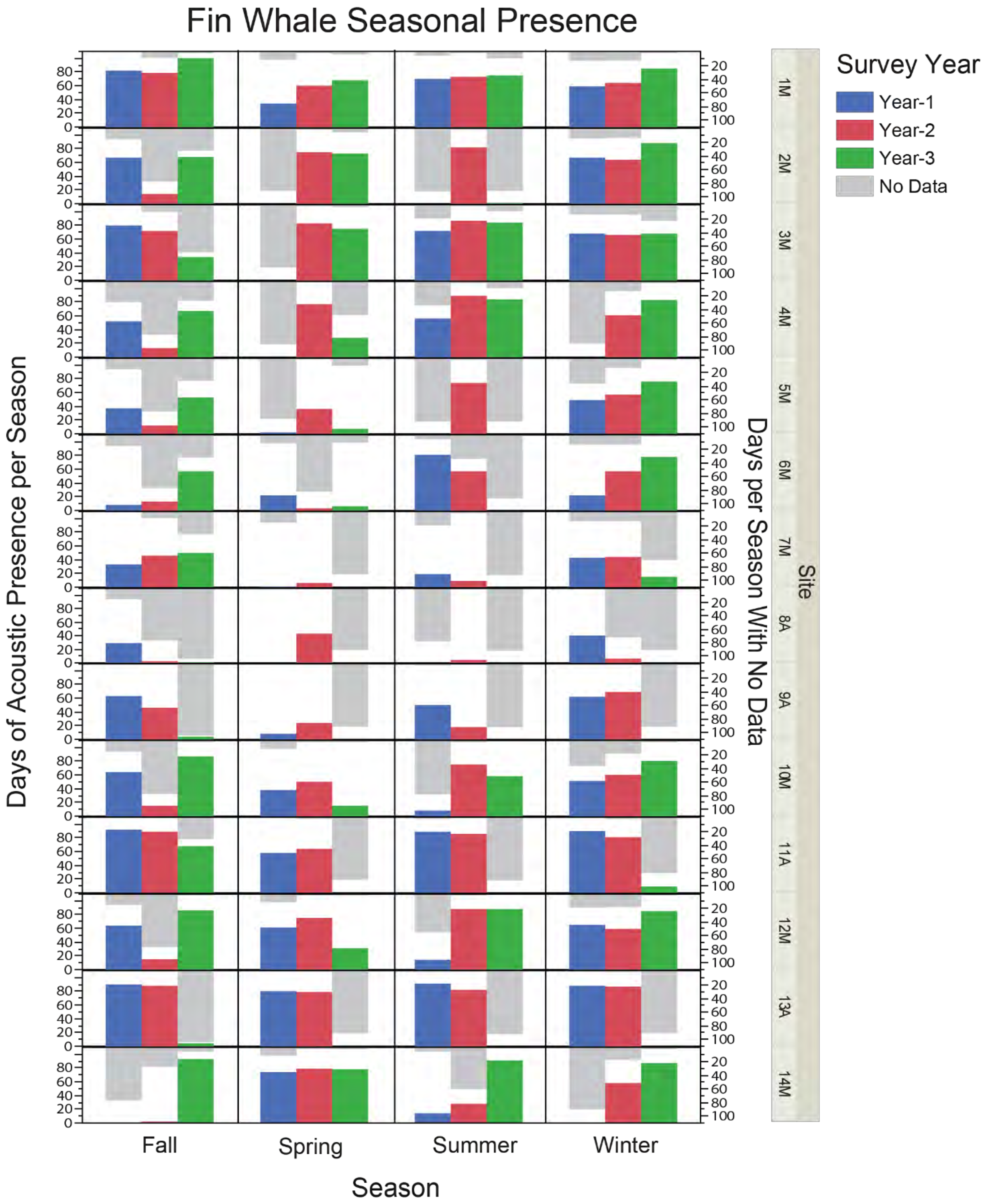


Figure 32. Internannual fin whale seasonal acoustic presence in New York Bight for survey Year-1 (blue), Year-2 (red), and Year-3 (green) as a function of days with acoustic presence per month. Data gaps for years 1-3 are shown in grey (inverse secondary y-axis) as the number of missing days per month.

Sei Whale Occurrence

Temporal Presence

Sei whale presence exhibited strong temporal trends during the Year-3 survey (Figure 33, Figure 34) similar to presence trends observed in the previous survey years. Sei whale presence began in November 2019, with detections on 3 calendar-days (10% of calendar-days) and remained relatively low through December (2 calendar-days, 6%) and January (4 calendar-days, 13%) until February (25 calendar-days, 86%). From February through May calendar-day presence exceeded 80% calendar-days each month. May recorded the highest presence of sei whales, with 30 calendar-days of presence (97% recording days). Percent monthly presence decreased in June to 53%, after which no sei whales were detected through the remainder of the calendar-days in the survey (n = 107 calendar-days).

Sei whale seasonal site-day presence (Table 21 (continued). Daily presence for sperm whales by month across all AMAR sites and corresponding percentage of total calendar-days in which sperm whale usual clicks were detected.

Month-Year	**Total Days Recorded**	**Sperm Whale**	
		# Days Detected	**% Days Detected**
19-Apr	30	5	17
19-May	31	8	26
19-Jun	30	6	20
19-Jul	31	8	26
19-Aug	31	10	32
19-Sep	30	7	23
19-Oct	31	1	3
19-Nov	30	0	0
19-Dec	31	0	0
20-Jan	10	0	0
20-Feb	0	NA	NA
20-Mar	0	NA	NA
20-Apr	0	NA	NA
20-May	0	NA	NA
20-Jun	0	NA	NA
20-Jul	0	NA	NA
20-Aug	0	NA	NA
20-Sep	0	NA	NA
20-Oct	0	NA	NA

Table *22***Error! Reference source not found.**, Figure 36) was highest during the winter (194 site-days with detections, 26%) and spring (243 site-days with detections, 33%) months, and lowest fall (6 site-days with detections, 1%) and summer (0 site days with detections).

Spatial Presence

Sei whales had more acoustic presence at the eastern and south-eastern sites (1M, 2M, 3M, and 14M), with percent calendar-day presence >20% for each site (Table 23). Site 2M recorded the highest presence among the sites, with 87 calendar-days (34%). Sites 5M, 6M, 7M, 10M and 11A recorded the lowest presence, where 6% or less calendar-days had sei whale presence. The spatial trend in sei whale presence, which was also observed in previous survey years, may suggest a preference for deeper waters near the shelf edge (

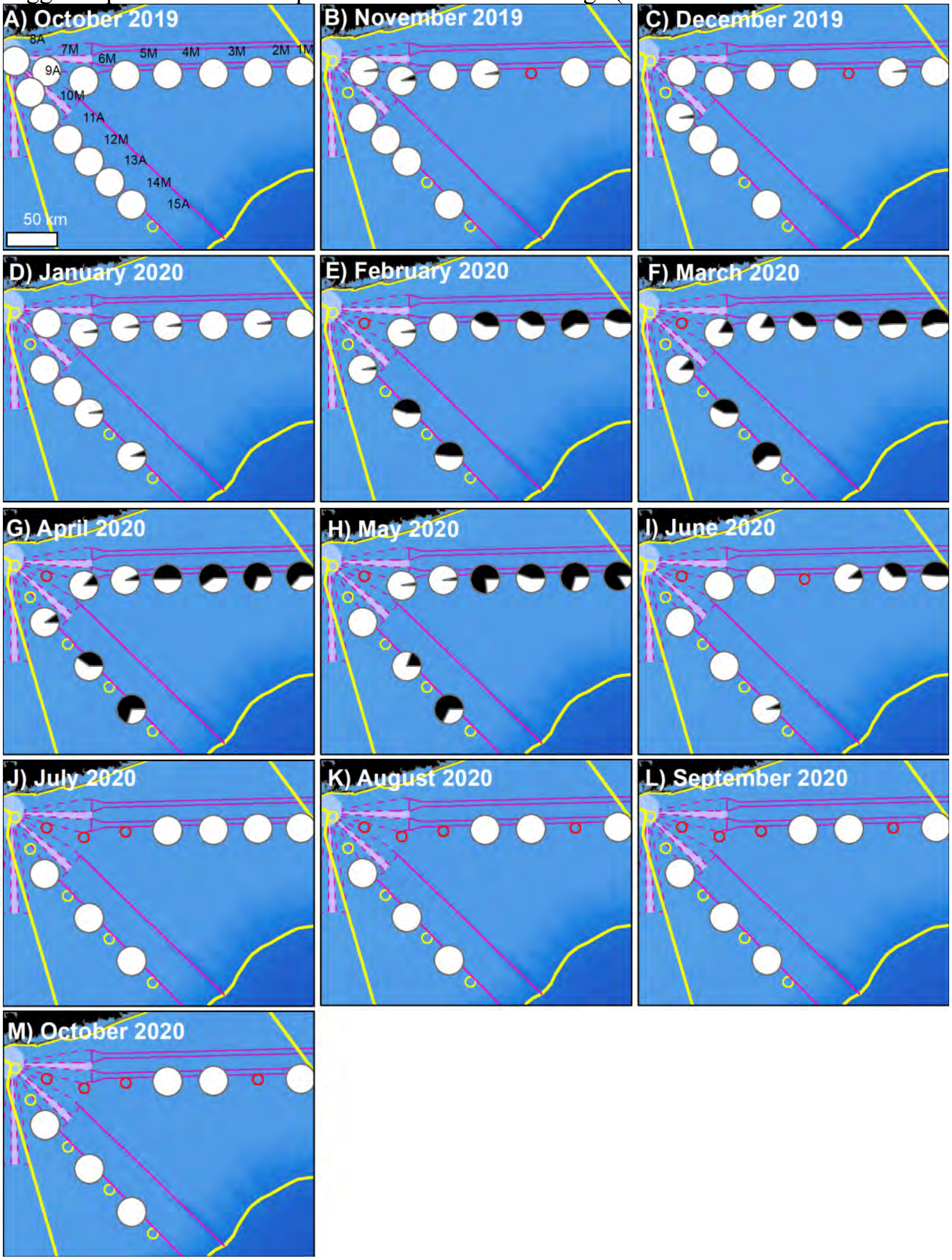
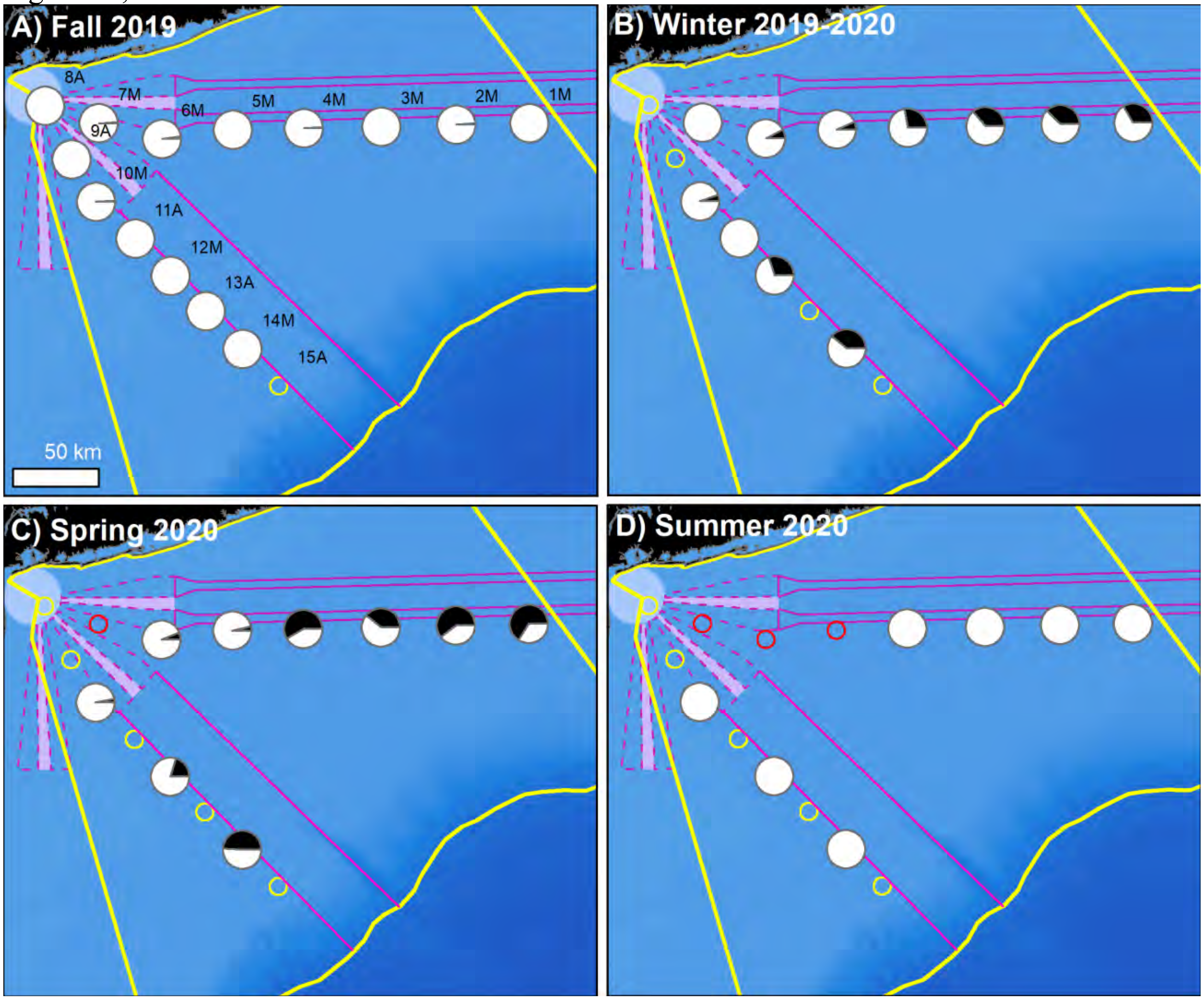
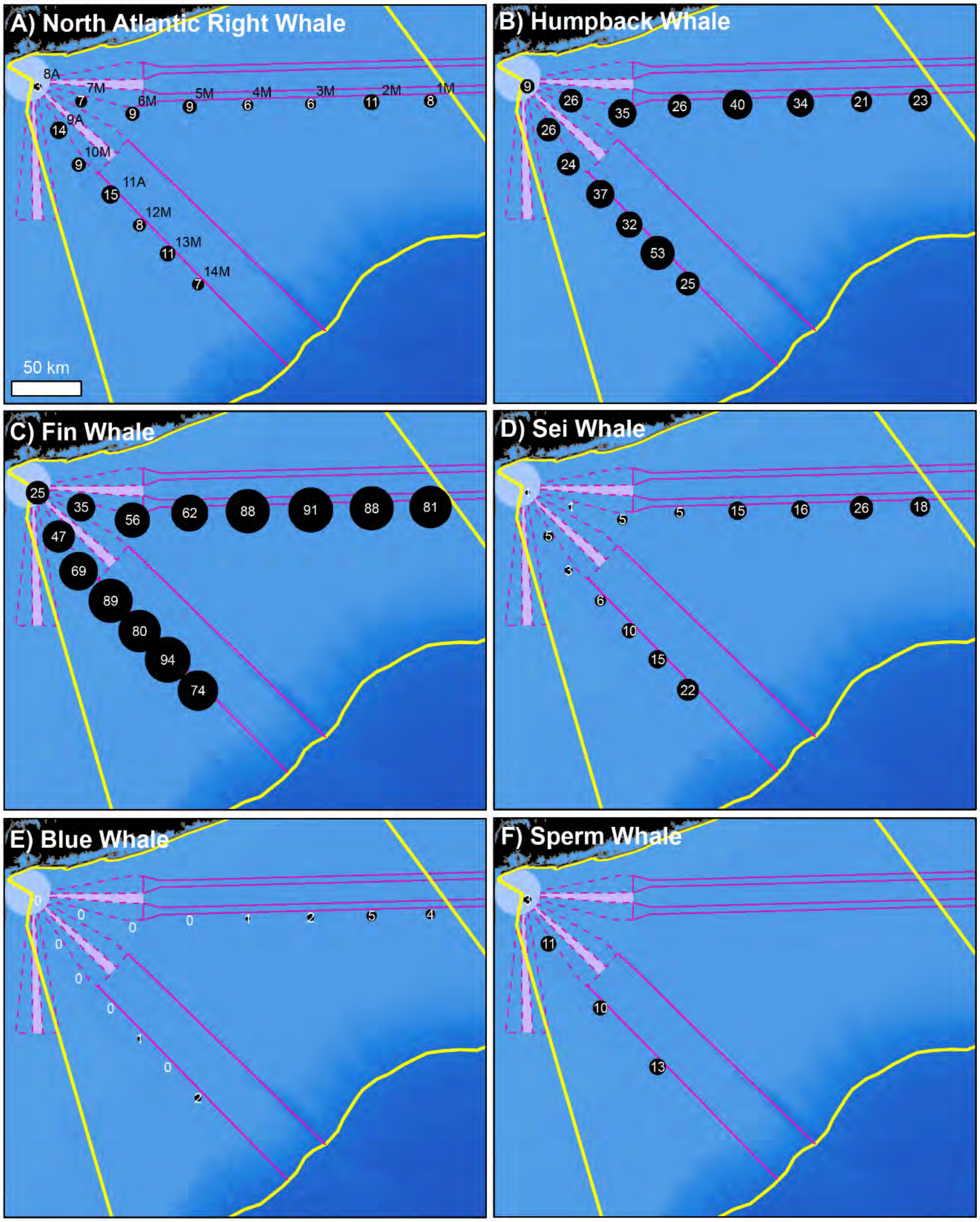


Figure 35, Figure 37).



3 Year Presence Summary (2017 – 2020)

There were more sei whale daily detections in Year-3 (n = 433) compared to Year-1 (n = 283), but fewer detections than Year-2 (n = 459). In all three years, the highest number of detections occurred between March and June at sites 1M-4M, and 12M-14M, though there were a few detections throughout the years on most sites (Figure 38, Table 25). Sei whales occurred for a slightly longer duration of time in late winter through late spring of Year-3, compared to Year-1 and Year-2, however the overall seasonal presence trends persisted across the three survey years (Figure 39). We conducted a one-way analysis of variance (ANOVA) to compare the proportion of days of sei whale presence per week between the three survey years to test if there was a difference in sei whale presence between years, exactly as described for previously mentiontioned species. The ANOVA showed that there was no significant difference in sei whale weekly presence between survey years ($F_{2,149} = 0.735$ $p = .481$), indicating that sei whale presence was not different during any of the survey years. Sei whale cumulative daily detections across the three years illustrate that most detections occurred at sites closer to the shelf edge and very few were detected near the NY Harbor (Figure 50D).



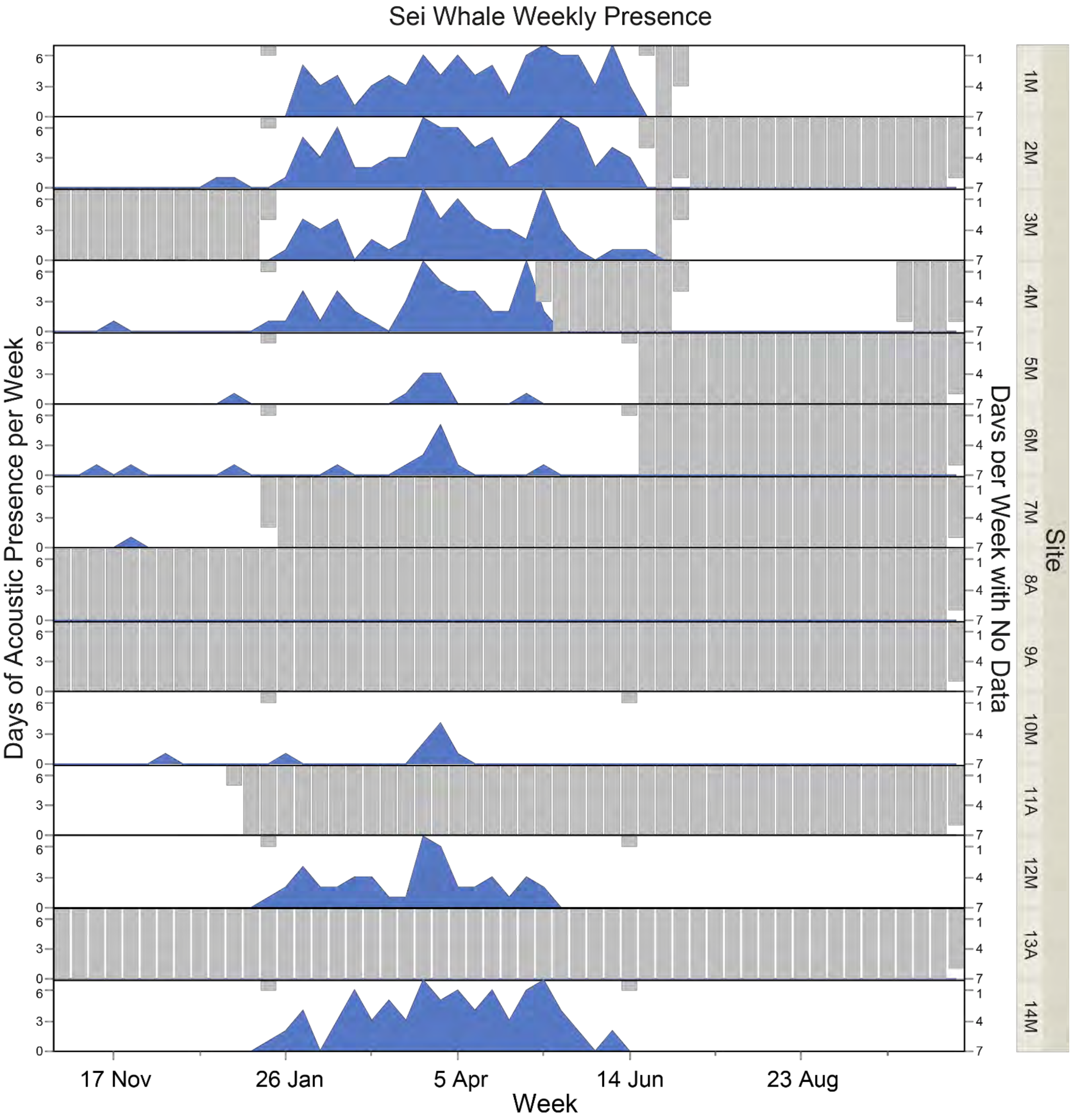


Figure 33. Year-3 weekly acoustic presence of sei whales detected in New York Bight between October 2019-October 2020, shown as number of days per week with confirmed sei whale acoustic detections across all sensors (blue area). The inverse secondary y-axis indicates the number of days for each week during which there are no sound data (grey bars).

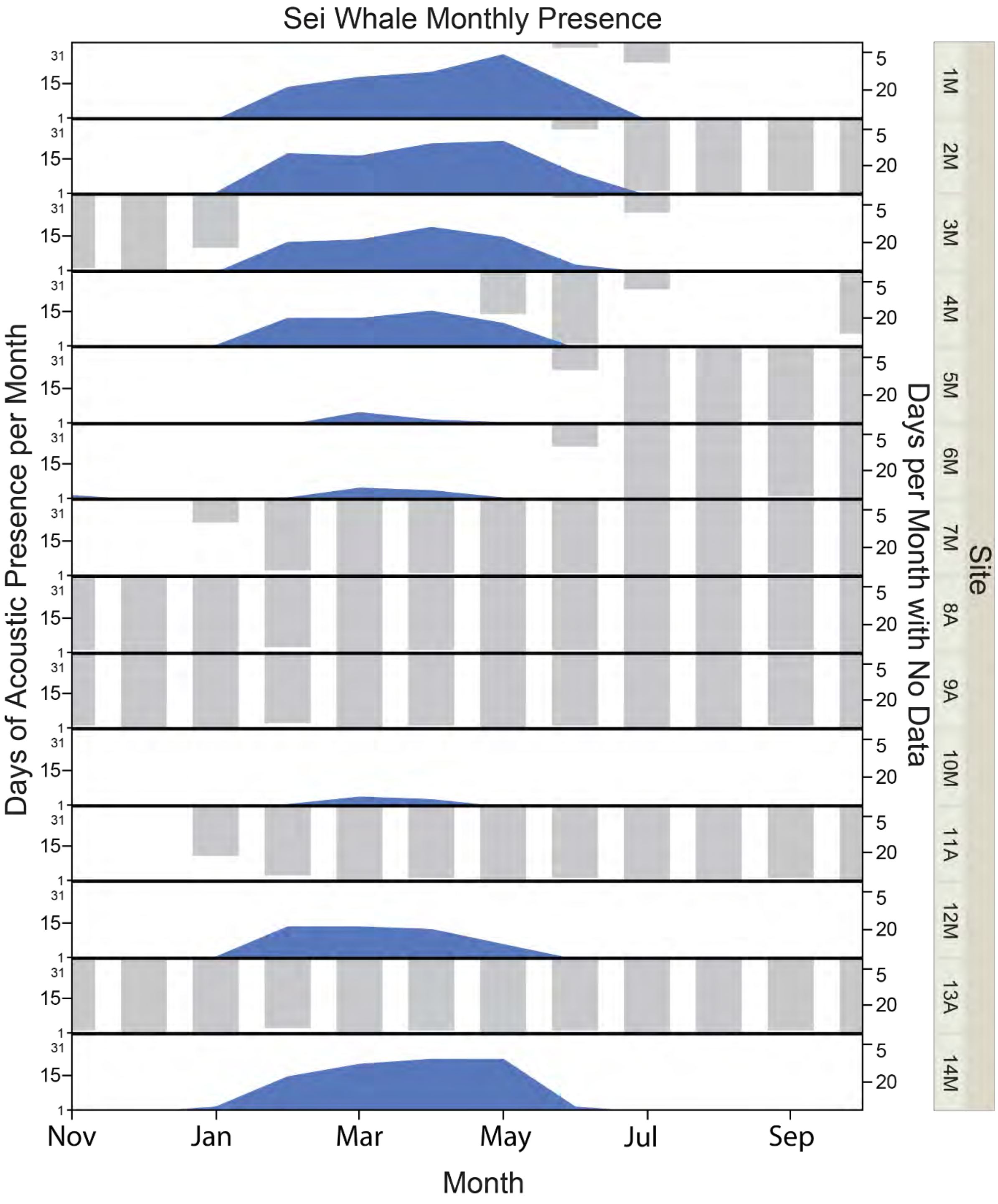


Figure 34. Year-3 monthly acoustic presence of sei whales detected in New York Bight between October 2019-October 2020, shown as number of days per week with confirmed fin whale acoustic detections across all sensors (blue line). The inverse secondary y-axis indicates the number of days for each month during which there are no sound data (grey bars).

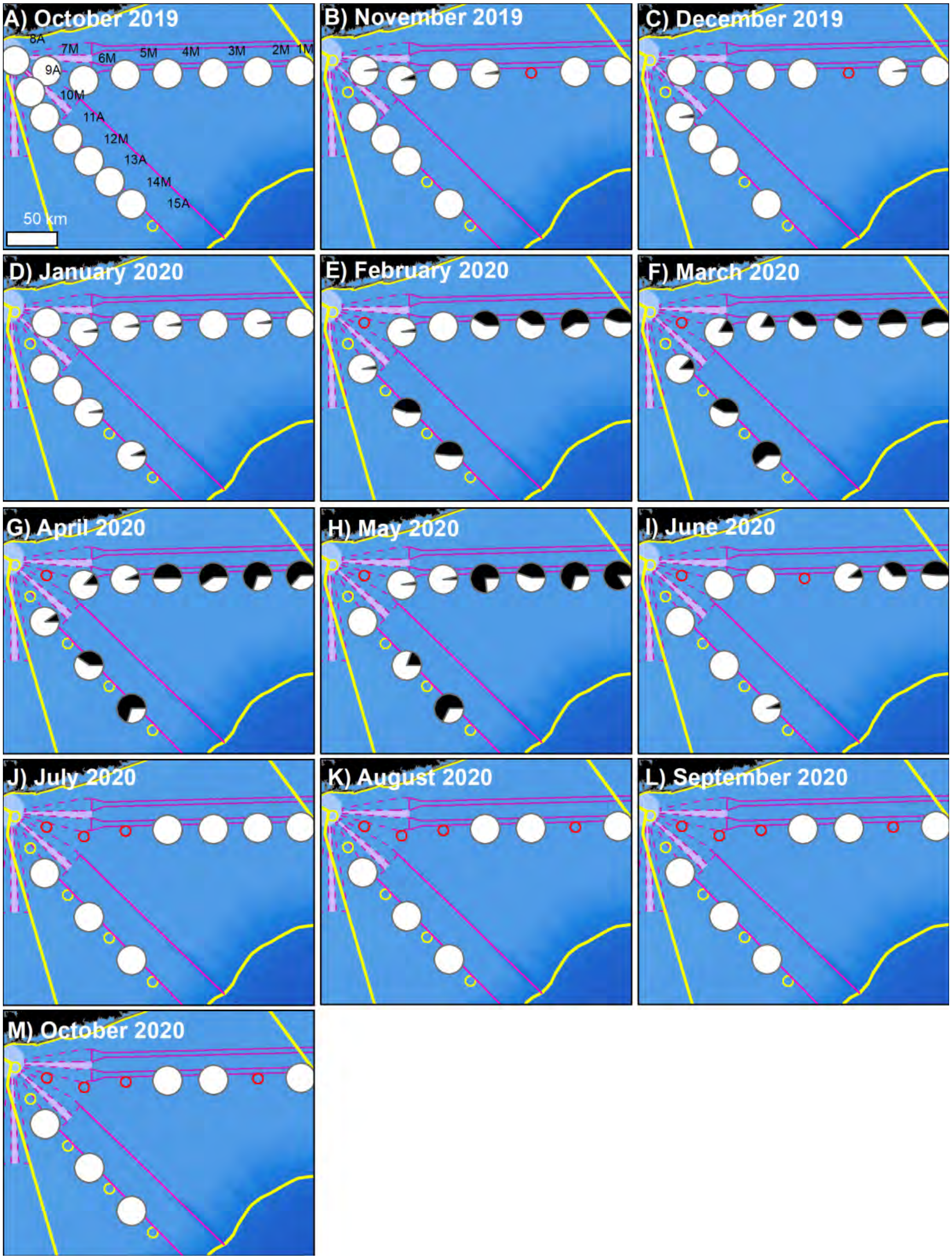


Figure 35. Year-3 spatial patterns of monthly presence of sei whales in New York Bight, shown as percentage of days per month on each recording unit. Black indicates the proportion of days per month with acoustic detections; white indicates no detections. Hollow circles denote AMAR/AURAL (in yellow) and MARU (in red) site locations in which there are no data for that season.

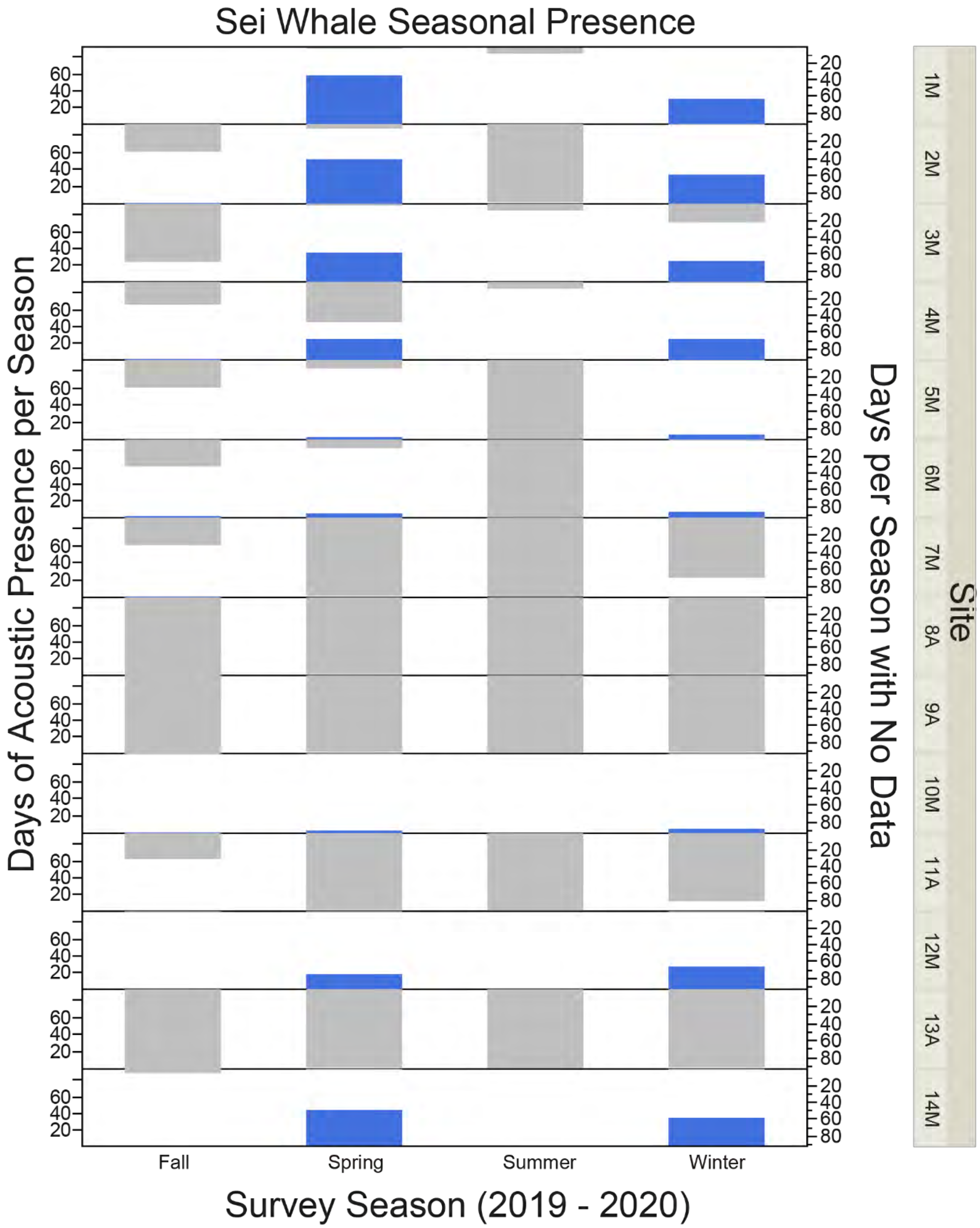


Figure 36. Year-3 seasonal acoustic presence of sei whales detected in New York Bight from Fall 2019 through Summer 2020, shown as number of days per month with confirmed right whale acoustic detections across all sensors for Fall (October – December), Winter (January – March), Spring (April – June), and Summer (July - September). Gray bars indicate the number of days for each season during which there are no sound data.

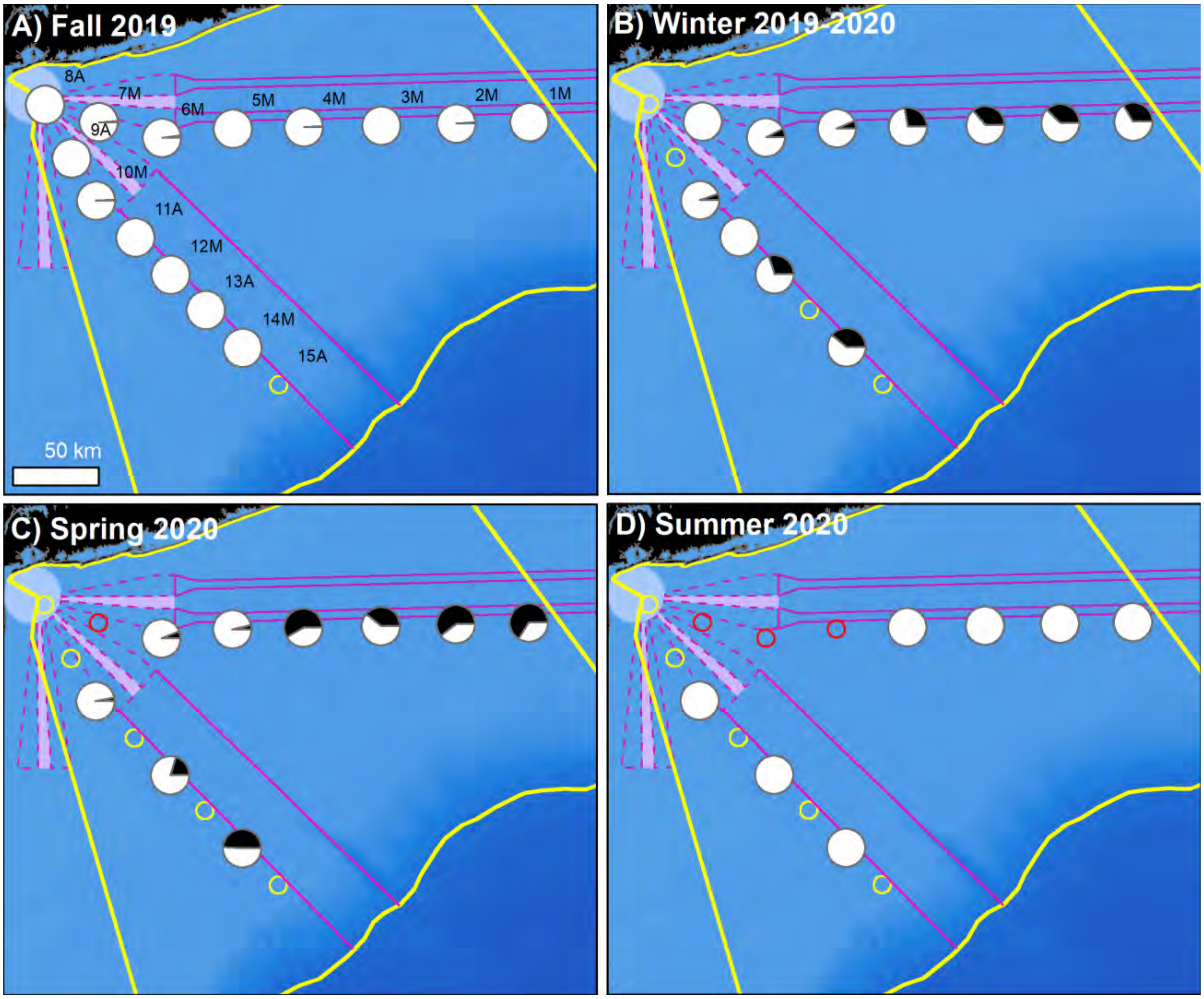


Figure 37. Year-3 spatial patterns of seasonal acoustic presence of sei whales in New York Bight, shown as percentage of days per season on each recording unit. Black indicates the proportion of days per month with acoustic detections; white indicates no detections. A) Fall (October – December), B) Winter (January – March), C) Spring (April – June), and D) Summer (July-September). Hollow circles denote AMAR (in yellow) and MARU (in red) site locations in which there are no data for that season.

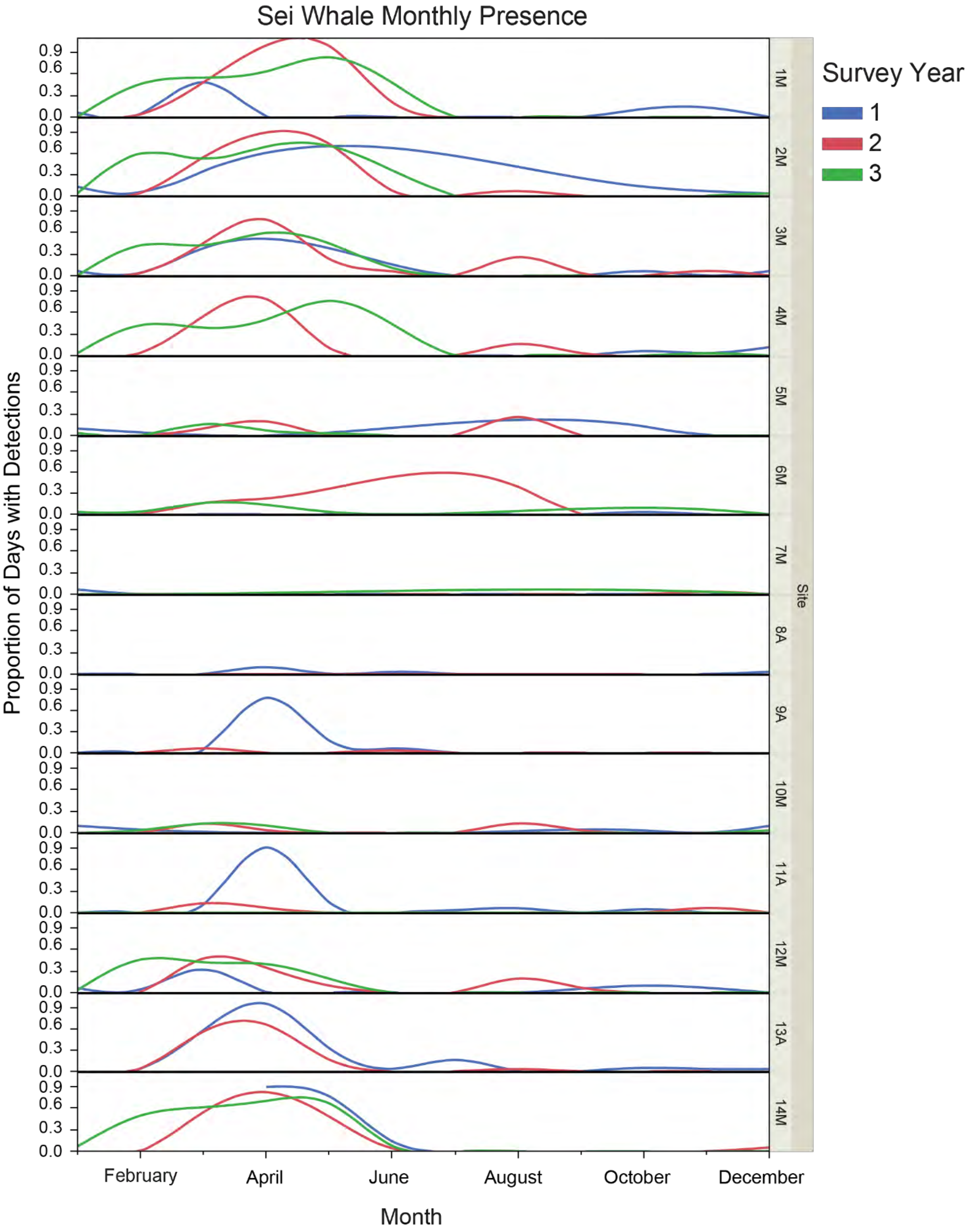


Figure 38. Internannual proporation of surveyed days with sei whale detections in New York Bight for survey Year-1 (blue), Year-2 (red), Year-3 (green) as a function of days per month with acoustic presence. Each line is smooth a cubic spline (lambda = 1e^{-07}).

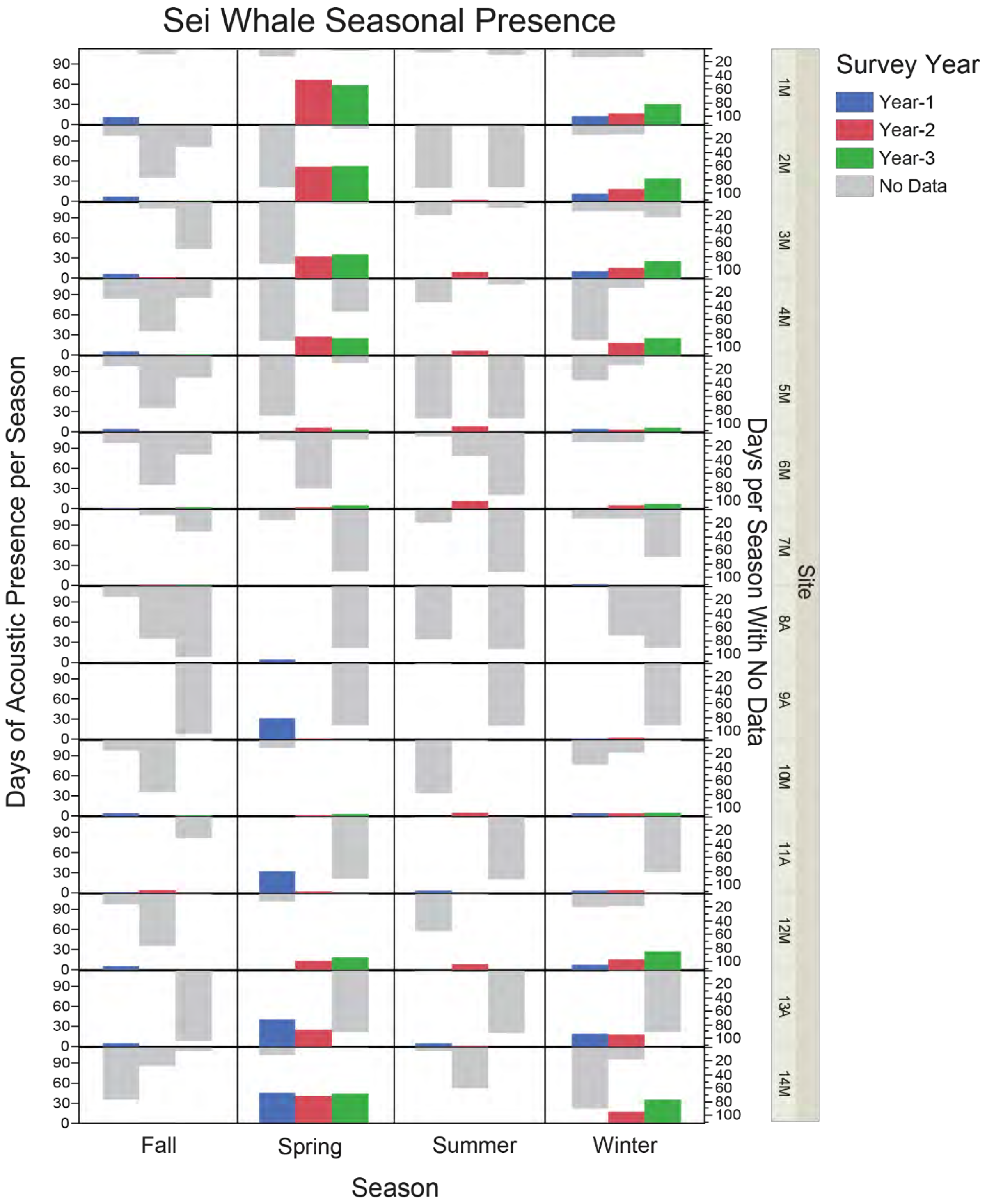


Figure 39. Internannual sei whale seasonal acoustic presence in New York Bight for survey Year-1 (blue), Year-2 (red), and Year-3 (green) as a function of days with acoustic presence per month. Data gaps for Years 1-3 are shown in grey (inverse secondary y-axis) as the number of missing days per month.

Blue Whale Occurrence

Temporal Presence

Blue whales were the least frequently detected species within NY Bight (Figure 49), with a total of 16 calendar-days (4%) and 63 site-days(0.54%) with detections in Year-3 (Table 20, Figure 40, Figure 41). Blue whales were detected in January (6 calendar-days, 19%) and February (11 calendar-days, 38%). All presence occurred between 24 January and 21 February, comprising four short weeks with daily detections in the area.

Spatial Presence

Blue whales were only detected on sites 1M, 2M, 3M, 4M, 12M, and 14M (Table 23, Figure 40, Figure 41, Figure 42). The aerial surveys observed blue whale individuals within the NY Offshore Planning Area (Tetra Tech and LGL 2020), thus blue whale acoustic detections may be from animals within NY Bight. However, since blue whale song can propagate more than 100 km from the calling individual, it is likely that some of the acoustic detections from vocalizing individuals during the Year-3 survey may have originated outside of NY Bight beyond the continental shelf edge. Since we did not observe multiple arrival-patterns of the signal across sites or overlapping calls, it is unclear whether the blue whale signals that were detected during those 4 weeks were produced by the same animal, or whether they are a different individual or individuals.

3 Year Presence Summary (2017 – 2020)

There were fewer calendar-day detections of blue whales in Year-3 compared to Year-1 (n = 53 calendar-days), and the same as Year-2 (n = 16 calendar-days; Table 20, Figure 45). During all three survey years, blue whales were detected during winter months (Table 22, Figure 45, Figure 46), however, in Year-1, blue whales were also detected during the later fall months. To test if blue whale acoustic presence was consistent across the three survey years, we conducted a one-way analysis of variance (ANOVA) to compare the proportion of days of blue whale presence per week between the three survey years. To do this, we excluded time periods without sound data (data gaps) and calculated the proportion of surveyed days per week in which there was blue whale presence. We also excluded AMAR sites from the analysis since few data were recovered from AMAR sites during Year-3. The ANOVA showed that there was no significant difference in blue whale weekly presence between survey years ($F_{2,149} = 1.682$, $p = 0.189$), indicating that blue whale presence was not different during any one survey year. The cumulative daily detection data for blue whales shows that song was detected at sites nearer to the shelf edge and illustrate relatively low detections throughout the 3-year survey compared to other whale species that were surveyed (

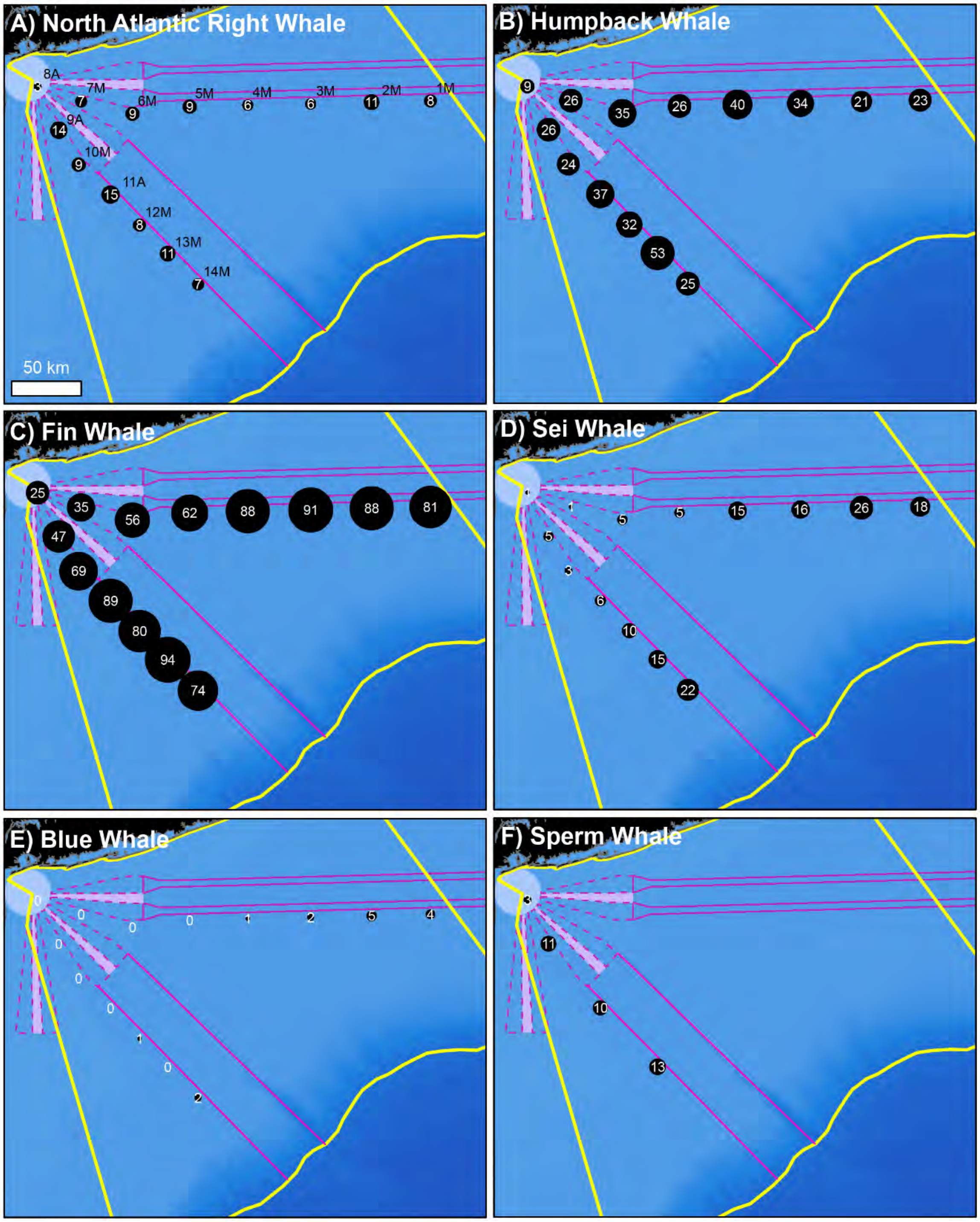


Figure 50E).

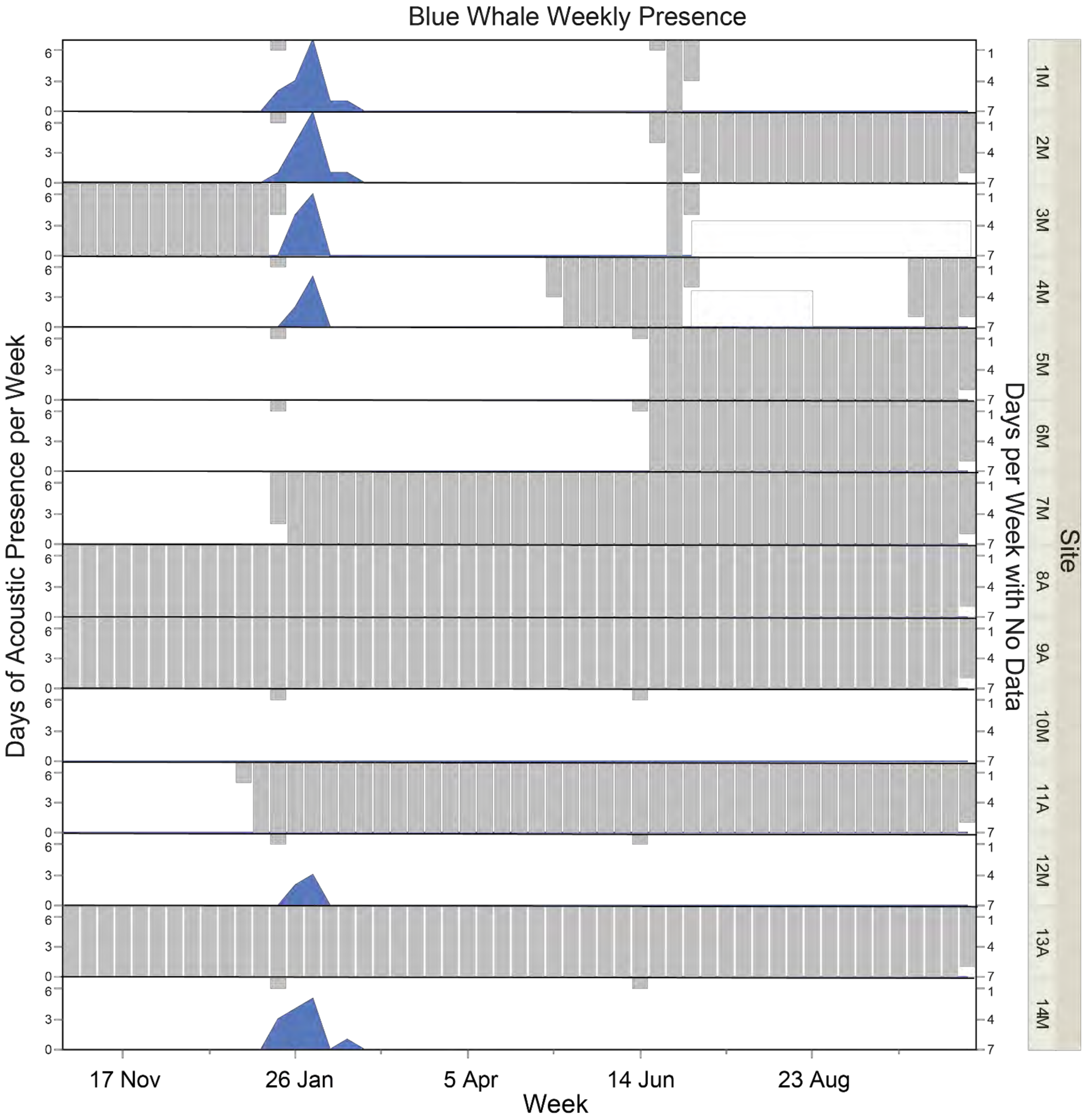


Figure 40. Year-3 weekly acoustic presence of blue whales detected in New York Bight between October 2019-October 2020, shown as number of days per week with confirmed blue whale acoustic detections across all sensors (blue area). The inverse secondary y-axis indicates the number of days for each week during which there are no sound data (grey bars).

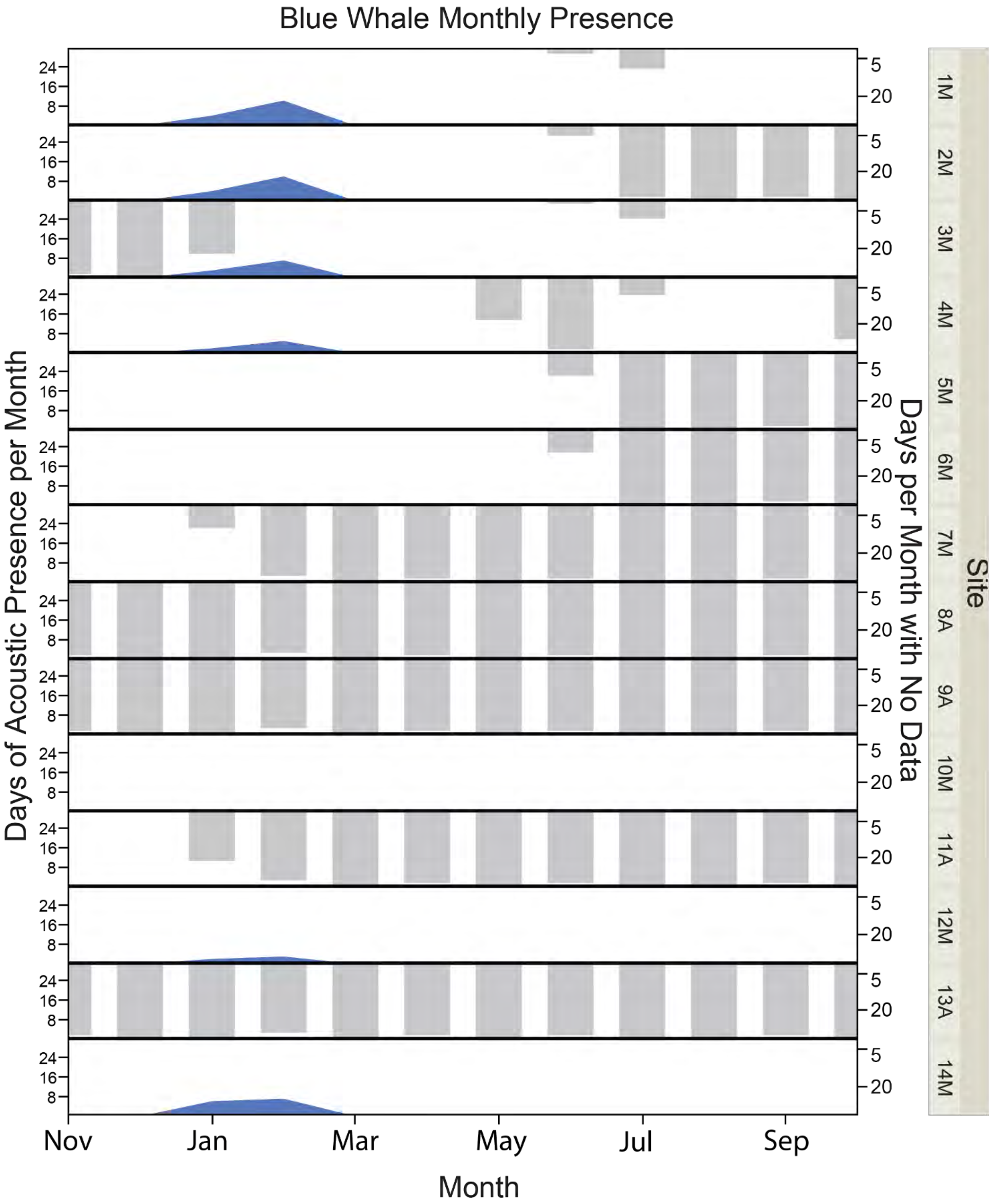


Figure 41. Year-3 monthly acoustic presence of blue whales detected in New York Bight between October 2019-October 2020, shown as number of days per week with confirmed blue whale acoustic detections across all sensors (blue line). The inverse secondary y-axis indicates the number of days for each month during which there are no sound data (grey bars).

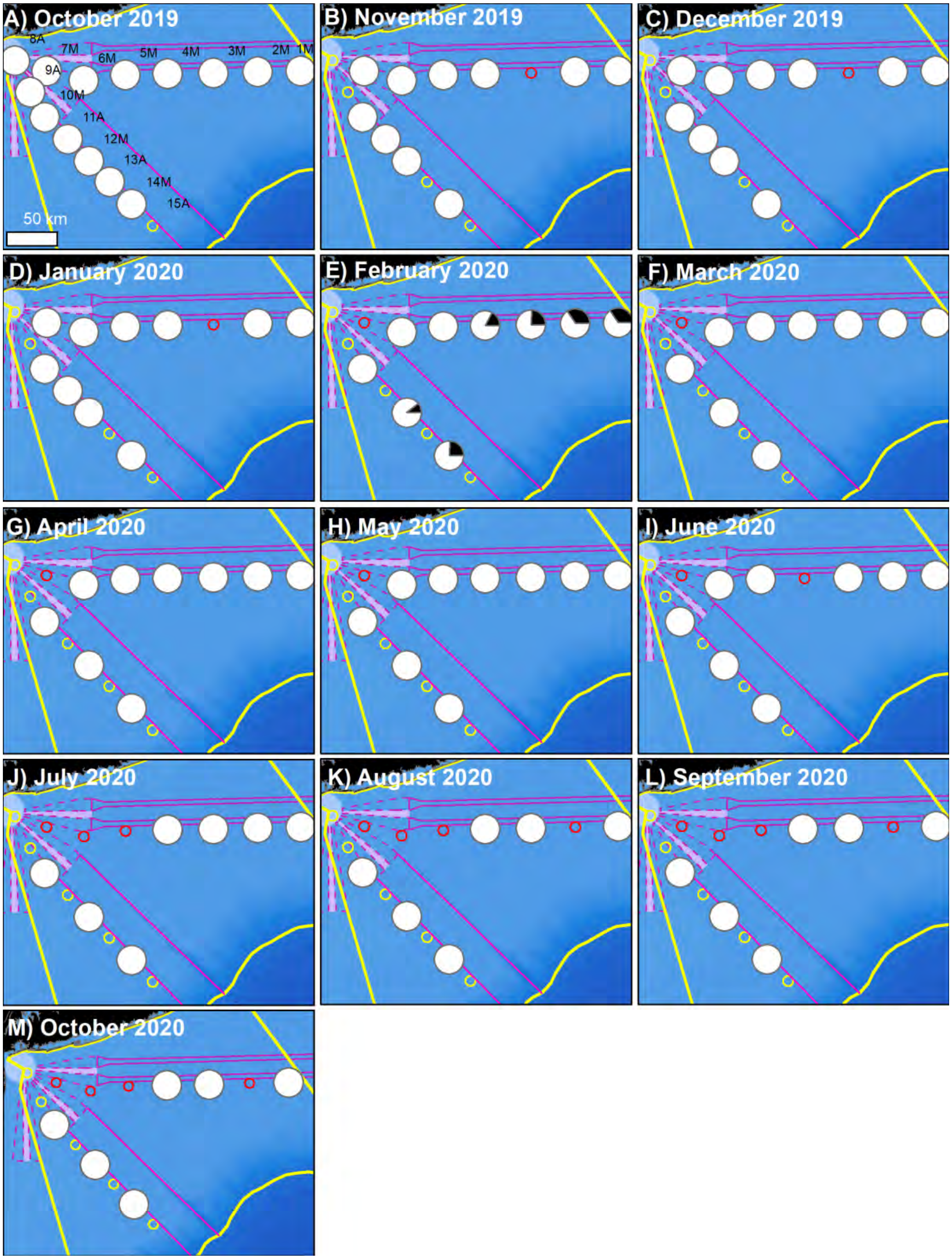


Figure 42. Year-3 spatial patterns of monthly presence of blue whales in New York Bight, shown as percentage of days per month on each recording unit. Black indicates the proportion of days per month with acoustic detections; white indicates no detections. Hollow circles denote AMAR/AURAL (in yellow) and MARU (in red) site locations in which there are no data for that season.

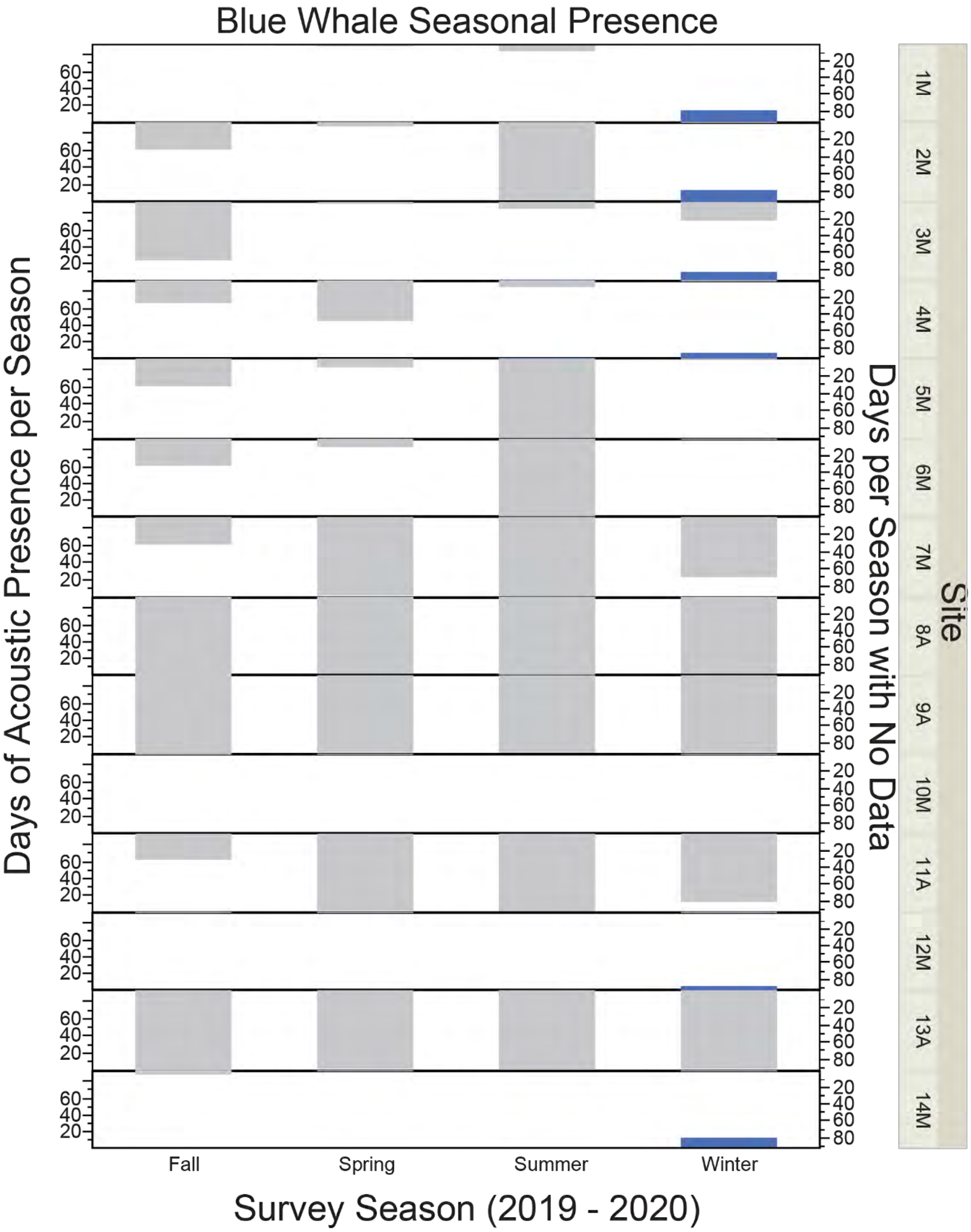


Figure 43. Year-3 seasonal acoustic presence of blue whales detected in New York Bight from Fall 2019 to Fall 2020, shown as number of days per month with confirmed right whale acoustic detections across all sensors for Fall (October – December), Winter (January – March), Spring (April – June), and Summer (July - September). Gray bars indicate the number of days for each season during which there are no sound data.

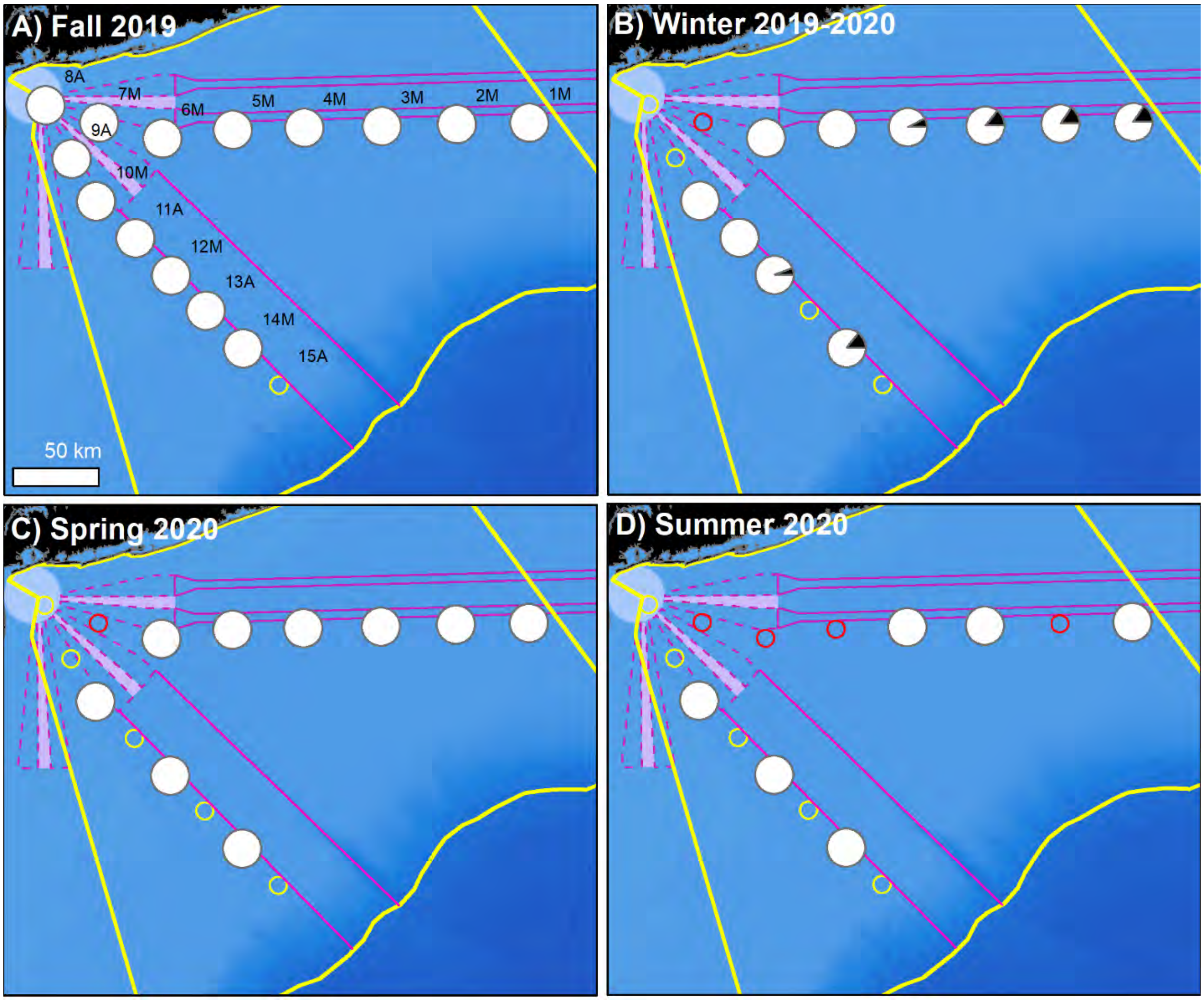


Figure 44. Year-3 spatial patterns of seasonal acoustic presence of blue whales in New York Bight, shown as percentage of days per season on each recording unit. Black indicates the proportion of days per month with acoustic detections; white indicates no detections. A) Fall (October – December), B) Winter (January – March), C) Spring (April – June), and D) Summer (July-September). Hollow circles denote AMAR/AURAL (in yellow) and MARU (in red) site locations in which there are no data for that season.

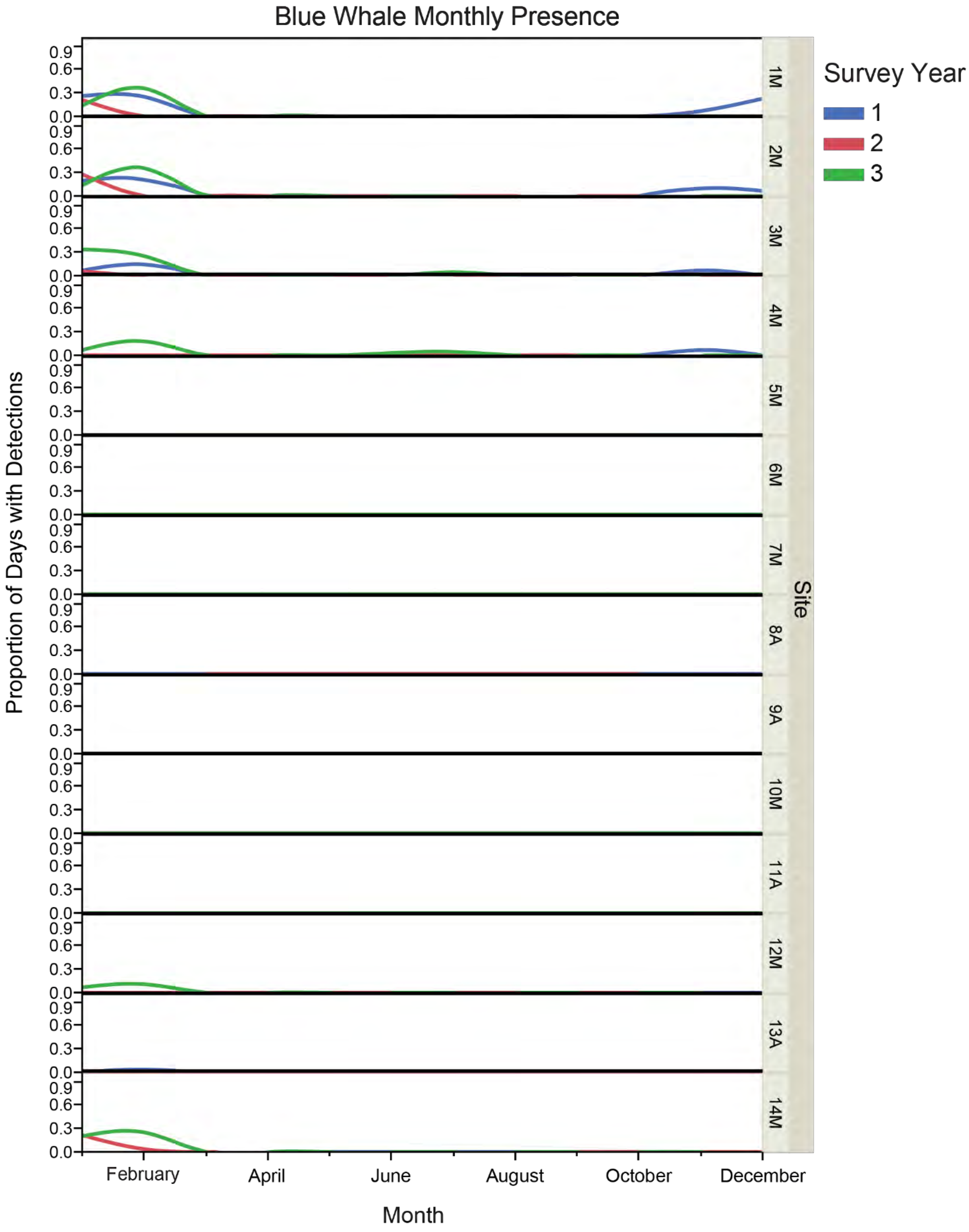


Figure 45. Internannual proportions of surveyed days with blue whale detections in New York Bight for survey Year-1 (blue), Year-2 (red), Year-3 (green) as a function of days per month with acoustic presence given days sampled per month. Each line is smooth a cubic spline (lambda = 1e^{-07}).

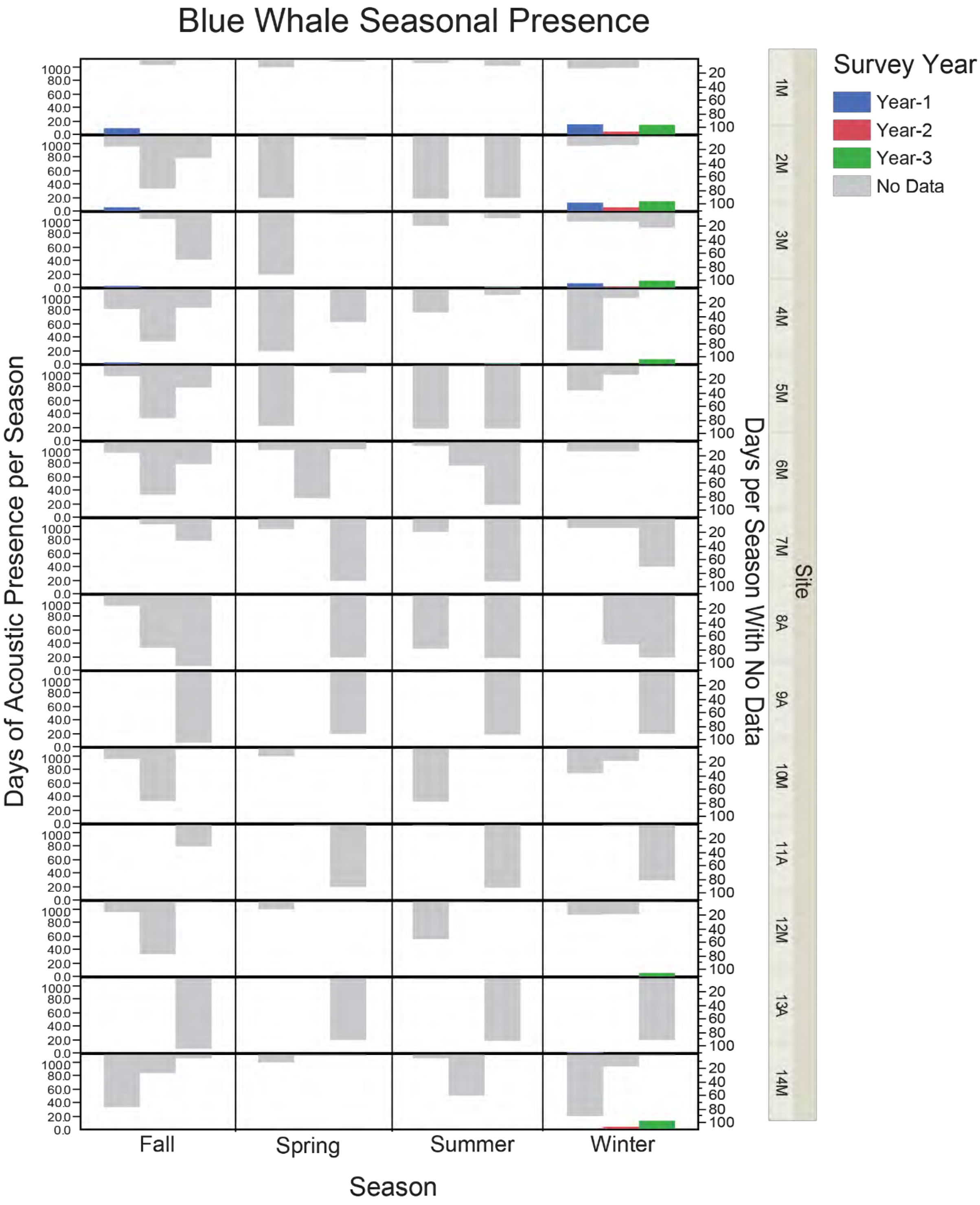


Figure 46. Internannual blue whale seasonal acoustic presence in New York Bight for survey Year-1 (blue),Year-2 (red), and Year-3 (green) as a function of days with acoustic presence per month. Data gaps for Years 1-3 are shown in grey (inverse secondary y-axis) as the number of missing days per month.

Sperm Whale Occurrence

Year-3 Presence

During the Year-3 survey, sites 8A, 9A, and 13A each recorded 4 days of data, which were captured during the final deployment of Year-2. Since AMAR units were not successfully recovered during Year-3, most Year-3 data are missing for those sites, therefore we do not have sperm whale presence information for those sites. The AMAR at site 11A recorded for just 87 days, 83 of which occurred during Year-3. The AMAR at site 11A was deployed in March 2019 for the A-D3 survey (Year-2), the battery depleted in January 2020, and the unit surfaced in February 2020. During those 83 days, sperm whale usual clicks were not detected by an analyst. (Table 19, Table 20, Table 21 , Table 23). With the high data loss for AMARs in Year-3, we cannot conclude from the acoustic data alone whether sperm whales occurred in NY Bight during Year-3.

3 Year Presence Summary (2017 – 2020)

Interannual sperm whale presence data (Figure 47) showed higher site-day presence during the Year-1 survey (n = 228, 17% site-day presence) than Year-2 (n = 47, 4% site-day presence), while the sampling effort between the two years differed by only 56 site-days (Year-1: 364 calendar-days, 1364 site-days; Year-2: 365 calendar-days, 1308 site-days). In Year-1, sperm whales occurred more frequently between January and September 2018, with a mean percent calendar-day presence of 58%. Sperm whales were not detected during November 2018 – February 2019. In Year-2, sperm whales were detected between May and September 2019, with a mean percent calendar-day presence of 25%. Given the lower site-day detection of sperm whales during winter months in Year-2 (n = 2 site-days, 0.007%) and that sperm whales were not recorded at site 11A during winter months in 2019, it is not surprising that site 11A did not detect sperm whale presence during its recording time in Year-3 (October 2019 – January 2020). During winter months of Year-1, however, sperm whale site-day detections were relatively higher (n = 62 site-days, 17%), suggesting that seasonality of sperm whales on the shelf is variable. Without Year-3 data, however, it is difficult to conclude sperm whale seasonal variability in NY Bight. Both Year-1 and Year-2 data showed lower presence of sperm whales during fall months (Figure 48). During Year-1 and Year-2, sperm whales were detected at all 4 AMAR site locations (Table 25, Figure 47), with the highest site-day presence near the shelf edge at site 13A (n = 97 site-days, 13%). Presence at site 8A (n = 16 site-days, 3%) was surprising, as this site is located nearest to New York Harbor and far from deep waters. Sites 9A and 11A recorded a similar number of days with presence (n = 83 and n = 79 days, respectively). Cumulative daily detections for sperm whales show relatively consistent presence across the four AMAR sites, except at site 8A, which had the fewest detections (Figure 50F)

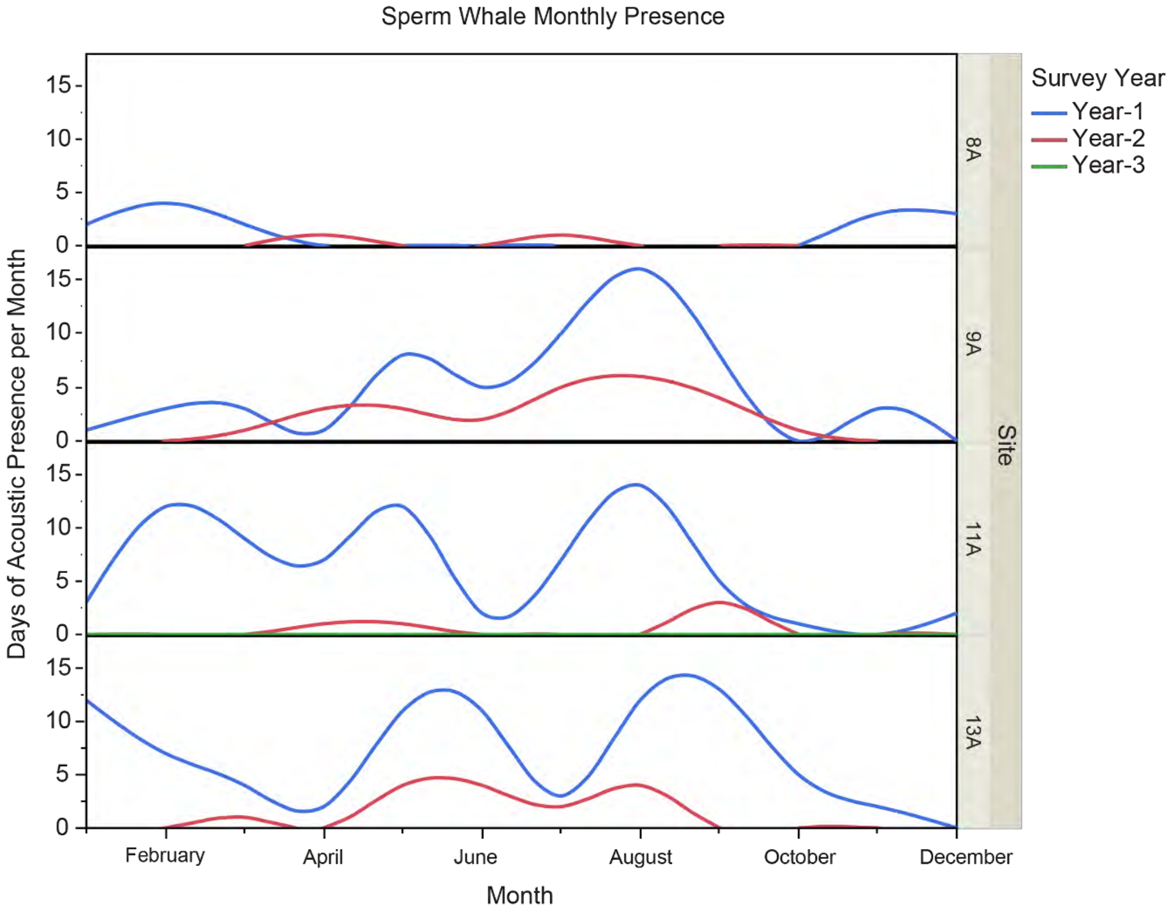


Figure 47. Internannual sperm whale monthly acoustic presence per site in New York Bight for survey Year-1 (blue), Year-2 (red), Year-3 (green) as a function of days per month with acoustic presence. Each line is a smooth cubic spline (lambda = 1e^{-07}). Note that these daily presence data are not corrected for survey effort.

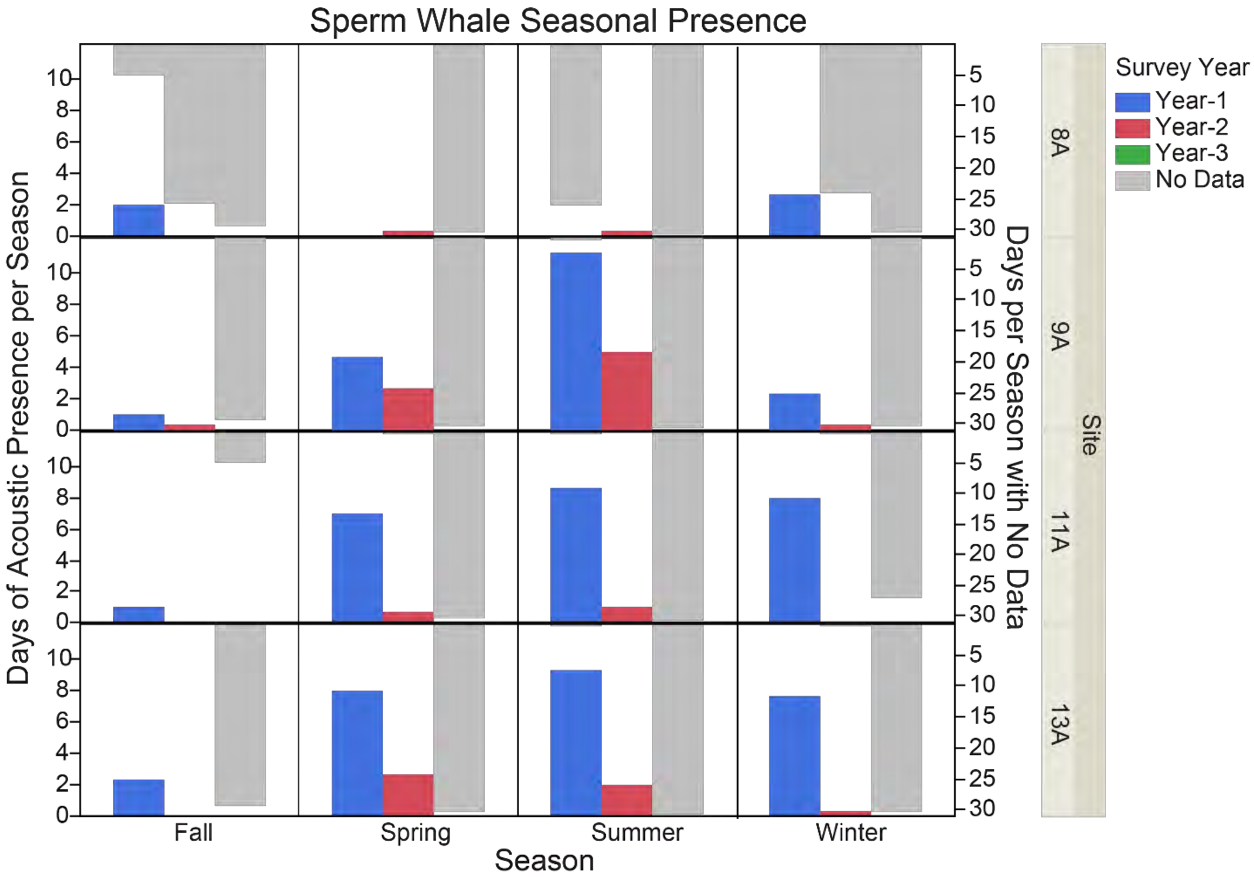


Figure 48. Internannual sperm whale seasonal acoustic presence in New York Bight for survey Year-1 (blue), Year-2 (red) and Year-3 (green) as a function of days with acoustic presence per month. Data gaps for years 1-3 are shown in grey (inverse secondary y-axis) as the number of missing days per month.

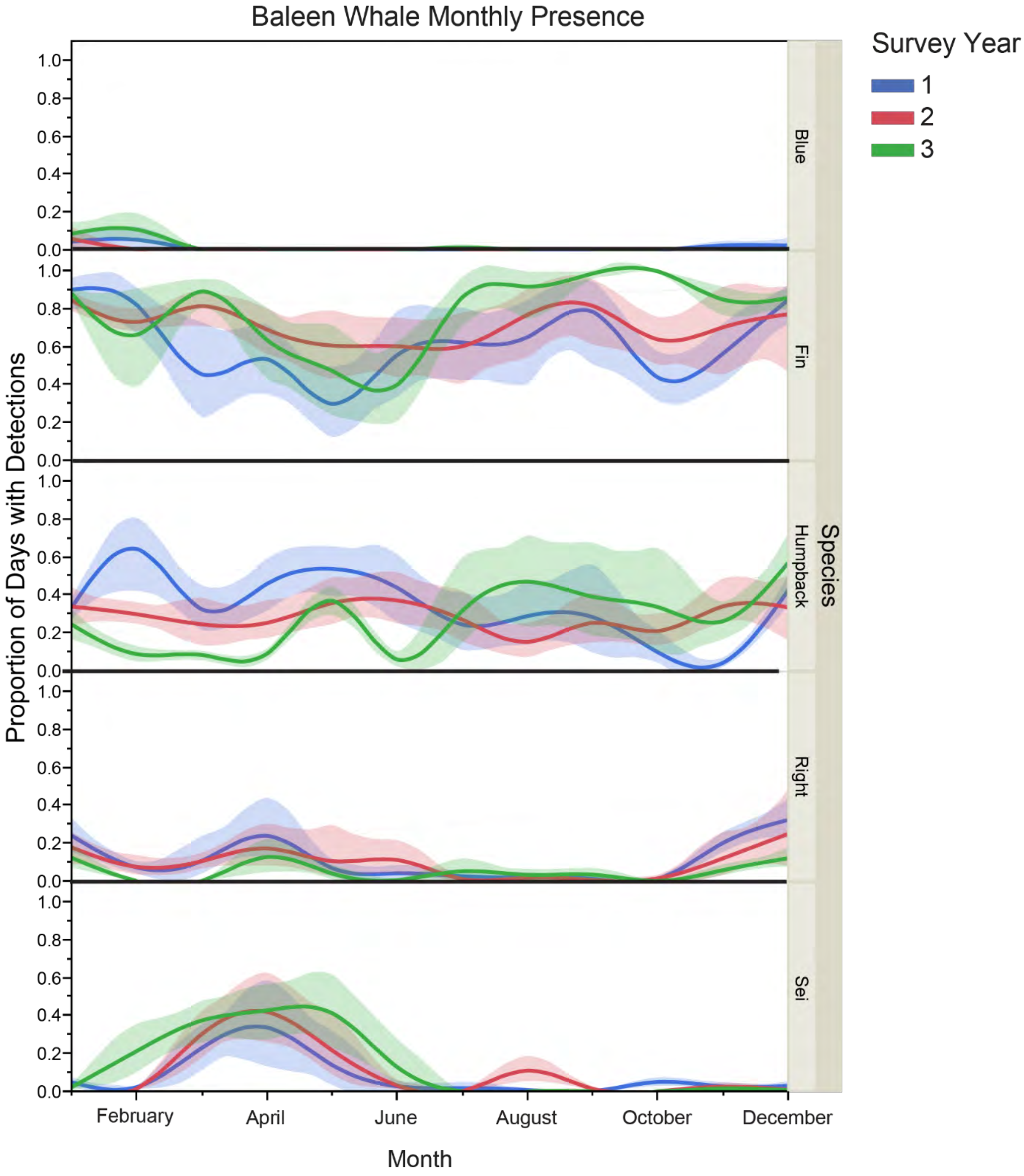


Figure 49. Daily acoustic presence of focal baleen whale species detected in New York Bight across the 3 survey years, shown as the proportion of surveyed calendar-days per week with confirmed acoustic detections. Survey Year-1 (October 2017-October 2018) is in blue, Survey Year-2 (October 2018-October 2019) is in red, and Survey Year-3 (October 2019 – October 2020). Each line is a smooth cubic spline (lambda = 1e^{-07}), with the shaded regions representing a bootstrap confidence of fit.

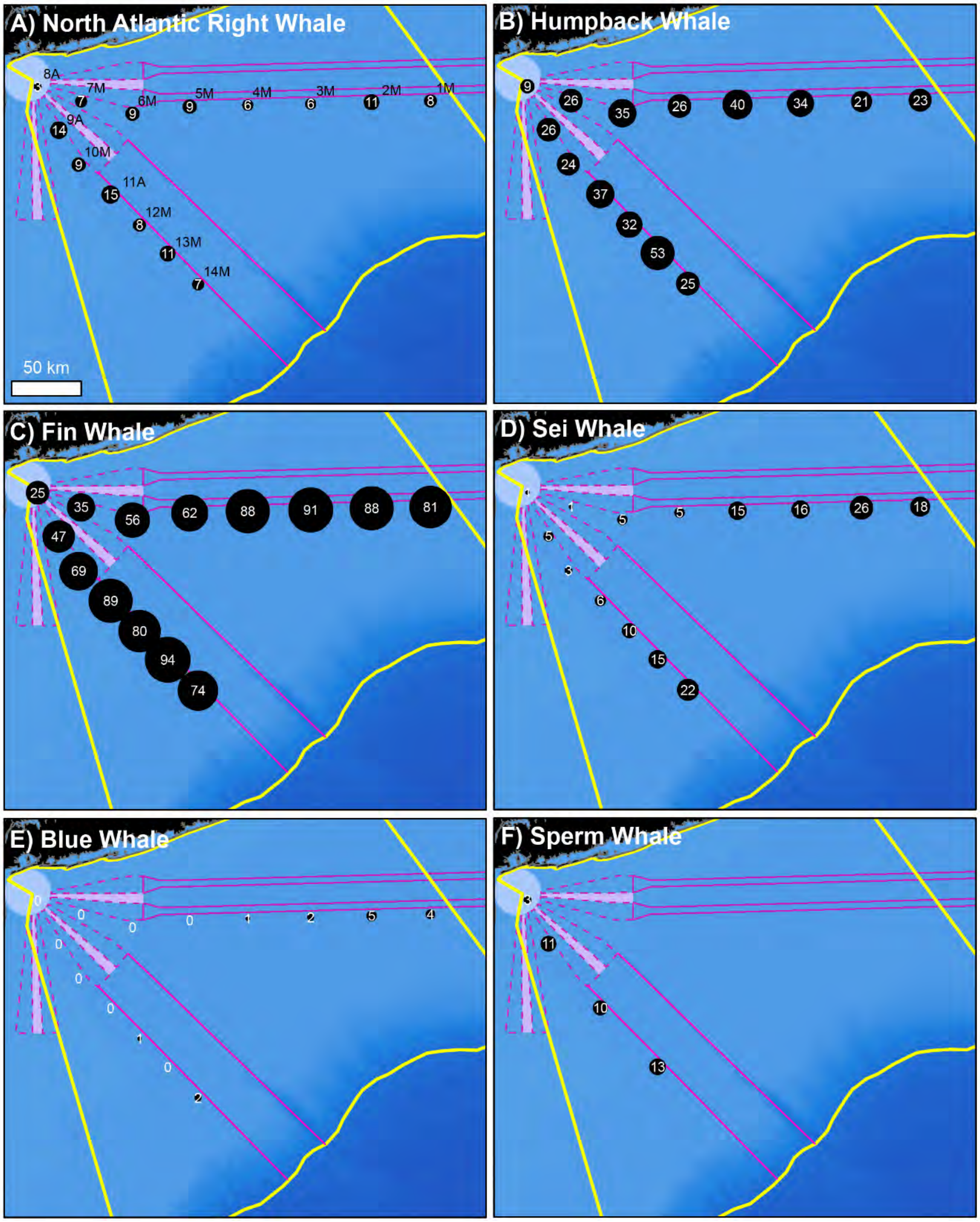


Figure 50. Cumulative spatial distribution of acoustic detections from focal whale species detected within New York Bight across the 3 survey years. The black circles correspond to the position of recording instruments, and are proportionately scaled in size for the percentage of days with detections over total days recorded. The while label at each sensor location shows the exact percentage. Since no data were recorded from site 15A over the three survey years, no data are shown.

Ambient Noise Analysis

Median Ambient Noise Levels

During Year-3, median values of the 10-minute average ambient noise levels across all frequency bands ranged between 84 dB (blue whale frequency band) and 113 dB (full frequency band). Sites 5M, 6M, 7M, 9A, and 10M recorded overall lower noise levels than the other sites, while sites 1M, 2M, 3M, 8A, and 11A tended to record higher noise levels (

Table 27).

Within the right whale frequency band (70 – 244 Hz), median noise levels ranged from 99 dB (sites 6M and 10M) to 106 dB (site 8A), nearly the exact same noise levels as Year-2 (

Table 27). Site 11A recorded the second highest median noise levels (104 dB) within the right whale band. Throughout the 3-year survey, site 8A recorded the highest noise levels (median = 106 dB) within the right whale frequency band and exceeded 120 dB approximately 5% of the recording time (Table 28, Figure 51A). Site 6M recorded the lowest noise levels during the 3-year survey, with median noise level of 99 dB, and the 5th percentile noise level of 90 dB (Table 28, Figure 51A).

Median noise levels within the humpback whale band (18 -708 Hz) during Year-3 ranged between 104 (6M, 7M, and 10M) to 111 dB (8A). Sites 13A (110 dB) and 11A (109 dB) recorded the next highest median noise levels (

Table 27). Sites 6M, 7M, and 10M recorded the lowest median noise levels (104 dB) during Year-3. Across the three survey years, site 8A had the highest median noise level (111 dB) and 95th percentile noise level (125 dB) across all sites (Table 28, Figure 51B). The lowest overall noise level during the 3-year survey was at site 6M (104 dB), which also recorded the lowest 5th percentile noise level (95 dB), among sites 7M and 10M.

The fin whale frequency band (18 – 28 Hz) recorded lower noise levels than all other frequency bands, except the blue whale frequency band, which overlaps with the fin whale band. During Year-3, the highest median noise level within the fin whale band was recorded at site 13A (104 dB) and the lowest median noise levels were recorded at sites 10M (87 dB), 5M (88 dB) and 6M (88 dB;

Table 27). Noise levels during Year-3 were similar to those of the previous two survey years, except that noise at site 13A was markedly higher. This is likely because site 13A only recorded for 4 days in Year-3 and is not representative of the noise conditions at this site. During the three-year survey, sites 1M (98 dB), 2M (97 dB), 3M (99 dB), and 11A (98 dB) recorded the highest median noise levels, and sites 5M (88 dB), 6M (88 dB), and 7M (85 dB) recorded the lowest median noise levels (Table 28, Figure 51C). The highest 95th percentile noise levels were recorded at sites 11A and 13A, where noise exceeded 114 dB 5% of the recording period. The lowest 5th percentile noise level was recorded at site 7M, where noise levels were less than 74 dB during 5% of the recording period.

Median noise levels within the sei whale frequency band (28 – 89 Hz) in Year-3 ranged from 99 dB (sites 5M, 6M, and 7M) to 107 dB (site 8A), which were similar to noise levels at those sites during Year-2 (

Table 27). The sites with the next highest median noise levels were 1M (105 dB), 2M (104 dB), 3M (104 dB), and 13A (104 dB). Across the three-year survey, median noise levels were also highest at sites 8A (106 dB) and 1M (106 dB). During 5% of the recording period, noise levels exceeded 123 dB within the sei whale band at site 8A, and 121 dB at site 1M (Table 28, Figure 51D). Sites 6M and 7M recorded the lowest 5th percentile noise levels across the three-year survey (87 dB).

Table 27. Median noise levels per site for Year-1, Year-2, and Year-3 per frequency band. Ambient noise levels are represented as Sound Level Equivalent (L_{eq}, in dB re: 1µPa). Sites marked with * indicate only 4 days of sound data were recorded during Year-3.

	Right (70 – 224 Hz)			**Humpback (18 – 708 Hz)**			**Sei (28 – 89 Hz)**		
Site	**Year-1**	**Year-2**	**Year-3**	**Year-1**	**Year-2**	**Year-3**	**Year-1**	**Year-2**	**Year-3**
1M	106	103	103	111	108	108	108	106	105
2M	107	102	102	112	107	107	109	104	104
3M	106	102	101	112	108	108	108	104	104
4M	103	100	100	110	106	106	105	103	101
5M	105	100	101	110	104	105	104	99	99
6M	96	99	99	102	104	104	98	100	99
7M	102	100	100	106	104	104	99	99	99
8A*	104	105	106	110	110	111	104	107	107
9A*	103	102	103	107	107	108	103	102	102
10M	104	99	99	109	105	104	103	101	99
11A	103	101	103	109	108	108	103	101	102
12M	104	101	101	109	107	107	103	102	101
13A*	103	101	102	108	108	110	103	101	104
14M	99	102	100	105	107	106	102	103	101
15A	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*
Median	104	101	101	109	107	107	103	102	101

Table 27 (continued). Median noise levels per site for Year-1, Year-2, and Year-3 per frequency band. Ambient noise levels are represented as Sound Level Equivalent (L_{eq}, in dB re: 1μPa). Sites marked with * indicate only 4 days of sound data were recorded during Year-3.

	Fin (18 – 28 Hz)			**Blue (14 – 22 Hz)**			**Full (9 Hz – 2.2 kHz)**		
Site	**Year-1**	**Year-2**	**Year-3**	**Year-1**	**Year-2**	**Year-3**	**Year-1**	**Year-2**	**Year-3**
1M	100	96	97	99	95	96	112	109	109
2M	102	94	96	101	93	94	113	107	108
3M	103	97	98	102	95	96	113	108	109
4M	99	93	91	97	90	88	111	107	107
5M	93	86	88	91	84	86	111	105	107
6M	87	89	88	84	86	86	103	105	105
7M	82	87	89	80	85	87	107	105	106
8A*	97	95	98	95	95	97	111	111	112
9A*	91	91	95	87	87	93	108	108	109
10M	95	90	87	94	87	84	112	105	106
11A	97	98	96	95	98	95	93	109	109
12M	95	93	93	94	92	92	110	107	108
13A*	93	94	104	92	93	104	109	109	113
14M	93	95	96	91	94	95	108	108	107
15A	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*
Median	95	93	95	94	92	93	110	107	108

Table 28. Average 10-minute ambient noise levels within each frequency band from October 2017 – October 2020. Ambient noise levels are represented as Sound Level Equivalent (L_{eq}, in dB re: 1μPa).

	Right (70 – 224 Hz)			**Humpback (18 – 708 Hz)**			**Sei (28 – 89 Hz)**		
Site	**95th**	**50th**	**5th**	**95th**	**50th**	**5th**	**95th**	**50th**	**5th**
1M	116	104	94	122	109	100	121	106	95
2M	115	103	94	121	108	99	119	105	95
3M	115	103	93	121	109	100	119	105	95
4M	113	101	93	119	107	99	117	102	93
5M	114	102	91	119	106	96	115	100	89
6M	109	99	90	114	104	95	112	99	90
7M	114	101	90	118	105	95	116	99	87
8A	120	106	92	125	111	97	123	106	91
9A	115	102	92	120	107	96	117	102	90
10M	112	100	90	118	106	95	114	101	89
11A	113	102	93	119	108	100	115	102	93
12M	113	102	93	119	107	98	115	102	93
13A	114	102	93	119	108	99	115	102	94
14M	112	101	91	118	107	98	116	101	93
15A	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*
Median	114	102	92	119	107	98	116	102	93

Table 28 (continued). Average 10-minute ambient noise levels within each frequency band from October 2017 – October 2020.Ambient noise levels are represented as Sound Level Equivalent (L_{eq}, in dB re: 1μPa).

	Fin (18 – 28 Hz)			**Blue (14 – 22 Hz)**			**Full (9 Hz – 2.2 kHz)**		
Site	**95th**	**50th**	**5th**	**95th**	**50th**	**5th**	**95th**	**50th**	**5th**
1M	110	98	87	108	96	85	122	110	101
2M	109	97	86	108	95	84	121	109	100
3M	113	99	87	113	97	85	122	110	101
4M	112	94	82	111	90	78	120	108	100
5M	108	88	81	106	87	80	119	107	97
6M	105	88	81	103	85	81	115	105	96
7M	102	85	74	99	84	72	118	106	97
8A	113	96	82	110	95	83	126	111	99
9A	110	91	76	109	87	76	121	108	97
10M	110	90	76	109	87	72	119	107	97
11A	114	98	85	114	97	83	120	109	101
12M	111	94	84	110	92	82	119	108	99
13A	114	95	83	114	94	81	120	109	100
14M	112	96	87	111	95	86	118	108	99
15A	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*
Median	110	94	82	110	93	82	120	108	99

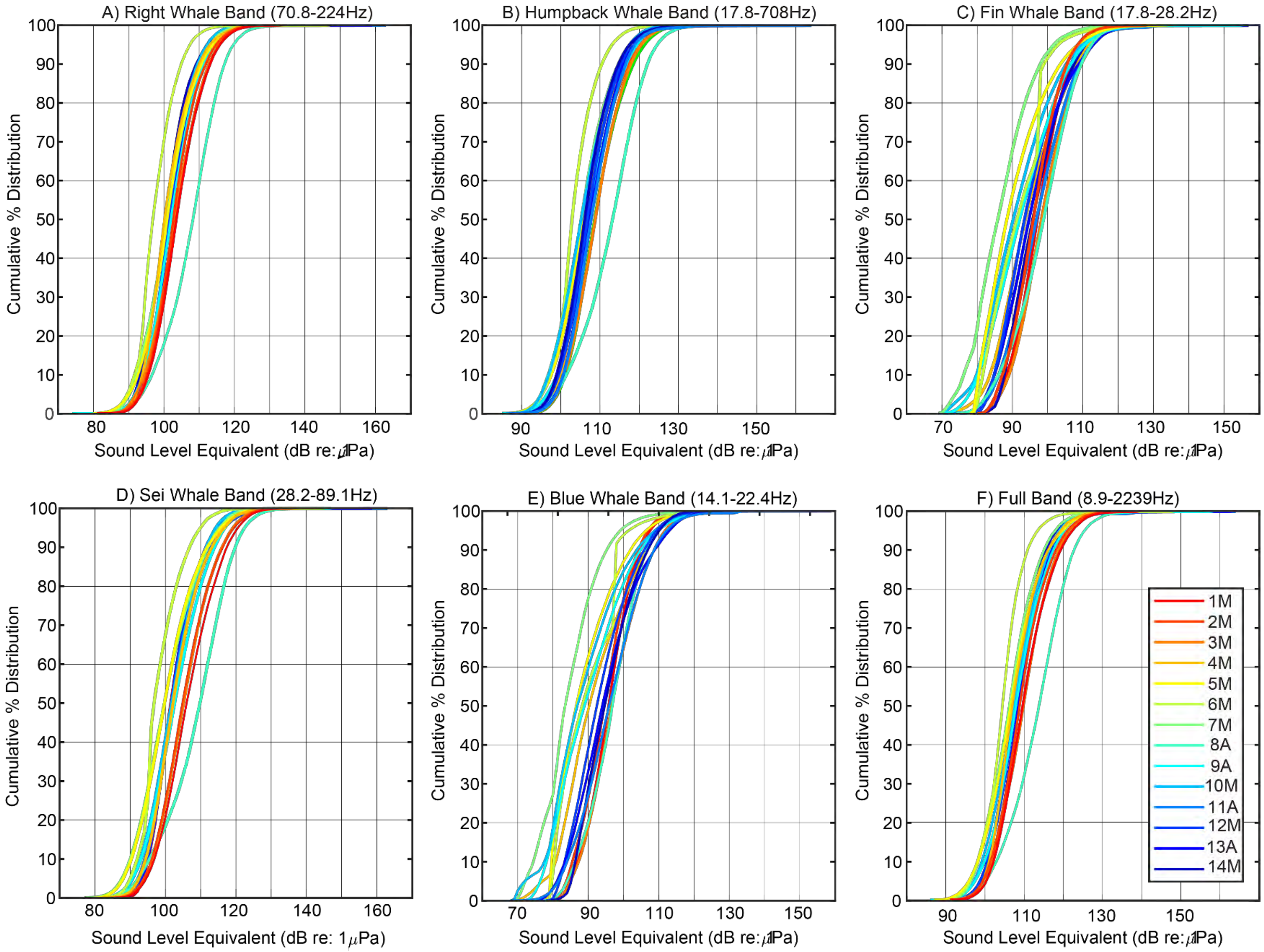


Figure 51. Cumulative percent distribution of ambient noise levels for each recording site in different whale frequency bands between October 2017 and October 2020, measured in 10-minute averages. A) right whale, B) humpback whale, C) fin whale, D) sei whale, E) blue whale, and F) full frequency bands.

COVID-19 Driven Changes in Noise

The timing of our Year-3 passive acoustic survey during the COVID-19 global pandemic allowed us to examine whether there were any significant changes in anthropogenic noise within NY Bight as observed in terrestrial habitats (e.g., Halfwerk 2020). With the most dramatic changes in human activity due to the pandemic occurring in April through June of 2020, we examined noise levels during April, May, and June for 2019 and 2020 on sensors which had comparable amounts of data collected: 1M, 2M, 12M, and 14M. Statistical analysis of 10-minute noise levels for each month in the 75-300 Hz frequency band shows that while there was no difference in median noise level between 2019 and 2020 (two-tailed paired t-test, t = -0.677, df = 11, P = 0.5126; Figure 52A) the 95th percentile noise levels were significantly lower in 2020 compared to 2019 (two-tailed paired t-test, t= -3.203, df = 11, P = 0.0084; Figure 52B). These data show that while the median sound level did not change during the pandemic, the highest sound levels (represented by the 95th percentile Leq values) significantly decreased during the pandemic, likely due to a decrease in the number of large vessels passing through the NY Bight. Further analysis of whale responses to these observed changes in noise levels are ongoing.

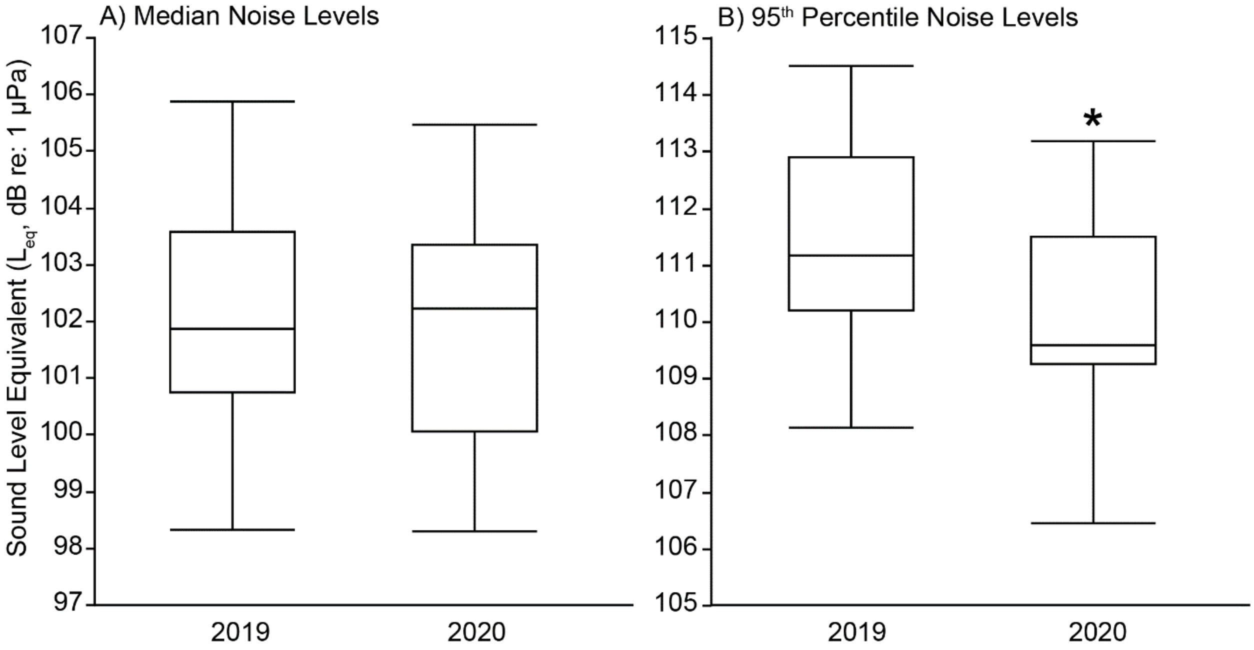
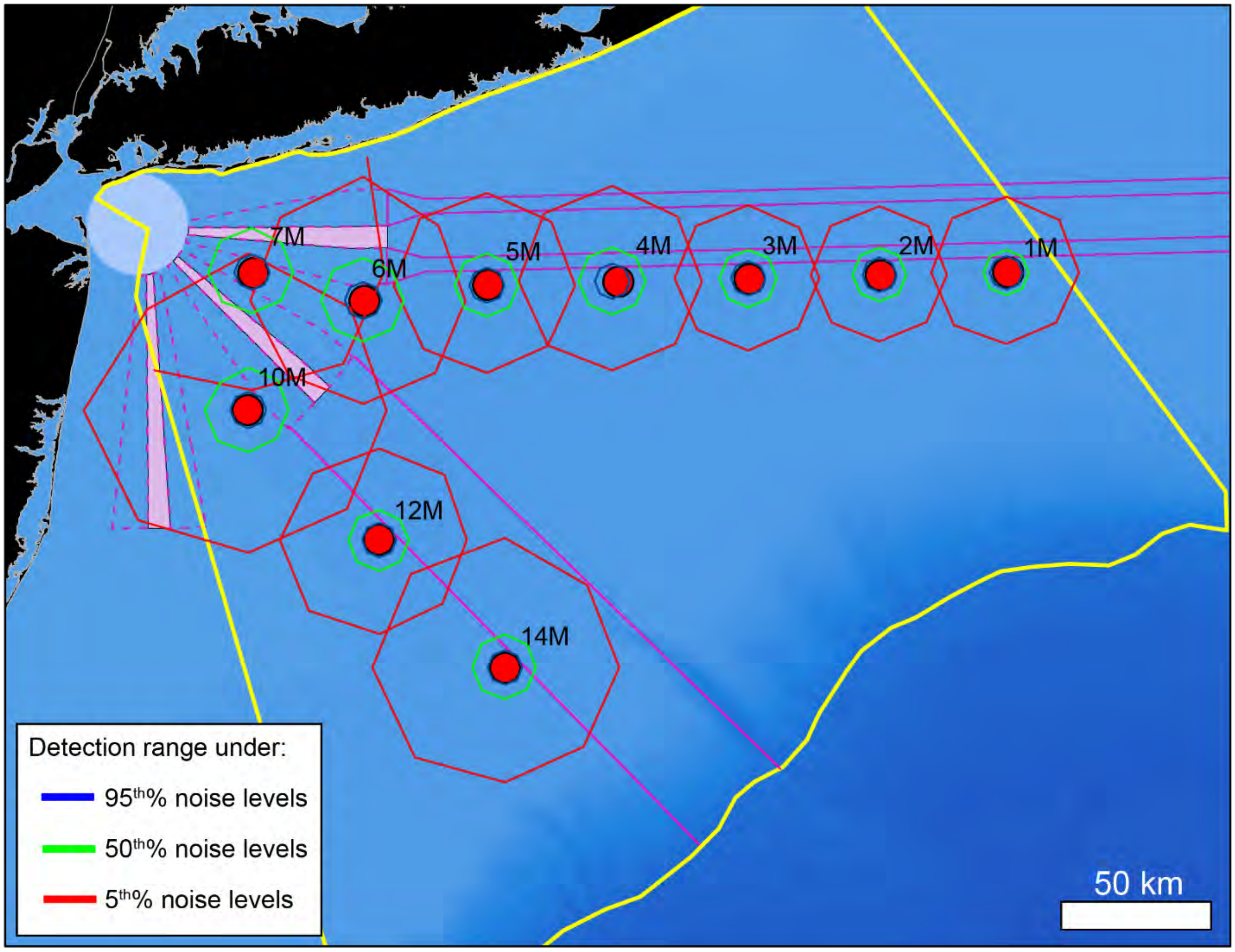


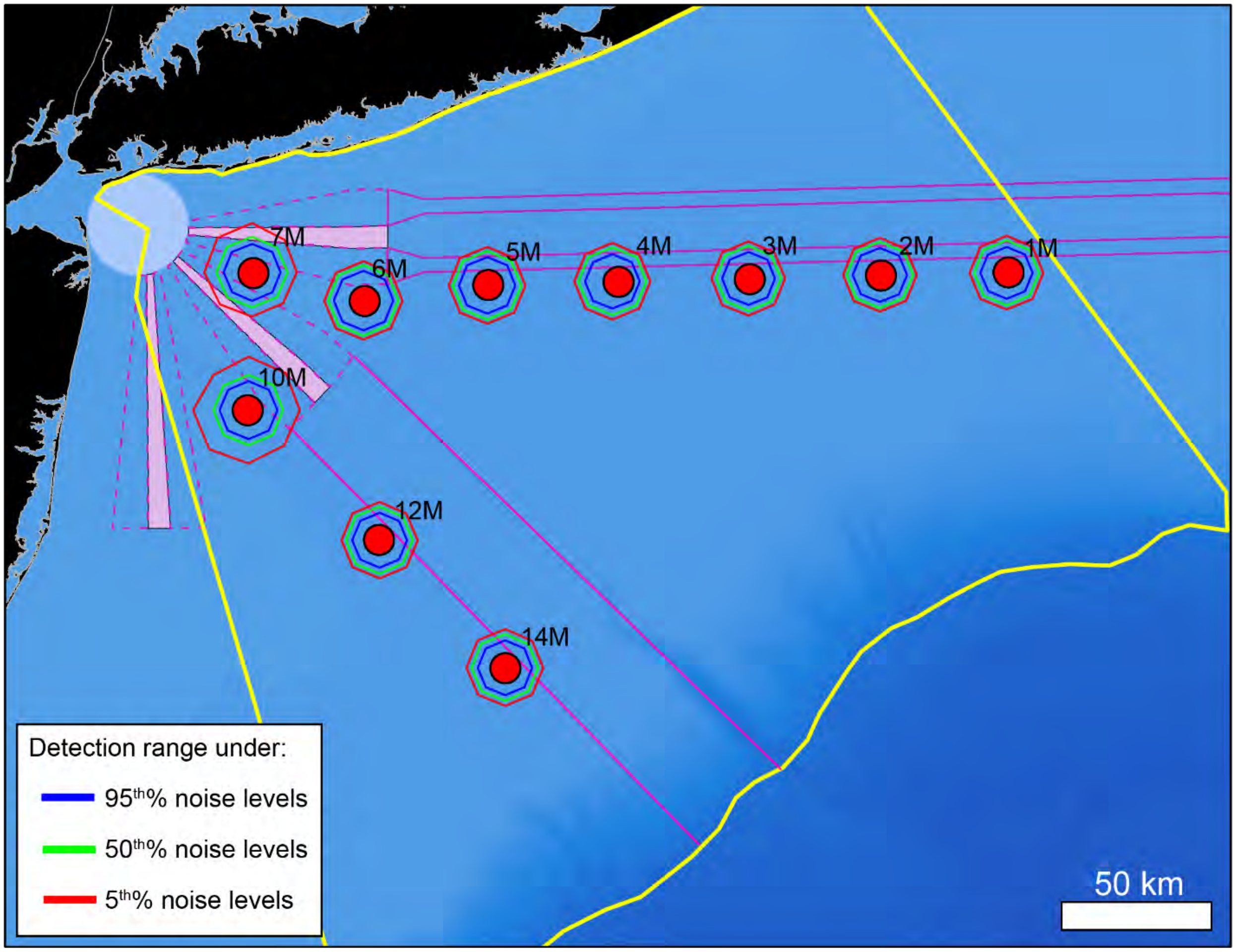
Figure 52. Changes in ambient noise levels (75-300 Hz) in New York Bight before and during the COVID-19 pandemic: April-June, 2019-2020, at sites 1M, 2M, 12M, and 14M. Box and whisker plots show median values (horizontal bars) and interquartile ranges for A) median L_{eq} values and B) 95th percentile L_{eq} values. In panel B, 2020 95th percentile L_{eq} levels are significantly lower than 2019.

Masking Potential

Masking potential was evaluated using preliminary detection range models as a function of the ambient noise environment to estimate the spatial extent over which target whale signals propagate. To illustrate the variability in range estimates, we plotted estimated detection range against received level for the recording sites with the highest and lowest median noise levels for each target species in Year-3 (see Table 29**Error! Reference source not found.**). We excluded the 8 kHz AMAR sites from this analysis, since only a small amount of data was collected at those sites and they were not representative of the detection ranges for Year-3.

Within the North Atlantic right whale frequency band, Site 1M recorded the highest median noise levels (103 dB) of the MARU site locations, and had the lowest estimated 50th percentile detection range (Table 29, Figure 53, Figure 59), when averaged across all 8 bearings (6 km). Under higher noise conditions (95th percentile = 116 dB), detection range was estimated to be 4 km at site 1M, and under lower noise conditions (5th percentile = 94 dB), detection range was estimated to be 19 km. Site 7M recorded among the lowest median noise conditions (101 dB), resulting in an estimated 50th percentile detection range of 11 km (Table 29). The 5th percentile noise levels at site 7M (90 dB) are estimated to allow for a right whale upcall to be received by the MARU from approximately 35 km away. The maximum detection range estimate was at site 10M under 5th percentile noise conditions (38 km). Across all sites, during their respective 95th percentile nose conditions, right whales may be detected to 4 km, on average. Across all sites, the average detection range under median noise conditions was 8 km, in contrast to the average detection range of 10 km during the Year-2 survey.

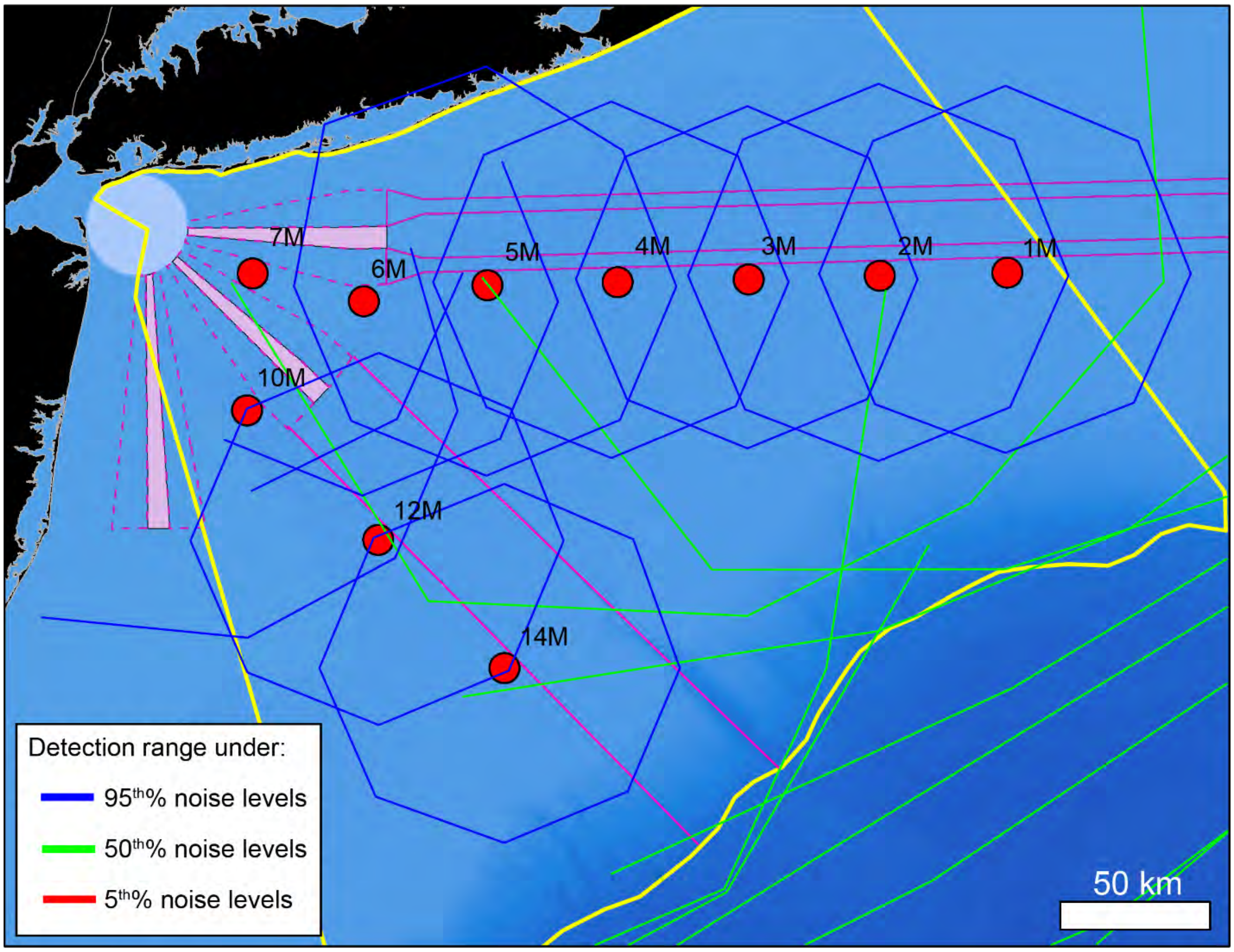




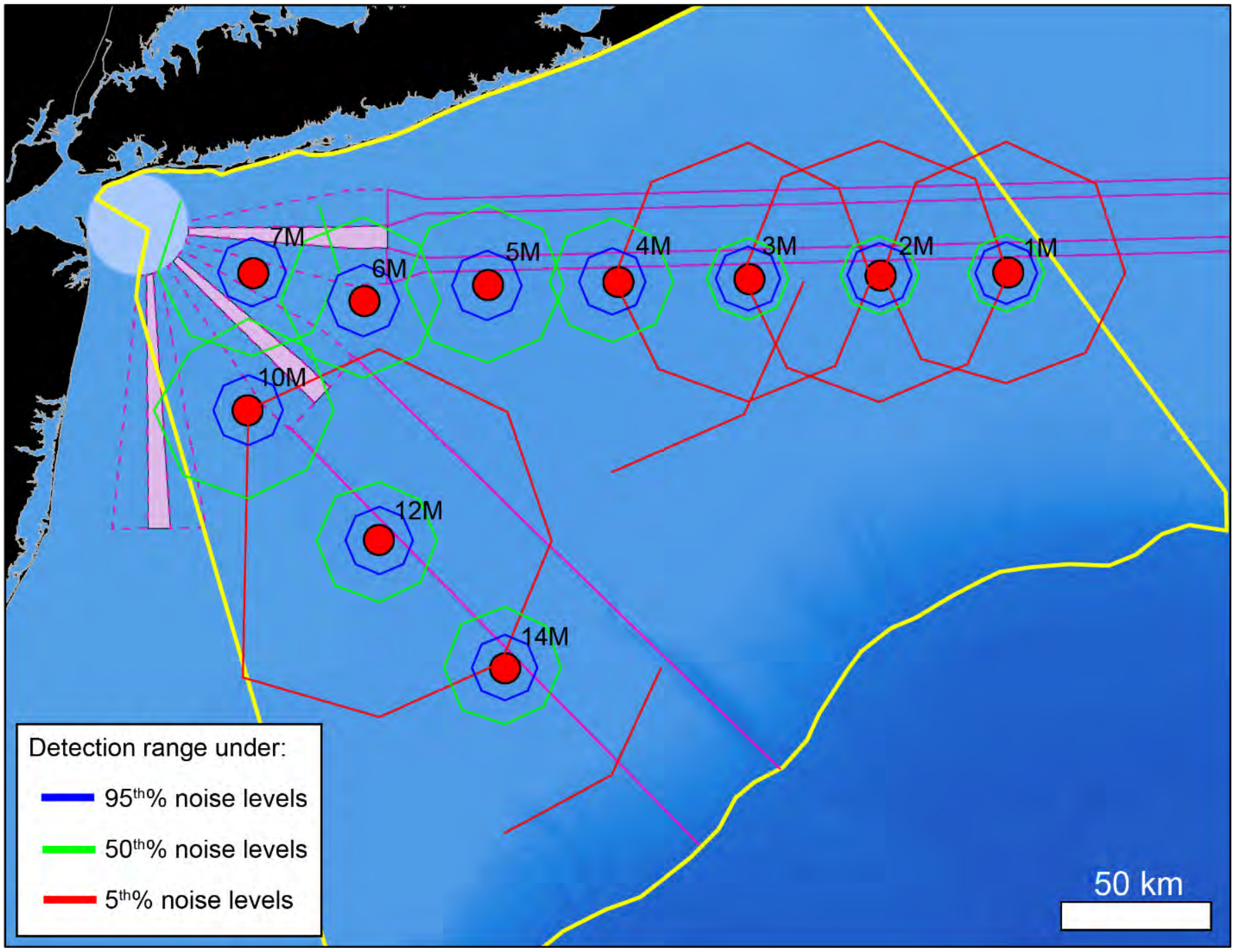
For humpback whales (Table 29, Figure 54, Figure 60**Error! Reference source not found.**), site 1M also recorded the highest median noise levels (109 dB) of the MARU sites and had the lowest estimated detection range of 8 km (Table 29), while site 7M recorded the lowest median noise levels (105 dB) and had the highest detection range (9 km). This suggests that during most of the Year-3 survey, humpback whales could be recorded from approximately 8-9 km from the MARU site location. The best noise conditions (5th percentile) allowed for detection ranges to reach 13 km (site 10M), while the 95th percentile noise conditions reduced detection ranges only to 7 km at all sites, except 6M.

Fin whales had the second largest detection range estimates (second to blue whales), since the low-frequency 20-Hz pulse tends to be high in amplitude. The average detection range across all

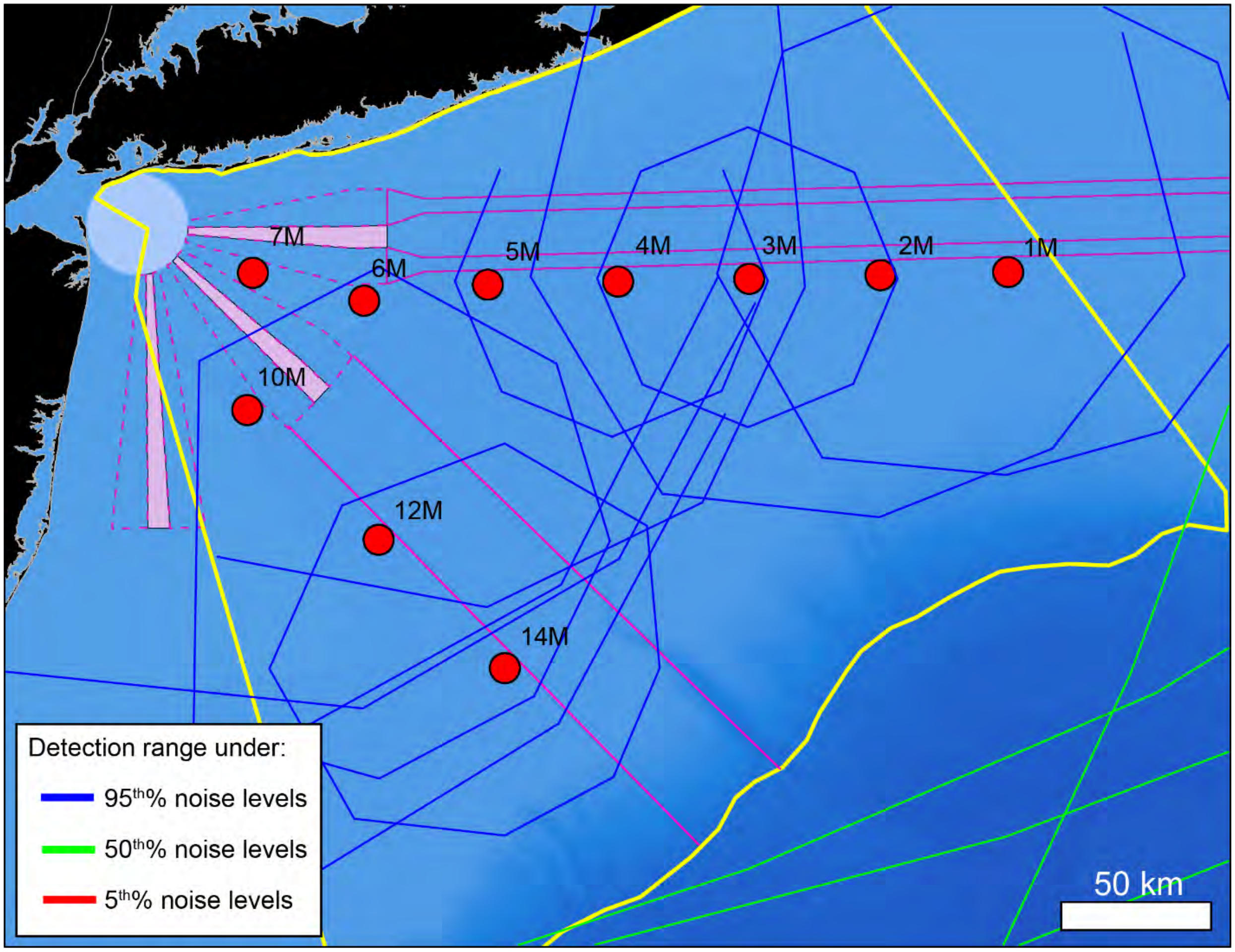
MARU sites was 193 km, under median noise conditions (Table 29, Figure 55, Figure 61**Error! Reference source not found.**). The site with the lowest detection range under median noise conditions was 14M (106 km), which had estimated detection ranges of 46 km and 375 km during 95th and 5th percentile noise conditions, respectively. Site 10M had the longest detection range estimate during median noise conditions (307 km). During 5th percentile noise conditions, the detection range estimate exceeded 500 km. The long-range estimates of the fin whale 20-Hz pulse in NY Bight illustrate that fin whales were likely detected beyond the shelf edge in some instances. The long detection range estimates of the fin whale signal also means that multiple sensors at different sites recorded the same instance of a signal. These 'multiple-arrivals' across sites allowed us to observe the arrival time of the call and determine that the sound originated within the survey area on many occasions, meaning that fin whales did occur within NY Bight.



Sei whales had an average detection range of 20 km, across all sites, under median noise conditions (Table 29, Figure 56, Figure 62). Site 1M had the lowest estimated detection range during median noise conditions (18 km), and a range of 15 km during 95th percentile noise conditions. Site 7M had an estimated detection range of 24 km during median noise conditions. During 5th percentile noise conditions, detection range estimate reached 94 km at site 7M.



Blue whale (Table 29, Figure 57, Figure 63) song had the longest estimated detection range estimates of the baleen whales in this study, due to the low-frequency, high-amplitude (194 dB re: 1µPa @ 1m RMS) characteristics of their signals. Detection range estimates often exceeded 600 km during median noise conditions. Site 14M had the shortest estimated detection range, with 205 km. At site 3M, under 95th percentile noise conditions, blue whales were estimated to be detectable up to 38 km from the MARU. Under 5th percentile noise conditions, blue whale signals are estimated to be detectable beyond 500 km, well outside of the NY Bight. Since blue whale signals were primarily detected in deeper, offshore sites with much greater propagation distances, singing blue whales are potentially >100 km offshore.



The AMAR at site 11A recorded for 87 days into Year-3, however, this is not enough data to be representative of the sperm whale click detection range in NY Bight during Year-3. In Year-1 and Year-2, we estimated sperm whale detection ranges to be between approximately 1 km and 4 km, respectively at site 11A at times of median noise levels. For sperm whale click detection range estimates in NY Bight, please refer to Figure 58, Figure 64, and Table 30, which show estimated detection ranges from Year-2 data.

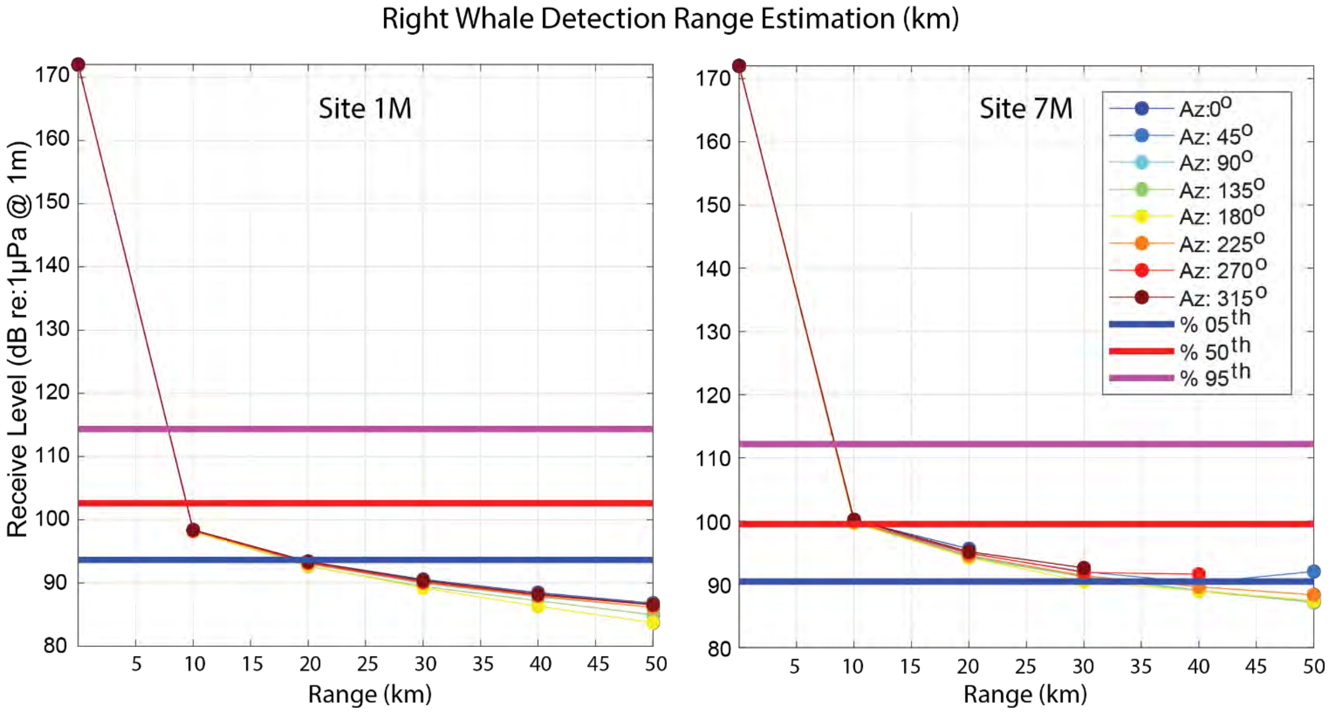


Figure 53. Estimated detection ranges of North Atlantic right whale upcalls under varying noise conditions between October 2019 and October 2020, given the estimated source level of 172 dB re: 1µPa @ 1m. Site 1M represents the site with the highest median noise levels and shortest detection range within the right whale frequency band (71 – 224 Hz), while site 7M represents the site with the lowest median noise levels and farthest detection range estimate. Each curved line represents the detection range per bearing (azimuth). The pink, red, and blue straight lines illustrate the 95th, 50th, and 5th percentiles noise levels, respectively, per site.

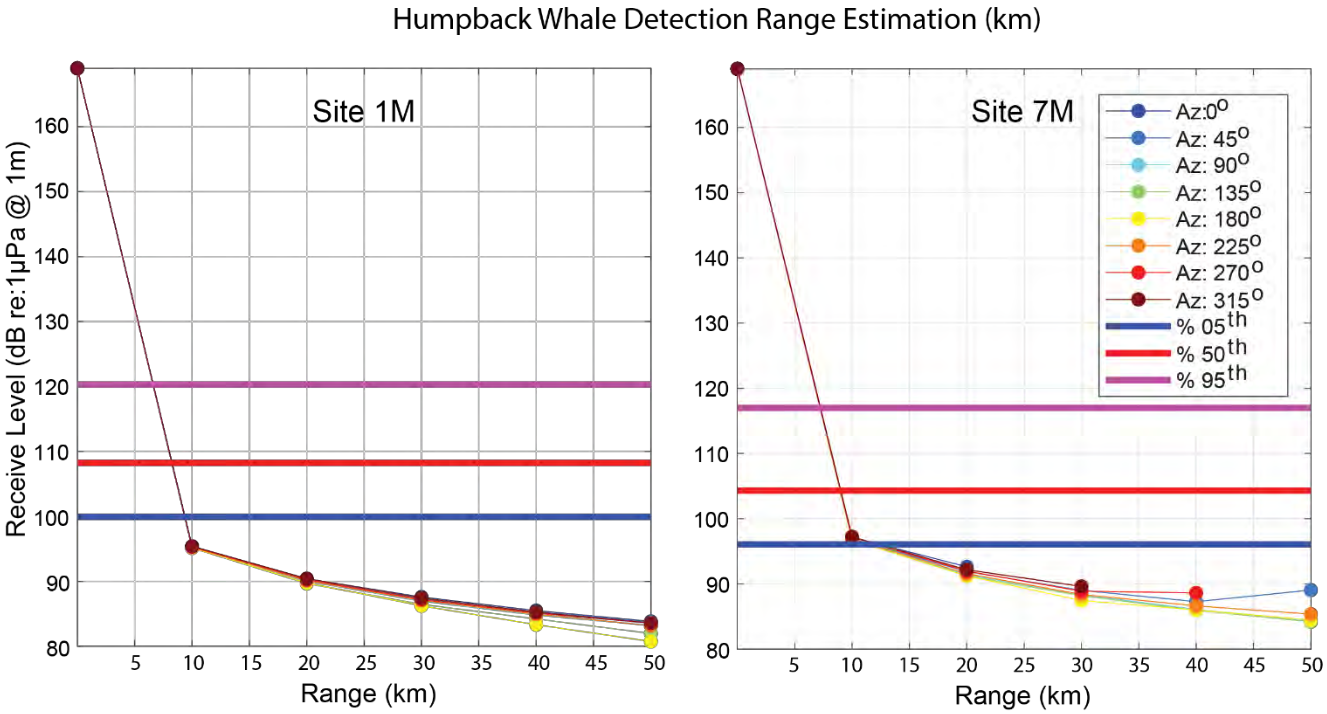


Figure 54. Estimated detection ranges of humpback whale song under varying noise conditions between October 2019 and October 202, given the estimated source level of 169 dB re: 1µPa @ 1m. Site 1M represents the site with the highest median noise levels and shortest detection range within the humpback whale frequency band (28 – 708 Hz), while site 7M represents the site with the lowest median noise levels and farthest detection range estimate. Each curved line represents the detection range per bearing (azimuth). The pink, red, and blue straight lines illustrate the 95th, 50th, and 5th percentiles noise levels, respectively, per site.

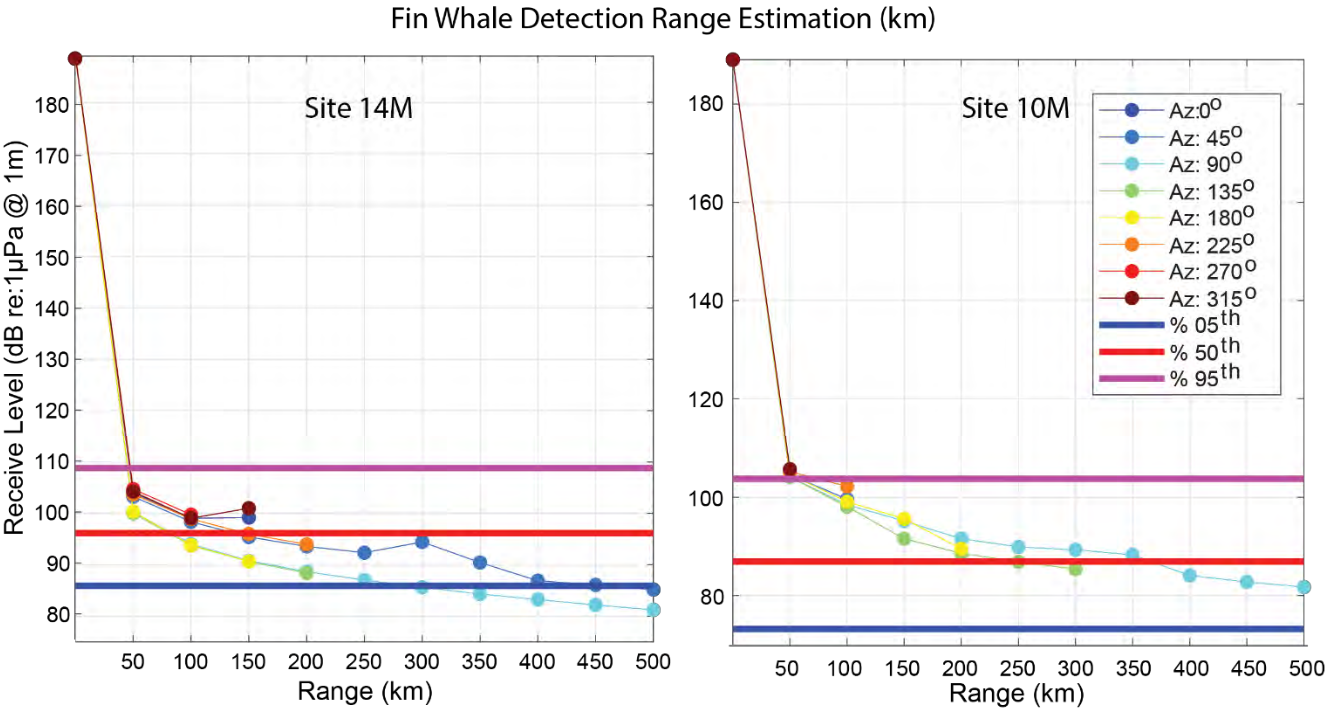


Figure 55. Estimated detection ranges of fin whale signals under varying noise conditions between October 2019 and October 202, given the estimated source level of 189 dB re: 1µPa @ 1m. Site 14M represents the site with the highest median noise levels and shortest detection range within the fin whale frequency band (18 – 28 Hz), while site 10M represents the site with the lowest median noise levels and farthest detection range estimate. Each curved line represents the detection range per bearing (azimuth). The pink, red, and blue straight lines illustrate the 95th, 50th, and 5th percentiles noise levels, respectively, per site.

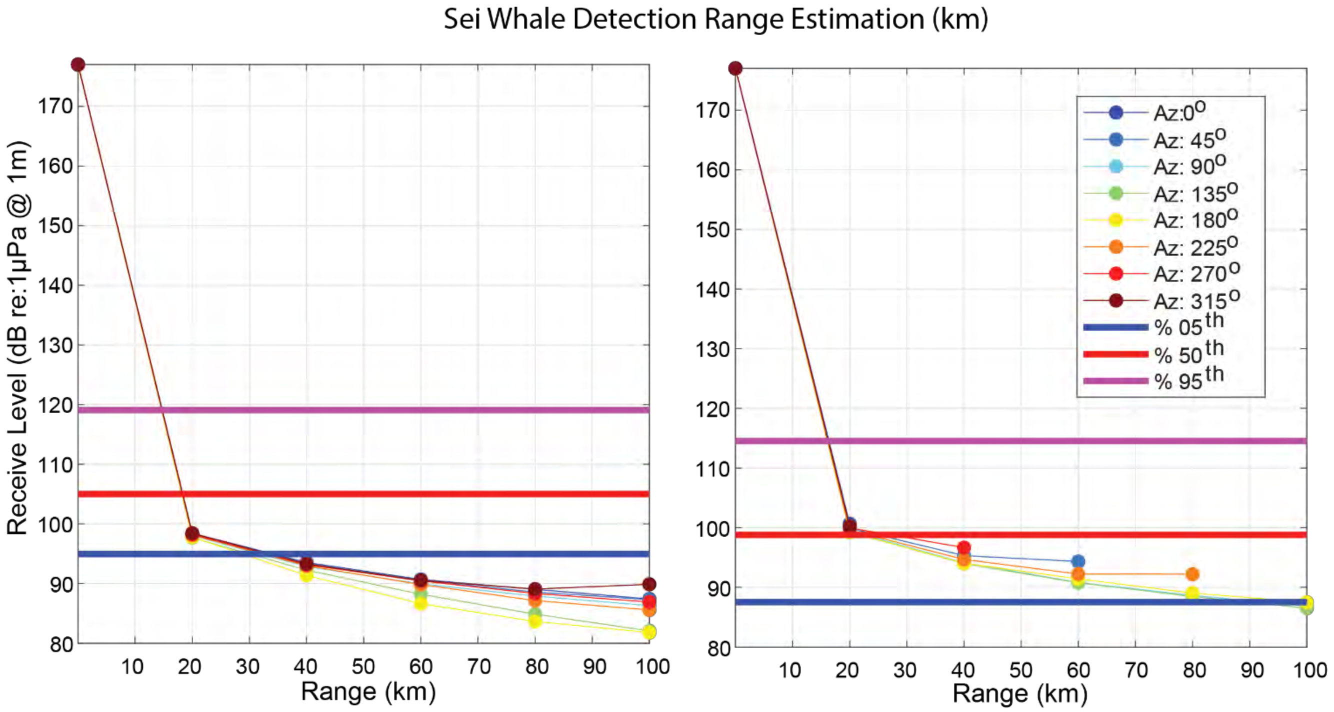


Figure 56. Estimated detection ranges of sei whale downsweeps under varying noise conditions between October 2019 and October 2020, given the estimated source level of 177 dB re: 1µPa @ 1m. Site 1M represents the site with the highest median noise levels and shortest detection range within the sei whale frequency band (45 – 112 Hz), while site 7M represents the site with the lowest median noise levels and farthest detection range estimate. Each curved line represents the detection range per bearing (azimuth). The pink, red, and blue straight lines illustrate the 95th, 50th, and 5th percentiles noise levels, respectively, per site.

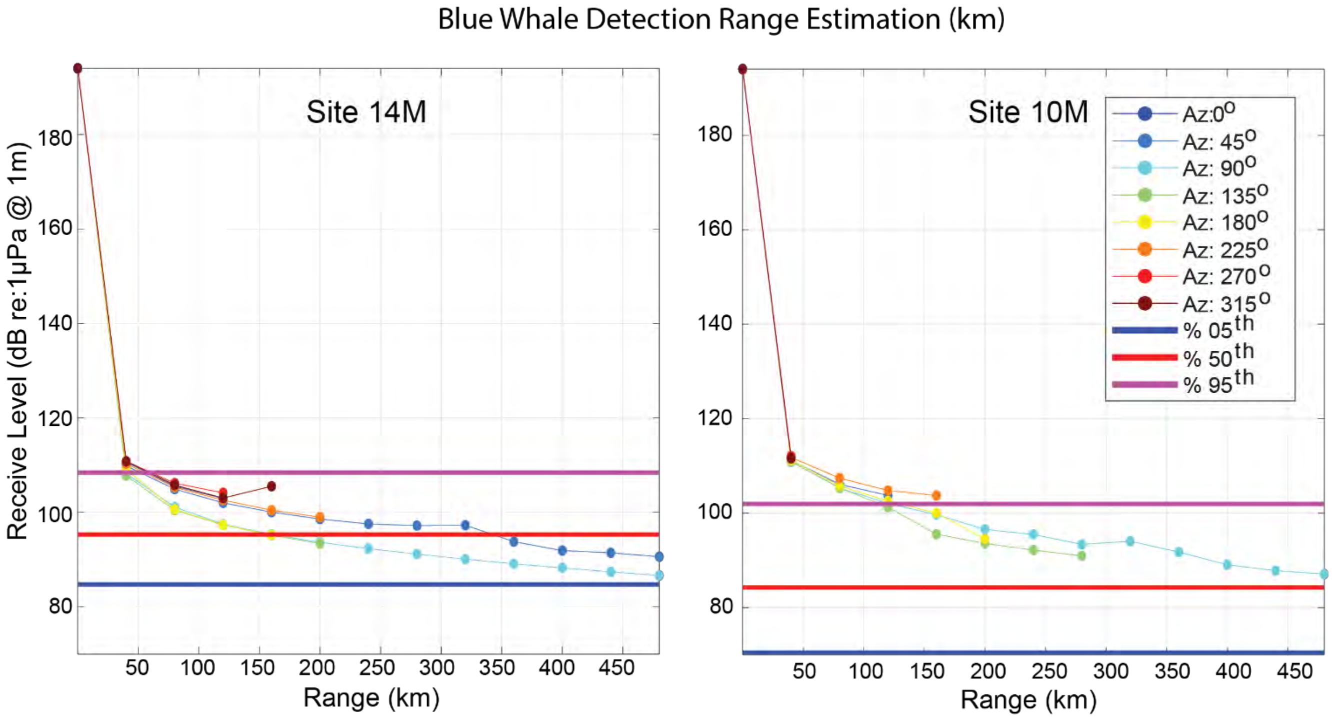


Figure 57. Estimated detection ranges of blue whale signals under varying noise conditions between October 2019 and October 2020, given the estimated source level of 194 dB re: 1µPa @ 1m. Site 14M represents the site with the highest median noise levels and shortest detection range within the blue whale frequency band (14 – 22 Hz), while site 10M represents the site with the lowest median noise levels and farthest detection range estimate. Each curved line represents the detection range per bearing (azimuth). The pink, red, and blue straight lines illustrate the 95th, 50th, and 5th percentiles noise levels, respectively, per site.

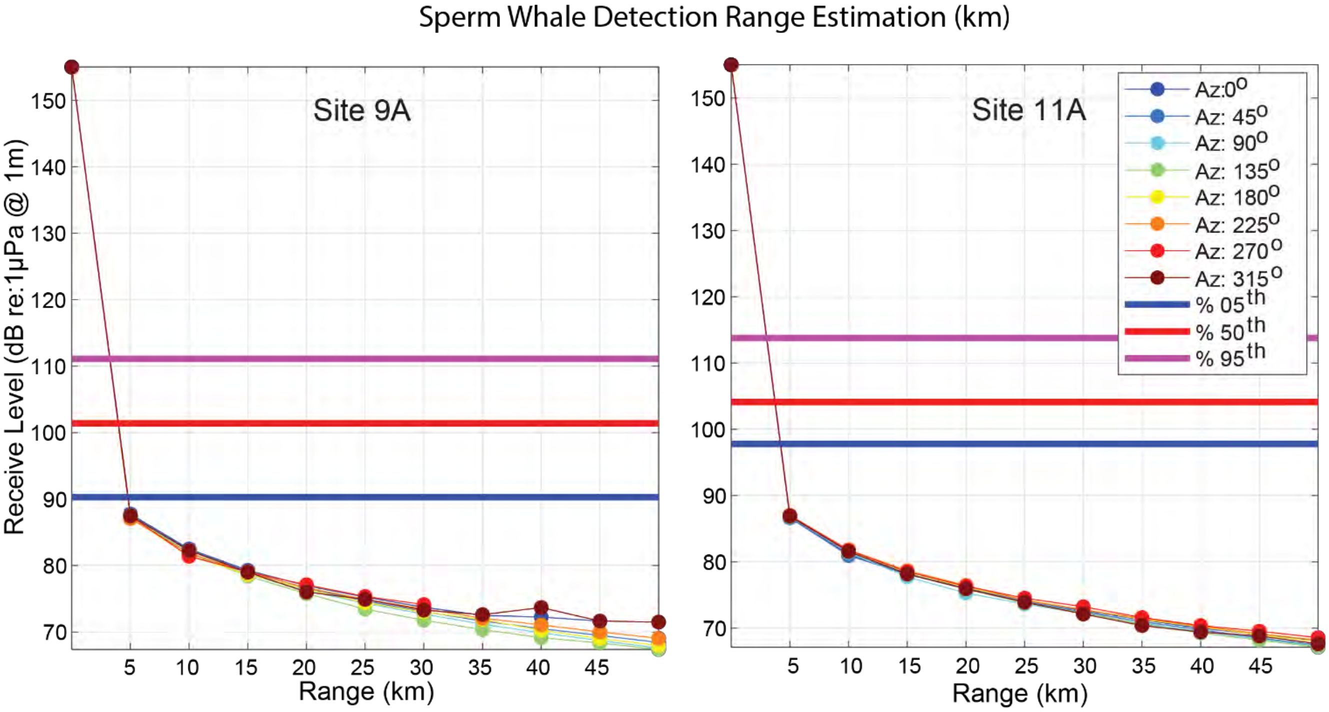


Figure 58. Estimated detection ranges of sperm whale clicks under varying noise conditions, given the estimated source level of 155 dB re: 1µPa @ 1 m at sites 9A and 11A within the sperm whale frequency band (1 – 4 kHz) for Year-2 data (October 2018 and October 2019). All AMARs had similar noise values. Each curved line represents the detection range per bearing (azimuth). The pink, red, and blue straight lines illustrate the 95th, 50th, and 5th percentiles noise levels, respectively, per site.

Table 29. Detection range estimates (km) per site for each baleen whale species during the Year-3 survey (October 2019 – October 2020). Range estimates are based on the average range estimates for 8 bearings for 5th, 50th, and 95th percentile noise levels for each site. “NA” indicates that the detection range estimate exceeded 500 km.

	Right			**Humpback**			**Fin**			**Sei**			**Blue**		
Site	5th	50th	95th	5th	50th	95th	5th	50th	95th	5th	50th	95th	5th	50th	95th
1M	19	6	4	9	8	7	288	114	47	32	18	15	NA	208	69
2M	17	7	4	9	8	7	301	138	48	35	19	15	NA	229	79
3M	18	7	4	9	8	7	299	109	43	34	19	15	NA	219	38
4M	23	9	4	10	9	7	NA	209	45	51	19	16	NA	455	40
5M	23	8	4	10	9	7	NA	274	51	69	20	16	NA	NA	88
6M	28	11	5	10	9	8	NA	262	50	61	21	17	NA	NA	107
7M	35	11	4	12	9	7	NA	274	54	94	24	16	NA	NA	118
10M	38	11	5	13	9	7	NA	307	60	85	23	17	NA	NA	122
12M	24	8	4	10	9	7	415	136	48	48	19	16	NA	273	63
14M	31	8	4	10	9	7	375	106	46	51	19	16	NA	205	51

Table 30. Detection range estimates (km) per site for sperm whales during the Year-2 survey (October 2018 – October 2019). Range estimates are based on the average range estimates for 8 bearings for 5th, 50th, and 95th percentile noise levels for each AMAR site. Due to high AMAR data loss, detection range estimates for Year-3 are not presented here.

Year-2	**Sperm**		
Site	**5th**	**50th**	**95th**
8A	5	4	3
9A	5	4	3
11A	4	4	3
13A	5	4	3

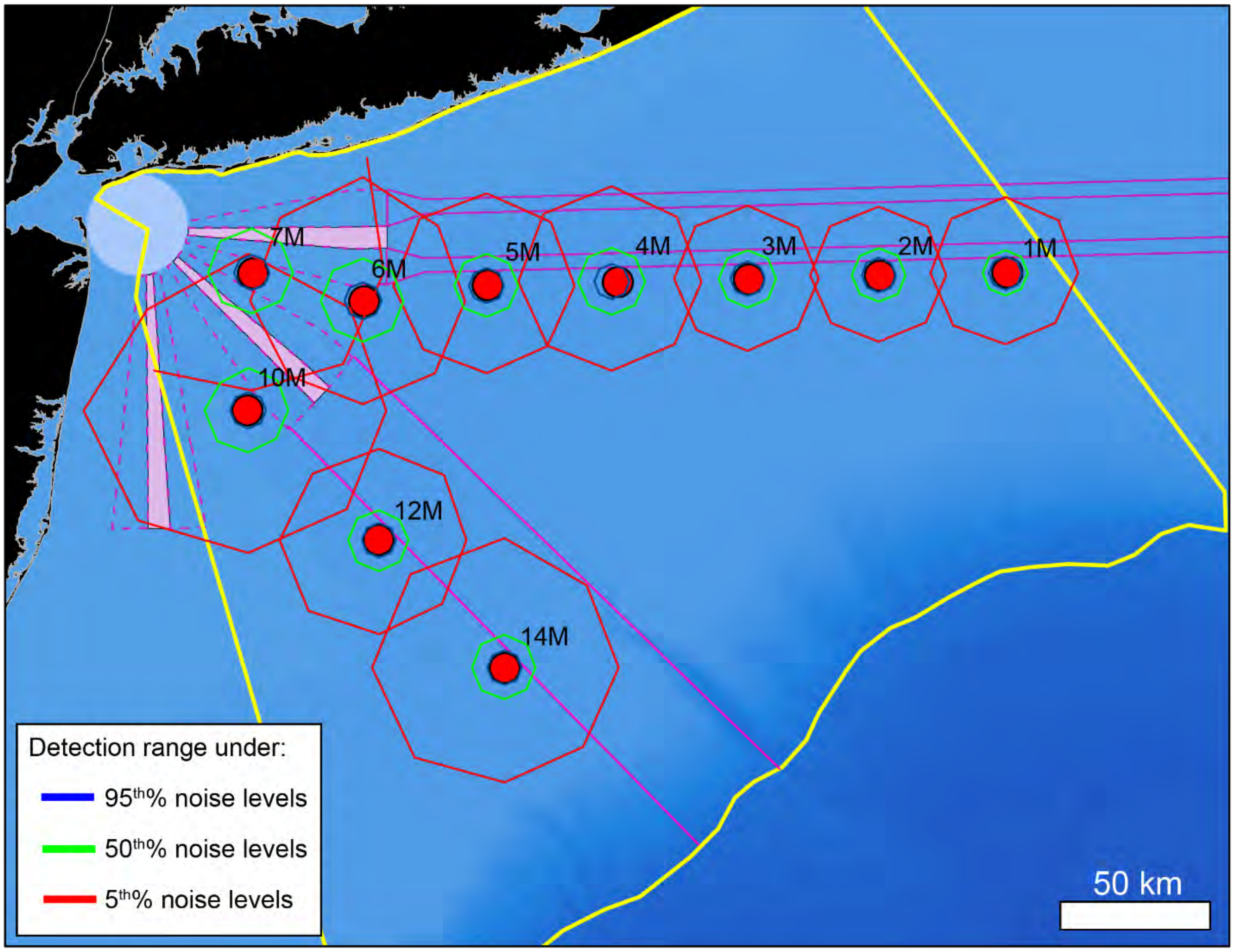


Figure 59. Map of estimated North Atlantic right whale acoustic detection ranges under different noise conditions in the New York Bight for MARU recording sites with data collected in Year-3 to show the representative variation in detection range across the survey array. The blue lines indicate range based on the highest 95th percentile noise levels, the green lines indicate ranges based on median noise levels, and the red lines indicate ranges based on the lowest 5th percentile noise levels.

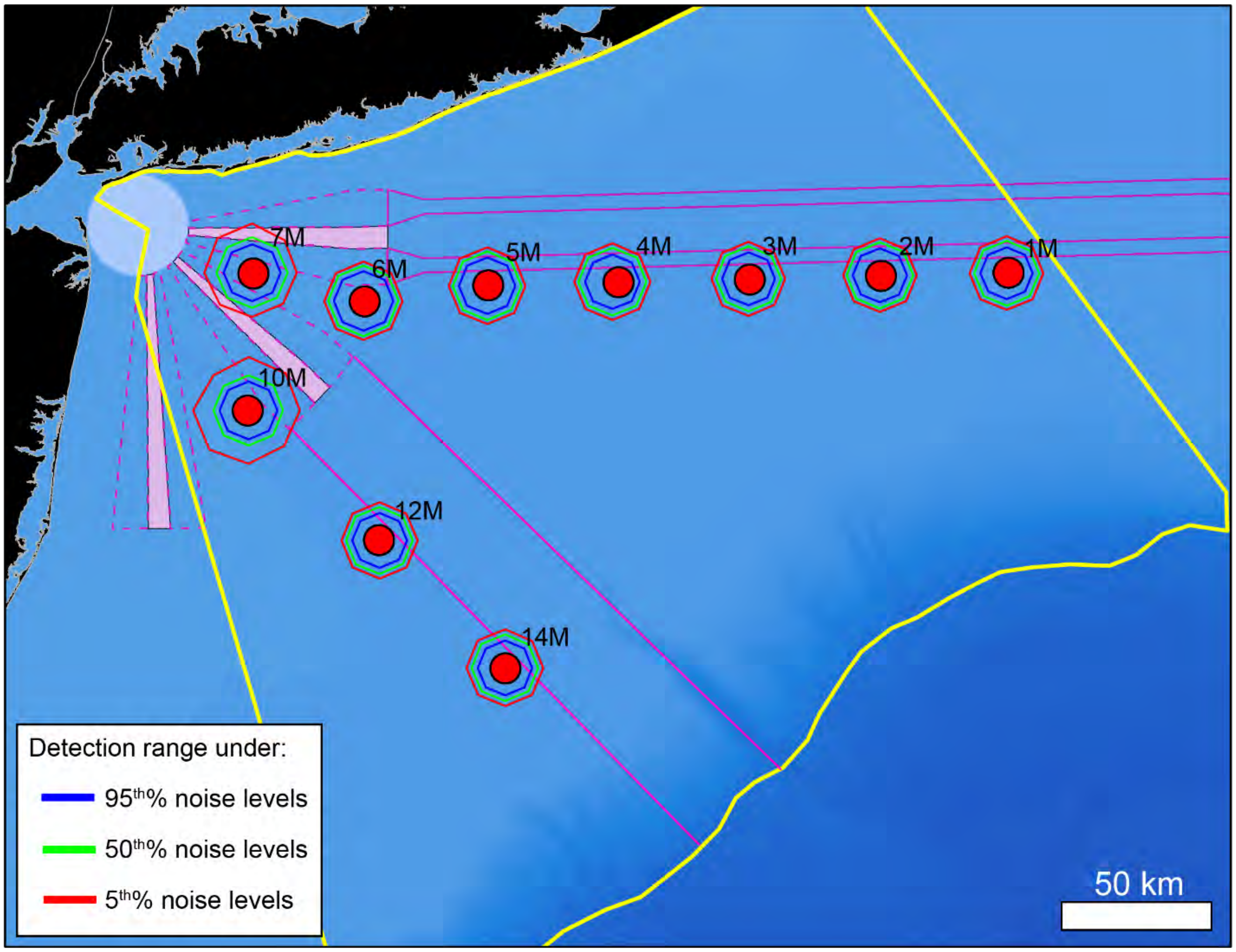


Figure 60. Map of estimated humpback whale song acoustic detection ranges under different noise conditions in the New York Bight for MARU recording sites with data collected in Year-3 to show the representative variation in detection range across the survey array. The blue lines indicate range based on the highest 95th percentile noise levels, the green lines indicate ranges based on median noise levels, and the red lines indicate ranges based on the lowest 5th percentile noise levels.

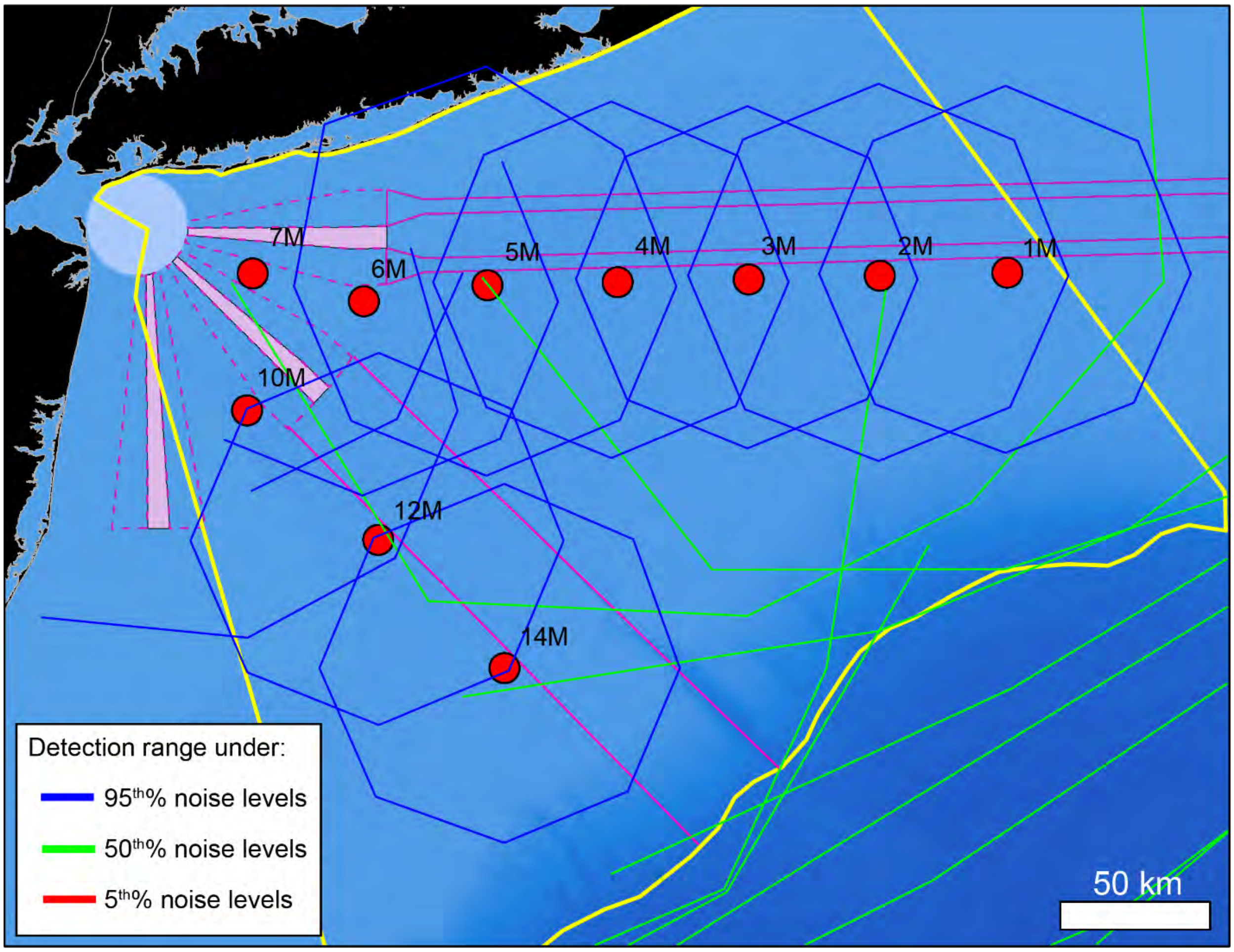


Figure 61. Map of estimated fin whale acoustic detection ranges under different noise conditions in the New York Bight for MARU recording sites with data collected in Year-3 to show the representative variation in detection range across the survey array. The blue lines indicate range based on the highest 95th percentile noise levels, the green lines indicate ranges based on median noise levels, and the lored lines indicate ranges based on the lowest 5th percentile noise levels. Note that at this spatial scale, detection ranges for the 5th percentile noise conditions are >500 km and outside the bounds of the map (and not shown here).

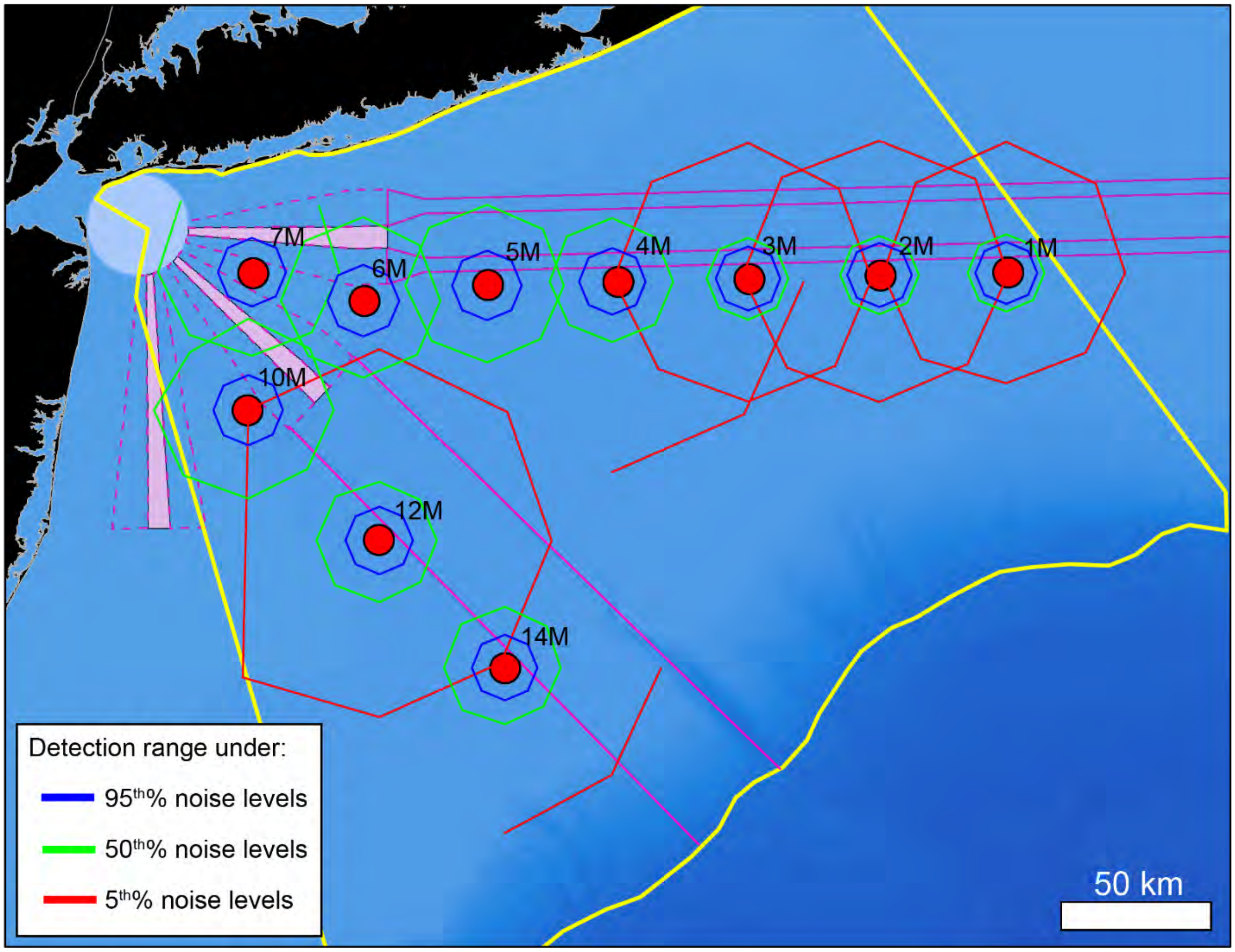


Figure 62. Map of estimated sei whale acoustic detection ranges under different noise conditions in the New York Bight for MARU recording sites with data collected in Year-3 to show the representative variation in detection range across the survey array. The blue lines indicate range based on the highest 95th percentile noise levels, the green lines indicate ranges based on median noise levels, and the red lines indicate ranges based on the lowest 5th percentile noise levels.

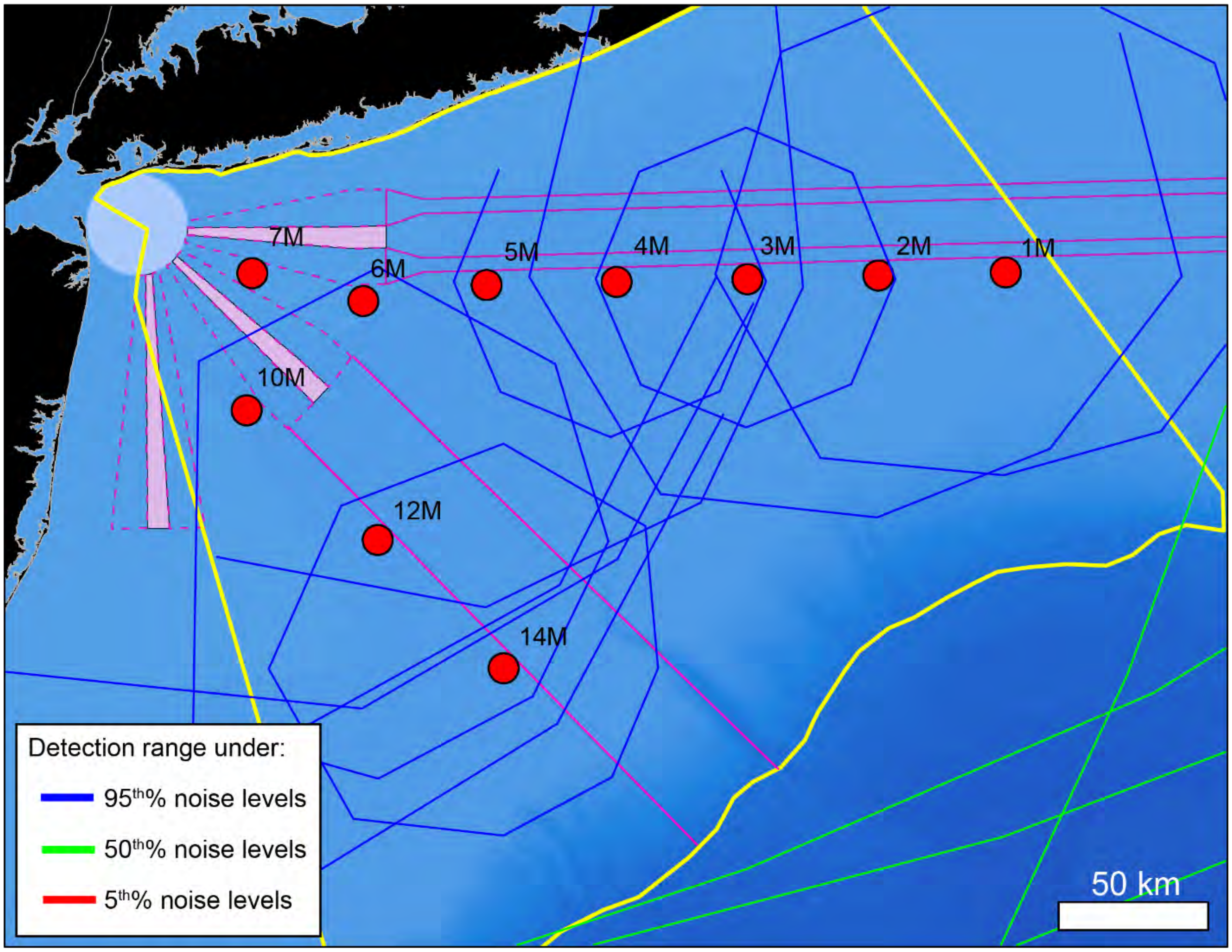


Figure 63. Map of estimated blue whale acoustic detection ranges under different noise conditions in the New York Bight for MARU recording sites with data collected in Year-3 to show the representative variation in detection range across the survey array. The blue lines indicate range based on the highest 95th percentile noise levels, the green lines indicate ranges based on median noise levels, and the red lines indicate ranges based on the lowest 5th percentile noise levels. Note that at this spatial scale, detection ranges for the 5th percentile noise conditions are >500 km and outside the bounds of the map (and not shown here).

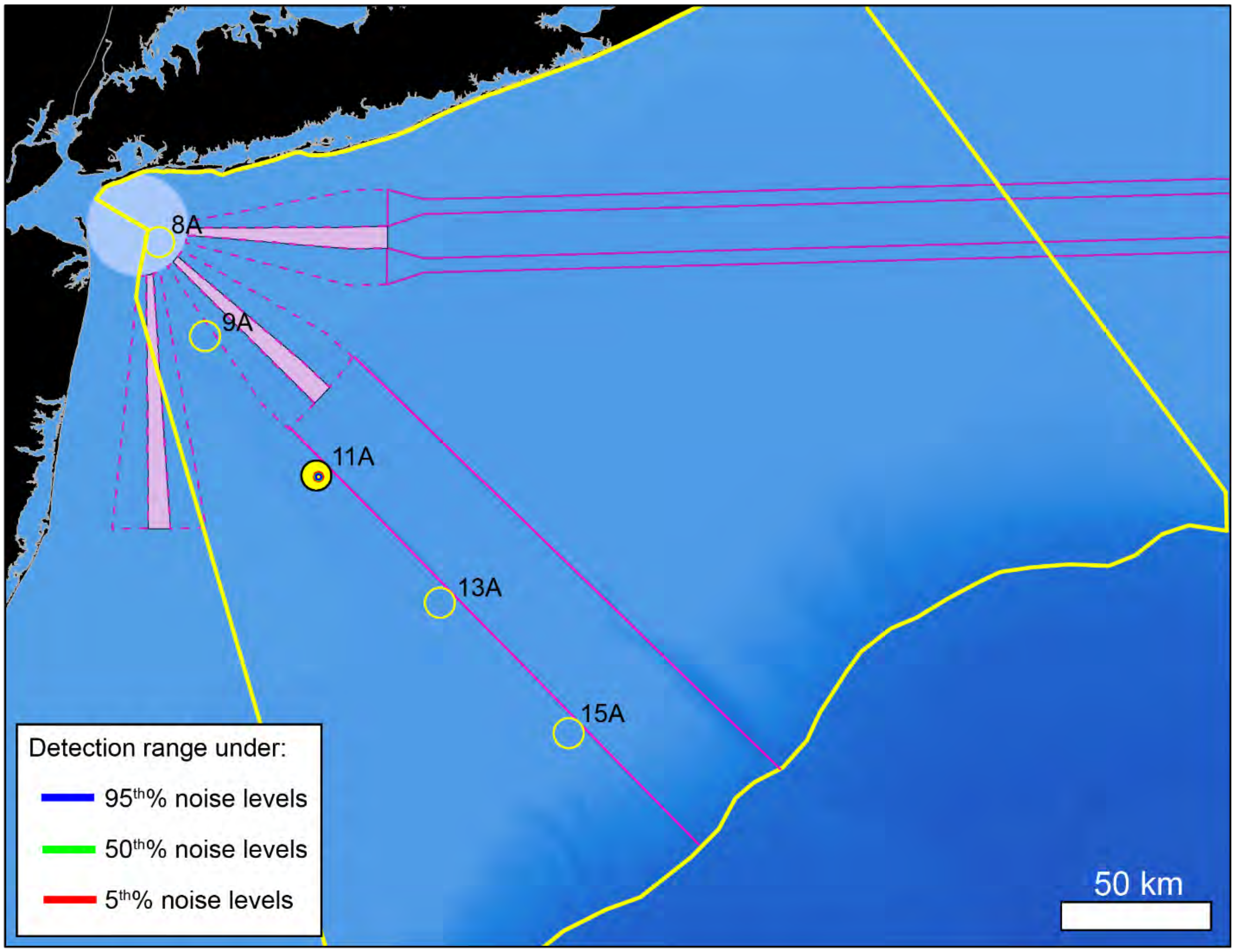


Figure 64. Map of estimated sperm whale acoustic detection ranges under different noise conditions in the New York Bight for the AMAR recording site with data collected in Year-3 to show the representative variation in detection range across the survey array. The blue lines indicate range based on the highest 95th percentile noise levels, the green lines indicate ranges based on median noise levels, and the red lines indicate ranges based on the lowest 5th percentile noise levels. Compared to the other baleen whales, sperm whales have a significantly smaller detection range, and it is difficult to distinguish detection ranges under different noise conditions at this spatial scale. In Year-3, only data from site 11A were recovered, missing AMAR sites are shown with hollow yellow circles.

Discussion

Similar to the Year-1 and Year-2 passive acoustic survey efforts, in Year-3, most of the focal baleen whale species were detected in NY Bight throughout much of the year. Fall, winter and spring were the time periods with the highest numbers of acoustic detections within NY Bight, and summer months exhibited the lowest level of cetacean acoustic occurrence. Two of the focal species, fin whales and humpback whales, were present in NY Bight throughout most of Year-3. Fin whales, sei whales and blue whales were primarily detected at the outer recording sites within NY Bight, while North Atlantic right whales and humpback whales were detected across the shelf (e.g., Figure 50). The detections across all sensors suggests a broad spatial scale of habitat usage across NY Bight.

Despite passive acoustic data loss due to sensor failure or loss due to trawling (~35% of survey days), the Year-3 passive acoustic survey still had a high detection rate of these focal species, except for sperm whales. The spatial representation of monthly and seasonal baleen whale acoustic occurrence indicates that despite data loss, there is still extensive large whale occurrence within NY Bight. The high number of visual sightings of fin whales withing the NY Offshore Planning Area corroborates our hypothesis that the uneven spatial pattern of acoustic detections of fin whales on adjacent sensors (Figure 28, Figure 30) is indicative that some fin whales are acoustically detected from within NY Bight, and not only detections of distant whales (for example, if it were only distant fin whale being detected, we would expect a more uniform detection pattern across sensors).

In comparing whale detection results across all three surveys, several notable changes in cetacean occurrence emerge. There were more days of detections with right whales in Year-2 compared to Year-1 (e.g., Figure 13), with increased days of occurrence in the spring and fall of Year-2. Right whale calving patterns in the southeast may explain the difference in detections between Year-1 and Year-2; there were few, if any, right whales observed in the southeast during Year-1, and consequently few right whales may have been making the southward migration that year (Pettis et al. 2019). In contrast, there were fewer days with detections in Year-2 compared to Year-1 for humpback whales, sei whales, blue whales, and sperm whales (Figure 13); these different detection patterns were not due to data loss or data gaps between years. At a broader temporal scale, the overall spatial and temporal seasonal patterns of whale occurrence are similar for both species across both survey years.

It is particularly interesting to compare trends in the three years of detections for these species to recently published Atlantic meta-analyses (Davis et al. 2017, Davis et al. 2020). When compared to the 2008-2009 NY Bight passive acoustic survey, detections across Year-1, Year-2, and Year-3 (2017-2019) suggests that whale occurrence has been increasing in NY Bight over the last decade (Davis et al. 2017, Muirhead et al. 2018, Davis et al. 2020, Zeh et al. 2020). An alternative explanation is that it is also possible that the 2008-2009 survey suffered from a higher false negative rate. The underlying environmental drivers for this temporal shift in occurrence is unclear, but may be related to directional increases in ocean temperature (Molinos et al. 2016, Poloczanska et al. 2016) as has been predicted or observed for fishes in the Western North

Atlantic (e.g., Pinsky et al. 2013, Morley et al. 2018). Whether this can be attributed to a combination of cetacean thermal preference, changes in ocean fronts, or is mediated through shifts is prey distribution is unclear.

As observed in Year-1 and Year-2, in Year-3 there were high ambient noise levels on all of the sensors from NY Bight, likely driven by abundant anthropogenic noise (see Appendix A). Because the sensor transect lines paralleled the shipping lanes, it is likely that shipping noise was the dominant anthropogenic sound source in the passive acoustic survey data. There were no consistent geographical trends in noise levels, likely because the instruments were consistently deployed relative to the shipping lanes for the entire transect. At the northeast convergence of the two shipping lanes, site 8A consistently experienced some of the higher sound levels compared to other locations (e.g.,

Table 27, Table 28), presumably because of the increased vessel traffic compared to other sites. These elevated ambient noise levels consequently limit both the acoustic detection range of whales (Figures 57-61) and restrict their conspecific communication space through increased acoustic masking (Figures 51-55) (Clark et al. 2009, Hatch et al. 2012, Cholewiak et al. 2018). From the lowest ambient sound level (5th percentile) to the median ambient sound levels in NY Bight, the communication space decreases by >60% (see Figure 53 – Figure 58). Additionally, the increased exposure of marine mammals to elevate noise levels upon entering NY Bight likely represents a source of chronic stress (Nowacek et al. 2007, Weilgart 2007, Shannon et al. 2016), which may have a variety of physiological, behavioral, or ecological consequences (e.g., Kight and Swaddle 2011); most of which have not been empirically measured for these focal species (Shannon et al. 2016).

With the drastic societal changes imposed by the COVID-19 pandemic, there was a significant reduction in the highest noise levels in NY Bight, paralleling reductions in human activity observed on land (Halfwerk 2020) and in other marine ecosystems around the world (Basan et al. 2021, Breeze et al. 2021, De Clippele and Risch 2021, Dunn et al. 2021, Gabriele et al. 2021, Pine et al. 2021, Ryan et al. 2021, Sertlek 2021). The reduction in ocean noise during the pandemic has been repeatedly attributed to decreases in vessel activity (Breeze et al. 2021, Dunn et al. 2021, Gabriele et al. 2021, Pine et al. 2021, Ryan et al. 2021). Terrestrial species were documented to change their acoustic behavior due to decreases or cessation in human-generated noise during the pandemic (Derryberry et al. 2020), and raises important questions of if and how these large whale species may have responded to reductions in noise levels. The reduction in ship noise would likely increase the acoustic communication range of vocalizing marine species (Pine et al. 2021). While there was a reduction in the highest noise levels in NY Bight during 2020 compared to the same months in 2019, the median noise levels were not significantly different, suggesting that the decreases in noise level may have primarily been a reduction of the extremes rather than a universal reduction across the entire soundscape.

While the overlapping aerial surveys in NY Bight observed all of the focal whale species included in the passive acoustic survey, the numbers of visual sightings across all three years were significantly smaller than the number of acoustic detections (Tetra Tech and Smultea Sciences 2018, Tetra Tech and LGL 2019, 2020). In Year-1, Year-2, and Year-3 of their aerial surveys, the Tetra Tech team observed North Atlantic right whales (Year-1: 13, Year-2: 4, Year-3: 7), humpback whales (Year-1: 36, Year-2: 177, Year-3: 66), fin whales (Year-1: 33, Year-2: 122, Year-3: 52), blue whales (Year-1: 4, Year-2: 0, Year-3: 1), sei whales (Year-1: 0, Year-2: 1, Year-3: 6) and sperm whales (Year-1: 7, Year-2: 23, Year-3: 42) (Tetra Tech and Smultea Sciences 2018, Tetra Tech and LGL 2019, 2020). Fin whales and humpback whales were the most abundant, and the other large whales species were observed in relatively limited numbers of individuals or observations (Tetra Tech and Smultea Sciences 2018, Tetra Tech and LGL 2020). The difference in spatial and temporal presence data of the target species between aerial surveys and passive acoustic monitoring underscore the differences in species detectability through the two methods and demonstrate the complimentary value that both methods contribute to understanding habitat use and large-scale spatiotemporal occurrence of the target whale species in NY Bight.

Species Specific Occurrence Patterns

North Atlantic Right Whales

Right whales were most frequently detected in NY Bight from fall through spring, with presence >5 days/week for most of this period. While higher levels of right whale presence were documented in Year-2 compared to Year-1, Year-3 showed a decline in right whale occurrence, even when accounting for decreased coverage from sensor loss. We also observed significantly higher number of right whale detections in spring, fall and winter in 2017-2019 compared to the 2008-2009 acoustic survey in both the mid-Bight and NY Harbor locations (Muirhead et al. 2018). In the 2008-2009 data, there were few detections close to the entrance of NY Harbor. In the 2017-2019 data, while there were few detections on unit 8A (closest to the NY Harbor entrance), there was relatively high presence at the nearby locations, 7M and 9A.

From previous passive acoustic surveys in the Mid-Atlantic and Gulf of Maine, we know that North Atlantic right whale occurrence can be highly variable across years (Kraus et al. 2016, Davis et al. 2017, Bailey et al. 2018, Salisbury et al. 2019, Charif et al. 2020).

For example, off the coast of Maryland, the month with the highest North Atlantic right whale occurrence varied between January through March (Bailey et al. 2018). This pronounced interannual variability in occurrence suggests major differences in right whale movement patterns through much of the Mid-Atlantic. It would be helpful to understand the coupling of spatial occurrence patterns for North Atlantic right whales in NY Bight compared to other areas in the Mid-Atlantic or Gulf of Maine, and whether occurrence in areas outside of NY waters are predictive of eventual occurrence within NY Bight. The Mid-Atlantic and NY Bight are thought to be part of the right whale migratory corridor (Kraus et al. 1986, Kraus and Rolland 2007). However, the extended presence of right whales in NY Bight outside of their migratory windows suggests right whales may not exclusively be migrating through this region. Similar patterns in extended seasonal occurrence of right whales outside of migration periods have been observed in other areas (Morano et al. 2012a, Hodge et al. 2015, Salisbury et al. 2016, Davis et al. 2017). Yet, it is unclear what role NY Bight plays in right whale ecology. Right whales have been observed feeding as far south as Nantucket Shoals (Leiter et al. 2017), but it is unclear whether calanoid copepods (right whales' principal food source) are in sufficient density in NY Bight to support feeding behavior. However, if right whales are not feeding in NY Bight, and they are also not migrating, it is unclear how they are using this habitat and why this region may be important.

Humpback Whales
Both song and social sounds of humpback whales were detected in NY Bight throughout Year-3. Since humpback song is hypothesized to be produced only by males, and associated with courtship or advertisement behavior, but it is unclear if the occurrence of song detected in NY Bight is suggestive of the region being associated with some aspect of humpback whale reproductive-related behavior, or whether there are other explanations for the occurrence of song, such as overwintering whales that sing because of a hormonal onset of song, or singing preceding or following migration to the breeding grounds. There have been similar observations of humpback song detected in the Western North Atlantic (Clark and Clapham 2004, Vu et al. 2012, Murray et al. 2014, Davis et al. 2020). Comparison of the 2008-2009 NY Bight acoustic survey data (Davis et al. 2020, Zeh et al. 2020) with the Year-1, Year-2, and Year-3 NY Bight data from this survey shows a higher level of detections in recent years, particularly during June-December. While there is not a direct overlap in sensor placement between these two survey efforts, there are likely overlapping detection ranges.

Similar to the seasonal trends for right whales, the year-round detections of humpback whales in NY Bight suggest this area is of year-round importance. While some portion of the Gulf of Maine population of humpbacks migrate between Gulf of Maine and the Tropical western Atlantic (Hayes et al. 2019, Heenehan et al. 2019), the Year-1, Year-2, and Year-3 NY Bight passive acoustic survey data suggest the possibility that not all of the humpback whale population is migrating. It is unclear what portions of the population may be using different regions of the Mid-Atlantic to overwinter, though the prevalence of song suggests there are males present. With the nearly year-round presence of humpback whales in many Mid-Atlantic areas (Davis et al. 2020), it raises the question whether there is site fidelity for different cohorts within the humpback whale stock, or whether overwintering whales moving between these locations.

Fin Whales
As with other areas in Mid-Atlantic and Gulf of Maine, fin whales are detected all year in NY Bight (Morano et al. 2012b, Davis et al. 2020). While fin whale song can be acoustically detected across large distances (e.g., Payne and Webb 1971, Širović et al. 2007), the heterogeneous spatial detection patterns across NY Bight during our three year survey (Figures 30, 32) suggests that it is not just distant fin whales that are the primary source of detections in NY Bight. This is corroborated by the large number of observations of fin whales within the NY Offshore Planning Area during the NY aerial surveys (Tetra Tech and Smultea Sciences 2018, Tetra Tech and LGL 2019). Despite their prevalence and number of observations in NY Bight, it is unclear how fin whales are using this habitat, and whether it has an important ecological role (such as for feeding or mating), or whether it is a migratory corridor.

The 2008-2009 passive acoustic data show the lowest levels of acoustic detections of fin whales during May-August in NY Bight (Morano et al. 2012b, Muirhead et al. 2018, Davis et al. 2020), whereas the 2017-2020 NY Bight acoustic survey data show decreases in detections occurring primarily in April-June (Figure 26, Figure 27, Figure 29). It unclear if this observed difference in the seasonality reflects a seasonal shift in fin whale occurrence in NY Bight across 10 years, or whether differences in the periods with the lowest detections between surveys is due to the limited number of sensors or differences in recording effort between the 2008-2009 and 2017-2020 PAM surveys.

Sei Whales

NY Bight likely represents the more southerly extent of the range for sei whales (Hayes et al. 2019), though a lower level of acoustic detections have been recorded as far south as the South Atlantic Bight (Davis et al. 2020). The 2017-2020 acoustic survey data collected in NY Bight are one of the most extensive time-series records of sei whale occurrence collected to date. All three years of survey data show that March- mid-June is the peak occurrence period for sei whales in NY Bight.

Sei whales have only recently been the focus of PAM surveys (Baumgartner et al. 2008, Tremblay et al. 2019, Davis et al. 2020, Nieukirk et al. 2020) and data on their occurrence in the Gulf of Maine and Mid-Atlantic have only recently been analyzed (Davis et al. 2020). As a result, Davis et al. (2020) represents the first synthesis of sei whale occurrence in the Western North Atlantic from PAM data and provides the first large-scale analyses of their occurrence across this region. The “Region 7” in Davis et al. (2020) is the transect line from Cornell’s 2008-2009 survey, and is similar to the present 2017-2020 acoustic survey data in identifying spring as the time period with peak occurrence in NY Bight. It is presently unclear what portion of the sei whale population stops at NY Bight, and how many individuals and what size classes or sex travel further south in the Mid-Atlantic. However, the fact that NY Bight is one of the southern-most regions with sustained sei whale occurrence highlights the likelihood that this area is important to their ecology.

During this survey, we observed many instances of frequency dispersion in the sei whale downsweeps (60% of the 20th-day ground-truth sei whale events), which negatively affected the template detector performance. As such, it is likely that sei whale daily presence is underestimated in these data. Frequency dispersion was more evident at sites near the shelf edge. Given this, it is possible that signals produced by sei whales further from the recording array were more likely to experience frequency dispersion by the time they were received by the recording unit, and therefore sei whales that vocalized further from the array were more often missed by the detector. Unexpectedly, the frequent occurrence of frequency dispersion in sei whale downsweeps in New York Bight could present an opportunity for future work sei whale detection range estimation (Newhall et al. 2012) and acoustics-based density estimation sampling (Marques et al. 2013). Signal-to-noise ratio also affected the TPR of the detection, where faint downsweeps were detected less. A sei whale downsweep from one individual could often be observed across multiple sensors, where the first arrival typically had a higher SNR than subsequent arrivals of the signal at nearby sites. In this example, it is possible that the detector would find the higher SNR signal and miss the subsequent, fainter signal arrivals at other sites.

However, in such a situation, sei whales would be marked as present during that calendar-day. Given that, it is possible that fewer calendar-days were falsely missed by the detector than what the detector performance metrics suggest. We do not suspect that the rate of missed downsweeps by the detector is biased over time, in which case these data present accurate broad temporal trends of sei whale occurrence in New York Bight.

Blue Whales

All three passive acoustic survey years exhibited an extremely limited number of days of detection of blue whales in NY Bight, which is consistent with the 2008-2009 survey (Muirhead et al. 2018, Davis et al. 2020). The small number of days with detections suggests blue whales do not spend much time in NY Bight, and instead are likely migrating through the area. An important question is how far into the NY Offshore Planning area they are travelling, or whether they are off the shelf. A single blue whale was acoustically tracked by Muirhead et al. (2018), and shown to be on the shelf, suggesting that individuals may be transiting through the planning area. Targeted efforts to understand blue whale spatial movements, either through aerial and/or shipboard visual surveys, focal follows, or tagging could help clarify the residency time and locations of blue whales within the NY Offshore Planning Area.

Sperm Whales

Despite the lack of detections in Year-3 due to extensive sensor loss, occurrence patterns for sperm whales from Year-1 and Year 2 within NY Bight continue to pose many questions about their ecology. The aerial surveys observed sperm whales at the shelf edge (Tetra Tech and Smultea Sciences 2018, Tetra Tech and LGL 2019), and we anticipated a large number of sperm whale detections at sensor sites closest to the shelf edge (i.e. 13A, 15A). It is particularly unfortunate that sensors at site 15A could not be recovered during the entire survey, as we anticipated the shelf edge would have the highest levels of sperm whale detections. However, the AMARs in Year-1 and Year-2 had regular detections of sperm whales (or sperm whale-like click trains) extending well onto the shelf. Because the transect line of units 8A-15A runs parallel to the Hudson Canyon may indicate that sperm whales are foraging in the canyon into shallower shelf waters. There was no clear seasonal signal detected in sperm whale occurrence data, so it is unclear if these are a limited number of resident individuals in the area, or whether there are animals regularly moving through New York Bight.

Management Implications of Passive Acoustic Survey Results

Data from this three year passive acoustic survey can inform adaptive or actionable management for protected species in NY Bight. The interannual variability of whale occurrence combined with extended periods when whales are detected may make implementation of seasonal management areas (which have been implemented in other high-traffic areas in Mid-Atlantic) difficult and/or only moderately effective.

The high number of detections of marine mammals in close proximity to the shipping lanes indicates that ship strikes remain a risk. Some of the focal whale species may be transiting across NY Bight, and consequently, are having to cross shipping lanes. However, because international vessel traffic has to cross this shelf region, moving the shipping lanes to decrease the possibility of ship strikes (as done for Stellwagen Bank National Marine Sanctuary; Petruny et al. 2014) may be extremely difficult or impractical. Consequently, other mitigation efforts (e.g., speed reductions, dynamic management areas) may need to be evaluated for their efficacy in reducing the probability of ship strikes. The use of real-time passive acoustic instruments for large whale detection (Spaulding et al. 2010, Baumgartner et al. 2019) may enable a rapid response to the occurrence of whale species in or near the shipping lanes, and may be part of a notification network to vessel captains to reduce their speeds when whales are near. A similar system has been operating in the Boston Traffic Separation Scheme as part of a ship strike mitigation effort (see http://www.listenforwhales.org).

With the spatial planning process for offshore wind energy across NY Bight (NYSDEC and NYSDOS 2015), wind lease areas will impose a large spatial footprint on NY Bight. For the eventual build-out of offshore wind, the year-round occurrence of marine protected species in NY Bight will make it difficult to implement seasonal exclusions on pile-driving. Instead, dynamic management areas and/or the use of real-time acoustic systems (Spaulding et al. 2010, Baumgartner et al. 2019) may be a more viable and effective approach for balancing development needs with mitigating impacts to marine mammals. Understanding whale occurrence in offshore wind planning areas is an important and ongoing part of wind farm site assessment (Hodge et al. 2015, Leiter et al. 2017, Stone et al. 2017, Bailey et al. 2018, Salisbury et al. 2019). Whales occurring in these wind energy areas may be exposed to a number of stressors associated with windfarm construction and operation (Carstensen et al. 2006, Petersen and Malm 2006, Tougaard et al. 2007, Thompson et al. 2010, Bergström et al. 2014, King et al. 2015, Schuster et al. 2015), but impulsive sounds from pile driving are of the most urgent concern (Madsen et al. 2006, Bailey et al. 2010, Thompson et al. 2010, Zampolli et al. 2013, Schuster et al. 2015, Kastelein et al. 2016, Amaral et al. 2020).

Recommendations for Future Study of Cetaceans in NY Bight

The three year passive acoustic survey produced a wealth of data on data-deficient marine mammal species in NY Bight and is one of the first to demonstrate the extensive occurrence of these species through much of the year and over much of the NY Offshore Planning Area. As such, it provides a demonstration of the efficacy of passive acoustic surveys for monitoring marine mammals in NY Bight and serves as an important foundation of data for future marine spatial planning and natural resource management efforts.

In addition to the data, this passive acoustic survey in NY Bight provides a number of lessons learned for future passive acoustic surveys. One immediate challenge encountered with our field efforts was limited weather windows to recover and redeploy instruments. For instruments that require large and heavy moorings for deployment (i.e. AMARs) or are large and cumbersome to recover ideally require relatively calm seas with swell height less than 2 m. Compared to our previous experience working far offshore in NY Bight, we were surprised how difficult it was to identify weather windows during which to conduct field efforts, particularly during seasons with inclement weather (including winter, as well as tropical storms and hurricanes). At one point during the survey, an Atlantic hurricane near Bermuda created swell activity in the outer edges of NY Bight exceeding 5-10 m, which made any field efforts impossible. Second, the extensive sensor loss, presumably due to trawling, should be a primary consideration for future survey designs. NY Bight has an extensive amount of fishing (Figure 65), particularly with bottom trawling, and bottom-mounted sensors, such as the MARUs, AMARs, and AURALs that were used here are particularly vulnerable to fishing activity. Future efforts should consider either placing bottom-mounted sensors in no-fishing zones (such as MPAs or artificial reefs), establishing regulated seasonal fishing exclusion zones where sensors are deployed, or developing encasements around instruments that would prevent susceptibility to being caught by fishing nets. Additionally, the productive waters of NY Bight led to an extensive amount of biofouling on the instruments, particularly for AMARs that were deployed for 6 months, which may have impeded recovery efforts by making sensors less buoyant when they rose to the surface for recovery. One of the considerations with sensors and recovery is the tradeoff between recorder longevity and the cost of replacement. Sensors that record for longer durations require fewer trips to redeploy sensors over the life of the project, however the longer duration recordings make sensors more vulnerable to biofouling. Conversely, more frequent recovery and redeployment of sensors significantly increases time and costs associated with increased field efforts. Thus, a balance of conservatism and pragmatism that is agreed upon by NY State and contractors may be required when designing future surveys. At its creation, the New York passive acoustic survey contract was structured as a lowest-cost bid proposal effort; the fundamental risk with this contractual mechanism is that while the cost to the state may be decreased, it drastically increases the risk of data loss and constrained survey design, particularly in a region as large and dynamic as the NY Bight. Future survey design efforts and the underlying contractual mechanisms should balance the project goals and survey design considerations with cost realism.

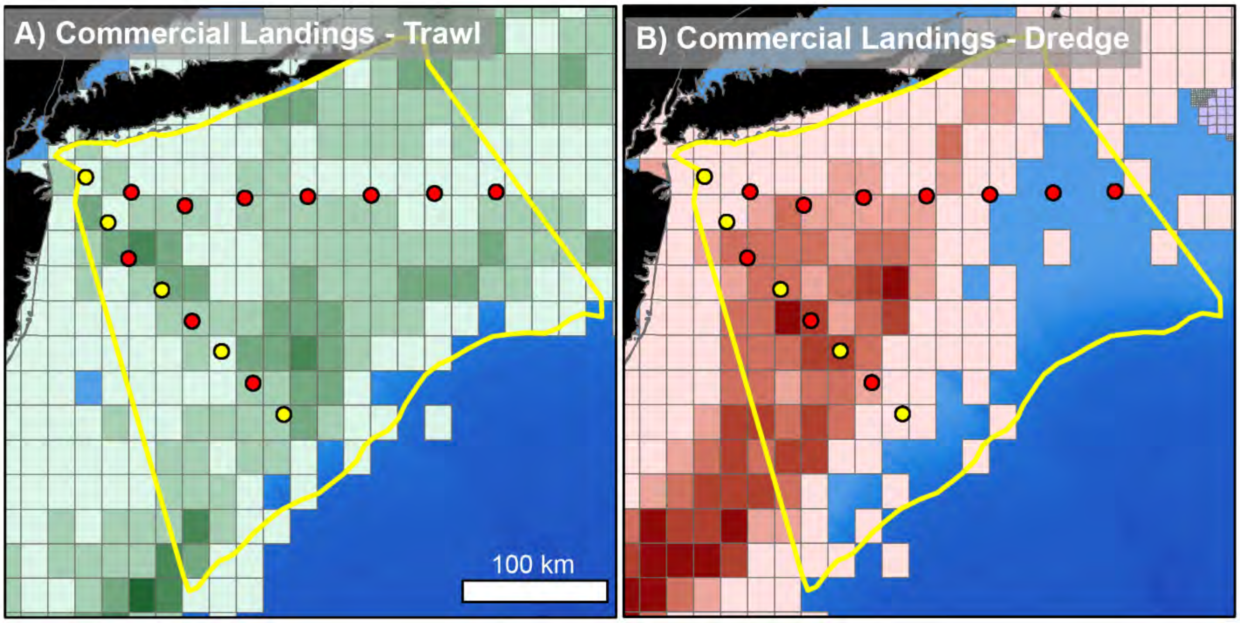


Figure 65. Locations of Year 1-3 passive acoustic instruments in New York Bight relative to commerical bottom fishing activity from VTR data for A) trawling and B) dredging. Red circles indicate the location of MARUs, yellow circles indicate locations of AMARs. Darkness of color

blocks indicates higher intensity of fishing. VTR data cover fishing activity between 2011 and 2015, but are likely reflective of current fishing activity. Data were obtained from the NY OPD Geographic Information Gateway (http://opdgig.dos.ny.gov).

Despite the large number of whale acoustic detections from the three year survey, there are still several data gaps that should be addressed for a more complete understanding of marine mammal habitat use of NY Bight. For example, the existing surveys have collected data along two transect lines paralleling the shipping lanes, yet there have been few data collected in the center region of NY Bight, as well as to the north and south of the shipping lanes. It is unclear how whales are using these other regions within the Bight, and how patterns of occurrence there compare with the areas directly next to the shipping lanes, which were the focus of this study. Therefore, a recommended next step would be to expand the surveyed area to include parts of the NY Bight which have not yet been monitored acoustically. In particular, a survey design following animal population monitoring survey design principles is recommended (e.g., as discussed in Buckland et al. 2015). Specifically, instruments deployed in a systematic randomized grid (i.e. an evenly spaced grid with a random start location) across the NY Bight would allow sites both next to the shipping lanes and other areas of the NY Bight to be simultaneously monitored. An example is given in Figure 66 using the same number of instruments used in the Year 1-3 passive acoustic surveys.

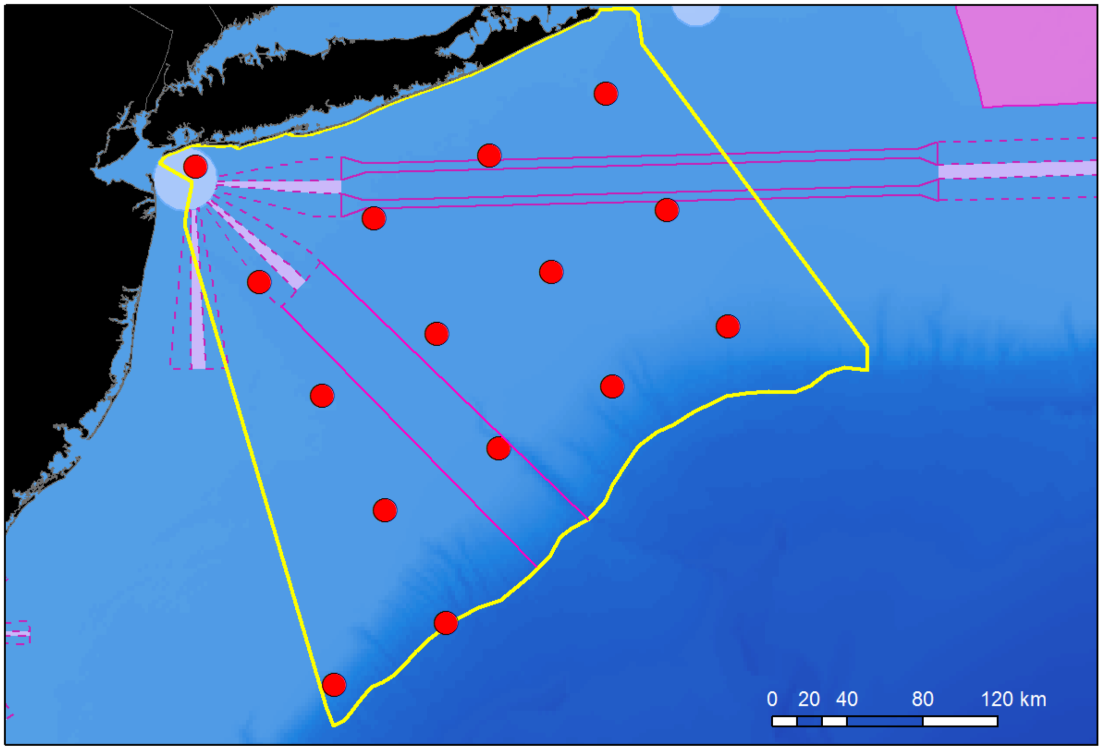


Figure 66. A hypothetical representation of a systematic grid of acoustic sensors covering the entire NY Offshore Planning Area for future monitoring efforts. The systematic grid of sensors

(red circles) was generated with a random start point created using *Distance* software (Thomas et al. 2010) and bounded by the borders of the NY Offshore Planning Area.

A gridded or spatially distributed survey design not only balances sampling close to the shipping lanes with other areas in the NY Bight, but will also collect data that can be more readily used in spatial and temporal statistical models. Such models can be used to understand patterns in the calling activities of the target species across the NY Bight by linking calling activity to environmental covariates. The resulting spatiotemporal models of cetacean distribution could be used in ship-strike risk analyses (e.g., Redfern et al. 2013, Smith et al. 2020).

The dataset collected in this study has yielded important baseline information that can be used to inform the design of the next stage of acoustic monitoring in NY Bight. For example, the expected detection rate of each species may inform potential duty cycling of instruments to optimize data collection, while predicted detection ranges will inform grid spacing.

Further, this study focused on daily occurrence of target species to quantify cetacean calling activity. Methods now exist that can estimate animal density from acoustic data (e.g., Marques et al. 2013), which may yield more detailed information about cetacean distribution patterns in NY Bight than occurrence data. Density data are also used in the cetacean distribution models for ship strike analyses (e.g., Redfern et al. 2013). Density estimation methods go beyond occurrence data by counting acoustic events, which may be defined as individual calls, animals or groups of animals. These acoustic events are corrected for (a) false detections made by automated detectors and (b) missed events by estimating the probability of detecting an acoustic event. Estimating the detection probability enables the area monitored to be quantified, and the methods also consider survey effort through time. Finally, knowledge about the target species' acoustic behavior is used to convert numbers of acoustic events into estimated numbers of animals. These density estimation methods are a useful way of standardizing data from multiple sites across time, even if absolute animal density cannot be estimated due to lack of information about acoustic behavior (see Warren et al. 2021 for a recent example with blue whales). Although Warren et al. (2021) did explore some of the components required for density analyses– for example preliminary detection ranges were estimated– a recommendation would be to formally incorporate density estimation methods in future survey designs and data analysis frameworks, where possible.

Additionally, it will become increasingly important to understand how and why marine mammals are using NY Bight as a habitat, and what role it plays in their life history. This critical ecological information may be needed to develop a more mechanistic perspective on what brings marine mammals to NY Bight, and what may be more effective mitigation strategies to minimize impacts on these protected species. The extensive occurrence of these focal whale species observed across all three passive acoustic survey years highlights the potential for NY Bight as an important habitat for marine mammal species.

Acknowledgements

This work could not have been completed without major contributions from several key individuals. Special thanks to Captain Fred Channel and Derek Jaskula for deploying and recovering recording devices in a wide range of seafaring conditions, to Deborah Cipolla-Dennis, Linda Harris, Edward Moore, and Holger Klink for invaluable administrative support, to Christopher Tessaglia-Hymes and Raymond Mack for engineering support, to Peter Dugan for optimizing and running automated detection algorithms on the audio data, and to Christopher Pelkie for assisting with data management. NYSDEC continuously provided extremely helpful guidance and feedback over the course of the study; we greatly appreciate of the input and support from Meghan Rickard, Lisa Bonacci, and Kim McKown.

Literature Cited

Amaral, J. L., J. H. Miller, G. R. Potty, K. J. Vigness-Raposa, A. S. Frankel, Y.-T. Lin, A. E. Newhall, D. R. Wilkes, A. N. Gavrilov. 2020. Characterization of impact pile driving signals during installation of offshore wind turbine foundations. *Journal of the Acoustical Society of America* 147:2323-2333.

Ambler, J. B. 2011. *Whales and the People Who Watch Them: Baleen Whales in Virginia's Near-shore Waters and the Educational and Conservation Potential of Whale Watching*. Ph.D. Dissertation, George Mason University.

Aoki, K., M. Amano, M. Yoshioka, K. Mori, D. Tokuda, N. Miyazaki. 2007. Diel diving behavior of sperm whales off Japan. *Marine Ecology Progress Series* 349:277-287.

Au, W. W. L., A. A. Pack, M. O. Lammers, L. M. Herman, M. H. Deakos, K. Andrews. 2006. Acoustic properties of humpback whale songs. *Journal of the Acoustical Society of America* 120:1103-1110.

Bailey, H., B. Senior, D. Simmons, J. Rusin, G. Picken, P. M. Thompson. 2010. Assessing underwater noise levels during pile-driving at an offshore windfarm and its potential effects on marine mammals. *Marine Pollution Bulletin* 60:888-897.

Bailey, H., A. N. Rice, J. E. Wingfield, K. B. Hodge, B. J. Estabrook, D. Hawthorne, A. Garrod, A. D. Fandel, L. Fouda, E. McDonald, E. Grzyb, W. Fletcher, A. L. Hoover. 2018. *Determining Offshore use by Marine Mammals and Ambient Noise Levels using Passive Acoustic Monitoring*. OCS Study: BOEM AT14-08, U.S. Department of the Interior, Bureau of Ocean Energy Management, Sterling, VA.

Barco, S. G., W. A. McLellan, J. M. Allen, R. A. Asmutis-Silva, R. Mallon-Day, E. M. Meagher, D. A. Pabst, J. Robbins, R. E. Seton, W. M. Swingle, M. T. Weinrich, P. J. Clapham. 2002. Population identity of humpback whales (*Megaptera novaeangliae*) in the waters of the US mid-Atlantic states. *Journal of Cetacean Research and Management* 4:135-141.

Basan, F., J. G. Fischer, D. Kuhnel. 2021. Soundscapes in the German Baltic Sea before and during the Covid-19 pandemic. *Frontiers in Marine Science* 8:689860.

Baumgartner, M. F., S. M. Van Parijs, F. W. Wenzel, C. J. Tremblay, H. C. Esch, A. M. Warde. 2008. Low frequency vocalizations attributed to sei whales (*Balaenoptera borealis*). *Journal of the Acoustical Society of America* 124:1339-1349.

Baumgartner, M. F., J. Bonnell, S. M. Van Parijs, P. J. Corkeron, C. Hotchkin, K. Ball, L.-P. Pelletier, J. Partan, D. Peters, J. Kemp, J. Pietro, K. Newhall, A. Stokes, T. V. N. Cole, E. Quintana, S. D. Kraus. 2019. Persistent near real-time passive acoustic monitoring for baleen whales from a moored buoy: System description and evaluation. *Methods in Ecology and Evolution* 10:1476-1489.

Bergström, L., L. Kautsky, T. Malm, R. Rosenberg, M. Wahlberg, N. A. Capetillo, D. Wilhelmsson. 2014. Effects of offshore wind farms on marine wildlife-a generalized impact assessment. *Environmental Research Letters* 9:034012.

Bioacoustics Research Program. 2017. *Raven Pro 2.0: Interactive Sound Analysis Software*. Cornell Lab of Ornithology. Available at: http://www.birds.cornell.edu/brp/raven/RavenOverview.html, Ithaca, NY.

Bort, J., S. M. Van Parijs, P. T. Stevick, E. Summers, S. Todd. 2015. North Atlantic right whale *Eubalaena glacialis* vocalization patterns in the central Gulf of Maine from October 2009 through October 2010. *Endangered Species Research* 26:271-280.

Breeze, H., S. H. Li, E. C. Marotte, J. A. Thenault, J. Wingfield, J. S. Xu. 2021. Changes in underwater noise and vessel traffic in the approaches to Halifax Harbor, Nova Scotia, Canada. *Frontiers in Marine Science* 8:674788.

Brown, D. M., J. Robbins, P. L. Sieswerda, R. Schoelkopf, E. C. M. Parsons. 2018. Humpback whale (*Megaptera novaeangliae*) sightings in the New York-New Jersey Harbor Estuary. *Marine Mammal Science* 34:250-257.

Buckland, S. T., E. A. Rexstad, T. A. Marques, C. S. Oedekoven. 2015. *Distance Sampling: Methods and Applications*. Springer, Cham.

Calupca, T. A., K. M. Fristrup, C. W. Clark. 2000. A compact digital recording system for autonomous bioacoustic monitoring. *Journal of the Acoustical Society of America* 108:2582.

Campbell-Malone, R., S. G. Barco, P.-Y. Daoust, A. R. Knowlton, W. A. McLellan, D. S. Rotstein, M. J. Moore. 2008. Gross and histologic evidence of sharp and blunt trauma in North Atlantic right whales (*Eubalaena glacialis*) killed by vessels. *Journal of Zoo and Wildlife Medicine* 39:37-55.

Carstensen, J., O. D. Henriksen, J. Teilmann. 2006. Impacts of offshore wind farm construction on harbour porpoises: Acoustic monitoring of echolocation activity using porpoise detectors (T-PODs). *Marine Ecology Progress Series* 321:295-308.

CETAP. 1982. *A Characterization of Marine Mammals and Turtles in the Mid- and North-Atlantic Areas of the U.S. Outer Continental Shelf, Final Report*. Bureau of Land Management, Washington, DC.

Charif, R. A., Y. Shiu, C. A. Muirhead, C. W. Clark, S. E. Parks, A. N. Rice. 2020. Phenological changes in North Atlantic right whale habitat use in Massachusetts Bay. *Global Change Biology* 26:734-745.

Cholewiak, D., C. W. Clark, D. Ponirakis, A. Frankel, L. T. Hatch, D. Risch, J. E. Stanistreet, M. Thompson, E. Vu, S. M. Van Parijs. 2018. Communicating amidst the noise: Modeling the aggregate influence of ambient and vessel noise on baleen whale communication space in a national marine sanctuary. *Endangered Species Research* 36:59-75.

Christian, M., V. M. Hendrick. 2007. Seasonal occurrence of North Atlantic right whale (*Eubalena glacialis*) vocalizations at two sites on the Scotian Shelf. *Marine Mammal Science* 23:856-867.

Clapham, P., R. M. Pace. 2001. *Defining Triggers for Temporary Area Closures to Protect Right Whales from Entanglements: Issues and Options*. U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Marine Fisheries Service, Northeast Region, Northeast Fisheries Science Center, Woods Hole, MA.

Clark, C. W., J. F. Borsani, G. Notarbartolo-di-Sciara. 2002. Vocal activity of fin whales, *Balaenoptera physalus*, in the Ligurian Sea. *Marine Mammal Science* 18:286-295.

Clark, C. W., P. J. Clapham. 2004. Acoustic monitoring on a humpback whale (*Megaptera novaeangliae*) feeding ground shows continual singing into late spring *Proceedings of the Royal Society of London B: Biological Sciences* 271:1051-1057.

Clark, C. W., W. T. Ellison, B. L. Southall, L. Hatch, S. M. Van Parijs, A. Frankel, D. Ponirakis. 2009. Acoustic masking in marine ecosystems: Intuitions, analysis, and implication. *Marine Ecology Progress Series* 395:201-222.

Conn, P. B., G. K. Silber. 2013. Vessel speed restrictions reduce risk of collision-related mortality for North Atlantic right whales. *Ecosphere* 4:43.

Corkeron, P., S. D. Kraus. 2018. Baleen whale species at risk of extinction. *Nature* 554:169.

Davies, K. T. A., S. W. Brillant. 2019. Mass human-caused mortality spurs federal action to protect endangered North Atlantic right whales in Canada. *Marine Policy* 104:157-162.

Davis, G. E., M. F. Baumgartner, J. Gurnee, J. Bell, C. Berchok, J. Bort Thornton, S. Brault, G. Buchanan, R. A. Charif, D. Cholewiak, C. W. Clark, P. Corkeron, J. Delarue, K. Dudzinski, L. Hatch, J. Hildebrand, L. Hodge, H. Klinck, S. Kraus, B. Martin, D. K. Mellinger, H. Moors-Murphy, S. Nieukirk, D. Nowacek, S. Parks, A. Read, A. N. Rice, D. Risch, A. Širović, M. Soldevilla, K. Stafford, J. Stanistreet, E. Summers, S. Todd, A. Warde, S. M. V. Parijs. 2017. Long-term passive acoustic recordings track the changing distribution of North Atlantic right whales (*Eubalaena glacialis*) from 2004 to 2014. *Scientific Reports* 7:13460.

Davis, G. E., M. Baumgartner, P. Corkeron, J. Bell, C. Berchok, J. Bonnell, J. Bort Thornton, S. Brault, G. Buchanan, D. Cholewiak, C. W. Clark, J. Delarue, L. T. Hatch, H. Klinck, D. Mellinger, S. Kraus, B. Martin, H. Moors-Murphy, S. Nieukirk, D. P. Nowacek, S. E. Parks, D. Parry, N. Pegg, A. Read, A. N. Rice, D. Risch, A. Scott, M. Soldevilla, K. Stafford, J. Stanistreet, E. Summers, S. Todd, S. M. Van Parijs. 2020. Exploring movement patterns and changing distribution of baleen whales in the western North Atlantic using a decade of passive acoustic data. *Global Change Biology* 26:4812-4840.

De Clippele, L. H., D. Risch. 2021. Measuring sound at a cold-water coral reef to assess the impact of COVID-19 on noise pollution. *Frontiers in Marine Science* 8:674702.

Derryberry, E. P., J. N. Phillips, G. E. Derryberry, M. J. Blum, D. Luther. 2020. Singing in a silent spring: Birds respond to a half-century soundscape reversion during the COVID-19 shutdown. *Science* 370:575-579.

Diogou, N., D. M. Palacios, S. L. Nieukirk, J. A. Nystuen, E. Papathanassiou, S. Katsanevakis, H. Klinck. 2019. Sperm whale (*Physeter macrocephalus*) acoustic ecology at Ocean Station PAPA (Gulf of Alaska) – Part 1: Detectability and seasonality. *Deep Sea Research I* DOI:10.1016/j.dsr.2019.05.007.

Dugan, P., M. Pourhomayoun, Y. Shiu, R. Paradis, A. Rice, C. Clark. 2013. Using high performance computing to explore large complex bioacoustic soundscapes: case study for right whale acoustics. *Procedia Computer Science* 20:156-162.

Dugan, P. J., D. W. Ponirakis, J. A. Zollweg, M. S. Pitzrick, J. L. Morano, A. M. Warde, A. N. Rice, C. W. Clark, S. M. Van Parijs. 2011. SEDNA – bioacoustic analysis toolbox. *IEEE OCEANS 2011*:1-10.

Dugan, P. J., H. Klinck, M. A. Roch, T. A. Helble. 2016. RAVEN X: High performance data mining toolbox for bioacoustic data analysis. *arxiv*:1610.03772.

Dunn, C., J. Theriault, L. Hickmott, D. Claridge. 2021. Slower ship speed in the Bahamas due to COVID-19 produces a dramatic reduction in ocean sound levels. *Frontiers in Marine Science* 8:673565.

Edwards, E. F., C. Hall, T. J. Moore, C. Sheredy, J. V. Redfern. 2015. Global distribution of fin whales *Balaenoptera physalus* in the post-whaling era (1980-2012). *Mammal Review* 45:197-214.

Erbe, C. 2015. The maskogram: A tool to illustrate zones of masking. *Aquatic Mammals* 41:434-443.

Erbe, C., C. Reichmuth, K. Cunningham, K. Lucke, R. Dooling. 2016. Communication masking in marine mammals: A review and research strategy. *Marine Pollution Bulletin* 103:15-38.

Estabrook, B. J., K. B. Hodge, D. P. Salisbury, D. Ponirakis, D. V. Harris, J. M. Zeh, S. E. Parks, A. N. Rice. 2019. *Year-1 Annual Survey Report for New York Bight Whale Monitoring Passive Acoustic Surveys October 2017- October 2018. Contract C009925*. New York State Department of Environmental Conservation, East Setauket, NY.

Estabrook, B. J., K. B. Hodge, D. P. Salisbury, D. Ponirakis, D. V. Harris, J. M. Zeh, S. E. Parks, A. N. Rice. 2020. *Year-2 Annual Survey Report for New York Bight Whale Monitoring Passive Acoustic Surveys October 2018- October 2019. Contract C009925*. New York State Department of Environmental Conservation, East Setauket, NY.

Gabriele, C. M., D. W. Ponirakis, H. Klinck. 2021. Underwater sound levels in Glacier Bay during reduced vessel traffic due to the COVID-19 pandemic. *Frontiers in Marine Science* 8:674787.

Goold, J. C., S. E. Jones. 1995. Time and frequency domain characteristics of sperm whale clicks. *Journal of the Acoustical Society of America* 98:1279-1291.

Grosslein, M. D., T. R. Azarovitz. 1981. *Fish Distribution*. Marine Ecosystems Analysis (MESA) Program, MESA New York Bight Atlas Monograph 15. New York Sea Grant Institute, Albany, NY.

Halfwerk, W. 2020. The quiet spring of 2020. *Science* 370:523-524.

Hatch, L., C. Clark, R. Merrick, S. Van Parijs, D. Ponirakis, K. Schwehr, M. Thompson, D. Wiley. 2008. Characterizing the relative contributions of large vessels to total ocean noise fields: a case study using the Gerry E. Studds Stellwagen Bank National Marine Sanctuary. *Environmental Management* 42:735-752.

Hatch, L. T., C. W. Clark, S. M. Van Parijs, A. S. Frankel, D. W. Ponirakis. 2012. Quantifying loss of acoustic communication space for right whales in and around a U.S. National Marine Sanctuary. *Conservation Biology* 26:983-994.

Hayes, S. A., E. Josephson, K. Maze-Foley, P. E. Rosel (eds) 2017. *U.S. Atlantic and Gulf of Mexico Marine Mammal Stock Assessments - 2016*. NOAA Technical Memorandum NMFS-NE-241. U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Silver Spring, MD.

Hayes, S. A., E. Josephson, K. Maze-Foley, P. E. Rosel (eds) 2019. *U.S. Atlantic and Gulf of Mexico Marine Mammal Stock Assessments - 2018.* . NOAA Technical Memorandum NMFS-NE-258. U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Silver Spring, MD.

Hayes, S. A., E. Josephson, K. Maze-Foley, P. E. Rosel, J. Turek (eds) 2021. *U.S. Atlantic and Gulf of Mexico Marine Mammal Stock Assessments - 2020.* NOAA Technical Memorandum NMFS-NE-271. U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Marine Fisheries Service Northeast Fisheries Science Center, Woods Hole, MA.

Heenehan, H., J. E. Stanistreet, P. J. Corkeron, L. Bouveret, J. Chalifour, G. E. Davis, A. Henriquez, J. J. Kiszka, L. Kline, C. Reed, O. Shamir-Reynoso, F. Védie, W. De Wolf, P. Hoetjes, S. M. Van Parijs. 2019. Caribbean sea soundscapes: Monitoring humpback whales, biological sounds, geological events, and anthropogenic impacts of vessel noise. *Frontiers in Marine Science* 6:347.

Hodge, K. B., C. A. Muirhead, J. L. Morano, C. W. Clark, A. N. Rice. 2015. North Atlantic right whale occurrence in two wind planning areas along the mid-Atlantic U.S. coast: Implications for management. *Endangered Species Research* 28:225-234.

Jaquet, N., S. Dawson, L. Douglas. 2001. Vocal behavior of male sperm whales: Why do they click? *Journal of the Acoustical Society of America* 109:2254-2259.

Jochens, A., D. Biggs, K. Benoit-Bird, D. Engelhaupt, J. Gordon, C. Hu, N. Jaquet, M. Johnson, R. Leben, B. Mate, P. Miller, J. Ortega-Ortiz, A. Thode, P. Tyack, B. Würsig. 2008. *Sperm Whale Seismic Study in the Gulf of Mexico: Synthesis Report*. OCS Study MMS 2008-006. Minerals Management Service, Gulf of Mexico OCS Region, U.S. Department of the Interior, New Orleans, LA.

Johnson, A., G. Salvador, J. Kenney, J. Robbins, S. Kraus, S. Landry, P. Clapham. 2005. Fishing gear involved in entanglements of right and humpback whales. *Marine Mammal Science* 21:635-645.

Kastelein, R. A., L. Helder-Hoek, J. Covi, R. Gransier. 2016. Pile driving playback sounds and temporary threshold shift in harbor porpoises (*Phocoena phocoena*): Effect of exposure duration. *Journal of the Acoustical Society of America* 139:2842-2851.

Kight, C. R., J. P. Swaddle. 2011. How and why environmental noise impacts animals: an integrative, mechanistic review. *Ecology Letters* 14:1052-1061.

King, S. L., R. S. Schick, C. Donovan, C. G. Booth, M. Burgman, L. Thomas, J. Harwood. 2015. An interim framework for assessing the population consequences of disturbance. *Methods in Ecology and Evolution* 6:1150-1158.

Knowlton, A. R., S. D. Kraus. 2001. Mortality and serious injury of northern right whales (*Eubalaena glacialis*) in the western North Atlantic Ocean. *Journal of Cetacean Research and Management* 2:193-208.

Knowlton, A. R., M. W. Brown. 2007. Running the gauntlet: Right whales and vessel strikes. Pages 409-435 in *The Urban Whale: North Atlantic Right Whales at the Crossroads* (S. D. Kraus, and R. M. Rolland, eds.). Harvard University Press, Cambridge, MA.

Kraus, S. D., J. H. Prescottt, A. R. Knowlton, G. S. Stone. 1986. Migration and calving of right whales (*Eubalaena glacialis*) in the Western North Atlantic. *Reports of the International Whaling Commission* Special Issue 10:139-144.

Kraus, S. D. 1990. Rates and potential causes of mortality in North Atlantic right whales (*Eubalaena glacialis*). *Marine Mammal Science* 6:278-291.

Kraus, S. D., M. W. Brown, H. Caswell, C. W. Clark, M. Fujiwara, P. K. Hamilton, R. D. Kenney, A. R. Knowlton, S. Landry, C. A. Mayo, W. A. McLellan, M. J. Moore, D. P. Nowacek, D. A. Pabst, A. J. Read, R. M. Rolland. 2005. North Atlantic right whales in crisis. *Science* 309:561-562.

Kraus, S. D., R. M. Rolland. 2007. Right whales in the urban ocean. Pages 1-38 in *The Urban Whale: North Atlantic Right Whales at the Crossroads* (S. D. Kraus, and R. M. Rolland, eds.). Harvard University Press, Cambridge, MA.

Kraus, S. D., S. Leiter, K. Stone, B. Wikgren, C. Mayo, P. Nughes, R. D. Kenney, C. W. Clark, A. N. Rice, B. Estabrook, J. Tielens. 2016. *Northeast Large Pelagic Survey Collaborative Aerial and Acoustic Surveys for Large Whales and Sea Turtles, Final Report. OCS Study BOEM 2016-054.* U.S. Department of Interior, Bureau of Ocean Energy Management, Office of Renewable Energy Programs, Herndon, VA.

Leiter, S. M., K. M. Stone, J. L. Thompson, C. M. Accardo, B. C. Wikgren, M. A. Zani, T. V. N. Cole, R. D. Kenney, C. A. Mayo, S. D. Kraus. 2017. North Atlantic right whale *Eubalaena glacialis* occurrence in offshore wind energy areas near Massachusetts and Rhode Island, USA. *Endangered Species Research* 34:45-59.

Madsen, P. T., R. Payne, N. U. Kristiansen, M. Wahlberg, I. Kerr, B. Møhl. 2002. Sperm whale sound production studied with ultrasound time/depth-recording tags. *Journal of Experimental Biology* 205:1899-1906.

Madsen, P. T., M. Wahlberg, J. Tougaard, K. Lucke, P. Tyack. 2006. Wind turbine underwater noise and marine mammals: implications of current knowledge and data needs. *Marine Ecology Progress Series* 309:279-295.

Marques, T. A., L. Thomas, S. W. Martin, D. K. Mellinger, J. A. Ward, D. J. Moretti, D. Harris, P. L. Tyack. 2013. Estimating animal population density using passive acoustics. *Biological Reviews* 88:287-309.

Mayer, G. F. (ed) 1982. *Ecological Stress and the New York Bight: Science and Management*. Estuarine Research Federation, Columbia, SC.

McDonald, M. A., J. A. Hildebrand, S. C. Webb. 1995. Blue and fin whales observed on a seafloor array in the Northeast Pacific. *Journal of the Acoustical Society of America* 98:712-721.

McDonald, M. A., J. A. Hildebrand, S. Mesnick. 2009. Worldwide decline in tonal frequencies of blue whale songs. *Endangered Species Research* 9:13-21.

Mellinger, D. K., C. W. Clark. 1997. Methods for automatic detection of mysticete sounds. *Marine and Freshwater Behaviour and Physiology* 29:163 - 181.

Mellinger, D. K., C. W. Clark. 2000. Recognizing transient low-frequency whale sounds by spectrogram correlation. *Journal of the Acoustical Society of America* 107:3518-3529.

Mellinger, D. K., C. W. Clark. 2003. Blue whale (*Balaenoptera musculus*) sounds from the North Atlantic. *Journal of the Acoustical Society of America* 114:1108-1119.

Mellinger, D. K., J. W. Bradbury. 2007. Acoustic measurements of marine mammal sounds in noisy environments. *Proceedings of the Second International Conference on Underwater Acoustic Measurements: Technologies and Results*:273-280.

Mellinger, D. K., K. M. Stafford, S. E. Moore, R. P. Dziak, H. Matsumoto. 2007. An overview of fixed passive acoustic observation methods for cetaceans. *Oceanography* 20:36-45.

Menza, C., B. P. Kinlan, D. S. Dorfman, M. Poti, C. Caldow (eds) 2012. *A Biogeographic Assessment of Seabirds, Deep Sea Corals and Ocean Habitats of the New York Bight: Science to Support Offshore Spatial Planning*. NOAA Technical Memorandum NOS NCCOS 141, National Oceanic and Atmospheric Administration, Silver Spring, MD.

Meyer-Gutbrod, E. L., C. H. Greene, P. J. Sullivan, A. J. Pershing. 2015. Climate-associated changes in prey availability drive reproductive dynamics of the North Atlantic right whale population. *Marine Ecology Progress Series* 535:243-258.

Meyer-Gutbrod, E. L., C. H. Greene. 2018. Uncertain recovery of the North Atlantic right whale in a changing ocean. *Global Change Biology* 24:455-464.

Meyer-Gutbrod, E. L., C. H. Greene, K. T. A. Davies, D. G. Johns. 2021. Ocean regime shift is driving collapse of the North Atlantic right whale population. *Oceanography* 34:22-31.

Mitchell, E. 1975. Preliminary report on Nova Scotia fishery for sei whales (*Balaenoptera borealis*). *Reports of the International Whaling Commission* 25:218-225.

Molinos, J. G., B. S. Halpern, D. S. Schoeman, C. J. Brown, W. Kiessling, P. J. Moore, J. M. Pandolfi, E. S. Poloczanska, A. J. Richardson, M. T. Burrows. 2016. Climate velocity and the future global redistribution of marine biodiversity. *Nature Climate Change* 6:83-88.

Morano, J. L., A. N. Rice, J. T. Tielens, B. J. Estabrook, A. Murray, B. Roberts, C. W. Clark. 2012a. Acoustically detected year-round presence of right whales in an urbanized migration corridor. *Conservation Biology* 26:698-707.

Morano, J. L., D. P. Salisbury, A. N. Rice, K. L. Conklin, K. L. Falk, C. W. Clark. 2012b. Seasonal changes in fin whale song in the Western North Atlantic Ocean. *Journal of the Acoustical Society of America* 132:1207-1212.

Morley, J. W., R. L. Selden, R. J. Latour, T. L. Frölicher, R. J. Seagraves, M. L. Pinsky. 2018. Projecting shifts in thermal habitat for 686 species on the North American continental shelf. *PLoS ONE* 13:e0196127.

Muirhead, C. A., A. M. Warde, I. S. Biedron, A. N. Mihnovets, C. W. Clark, A. N. Rice. 2018. Seasonal acoustic occurrence of blue, fin, and North Atlantic right whales in the New York Bight. *Aquatic Conservation: Marine and Freshwater Ecosystems* 28:744-753.

Munger, L. M., S. M. Wiggins, J. A. Hildebrand. 2011. North Pacific right whale up-call source levels and propagation distance on the southeastern Bering Sea shelf. *Journal of the Acoustical Society of America* 129:4047-4054.

Murray, A., A. N. Rice, C. W. Clark. 2014. Extended seasonal occurrence of humpback whales in Massachusetts Bay. *Journal of the Marine Biological Association of the U.K.* 94:1117-1125.

National Oceanic and Atmospheric Administration (NOAA). 1974. *Marine EcoSystems Analysis Program: Bibliography of the New York Bight*. National Oceanic and Atmospheric Administration, Office of Coastal Management, Environmental Science Information Center, Rockville, MD.

National Oceanic and Atmospheric Administration (NOAA). 1976. *Marine EcoSystems Analysis (MESA) Program: The New York Bight Project - 1975; Stony Brook, Long Island, New York*. NOAA Special Report. National Oceanic and Atmospheric Administration, Environmental Research Laboratories, Boulder, CO.

National Oceanic and Atmospheric Administration (NOAA). 2016. Endangered and threatened species; Critical habitat for endangered North Atlantic right whale. *Federal Register* 81:4838-4874.

New York State Department of Environmental Conservation (NYSDEC). 2005. *Comprehensive Wildlife Conservation Strategy: A Strategy for Conserving New York's Fish and Wildlife Resources*. NYSDEC, Albany, NY. Available at: https://www.dec.ny.gov/docs/wildlife_pdf/cwcs2005.pdf.

New York State Department of Environmental Conservation (NYSDEC), New York State Department of State (NYSDOS). 2015. New York Ocean Action Plan; 2015 - 2025. Pages 123-123 New York State Department of Environmental Conservation, Albany, NY.

Newhall, A. E., Y.-T. Lin, J. F. Lynch, M. F. Baumgartner, G. G. Gawarkiewicz. 2012. Long distance passive localization of vocalizing sei whales using an acoustic normal mode approach. *Journal of the Acoustical Society of America* 131:1814-1825.

Nieukirk, S. L., D. K. Mellinger, R. P. Dziak, H. Matsumoto, H. Klinck. 2020. Multi-year occurrence of sei whale calls in North Atlantic polar waters. *Journal of the Acoustical Society of America* 147:1842-1850.

Normandeau Associates Inc., APEM Ltd. 2018. *Digital Aerial Baseline Survey of Marine Wildlife in Support of Offshore Wind Energy. First Annual Report: 2016-2017.* NYSERDA, Albany, NY.

Northeast Fisheries Science Center (NEFSC), Southeast Fisheries Science Center (SEFSC). 2016. *Annual Report of a Comprehensive Assessment of Marine Mammal, Marine Turtle, and Seabird Abundance and Spatial Distribution in US Waters of the Western North Atlantic Ocean – AMAPPS II.* Northeast Fisheries Science Center, National Marine Fisheries Service, National Oceanic and Atmospheric Administration, Woods Hole, MA.

Nowacek, D. P., L. H. Thorne, D. W. Johnston, P. L. Tyack. 2007. Responses of cetaceans to anthropogenic noise. *Mammal Review* 37:81-115.

Oliveira, C., M. Wahlberg, M. A. Silva, M. Johnson, R. Antunes, D. M. Wisniewska, A. Fais, J. Gonçalves, P. T. Madsen. 2016. Sperm whale codas may encode individuality as well as clan identity. *Journal of the Acoustical Society of America* 139:2860-2869.

Pace, R. M., P. J. Corkeron, S. D. Kraus. 2017. State–space mark–recapture estimates reveal a recent decline in abundance of North Atlantic right whales. *Ecology and Evolution* 27:8730-8741.

Parks, S. E., P. L. Tyack. 2005. Sound production by North Atlantic right whales (*Eubalaena glacialis*) in surface active groups. *Journal of the Acoustical Society of America* 117:3297-3306.

Parks, S. E., C. W. Clark. 2007. Acoustic communication: Social sounds and the potential impacts of noise. Pages 310-332 in *The Urban Whale: North Atlantic Right Whales at the*

Crossroads (S. D. Kraus, and R. M. Rolland, eds.). Harvard University Press, Cambridge, MA.

Parks, S. E., I. Urazghildiiev, C. W. Clark. 2009. Variability in ambient noise levels and call parameters of North Atlantic right whales in three habitat areas. *Journal of the Acoustical Society of America* 125:1230-1239.

Parks, S. E., M. Johnson, D. Nowacek, P. L. Tyack. 2011. Individual right whales call louder in increased environmental noise. *Biology Letters* 7:33-35.

Parks, S. E., J. D. Warren, K. Stamieszkin, C. A. Mayo, D. Wiley. 2012. Dangerous dining: surface foraging of North Atlantic right whales increases risk of vessel collisions. *Biology Letters* 8:57-60.

Payne, R., D. Webb. 1971. Orientation by means of long range acoustic signaling in baleen whales. *Annals of the New York Academy of Sciences* 188:110-141.

Pearce, J. B., D. J. Radosh, J. V. Caracciolo, F. W. Steimle. 1981. *Benthic Fauna*. Marine Ecosystems Analysis (MESA) Program, MESA New York Bight Atlas Monograph 14. New York Sea Grant Institute, Albany, NY.

Pendleton, D. E., P. J. Sullivan, M. W. Brown, T. V. N. Cole, C. P. Good, C. A. Mayo, B. C. Monger, S. Phillips, N. R. Record, A. J. Pershing. 2012. Weekly predictions of North Atlantic right whale *Eubalaena glacialis* habitat reveal influence of prey abundance and seasonality of habitat preferences. *Endangered Species Research* 18:147-161.

Petersen, J. K., T. Malm. 2006. Offshore windmill farms: Threats to or possibilities for the marine environment. *Ambio* 35:75-80.

Petruny, L. M., A. J. Wright, C. E. Smith. 2014. Getting it right for the North Atlantic right whale (*Eubalaena glacialis*): A last opportunity for effective marine spatial planning? *Marine Pollution Bulletin* 85:24-32.

Pettis, H. M., R. M. Pace, P. K. Hamilton. 2019. *North Atlantic Right Whale Consortium 2018 Annual Report Card*. Report to the North Atlantic Right Whale Consortium. Available at: https://www.narwc.org/uploads/1/1/6/6/116623219/2018report_cardfinal.pdf.

Pettis, H. M., R. M. Pace, P. K. Hamilton. 2021. *North Atlantic Right Whale Consortium 2020 Annual Report Card*. Report to the North Atlantic Right Whale Consortium. Available at: https://www.narwc.org/uploads/1/1/6/6/116623219/2020narwcreport_cardfinal.pdf.

Piggott, C. L. 1964. Ambient sea noise at low frequencies in shallow water of the Scotian Shelf. *Journal of the Acoustical Society of America* 36:2152-2163.

Pine, M. K., L. Wilson, A. G. Jeffs, L. McWhinnie, F. Juanes, A. Sceuderi, C. A. Radford. 2021. A gulf in lockdown: How an enforced ban on recreational vessels increased dolphin and fish communication ranges. *Global Change Biology* 27:4839-4848.

Pinsky, M. L., B. Worm, M. J. Fogarty, J. L. Sarmiento, S. A. Levin. 2013. Marine taxa track local climate velocities. *Science* 341:1239-1242.

Poloczanska, E. S., M. T. Burrows, C. J. Brown, J. G. Molinos, B. S. Halpern, O. Hoegh-Guldberg, C. V. Kappel, P. J. Moore, A. J. Richardson, D. S. Schoeman, W. J. Sydeman. 2016. Responses of marine organisms to climate change across oceans. *Frontiers in Marine Science* 3:21.

Porter, M. B. 2019. Beam tracing for two- and three-dimensional problems in ocean acoustics. *Journal of the Acoustical Society of America* 146:2016-2029.

Record, N. R., J. A. Runge, D. E. Pendleton, W. M. Balch, K. T. A. Davies, A. J. Pershing, C. L. Johnson, K. Stamieszkin, R. Ji, Z. Feng, S. D. Kraus, R. D. Kenney, C. A. Hudak, C. A. Mayo, C. Chen, J. E. Salisbury, C. R. S. Thompson. 2019. Rapid climate-driven circulation changes threaten conservation of endangered North Atlantic right whales. *Oceanography* 32:162-169.

Redfern, J. V., M. F. McKenna, T. J. Moore, J. Calambokidis, M. L. Deangelis, E. A. Becker, J. Barlow, K. A. Forney, P. C. Fiedler, S. J. Chivers. 2013. Assessing the risk of ships striking large whales in marine spatial planning. *Conservation Biology* 27:292-302.

Reeder, D. B., E. S. Sheffield, S. M. Mach. 2011. Wind-generated ambient noise in a topographically isolated basin: A pre-industrial era proxy. *Journal of the Acoustical Society of America* 129:64-73.

Rice, A. N., J. T. Tielens, B. J. Estabrook, C. A. Muirhead, A. Rahaman, M. Guerra, C. W. Clark. 2014. Variation of ocean acoustic environments along the western North Atlantic coast: A case study in context of the right whale migration route. *Ecological Informatics* 21:89-99.

Richardson, W. J., C. R. Greene, C. I. Malme, D. H. Thomson. 1995. *Marine Mammals and Noise, 1st ed.* Academic Press, San Diego.

Roberts, J. J., B. D. Best, L. Mannocci, E. Fujioka, P. N. Halpin, D. L. Palka, L. P. Garrison, K. D. Mullin, T. V. N. Cole, C. B. Khan, W. A. McLellan, D. A. Pabst, G. G. Lockhart. 2016. Habitat-based cetacean density models for the U.S. Atlantic and Gulf of Mexico. *Scientific Reports* 6:22615.

Rolland, R. M., S. E. Parks, K. E. Hunt, M. Castellote, P. J. Corkeron, D. P. Nowacek, S. K. Wasser, S. D. Kraus. 2012. Evidence that ship noise increases stress in right whales. *Proceedings of the Royal Society B: Biological Sciences* 279:2363-2368.

Romagosa, M., O. Boisseau, A.-C. Cucknell, A. Moscrop, R. McLanaghan. 2015. Source level estimates for sei whale (*Balaenoptera borealis*) vocalizations off the Azores. *Journal of the Acoustical Society of America* 138:2367-2372.

Ryan, J. P., J. E. Joseph, T. Margolina, L. T. Hatch, A. Azzara, A. Reyes, B. L. Southall, A. DeVogelaere, L. E. P. Reeves, Y. W. Zhang, D. E. Cline, B. Jones, P. McGill, S. Baumann-Pickering, A. K. Stimpert. 2021. Reduction of low-frequency vessel noise in Monterey Bay National Marine Sanctuary during the COVID-19 pandemic. *Frontiers in Marine Science* 8:656566.

Salisbury, D. P., C. W. Clark, A. N. Rice. 2016. Right whale occurrence in the coastal waters of Virginia, U.S.A.: implications of endangered species presence in a rapidly developing energy market. *Marine Mammal Science* 32:509-519.

Salisbury, D. P., B. J. Estabrook, H. Klinck, A. N. Rice. 2019. *Understanding Marine Mammal Presence in the Virginia Offshore Wind Energy Area*. OCS Study: BOEM 2019-007. US Department of the Interior, Bureau of Ocean Energy Management, Sterling, VA.

Schulz, T. M., H. Whitehead, S. Gero, L. Rendell. 2011. Individual vocal production in a sperm whale (*Physeter macrocephalus*) social unit. *Marine Mammal Science* 27:149-166.

Schuster, E., L. Bulling, J. Koppel. 2015. Consolidating the state of knowledge: A synoptical review of wind energy's wildlife effects. *Environmental Management* 56:300-331.

Scott, T. M., S. S. Sadove. 1997. Sperm whale, *Physeter macrocephalus*, sightings in the shallow shelf waters off Long Island, New York. *Marine Mammal Science* 13:317-321.

Sertlek, H. O. 2021. Hindcasting soundscapes before and during the COVID-19 pandemic in selected areas of the North Sea and the Adriatic Sea. *Journal of Marine Science and Engineering* 9:702.

Shannon, G., M. F. McKenna, L. M. Angeloni, K. R. Crooks, K. M. Fristrup, E. Brown, K. A. Warner, M. D. Nelson, C. White, J. Briggs, S. McFarland, G. Wittemyer. 2016. A synthesis of two decades of research documenting the effects of noise on wildlife. *Biological Reviews* 91:982-1005.

Siderius, M., M. B. Porter. 2008. Modeling broadband ocean acoustic transmissions with time-varying sea surfaces. *Journal of the Acoustical Society of America* 124:137-150.

Širović, A., J. A. Hildebrand, S. M. Wiggins. 2007. Blue and fin whale call source levels and propagation range in the Southern Ocean. *Journal of the Acoustical Society of America* 122:1208-1215.

Smith, J. N., N. Kelly, S. Childerhouse, J. V. Redfern, T. J. Moore, D. Peel. 2020. Quantifying ship strike risk to breeding whales in a multiple-use marine park: The Great Barrier Reef. *Frontiers in Marine Science* 7:00067.

Snyder, M. A., P. A. Orlin. 2007. Ambient noise classification in the Gulf of Mexico. *IEEE OCEANS 2007*:1-10.

Soldevilla, M. S., A. N. Rice, C. W. Clark, L. P. Garrison. 2014. Passive acoustic monitoring on the North Atlantic right whale calving grounds. *Endangered Species Research* 25:115-140.

Spaulding, E., M. Robbins, T. Calupca, C. W. Clark, C. Tremblay, A. Waack, A. Warde, J. Kemp, K. Newhall. 2010. An autonomous, near-real-time buoy system for automatic detection of North Atlantic right whale calls. *Proceedings of Meetings on Acoustics* 6:010001-22.

Stanistreet, J. E., D. P. Nowacek, J. T. Bell, D. M. Cholewiak, J. A. Hildebrand, L. E. W. Hodge, S. M. Van Parijs, A. J. Read. 2018. Spatial and seasonal patterns in acoustic detections of sperm whales *Physeter macrocephalus* along the continental slope in the western North Atlantic Ocean. *Endangered Species Research* 35:1-13.

Stone, K. M., S. M. Leiter, R. D. Kenney, B. C. Wikgren, J. L. Thompson, J. K. D. Taylor, S. D. Kraus. 2017. Distribution and abundance of cetaceans in a wind energy development area offshore of Massachusetts and Rhode Island. *Journal of Coastal Conservation* 21:527-543.

Taylor, S., T. R. Walker. 2017. North Atlantic right whales in danger. *Science* 358:730-731.

Teloni, V., J. P. Mark, M. J. Patrick, M. T. Peter. 2008. Shallow food for deep divers: dynamic foraging behavior of male sperm whales in a high latitude habitat. *Journal of Experimental Marine Biology and Ecology* 354:119-131.

Tetra Tech, Smultea Sciences. 2018. *Year 1 Annual Survey Report for New York Bight Whale Monitoring Aerial Surveys March 2017 – February 2018*. Technical report prepared by Tetra Tech, Inc. and LGL Ecological Research Associates, Inc. Prepared for New York State Department of Environmental Conservation, Division of Marine Resources, East Setauket, NY.

Tetra Tech, LGL. 2019. *Year 2 Annual Survey Report for New York Bight Whale Monitoring Aerial Surveys, March 2018 – February 2019*. Technical report prepared by Tetra Tech, Inc. and LGL Ecological Research Associates, Inc. Prepared for New York State Department of Environmental Conservation, Division of Marine Resources, East Setauket, NY.

Tetra Tech, LGL. 2020. *Final Comprehensive Report for New York Bight Whale Monitoring Aerial Surveys, March 2017 – February 2020.* . Technical report prepared by Tetra Tech, Inc. and LGL Ecological Research Associates, Inc. Prepared for New York State Department of Environmental Conservation, Division of Marine Resources, East Setauket, NY.

Thomas, L., S. T. Buckland, E. A. Rexstad, J. L. Laake, S. Strindberg, S. L. Hedley, J. R. B. Bishop, T. A. Marques, K. P. Burnham. 2010. *Distance* software: design and analysis of distance sampling surveys for estimating population size. *Journal of Applied Ecology* 47:5-14.

Thompson, P. M., D. Lusseau, T. Barton, D. Simmons, J. Rusin, H. Bailey. 2010. Assessing the responses of coastal cetaceans to the construction of offshore wind turbines. *Marine Pollution Bulletin* 60:1200-1208.

Tougaard, J., P. T. Madsen, M. Wahlberg. 2007. Underwater noise from construction and operation of offshore wind farms. *Bioacoustics* 17:143-146.

Tremblay, C. J., S. M. V. Parijs, D. Cholewiak. 2019. 50 to 30-Hz triplet and singlet down sweep vocalizations produced by sei whales (*Balaenoptera borealis*) in the western North Atlantic Ocean. *Journal of the Acoustical Society of America* 145:3351-3358.

U.S. Army Corps of Engineers (USACE). 1994. *New York Bight Study: An Annotated Biblography of the New York Bight: Emphasis on Biological Studies*. Technical Report EL-94-11. U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, MS.

Urazghildiiev, I. R., C. W. Clark, T. P. Krein, S. E. Parks. 2009. Detection and recognition of North Atlantic right whale contact calls in the presence of ambient noise. *IEEE Journal of Oceanic Engineering* 34:358-368.

Urick, R. J. 1983. *Principles of Underwater Sound, 3rd edition*. Peninsula Publishing, Los Altos, CA.

Van Parijs, S. M., C. W. Clark, R. S. Sousa-Lima, S. E. Parks, S. Rankin, D. Risch, I. C. Van Opzeeland. 2009. Management and research applications of real-time and archival passive acoustic sensors over varying temporal and spatial scales. *Marine Ecology Progress Series* 395:21-36.

Vu, E. T., D. Risch, C. W. Clark, S. Gaylord, L. T. Hatch, M. A. Thompson, D. N. Wiley, S. M. Van Parijs. 2012. Humpback whale song occurs extensively on feeding grounds in the western North Atlantic Ocean. *Aquatic Biology* 14:175-183.

Ward-Geiger, L. I., G. K. Silber, R. D. Baumstark, T. L. Pulfer. 2005. Characterization of ship traffic in right whale critical habitat. *Coastal Management* 33:263 - 278.

Waring, G. T., E. Josephson, K. Maze-Foley, P. E. Rosel (eds) 2010. *U.S. Atlantic and Gulf of Mexico Marine Mammal Stock Assessments - 2010. NOAA Technical Memorandum NMFS-NE-219*. U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Silver Spring, MD.

Waring, G. T., E. Josephson, K. Maze-Foley, P. E. Rosel (eds) 2015. *U.S. Atlantic and Gulf of Mexico Marine Mammal Stock Assessments - 2014. NOAA Technical Memorandum NMFS-NE-231*. U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Silver Spring, MD.

Warren, V. E., A. Širović, C. McPherson, K. T. Goetz, C. A. Radford, R. Constantine. 2021. Passive acoustic monitoring reveals spatio-temporal distributions of Antarctic and pygmy blue whales around central New Zealand. *Frontiers in Marine Science* 7:575257.

Watkins, W. A., W. E. Schevill. 1977. Sperm whale codas. *Journal of the Acoustical Society of America* 62:1485-1490.

Watkins, W. A., P. Tyack, K. E. Moore, J. E. Bird. 1987. The 20-Hz signals of finback whales (*Balaenoptera physalus*). *Journal of the Acoustical Society of America* 82:1901-1912.

Watwood, S. L., P. J. O. Miller, M. Johnson, P. T. Madsen, P. L. Tyack. 2006. Deep-diving foraging behaviour of sperm whales (*Physeter macrocephalus*). *Journal of Animal Ecology* 75:814-825.

Weilgart, L. S. 2007. The impacts of anthropogenic ocean noise on cetaceans and implications for management. *Canadian Journal of Zoology* 85:1091-1116.

Weirathmueller, M. J., W. S. D. Wilcock, D. C. Soule. 2013. Source levels of fin whale 20 Hz pulses measured in the Northeast Pacific Ocean. *Journal of the Acoustical Society of America* 133:741-749.

Wenzel, F. W., D. K. Mattila, P. J. Clapham. 1988. *Balaenoptera musculus* in the Gulf of Maine. *Marine Mammal Science* 4:172-175.

Whitehead, H., L. Weilgart. 1991. Patterns of visually observable behaviour and vocalizations in groups of female sperm whales. *Behaviour*:275-296.

Whitt, A. D., K. Dudzinski, J. R. Laliberté. 2013. North Atlantic right whale distribution and seasonal occurrence in nearshore waters off New Jersey, USA, and implications for management. *Endangered Species Research* 20:59-69.

Wiggins, S. M., M. A. McDonald, L. M. Munger, S. E. Moore, J. A. Hildebrand. 2004. Waveguide propagation allows range estimates for North Pacific right whales in the Bering Sea. *Canadian Acoustics* 32:146-154.

Zampolli, M., M. J. J. Nijhof, C. A. F. de Jong, M. A. Ainslie, E. H. W. Jansen, B. A. J. Quesson. 2013. Validation of finite element computations for the quantitative prediction of underwater noise from impact pile driving. *Journal of the Acoustical Society of America* 133:72-81.

Zeh, J. M., M. L. Rekdahl, A. N. Rice, C. W. Clark, H. C. Rosenbaum. 2020. Detections of humpback whale (*Megaptera novaeangliae*) vocalizations on an acoustic sensor in the New York Bight. *Marine Mammal Science* 3:751-760.

Appendix A: Long Term Spectrograms and Noise Statistics per Site

Long-term spectrograms were generated to visually represent ambient noise variation in the time and frequency domain, where L_{eq} values were averaged within discrete 1-hour time bins. Spectrograms were generated with both linear (Figure 67, Figure 68) and 1/3 octave (Figure 69, Figure 70) frequency scales. Since 1/3 octave bandwidths approximates the frequency sensitivity of the mammalian ear (Southall et al. 2007), frequency bandwidths based on 1/3rd octaves were selected to represent the frequency band in which each whale species hearing is potentially most sensitive or the band in which their signals are produced (Table 11). The spectrograms in Figure 67 - Figure 70 illustrate noise levels across time and frequency, where higher noise levels are registered in red and lower noise levels register in blue. In addition of biological sound, long-term spectrograms can depict environmental acoustic events (e.g., wave action from storms and tidal sounds) and anthropogenic sounds (e.g., from vessels, underwater construction, seismic airgun explosions, etc.). In Figure 67 and Figure 68, there is a noticeable decrease in noise across sites from June through August in 2018 and in 2019, showing seasonal noise trends which are likely related to lower wind speed in NY Bight during the summer months (e.g., Piggott 1964, Snyder and Orlin 2007, Reeder et al. 2011). Noise at sites 8A (Figure 68) is noticeable higher than other sites, represented by the yellow and red coloration in the lower frequencies, which is attributed to vessel noise at the convergence of the shipping lanes near NY Harbor.

Discrete ship noise events are visible in 1/3 octave spectrograms (Figure 69, Figure 70), particularly at site 8A, represented by the red coloration (higher dB value) in the spectrogram between 300 and 600 Hz. Fin whale 20-Hz pulses are clearly visible in the 1/3 octave spectrograms for sites 1M – 5M (Figure 69) and 10M, 11A, 12M, 13A, and 14M (Figure 70), marked by the red coloration in the spectrograms.

Power spectral density (PSD) plots (Figure 71) of L_{eq} values were used to compare the dominant frequencies of each recording site. The PSD plot captures variation of sound pressure levels across the frequency domain of long-term ambient noise data (Wenz 1972) by representing the sound pressure level (dB re: $1\mu Pa^2/Hz$) as a function of frequency in the signal (Merchant et al. 2013). Here, data from the full 3-year survey (October 2017 – October 2020) and each site location are represented using the 5th, 50th, and 95th noise percentiles. Note that the peak in Leq around 20 Hz at all sites, except site 8A, represents sound from fin whale 20-Hz pulses, which shows to be a dominant signal around 20 Hz in NY Bight. At all sites, noise levels below 500 Hz are elevated compared to the rest of the frequencies, which reflects vessel noise.

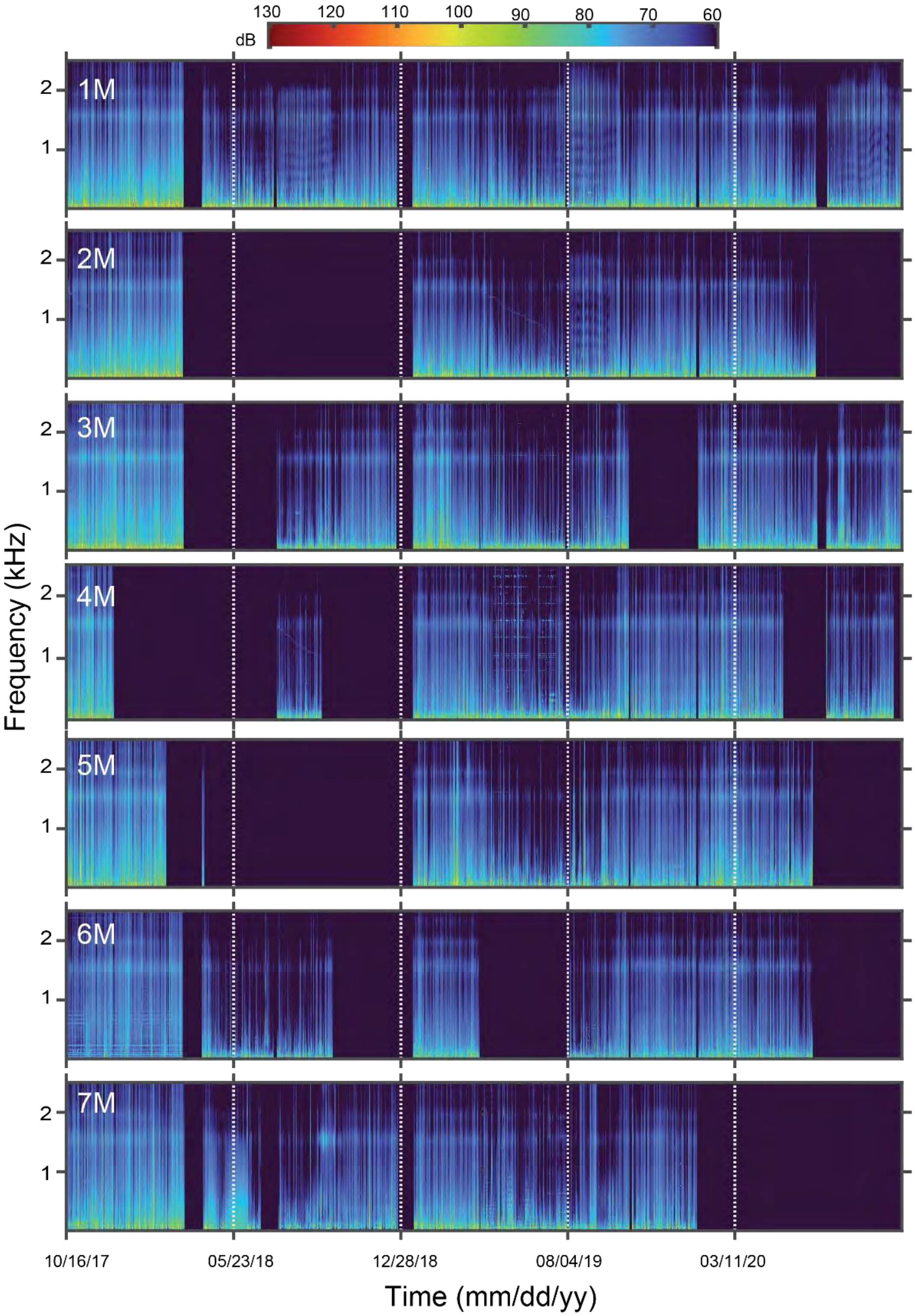


Figure 67. 1-hour averaged spectrogram for sites 1M – 7M between October 2017-October 2020. The colormap reflects noise levels (dB re: 1μPa). The deep blue gaps indicate time periods in which there are no sound data. The colormap reflects noise levels (dB re: 1μPa) where red represents higher dB levels and blue represents lower dB levels.

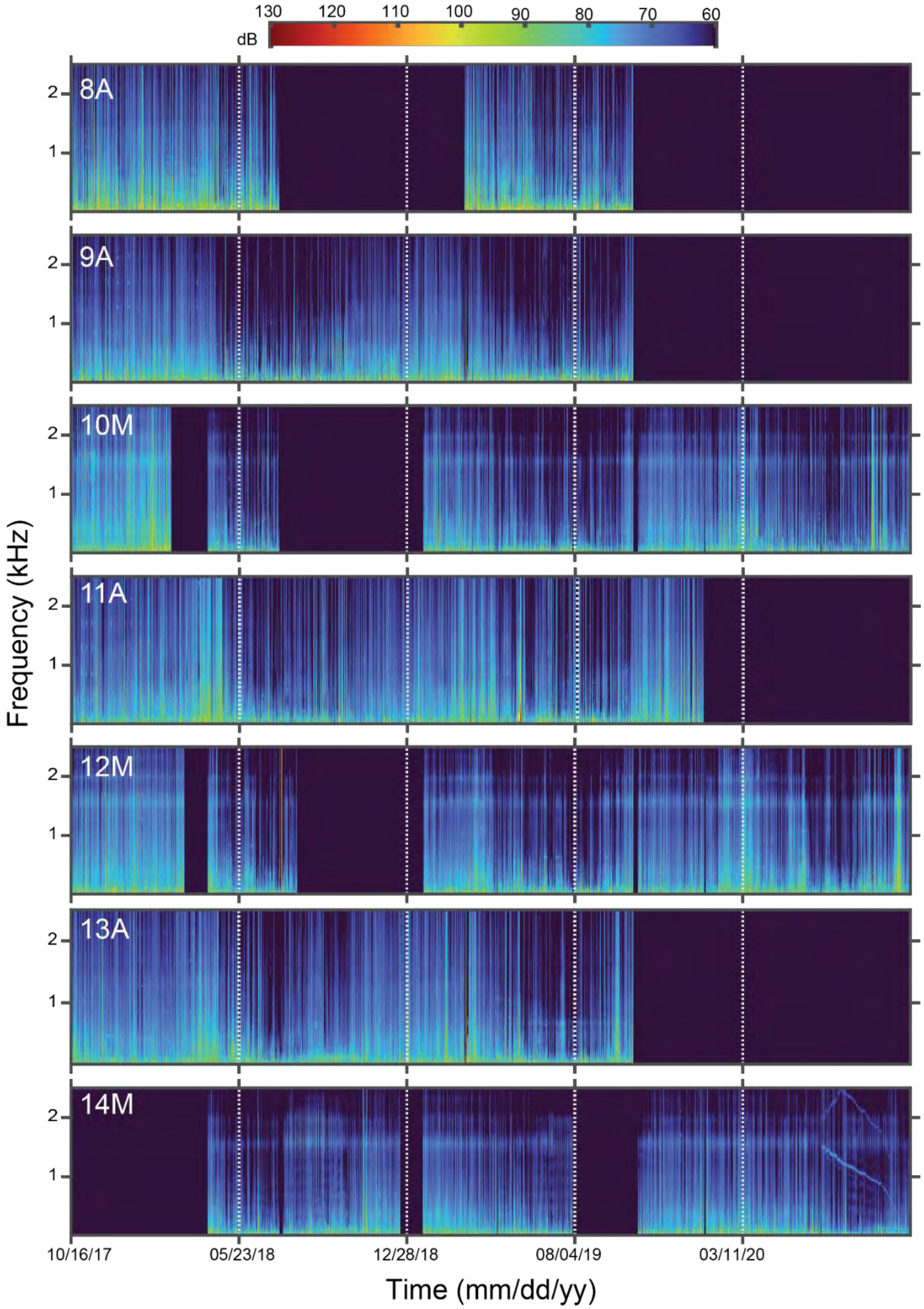


Figure 68. 1-hour averaged spectrogram for sites 8A – 14M between October 2017-October 2020. The colormap reflects noise levels (dB re: 1μPa). The deep blue gaps indicate time periods in which there are no sound data. The colormap reflects noise levels (dB re: 1μPa) where red represents higher dB levels and blue represents lower dB levels.

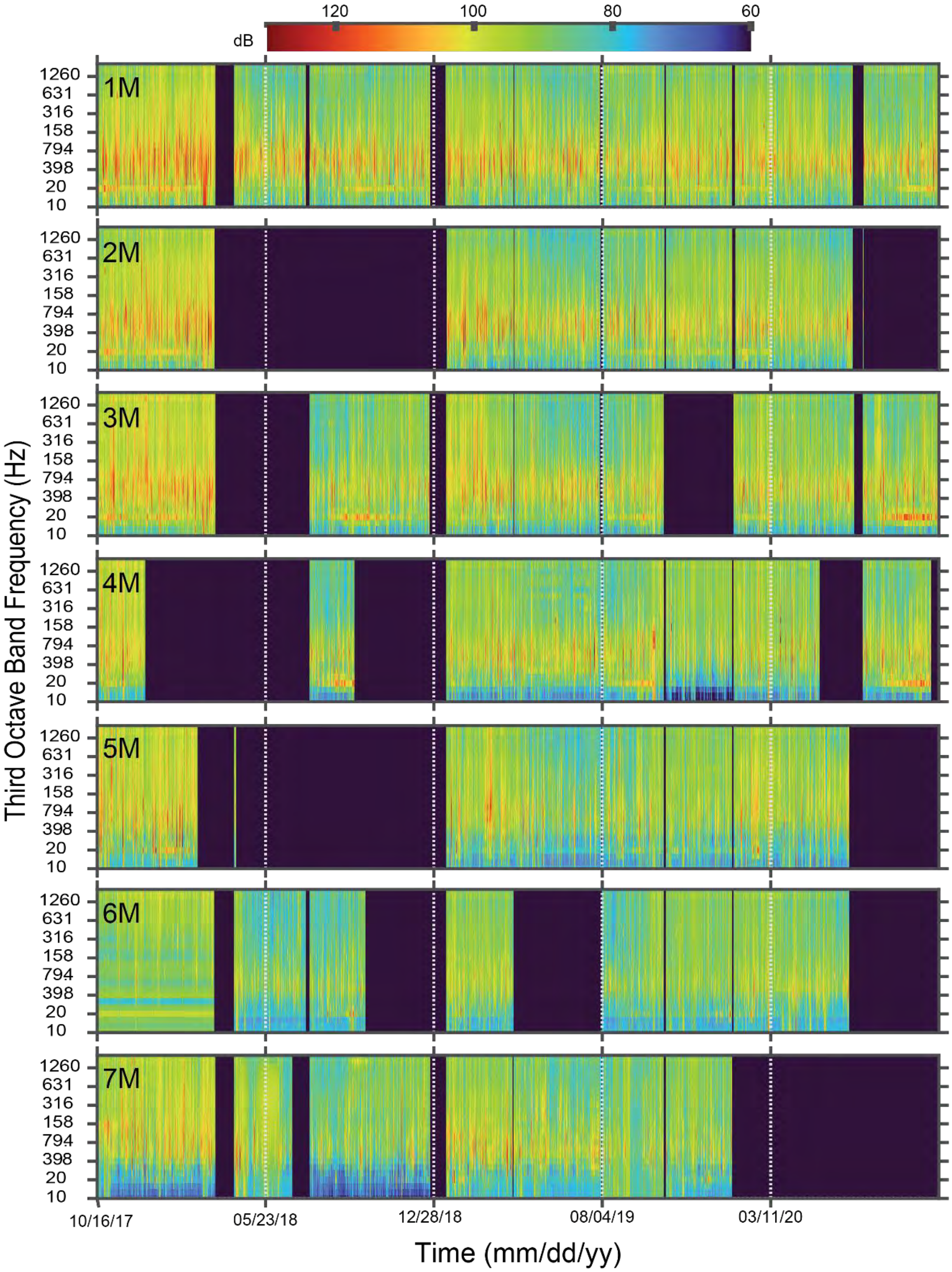


Figure 69. 1-hour averaged spectrogram for sites 1M – 7M between October 2017-October 2020.Each spectrogram has a 1/3 Octave frequency scale. The colormap reflects noise levels (dB re: 1μPa) where red represents higher dB levels and blue represents lower dB levels. The deep blue gaps indicate time periods in which there are no sound data.

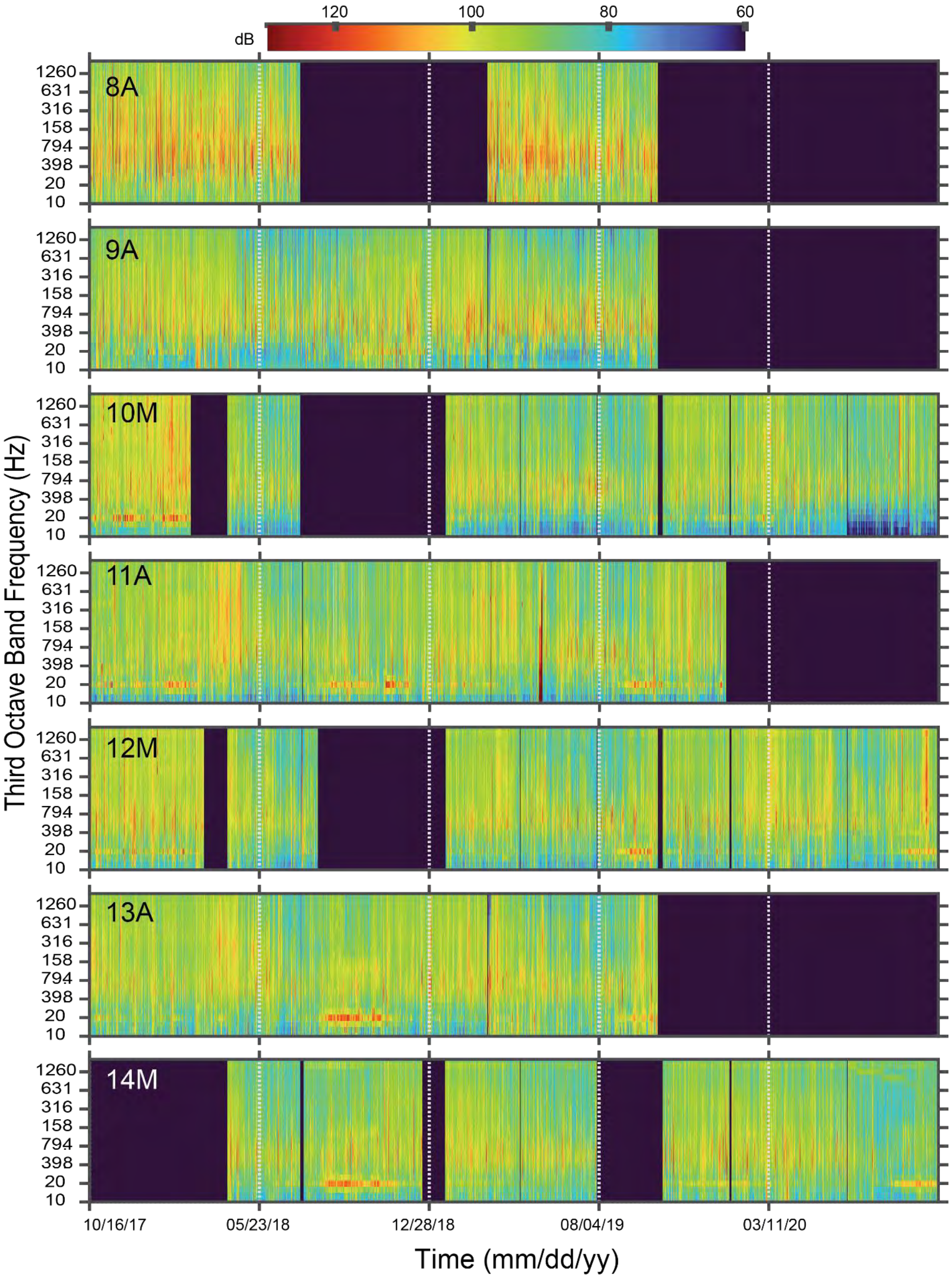


Figure 70. 1-hour averaged spectrogram for sites 8A – 14M between October 2017-October 2020. Each spectrogram has a 1/3 Octave frequency scale. The colormap reflects noise levels (dB re: 1μPa) where red represents higher dB levels and blue represents lower dB levels. The

deep blue gaps indicate time periods in which there are no sound data.

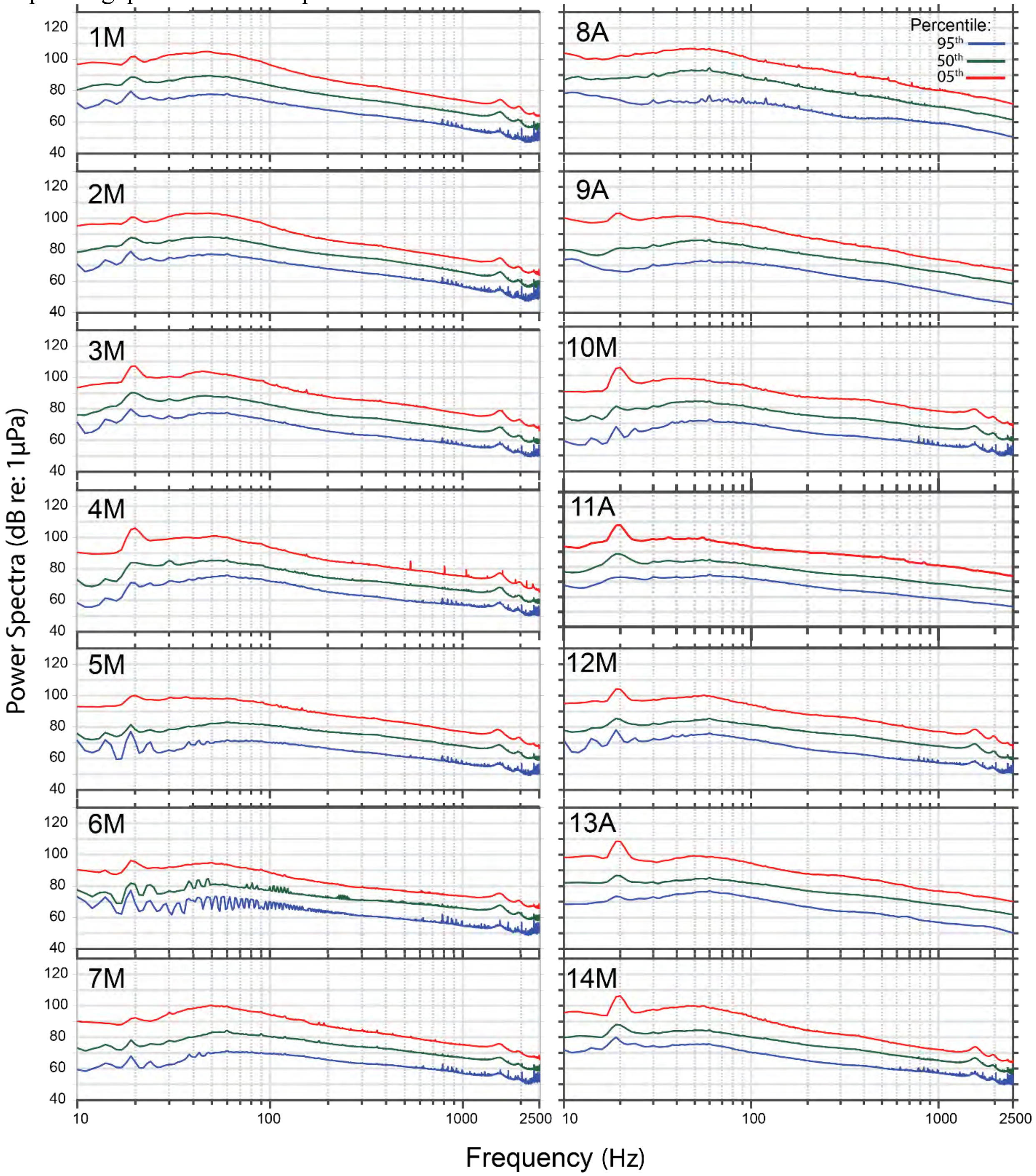


Figure 71. Power spectral density plots for each site between October 2017-October 2020, with percentile (5th, 50th, 95th) noise levels (dB re: 1μPa) across a logarithmic frequency scale for the full frequency band. The peak around 20 Hz at most sites represents sound contribution of fin whale song, and the higher noise levels below 100 Hz across all frequency bands likely reflect ship noise.

Appendix B: Detector Performance Evaluation

Below are detector performance summaries of the 10th-day ground-truth dataset for the right whale detector (Table 31, Table 32, Figure 72, Figure 73), and the 20th-day ground-truth subset for the fin (Table 33, Figure 74) and sei whale (Table 34, Table 35, Figure 75, Figure 76) detectors. These ground-truth datasets comprise manually detected target signals from every 10th day for right whales and on every 20th day for sei whales and fin whales, which began on 24 October, 2017 and ended on 11 October, 2020 (see section on Evaluation of Whale Call Automated Detector Performance for more details). For the right whale and sei whale detectors, we present data tables that summarize detector performance on a signal-to-detection basis and a daily scale. For fin whales, we present detector performance on a signal-to-detection basis, and do not include daily scale results in the table due to sampling method (see section on Evaluation of Whale Call Automated Detector Performance for more details).

Table 31. Performance of the right whale upcall detector for the 10th-day ground-truth dataset. Score Threshold is the sensitivity level of the algorithm, TPR is the true positive rate, FDR is false discovery rate, FP/hr represents the number of false positives (FP) per hour, TP Truth (true positive) represents the number of true upcalls the detector found, FN Truth (false negative) represents the number of upcalls the detector missed, Total Truth represents the number of upcalls in the ground-truth data, TP Test represents the number of detector events that found a true upcall (may contain more than one detection event per true call), FP Test represents the number of false positive detections, and Total Test represents the total number of detection events.

Score Threshold	TPR	FDR	FP/hr	TP Truth	FN Truth	Total Truth	TP Test	FP Test	Total Test
0.2	0.67	0.99	16.81	491	244	735	587	68995	69582
0.25	0.65	0.99	11.25	478	257	735	573	46187	46760
0.3	0.64	0.98	7.93	467	268	735	560	32524	33084
0.35	0.61	0.98	5.77	451	284	735	540	23694	24234
0.4	0.60	0.97	4.3	440	295	735	525	17655	18180
0.45	0.58	0.96	3.27	423	312	735	506	13439	13945
0.5	0.55	0.96	2.52	404	331	735	486	10324	10810
0.55	0.53	0.94	1.97	391	344	735	471	8090	8561
0.6	0.50	0.93	1.53	369	366	735	445	6260	6705
0.65	0.48	0.92	1.19	355	380	735	431	4878	5309
0.7	0.47	0.90	0.92	342	393	735	416	3788	4204
0.75	0.43	0.88	0.71	319	416	735	390	2924	3314
0.8	0.40	0.86	0.54	296	439	735	364	2206	2570
0.85	0.36	0.83	0.39	265	470	735	326	1587	1913
0.9	0.29	0.79	0.25	216	519	735	267	1031	1298
0.95	0.19	0.73	0.12	138	597	735	182	485	667

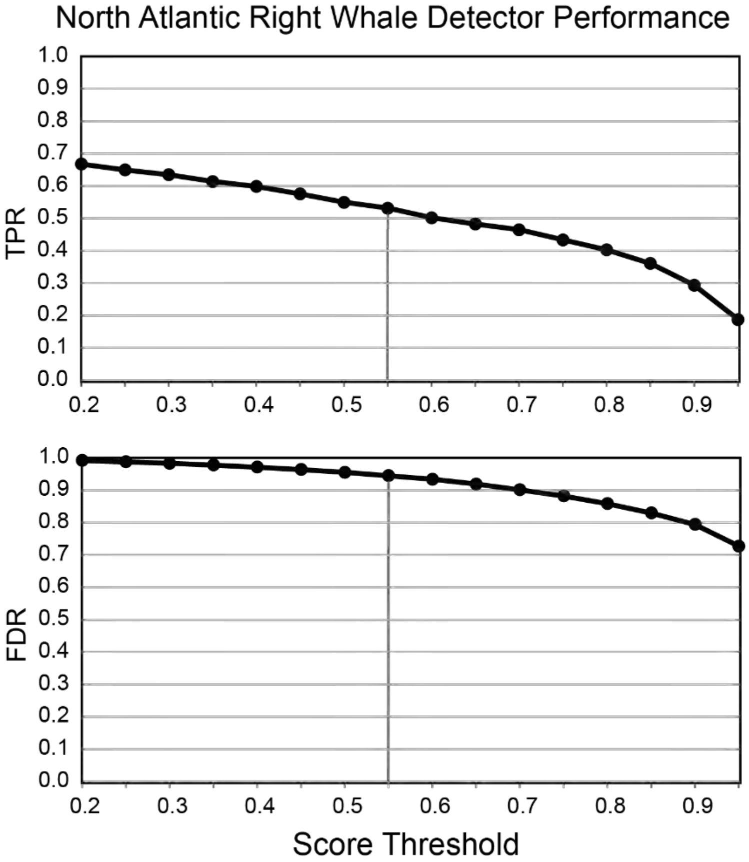


Figure 72. True positive rate (TPR) and false detection rate (FDR) of the right whale upcall detector by detector score threshold for the 10th-day ground-truth dataset. These plots reflect performance on a signal-to-event basis. The vertical grey line denotes the score threshold (0.55) that was used for detector during the 3-year survey.

Table 32. Summary of the right whale automated detector algorithm daily performance evaluation for the 10th-day ground-truth dataset. Score Threshold is the sensitivity level of the algorithm, Total True Days represents days with upcalls, Total Days with Detections represents days that had automated detections, Total TP Days are days with true positives (TP), Total FP Days are days with false positives (FP) and no TPs, true positive rate (TPR), and false discovery rate (FDR).

Score Threshold	Total True Days	Total Days with Detections	Total TP Days	Total FN Days	Total FP Days	TPR	FDR
0.2	29	169	23	6	140	0.79	0.83
0.22	29	169	23	6	140	0.79	0.83
0.24	29	169	23	6	140	0.79	0.83
0.26	29	169	23	6	140	0.79	0.83
0.28	29	169	23	6	140	0.79	0.83
0.3	29	169	23	6	140	0.79	0.83
0.32	29	169	23	6	140	0.79	0.83
0.34	29	169	23	6	140	0.79	0.83
0.36	29	169	23	6	140	0.79	0.83
0.38	29	169	23	6	140	0.79	0.83
0.4	29	169	23	6	140	0.79	0.83
0.42	29	169	23	6	140	0.79	0.83
0.44	29	169	22	7	140	0.76	0.83
0.46	29	169	21	8	140	0.72	0.83
0.48	29	169	21	8	140	0.72	0.83
0.5	29	169	20	9	140	0.69	0.83
0.52	29	169	20	9	140	0.69	0.83
0.54	29	169	20	9	140	0.69	0.83
0.56	29	169	20	9	140	0.69	0.83
0.58	29	169	20	9	140	0.69	0.83
0.6	29	169	20	9	140	0.69	0.83
0.62	29	169	20	9	140	0.69	0.83
0.64	29	167	20	9	138	0.69	0.83
0.66	29	167	20	9	138	0.69	0.83
0.68	29	162	20	9	133	0.69	0.82
0.7	29	157	20	9	128	0.69	0.82
0.72	29	150	19	10	121	0.66	0.81
0.74	29	142	19	10	113	0.66	0.80
0.76	29	133	19	10	104	0.66	0.78
0.78	29	129	19	10	100	0.66	0.78
0.8	29	121	19	10	92	0.66	0.76
0.82	29	112	19	10	83	0.66	0.74
0.84	29	105	19	10	76	0.66	0.72

0.86	29	98	18	11	69	0.62	0.70
0.88	29	87	18	11	58	0.62	0.67
0.9	29	71	18	11	42	0.62	0.59

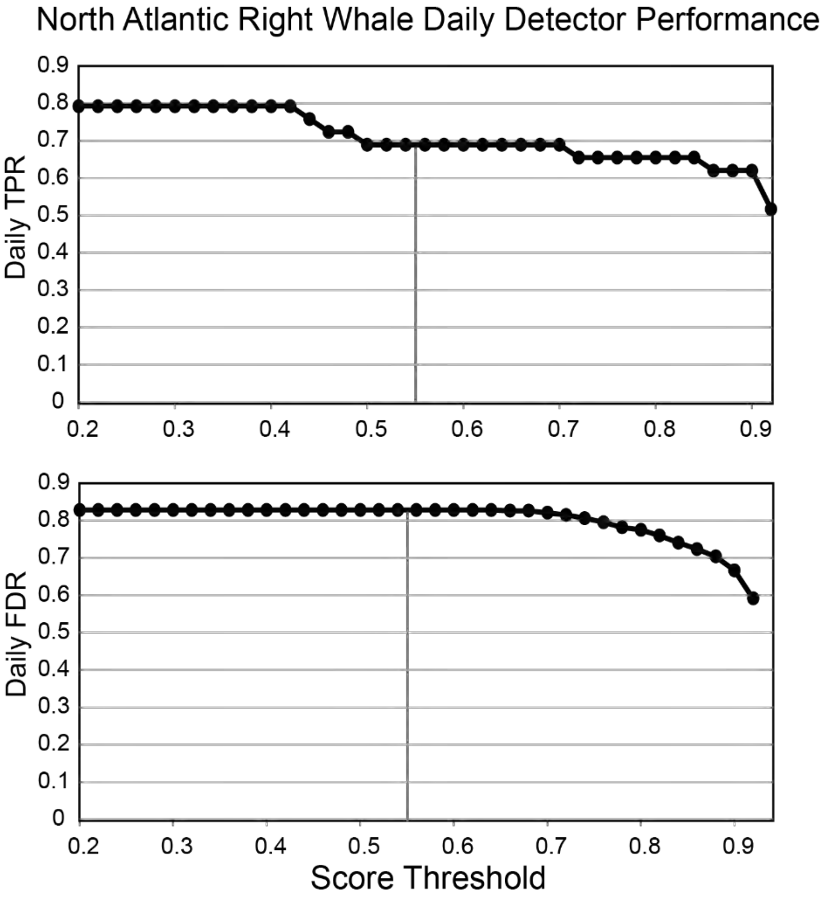


Figure 73. Daily true positive rate (TPR) and false detection rate (FDR) of the right whale upcall detector by detector score threshold for the 10th-day ground-truth dataset. The vertical grey line denotes the score threshold (0.55) that was used for detector during the 3-year survey.

Table 33. Performance of the fin whale 20-Hz pulse detector for the 20th-day ground-truth dataset. Score Threshold is the sensitivity level of the algorithm, TPR is the true positive rate, FDR is false discovery rate, FP/hr represents the number of false positives (FP) per hour, TP Truth (true positive) represents the number of true upcalls the detector found, FN Truth (false negative) represents the number of upcalls the detector missed, Total Truth represents the number of upcalls in the ground-truth data, TP Test represents the number of detector events that found a true upcall (may contain more than one detection event per true call), FP Test represents the number of false positive detections, and Total Test represents the total number of detection events.

Score Threshold	TPR	FDR	FP/hr	TP Truth	FN Truth	Total Truth	TP Test	FP Test	Total Test
0.25	0.99	0.98	253.75	442	6	448	13944	695611	709555
0.3	0.99	0.98	224.62	442	6	448	13583	615776	629359
0.35	0.98	0.98	196.26	441	7	448	13109	538027	551136
0.4	0.98	0.97	165.68	437	11	448	12520	454199	466719
0.45	0.97	0.97	139.9	433	15	448	11831	383523	395354
0.5	0.95	0.97	120.7	424	24	448	11190	330869	342059
0.55	0.94	0.97	107.53	419	29	448	10601	294786	305387
0.6	0.93	0.96	97.17	415	33	448	10001	266376	276377
0.65	0.91	0.96	87.52	407	41	448	9332	239917	249249
0.7	0.87	0.96	78.58	390	58	448	8549	215414	223963
0.75	0.81	0.96	69.67	363	85	448	7585	191002	198587
0.8	0.74	0.96	57.91	331	117	448	6451	158745	165196
0.85	0.63	0.96	38.73	281	167	448	4688	106186	110874
0.9	0.39	0.94	8.54	175	273	448	1374	23401	24775
0.95	0.00	NaN	0	0	448	448	0	0	0

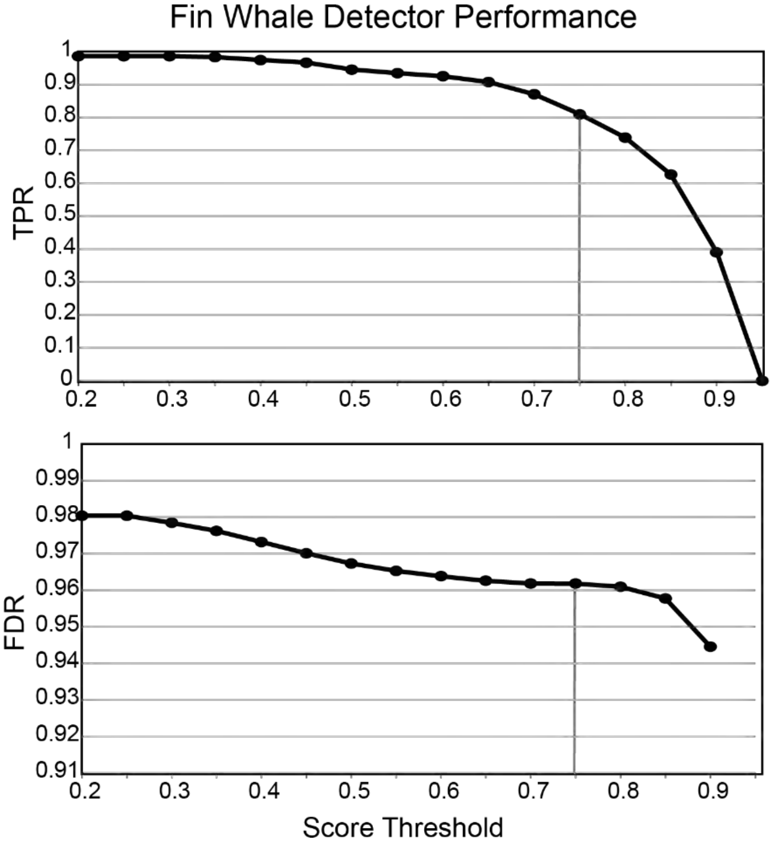


Figure 74. True positive rate (TPR) and false detection rate (FDR) of the fin whale 20-Hz pulse detector by detector score threshold for the 20th-day ground-truth dataset. The vertical grey line denotes the score threshold (0.75) that was used for detector during the 3-year survey.

Table 34. Performance of the sei whale downsweep template detector for the 20th-day ground-truth dataset. Score Threshold is the sensitivity level of the algorithm, TPR is the true positive rate, FDR is false discovery rate, FP/hr represents the number of false positives (FP) per hour, TP (true positive) Truth represents the number of true upcalls the detector found, FN (false negative) Truth represents the number of upcalls the detector missed, Total Truth represents the number of upcalls in the ground-truth data that were validated through human review, TP Test represents the number of detector events that found a true upcall (may contain more than one detection event per true call), FP Test represents the number of false positive detections, and Total Test represents the total number of detection events.

Score Threshold	**TPR**	**FDR**	**FP/hr**	**TP Truth**	**FN Truth**	**Total Truth**	**TP Test**	**FP Test**	**Total Test**
0.2	0.97	1.00	674.76	1635	45	1680	1869	1877606	1879475
0.22	0.97	1.00	656.7	1623	57	1680	1854	1827371	1829225
0.24	0.96	1.00	634.23	1611	69	1680	1836	1764822	1766658
0.26	0.95	1.00	606.9	1599	81	1680	1816	1688796	1690612
0.28	0.94	1.00	574.26	1579	101	1680	1794	1597948	1599742
0.3	0.92	1.00	535.97	1549	131	1680	1760	1491405	1493165
0.32	0.91	1.00	487.35	1521	159	1680	1725	1356127	1357852
0.34	0.88	1.00	434.35	1485	195	1680	1677	1208636	1210313
0.36	0.86	1.00	378.15	1446	234	1680	1634	1052267	1053901
0.38	0.85	1.00	320.73	1421	259	1680	1602	892485	894087
0.4	0.81	1.00	263.65	1368	312	1680	1540	733631	735171
0.42	0.79	1.00	209.83	1320	360	1680	1481	583877	585358
0.44	0.76	1.00	161.74	1271	409	1680	1427	450062	451489
0.46	0.72	1.00	121.4	1217	463	1680	1368	337800	339168
0.48	0.69	0.99	89.98	1161	519	1680	1306	250391	251697
0.5	0.66	0.99	67.02	1108	572	1680	1249	186480	187729
0.52	0.63	0.99	50.61	1052	628	1680	1194	140818	142012
0.54	0.59	0.99	38.97	993	687	1680	1128	108450	109578
0.56	0.56	0.99	30.23	935	745	1680	1063	84127	85190
0.58	0.52	0.98	22.2	873	807	1680	994	61772	62766
0.6	0.48	0.98	13.02	812	868	1680	920	36231	37151
0.62	0.45	0.95	5.51	751	929	1680	853	15333	16186
0.64	0.41	0.90	2.63	685	995	1680	778	7322	8100
0.66	0.38	0.84	1.39	630	1050	1680	713	3870	4583
0.68	0.33	0.77	0.76	558	1122	1680	635	2119	2754
0.7	0.29	0.67	0.4	490	1190	1680	556	1124	1680
0.72	0.25	0.52	0.19	426	1254	1680	486	534	1020
0.74	0.21	0.34	0.08	352	1328	1680	400	210	610
0.76	0.18	0.20	0.03	295	1385	1680	332	83	415
0.78	0.14	0.12	0.01	234	1446	1680	254	34	288
0.8	0.09	0.09	0.01	145	1535	1680	157	16	173

0.82	0.05	0.07	0	75	1605	1680	80	6	86
0.84	0.02	0.06	0	29	1651	1680	32	2	34
0.86	0.00	0.17	0	5	1675	1680	5	1	6
0.88	0.00	NAN	0	0	1680	1680	0	0	0

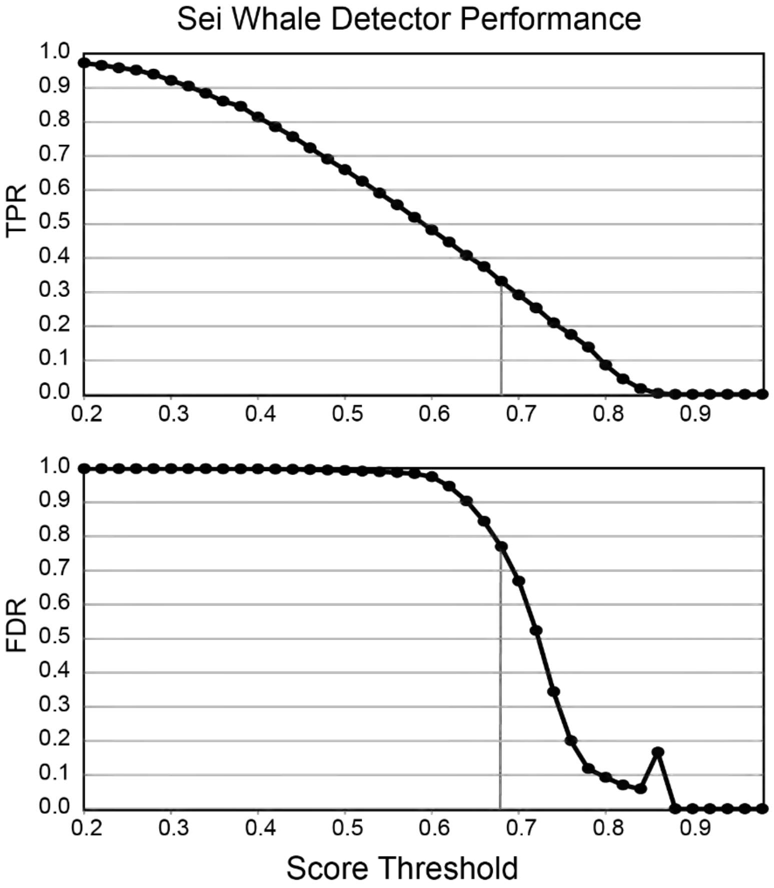


Figure 75. True positive rate (TPR) and false detection rate (FDR) of the sei whale downsweep detector by detector score threshold for the 20th-day ground-truth dataset. The vertical grey line denotes the score threshold (0.68) that was used for detector during the 3-year survey.

Table 35. Summary of the sei whale automated detector algorithm daily performance evaluation for the 20th-day ground-truth dataset. Score Threshold is the sensitivity level of the algorithm, Total True Days represents days with sei whale downsweeps, Total Days with Detections represents days that had automated detections, Total TP Days are days with true positives (TP), Total FP Days are days with false positives (FP) and no TPs, true positive rate (TPR), and false discovery rate (FDR).

Score Threshold	Total True Days	Total Days with Detections	Total TP Days	Total FN Days	Total FP Days	TPR	FDR
0.2	19	116	19	0	97	1.00	0.84
0.22	19	116	19	0	97	1.00	0.84
0.24	19	116	19	0	97	1.00	0.84
0.26	19	116	19	0	97	1.00	0.84
0.28	19	116	19	0	97	1.00	0.84
0.3	19	116	19	0	97	1.00	0.84
0.32	19	116	19	0	97	1.00	0.84
0.34	19	116	18	1	97	0.95	0.84
0.36	19	116	17	2	97	0.89	0.84
0.38	19	116	17	2	97	0.89	0.84
0.4	19	116	16	3	97	0.84	0.84
0.42	19	116	15	4	97	0.79	0.84
0.44	19	116	15	4	97	0.79	0.84
0.46	19	116	15	4	97	0.79	0.84
0.48	19	116	15	4	97	0.79	0.84
0.5	19	116	14	5	97	0.74	0.84
0.52	19	116	14	5	97	0.74	0.84
0.54	19	116	14	5	97	0.74	0.84
0.56	19	116	14	5	97	0.74	0.84
0.58	19	115	13	6	96	0.68	0.83
0.6	19	115	13	6	96	0.68	0.83
0.62	19	115	12	7	96	0.63	0.83
0.64	19	110	10	9	91	0.53	0.83
0.66	19	96	9	10	77	0.47	0.80
0.68	19	85	7	12	66	0.37	0.78
0.7	19	67	7	12	48	0.37	0.72
0.72	19	49	6	13	30	0.32	0.61
0.74	19	31	6	13	12	0.32	0.39
0.76	19	23	6	13	4	0.32	0.17
0.78	19	15	6	13	0	0.32	0.00
0.8	19	11	5	14	0	0.26	0.00
0.82	19	6	4	15	0	0.21	0.00
0.84	19	5	4	15	0	0.21	0.00

0.86	19	2	2	17	0	0.11	0.00
0.88	19	0	0	19	0	0.00	NA
0.9	19	0	0	19	0	0.00	NA

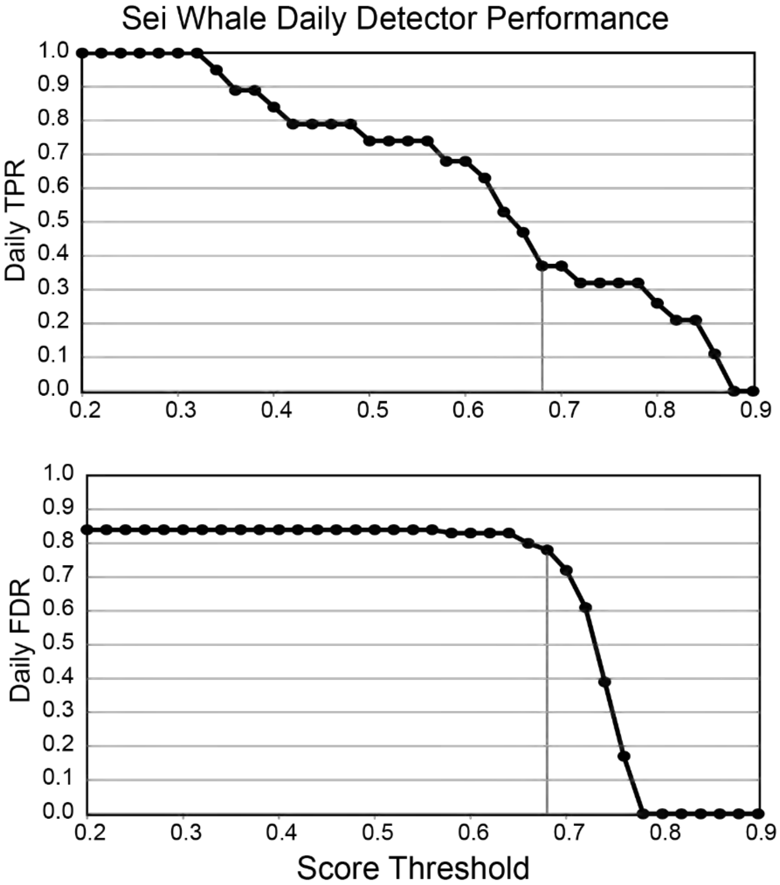


Figure 76. Daily true positive rate (TPR) and false detection rate (FDR) of the sei whale downsweep detector by detector score threshold for the 20th-day ground-truth dataset. The vertical grey line denotes the score threshold (0.68) that was used for detector during the 3-year survey.