Sounds from airguns and fin whales recorded in the mid-Atlantic Ocean, 1999–2009

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Between 1999 and 2009, autonomous hydrophones were deployed to monitor seismic activity from 16° N to 50° N along the Mid-Atlantic Ridge. These data were examined for airgun sounds produced during offshore surveys for oil and gas deposits, as well as the 20 Hz pulse sounds from fin whales, which may be masked by airgun noise. An automatic detection algorithm was used to identify airgun sound patterns, and fin whale calling levels were summarized via long-term spectral analysis. Both airgun and fin whale sounds were recorded at all sites. Fin whale calling rates were higher at sites north of 32° N, increased during the late summer and fall months at all sites, and peaked during the winter months, a time when airgun noise was often prevalent. Seismic survey vessels were acoustically located off the coasts of three major areas: Newfoundland, northeast Brazil, and Senegal and Mauritania in West Africa. In some cases, airgun sounds were recorded almost 4000 km from the survey vessel in areas that are likely occupied by fin whales, and at some locations airgun sounds were recorded more than 80% days/month for more than 12 consecutive months. © *2012 Acoustical Society of America*. [DOI: 10.1121/1.3672648]

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I. INTRODUCTION

Passive acoustic surveys have become an effective means of monitoring both the natural and anthropogenic contributions to ambient noise levels in the world's oceans. Autonomous and cabled hydrophones are now used widely to study the sounds generated by undersea earthquakes, ice noise, and marine animals. Research has also confirmed that low-frequency (<1000 Hz) human sources of noise pollution have dramatically increased over the last 50 years (Andrew *et al.*, 2002; McDonald *et al.*, 2008). The primary sources of low-frequency anthropogenic noise are the sounds associated with shipping, military and research activities, and oil and gas exploration and development (Richardson *et al.*, 1995; Croll *et al.*, 2001; Hildebrand, 2009). Of growing concern is the effect these increasing levels of low-frequency noise have on protected species, such as baleen whales that are acoustically sensitive and use low-frequency sound for communication and possibly navigation or prey-finding (Richardson *et al.*, 1995; Clark *et al.*, 2009). In particular, the sounds from airgun surveys have been the focus of several recent marine mammal investigations (e.g., Di Iorio and Clark, 2010; Madsen *et al.*, 2006; Weir, 2008a,b), and the potential and observed effects have been reviewed [e.g., National Research Council (NRC), 2003, 2005; Gordon *et al.*, 2004; Bradley and Stern, 2008]. To assess the potential effects of airgun sounds on whales, the temporal and geographical occurrence of this sound and the distribution of species that are potentially impacted must be described.

In 1999, a consortium of U.S. investigators deployed an array of autonomous hydrophones (Fox *et al.*, 2001) to monitor seismic activity along the Mid-Atlantic Ridge (Smith *et al.*, 2002; Dziak *et al.*, 2004). Although this experiment was designed to monitor the low-frequency signals of earthquakes, the instruments were also capable of recording the low-frequency calls of several species of baleen whales, as well as anthropogenic sounds such as ship noise and seismic airgun pulses. These instruments were located within potential migratory routes for fin (*Balaenoptera physalus*) and blue (*B. musculus*) whales and were in a remote region that rarely if ever is included in marine mammal surveys (Mellinger and Barlow, 2003).

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In a previous study, Nieukirk *et al.* (2004) found that sounds from both airguns and baleen whales were recorded at these mid-ocean sites. Here we update our previous work, expand our study area, and characterize the seasonal and interannual variability in airgun sounds in what is now a ten-year acoustic dataset collected from waters near the Mid-Atlantic Ridge. To address potential masking of marine mammal sounds, we also examined the acoustic record for the 20 Hz pulse calls of fin whales (Watkins *et al.*, 1987). We chose this species because fin whale vocalizations are typically plentiful in acoustic records from the Atlantic (Watkins *et al.*, 1987; Clark and Gagnon, 2002; Nieukirk *et al.*, 2004), and because fin whale 20 Hz vocalizations are short pulsive calls that have the potential to be masked by airgun sounds.

II. BACKGROUND

A. Airgun sounds

Marine seismic surveys are a major source of anthropogenic sound in many of the world's oceans (Hildebrand, 2009). Seismic surveys are conducted primarily in the pursuit of oil and gas reserves (Caldwell and Dragoset, 2000), but research institutions also use this technology to explore the complex geology of the seafloor. Sounds generated by seismic airguns are low-frequency (2–188 Hz at the source), short-duration ($<$0.1 s), high amplitude (216–261 dB p-p re 1 μPa @ 1 m) pulses that are produced as pressurized air is suddenly released from the airgun cylinders into the water (Parkes and Hatton, 1986; Richardson *et al.*, 1995; Dragoset, 2000). The expansion of this released air and the following contraction and re-expansion of this air mass creates a loud seismic pulse that can be used to image the seafloor and the rock layers below. The resulting seismic pulse refracts and reflects off subsurface seafloor structures and is received by hydrophone streamers towed behind the survey vessel. Airguns are fired every 10–60 s for days or weeks at a time, with occasional interruptions for such actions as turning the ship that tows the airgun array. Although seismic airgun arrays are designed to direct the majority of emitted energy downward toward the seafloor, their sound emission horizontally is also significant (NRC, 2003; Madsen *et al.*, 2006).

B. Fin whale sounds

The sounds produced by the fin whale are among the best-studied marine mammal vocalizations (Thompson *et al.*, 1979; Watkins, 1981; Watkins *et al.*, 1987; Edds, 1988; Thompson *et al.*, 1992; Clark *et al.*, 2002; Hatch and Clark, 2004). Although fin whales produce numerous sounds, the highly stereotyped, short (0.5–1.0 s) downsweeping sound in the 18–25 Hz frequency band known as the "20 Hz pulse" is the most common (Watkins *et al.*, 1987; Hatch and Clark, 2004). Series of pulses occur in long, patterned, song-like sequences with regular interpulse spacing that changes with geographic location and possibly with time (Cummings *et al.*, 1986; Watkins *et al.*, 1987; Thompson *et al.*, 1992; Clark *et al.*, 2002; Hatch and Clark, 2004; Castellote *et al.*, 2011). Current evidence indicates that this is a male breeding display, as only males have been identified making these sounds (Croll *et al.*, 2002). Thus, acoustic surveys of fin whale patterned sequences are likely to detect only males, but we assume that such survey results are approximately representative of the relative numbers of all whales in an area. Fin whale calls are recorded year-round in coastal Atlantic waters, which has further reinforced the concept that a seasonal migration to warmer waters for calving or breeding is not as predictable as that observed for other baleen whales like the humpback whale (*Megaptera novaeangliae*). Because the North Atlantic fin whale population is thought to exceed 50 000 animals (Sigurjonsson, 1995) and fin whale calls are quite loud and are produced in long series (183 dB re 1 μPa at 1 m; Cummings and Thompson, 1994), these sounds are a significant contributor to ocean ambient sound, seasonally raising sound levels in some areas by as much as 25 dB (Curtis *et al.*, 1999).

III. METHODS

From 1999 to 2008, hydroacoustic records of Atlantic ocean-basin earthquakes were collected by an international consortium of geophysicists studying the Mid-Atlantic Ridge (Smith *et al.*, 2002; Dziak *et al.*, 2004; Simão *et al.*, 2010). The instruments used in these experiments, autonomous hydrophones designed for continuous deep-sea recording (Fox *et al.*, 2001), were developed by engineers from NOAA's Pacific Marine Environmental Laboratory (PMEL) and Oregon State University. Each mooring package consisted of an anchor, an acoustic release, a hydrophone and titanium pressure case containing a logging system, and a syntactic foam float designed to suspend the hydrophone in the Deep Sound Channel (a depth of ~900 m) to maximize acoustic coverage of the area. Arrays of these hydrophone moorings monitored sound continuously, recording the ambient acoustic signal to disk at a sampling rate of 110 Hz, 250 Hz or 500 Hz. This low sample rate was designed to efficiently monitor seismicity from earthquakes but was also adequate for monitoring low-frequency sounds from seismic airguns and some marine mammals, including fin whales. These instruments were moored along the east and west flanks of the Mid-Atlantic Ridge between 16° N and 50° N in three basic arrays (Fig. 1). The location of the hydrophone moorings changed somewhat each year depending on the section of the ridge that was monitored, but arrays were configured to straddle the ridge.

After the archived data were recovered, we used the bioacoustics software package *Ishmael* (Mellinger, 2001; see http://www.bioacoustics.us/Ishmael.html) to detect airgun sounds automatically. Airgun sounds are broadband, very repetitive pulsive sounds [Fig. 2(a)]; therefore, we used a combination of an energy sum detector (10–55 Hz) and a sequence detector (Mellinger *et al.*, 2004; autocorrelation window length = 200 s, hop size fraction = 0.25, period length = 9–25 s) to configure the automatic detection algorithm. Detections were then visually confirmed by an experienced analyst. Because seismic surveys are typically conducted over periods of weeks or months, we verified the number of days in a month with airgun sounds.

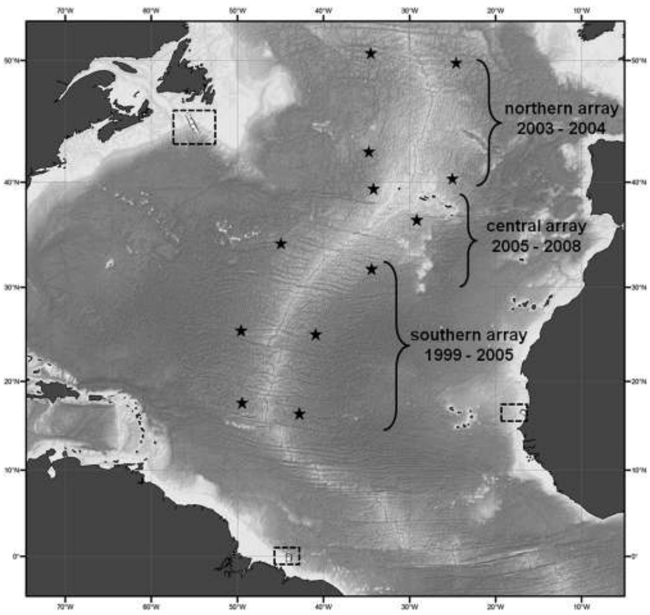

FIG. 1. Locations of 12 autonomous hydrophone moorings (stars) moored along the Mid-Atlantic Ridge, and approximate locations (dotted boxes with circles) of seismic airgun activity located via the array.

The high source level of airguns made it possible to simultaneously record the same series of airgun sounds at more than one site. To understand further the seasonal and spatial patterns (or lack thereof) of airgun signals, we acoustically located the sources of airguns. Locating airgun sound sources proved challenging because clear airgun signals were often blocked by the bathymetry or absent due to gaps in recording. Because of the large distances involved, and consequent distortion of airgun signals, locations derived acoustically from only three sites often had large errors, so we located airgun sound sources only when signals were received clearly at four or more sites. When the first or last airgun shot in a series was clear at four or more sites, we used a modified least-squares optimization method (Fox *et al.*, 2001) in IDL® (Interactive Data Language Research Systems, Boulder, Co.) to locate the approximate source of the airgun pulses. We also examined propagation of sounds from airgun source locations to our hydrophones using the acoustic propagation code RAM (Collins, 1993).

The acoustic record was also analyzed for fin whale calls. Because the low sampling rate of the recorders limited the available frequency band, we targeted the fin whale 20 Hz pulse [Fig. 2(b)]. We calculated long-term spectrograms and used methods similar to those developed by Curtis *et al.* (1999) and Širović *et al.* (2004) to derive an index of fin whale calling. This *fin index*, a numeric value gauging the daily average of normalized spectral energy over the vocalization band of this species, was derived by first calculating a log-scaled spectrogram $S(t,f)$ of the sound (spectrogram frame and FFT size = 1 s, overlap = 0.5 s,

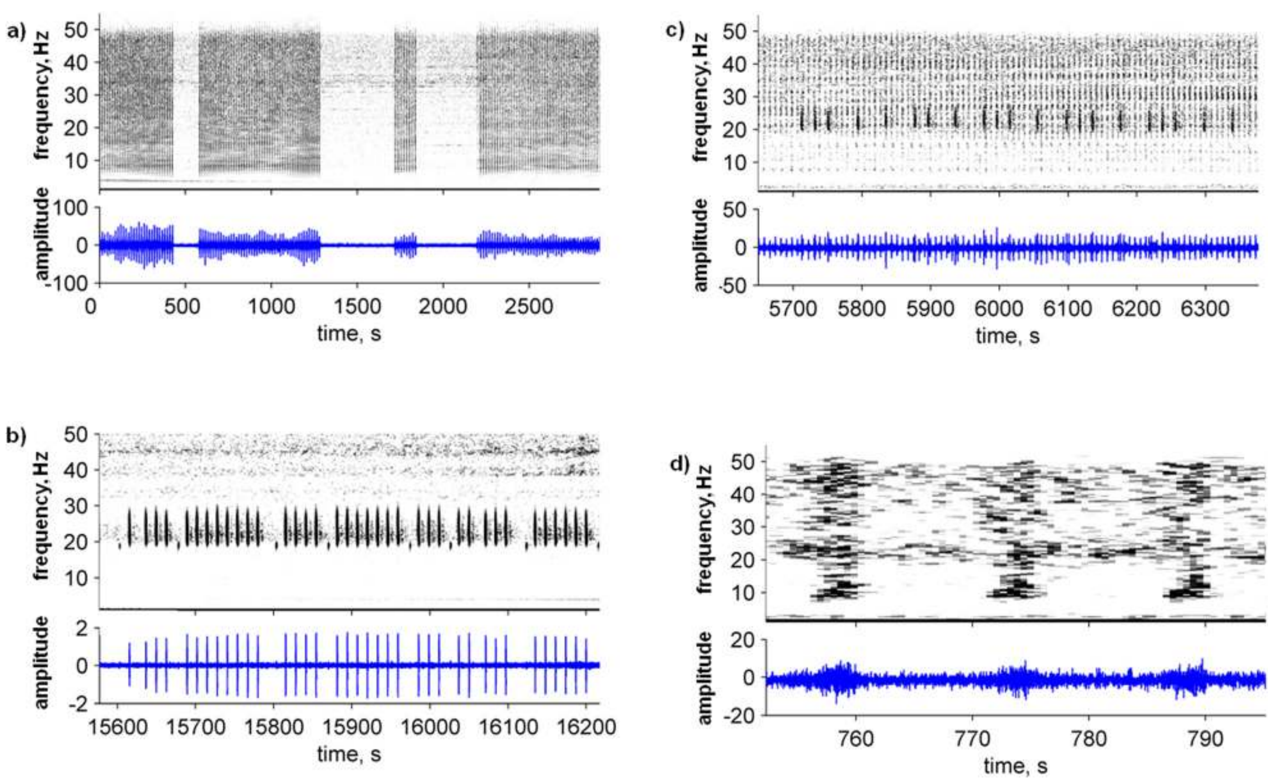

FIG. 2. (Color online) (a) Spectrogram and time of series of airgun pulses recorded 19 August 2002 on the 26° N 50° W hydrophone (spectrogram parameters: frame and FFT length 4.7 s (512 samples) overlap 0.75, Hamming window, for a filter bandwidth of 0.9 Hz). (b) Spectrogram and time series of fin whale 20 Hz pulses recorded 05 November 2005 on the 32° N 35° W hydrophone (spectrogram parameters: frame and FFT length 8.2 s (2048 samples) overlap 0.75, Hamming window for a filter bandwidth of 0.50 Hz). (c) Example of co-occurrence of airgun and fin whale sounds. In instances where the fin whale sounds were of lower amplitude than those in this figure, fin whale pulses would be obscured by airgun noise. (d) Example of airgun pulses (spectrogram parameters: frame and FFT length 2.3 s (256 samples) overlap 0.75, Hamming window, for a filter bandwidth of 1.8 Hz) recorded over 3900 km from the source. These sounds were recorded on the 32° N 35° W hydrophone; the survey vessel producing them was acoustically located in Brazilian waters.

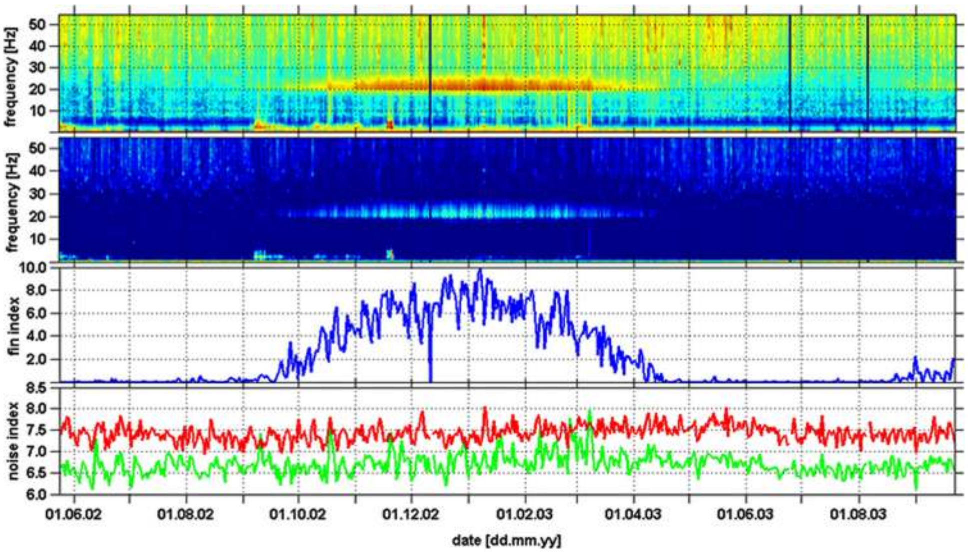

FIG. 3. (Color online) Example calculation of the fin index: (a) Log-scaled spectrogram $S(t,f)$ of the sound (spectrogram frame and FFT size = 1 s, overlap = 0.5 s, Hann window, for a filter bandwidth of 4.0 Hz) and then averaged over 1-day periods; (b) normalized spectrogram $\check{S}(t,f)$ (at each time step t, the noise floor $n_{50}(t)$ was subtracted from the spectrogram at that time step, with negative values converted to 0); (c) resulting fin index, or relative estimate of fin whale calling; (d) levels of sound in the adjacent frequency bands (upper: 40–45 Hz; lower: 8–13 Hz), used to ensure transient noise was not affecting the fin whale index.

Hann window, for a filter bandwidth of 4.0 Hz). The spectrogram was then averaged over 1-day periods (Fig. 3). Next, normalization was performed by finding, at each time step t, the noise floor $n_{50}(t)$: the median (50th-percentile) value in the spectrum at time t between the frequencies of 0 and 55 Hz. This was subtracted from the spectrogram at that time step, with negative values converted to 0, to produce the normalized spectrogram $\check{S}(t,f)$:

$$\hat{S}(t,f) = S(t,f) - n_{50}(t).$$

Finally, the fin index $I(t)$ was calculated at each time step t as the sum of the normalized spectrogram values between the frequencies of $f_0 = 19.0$ and $f_1 = 22.0$ Hz, a band designed to exclude sound from blue whales that are near in frequency:

$$I(t) = \sum_{f=f_0}^{f_1} \max(\hat{S}(t,f), 0).$$

This fin index ranged from 0 to approximately 12 and depicted a relative estimate of fin whale calling in the data. To ensure background noise was not confounding the index, we also plotted the levels of sound in the adjacent frequency bands and compared these to the index curve; if overall trends in the noise and fin index curves were similar the fin index was not used. Fin whale index numbers were then checked by an analyst who examined the raw spectrogram data, verified the presence of fin whale calls, and confirmed that the spectrogram-derived indices were indeed representative of the actual level of fin whale calls. Least squares linear regression was used to analyze seasonal and geographic trends in the data and results were considered significant at the $p = 0.05$ level. We were not able to locate individual vocalizing fin whales due to the wide spacing of the hydrophone moorings.

IV. RESULTS

During the ten years of this study, over 246 000 hours of acoustic data were collected and analyzed. Some deployments experienced hard drive failures, and in a few instances instruments and their data were not recovered because of malfunctioning acoustic releases or other failures of the mooring hardware. As mentioned, the hydrophone moorings were also deployed at different locations at different times throughout the study area. This resulted in incomplete (non-continuous) 10-year acoustic coverage at each mooring location, but the results were adequate for observing latitudinal and seasonal trends in airgun sounds and fin whale calling. In addition, the position of the moorings on either side of the ridge may have resulted in bathymetric blocking of some of the sounds of interest; we assume the results represent a minimum estimate of fin whale calling behavior and airgun use in the mid-Atlantic.

A. Airguns

Sounds from seismic surveys were recorded frequently at all sites and in all years of the study (Fig. 4). Recorded airgun sound levels fluctuated over time, but airguns were recorded during at least 9 months each year at every site. In many months, more than 80% of the days in the month contained sounds from airguns. During 2003 and 2005, the percentage of days in a month with airgun sounds routinely exceeded 95% at the southernmost sites.

To evaluate seasonal patterns in the data, we examined the southern array, which had almost six years (1999–2005) of nearly continuous acoustic coverage. In 1999–2001, we recorded airgun sounds throughout the year; levels peaked during the summer months, probably because airgun survey ships are most active in the northern hemisphere during the summer (1999–2001 data published in Nieukirk *et al.*, 2004). During 2001–2002, this trend continued. In 2003, these high levels of airgun activity were also observed in summer, but levels remained high (>80% days/month) into the winter months. In the first few years of the study, there were fewer days with airguns sounds in February through April, but that pattern did not persist into the later years.

We examined the acoustic data collected during 2002–2003 to identify spatial patterns in airgun noise levels.

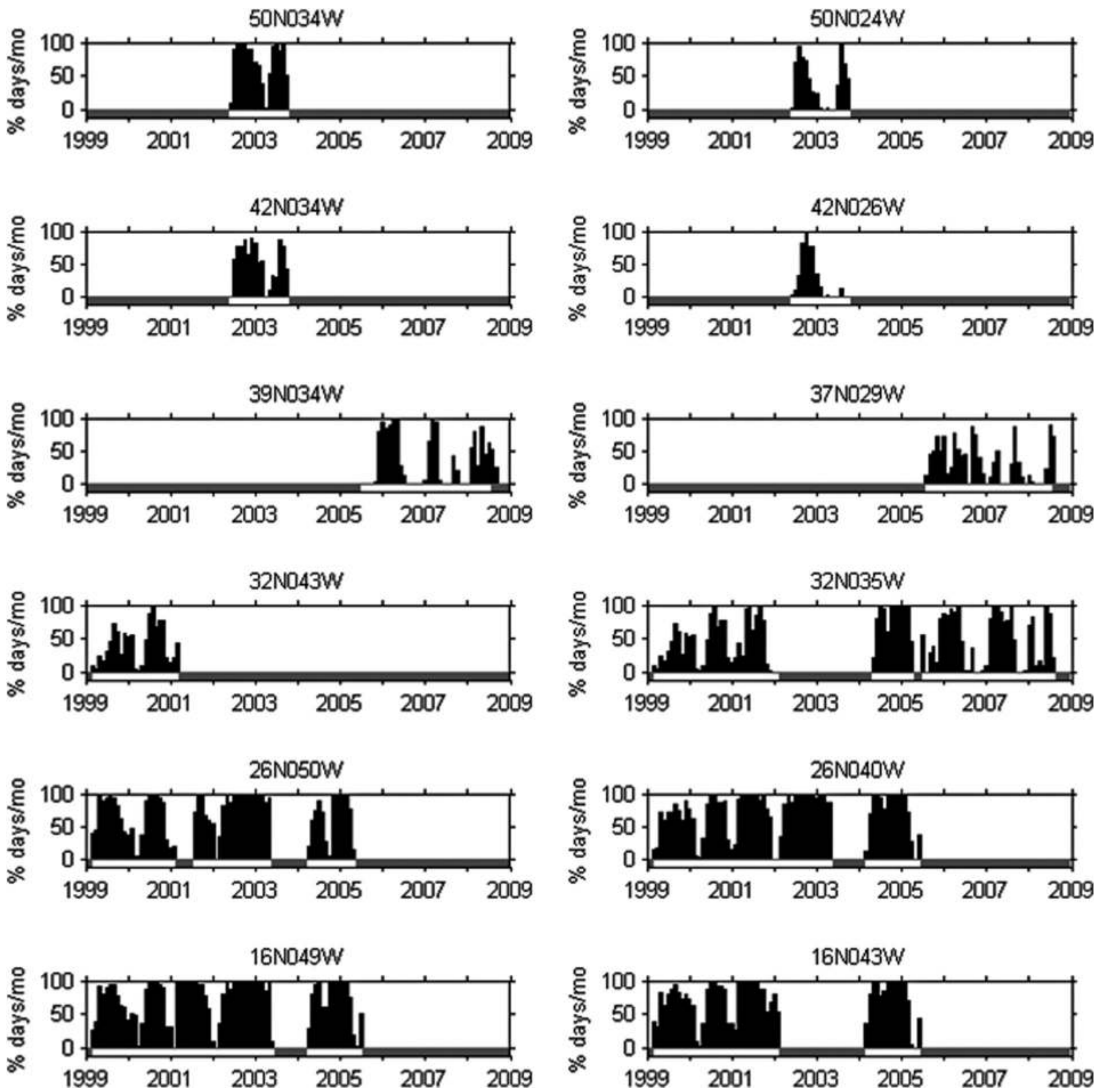

FIG. 4. Seasonal patterns of airgun pulses detected in data at the 12 mooring sites. Black bars represent percentage of days/month that airgun pulses were detected. Gray bars indicate periods for which there were no data available.

During this time period, seven instruments were deployed with latitudinal coverage from approximately 16–50°N. Extensive airgun activity was observed on days in July-–January at most sites. On the instruments at 26° N, extensive airgun activity (>80% of days in a month) also continued into the winter months. There were no apparent east-west trends or north-south trends in airgun noise.

Locating the sources of airgun sounds revealed that three geographic areas were major sources of airgun signals: Newfoundland, northeastern Brazil, and Senegal and Mauritania in West Africa (Fig. 1). Extensive airgun activity was observed off Newfoundland during boreal summer months, and shifted to off Brazil and Africa during the winter months. In some cases, airgun sounds were recorded almost 4000 km from survey vessels working off Brazil.

Acoustic propagation modeling from airgun source locations off the coast of northeast Brazil revealed large (> 40 dB) variability in propagation loss over distances of tens of kilometers and depth ranges of several hundred meters. Since these ranges are smaller than our uncertainty in the position of calling fin whales, we were unable to correlate changes in fin whale calling behavior with changes in received levels of airguns.

B. Fin whales

The 20 Hz pulses produced by fin whales were recorded at all sites in this experiment from approximately August to April of each year. Our proxy for the relative levels of calling fin whales, the fin index, peaked during late December to early January for most sites and most years (Fig. 5). In all cases the fin index did not appear to be confounded by noise in the adjacent frequencies. Fin index levels were the highest at the sites north of 32° N. Although the fin index at the

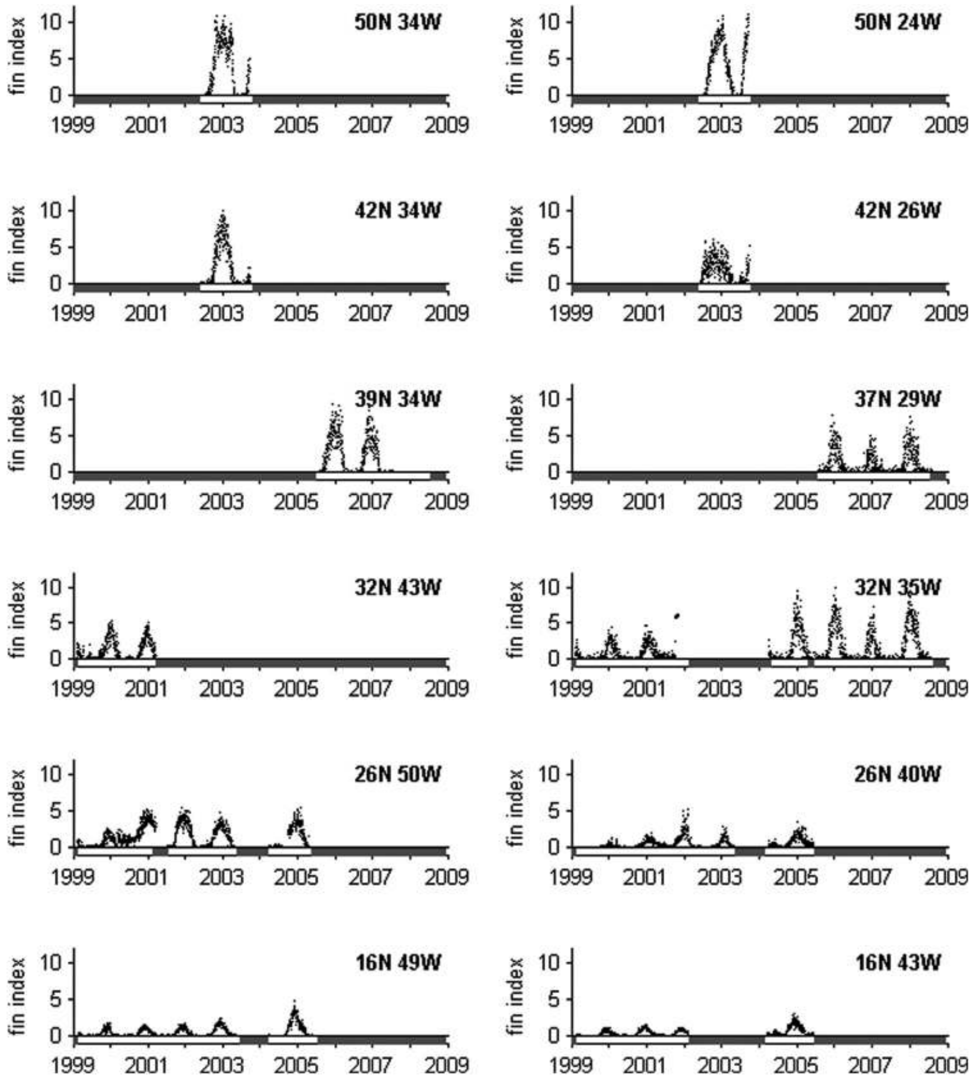

FIG. 5. Seasonal patterns of fin whale 20 Hz pulses detected in data at the 12 mooring sites. Black dots represent the calculated fin index, or relative estimate of fin whale calling. Gray bars indicate periods for which there were no data available.

southernmost sites also peaked in December–January, maximum index levels were approximately half of those observed at the more northerly sites. At some sites, fin index level peaks were quite distinct, as levels increased gradually in the late summer and fall, peaked in winter with clear maxima (i.e., at 50° N 24° W and at 32° N 35° W), and then began decreasing during the spring months. At other sites (e.g., 42° N 26° W), levels increased in July, peaked at much lower levels in August, then fluctuated during August–December and again returned to minimum levels in spring. At the 32° N 35° W site, an area for which we had data spanning 10 years, fin index levels increased almost 2 months later than at the sites to the north; this pattern was consistent over multiple years. There were no clear trends in the time of peak calling with latitude ($R^2 = 0.02$, $p = 0.41$). However, there was a significant increase in the annual peak fin whale call index during the experiment ($R^2 = 0.47$, $p < 0.001$; Fig. 6).

C. Overlap in airgun and fin whale sounds

Because the airgun activity levels were high during summer, fall and winter months, these high noise levels clearly occur during times when fin whale calling activity is frequent [Fig. 2(c)]. Fin whale seasonal calling patterns were relatively consistent at each site, but airgun patterns varied from year to year. Thus, in some years (e.g., 2005) there was a great deal of overlap of peak fin whale calling activity and high airgun levels, while in others (e.g., 2001) we recorded lower levels of airgun activity during times when high levels of fin whale 20 Hz pulses were recorded (Fig. 7).

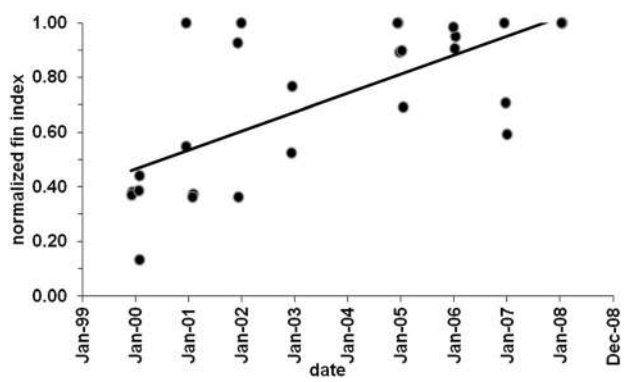

FIG. 6. Normalized annual fin index peak. For each site, data were normalized by dividing the annual peak index by the maximum peak index over all years. Linear regression trend line: $R^2 = 0.47$, $p < 0.001$. The positive trend indicates that fin whale calling increased over the duration of this study.

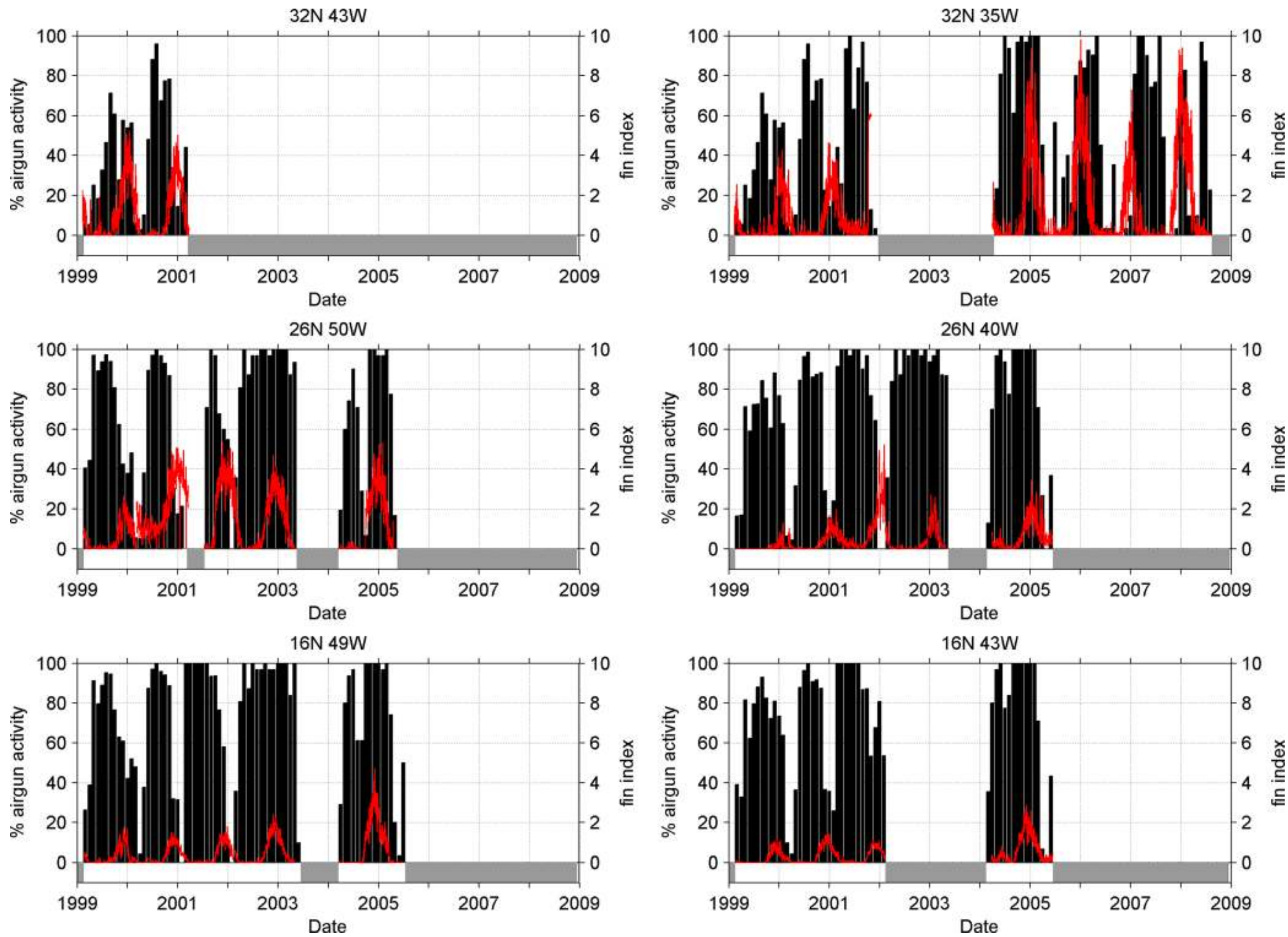

FIG. 7. (Color online) Seasonal patterns of airguns (black bars, left y axis) and fin index (light gray line, right y axis) for sites in the southern array. Dark gray bars indicate periods for which there were no data available.

V. DISCUSSION

A. Airgun sounds

From a low-frequency ocean acoustic dataset, we were able to conduct a long-term, basin-spanning observation of airgun noise levels in an area that is rarely surveyed but is likely the migratory corridor for numerous species of cetaceans. Airgun sounds were recorded at all sites, in all months of the year, and at distances far from the source. These distances should not be surprising, as pulses from a geophysical survey off the California coast were recorded on land seismometers 6100 km from the source (Okal and Talandier, 1986). Because our instruments were located in the deep sound channel, seismic survey vessels working in both the northern and southern hemispheres and the eastern and western Atlantic were recorded despite the remote mid-ocean location of these hydrophone arrays. When multiple sources of airguns were recorded simultaneously, the resulting high levels of noise usually obscured any biological sounds in our acoustic data (see also Clark and Charif, 1998; McDonald *et al.*, 1995). During such periods, the sound from airguns, which is usually considered a transient noise (Richardson *et al.*, 1995; McDonald *et al.*, 1995) actually becomes a prevalent part of ambient/background noise levels for this area. During a few recording time periods, we had good acoustic coverage of an area but detected no airgun sounds; this likely happened because survey ships were not operating during this time period.

B. Fin whale calling

The focal species for this study, the fin whale, is a highly vocal whale that produces loud, 20 Hz pulse vocalizations in long sequences that are ideal for analysis via long-term spectral techniques. Our proxy for fin whale abundance, the fin index, yielded consistent results and did not appear to be affected by confounding noise in the 19–22 Hz band. Fin index data also agreed with a previous analysis of the 1999–2001 data in which we used visual inspection of spectrograms to count presence/absence of fin whale pulses per hour [Nieukirk *et al.*, 2004; Fig. 3(a)]. The fin whale calling patterns we observed are similar to more coastal studies of Atlantic SOSUS data to the north (coasts of Britain and Ireland; Charif and Clark, 2009) and west (Clark and Gagnon, 2002; Watkins *et al.*, 1987) of our study area. In our study, fin whale vocalizations were detected from August to April, with peaks November to January for most sites. Charif and Clark (2009) reviewed ten years of SOSUS data collected off the coasts of Britain and Ireland and report fin whale 20 Hz calls in all months of the year, with a peak in

December and January. SOSUS data from the western Atlantic revealed patterns similar to ours—calls in October through June, rare detections during the summer months, and peak calling later in the year, during March and April. At some sites there were no clear peaks in calling levels, but instead levels were variable for months (July–February), possibly because we were recording many distant whales, or because calling whales were constantly moving into and out of the range of these instruments.

It is unclear why the fin index was higher at the more northerly sites. Because a clear wintertime migration to warmer southern waters has not been observed in fin whales, the high calling levels we observed may simply be a reflection of the winter breeding display of high numbers of whales [> 25 000; North Atlantic Marine Mammal Commission (NAMMCO), 2004] estimated to be feeding in the waters off Greenland and Iceland. The regional differences observed in fin index levels may also be reflected in the long-term spectrogram data. Animals from more northern latitudes have a shorter inter-pulse interval than whales singing in more southern Atlantic waters (Watkins *et al.*, 1987; Hatch and Clark, 2004), a difference that may result in less acoustic power in the 19–22 Hz frequency band and thus a lower fin index for the southern sites; this could be modeled in future studies. When data were available for multiple years, index levels often increased over time (e.g., at 32°N 35°W), a pattern opposite of the trend observed by Charif and Clark (2009) to the northeast of our study. Because of our data collection methods, we are unable to determine if these higher calling levels are from louder whales or more vocalizations.

C. Airgun and fin whale sounds

What do the observed noise levels mean for an animal using this mid-Atlantic migratory corridor? Loud, broadband sounds like the pulses produced by seismic airguns have the potential to adversely affect baleen whales, either directly by impacting the animals physically (temporary or permanent hearing threshold shift (deafness), physiological changes) or indirectly by affecting their prey, changing their behavior (startle response, moving away from source, changing vocalizations), or by masking their vocalizations (Richardson *et al.*, 1995; Gordon *et al.*, 2004; Compton *et al.*, 2008). In past studies of baleen whales exposed to seismic airgun sounds, results have been varied. Clark and Gagnon (2006) observed that singing fin whales stopped singing when exposed to airgun sounds from three or more vessels operating simultaneously, and stayed silent throughout the days of the survey. Castellote *et al.* (2012) observed changes in fin whale vocalizations as well as movement away from vessels conducting seismic surveys. Di Iorio and Clark (2010) found that blue whales called consistently more on days with sound from a seismic exploration "sparker" than on days without it. McDonald *et al.* (1995) observed that a blue whale stopped vocalizing when within 10 km of an active seismic vessel. Migrating bowhead whales (*Balaena mysticetus*) avoided airguns at ranges exceeding 20 km and received levels of 120–130 dB re1 μPa RMS (Richardson *et al.*, 1999), while bowhead whales have been observed to change their surfacing patterns at ranges up to 73 km from seismic survey vessels (Gordon *et al.*, 2004, Table II). There is some evidence that the behavioral state of baleen whales (e.g., feeding or migrating, Gordon *et al.*, 2004; resting behavior, McCauley *et al.*, 1998) and the proximity to the noise source affect a whale's level of reaction to airgun sounds. Migrating whales and those individuals exposed to received noise levels exceeding 150 dB were observed to exhibit the strongest reactions (Gordon *et al.*, 2004, Table II). In this study, the migratory fin whales we recorded are occasionally exposed to seismic research vessels surveying areas of the Mid-Atlantic Ridge in close proximity to our moorings (cf. Nieukirk *et al.*, 2004, Fig. 1), but the sources of the majority of airgun signals are thousands of kilometers from the mid-Atlantic. Individuals were thus far from the source of noise, and direct effects from airguns were not likely.

The most likely effect of the observed frequent seismic noise is a decrease in the effective range of communication among whales using these waters. Masking of vocalizations occurs when ambient noise levels make the signal of interest less detectable and is of concern for a highly mobile species like the fin whale that may be using low-frequency sounds to communicate over long distances while migrating thousands of kilometers (Tyack, 2008; Clark *et al.*, 2009). Masking of these 20 Hz vocalizations is possible because seismic pulses are, like fin pulses, broadband, very low-frequency sounds (Gordon *et al.*, 2004) that repeat every ~10–25 s (Hatch and Clark, 2004). There is also clear geographic and seasonal overlap in these two low-frequency sounds: fin whale sounds were recorded at all sites, as were airgun sounds, and fin whale vocalization levels increased during the late summer and fall months, a time when airgun noise levels were often high (>80% days/month with airgun sounds) at all sites. In addition, because airgun pulses increase in duration as the distance from the source increases, and because this noise is also produced in long sequences for prolonged periods of time by multiple sources around the Atlantic, masking of fin whale vocalizations is quite possible, though masking is eventually limited by the decrease in intensity with distance from the airgun source. Some authors have argued that sounds recorded via hydrophone arrays moored in the SOFAR channel would not be heard by whales (McDonald *et al.*, 1995). We argue that because sound waves propagating along the deep sound channel axis are in fact being refracted above and below it (Urick, 1983), sound from distant airguns does in fact reach shallower depths where whales vocalize.

Although there are clear overlaps in the geographic and seasonal occurrences of these two low-frequency sounds, assessing the impact of this noise on fin whale communication and the biological significance to individuals or populations is difficult. We are unable to precisely locate a vocalizing whale with this array because of the distance between instruments (>700 km), but given that the source level of a fin whale call is ~183 dB re 1 μPa at 1 m (Cummings and Thompson, 1994), we estimate that the recorded fin whales are within tens of kilometers of our instruments (see Stafford *et al.*, 2007). Although we can roughly estimate the location of the signaling/vocalizing whale, we do not know the distance over which fin whales communicate (Tyack, 2008). If the receiver of the signal is close to the vocalizing whale, and both animals are far from the source of airgun pulses, then masking may be less likely. Evidence from field studies suggests fin whales (Watkins and Schevill, 1979) and humpback whales (Tyack and Whitehead, 1983) are communicating over at least tens of kilometers, while Payne and Webb (1971) suggested whales could use low-frequency sound to communicate over thousands of miles. More recent models estimate fin whale calls could propagate over 400 km (Spiesberger and Fristrup, 1990). Di Iorio and Clark (2010) point out that for "animals engaged in long-term singing directed to a distant audience, information loss is minor if singing is temporarily interrupted." However, if animals stop signaling for long periods of time or avoid or abandon habitat, there could be significant population-level effects, especially for endangered species (Tyack, 2008). Current evidence suggests that the 20 Hz pulse vocalization is produced by males (Watkins *et al.*, 1987) and is likely a breeding display to attract females, perhaps to patchily distributed food (Croll *et al.*, 2002). The contracted range of fin whale populations in post-whaling years may have increased the separation of whales during the breeding season, and a decrease in communication range could adversely affect recovery of this endangered species (NRC, 2003; Tyack, 2008).

Like other vocal animals, whales can compensate for increased ambient noise levels and avoid masking by vocalizing more often, changing the timing or frequency of vocalizations, or increasing the source level of the sounds they produce. Right whales have been observed to increase the frequency of their calls in noisy areas (Parks *et al.*, 2007), blue whales increased their rate of calling in response to airgun sounds (Di Iorio and Clark, 2010), humpback whales increased the length of songs in response to sonar noise (Miller *et al.*, 2000), and killer whales increased the amplitude of their vocalizations in response to increased levels of background noise (Holt *et al.*, 2009). The biological costs associated with such changes in signaling are unclear. For the fin whale, the repetitive nature of the long series of 20 Hz pulses increases the chance that these short sounds could be heard in a noisy environment. Further scrutiny of fin whale vocalization patterns and source levels during times of high and low seismic noise levels may reveal the extent to which these animals may be compensating for increased levels of anthropogenic sound. Future studies with a tighter array geometry that allows localization of calling fin whales will be necessary to answer such questions.

VI. CONCLUSIONS

In this study, our goal was to document the levels of airgun noise and fin whale sounds that were recorded in this mid-Atlantic long-term, hydroacoustic data set. Despite the remote location of this array, significant levels of biological and anthropogenic sounds were recorded during the ten years of this study. Seismic airgun noise overlapped fin whale calls geographically and seasonally in our acoustic records. In some locations, airgun noise occurred quite frequently (>80% days/month) for more than 12 consecutive months. Most of the seismic survey vessels we located were operating in areas that are important, if not critical, to many endangered marine mammal species. These areas included waters northeast of Brazil, west of North Africa, and south of Newfoundland. Of particular concern is the seismic noise originating in the waters off Newfoundland, an area of vital importance to the critically endangered northern right whale (*Eubalaena glacialis*). Because of the efficient propagation of this loud, low-frequency noise, whales are likely exposed to these sounds not only on their feeding grounds but also during migration. Given our growing understanding of the impacts of ocean noise on sensitive marine mammals, we argue that the cumulative impacts of this noise and other anthropogenic sounds should be carefully considered, especially in light of other potential stressors such as climate change and pollution/contaminant loads. This basin-wide study has reinforced the fact that ocean noise in an international problem and should be managed as such.

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