OCS Study
BOEM 2014-608

Characterization and Potential Impacts of Noise Producing Construction and Operation Activities on the Outer Continental Shelf: Data Synthesis

U.S. Department of the Interior
Bureau of Ocean Energy Management
Gulf of Mexico OCS Region

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Characterization and Potential Impacts of Noise Producing Construction and Operation Activities on the Outer Continental Shelf: Data Synthesis

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Prepared under BOEM Contract
M10PC000C55
by
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Published by

U.S. Department of the Interior
Bureau of Ocean Energy Management
Gulf of Mexico OCS Region

New Orleans, LA
June 2014

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CITATION

Martin, B, .D. Zeddies, J. MacDonnell, J. Vallarta, and J. Delarue. 2014. Characterization and potential impacts of noise producing construction and operation activities on the Outer Continental Shelf: data synthesis. U.S. Dept. of the Interior, Bureau of Ocean Energy Management, Gulf of Mexico OCS Region, New Orleans, LA. OCS Study BOEM 2014-608. 84 p.

ACKNOWLEDGEMENTS

JASCO thanks Rob Reynolds (Zephyr Marine) and Rob Morris (Edgetech) for assistance locating the AMARs at Nantucket Sound after Deployment 1. Thanks also to Joe Pritchard, Captain of *Big Game*, and Jim Tigit, Captain of *Minute Man*, for assistance with deployments, retrievals, and shipping. The deployments and retrievals were performed by Eric Lumsden, Jeff MacDonnell, Christopher Whitt, David Zeddies, Scott Trivers, and Nicole Chorney. The manual analysis was performed by Eric Lumsden, Craig Evans, Frederic Paquet, and Julien Delarue.

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1. INTRODUCTION

1. Background

The integration of wind energy generation into existing power grids is accelerating around the globe and in the United States. The onshore wind power base in the U.S. has grown almost 1500% in just over a decade; from 2.5 GW in 1999 to 37 GW in 2010 (Figure 1-1). The American Wind Energy Association (2010) points out that sound economics are driving this trend, including: price stability; price hedging to offset volatility of fossil fuel sources; rapid construction opportunities compared to nuclear, hydro, and coal-fired power generation systems; and the benefits of much reduced environmental risks.

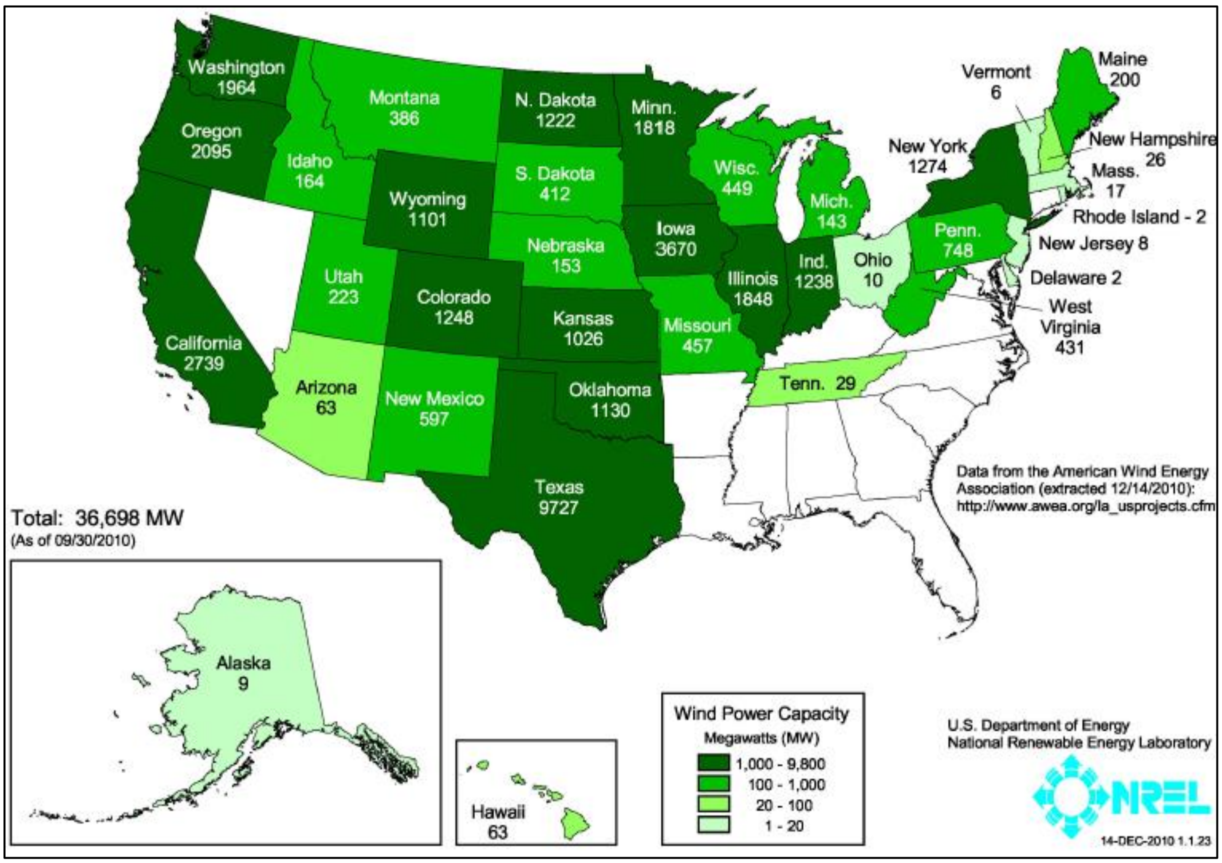

Figure 1-1. Installed onshore wind power capacity (30 Sep 2010).

Many densely populated states of the eastern seaboard have little installed onshore wind power. There are many contributing factors, such as the lack of available land and the relatively poor value of the onshore wind resource. There is, however, great potential for offshore wind energy generation in this region. The relatively shallow coastal waters of the U.S. Atlantic seaboard from Massachusetts to South Carolina are an excellent wind resource (Figure 1-2) within reach of the populated centers. An Oceana study (Mahan et al. 2010) estimates that 127 GW of energy are economically recoverable from this offshore wind resource. This 127 GW is approximately half of the current energy demand of the region, and many of the States could supply all of their power with offshore wind alone. In anticipation of increased offshore power generation applications, the Bureau of Ocean Energy Management, Regulation and Enforcement (BOEMRE, now the Bureau of Ocean Energy Management [BOEM]) created the Final Rule for Renewable Energy (Department of the Interior 2009), which sets out guidelines for granting leases on the Outer Continental Shelf (OCS) for wind, solar, current, and wave energy projects.

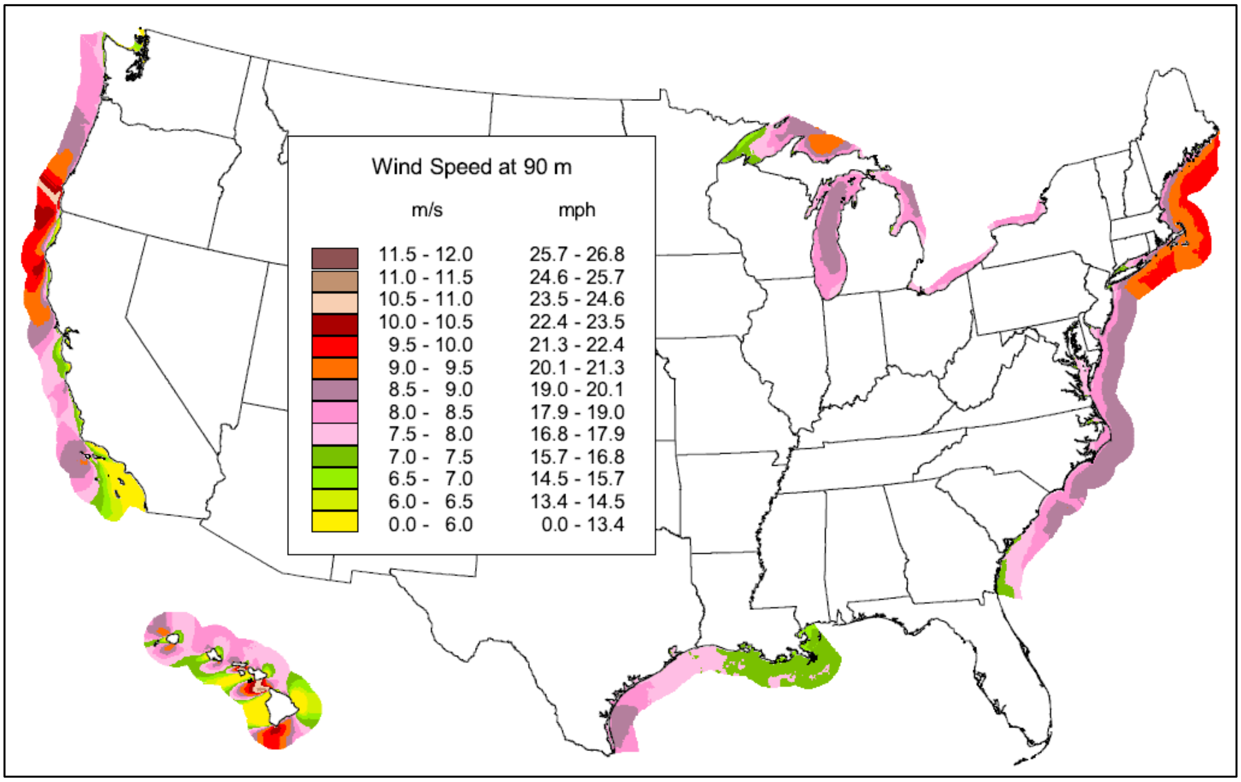

Figure 1-2. United States offshore wind resource at 90 m above the surface (average annual wind speeds).

Environmental impact during construction, operation, and removal is a key concern for permitting under BOEMRE's Final Rule. To facilitate its permitting process, BOEMRE issued a call for proposals to obtain baseline data of natural and anthropogenic underwater noise and marine mammal distributions at up to six selected sites within the Atlantic OCS Planning Areas. JASCO Applied Sciences (JASCO) was selected to conduct this study. Additional acoustic data might be collected when an offshore renewable energy project is built. JASCO staff could then compare construction noise with baseline noise, and investigate changes in marine mammal detections at the sites.

JASCO was contracted to record and analyze acoustic data near the Cape Wind site in Nantucket Sound, and at a lease site under consideration by Bluewater Wind in offshore Delaware Bay. This report describes the recording and analysis program, and provides results, discussion, and recommendations.

2. SUMMARY OF RESULTS

The project's goal was to provide a statistical description of ambient sound levels for one year at two locations likely to be developed for offshore wind-energy production. The chosen sites were offshore Delaware Bay and Nantucket Sound. The preconstruction description of ambient sound levels provides a baseline that can later be used for comparisons, such as during construction, operation, and maintenance of the wind farms. These baseline descriptions can also be used for comparison with other sites. The statistical description of ambient sounds levels was presented as percentile spectral-level histograms of the spectral density values. As a measure of relative overall sound levels and as an indication of possible sources of sound, the percentile levels were compared with the envelope values of the Wenz curves (Wenz 1962). In general, the Wenz curves are reasonable predictors of the ambient noise levels at the two locations; however, there are frequency bands and seasons when sound levels are greater than those predicted by the Wenz curves.

Both manual and automated detection and classification were performed on the recordings to identify prominent sources of sound. Anthropogenic sources, such as heavy shipping, were found at each site throughout the year and could exceed the maximal predictions of the Wenz curves. Large storms, including hurricanes and Nor'easters, produce rain and wind with high waves and are natural sources of sound.

Biological sound activity included marine mammal and fish sounds. Delphinids (likely bottlenose dolphins (*Tursiops truncatus*) and some unidentified species) and fin whales (*Balaenoptera physalus*) were the most commonly detected marine mammals at offshore Delaware Bay. North Atlantic right whale (*Eubalaena glacialis*) calls were detected on a few occasions at both sites. Humpback whale (*Megaptera novaeangliae*) call detections occurred only at the offshore Delaware Bay site. Fish choruses were heard in late summer and fall at offshore Delaware Bay and in winter and summer at Nantucket Sound. These events occasionally exceeded the Wenz curves.

Ambient sound levels differ throughout the year at each site and between each site, but the differences are largely attributable to identifiable events and sources.

2. METHODS

1. Acoustic Data Collection

Underwater acoustic recording was performed for a period of one year at two sites. The sites, chosen by BOEMRE, were near the future Cape Wind installation in Nantucket Sound and the proposed Bluewater Wind project in offshore Delaware Bay (Figure 2-1). Four offshore Delaware Bay deployments and retrievals were carried out aboard charter vessel *Big Game* from Cape May, New Jersey, starting in June 2010 (Table 1). Similarly, four Nantucket Sound deployments and retrievals were carried out aboard charter vessel *Minute Man* from Falmouth, Massachusetts, also starting in June 2010 (Table 2).

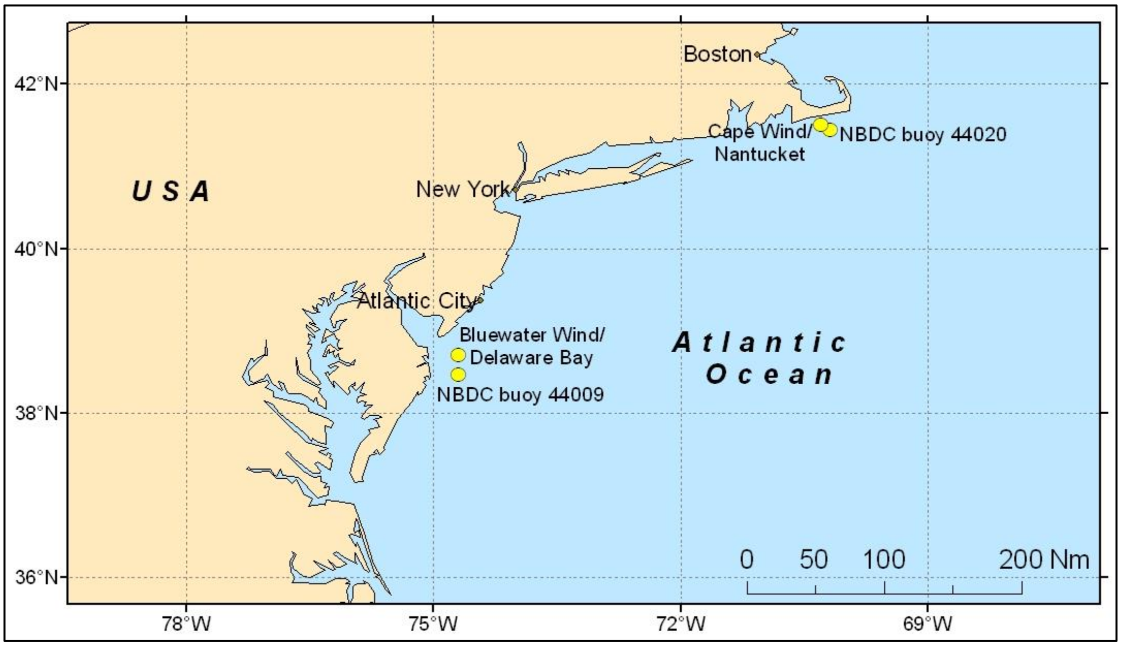

Figure 2-1. Recorder deployment and weather buoy locations in Nantucket Sound and offshore Delaware Bay.

Table 1.

Details of the Offshore Delaware Bay Deployments

Latitude	Longitude	Depth (ft)	Deployment, Record start	Record end	Recording days	Retrieval
38°42.314′ N	74°42.196′ W	69	2010 Jun 29	2010 Oct 4	97	2010 Oct 19
38°42.141′ N	74°42.447′ W	61	2010 Oct 19	*	*	*
38°42.078′ N'	74°42.475′ W	61	2011 Jan 22	2011 May 1	99	2011 Jun 6
38°42.433′ N	74°42.052′ W	70	2011 May 3	2011 Aug 4	93	2011 Aug 4

* Recorder was lost.

Table 2.

Details of the Nantucket Sound Deployments

Latitude	Longitude	Depth (ft)	Deployment, Record start	Record end	Recording days	Retrieval
41°30.087′ N	70°17.901′ W	55	2010 Jun 27	*	*	2011 Jan 11
41°30.212′ N	70°17.796′ W	55	2010 Oct 21	2011 Jan 11	82	2011 Jan 11
41°30.119′ N	70°17.913′ W	54	2010 Jan 11	2011 Apr 14	93	2011 Apr 14
41°29.870′ N	70°18.526′ W	50	2011 Apr 14	2011 Aug 2	108	2011 Aug 2

* Did not record.

Underwater sound was recorded with Autonomous Multichannel Acoustic Recorders (AMARs, JASCO Applied Sciences; Figure 2-2). Acoustic data were recorded continuously on one channel at 24-bits per sample and a sample rate of 32 kHz. Electronic attenuation occurs below 16 Hz, so the useful frequency range of these recordings was considered to be 16 Hz to 16 kHz, with a dynamic range of 100 dB. Each recorder was fitted with an M15C (−160 ± 1 dB re 1 V/µPa sensitivity) or an M8 (−165 ± 3 dB re 1 V/µPa sensitivity) omnidirectional hydrophone (Geospectrum Technologies Inc.). The in-water, recording noise floor was 37 dB re 1 µPa/√Hz with the M15 hydrophone and 42 dB re 1 µPa/√Hz with the M8 hydrophone (both at 2 kHz). Data were stored in 30 min files on 768 GB internal solid-state flash memory. Hydrophone calibration results are provided in Appendix B.

Each AMAR was deployed with a float collar fastened to a 55 kg anchor weight and attached with a line so that the hydrophone would be approximately 2 m above the seafloor (Figure 2-3). A shroud (flow shield) was used to cover the cage surrounding the hydrophone in order to reduce flow noise, and tubing was added around the anchor line to prevent chafing. A sinking ground line, longer than 2.5 times the water depth, was attached from the recorder anchor weight to a secondary anchor for retrieval by grappling.

Figure 2-2. Autonomous Multi-channel Acoustic Recorder (AMAR, JASCO Applied Sciences).

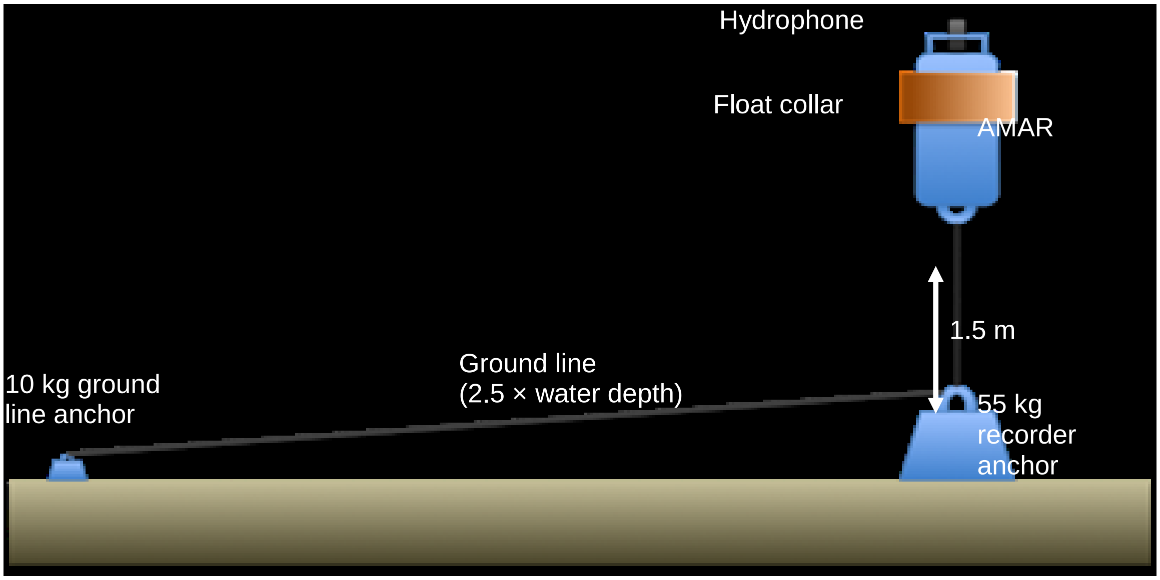

Figure 2-3. Mooring design for Autonomous Multi-channel Acoustic Recorder (AMAR) deployment with ground line for grapple retrieval.

2. Non-Acoustic Data Collection

Wind speed, wave height, and sea-surface temperature during the deployments were obtained from the National Buoy Data Center (Meindl and Hamilton 1992): Buoy 44020 for the Nantucket Sound site and Buoy 44009 for the offshore Delaware Bay site (the locations of the buoys are shown in Figure 2-1). The buoy data were obtained at 10-minute temporal resolution for the duration of the deployments. Occasional missing data were supplied by averaging adjacent points when a single data point was missing, or replicating the closest valid data point when more than one data point were missing.

3. Acoustic Data Analysis

Automated processing of the entire dataset was performed with JASCO's Acoustic Analysis software suite to: (1) compute ambient sound levels, (2) detect shipping vessel noise and anthropogenic events, and (3) detect marine mammal and fish calls.

2.3.1. Ambient Sound Levels

Ambient sound levels from each recorder were examined to document the range of sound levels encountered and their rate of occurrence. Sound level as a function of time and frequency is known as the spectral density over time and can be plotted as a spectrogram (see e.g., Figure 3-4). The spectral density is calculated using the fast Fourier transform (FFT; Oppenheim and Shafer 1999) and is the sound power in 1 Hz wide frequency bands.

The range and occurrence rate of sound levels are presented as exceedance percentiles of the spectral density levels. These percentiles are histograms of the spectral density in each frequency bin per minute of data. The 5th, 25th, 50th, 75th, and 95th percentiles are plotted. The 5th percentile curve is the frequency dependent sound power level that was exceeded 5% of the time during the deployment. Equivalently, 95% of the time, the spectral levels were below the 5th percentile curve. The 95th percentile represents the quietest noise state that is expected to occur, and the 5th percentile represents the loudest.

The 50th percentile is equal to the median of the spectral distribution (i.e., median of the 1 min spectral density levels) and can be compared to the Wenz ambient noise curves (Figure 2-4). The Wenz curves show the range in ambient spectral density levels, as a function of frequency, measured off the U.S. Pacific coast over a range of weather, vessel traffic, and geologic conditions. The Wenz curve limits of prevailing noise (thick black lines in Figure 2-4) are plotted over the spectral distribution results as blue dashed lines; these curves are generalized and are provided for approximate comparison only.

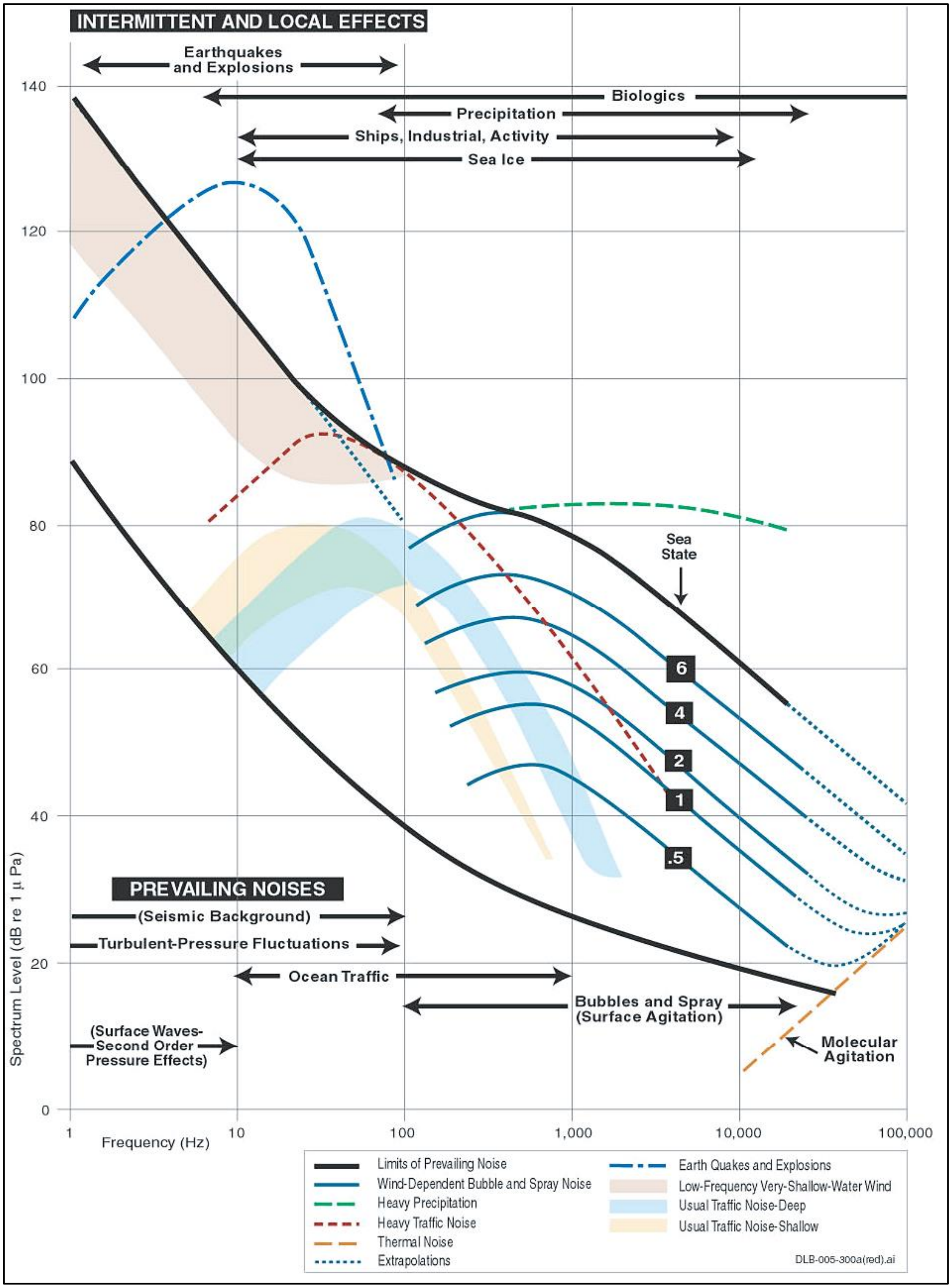

Figure 2-4. The Wenz curves describing pressure spectral density levels of marine ambient noise from weather, wind, geologic activity, and commercial shipping (National Research Council 2003 adapted from Wenz 1962). The thick black lines indicate the limits of prevailing noise.

2.3.2. Automated Shipping Detector

Large shipping vessels generally travel at a constant speed. Their acoustic signature consists of a number of narrow, frequency-band peaks (tonals) generated by the vessel's motors, propellers, pumps, and gearing (Arveson and Vendittis 2000) (Figure 2-5). An automated shipping detector was implemented to detect tonals in the recorded acoustic data.

To detect tonals, the acoustic data were divided into two-second intervals and their spectra calculated using the fast Fourier transform (FFT) with a Hamming window and 50% overlap. Sixty two-second samples were then averaged to obtain spectrograms representing one minute intervals of recorded data. The spectra were normalized in the frequency band between 1 and 1000 Hz using the split-window normalizing method (Crocker 1998) and searched for narrowband peaks. A positive detection was counted when a tonal was present in three of four adjacent one-minute intervals. Detection confidence was indicated by the number of peaks detected. Though this approach works well for heavy shipping traffic, it is not appropriate for detecting fishing vessels or pleasure craft that regularly change speed.

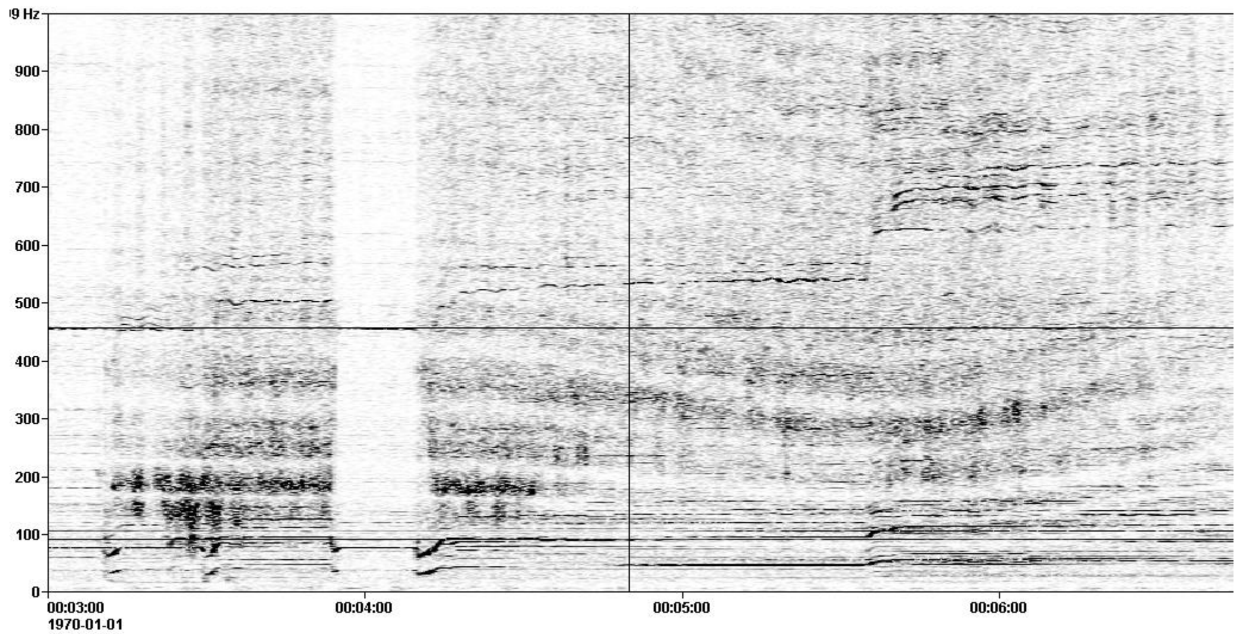

Figure 2-5. Spectrogram showing tonals from heavy shipping activity. 2 s FFT, 2 s time window, 1.75 s overlap, Hamming window. This curved pattern in the center of the image is a typical bathtub pattern that occurs as a vessel approaches and then leaves a sensor (closest point of approach is at the inflection point). Note that many of the tonals from the shipping show rapid changes in frequency as the vessel speed or gearing is changed.

2.3.3. Marine Life Call Detection

2.3.3.1. Manual Analysis Protocol

Four trained analysts manually reviewed samples of the data by visually examining spectrograms and listening to the recordings. The objective of the manual analysis was to review a fraction of the data throughout the deployments to assess where and when marine mammals and fish were acoustically present in the area.

Five percent of the data from each recorder were manually analyzed. The analysis focused on the first 90 s of every 30 min of continuously-recorded data, totaling 72 min of data per day per recorder. Within each 90 s data sample, the analysts annotated one call per species. JASCO has developed a custom software tool, *SpectroPlotter*, which provides standardized annotations and a consistent approach among analysts. *SpectroPlotter* was used by all analysts to review and annotate the data samples.

In case of doubt regarding species identification within a sample, the data immediately before and after the sample were examined for the presence of more easily identifiable calls. Unidentified sounds believed to be biological in origin were tagged as "Unknown" and kept for subsequent review.

2.3.3.2. Analysis Validation

The lead analyst, Julien Delarue, helped the other analysts classify calls that were difficult to assign to a species. Delarue also reviewed a subset of annotations from all analysts to ensure accurate classification of calls by species and to provide feedback to the analysts, who fixed any incorrect classifications. The review focused on:

- Annotations assigned to baleen whales (particularly the endangered right whale as well as fin and humpback whales).
- Fish sounds (although many were not assigned to a species, the aim was to define the period of occurrence of the most common sounds).
- Unknown sounds (particularly those whose time and frequency parameters and associated comments pointed towards a possibly known source).

Delarue consulted with external researchers when new or unidentified call types were detected.

2.3.3.3. Result Compilation

The detections of each species or call types (when the calling species was unknown) were compiled and plotted to show their hourly and daily distribution throughout each deployment in relation to hours of darkness (from sunset to sunrise). The latter aimed at revealing potential diurnal patterns of sound production.

2.3.3.4. Automated Detections

The automated acoustic analysis suite includes a procedure designed to provide a high probability of detecting marine life calls in the acoustic recordings. The first step in call detection is to determine the spectral density (sound level as a function of time and frequency). Biological signals are often of short duration, so the spectral density is calculated using a short-time implementation of the fast Fourier transform (STFT) (Oppenheim and Schafer, 1999). There are several STFT parameters (sampling rate, window length, zero padding, and analysis window overlap) and the choice of values affects the overall performance of the detector. JASCO has gained much experience in optimizing the parameters for the best detections.

The contour data space is defined from the spectral density by normalizing the levels in each frequency bin at each time step by the median amplitude of the frequency bin for a processing block (i.e., STFT window length). The normalized values are then compared to an empirically chosen detection threshold (typically four times the median value). The bins above the threshold are set to 1 and the bins below the threshold are set to 0 (Figure 2-6) so that each cell of the spectrogram is either a 1 or a 0. From the contour data space, the contour of a biological call can be found using a simple, but robust, contour-following algorithm that has been described as a variation of the flood-fill algorithm (Nosal 2008).

The contour-following algorithm begins at the first time point in the contour data space and considers each cell with a 1 as the potential start of a marine-life call. For each of these potential call starts, a joining algorithm searches adjacent cells for other cells that are also set to 1 (Figure 2-6). Merging cells set to 1 creates a contour of the marine life call (similar to how the human brain 'joins the dots' to 'know' that there are three calls in Figure 2-7c). Each cell with a 1 is only added to one contour, and this algorithm is not concerned with distinguishing the boundaries between different calls.

Once a contour is complete, the signal parameters (start time, duration, and frequency components) are extracted and a contour is compared to minimum duration and bandwidth values before being stored in the output file. JASCO used these detection counts to indicate which files may contain biologic calls of interest. A sample of automated detections was reviewed by Delarue to verify validity of fin whale and right whale auto-detections. The validated detections were included in the plots described in Section 2.3.3.3.

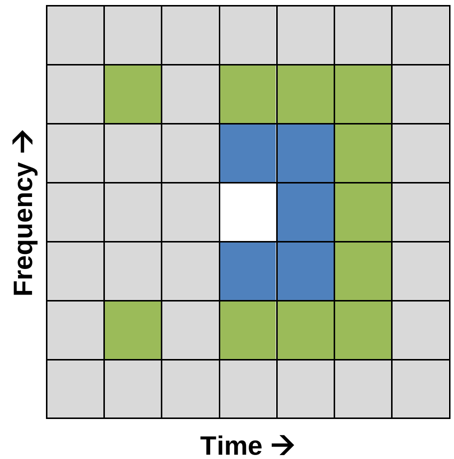

Figure 2-6. The contour-follower mask. The starting white cell for joining to the contour must be 1 to initiate contour following. All green and blue cells equal to 1 are added to the contour. The algorithm advances from left to right in time so gray cells left of the test cell need not be checked again; however, the far left cells are checked to join any broken contours. A contour can be broken because a green cell equal to 1 is added to the contour even if all blue cells are 0.

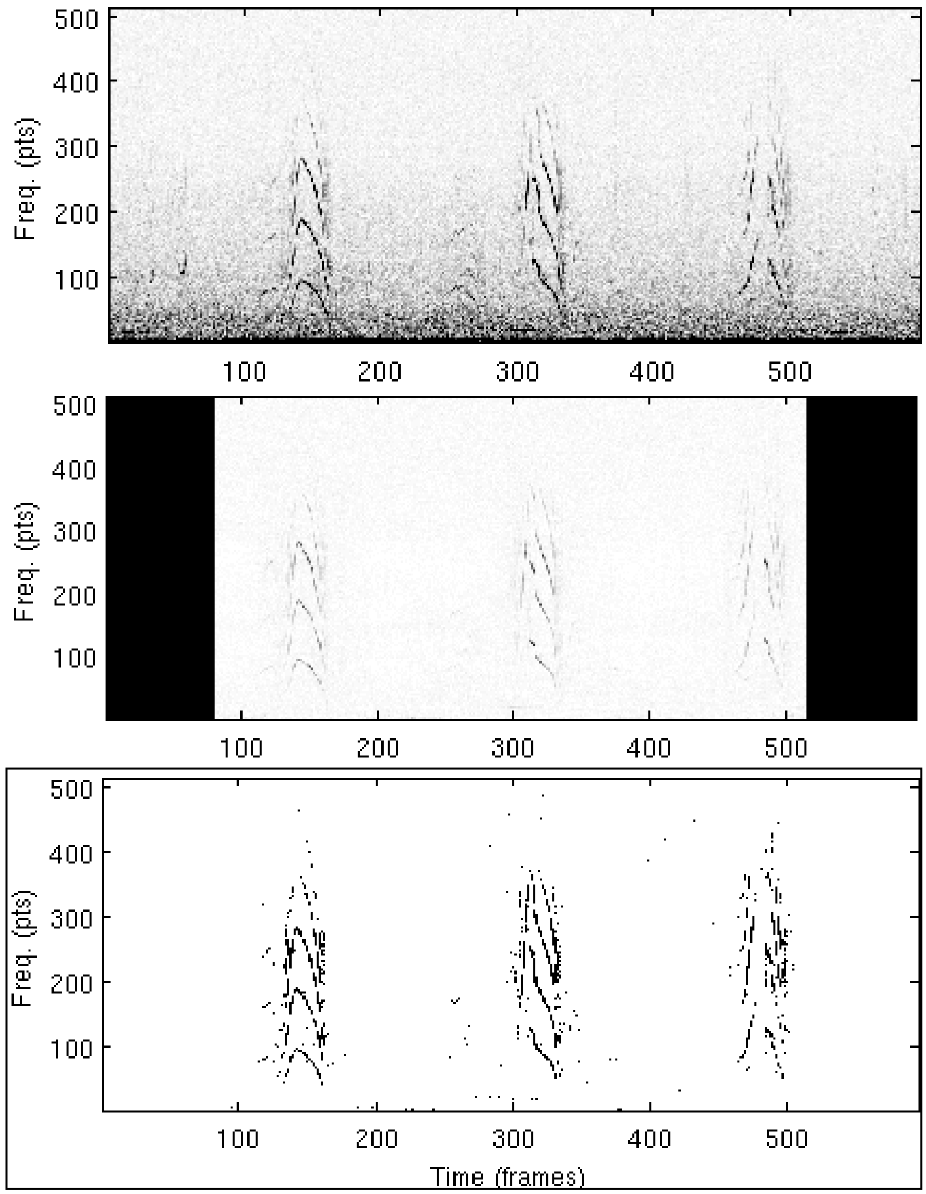

Figure 2-7. Event detection process: (a) Original spectrogram, (b) normalized spectrogram (the 4 s at the start and end (black bands) are set to 0 because of moving average border effects), and (c) detected contours.

3. RESULTS

1. Offshore Delaware Bay

3.1.1. Deployment 1, June–October 2010

3.1.1.1. Weather and Ambient Noise

Weather data from NOAA Buoy 44009 in offshore Delaware Bay were obtained (Figure 3-1). During Deployment 1, the offshore Delaware Bay water temperature was near 25 °C and then dropped toward 20 °C in September. Several major weather events occurred during this time period: Hurricane Earl passed through the region on 4 Sep (Figure 3-2) and Hurricane Igor on 20 Sep (Figure 3-3). More storms with high winds and wave heights occurred on 23–24 August and in late September, and there was a notable Nor'easter on 10–11 October.

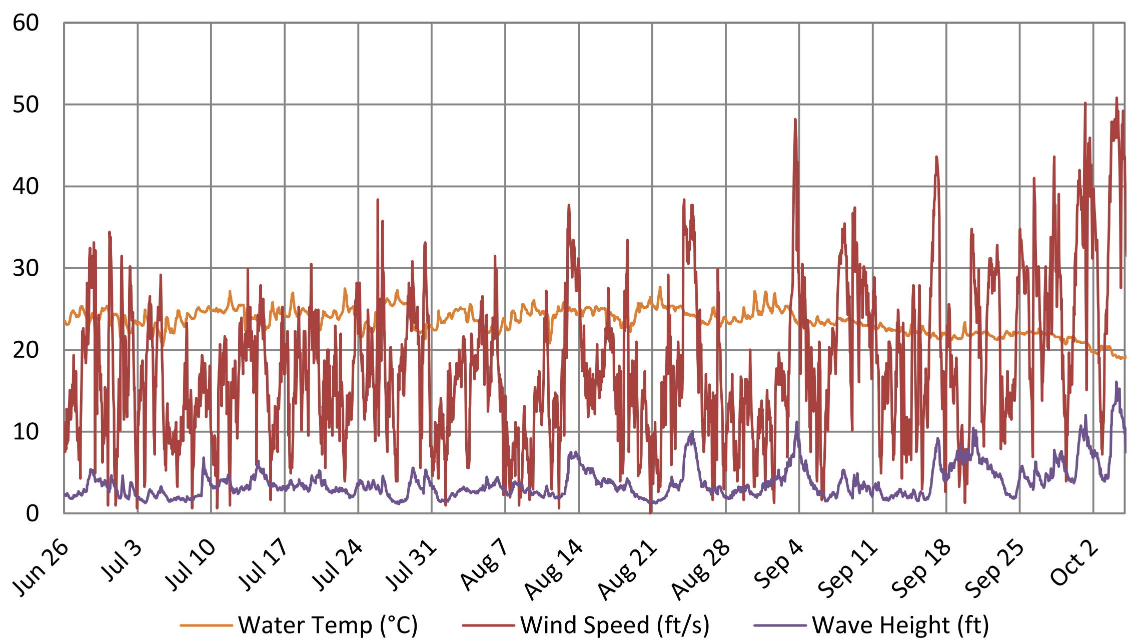

Figure 3-1. Weather data during Deployment 1 in offshore Delaware Bay. Water temperature, wind speed, and wave height from NOAA Buoy 44009, Jun–Oct 2010.

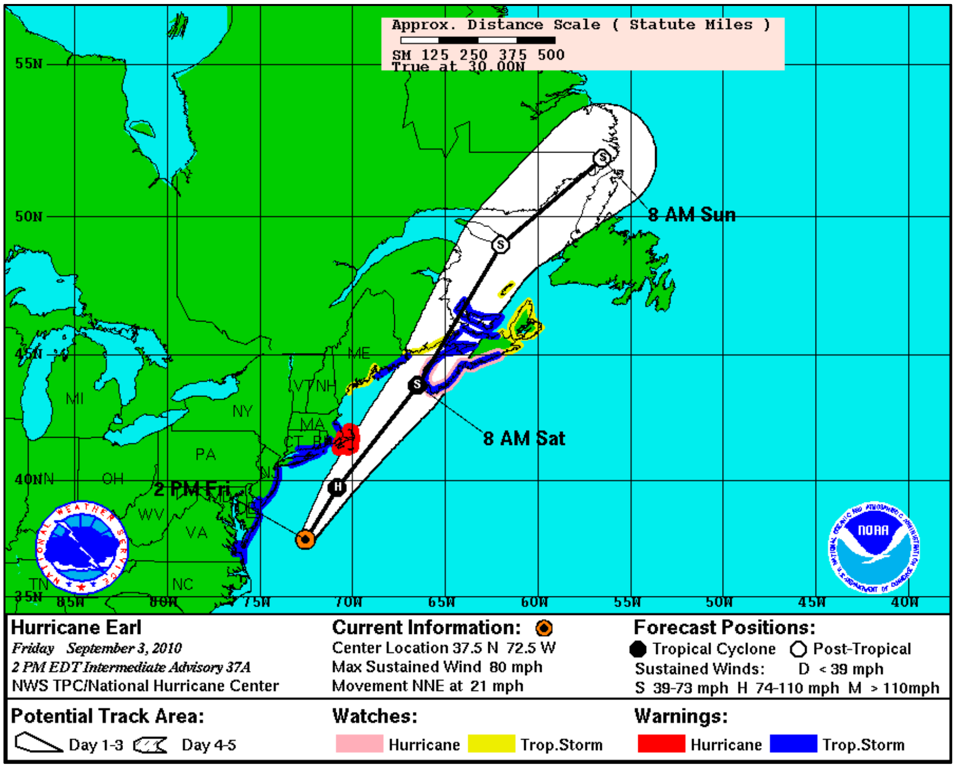

Figure 3-2. Track of Hurricane Earl, as projected 14:00 EDT, 4 Sep 2010.

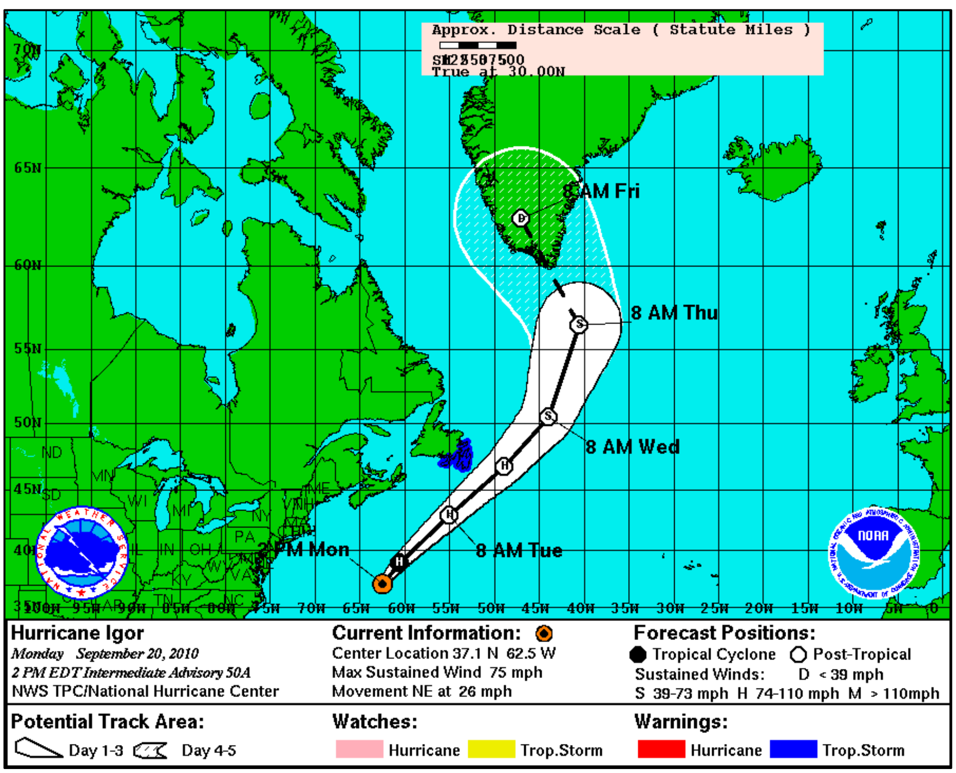

Figure 3-3. Track of Hurricane Igor, as projected 14:00 EDT, 20 Sep 2010.

The spectral composition over time of the acoustic recording is shown as a spectrogram in Figure 3-4. A diurnal pattern in sound levels is suggested by the vertical stripes in the spectrogram.

There are several events of increased sound level. The low-frequency (< 100 Hz) sound events correlate with increased wave height during storms, including Hurricanes Earl and Igor, and the Nor'easter in October. The increased sound levels from 25 August to 4 October in the higher frequency bands (200–700 Hz and 1000–4000 Hz) were due to fish sounds (see Section 3.1.1.4).

The 5th percentile of the spectral density levels is at or above the Wenz curve limits of prevailing noise from 10 Hz to 10 kHz (Figure 3-5). Boating (pleasure craft and fishing boats) and biological activity (fish sounds in September) contributed to the high ambient sound levels at frequencies between 200 and 4000 Hz. In particular, the two peaks along the 5th percentile between 1000 and 3000 Hz can be assigned to striped cusk-eel (*Ophidion marginatum*) choruses (see section 3.1.1.4 and Figure 3-12). Shipping and frequent storms increased the ambient levels at frequencies below 100 Hz.

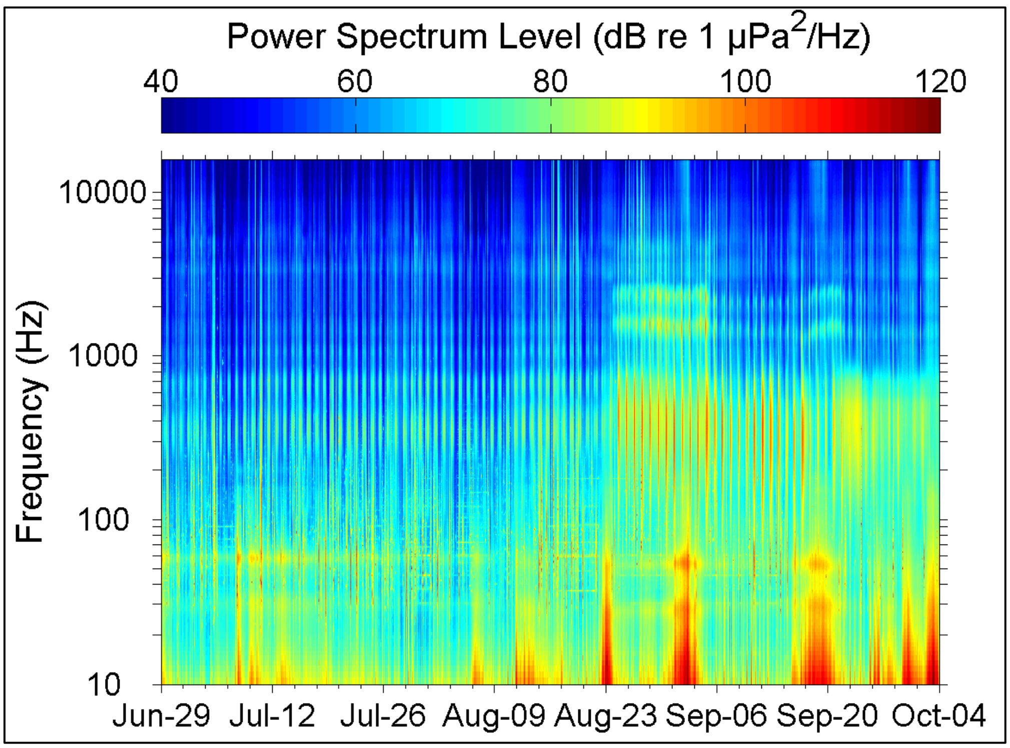

Figure 3-4. Spectral data for Deployment 1 in offshore Delaware Bay. Spectrogram of acoustic recordings 27 Jun through 4 Oct 2010. This is a typical spectrogram showing measured sound levels as colors, with time on the horizontal axis and frequency on the vertical axis. This spectrogram was generated using the fast Fourier transform (FFT) method with 32 000 points, a Hamming window, and 50% overlap. These plots show how the sound energy is distributed in time and frequency.

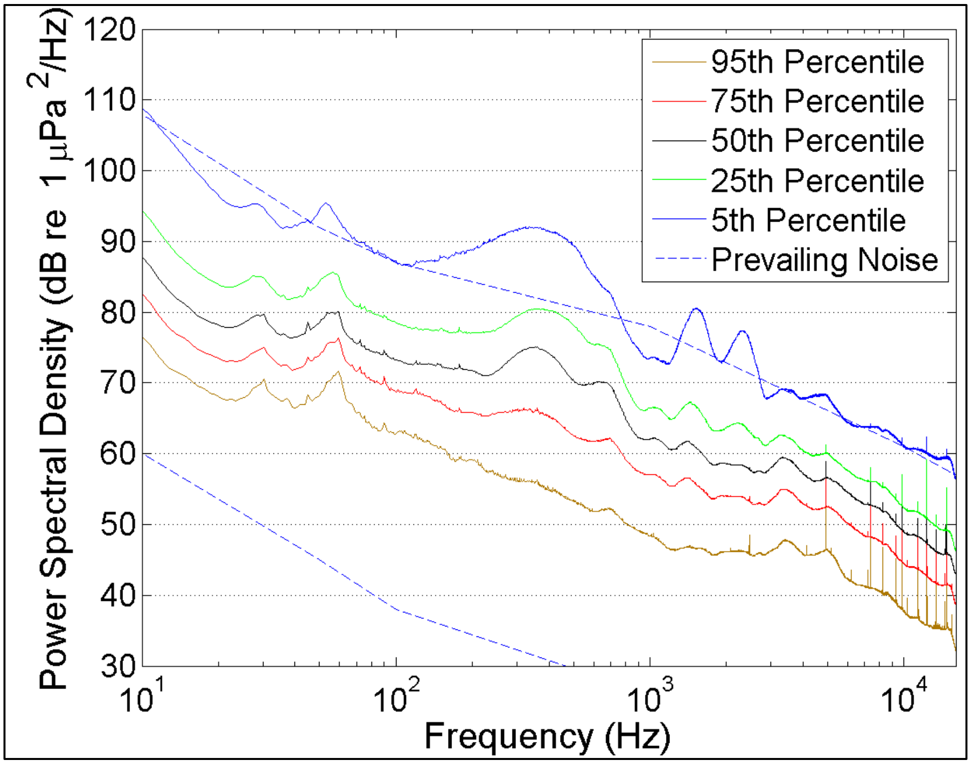

Figure 3-5. Percentiles of power spectral density levels of the ambient noise during Deployment 1 in offshore Delaware Bay, 29 Jun to 4 Oct 2010. The blue dashed lines indicate the limits of prevailing noise of the Wenz curves.

A sample spectrogram of a ship passing the offshore Delaware Bay recorder is shown in Figure 3-6. The automated detector was triggered regularly by heavy shipping (Figure 3-7) during Deployment 1, except on 23 Aug, and 4 and 20 Sep, which coincided with major storms (see Figure 3-1). Shipping traffic likely ceased during these storms, although increased ambient sound levels during the storms may have masked the shipping noise.

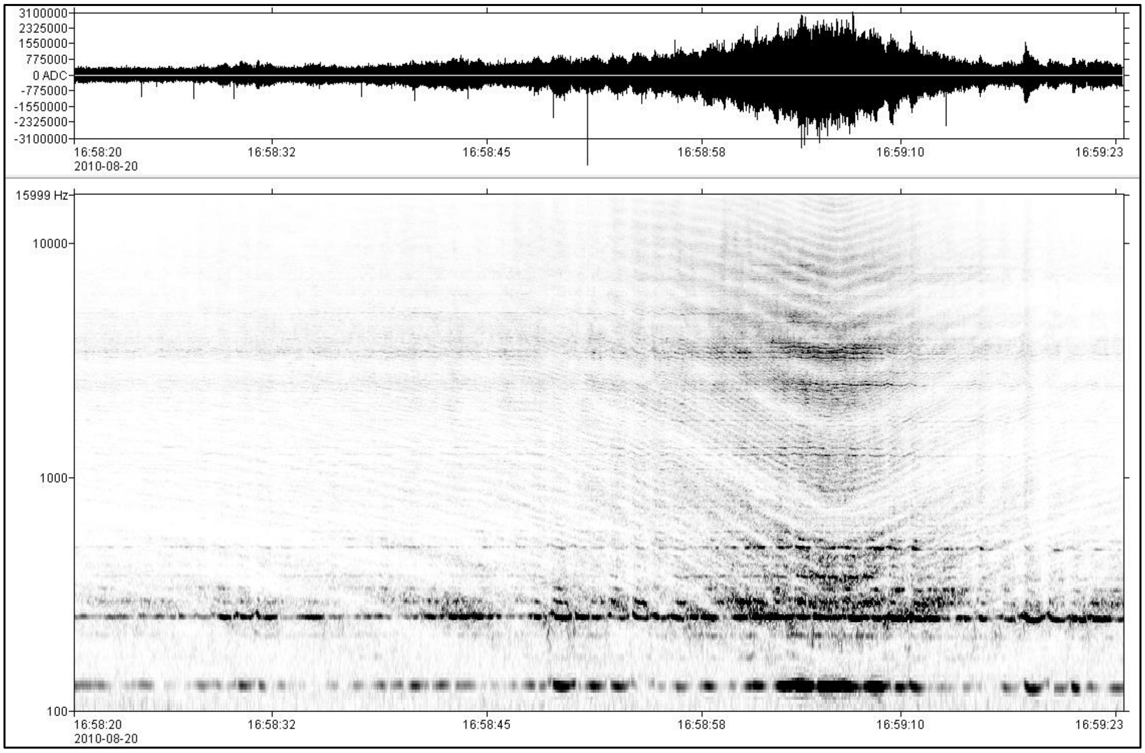

Figure 3-6. Spectrogram of noise from a ship passing near the offshore Delaware Bay recorder, 17:00, 20 Aug 2010. The closest point of approach creates the characteristic bathtub pattern of tonals, which is a Lloyd's mirror interference pattern. (8192 pt FFT, 2048 real data points, 1024 pt advance, Hamming window.)

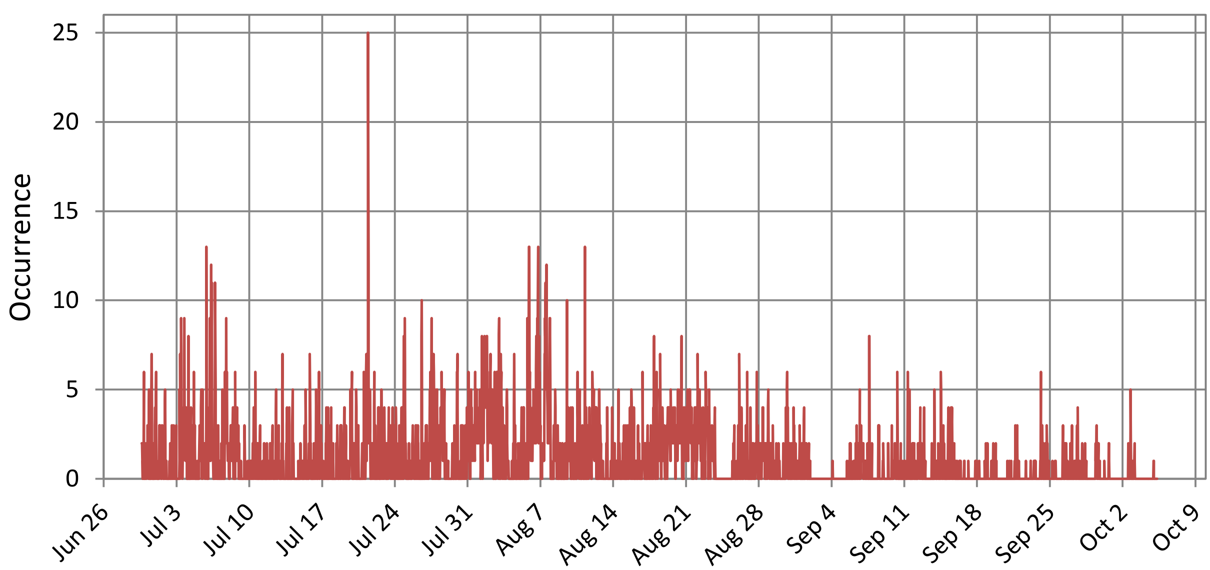

Figure 3-7. Shipping detections per 30 min file during Deployment 1 in offshore Delaware Bay.

3.1.1.2. Delphinid Detections

Delphinids were the most commonly detected marine mammals during this deployment. Delphinid calls were detected on 86 of the 99 recording days. The occurrence of detections declined after 15 Aug 2010. Thereafter, detections occurred with a diurnal pattern with most calls recorded during hours of darkness, particularly after 15 Sep. This pattern does not occur before 15 Aug (Figure 3-8). The detections included whistles, buzzes, and clicks (Figure 3-9) as well as barking sounds thought to be subadult social calls (Laela Sayigh, pers. communication).

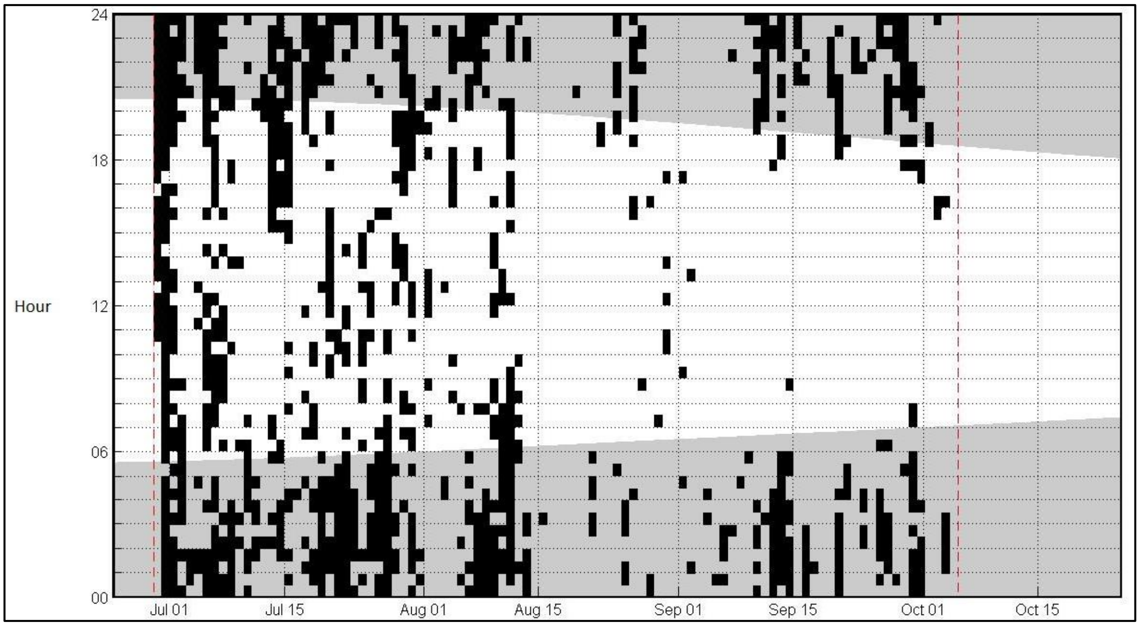

Figure 3-8. Half-hourly occurrence of unknown delphinid calls between 29 Jun and 4 Oct 2010 based on the manual analysis of 5% of the data. Each black rectangle represents a 30-minute sound file. The red dashed lines show the recording start and end. The shading indicates hours of darkness from sunset to sunrise (Begler 2009).

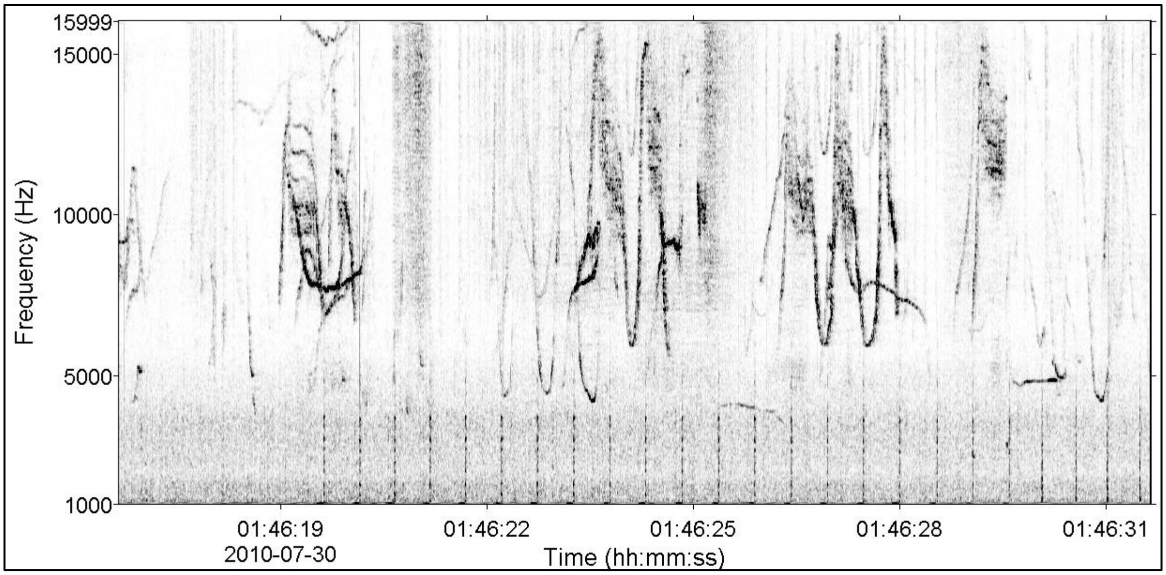

Figure 3-9. Dolphin calls recorded 30 Jul 2010 at the offshore Delaware Bay site. The impulsive sounds below 3000 Hz are fish sounds (see Figure 3-11). (Frequency resolution: 10 Hz; frame size: 0.02 s; time step: 0.01 s; Reisz window.)

3.1.1.3. Fin Whale Detections

Fin whale calls were detected on 11 days, mainly after 15 Sep 2010. Most detections consisted of songs (e.g., Watkins et al. 1987). Fin whale calls were detected mainly during daylight hours (Figure 3-10).

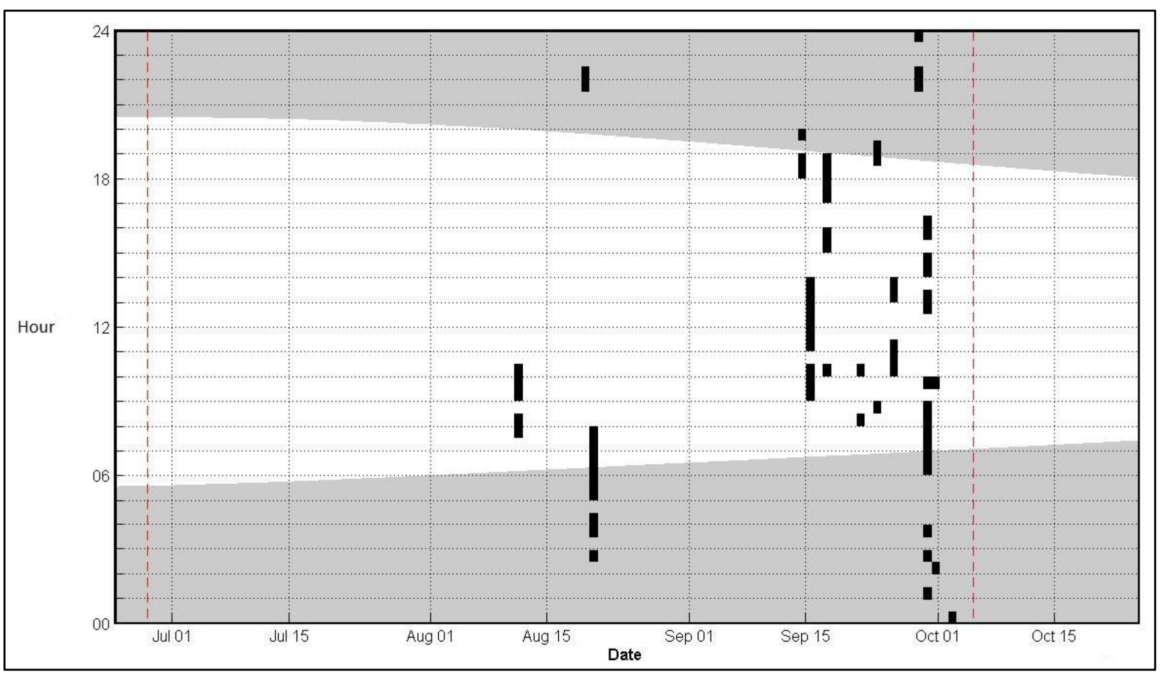

Figure 3-10. Half-hourly occurrence of fin whale calls between 29 Jun and 4 Oct 2010 based on the manual analysis of 5% of the data. Each black rectangle represents a 30-minute sound file. The red dashed lines show the recording start and end. The shading indicates hours of darkness from sunset to sunrise (Begler 2009).

3.1.1.4. Fish Detections

Much biological activity related to soniferous fishes was detected at the offshore Delaware Bay site during the first deployment. Three dominant sound types were identified. The first sound type consisted of knock-like sounds produced in trains (Figure 3-11). These sounds were detected from the first day of deployment until 27 Aug. The repetition rate was initially slow but increased at the end of the detection period, which coincided with the appearance of the second sound type: a “jack-hammer” sound that has been assigned to striped cusk-eels (see the “chatter” sound of Sprague and Luczkovich 2001). These chatter sounds began on 25 Aug and lasted until the end of the deployment. The sounds were initially spaced out but eventually became so prominent as to form two energy bands visible in the spectrogram (Figure 3-5), even in the absence of clearly identifiable chatter sounds (Figure 3-12).

Because of the narrow temporal overlap between the cessation of the knock-like sounds and the start of the chatter sounds along with the increase in repetition rate of the knock trains, which ultimately approached or matched the chatter sounds, both sounds may be produced by cusk-eels, although this is unconfirmed. Figure 3-13, therefore, shows the occurrence of only confirmed cusk-eel calls. Masking by ship noise likely explains some of the episodic differences in diurnal sound production patterns visible in Figure 3-13. Sprague and Luczkovich (2001) recorded this sound type at various times of day in North Carolina and did not describe any diurnal patterns in sound production. The chatter sound appears to be linked to spawning in striped cusk-eels. The current data shows a clear diurnal pattern with peaks 15-35 dB above the normal sound levels occurring near dusk every day (Figure 3-14–Figure 3-15).

The third and last commonly occurring sound type was sequences of 2–4 low-frequency knocks (Figure 3-11). These first appeared on 20 Aug and occurred until the end of the deployment. Other sounds (buzzes, grunts, thumps) likely produced by fish or invertebrates occurred occasionally throughout the deployment.

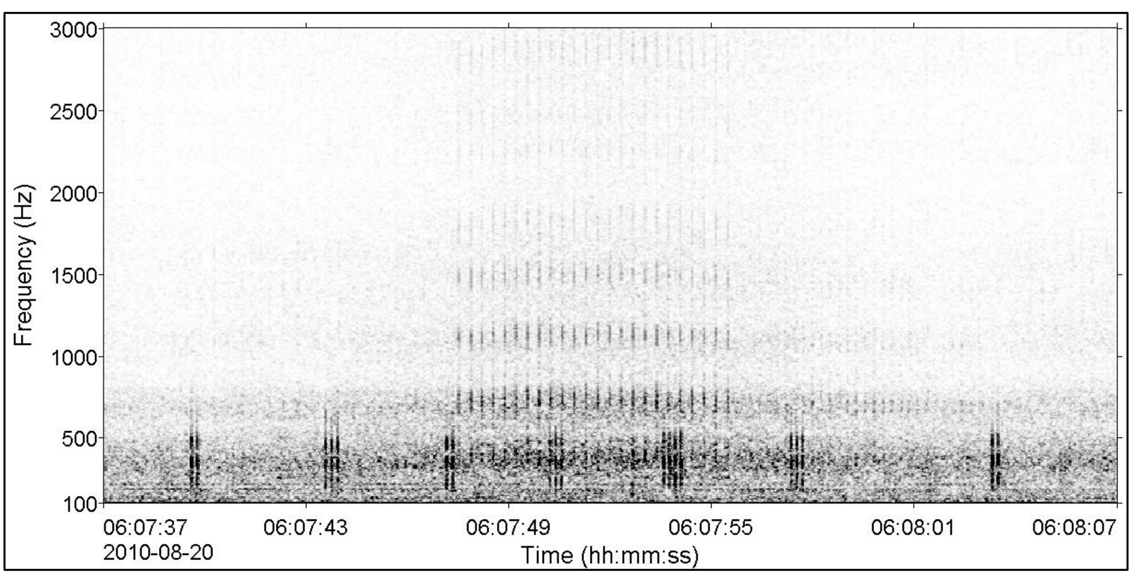

Figure 3-11. Fish sounds recorded on 20 Aug at the offshore Delaware Bay site. Note the repeated pairs/triplets of knocking sounds between 200–600 Hz and the broadband knock train between 300–3000 Hz (frequency resolution: 10 Hz; frame size: 0.128 s; time step: 0.032 s; Reisz window).

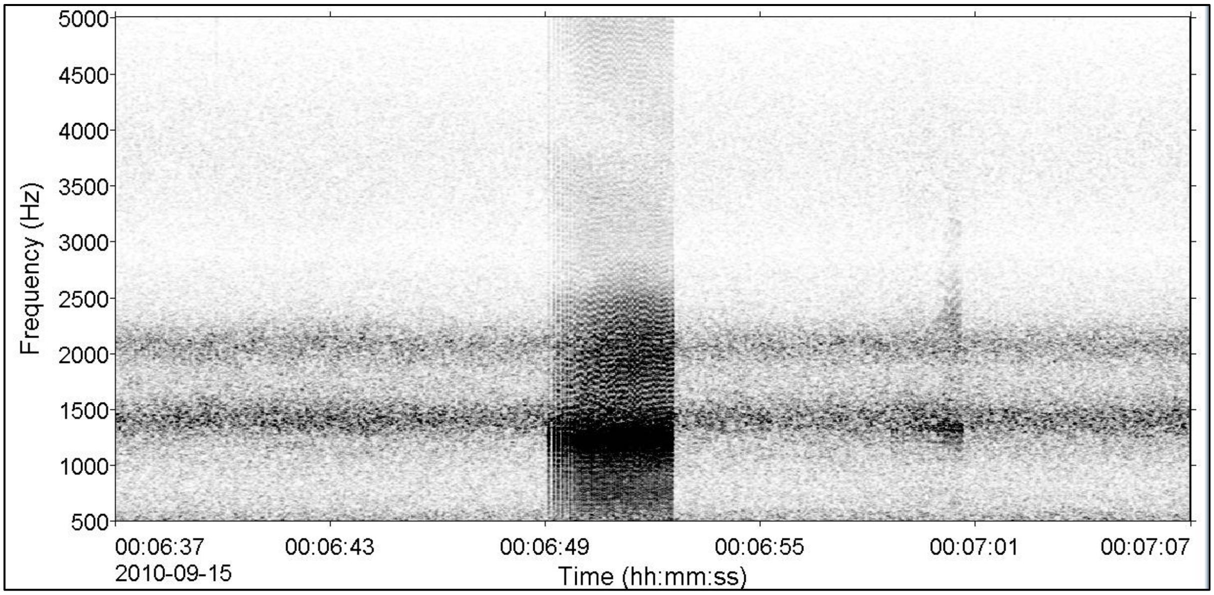

Figure 3-12. Fish sounds recorded 15 Sep at the offshore Delaware Bay site. These sounds have been assigned to striped cusk-eels. The figure shows a single sound and the two continuous energy bands associated with distant chorusing cusk-eels (frequency resolution: 5 Hz; frame size: 0.128 s; time step: 0.032 s.; Reisz window).

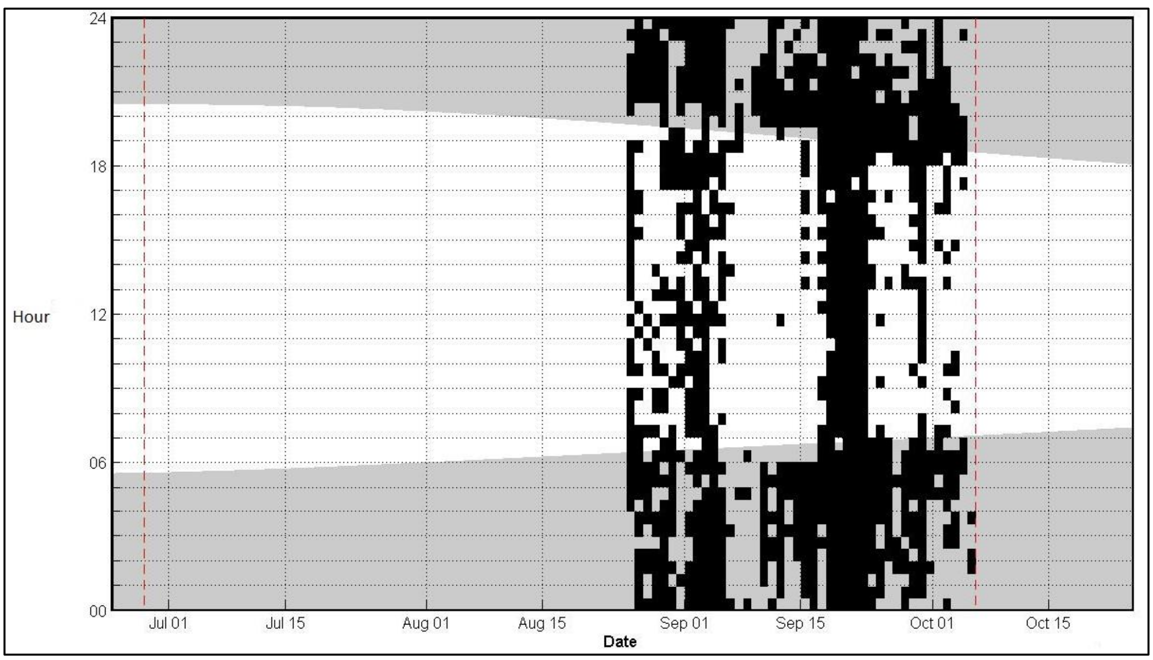

Figure 3-13. Half-hourly occurrence of striped cusk-eel chatter sounds between 29 Jun and 4 Oct 2010 based on the manual analysis of 5% of the data. Each black rectangle represents a 30-minute sound file. The red dashed lines show the recording start and end. The shading indicates hours of darkness from sunset to sunrise (Begler 2009).

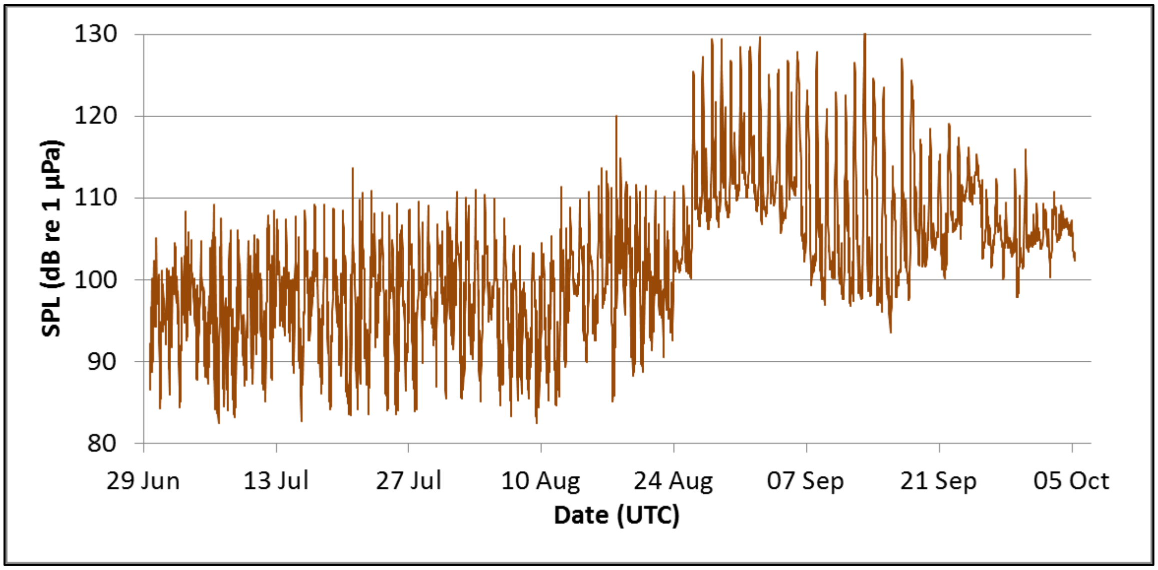

Figure 3-14. Average broadband (100–1000 Hz), SPL every 30 min, Jul–Oct 2010 in offshore Delaware Bay. Peaks occur once per day at 00:00–01:00 UTC (20:00–21:00 local time). Manual review of the data shows the peaks from 26 Aug onwards to be fish choruses. The fish chorus was present throughout the day, with periods of particularly intense calling at dusk that increased the sound levels by 15–35 dB for a period of 1–2 hours (Figure 3-15).

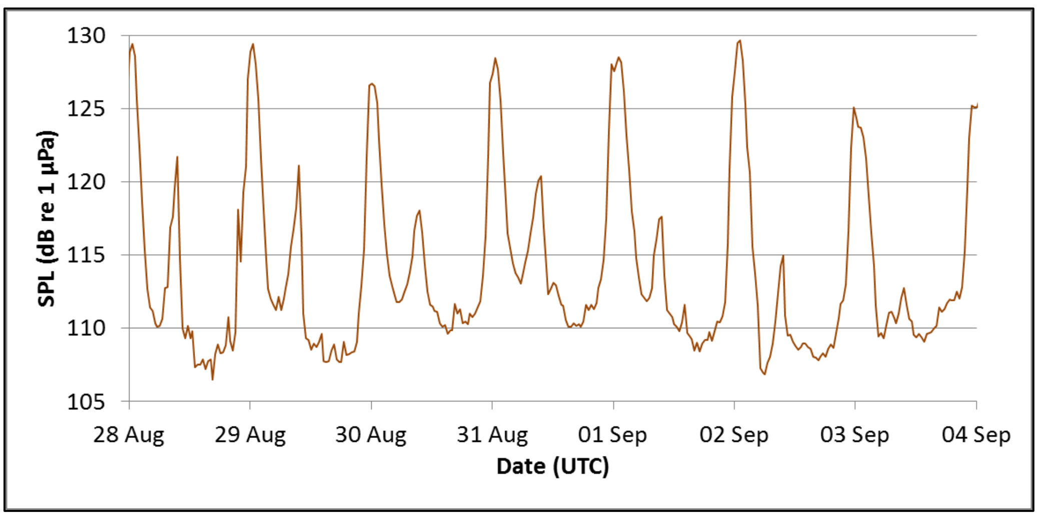

Figure 3-15. Sound pressure levels (SPLs) versus time for week of 28 Aug–04 Sep 2010. The data show a strong peak at dusk and a weaker peak at dawn each day due to fish-chorus noise.

3.1.2. Deployment 2, October 2010 to January 2011

Unsuccessful attempts to retrieve the recorder were made in January and April 2011. More searches were conducted with a side-scan sonar in June and September 2011. The recorder is presumed lost. Possible explanations for the loss include flounder dragging that occurs in the area, an error in communicating location coordinates, or mooring breakage.

3.1.3. Deployment 3, January–April 2011

3.1.3.1. Weather and Ambient Noise

Weather data from NOAA Buoy 44009 in offshore Delaware Bay were obtained (Figure 3-16). During Deployment 3, the water temperature in offshore Delaware Bay steadily rose from about 3 °C in late January to about 10 °C in early May. There were several weather events during this time period, though not of the magnitude seen during the first deployment.

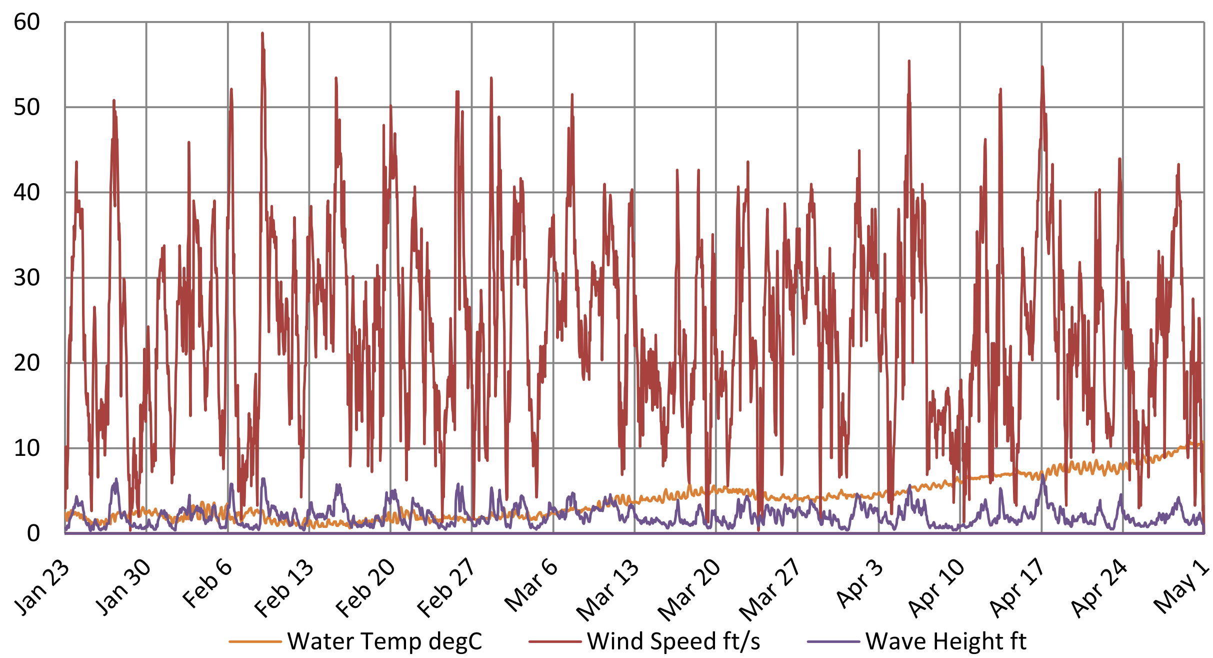

Figure 3-16. Weather data during Deployment 3 in offshore Delaware Bay.

The spectral composition over time of the acoustic recording is shown as a spectrogram in Figure 3-17. There were events of increased low-frequency sound. Some of the low-frequency (<20 Hz) sound energy is attributed to heavy weather, such as on 26 Jan and 16 Apr. Most of the sound energy at low frequencies (<100 Hz) is from anthropogenic sources such as shipping (see below), especially between 11 and 17 Mar when there was a particularly noisy ship with possible engine damage or perhaps a dredging operation.

Percentile spectral levels of recorded sound were calculated and compared to the Wenz curves of prevailing noise (Figure 3-18). During Deployment 3 the ambient sound levels were well predicted by the Wenz curves except below 100 Hz where there were obvious anthropogenic sounds from a damaged ship or other activities and events (including storms).

The percentiles show an unusual slope in the region of 300–5000 Hz, which implies that some type of source was present at all times. No biologic source was found to explain this energy. The continual presence of shipping near the recorder is likely the source of this noise. The peak near 25 Hz in the 5th percentile is attributed to fin whale song notes (see Section 3.1.3.2), which were prominent during the first month of recording.

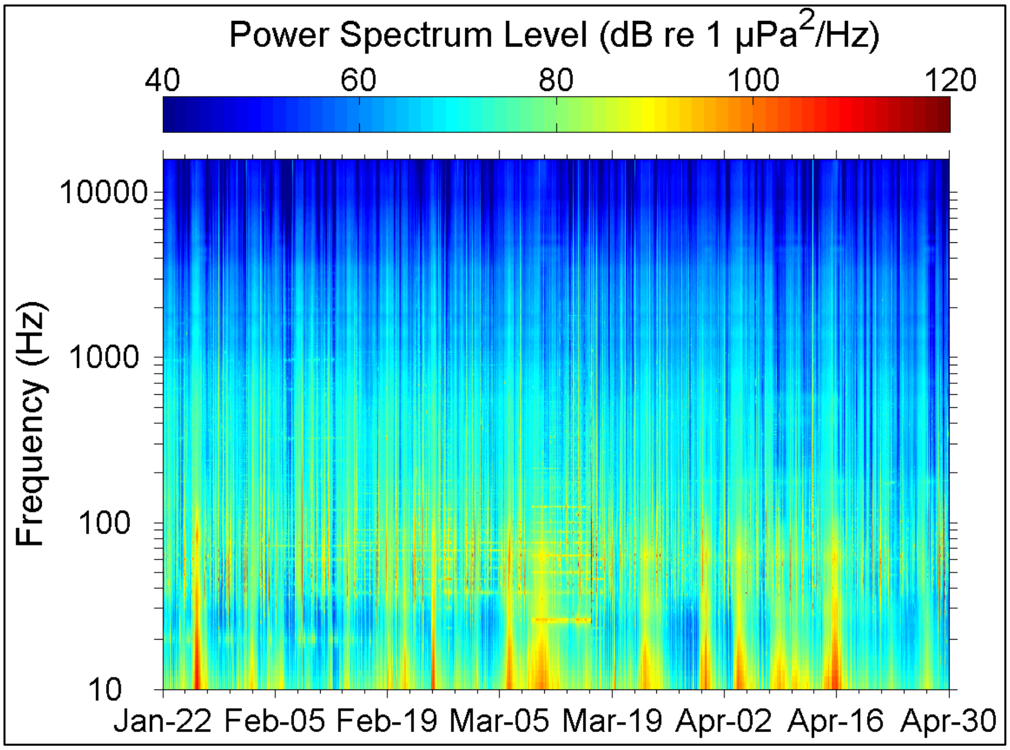

Figure 3-17. Spectral data from Deployment 3 in offshore Delaware Bay (32 000-point FFT, Hamming window, 50% overlap). Fin whale calls caused the slight increase in sound at 20 Hz in Jan and Feb. The horizontal lines in the range of 40–1000 Hz in Jan–Mar are from shipping.

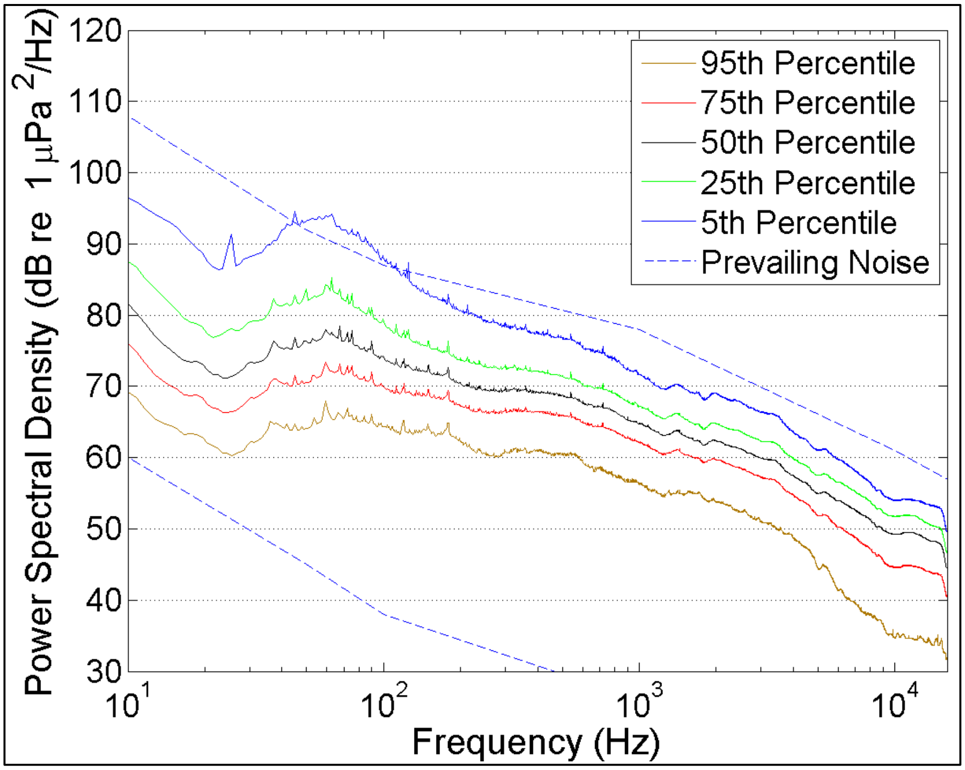

Figure 3-18. Percentiles of power spectral density levels during Deployment 3 in offshore Delaware Bay, 22 Jan to 1 May 2011. The blue dashed lines indicate the limits of prevailing noise of the Wenz curves.

Tonal signals produced by heavy shipping were detected throughout the third deployment (Figure 3-19). During 11–17 Mar, sustained anthropogenic sound was detected. A sample spectrogram of this source is shown in Figure 3-20. Two broadband Lloyd's mirror interference patterns are apparent in this figure, so two vessels were present.

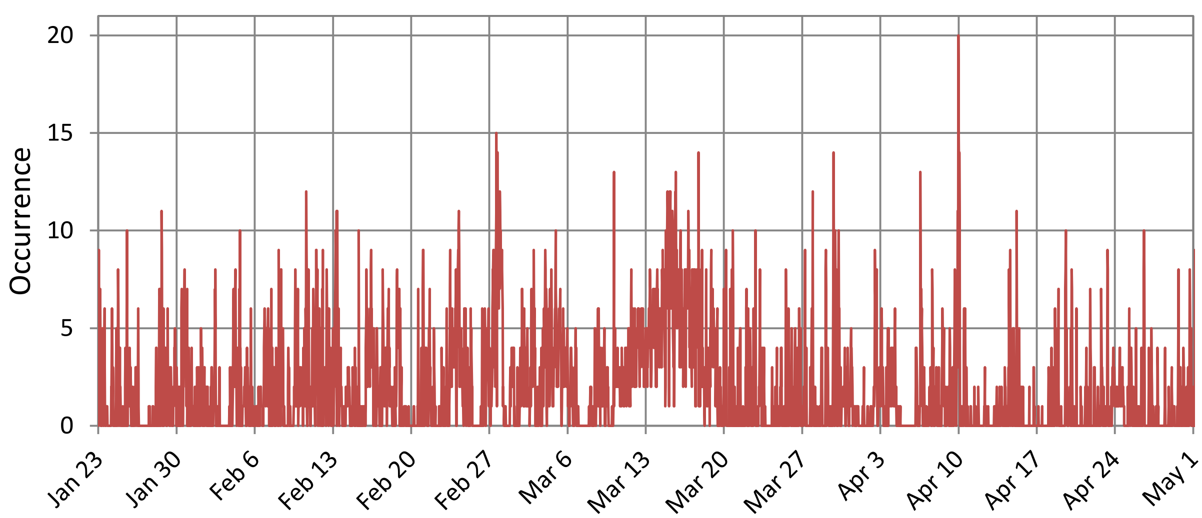

Figure 3-19. Shipping detections during Deployment 3 in offshore Delaware Bay.

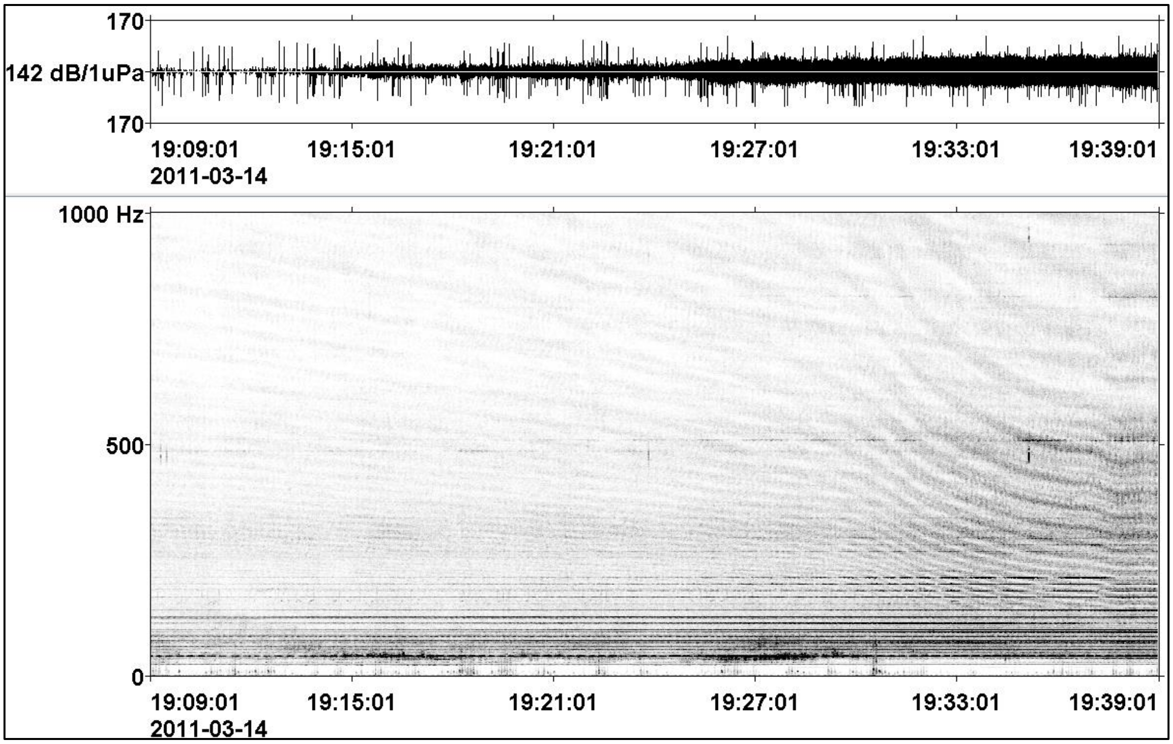

Figure 3-20. Spectrogram of the continuous source near the offshore Delaware Bay recorder, 15 Mar 2011.

3.1.3.2. Fin Whales Detections

Fin whale songs (Figure 3-22) were detected continually from deployment until 20 Feb with a few sporadic detections in late February-early March, on 17 Mar, and on 7 Apr 2011. No obvious diurnal pattern was observed (Figure 3-21).

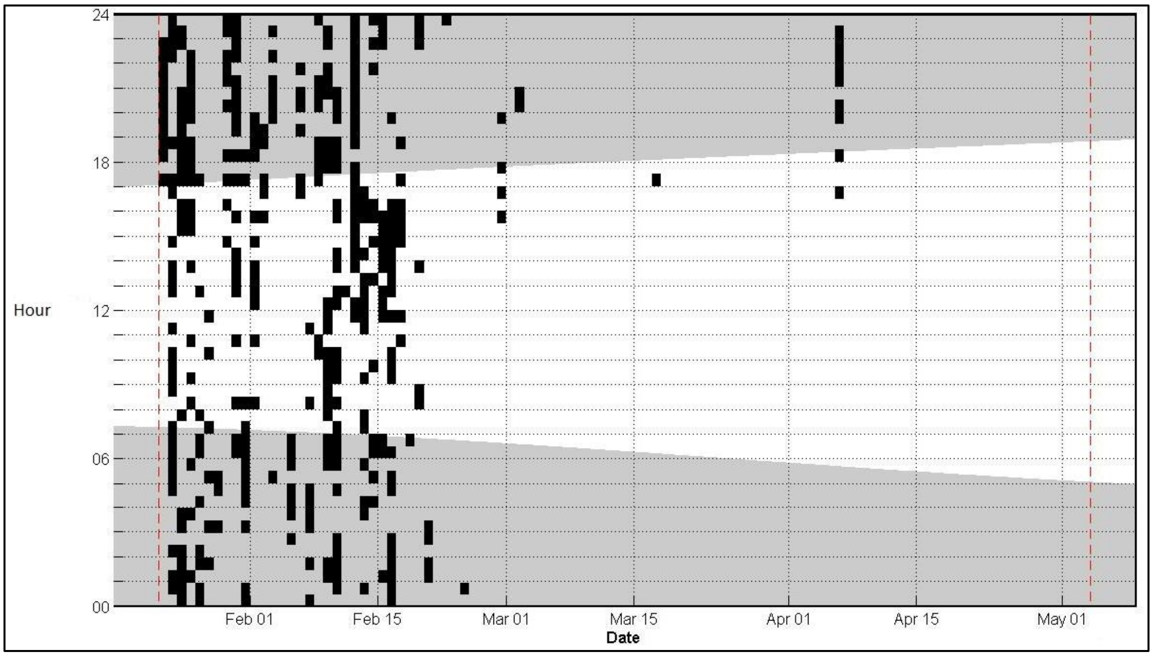

Figure 3-21. Half-hourly occurrence of fin whale calls between 22 Jan and 1 May 2011 based on the manual analysis of 5% of the data. Each black rectangle represents a 30-minute sound file. The red dashed lines show the recording start and end. The shading indicates hours of darkness from sunset to sunrise (Begler 2009).

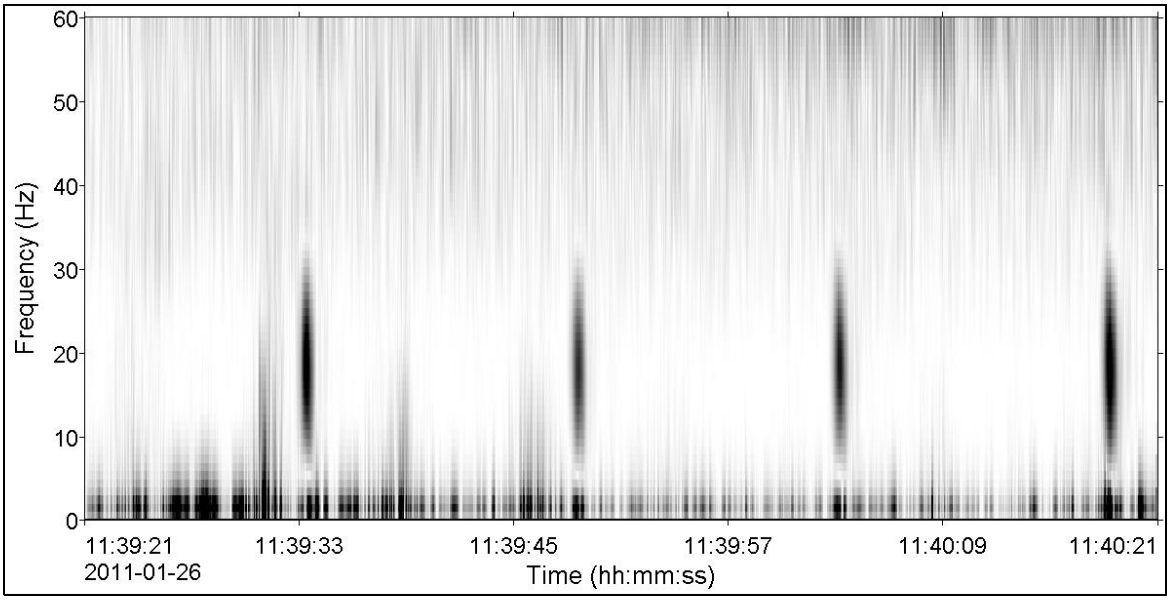

Figure 3-22. Fin whale song notes recorded 26 Jan 2011 at the offshore Delaware Bay site (frequency resolution: 1 Hz; frame size: 0.1 s; time step: 0.025 s; Reisz window).

3.1.3.3. Right Whale Detections

Right whale upcalls (e.g., Parks and Tyack 2005; Figure 3-23) were detected on eight days during the deployment, with 69% of the detection occurring between 30 Jan and 1 Feb 2011 (Figure 3-24). These calls were likely produced by individuals transiting between their breeding grounds off Florida and Georgia and their feeding areas off northeastern U.S. and Canada, although the direction of travel is unclear.

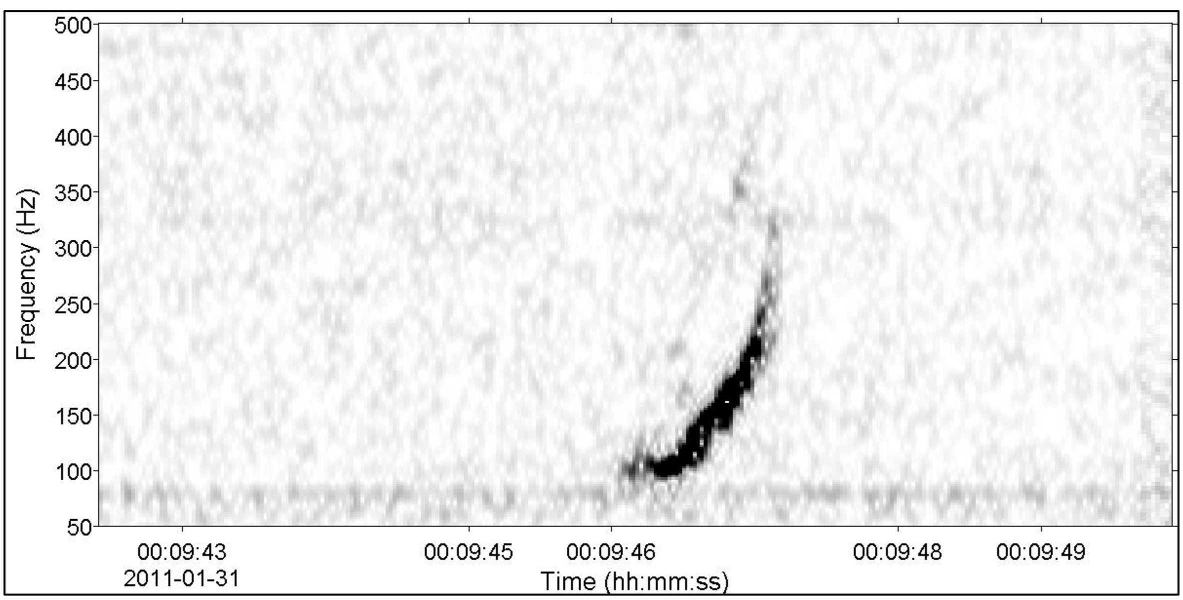

Figure 3-23. North Atlantic right whale upcall recorded off offshore Delaware Bay on 31 Jan 2011 (frequency resolution: 2 Hz; frame size: 0.1 s; time step: 0.025 s.; Reisz window).

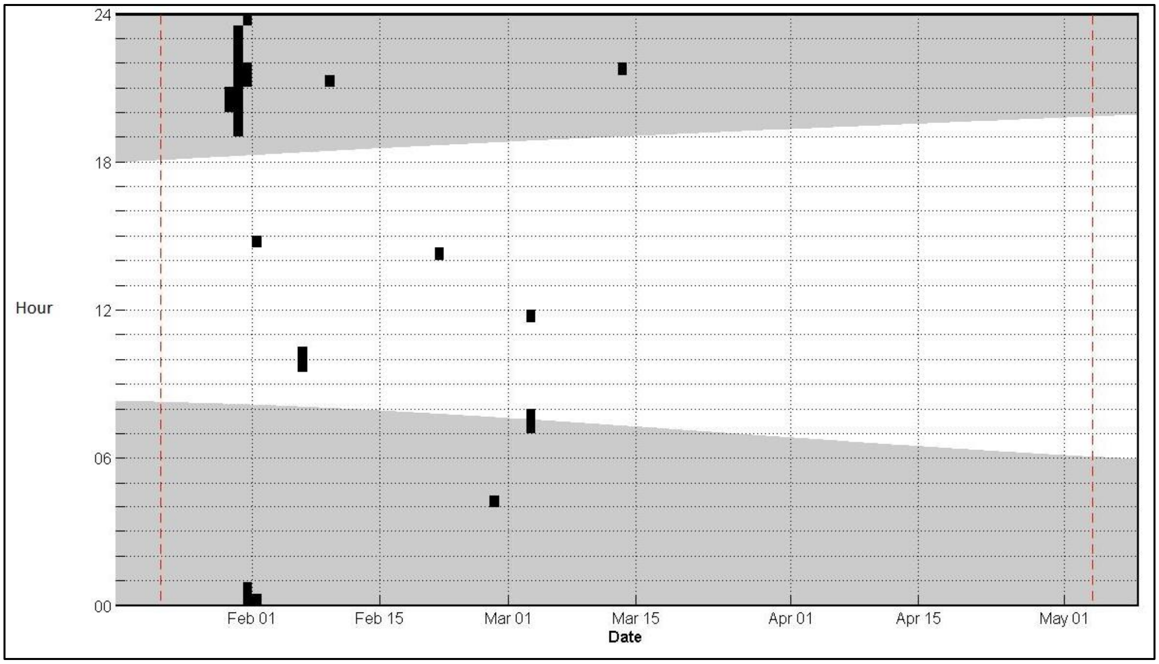

Figure 3-24. Half-hourly occurrence of North Atlantic right whale calls between 22 Jan and 1 May 2011 based on the manual analysis of 5% of the data. Each black rectangle represents a 30-minute sound file. The red dashed lines show the recording start and end. The shading indicates hours of darkness from sunset to sunrise (Begler 2009).

3.1.3.4. Humpback Whale Detections

Humpback whale moans (Figure 3-25) were detected on eight days during Deployment 3. Detections were concentrated in early February, 18–19 Feb, and 8 Apr 2011 (Figure 3-26). As for right whales, these detections are likely attributable to individuals moving between their Caribbean breeding grounds and their North Atlantic feeding grounds.

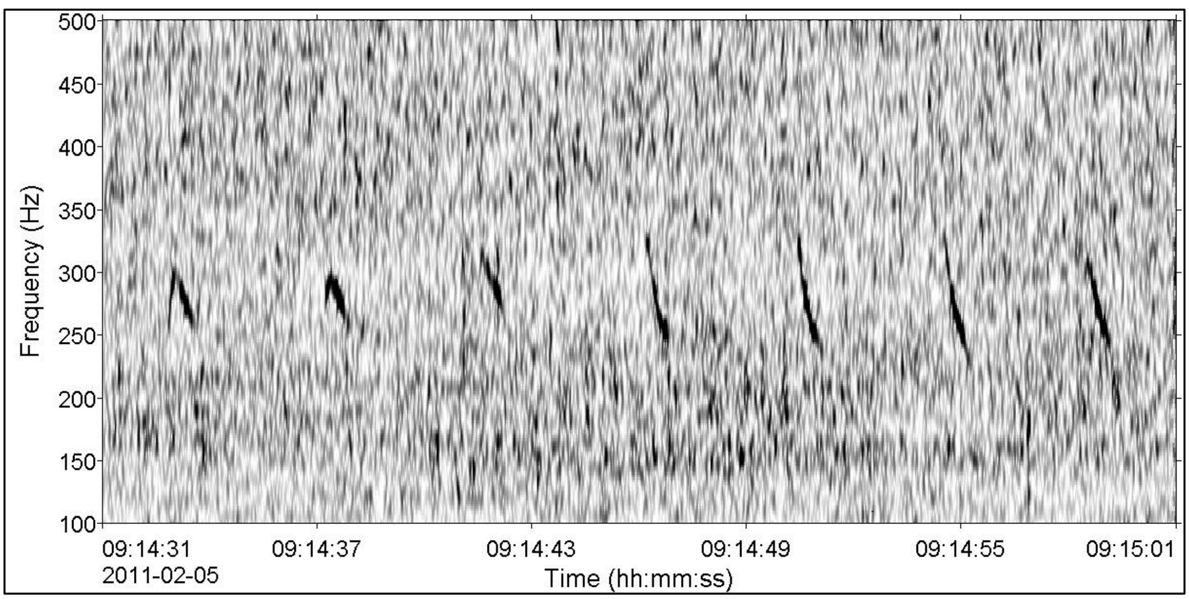

Figure 3-25. Humpback whale moans recorded off offshore Delaware Bay on 5 Feb 2011 (frequency resolution: 2 Hz; frame size: 0.1 s; time step: 0.025 s; Reisz window).

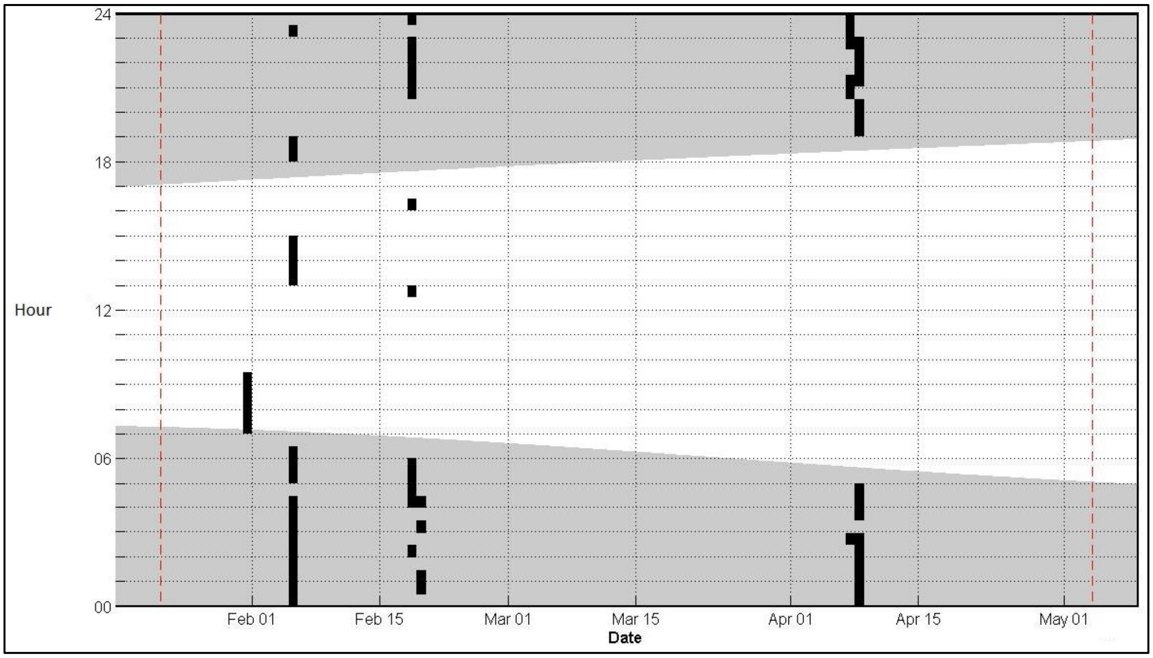

Figure 3-26. Half-hourly occurrence of humpback whale calls between 22 Jan and 1 May 2011 based on the manual analysis of 5% of the data. Each black rectangle represents a 30-minute sound file. The red dashed lines show the recording start and end. The shading indicates hours of darkness from sunset to sunrise (Begler 2009).

3.1.3.5. Delphinid Detections

Calls of unidentified delphinid species were detected on 31 days during the third deployment. Most detections occurred from early February to early March and in the second half of April 2011. There were no detections between 18 Mar and 20 Apr 2011.

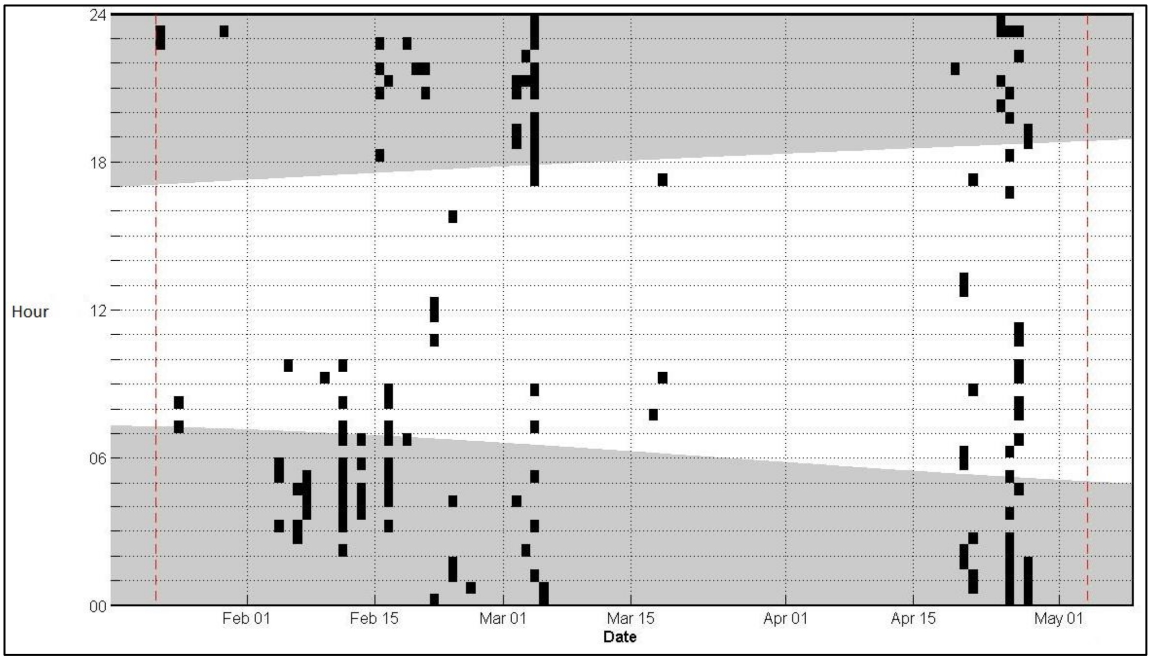

Figure 3-27. Half-hourly occurrence of unknown delphinid calls between 22 Jan and 1 May 2011 based on the manual analysis of 5% of the data. Each black rectangle represents a 30-minute sound file. The red dashed lines show the recording start and end. The shading indicates hours of darkness from sunset to sunrise (Begler 2009).

3.1.3.6. Fish Detections

No prominent fish sound sounds were detected during the third deployment although buzzes, grunts, and thumps, presumably produced by fish or invertebrates, occurred occasionally.

3.1.4. Deployment 4, May–August 2011

3.1.4.1. Weather and Ambient Noise

Weather data from NOAA Buoy 44009 in offshore Delaware Bay were obtained (Figure 3-28). During Deployment 4, the offshore Delaware Bay water temperature rose from approximately 12 °C in early May to about 26 °C in June through August. Although wind speed remained low compared to the other deployments, wave heights were higher in May.

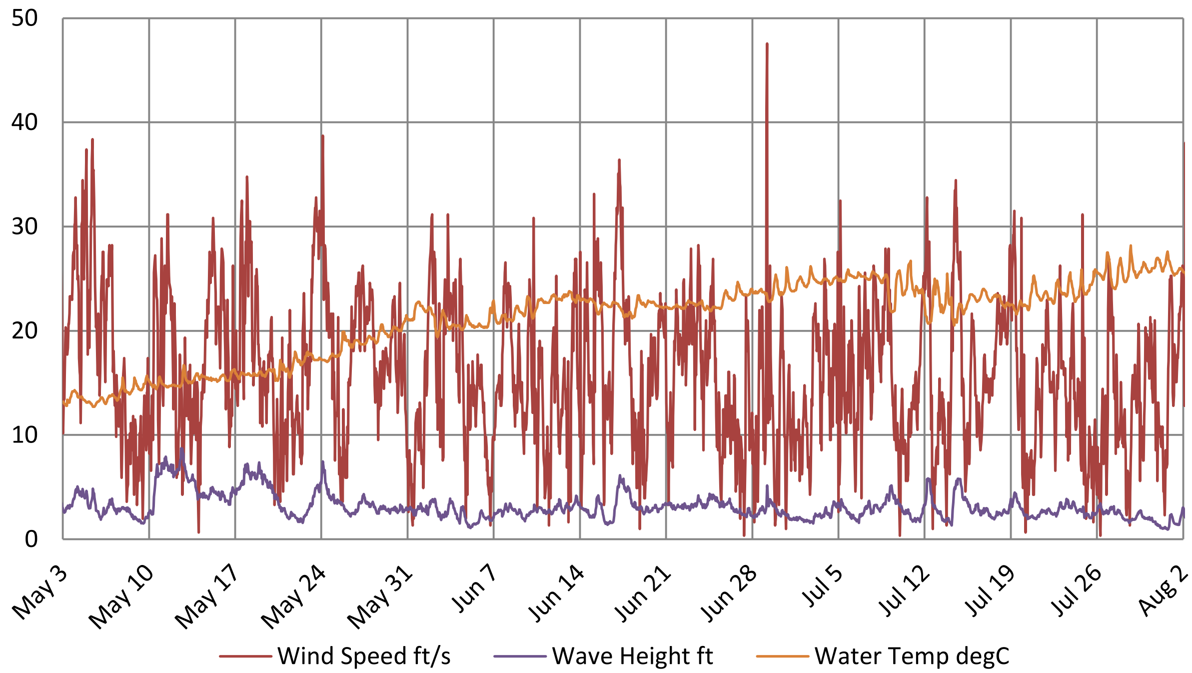

Figure 3-28. Weather data during Deployment 4 in offshore Delaware Bay.

The spectral composition over time of the acoustic recording is shown as a spectrogram in Figure 3-29. Diurnal variations in sound level are evident as vertical stripes in the spectrogram from mid-June to the end of the recordings. Low frequency (<100 Hz) tonal signals from heavy shipping or similar anthropogenic activity is evident during Deployment 4. Throughout May large wave heights also contributed to the low frequency sound levels.

Percentile spectral levels of recorded sound were calculated and compared to the Wenz curves limits of prevailing noise (Figure 3-30). During Deployment 4, the ambient sound levels were well predicted by the Wenz curves except below 100 Hz where the 5th percentile exceeded the maximal Wenz curve prediction. Heavy shipping (and possibly wave activity) appears to account for these increased sound levels below 100 Hz.

Tonal signals produced by heavy shipping were detectable throughout Deployment 4, (Figure 3-19). A heavy shipping event was detected from 10 to 15 July as a ship was making a slow transit or was possibly at anchor with active generators.

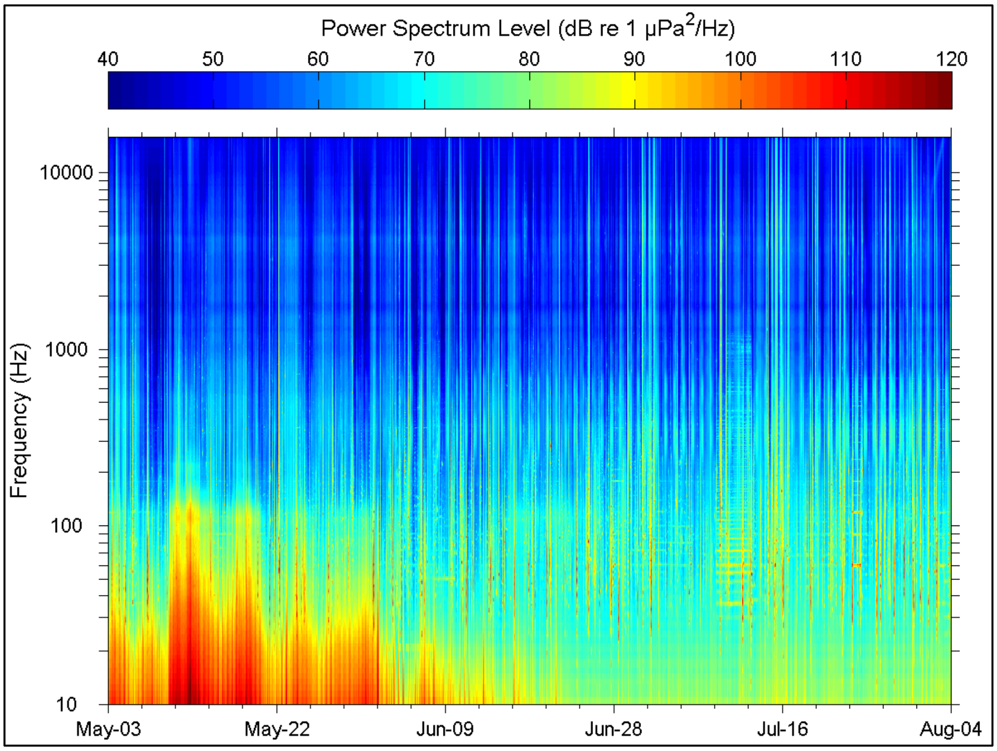

Figure 3-29. Spectral data from Deployment 4 in offshore Delaware Bay (32 000-point FFT, Hamming window, 50% overlap). Increased wave heights and wind speeds caused higher sound levels in May. A prominent shipping event can be seen in early to mid-July.

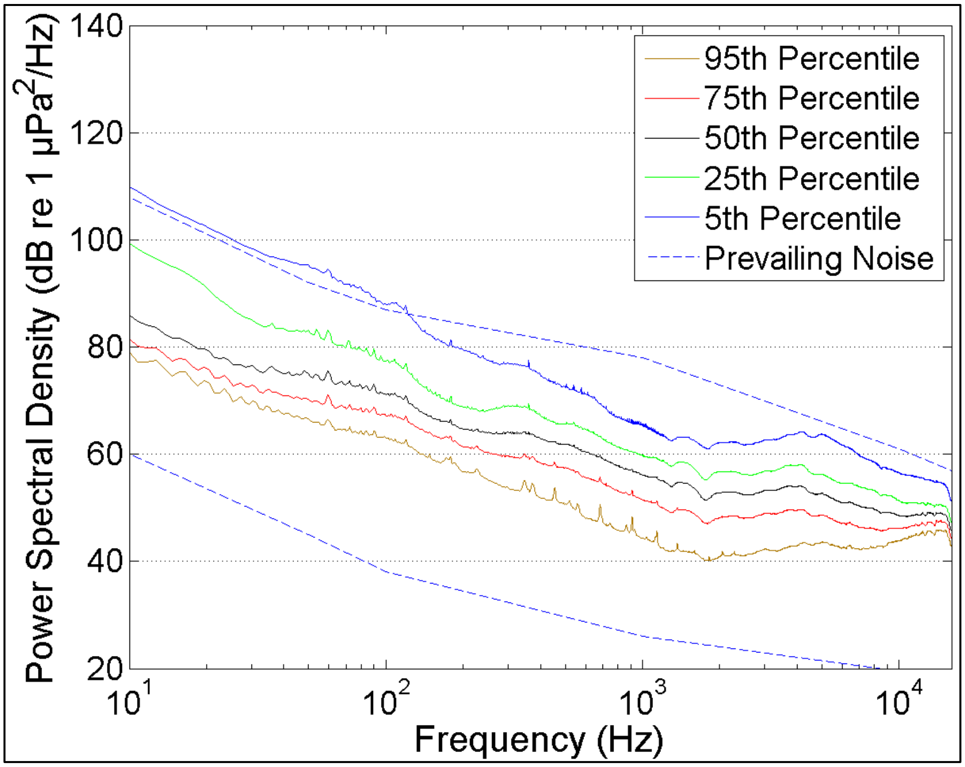

Figure 3-30. Percentiles of power spectral density levels of the ambient noise during Deployment 4 in offshore Delaware Bay, 3 May to 4 Aug 2011. The blue dashed lines indicate the limits of prevailing noise of the Wenz curves.

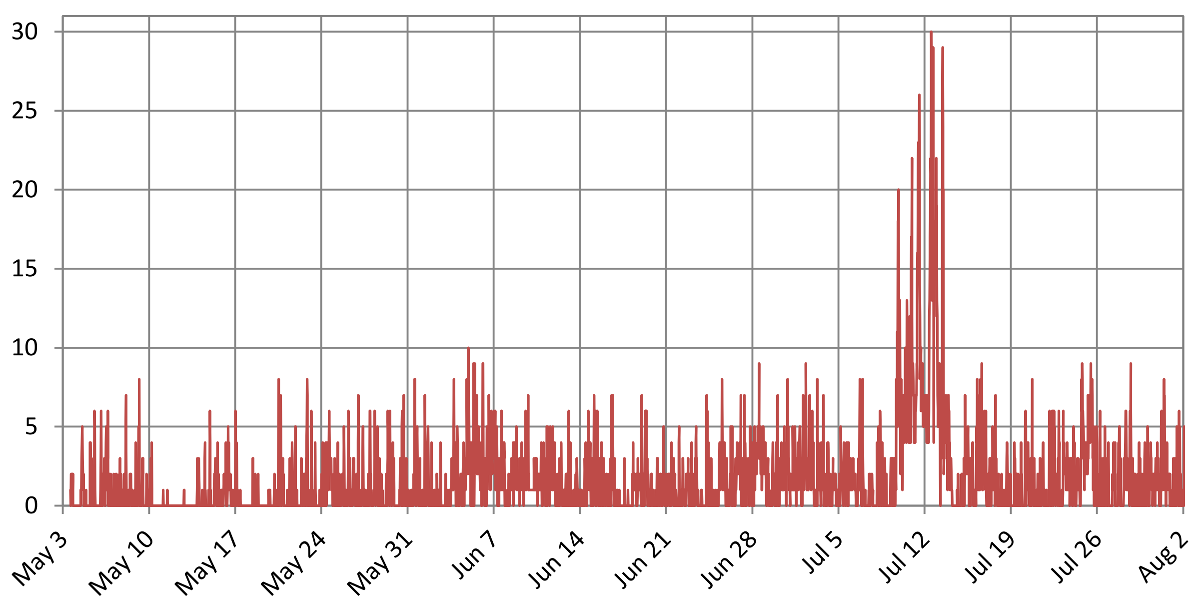

Figure 3-31. Shipping detections during Deployment 4 in offshore Delaware Bay.

3.1.4.2. Delphinid Detections

Delphinids were by far the most commonly detected species during this deployment. Calls were detected on each day of the deployment. No obvious diurnal calling pattern was noted although more calls were detected during hours of darkness from the second half of June onward (Figure 3-32). As for previous deployments, the calling species remain unidentified.

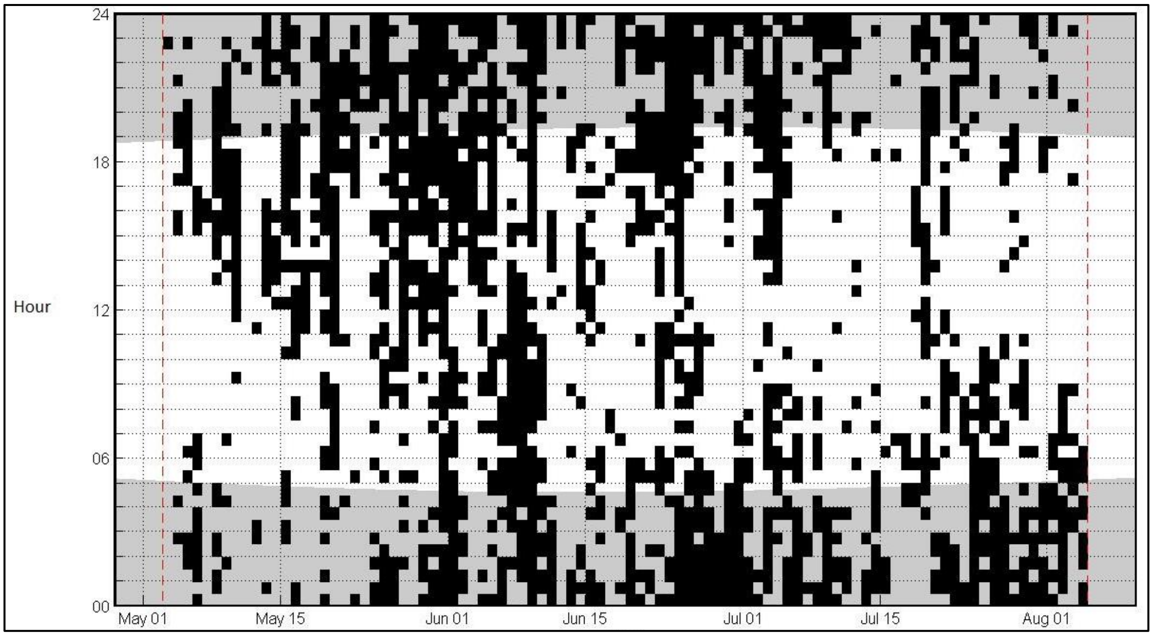

Figure 3-32. Half-hourly occurrence of unknown delphinid calls between 3 May and 3 Aug 2011 based on the manual analysis of 5% of the data. Each black rectangle represents a 30-minute sound file. The red dashed lines show the recording start and end. The shading indicates hours of darkness from sunset to sunrise (Begler 2009).

3.1.4.3. Fin Whale Detections

Fin whale calls were detected on seven days between 2 and 20 Jun 2011. Detections consisted exclusively of higher-frequency calls (Watkins 1981), and no songs were detected.

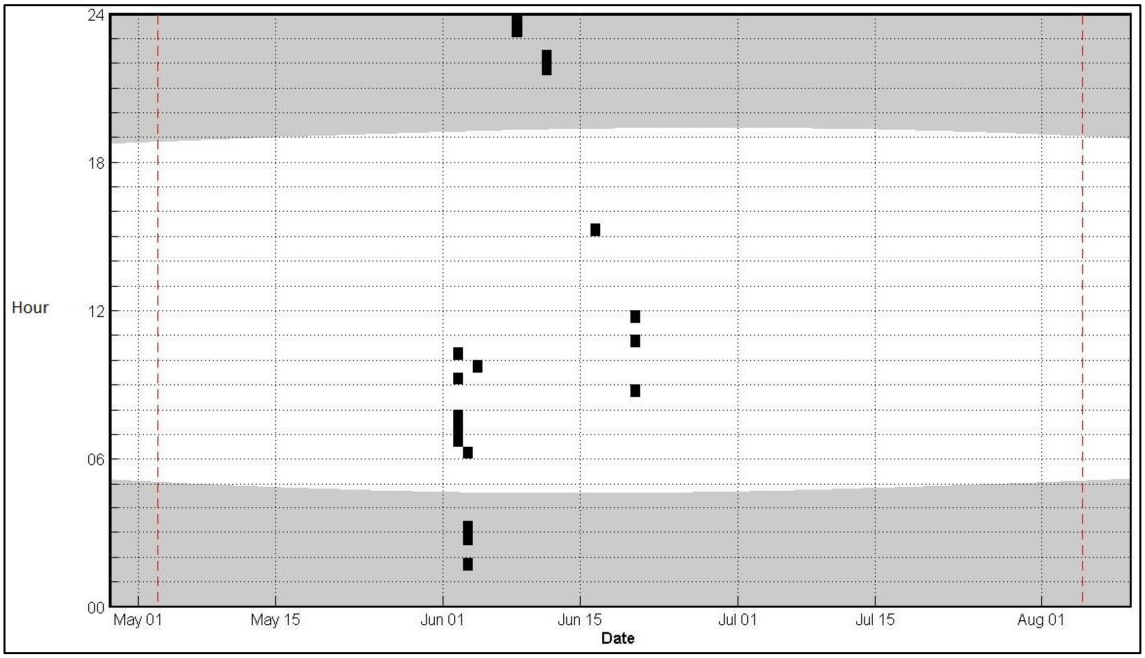

Figure 3-33. Half-hourly occurrence of fin whale calls between 3 May and 3 Aug 2011 based on the manual analysis of 5% of the data. Each black rectangle represents a 30-minute sound file. The red dashed lines show the recording start and end. The shading indicates hours of darkness from sunset to sunrise (Begler 2009).

3.1.4.4. Humpback Whale Detections

Humpback whale calls were detected once, on 2 Jun 2011.

3.1.4.5. Fish Detections

Similarly to Deployment 3, no prominent fish sounds were detected during Deployment 4 although buzzes, grunts, and thumps, presumably produced by fish or invertebrates, occurred occasionally.

2. NANTUCKET SOUND

3.2.1. Deployment 1, June–October 2010

No data were acquired in Nantucket Sound due to power failure during the deployment.

3.2.2. Deployment 2, October 2010 to January 2011

3.2.2.1. Weather and Ambient Noise

Weather data from NOAA Buoy 44020 in Nantucket Sound were obtained (Figure 3-1). During Deployment 2, the Nantucket Sound water temperature decreased continuously from 15 °C to about 5 °C. A series of weather events occurred that produced increased wave height, notably a major Nor'easter (the North America blizzard of 26–27 Dec).

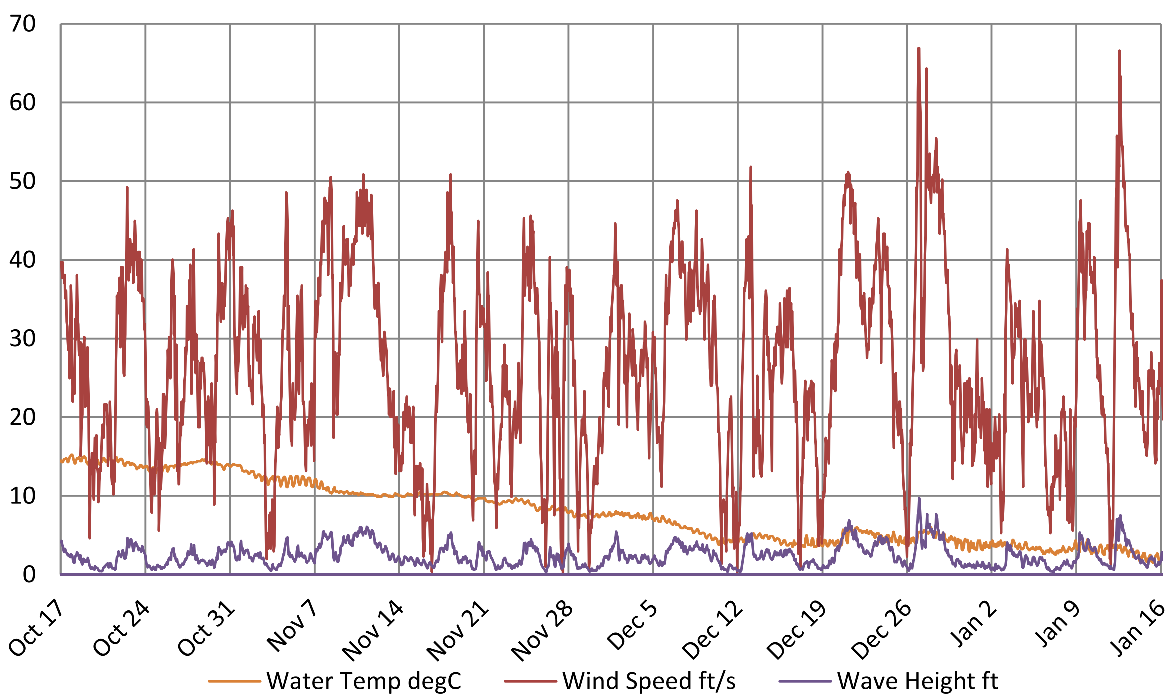

Figure 3-34. Weather data for Deployment 2 in Nantucket Sound. Water temperature, wind speed, and wave height from NOAA Buoy 44020.

The spectral composition over time of the acoustic recording is shown as a spectrogram in Figure 3-35. There are regular increases in noise from 100–1000 Hz that appear to relate to periods of higher wind speed. Overall, the spectrogram indicates that this period was relatively quiet, despite notable weather events. The percentile spectral levels (Figure 3-36) are well within the Wenz curve limits of prevailing noise. The 5th percentile shows several tonals in the 40–200 Hz range, which are likely attributed to the numerous, stereotyped fish sounds recorded from mid-December onward (see section 3.2.2.2; Figure 3-38). Tonal signals produced by heavy shipping were detected during Deployment 2 (Figure 3-19).

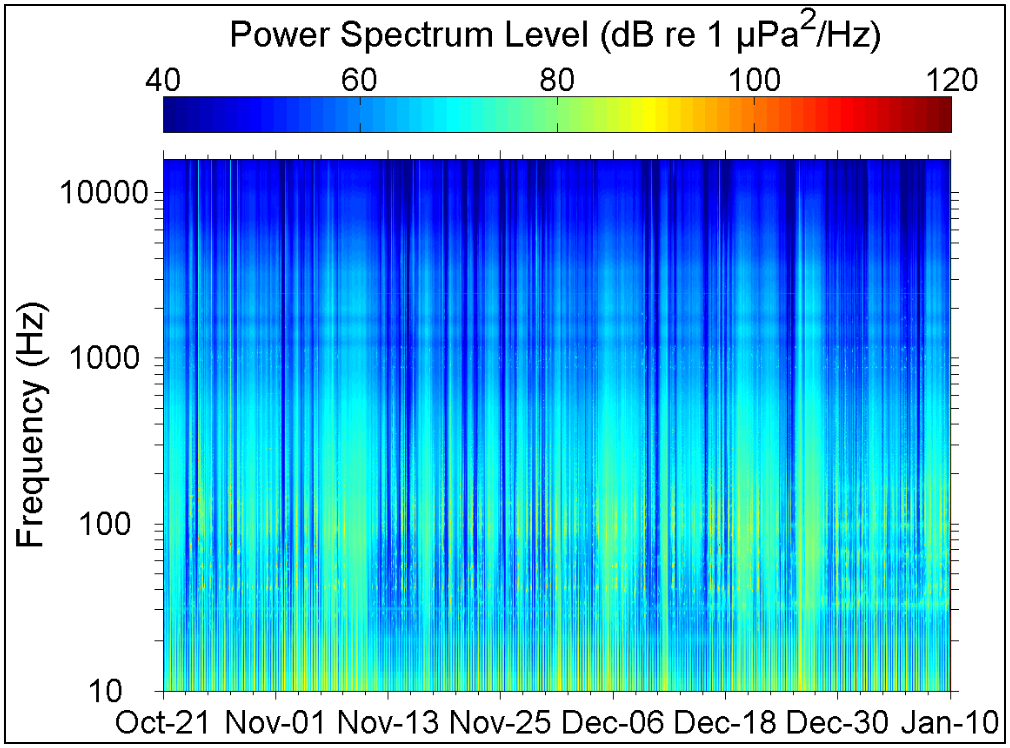

Figure 3-35. Spectral data for Deployment 2 in Nantucket Sound. Spectrogram of acoustic recording, 4 Oct 2010 to 10 Jan 2011 (32 000-point FFT, Hamming window, 50% overlap).

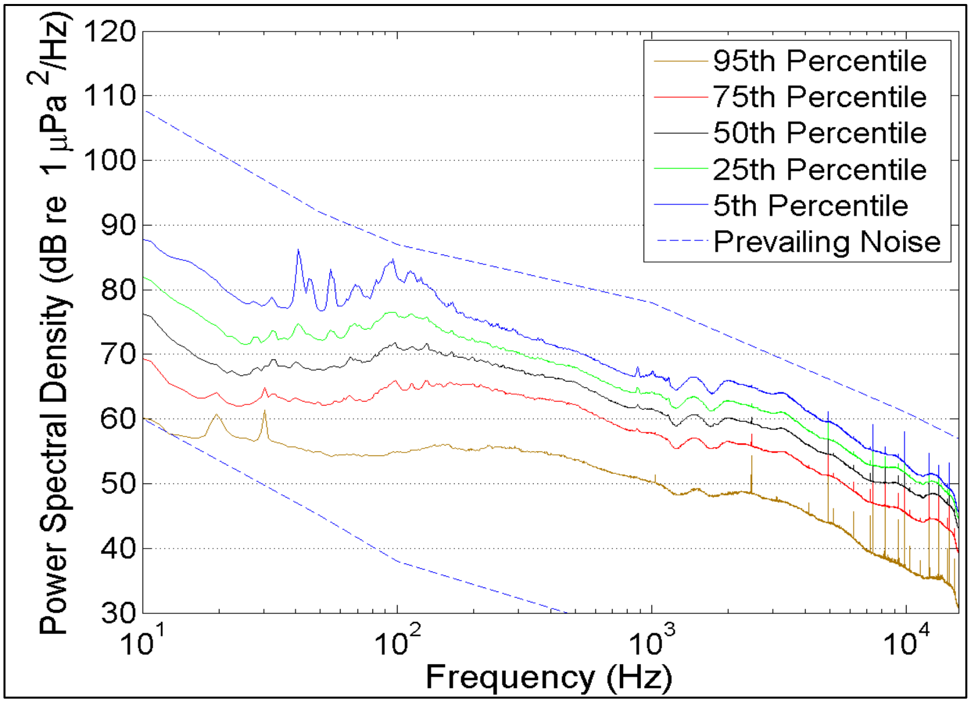

Figure 3-36. Percentiles of power spectral density levels of the ambient noise during Deployment 2 in Nantucket Sound. The blue dashed lines indicate the limits of prevailing noise of the Wenz curves.

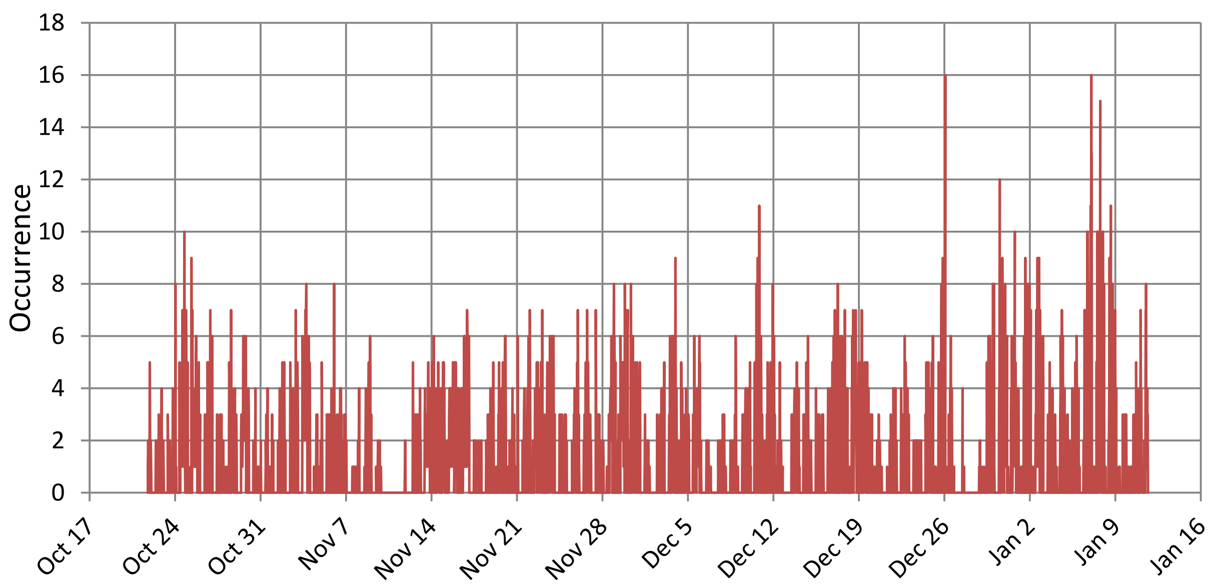

Figure 3-37. Shipping detections per 30 min file during Deployment 2 in Nantucket Sound.

3.2.2.2. Fish Detections

Stereotyped fish sounds (Figure 3-38) were detected from 12 Dec 2010 until the end of the deployment. Detections continued into the next deployment (see section 3.2.3.2). Although the first five days of detections showed evidence of a diurnal sound production pattern, sounds were detected almost continually thereafter (Figure 3-39). The source of these sounds is unknown.

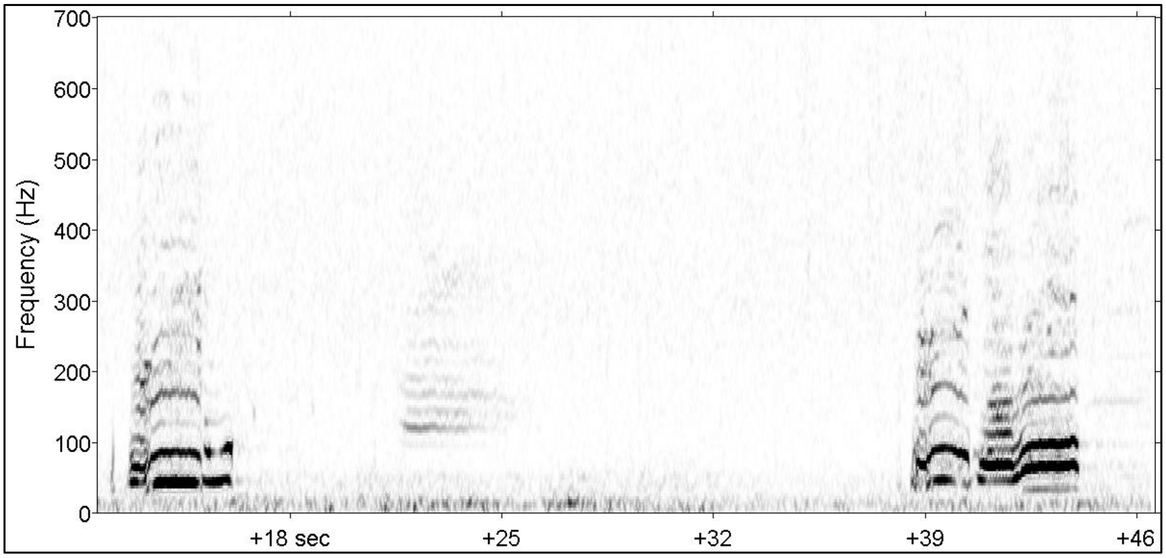

Figure 3-38. Unknown fish sounds recorded at the Nantucket site on 25 Dec 2011 (frequency resolution: 5 Hz; frame size: 0.128 s; time step: 0.032 s; Reisz window).

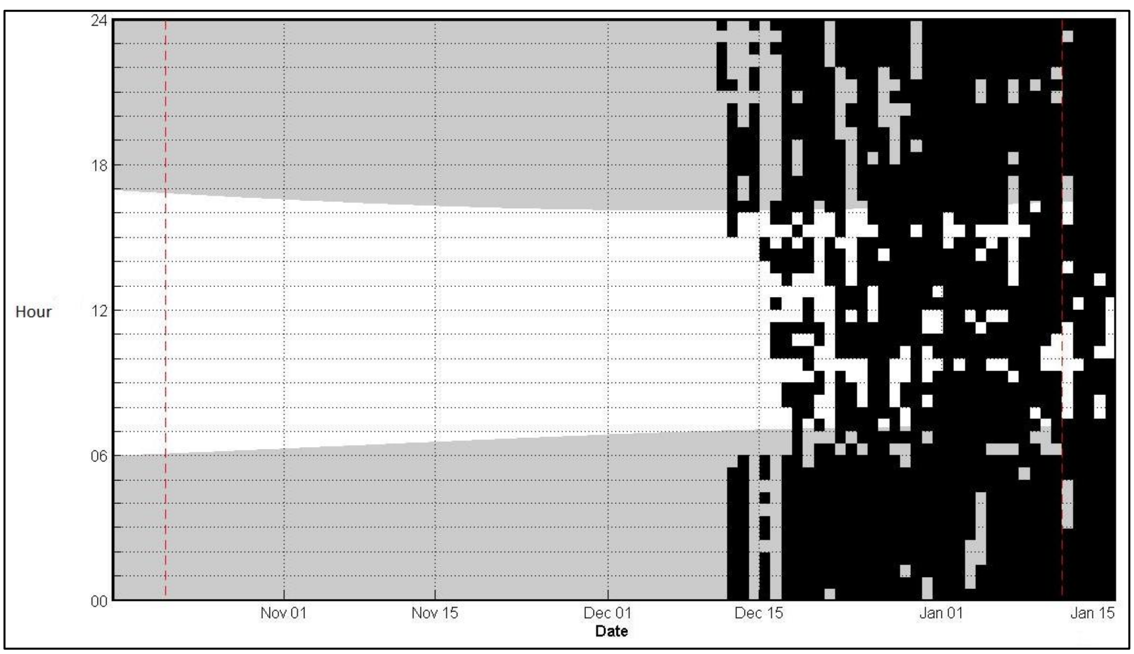

Figure 3-39. Half-hourly occurrence of unknown fish sounds (as in Figure 3-38) between 21 Oct 2010 and 11 Jan 2011 based on the manual analysis of 5% of the data. Each black rectangle represents a 30-minute sound file. The red dashed lines show the recording start and end. The shading indicates hours of darkness from sunset to sunrise (Begler 2009).

3.2.3. Deployment 3, January–April 2011

3.2.3.1. Weather and Ambient Noise

Weather data from NOAA Buoy 44020 in Nantucket Sound were obtained (Figure 3-1). During Deployment 3, the Nantucket Sound water temperature rose from 4 °C to about 10 °C. Wind and wave heights were high during some periods, but they were less pronounced than during Deployment 2.

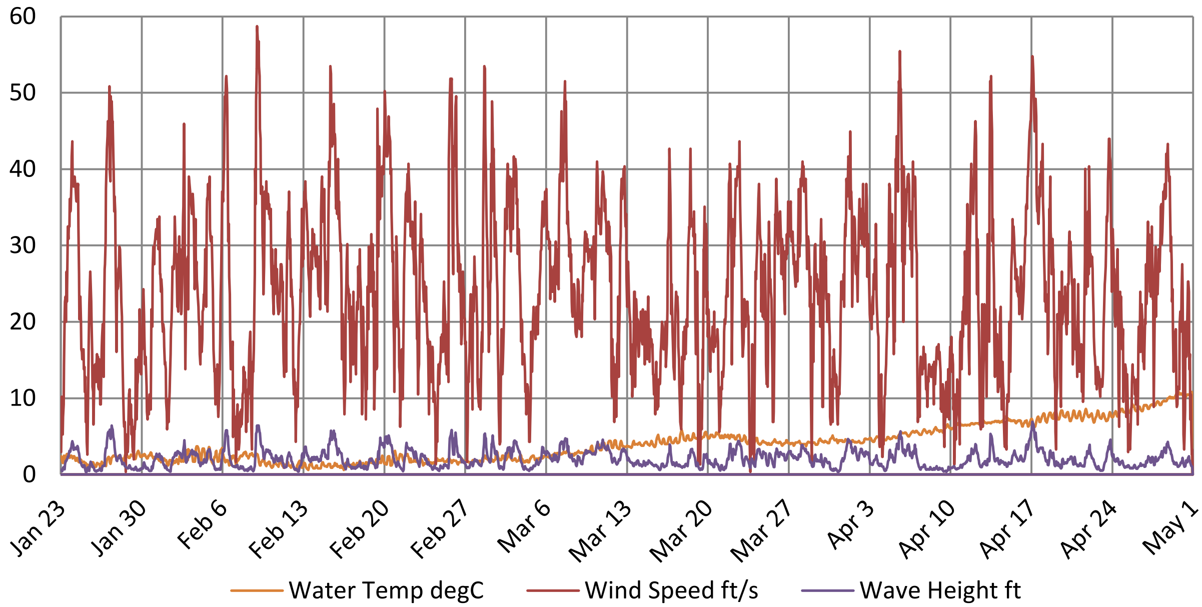

Figure 3-40. Weather data for Deployment 3 in Nantucket Sound. Water temperature, wind speed, and wave height from NOAA Buoy 44020.

The spectral composition over time of the acoustic recording is shown as a spectrogram in Figure 3-41. Overall, the spectrogram indicates this period was relatively quiet. Periods of elevated noise in the 100–1000 Hz band relate to extended periods of high wind speeds. The percentile spectral levels (Figure 3-42) are within the Wenz curve limits of prevailing noise. Shipping was detected regularly at levels comparable to the previous deployments (Figure 3-43).

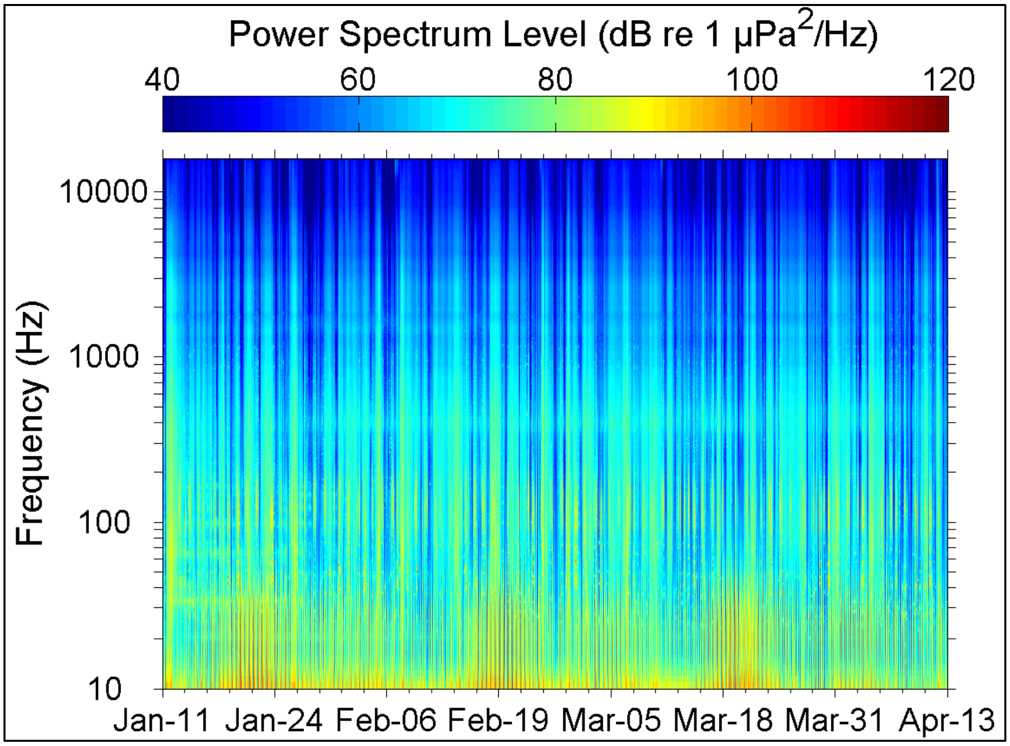

Figure 3-41. Spectral data for Deployment 3 in Nantucket Sound. Spectrogram of acoustic recording (32 000-point FFT, Hamming window, 50% overlap).

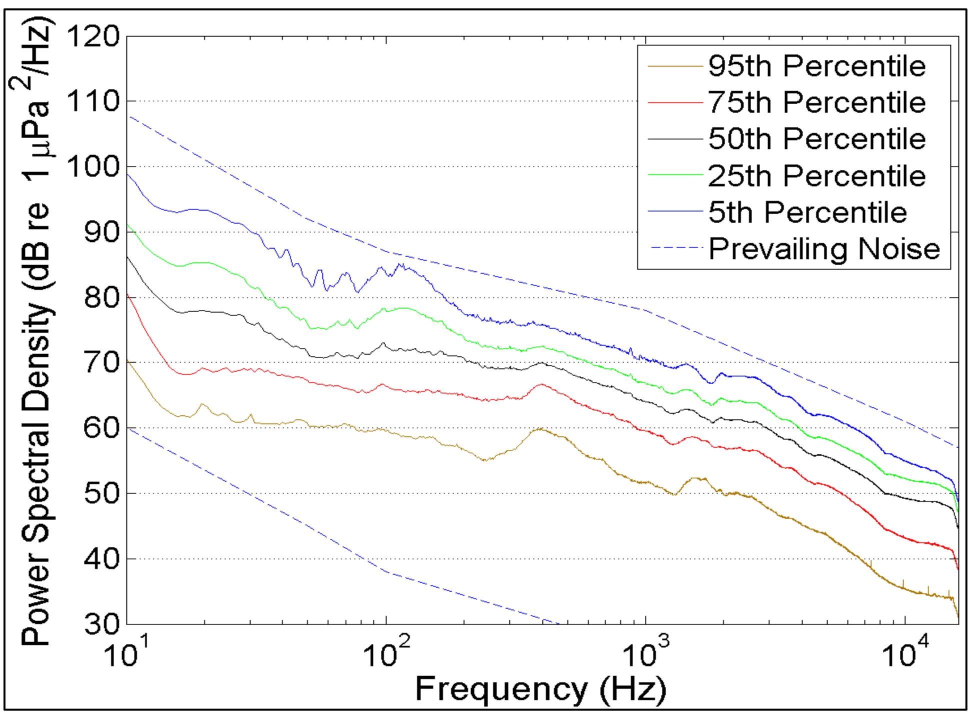

Figure 3-42. Percentiles of power spectral density levels of the ambient noise during Deployment 3 in Nantucket Sound. The blue dashed lines indicate the limits of prevailing noise of the Wenz curves.

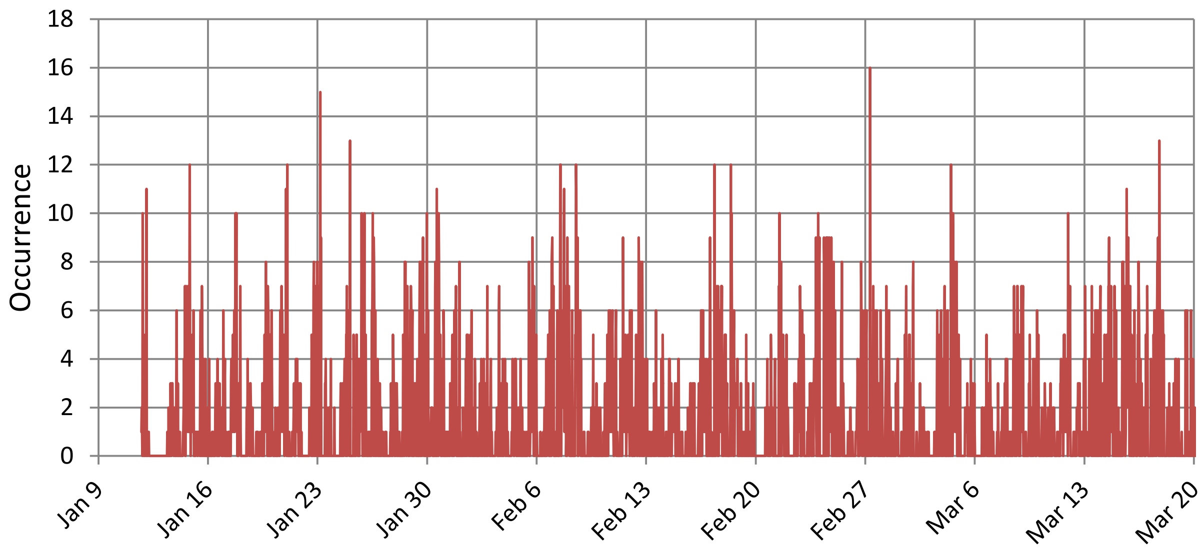

Figure 3-43. Shipping detections during Deployment 3 in Nantucket Sound. Detections per 30 min file.

3.2.3.2. Fish Detections

The fish sounds (see Figure 3-38) first detected during Deployment 2 continued until 3 Feb 2011 when they stopped abruptly. A few sporadic detections occurred on 5 and 9 Feb, 15 Mar, and 14 Apr 2011. The abrupt end of the detections may be due to movement of the fish out of the recorder's detection range or the soniferous behavior of that species may be seasonal.

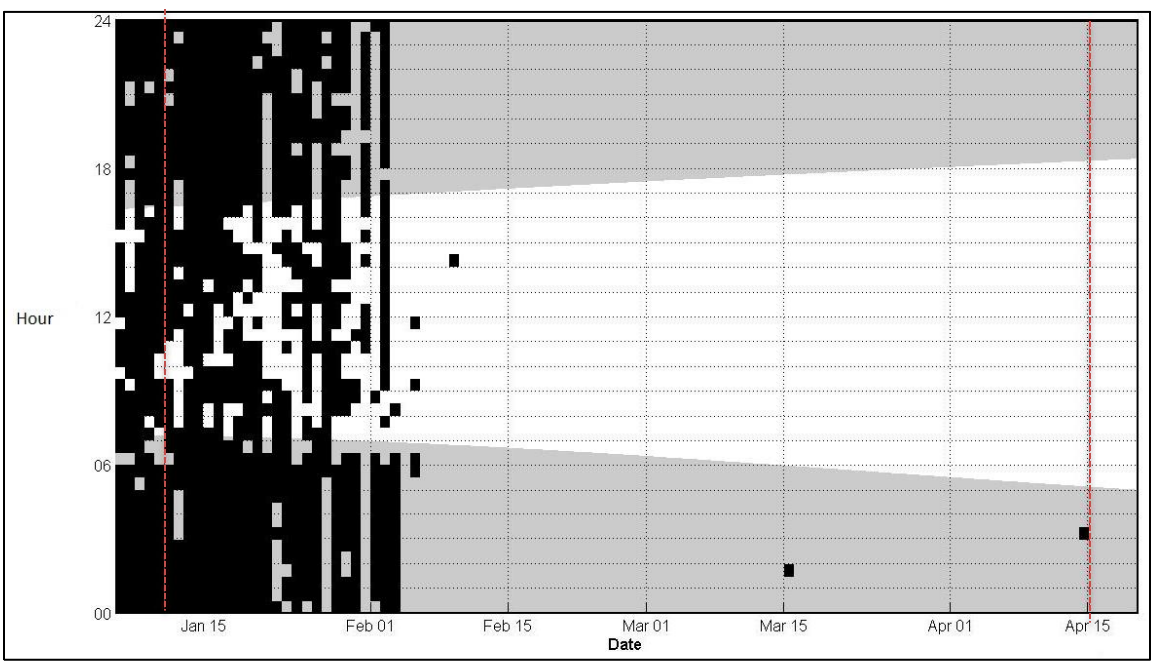

Figure 3-44. Half-hourly occurrence of unknown fish sounds (as in Figure 3-38) between 11 Jan and 14 Apr 2011 based on the manual analysis of 5% of the data. Each black rectangle represents a 30-minute sound file. The red dashed lines show the recording start and end. The shading indicates hours of darkness from sunset to sunrise (Begler 2009).

3.2.4. Deployment 4, April–August 2011

3.2.4.1. Weather and Ambient Noise

Weather data from NOAA Buoy 44020 in Nantucket Sound were obtained (Figure 3-45). During Deployment 4, the Nantucket Sound water temperature rose from approximately 5 °C in early April to about 21 °C in late August. Large weather events occurred in April and mid-May and became less intense through the summer.

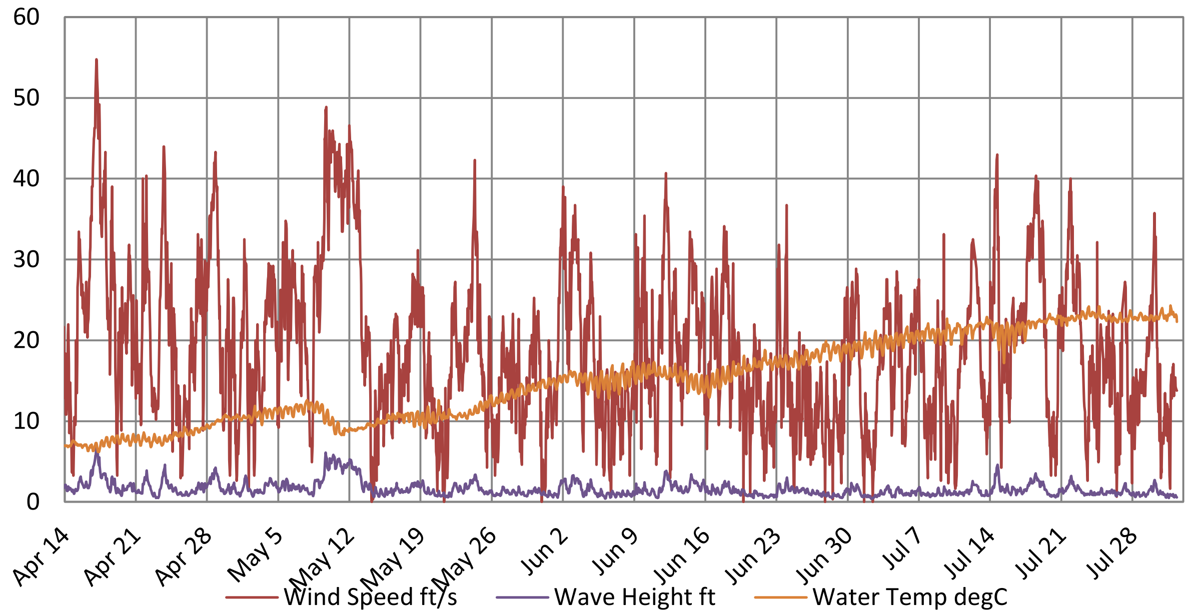

Figure 3-45. Weather data for Deployment 4 in Nantucket Sound. Water temperature, wind speed, and wave height from NOAA Buoy 44020.

The spectral composition over time of the acoustic recording is shown as a spectrogram (Figure 3-46). Some data from early May were lost due to a faulty memory chip. Diurnal variations are evident as vertical stripes throughout the rest of the spectrogram. Low-frequency noise events associated with weather occurred in April and May and to a lesser extent in June and July. Beginning in late June, sound energy between 800 and 3000 Hz increased. This was linked to the onset of striped cusk-eel choruses, whose energy is concentrated in two main bands centered near 1.4 and 2.2 kHz (see section 3.2.4.3 and Figure 3-12). Percentile spectral levels (Figure 3-47) exceeded the Wenz curve predictions in the frequency range of 800–3000 Hz. The percentile spectral levels (Figure 3-47) also show increased noise above 10 kHz, but this is an artifact associated with the faulty memory chip. Shipping was detected regularly at levels similar to the previous deployments (Figure 3-48).

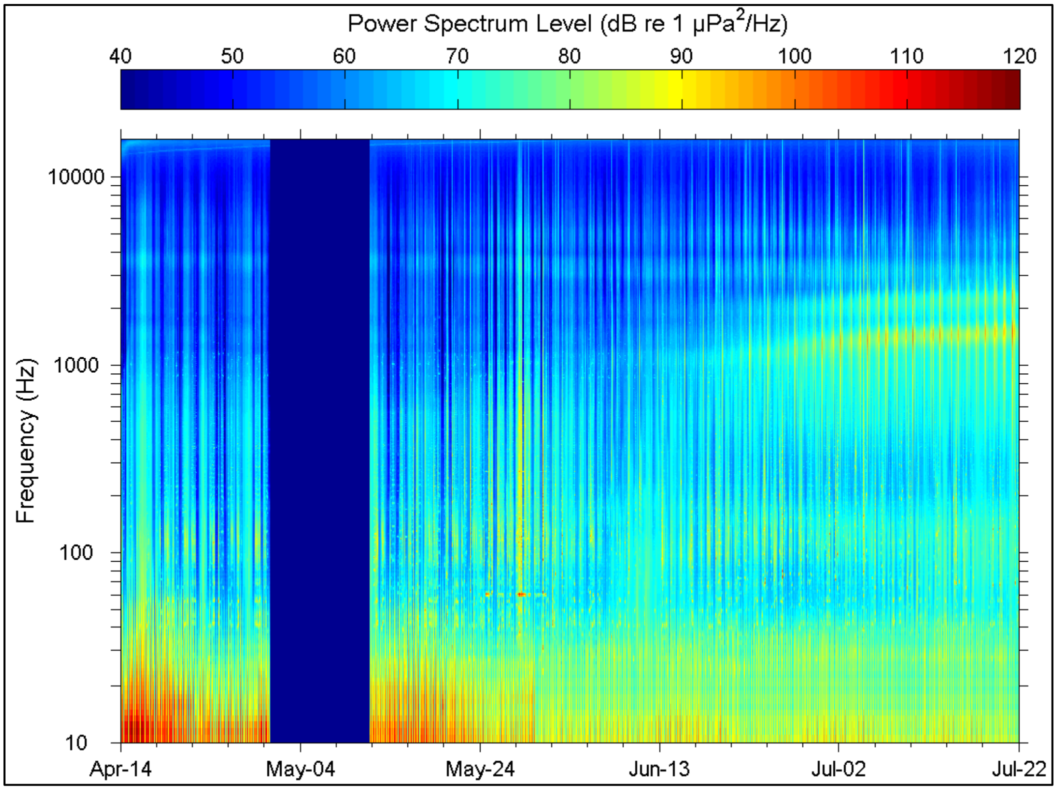

Figure 3-46. Spectral data for Deployment 4 in Nantucket Sound. Spectrogram of acoustic recording (32 000-point FFT, Hamming window, 50% overlap.). Data from early May were lost due to a faulty memory chip.

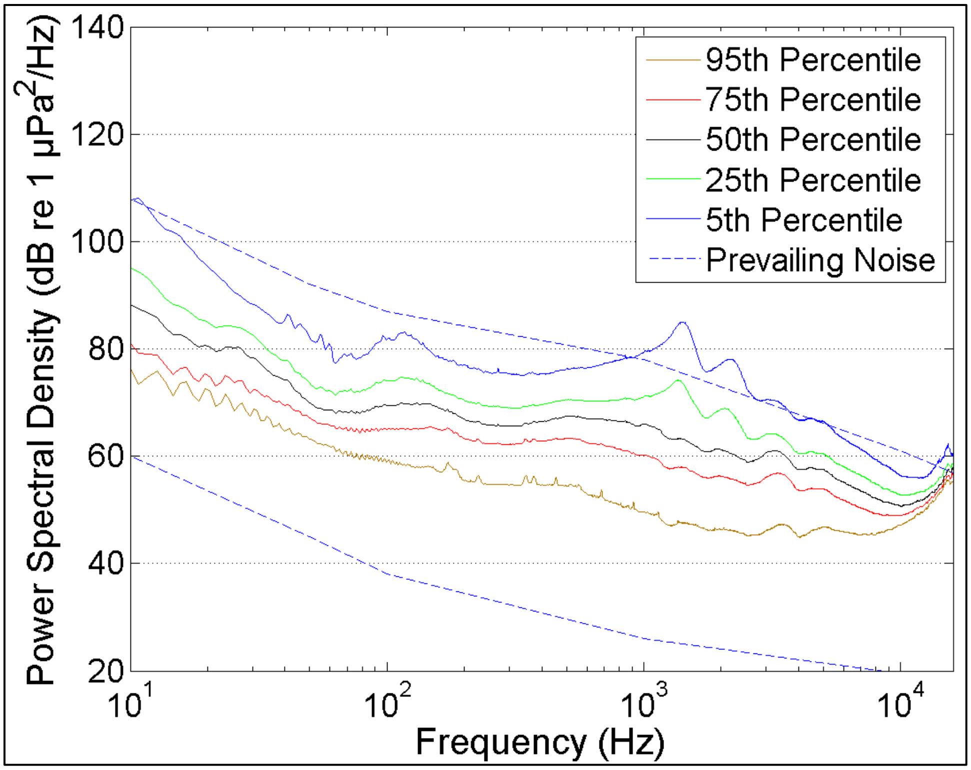

Figure 3-47. Percentiles of power spectral density levels of the ambient noise during Deployment 4 in Nantucket Sound. The blue dashed lines indicate the limits of prevailing noise of the Wenz curves.

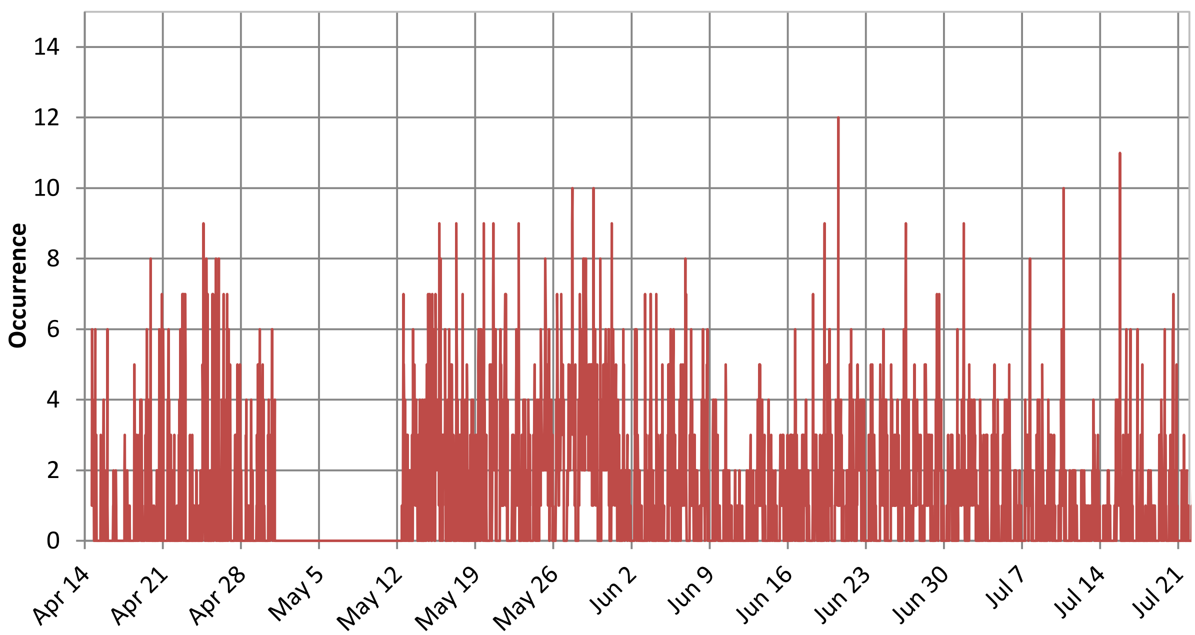

Figure 3-48. Shipping detections during Deployment 4 in Nantucket Sound. Detections per 30 min file. Data from early May were lost due to a faulty memory chip.

3.2.4.2. Right Whale Detections

Right whale upcalls were detected over a five-hour period on 27 Apr 2011.

3.2.4.3. Fish Detections

Striped cusk-eel chatter sounds (Figure 3-12) were the most conspicuous biological noise. As in the offshore Delaware Bay Deployment 1, they were preceded by knock trains (Figure 3-11). The first knock trains were detected on 30 Apr 2011. Although no data were recorded during the first two weeks of May, knocks were still present in low numbers by mid-May. Their occurrence increased progressively in the second half of May. The first cusk-eel chatter sounds were on 1 Jun. The knock sounds disappeared by the second week of June. Cusk-eel sounds were detected continuously thereafter until the end of the recordings (Figure 3-49). Sprague and Luczkovich (2001) noted an increase in the dominant frequency of chatter sounds with increasing water temperature. This may explain a similar increase in frequency visible in Figure 3-46 because the water temperature increased progressively during the recording period (Figure 3-45). The cusk-eel chatter sounds showed clear diurnal pattern where the sound level increased dramatically at dusk for a period of about 30 min (Figure 3-50).

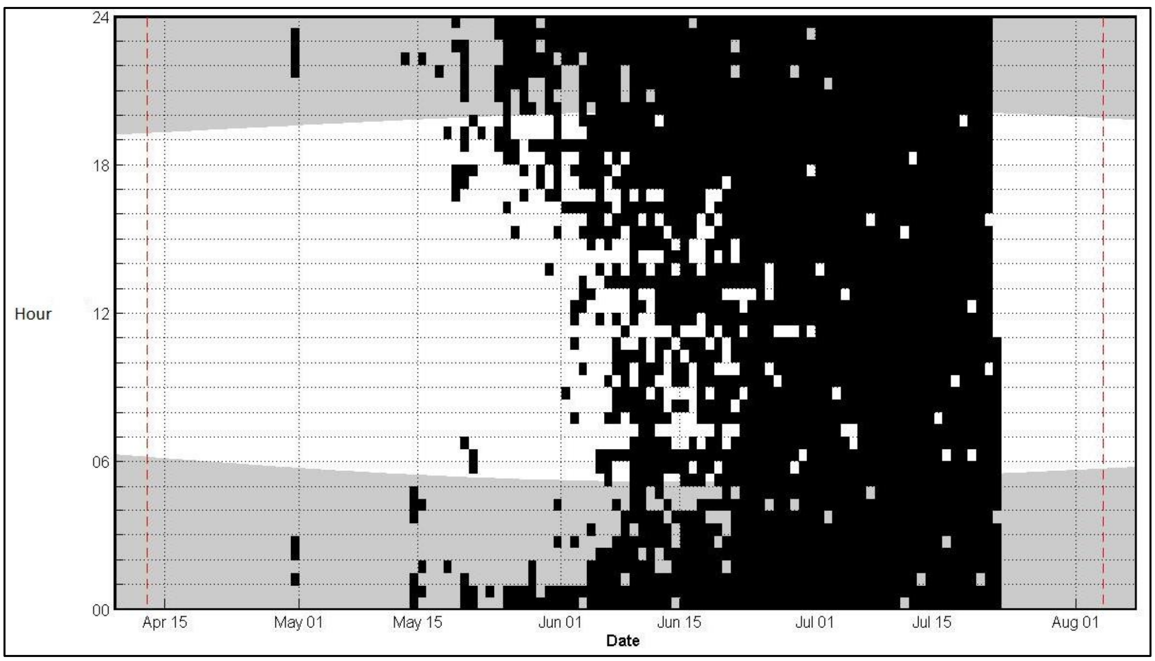

Figure 3-49. Half-hourly occurrence knock trains (30 Apr to 7 Jun) and striped cusk-eel chatter sounds (1 Jun until the end) between 14 Apr and 3 Aug 2011 based on the manual analysis of 5% of the data. Each black rectangle represents a 30-minute sound file. The red dashed lines show the recording start and end. The shading indicates hours of darkness from sunset to sunrise (Begler 2009).

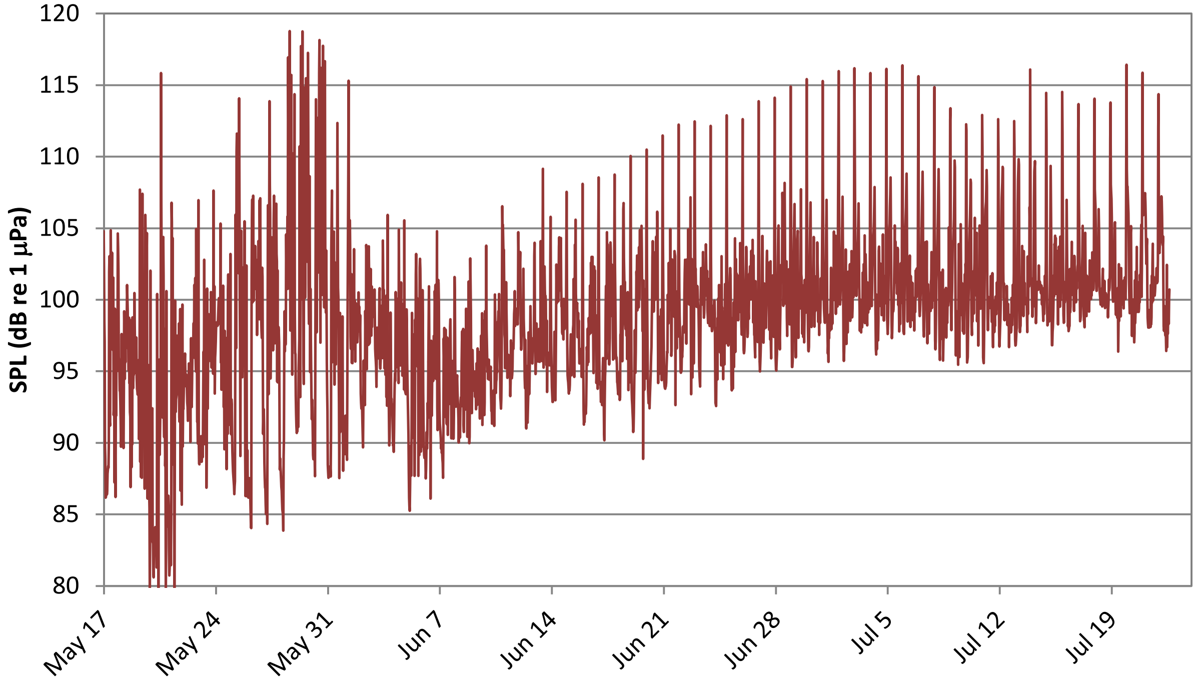

Figure 3-50. Broadband sound pressure level (SPL; 100–1000 Hz) during Deployment 4 in Nantucket Sound. A diurnal pattern appears in mid-June associated with fish choruses at dusk.

4. DISCUSSION

The objective of this project was to provide a statistical description of sound levels and sources at two locations likely to be developed for wind energy capture. This preconstruction description of sound levels and sources provides a baseline that can later be used for comparisons, such as during construction, operation, and maintenance of the wind farms. These baseline descriptions can also be compared to other sites. The ambient noise was recorded over one year, with the year divided into four deployments.

Analysis of ambient sound begins with spectrograms of the recordings. Diel (usually diurnal) fluctuation can be seen in the spectrograms of some deployments. This daily pattern is likely due to fish choruses.

The statistical distribution of ambient sounds levels was presented as percentile histograms of the spectral density values. Percentile levels for the 5th, 25th, 50th, 75th, and 95th percentiles are given, where the 50th percentile is equal to the median of the spectral distribution and the 95th percentile is the level exceeded by 95% of the data (see Section 2.3.1). The 95th percentile represents the quietest noise state that is expected to occur. The 5th percentile represents the loudest state expected to occur and is typically due to occasional events such as nearby shipping, extreme weather, or intense biological activity. As a measure of relative overall sound levels and as an indication of possible sources of sound, the percentile spectral levels were compared with the Wenz curve limits of prevailing noise (see Figure 2-4), which represent the contributions of various sound sources to ambient sound levels in the oceans. In general, the Wenz curves are reasonable predictors of the ambient noise levels at the two locations; however, there are frequency bands and seasons when sound levels are greater than predicted by the Wenz curves.

Both manual and automated detection of some sources was performed on the recordings in an effort to identify prominent sources of sound. Heavy shipping noise was found at each site throughout the year and contributed to the ambient sound levels at lower frequencies (10–1000 Hz). This anthropogenic sound, either from shipping or a related activity, such as fishing, could exceed the maximal predictions of the Wenz curves (e.g., offshore Delaware Bay Deployment 3). Boating, such as pleasure or fishing vessels, was also routinely detected and contributed the overall ambient noise levels. Natural sources contributed to the ambient sound levels and also exceeded the predictions of the Wenz curves. Large storms, such as Hurricanes Earl and Igor during Deployment 1 in offshore Delaware Bay, produced rain and wind with high waves that increased the sound levels. Storms were common in spring and fall, but less frequent in winter and summer.

1. BIOLOGICAL ACTIVITY

Biological activity was found in all deployments. Delphinids were detected only in offshore Delaware Bay and were most common from early May until mid-August. Occurrence was low in winter and no calls were detected from mid-March to mid-April 2011. The species producing the detected whistles and clicks remain unidentified, primarily because of a lack of published call descriptions for several species that may occur in this area. Shipboard and aerial surveys conducted by NOAA’s Northeast Fisheries Science Center and Southeast Fisheries Science Center during the summers of 1998, 1999, 2002, 2004, 2006, and 2007 indicate several delphinid species that could have produced the detected calls (whistles and clicks) occur along the eastern seaboard at or near the latitude of Delaware. These include bottlenose (*Tursiops truncatus*), Risso's (*Grampus griseus*), short-beaked common (*Delphinus delphis delphis*), Atlantic spotted (*Stenella frontalis*), striped (*Stenella coeruleoalba*), and rough-toothed (*Steno bredanensis*) dolphins and short-finned (*Globicephala macrorynchus*) and/or long-finned (*Globicephala melas melas*) pilot whales (Waring et al. 2011). Except for bottlenose dolphins, all species were sighted exclusively near or beyond the shelf break, i.e., far from the inshore, shallow deployment location. The distribution of these species during fall through spring is unknown, but they are all known to be associated with the shelf break. Although one cannot rule out some occasional intrusions on the continental shelf closer to shore, this leaves bottlenose dolphins as the most likely source of most of the detections.

The stock structure of bottlenose dolphins along the eastern seaboard is complex and distinguishes offshore, coastal, and estuarine stocks of bottlenose dolphins. Coastal bottlenose dolphins are further distinguished among northern migratory and southern migratory coastal stocks. In summer, northern migratory coastal bottlenose dolphins range from New Jersey south to the mouth of Chesapeake Bay inshore of the 25 m isobaths (the offshore Delaware Bay recorder was deployed in 18 m of water). In winter, they migrate south and occupy coastal waters from Cape Lookout, North Carolina, to the North Carolina-Virginia border (Waring et al. 2011). This is consistent with the observed patterns of acoustic occurrence, with maximum detections in the summer, decreasing detections in the fall and few to no detections in winter and early spring (Waring et al. 2011). The northern extent of the southern migratory coastal stock is between Cape Lookout, North Carolina and east Virginia; therefore, they are not expected to have come within range of the offshore Delaware Bay recorders. Northern migratory coastal bottlenose dolphins are likely responsible for a large portion of the detections.

Offshore bottlenose dolphins occur mainly along the outer continental shelf and continental slope of the western Atlantic Ocean. In winter, the offshore morphotype has occurred close to shore south of Cape Hatteras, North Carolina (Waring et al. 2011). A similar shift in distribution may occur off Delaware, possibly explaining some of the winter acoustic detections.

Fin whales were the dominant cetacean species detected in winter. Most fall and all winter detections consisted of songs (see e.g., Watkins et al. 1987). Song structure has been shown to vary geographically and may be used as an index of stock structure (Hatch and Clark 2004, Delarue et al. 2009, Castellote et al. 2011). The detected songs matched those recorded in the Gulf of Maine and off New York (Morano et al. 2012), suggesting that fin whales from these areas and off Delaware are affiliated. The end of detections in the second half of February presumably coincides with a northern movement of fin whales toward their summer feeding grounds off the northeastern U.S. Indeed, calling rates are high during the main period when fin whales display songs (August–April in the North Atlantic; Neukirk et al. 2012) so it is unlikely that fin whales were present and not calling during that period. Additionally, high calling rates yield a good detection probability with the 5% analysis protocol that was used. In summer, sound production is less regular (Watkins 1981) so the 5% analysis protocol may underestimate fin whale occurrence.

Right whales were detected on a few occasions at the offshore Delaware Bay site and once at Nantucket Sound. These low numbers of detections may be surprising, considering that the offshore Delaware Bay recorder lay within the migration corridor of that species, which migrates annually between breeding grounds off Georgia and Florida and feeding grounds off the New England and Maritime Canada coast (Firestone et al. 2008). Indeed, the offshore Delaware Bay recorder was about 16 nautical miles (nmi) from the coast and 94.1% of all sightings recorded in the Mid-Atlantic region (between 31°15′ and 41°20′ N and west of 69°45′ N) occurred within 30 nmi from shore; however, 64% of all sightings were within 10 nmi from shore (77% within 15 nmi; Knowlton et al. 2002). At the latitude of the Delaware recorder, few right whale sightings have been recorded, and most of them were within 5 nmi from shore (Knowlton et al. 2002), which could explain the low number of detections. The migration corridor appears to extend much farther offshore south of Long Island and farther north, which likely explains why right whales were detected at the Nantucket site for only a few hours on a single day. A study that modeled the timing of right whale migration found that the average period of transit off Delaware is in the first week of April ± 15 days (Firestone et al. 2008). No detections occurred during this period.

Another factor that may have affected right whale detection is their calling rate in conjunction with the chosen analysis protocol (5% manual review). Parks et al. (2011) have found right whales to be relatively quiet when traveling, as would be expected near the Delaware recorder. A low-coverage analysis protocol may, therefore, miss calls produced sporadically; however, most of the detected calls were upcalls and these are produced by all age and sex classes (Parks et al. 2011). The verification of upcall automated detections yielded a single detection that was not previously found by manual analysts, suggesting that the 5% manual review provides a reliable view of right whales' acoustic occurrence.

Fish proved to be a substantial source of noise in both deployment areas. Notable loud events of prolonged duration occurred that often exceeded the Wenz curves, such as the striped cusk-eel chatter sounds in offshore Delaware Bay and Nantucket Sound between June and October and the unidentified calls recorded in Nantucket Sound between mid-December and early February. More work is needed to assign most of the recorded sounds to species. The delay in the onset of the chatter sounds between Nantucket (early June) and Delaware (late August) could be due to a southern shift in distribution of striped cusk-eels during the summer, or the environmental conditions required for spawning may have developed at different times in the two areas.

2. Ambient and Anthropogenic Sound Levels

4.2.1. Variations over Time

To determine how ambient sound levels in offshore Delaware Bay change throughout the year, the 95th, 50th, and 5th percentile values are compared for Deployments 1, 3, and 4 (Figure 4-1). The sound levels are, in general, comparable between the deployments except for the sound levels between 200 and 4000 Hz, where the 5th percentile for Deployment 1 is considerably higher than for Deployments 3 and 4. The increased energy in this frequency band was attributed to striped cusk-eel sounds; therefore, the primary cause of seasonal variation in sound levels at the offshore Delaware Bay site was biological activity. Contributions from weather and anthropogenic sources were relatively constant.

The same 95th, 50th, and 5th percentile values were compared for the year at the Nantucket Sound site (Figure 4-2). Again, the sound levels are, in general, comparable between the deployments. And again, a notable exception was found between about 200 and 4000 Hz where the sound energy in this band is considerably higher at the 5th percentile during Deployment 4 than during Deployments 2 and 3. The increased energy in this frequency band was also cusk-eel chatter sounds, indicating that the primary driver of seasonal variation in sound levels at the Nantucket site was also biological activity.

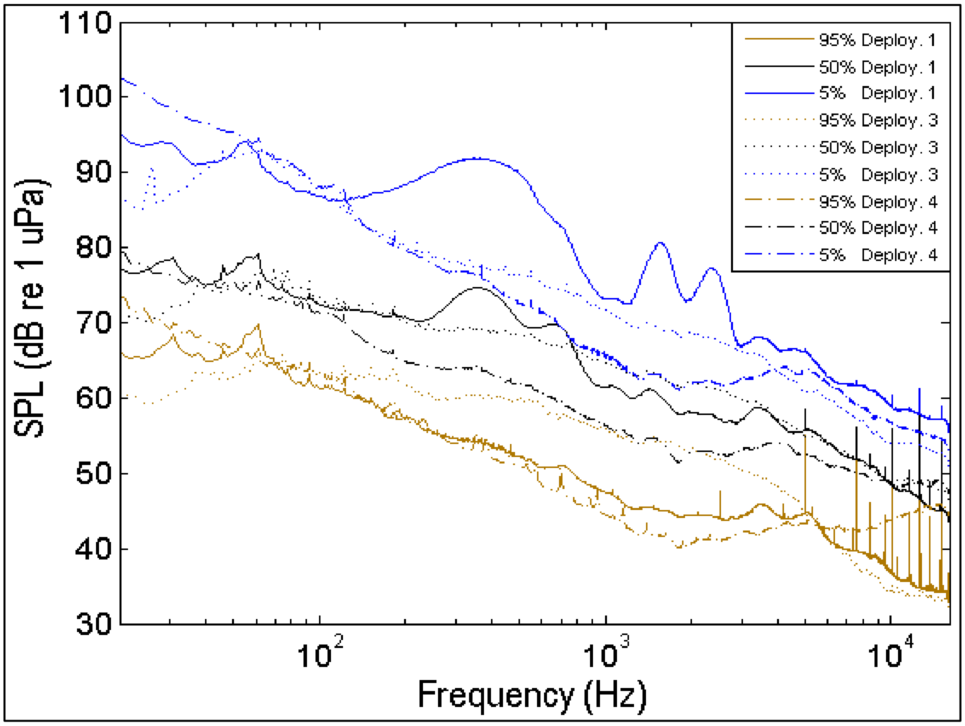

Figure 4-1. The 5th, 50th, and 95th percentiles of sound pressure levels during Deployments 1, 3, and 4 in offshore Delaware Bay.

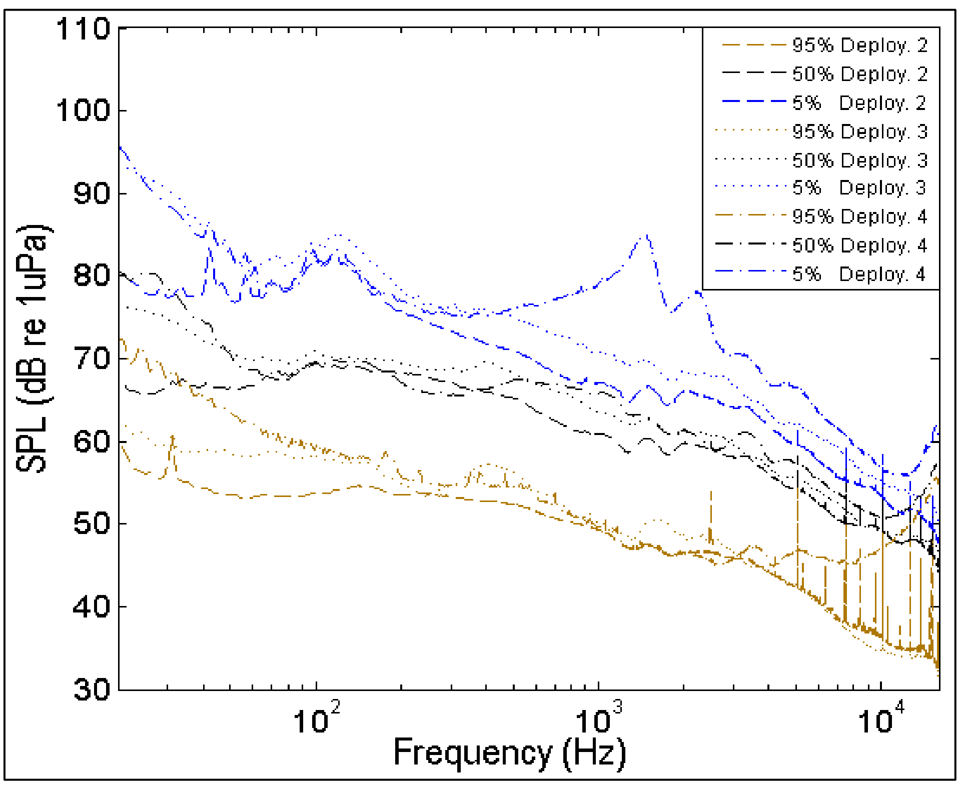

Figure 4-2. The 5th, 50th, and 95th percentiles of the sound pressure levels during Deployments 2, 3, and 4 in Nantucket Sound.

4.2.2. Variations between Sites

By subtracting the ambient sound levels measured at the Nantucket Sound site from those at the offshore Delaware Bay site, a direct comparison between the two test sites can be made for Deployments 3 and 4 (Figure 4-3). Figure 4-3 shows that for frequencies between 40 and 100 Hz the ambient noise at the offshore Delaware Bay site is consistently louder than at the Nantucket Sound site. During Deployment 3 in offshore Delaware Bay, heavy shipping and anthropogenic sounds were pronounced and likely account for the higher ambient levels at these frequencies. At higher frequencies (100–6000 Hz) the difference between the offshore Delaware Bay and the Nantucket Sound sites is consistently positive for the 95th percentile, which indicates that the quietest times in offshore Delaware Bay were louder than the quietest times in Nantucket Sound. Shipping and possibly other anthropogenic activity likely account for the elevated sound levels during the quietest times in offshore Delaware Bay relative to Nantucket Sound. Deployment 3 was during colder months (January to April), so shipping, boating, and other human activities may have decreased or stopped periodically in the colder climate of Nantucket Sound, more so than in offshore Delaware Bay. The small difference between sites in the 5th and 50th percentiles indicates that the overall ambient sound levels and the sources of sound are similar at the two sites.

Subtracting the sound levels at the Nantucket Sound site from those at the offshore Delaware Bay site for Deployment 4 (Figure 4-4) shows that identifiable sources and events determined the relative levels at each site. Figure 4-4 shows that in the low-frequency band (40–100 Hz) the sound levels in offshore Delaware Bay are greater than in Nantucket Sound. During Deployment 4 in offshore Delaware Bay, shipping noise was prevalent, exceeding the Wenz curve predictions, and accounting for the difference in sound levels at low frequencies between the sites. At higher frequencies (800–1300 Hz) the sound levels in Nantucket Sound were greater than in offshore Delaware Bay (negative values in Figure 4-4). The high sound levels in this frequency range in Nantucket Sound were due to soniferous fish.

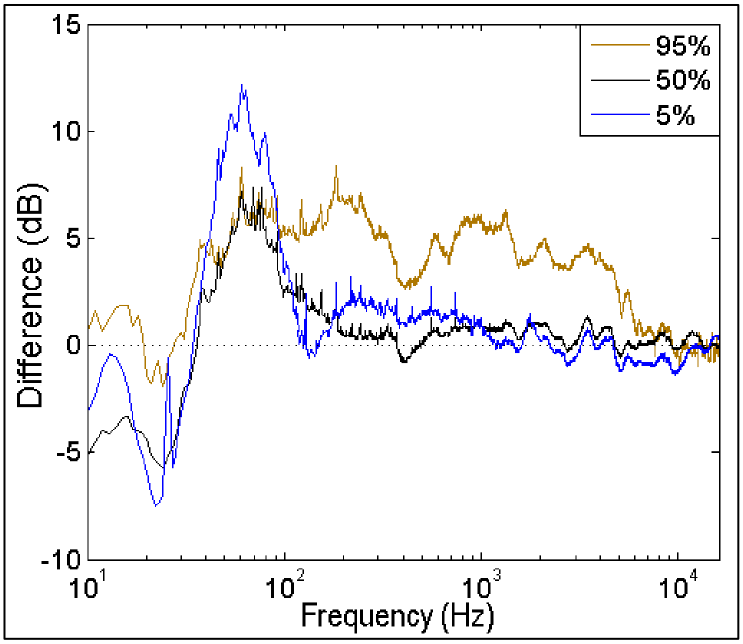

Figure 4-3. Deployment 3 sound pressure level difference (offshore Delaware Bay minus Nantucket Sound).

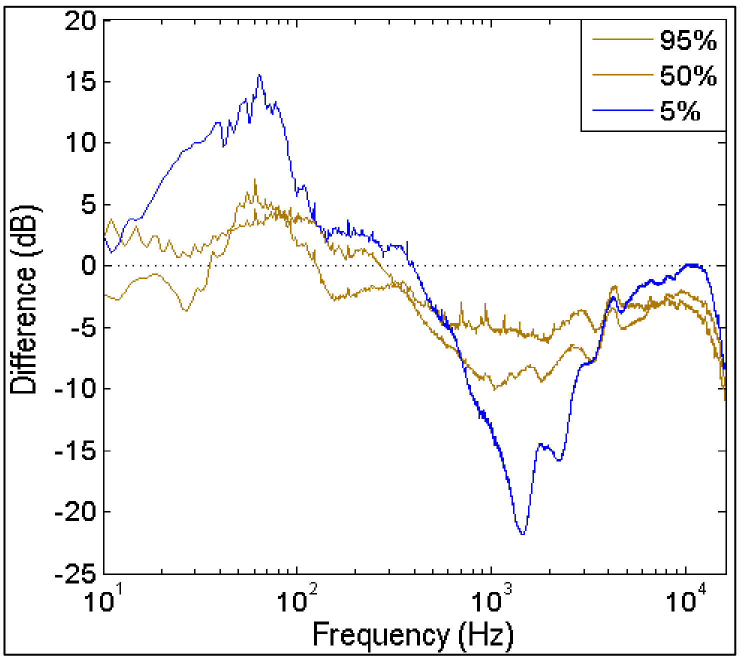

Figure 4-4. Deployment 4 sound pressure level difference (offshore Delaware Bay minus Nantucket Sound).

5. CONCLUSIONS AND RECOMMENDATIONS

Percentile-level descriptions of the ambient sound levels over one year at offshore Delaware Bay and Nantucket Sound were determined and compared with the envelope values of the Wenz curves. The Wenz curves were reasonable predictors of the ambient noise levels at the two locations, but there were frequency bands and seasons when sound levels exceeded the maximal values predicted by the Wenz curves. Both natural and anthropogenic sound sources exceeded the Wenz curves: heavy shipping and large storms at lower frequencies (<100 Hz) and biological sources (fish) at higher frequencies (200–4000 Hz). The ambient sound levels differed between the deployments at each site and between sites, but the differences are largely attributed to identifiable events and sources.

Future developments at the offshore Delaware Bay site should consider the presence of endangered right, fin, and humpback whales mainly from January to March. Delphinid occurrence, on the other hand, was lowest in winter and spring. Further work is needed to identify the fish species whose calls were detected at the Nantucket site in winter. Avoiding the two-month detection period, if it happens to be a species of commercial value to local fisheries, should be considered when planning future work. Although right whale calls were detected at the Nantucket site for a few hours in April 2011, marine mammals were essentially absent from this site.

The acoustic recordings provide an accurate acoustic baseline that may be used for comparisons to ambient levels during wind turbine construction. These baseline descriptions can also be used for comparison with other sites.

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Appendix A

STFT Analysis

The choice of short-term Fourier transform (STFT) parameters affects the overall performance of the detector and classifier. The available parameters and their impact are described in A-1. The effects of different STFT parameter choices on two signal types are shown in Figure A-1.

Table A-1.

Short-term Fourier Transform (STFT) Analysis Parameters

Parameter	Definition	Effect of Increasing	Effect of Decreasing
Fs, Sampling Rate (determined by data collection system)	Number of samples of the data acquired per second; Highest frequency that can be analyzed is one half the sampling rate. (Nyquist frequency limit).	Higher sampling rates result in more demanding signal processing.	Less information since there is less frequency range represented. Faster to process.
Analysis Window Length	Total number of data points in the FFT; For efficient FFT implementations this must be a power of 2.	Increases the frequency resolution, but decreases the time resolution. Frequency resolution is equal to 1/duration in time of the FFT (e.g., a 2 s long FFT has a resolution of 0.5 Hz). Longer is better for signals where the frequency changes slowly in time.	Short durations are better if the signal frequencies change rapidly in time.
Zero Padding	The actual data samples that are in the FFT may be less than the FFT length if the remaining points are zero, which is known as zero padding.	Increasing the zero padding allows the analysis to keep a high frequency resolution, but have better time resolution. This technique provides a better resolution, but does not improve the ability to discriminate two closely spaced tonal frequencies–that requires more data and a longer FFT.	Some signals have constant frequencies for short durations, which are best represented by long FFTs with less actual data in the FFT.
Analysis Window Advance	The number of data points that the data flow advances with each FFT. For example, a 2048 point FFT advances by 25% or 512 data points.	Provides lower time resolution, speeds up the analysis, and makes each output more sharply defined. A ‘window’ function in time is normally applied before an FFT to reduce frequency sidelobes. As a result there should always be some overlap to ensure all data is represented in the analysis.	A smaller advance will provide more output points when a signal is present thereby improving detection and contour following; however, this increases processing time due to data redundancy.

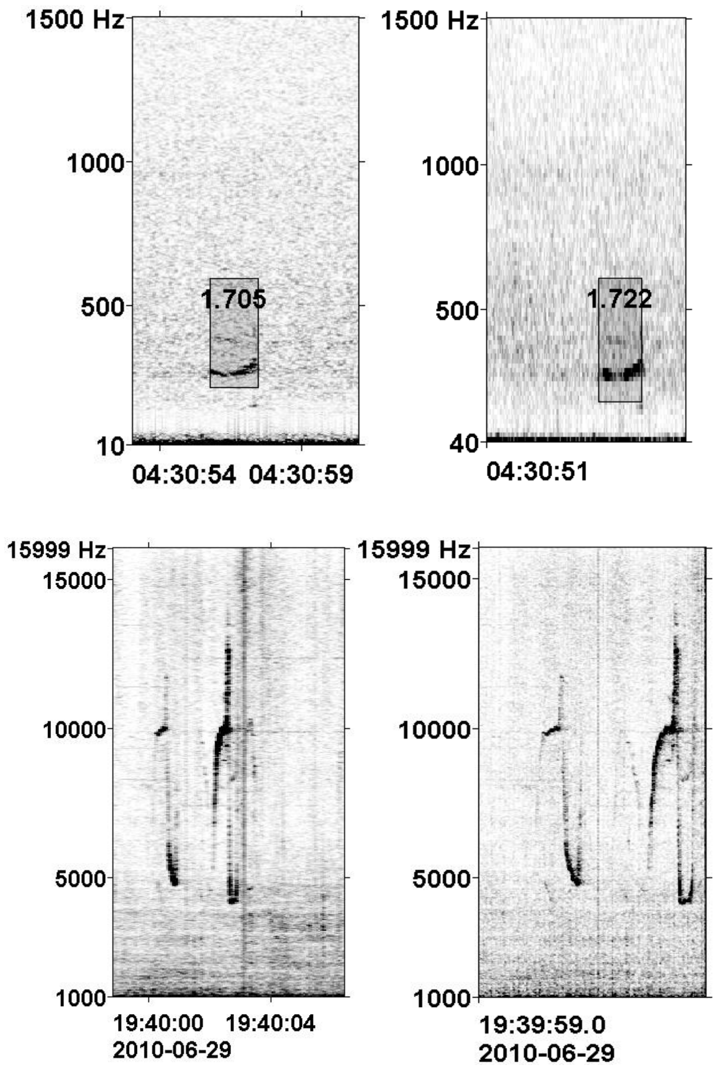

Figure A-1. Effects of different Short-term Fourier transform (STFT) settings. Top panels–humpback moan recorded at a sampling rate of 32 kHz. Top left-hand panel was analyzed with a 0.25 second analysis window, and an advance of 0.0625 s. Top right-hand panel was analyzed with a 0.0625 s analysis window and 0.016 s advance. Bottom panels–dolphin whistle processed with the same settings. The short settings are better suited to the rapidly changing dolphin whistle, while the longer settings are better suited to the slowly changing humpback moan.

Appendix B

Hydrophone Calibrations

A GRAS 42AC pistonphone calibrator, which is NIST traceable, was used to verify the sensitivity of the recording apparatus as a whole, i.e., the hydrophone, pre-amplifier, and AMARS for both lab and field calibrations. Single-frequency calibrations of each hydrophone channel were performed in the lab before mobilization and in the field before each deployment. The pistonphone produces a known pressure signal on the hydrophone element (a 250 Hz sinusoid) which verifies the pressure response of the recording system. Each hydrophone model has a custom-fit adapter that couples it to the pistonphone (Figure B-1). Ambient atmospheric pressure was measured with a Garmin GPSMap 76CX (at left of Figure B-1) to compensate for deviations in ambient pressure (from the nominal 1 atm) and increase the accuracy of the calibrations. The single-frequency measurements were used to correct the manufacturer’s nominal calibration curves for each hydrophone type for the actual sensitivity of the entire system.

Figure B-1. Example of a GRAS pistonphone calibrator on a hydrophone. Each hydrophone type has a customized adapter whose volume was measured with a NIST verified Larson-Davis Sound Level Meter.

Calibration Curves

M8E Hydrophones

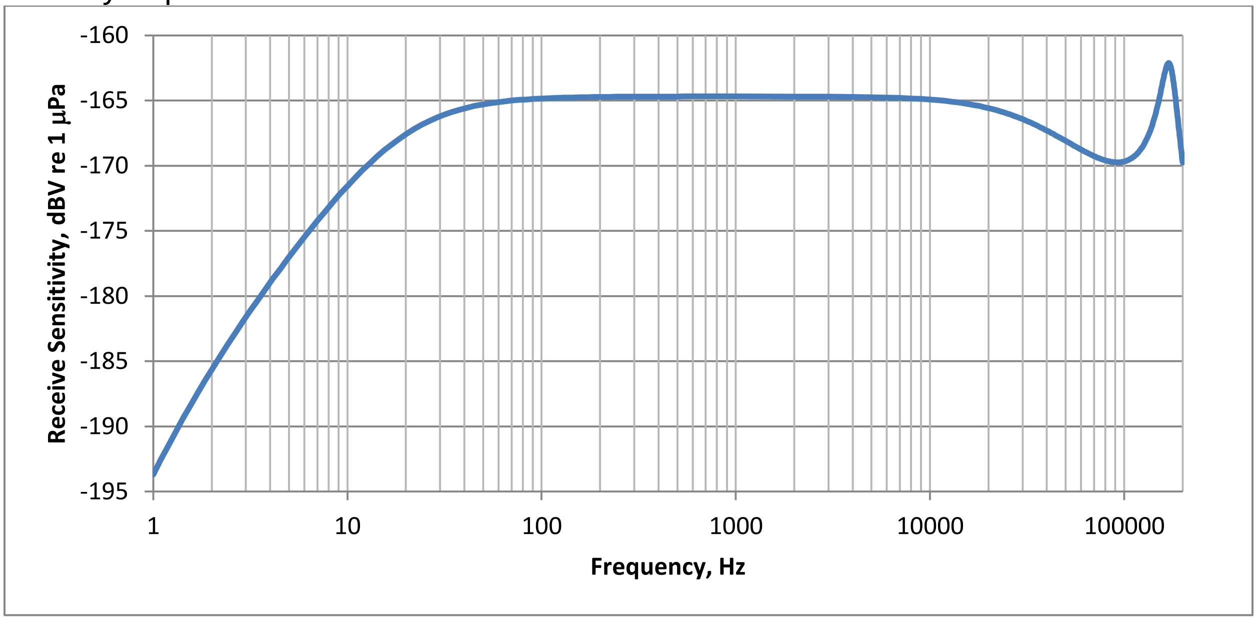

Figure B-2. M8E Nominal Calibration Curve

M15B Hydrophones

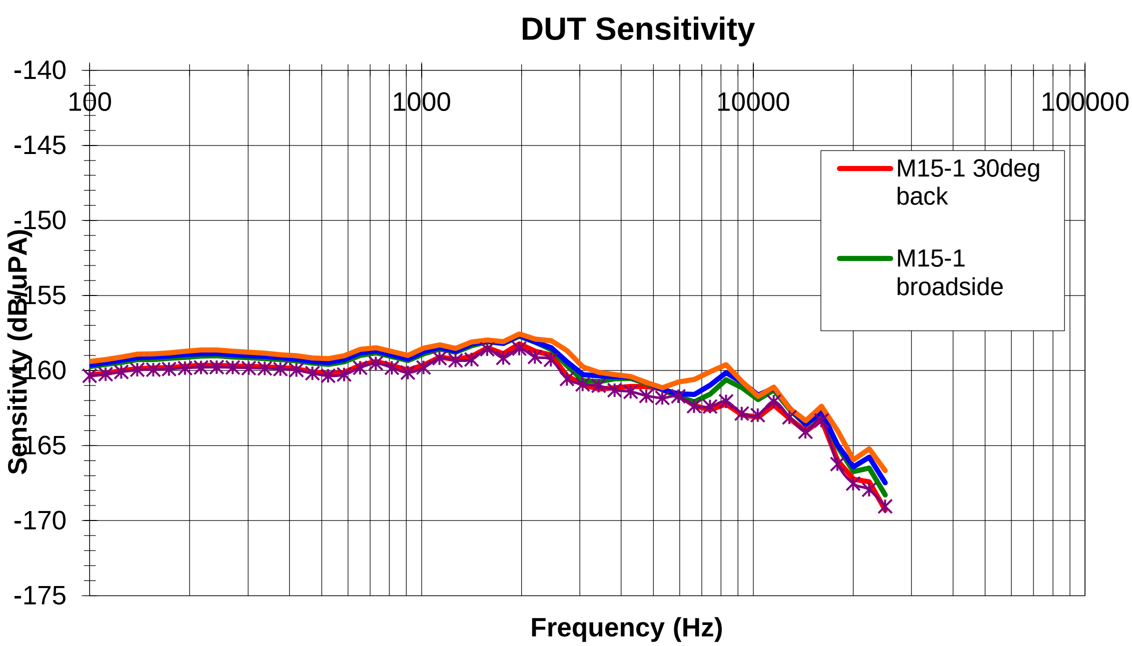

Figure B-3. Nominal Calibration curves for M15B hydrophones. Note: "back" traces are further from the projector and have not been normalized. The "fwd" trace is slightly closer.

In Field Calibration Values

Table B-1

Hydrophone IDs and Single Frequency Calibration Values

Station & Deployment	Hydrophone Type	Hydrophone ID	In-Field Calibration Value dB re 1 µPa @ 250 Hz
Nantucket–1	Did not record		
Delaware Bay–1	M15B	173	-158.9
Nantucket–2	M8E	153	-161.3
Delaware Bay–2	Lost		
Nantucket–3	M8E	155	-164.4
Delaware Bay–3	M8E	152	-162.7
Nantucket–4	M15B	87	-158.6
Delaware Bay–4	M15B	174	-158.1

The Department of the Interior Mission

As the Nation's principal conservation agency, the Department of the Interior has responsibility for most of our nationally owned public lands and natural resources. This includes fostering the sound use of our land and water resources; protecting our fish, wildlife, and biological diversity; preserving the environmental and cultural values of our national parks and historical places; and providing for the enjoyment of life through outdoor recreation. The Department assesses our energy and mineral resources and works to ensure that their development is in the best interests of all our people by encouraging stewardship and citizen participation in their care. The Department also has a major responsibility for American Indian reservation communities and for people who live in island communities.

The Bureau of Ocean Energy Management Mission

The Bureau of Ocean Energy Management (BOEM) works to manage the exploration and development of the nation's offshore resources in a way that appropriately balances economic development, energy independence, and environmental protection through oil and gas leases, renewable energy development and environmental reviews and studies.