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Acoustic Noise and Electromagnetic Study in Support of the Rhode Island Ocean SAMP

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Executive Summary

The goal of our study was to assess the environmental impact of an offshore wind farm consisting of 8 turbines in an area south of Block Island, Rhode Island. In this study, we considered the underwater acoustic noise generated by the various phases of the life cycle of a wind farm from site surveys, construction, operation, and decommissioning. In particular, the equipment can cause slightly elevated levels of noise in the area adjacent to the turbines both in the atmosphere and in the ocean. To understand the acoustic impact of the offshore wind farm on the surrounding area, a measurement program for the existing ambient noise field was undertaken. The major sources of underwater noise have been found to be shipping, wind-generated waves and bubbles, rain and marine animals. The modeling suggests that the operation of the 8 turbine wind farm would have little impact on marine life. The construction of the wind farm involves driving piles and noise from this operation would have a significant effect on any nearby animals. We recommend that the construction be done after the spring migration of right whales past Block Island. A larger farm being planned for an area east of Block Island was shown to increase the underwater noise levels inside the larger farm. One of recommendations from this study was to encourage the developer to design the support structures that would lower the underwater noise levels. Airborne noise was measured and we conclude that no turbine noise will be detectable on Block Island. In addition to the acoustic measurements, electric and magnetic ambient fields were measured at the candidate sites and at other sites associated with electric power transmission underwater. The fields have the potential to affect animals such as turtles, marine mammals, birds and fish within 30 feet of the underwater power transmission cables.

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Abstract

The goal of our study was to assess the environmental impact of an offshore wind farm consisting of 8 turbines in an area south of Block Island, Rhode Island. In this study, we considered the underwater acoustic noise generated by the various phases of the life cycle of a wind farm from site surveys, construction, operation, and decommissioning. In particular, the equipment can cause increased levels of noise both in the atmosphere and in the ocean. To understand the acoustic impact of the offshore wind farm on the ecosystem, a measurement program for the existing ambient noise field was undertaken. An ambient noise budget for the area was computed and showed that the major sources of underwater noise in this area was found to be shipping, wind-generated waves and bubbles, rain and marine animals. The underwater noise generated by the wind turbines was modeled using European data. The modeling suggests that the 8 turbine wind farm would have little impact on marine life. The construction of the wind farm involves driving piles and noise from this operation would have a significant effect on any nearby animals. We recommend that the construction be done after the spring migration of right whales past Block Island. A larger farm being planned for an area east of Block Island was shown to increase the underwater noise levels inside the larger farm. One of recommendations from this study was to encourage the developer to design the support structures that would lower the underwater noise levels as compared to the European wind farms. Airborne noise was measured and we conclude that no turbine noise will be detectable on Block Island. In addition to the acoustic measurements, electric and magnetic ambient fields were measured at the candidate sites and at other sites associated with electric power transmission underwater. The fields have the potential to affect animals such as turtles, marine mammals, birds and fish within 10 meters of the power transmission cables.

Introduction:

The goal of this preliminary report is to assess the environmental impact of an offshore wind farm consisting of 8 turbines being considered in an area south of Block Island, Rhode Island. This report is based on passive underwater acoustic monitoring at the planned site for five weeks, a transmission loss measurement near Block Island, recordings of drilling noise at the site for test borings, measurements of air noise at Block Island for five days over the course of two months in the summer, and a limited number of measurements of radiated air noise from an existing land-based turbine. Additional research is ongoing, including passive acoustic monitoring for one year. As part of this study, the underwater acoustic noise generated by the various phases of the life cycle of a wind farm from site surveys, construction, operation, and decommissioning was considered. However, predicted construction noise from pile driving and noise radiated by the wind turbines into the water during operation was the focus of this study. We also begin to document the potential effects of the electromagnetic fields generated by the production and transmission of the electrical power from the wind farm to shore. The equipment and facilities associated with generating offshore wind power have the potential to affect the surrounding environment. In particular, the equipment can cause increased levels of noise both in the atmosphere and in the ocean. Also, increased electric and magnetic fields can be generated in the process of creating the electrical power and in transmitting the power to shore. All of these sources have the potential to affect animals such as turtles, marine mammals, birds and fish.

One of the fundamental activities in any environmental assessment is the measurement of the existing conditions at the proposed candidate site. The National Research Council's 2003 report, "Ocean Noise and Marine Mammals" (Frisk, et al., 2003) stated that ambient noise is "the noise associated with the background din emanating from a myriad of unidentified sources. Its distinguishing features are that it is due to multiple sources, individual sources are not identified (although the type of noise source—e.g., shipping, wind—may be known), and no one source dominates the received field." While there exists the potential to increase the overall noise levels with additional noise sources, assessing the impact of a new source in light of existing levels is well established in a regulatory context (Ontario Ministry of Environment, 2009).

The candidate site for an offshore wind farm south of Block Island has an ambient noise field that varies with season, wind speed, boat traffic, rainfall rate, etc. To understand the acoustic impact of the offshore wind farm on the ecosystem, a measurement program for the existing ambient noise field was undertaken. Figure 1 shows the Ocean SAMP area and the locations of the various measurements in support of the noise study: green triangle - transmission loss measurement, black circles - Passive Aquatic Listener locations, and red square - recording of drilling noise by the L/B Kayd. In addition to underwater noise, airborne noise was measured at the drilling site and on Block Island near Southeast Light. Also, electric and magnetic ambient fields were measured at the candidate site and at other sites associated with electric power transmission underwater.

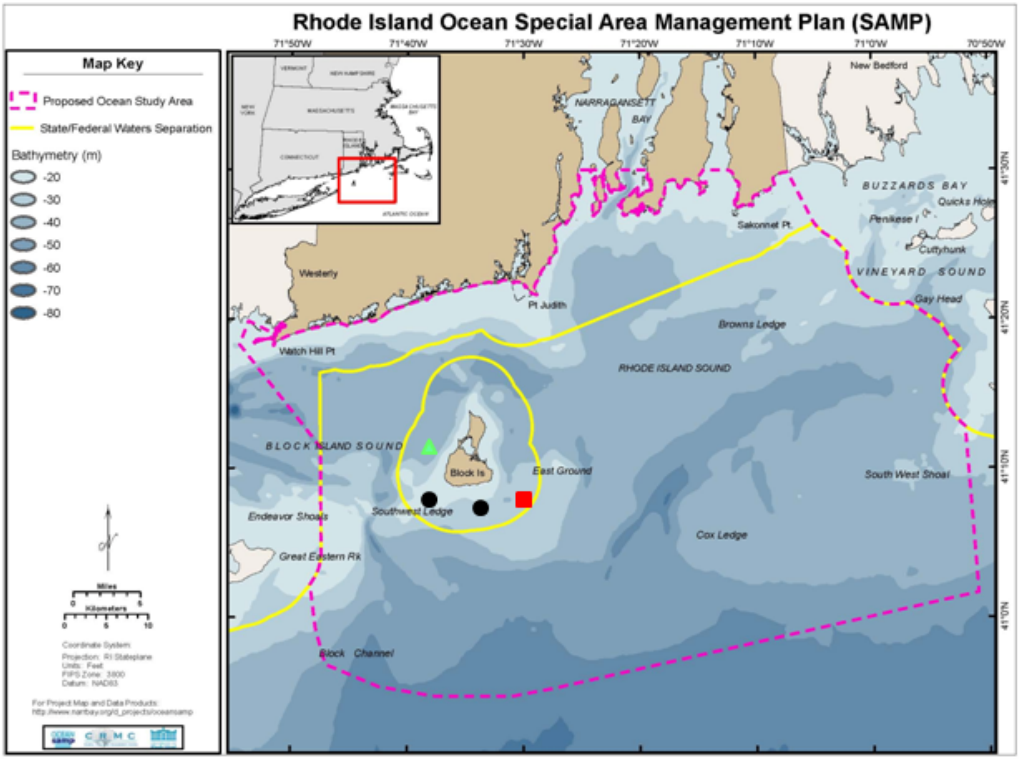

Figure 1: The Ocean SAMP area and the locations of the various measurements in support of the underwater noise study: green triangle - transmission loss measurement, black circles - PAL locations, and red square - recording of drilling noise by the L/B Kayd.

European researchers have quantified the noise and other effects from offshore wind farms in Denmark (DONG Energy, 2006). Our analysis of the effects of the additional noise caused by the offshore wind farm has utilized the existing injury and behavior criteria from the National Marine Fisheries Service (NMFS). New injury and behavior criteria for marine mammals including cetaceans and pinnipeds have been published (Southall, et al., 2007) and the incorporation of the new criteria into this study is ongoing.

Pile driving and other activities associated with construction and removal of the wind turbine structures will have the most intense acoustic signals(Richardson, Greene, Malme, & Thomson, 1998). In this report, we model the acoustic signature of pile driving using standard pile driving source functions, the geological and oceanographic properties of the potential sites, and the Monterey-Miami Parabolic Equation (MMPE) acoustic transmission loss model(Smith, 2006).

1. Wind Turbine Noise

Air noise

In general, there are four different types of sounds produced by wind turbines: tonal, broadband, low frequency, and impulsive. Tonal sounds occur at discrete frequencies and can be caused by components within the turbine. Broadband sounds occur when the turbine blades spin through the air and interact with the atmospheric turbulence. Low frequency sounds are associated with downwind rotors. Finally, impulsive sounds are "short acoustic impulses…that vary in amplitude with time." (Rogers, Manwell, & Wright, 2002)

The sources of the noise produced by the operation of wind turbines can be divided into two categories: mechanical and aerodynamic. The mechanical sound is produced from both the gearbox and the control mechanism, such as cooling fans, the generator, and yaw drives. The emitted sounds are often tonal, as they are linked with the rotation of equipment (Rogers, Manwell, & Wright, 2002). Besides gear tone, it is primarily the aerodynamic generation mechanism that is the dominant source of noise from wind turbines. The broadband noise produced by the turbine often originates from airflow around the turbine blades and typically increases with rotor speed(Colby W. D., Dobie, Leventhall, Lipscomb, McCunney, & Seilo, 2009).

Environmental factors can also affect the noise produced by wind turbines. Often if the ground is very warm, the air will cause the produced noise to refract upwards, which results in reduced sound levels. Conversely, when the ground is very cool, the sound levels of the turbine noise increase. In addition to temperature, barriers, trees, shrubbery, etc can cause attenuation of the sound.(Colby W. D., Dobie, Leventhall, Lipscomb, McCunney, & Seilo, 2009)

Underwater Noise

Underwater noise from the operation of offshore wind turbines is created by many of the same sources as air noise. However, the most efficient path for the noise from the turbine into the water is through the support structure. The noise transmitted through the air is of much lower level due to the impedance mismatch between air and water. To convert air intensity levels to water intensity level, we use the following expression SPL_{water} (dB re 1 μPa)= SPL_{air}(dB re 20 μPa) + 62. Of the 62 dB conversion quantity, the impedance contrast contributes 36 dB. Therefore, underwater noise generated directly by aerodynamic sources can be neglected. The underwater noise transmitted through the structure from the turbine is analogous to shipping noise, in that it is continuous, low frequency (<1000 Hz), and low level. Because there are no installed wind turbines in the waters off the US, we have relied on data measured at European wind farms. (Betke, Glahn, & Matuschek, 2004) Simultaneous measurements of vibration on the monopile showed that the noise was dominated by gear noise.

2. Zones of Influence

Our approach for assessing the impact of underwater noise uses the concept of zones of influence to categorize the effects on marine life. Figure 2 shows a general schematic of the zones of influence for the effects of noise on marine animals. (Richardson, Greene, Malme, & Thomson, 1998) At some range from the source of noise, there is a *Zone of No Effect* in which the sound levels are so low that they are not detectable in the ambient noise. Inside the *Zone of No Effect*, there is the *Zone of Audibility* where while the sound is detectable but is not intense enough to cause any observable response. Inside the *Zone of Audibility,* there is the *Zone of Responsiveness* where the sound is loud enough to cause a behavioral reaction such as a startle response, movement to or away from the source, etc. Closer to the source, there is the *Zone of Masking* where the sound from the source is loud enough to mask important acoustic signals including conspecific calls. The zones of audibility, responsiveness, and masking may be coterminous or in a different order for an individual animal at different times in its life and for among individuals and species. Finally, very near the source, there is a *Zone of Injury* where the acoustic signals are intense enough to cause physical harm. It is important to note that Temporary Threshold Shift (TTS), a short term degradation of the hearing capability of an animal is not considered injury per se because there is no tissue damage.(Southall, et al., 2007) Rather, TTS can be thought of as hearing fatigue, a phenomenon often observed in humans after concerts, auto races or operating loud machinery for a short time. Permanent Threshold Shift (PTS) is an injury to the ear which is permanent and not recoverable. The *Zone of Injury* is a region where PTS or more severe injury may occur.

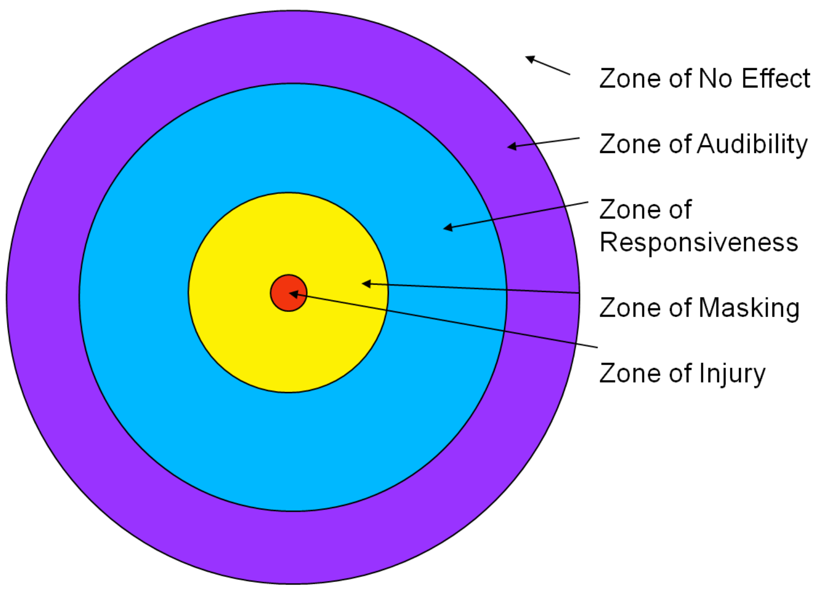

Figure 2: Zones of influence for the effects of noise on marine animals. Adapted from Richardson, et al, 1998.

Criteria for estimating the effects of noise on marine mammals are shown in Table 1. These correspond to the *Zone of Responsiveness*, or what is termed Level B behavioral takes. Another recent development of criteria is given by Southall (Southall, et al., 2007). The criteria suggested by Southall and his colleagues are higher than those listed in Table 1 for injury. For comparison, detectability is usually about 120 dB re 1 μPa rms (root mean square) or greater in water for typical ocean environments. We assume that the existing NMFS criteria will apply to this development. Root mean square is a property of signals can be thought of as the square root of the average power of a signal as is defined formally as

$$p_{rms} = \sqrt{\frac{1}{T}\int_0^T |p(t)|^2 \, dt}$$

Table 1: Criteria for estimating the effects of noise on marine animals. NMFS criteria taken from (Department of Commerce, 2008).

Criteria	NMFS Criteria
Level A Injury (Pinnipeds)	190 dB re 1 μPa rms (impulse)
Level A Injury (Cetaceans)	180 dB re 1 μPa rms (impulse)
Level B Harassment/Behavior	160 dB re 1 μPa rms (impulse)

4. Noise Budget

One way to quantify the potential effects of anthropogenic, underwater sound on marine animals is with an ambient noise budget (Miller, Bradley, & Nystuen, 2008). An ambient noise budget is a listing of the various sources of noise at a receiver and their associated ranking by some measure. A number of different types of budgets can be conceived using acoustic measures such as intensity, energy, or duration. These budgets are usually parameterized by frequency and are typically computed over bands such as 1/3 octave.

Noise budgets may be useful for marine mammal masking studies, habitat characterization, environmental studies, and for studies of the evolution of animal hearing. The use of a sound budget allows for the estimation of the acoustic environment prior to man's introduction of sound into the oceans and a computation of anthropogenic contributions to the noise environment. In addition, an understanding of how anthropogenic activities might be affecting animals can be produced. For example, noise from shipping may be interfering with the communication and behavior of marine mammals (Tyack & Clark, 2000; Clark, et al., 2009). The Wenz curves (Wenz, 1962), a common way to display the contributions of the myriad of oceanic sound sources, have been used as a basis for averaged noise budgets. The Wenz curves are shown in Figure 3. Note that the units of the Wenz curves are dB re 1 $\mu Pa^2/Hz$, i.e. the average intensity in a 1 Hz band. With the assumption that the curves correctly represent the acoustic environment of marine life, noise budgets will provide marine mammal hearing evolution studies with the baseline data for establishing mammal hearing response because we can separate the natural sources from the human-induced sources. More importantly, if that budget is changing with time, it provides details of the change and can be used to predict impact and adjustments that might be necessary to mitigate the change.

In 2003, a panel convened by the US National Academies' National Research Council to study the effect of sound on marine animals wrote a report recommending the use of noise budgets (Frisk, et al., 2003). A conceptual framework was developed by the committee members using average intensity (AI) budget in 1/3-octave bands rather than the 1-Hz bands used by the Wenz curves. While 1-Hz bands are used for convenience, the 1/3-octave bands are very similar to the bandwidth of animal hearing. The intensity of sound in 1/3-octave bands has been considered to be appropriate for marine mammal hearing and masking studies. (Ketten, 2000)

In an ocean with constant sound speed and density, the instantaneous intensity of a wave far from a small source labeled *n* is given by $I_n(f,t) = \mathrm{Re}\left[p_n(f,t)u_n^*(f,t)\right] = \frac{|p_n(f,t)|^2}{\rho c}$ where $p_n(f,t)$ is the acoustic pressure in a band of frequencies centered at frequency *f* and time *t* and $u_n(r,t)$ is the radial component of acoustic particle velocity. The average intensity in the frequency band is $\langle I_n(f) \rangle = \frac{1}{T\rho c}\int_0^T |p_n(f,t)|^2 dt$ where T is the averaging time. If one is able to classify the source *n* of sound for all times between 0 and T, a noise budget can be calculated using the average intensity in the frequency band for each source.

Since the publication of the NRC report, a large of amount of noise data in various ocean sites has been gathered using PAL (Passive Aquatic Listener) systems (Ma, Nystuen, & Lien, 2005; Nystuen, Moore, & Stabeno, 2010) and other passive acoustic monitoring systems. Sound budgets based on temporal detections and classifications have been reported(Hatch, et al., 2008; Nystuen & Howe, 2005). These temporal detection (TD) noise budgets are closely related to the AI budget model but use the duration of maximum received level in frequency bands. Unique spectral characteristics of different sound sources are used to identify the sound source. Typical sources include breaking waves from wind (to measure wind speed), raindrop splashes (to measure rain), drizzle, shipping (both distant and local), and marine mammals (especially whales).

5. Air Noise

The human ear is capable of hearing a wide range of sounds based on their sound pressure level or frequency content. The average human ear is able to perceive sounds that range from 20 Hz to 20,000 Hz. Humans are affected by noise based on the intensity as follows (Rogers, Manwell, & Wright, 2002):

- <90 dBA: No adverse effects
- 115 dBA: Fatigue, Stomach Pains, Hypertension, etc.
- 120 dBA: Threshold of pain at 10 Hz
- >120 dBA: Exposure for 24 hours or longer can cause permanent physiology damage.

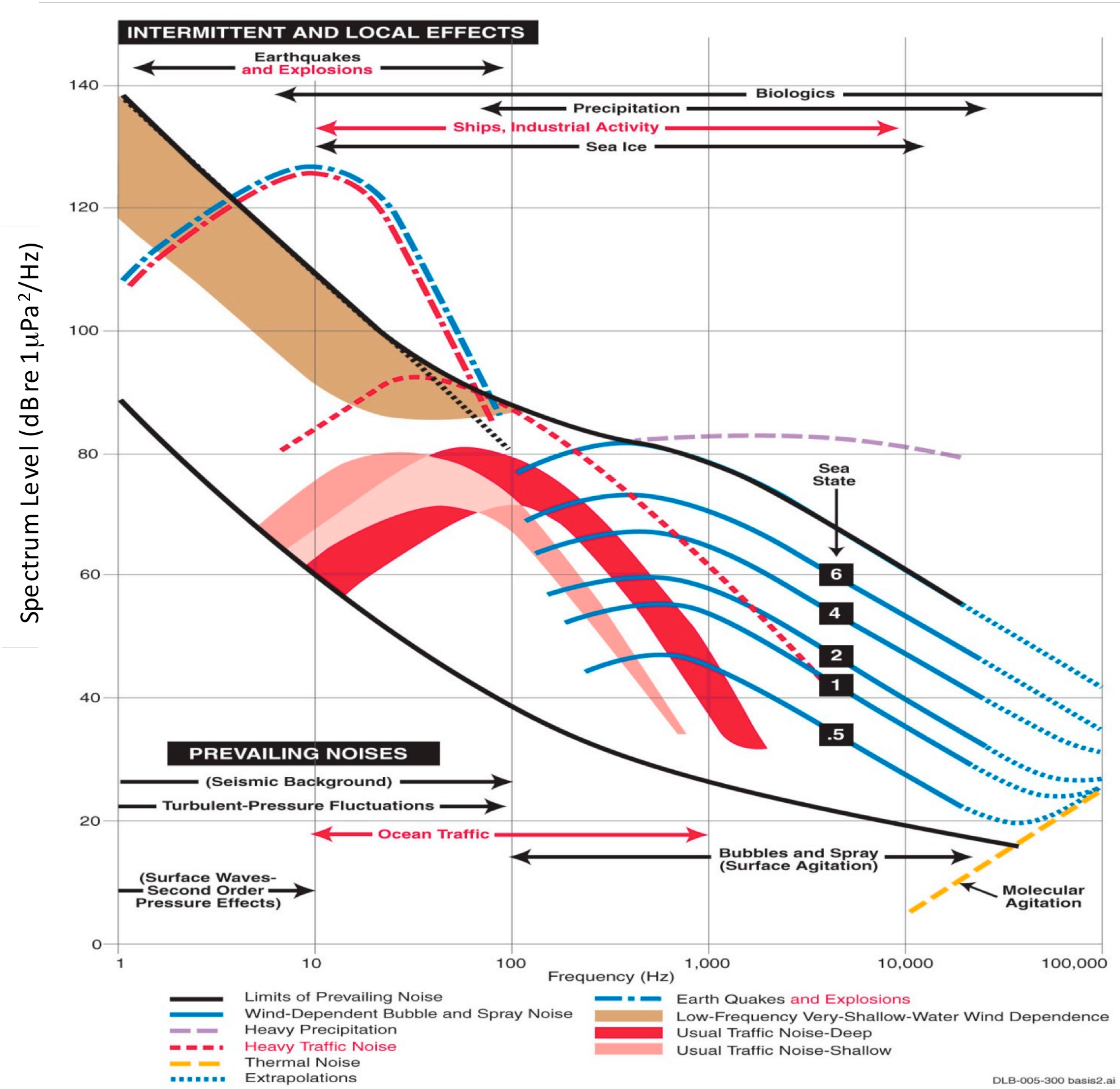

Figure 3: The Wenz curves depicting average ambient noise levels as a function of frequency for various sources. Note that the units are dB re 1 μPa²/Hz. (courtesy of David L. Bradley)

It is the low frequency sound, typically ranging from 10 to 200 Hz, that is the subject of concern of some physicians and scientists when it comes to the development of wind turbines near human habitats. Some believe that these sounds can cause adverse health effects such as "wind turbine syndrome". In a testimony before the New York State legislature Energy Committee(Pierpont, 2006), Dr. Nina Pierpont, a proponent of "wind turbine syndrome", defines it as a set of symptoms that include:

- Sleep Problems
- Headaches
- Dizziness
- Anxiety

- Concentration & Learning Problems
- Tinnitus

Low frequency sounds typically need to be at a high sound pressure level to be heard by an average human. As stated in the expert panel review conducted for both the American Wind Energy Association (AWEA) and Canadian Wind Energy Association (CanWEA), "As the annoyance of a given sound increases as loudness increases, there is also a more rapid growth of annoyance at low frequencies. However, there is no evidence for direct physiological effects from either infrasound or low frequency sound at the levels generated from wind turbines, indoors or outside. Effects may result from the sounds being audible, but these are similar to the effects from other audible sounds."(Colby W. D., Dobie, Leventhall, Lipscomb, McCunney, & Seilo, 2009)

Powerful and intense, but very short-duration sounds above 130 dBA (i.e. explosions) are capable of causing cochlear damage, as well as permanent hearing loss; but the majority of occupational hearing loss is due to prolonged exposure to high noise levels between 90 and 105 dBA. In 1983 in the US, the Occupational Safety and Health Administration authorities (OSHA, 1983), as well as in 1998 by the National Institute for Occupational Health and Safety (NIOSH, 1998), warned that the risk of occupational hearing loss begins at 85 dBA, over an eight hour day and a forty year career. Sound pressure levels that are below 75 dBA do not pose a danger of noise induced hearing loss and therefore the sound levels that are produced by wind turbines will not cause noise induced hearing loss because they are simply not high enough. Through studies performed (Suter, 1991),it has been shown that simple tasks may be unaffected at noise levels as high as 115 dBA, but complex tasks may be affected at noise levels as low as 75 dBA. Noise levels that are below 70 dBA do not result in task interference. Therefore, the noise produced by the operation of wind turbines interferes with neither simple nor complex tasks. (Colby W. D., Dobie, Leventhall, Lipscomb, McCunney, & Seilo, 2009)

Annoyance is "a subjective response that varies among people to many types of sounds". Although annoyance can be a frustrating effect of certain sounds, it is not considered an adverse health effect. The belief that chronic noise exposure might lead to chronic health problems has been the subject of many debated and hundreds of contradictory studies. There is no definitive evidence that supports claims of "wind turbine syndrome"(The Health Impact of Wind Turbines: A Review of the Current White, Grey, and Published Literature , 2008).

6. Results of the Study:

Acoustic data collection using calibrated systems in air

Air noise data were collected at the following three sites: 1) near the Portsmouth High School Wind Turbine (1.5 MW), 2) on Mohegan Bluffs on Block Island and 3) near sediment coring at sea near the Lift/Barge (L/B) Kayd. All air noise data were collected in 2009 using a Bruel and Kjaer Hand-Held Analyzer Type 2250L with a Type 4189, prepolarized free-field ½" microphone calibrated by the factory. Spectrograms were computed by the 2250L in 1/3-octave bands with 1 second averages. The duration of the measurements varied for each of the three scenarios. The land measurements were about 15 minutes in duration, while the at sea measurements of the drill ship noise were about 2.5 minutes due to logistics and ship safety.

A typical air noise spectrogram measured near the site south of Block Island is shown in Figure 4. The more intense epochs in Figure 4 are shown in red and are associated with gusts of wind. These gusts of wind contain low frequency noise typically below 500 Hz.

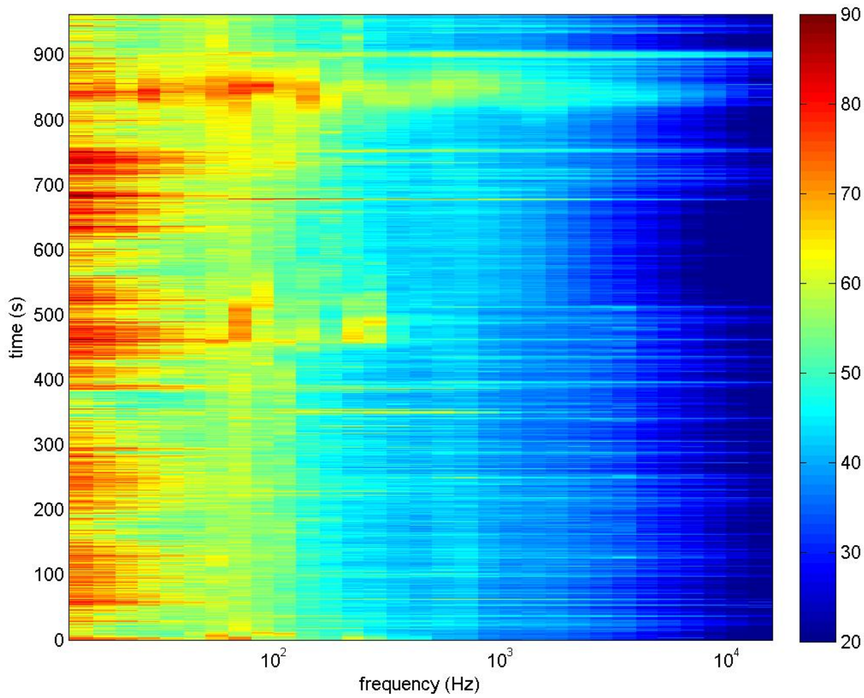

Figure 4: Air noise spectrogram as a function of frequency and time taken at sea just south of Block Island. The units are dB re 20 μPa^2 in a 1/3 octave band.

There have been reported instances of wind turbine syndrome from land-based systems in the US and Canada (Pierpont, Wind Turbine Syndrome, 2010). In the Canadian Province of Ontario, the Ministry of the Environment created noise guidelines to limit wind turbine noise levels 30 meters away from a dwelling or campsite to 40 dBA. These regulations also set a minimum distance of 550 meters (1,804 feet) for a group of up to five relatively quiet [102 dBA] turbines within a 3-kilometer (1.86-mile) radius, rising to 1,500 meters (4,921 feet) for a group of 11 to 25 noisier (106-107 dbA) turbines. (Ontario Ministry of Environment, 2009)

The noise spectrogram for the Portsmouth High School Wind Turbine measured at a distance of 65 meters is shown in Figure 5. Units are dB re 20 μPa^2 in a 1/3-octave band. The color scale is the same as used in Figure 4. Measurements of the noise from this wind turbine were measured on three days in July and August, 2009. Based on these very typical air noise measurements described above and published reports on wind turbine noise in air, the noise from the 5-8 wind turbines planned for state waters south of Block Island (approximately 3 nm from the island) will not be detectable by residents on the island. This is based on reasonable models for transmission loss in air combining both geometrical losses and absorption(Piercy & Daigle, 1998). It is possible that blade noise would be detectable by humans very near (<200 meters) from the wind turbines. Air noise from the impact pile driving may be detectable on Block Island especially at night when propagation conditions allow for downward refraction.

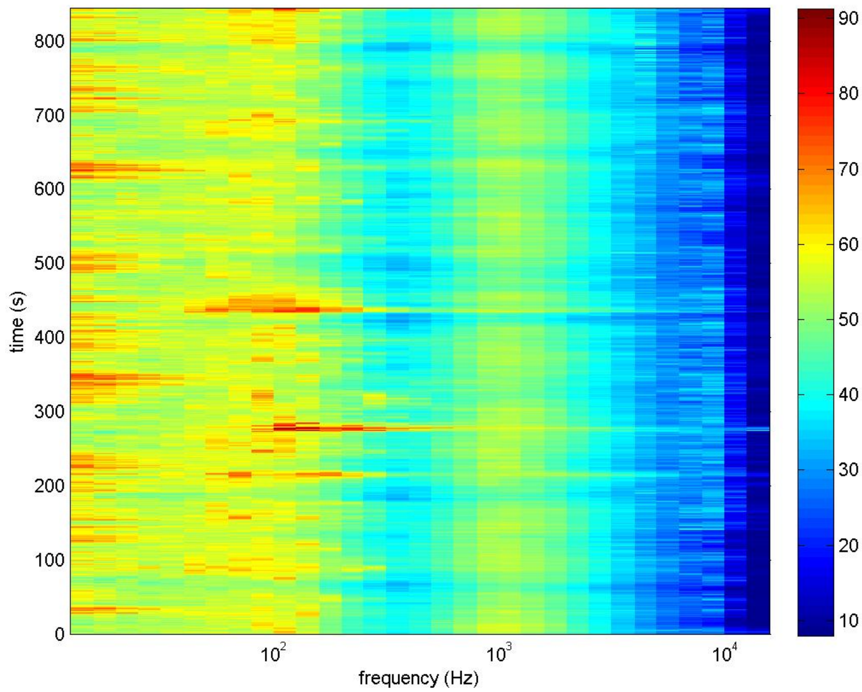

Figure 5: Noise spectrogram for the Portsmouth High School Wind Turbine measured at a distance of 65 meters. Units are dB re 20 μPa^2 in a 1/3-octave band. The color scale is the same as used in Figure 4.

Eight cores were taken southeast of Block Island using the drilling ship and lift barge L/B Kayd in August, 2009. Measurements of air noise were collected on August 9, 2009 during the drilling and a typical spectrogram is given in Figure 6.

Acoustic data collection using calibrated systems underwater

The ambient noise levels were measured underwater at the candidate locations. Underwater noise measurements were made with Passive Aquatic Listeners (PALs). This system was deployed for five weeks in October and November of 2008. Figure 7 shows the locations of the PALs and the Automated Identification System (AIS)-derived shipping for the period of October 6 through November 14, 2008. Two PAL systems were deployed off Block Island in the fall of 2009 and are due to be recovered in summer of 2010 providing data for the estimation of noise budgets for all four seasons. Table 2 shows the band numbers of center frequencies in kHz for PAL spectra. The bands range from 0.1 kHz to 49.5 kHz.

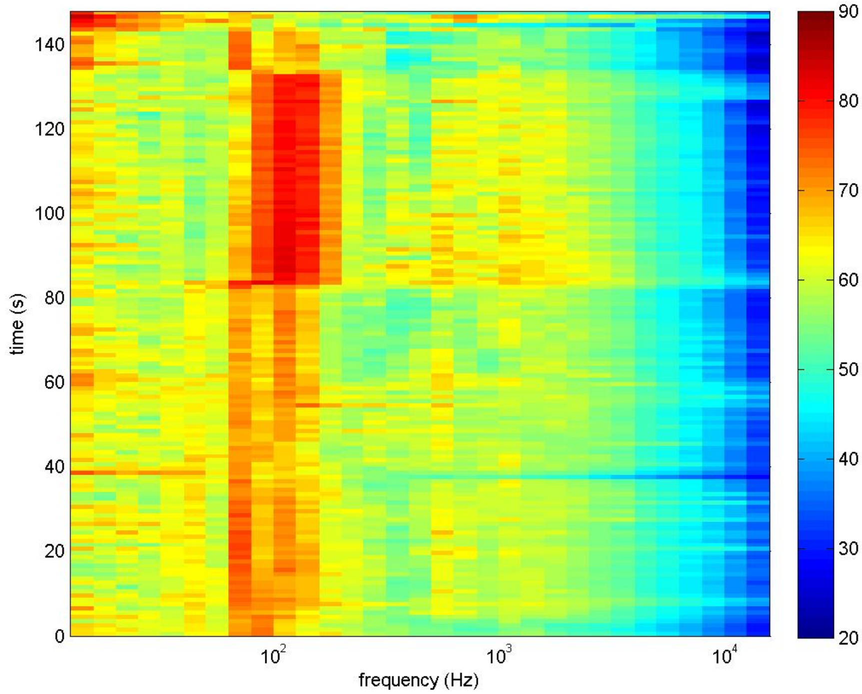

Figure 6: Noise spectrogram of drilling and lift barge L/B Kayd measured at a distance of 100 meters. Units are dB re 20 μPa^2 in a 1/3-octave band. The color scale is the same as used in Figure 4.

Table 2: Band numbers and center frequencies in kHz for the PAL spectra.

0: 0.1,	12: 2.4,	24: 11.4,	36: 23.1,	48: 34.9,	60: 46.6,
1: 0.3,	13: 2.6,	25: 12.4,	37: 24.1,	49: 35.8,	61: 47.6,
2: 0.5,	14: 2.8,	26: 13.4,	38: 25.1,	50: 36.8,	62: 48.5,
3: 0.7,	15: 3.0,	27: 14.4,	39: 26.1,	51: 37.8,	63: 49.5,
4: 0.9,	16: 3.6,	28: 15.3,	40: 27.1,	52: 38.8,	
5: 1.1,	17: 4.6,	29: 16.3,	41: 28.0,	53: 39.7,	
6: 1.3,	18: 5.6,	30: 17.3,	42: 29.0,	54: 40.7,	
7: 1.5,	19: 6.5,	31: 18.3,	43: 30.0,	55: 41.7,	
8: 1.7,	20: 7.5,	32: 19.2,	44: 31.0,	56: 42.7,	
9: 1.9,	21: 8.5,	33: 20.2,	45: 31.9,	57: 43.7,	
10: 2.1,	22: 9.5,	34: 21.2,	46: 32.9,	58: 44.6,	
11: 2.2,	23: 10.4,	35: 22.2,	47: 33.9,	59: 45.6,	

The PALs were programmed to make short recordings of 4.5 seconds every nine minutes, perform a Fourier Transform on the time series, and then do a spectral analysis to identify the sound source. If the sound is uniform during the sample, the source is deemed “background” and unique spectral characteristics for known background sources such as wind, rain and shipping are used to identify the sound source. The robustness of the algorithm has been investigated by Nystuen and his colleagues (Ma, Nystuen, & Lien, 2005; Nystuen, Moore, & Stabeno, 2010; Nystuen & Howe, 2005). Although the duty cycle is relatively small, PALs have been shown to be useful for detecting the presence of marine mammals (Miksis-Olds, Nystuen, & Parks, 2010; Grebner, Parks, Bradley, Miksis-Olds, Capone, & Ford, 2010). The spectral components of the sample are saved in the bands listed in Table 2, and the original temporal sample is discarded. However, transient sounds within the 4.5 second sample are also detected. If the detection threshold of 13 dB signal-to-noise within a user chosen frequency band is met (user set), then an audio sample is saved in addition to the spectral data and the delay before the next recording is decreased to two minutes. This allows repeated adaptive sampling of relatively rare events (more frequent samples when something interesting is happening), but introduces a bias in that these events detections are overrepresented (higher temporal density of samples).

To remove this bias, each saved spectrum is weighted by the time between itself and the samples before and after it. For example, spectra are known at 0, 2, and 11 minutes. The spectrum at 2 minutes is representative of the time from 1 minute to 6.5 minutes. An unbiased time series of sound level is produced for each frequency of interest, allowing the creation of a histogram of sound level over the entirety of the data.

In summary, for each sound sample, the spectral characteristics of the sample are saved and used to identify the sound source. For most samples, this is a measure of background sound sources, and these sources are identified uniquely by their spectral characteristics. However, some sound samples contain transient signals. For these samples the PALs save the original audio sample as well as the spectral components. The source of the transient signal (anthropogenic, animal vocalization, etc.) can often be identified by listening to it and comparing to known recording of these types of sounds. This allows a probable sound source to be identified for the majority of the PAL deployment. The mean sound intensity for each source is used to construct a noise budget.

The locations of the two PALs (labeled Eider and Puffin) are shown in Figure 7. A histogram for the 1/3-octave band centered at 500 Hz for PAL Eider is shown in Figure 8. A Gaussian probability density function was fitted to the data in a least square sense and the resulting pdf is also shown in Figure 8. The mean of the data was approximately 98 dB and the standard deviation was about 5 dB. The ambient noise budget for the Eider PAL in the 1/3-octave band centered at 500 Hz is shown in Figure 9. The main contributors to the noise budget at this location were shipping with 3244 pW/m^2 or 97 dB re 1 μPa^2 and wind related noise was with 3361 pW/m^2 or 97 dB re 1 μPa^2. Rain was next with 1167 pW/m^2 or 92 dB re 1 μPa^2 and lastly, biological noise with 341 pW/m^2 or 87 dB re 1 μPa^2. The data from the Puffin PAL was found to be not usable, possibly due to a malfunctioning hydrophone.

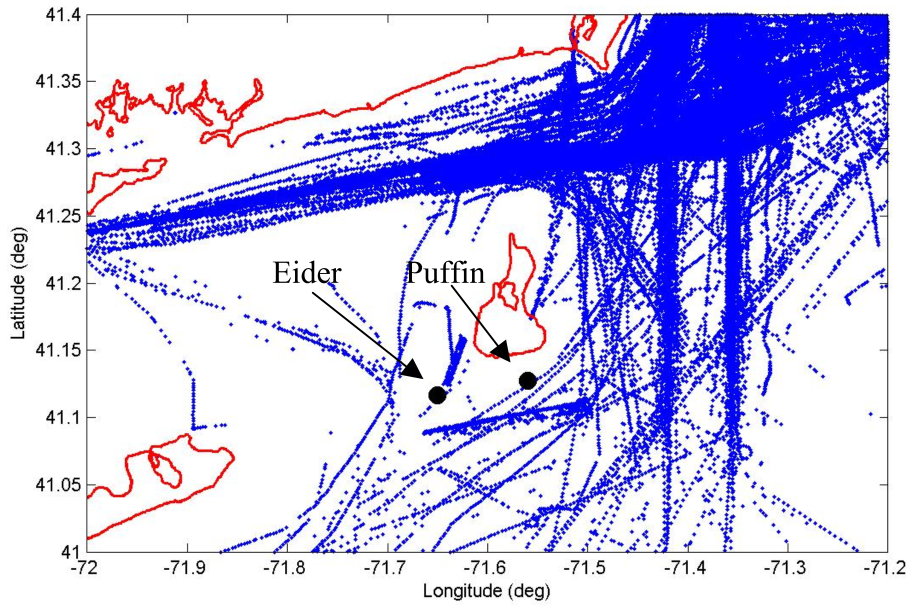

Figure 7: The solid black dots depict the locations of the two Passive Aquatic Listener systems labeled Eider on the western PAL and Puffin on the eastern PAL. The small blue dots indicate Automated Identification System (AIS)-derived ship positions. These data were collected October 6 – November 14, 2008. The shoreline is indicated in red.

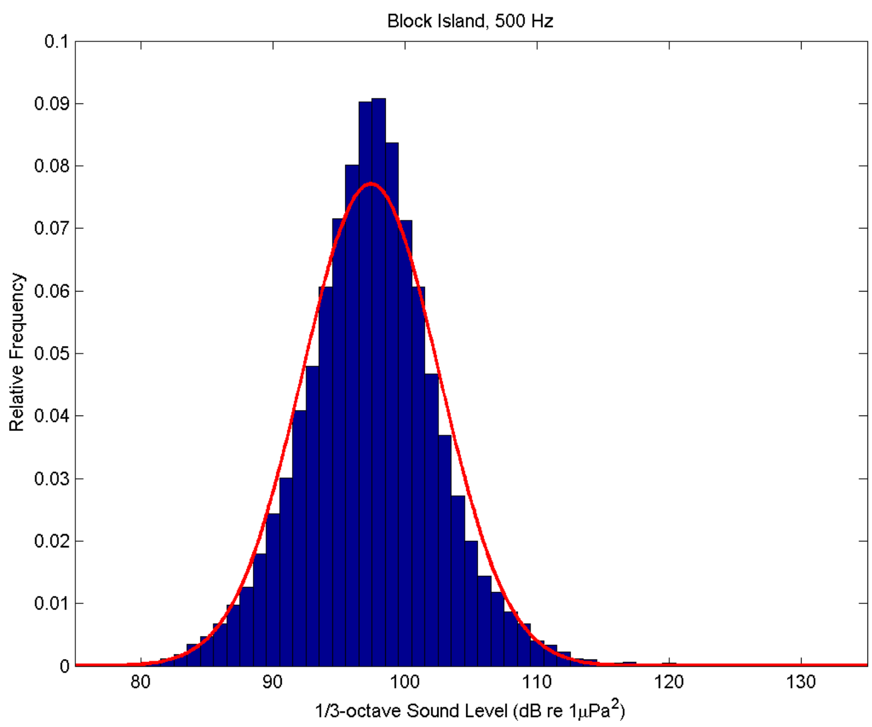

Figure 8: Histogram of ambient noise sound level in a 1/3-octave band centered at 500 Hz as measured on the Eider PAL. The red line is a Gaussian distribution fit to the data in a least squares sense.

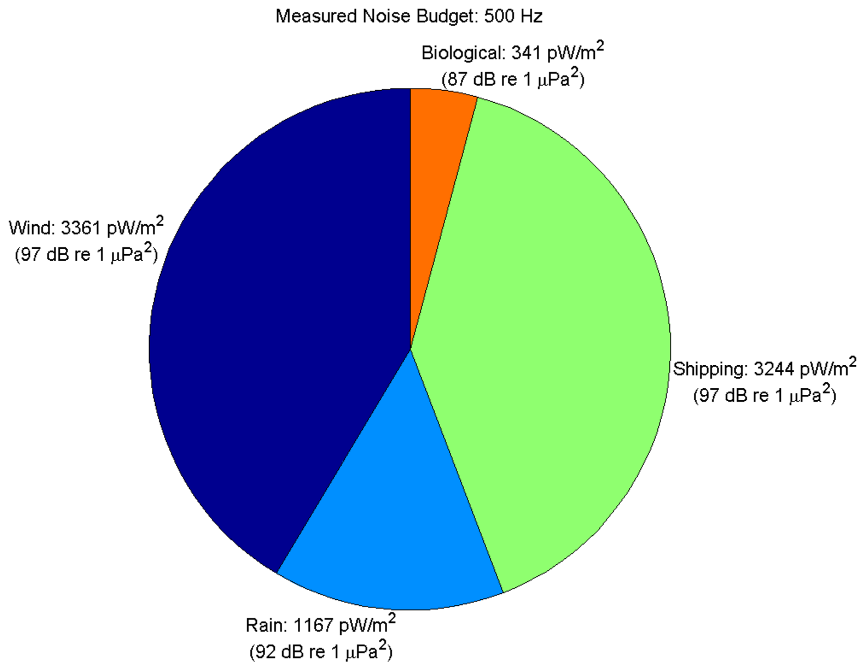

Figure 9: Noise budget as measured by PAL Eider south of Block Island in the 1/3 octave band centered at 500 Hz.

Transmission Loss Modeling

Transmission Loss (TL) is a measure of the rate at which sound energy is lost as a function of range, and is defined as:

$$TL = 10 \log_{10} (I_0/I_R)=20 \log_{10} (P_0 / P_R)$$

where:

I_0 = acoustic intensity at a point one m away from the source
I_R = acoustic intensity at range R m from the source
P_0 = pressure at a point one m away from the source
P_R = pressure at range R m from the source

Transmission Loss results from geometric losses due to one of two types of spreading, spherical or cylindrical and attenuation due to absorption, scattering, viscosity, and thermal losses. The usual method of modeling the Transmission Loss due to spreading is using the expression:

$$TL = N \log_{10}(r)$$

where:

r = range from the source
N = coefficient of geometric spreading

The value of N is equal to 20 for spherical spreading and 10 for cylindrical spreading. In shallow water the value of N will lie between 10 and 20. Accurate modeling of transmission loss (TL) is usually done using standard acoustic propagation models such as Miami-Monterey Parabolic Equation (MMPE) propagation code. In the early 90's, a numerical code known as the University of Miami Parabolic Equation (UMPE) Model was documented and made available to the general research community. This model was based on the split-step Fourier (SSF) technique, and had been adapted from previous versions developed by Prof. Fred Tappert at the University of Miami. A subsequent version, known as the Monterey-Miami Parabolic Equation (MMPE) Model, was developed in the mid-90's that was more streamlined and user friendly. This code was thoroughly tested against several existing benchmark scenarios and was found to perform reasonably well during the Shallow Water Acoustic Modeling Workshop held in Monterey, CA in 1999.

Inputs to this propagation model include the environmental description i.e., sound speed in the water column as a function of depth, geoacoustic parameters of the sediment layer and basement i.e., compressional wave speed and attenuation, shear speed and attenuation and density. During the transmission loss field test in October, 2009, we deployed a CTD to measure the temperature and salinity which was then used to calculate the sound speed. The bottom was assumed to consist of a sediment layer and a basement. The sediment parameters and the thickness of the sediment layer were estimated using a simple iterative inversion by matching the modeled and measured TL. Water depth at the location was 35 m. Range independent conditions were assumed for the acoustic modeling.

Measurements of transmission loss at 200 Hz were made near Block Island in summer 2009 to support the modeling effort at the location shown in Figure 10. The measurements were made primarily to support the PhD dissertation of Steven Crocker working on project unrelated to the SAMP effort. These measurements were taken in an area with sediments deposited by glacial lake bed. During the field test, an acoustic array of receive hydrophones and vector sensors were deployed from a small boat which remained stationary throughout the experiment. A J-15 sound source was deployed from another boat which moved away from the receiver ship. The location of the receive hydrophone array is labeled UP001 in Figure 10. A boat towing the J-15 transducer transmitting the 200 Hz tone traveled from the location labeled UP002 to UP001 and then to UP003. This provided us with a measurement of TL as a function of range assuming that the environmental conditions remained stationary. The depth of the source was 14 m and the receivers were at 9m and 21 m. Figure 11 shows the results of TL modeling using MMPE. The variation of TL as a function of range and depth is shown in this figure. The two white straight lines in these figures represent the water-sediment interface and sediment-basement interface.

Figure 12 shows the measured transmission loss (red), modeled transmission loss using MMPE (blue). The green line represents the TL corresponding to N log(r). We tried different values for N to get a good fit and a value of N=17 provides a good fit as seen in the figure. In Figure 12 the green line represents TL calculated using 17log(r). Upper plot is TL at 9 meter depth and lower plot is at 21 meter depth. Frequency is 200 Hz. A simple TL model as 17 log(r) allows us to quickly compute TL for any acoustic propagation path without using a sophisticated propagation model.

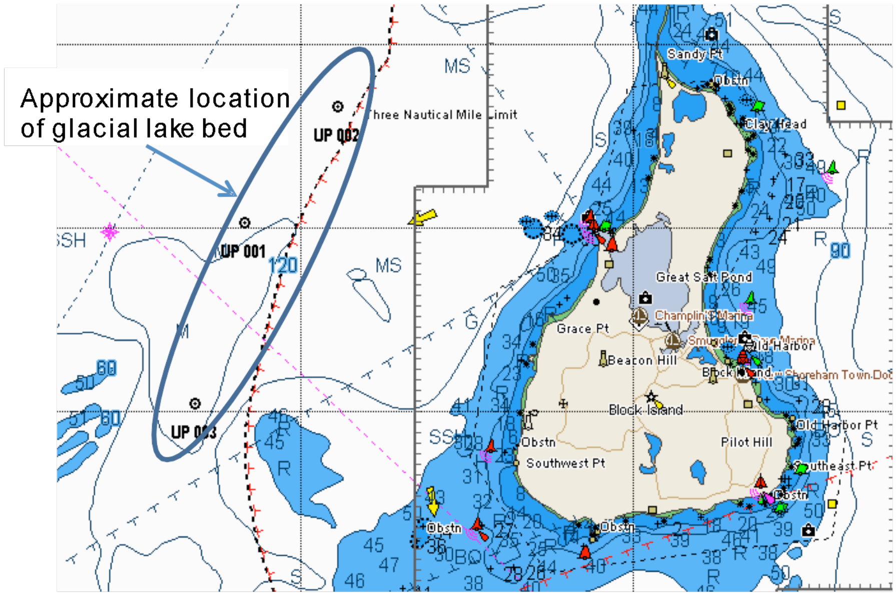

Figure 10: Location of measurements of transmission loss. The signal used was a CW tone with a frequency of 200 Hz. The location of the receive hydrophone array is labeled UP001. A boat towing the J-15 transducer transmitting the 200 Hz tone traveled from the location labeled UP002 to UP001 and then to UP003.

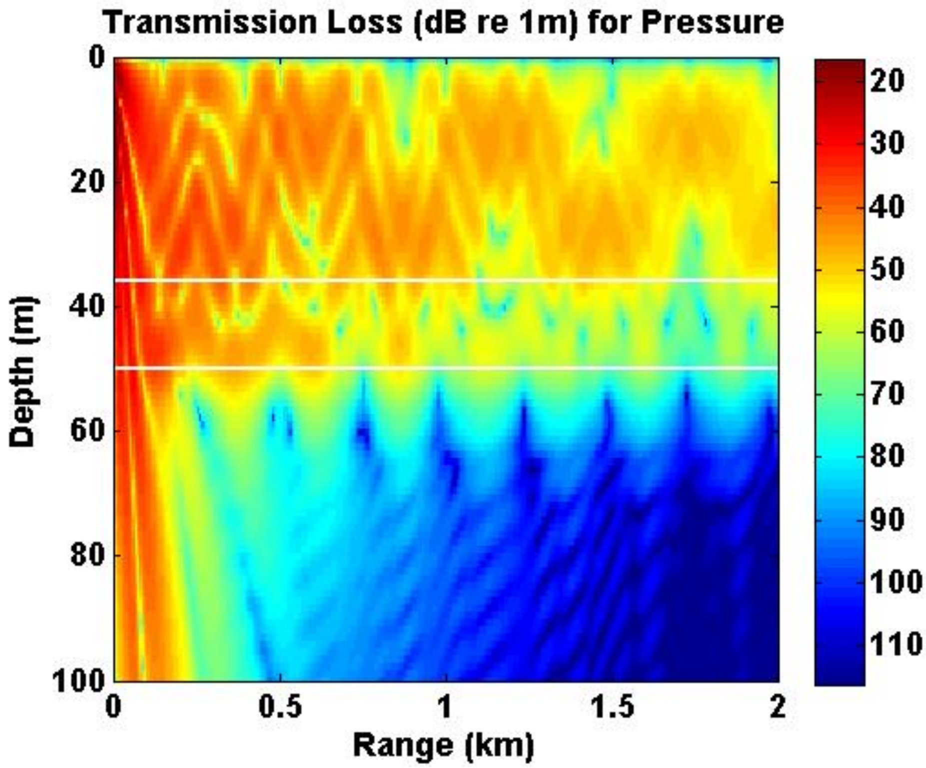

Figure 11: Modeled transmission loss at 200 Hz for a region near Block Island. Sediment parameters were adjusted to fir the measured TL.

Predicted levels of wind turbine operational noise underwater

Based on data from studies in other countries, noise from the operation of offshore wind turbines is expected to be much lower in average intensity level than that of construction noise. This noise is more analogous to shipping noise, in that it is continuous, low frequency (<1000 Hz), and low level. Because there are no installed wind turbines in the waters off the US, we have relied on data measured at European wind farms. Measurements were taken at a range of 110 meters from a monopile-mounted 1.5 MW GE turbine in Utgruden, Sweden. (Betke, Glahn, & Matuschek, 2004) The measurement set-up is shown in Figure 13 where the water depth was about 10 meters. The underwater noise levels in 1/3 octave bands are shown in Figure 14 for four cases: a) 1500 kW, 17 m/s in September, 2003, b) 1500 kW, 12 m/s in September, 2003, c) 80 kW, 3.5 m/s in October, 2002 and d) 80 kW, 3.5 m/s in October, 2003. Betke concluded that the sound levels measured would not cause damage to the hearing organs of marine mammals, but might affect their behavior in the vicinity of the turbine.

Using the measurements made during the Betke study, we can estimate the average noise budget for various wind farm configurations near Block Island. The Utgruden test and the Block Island wind farm differ in three important ways. 1) The support structures for the Utgruden turbines are monopiles while the Block Island wind farm will use lattice jacket structures. 2) The water depths and sediment characteristics in Utgruden and the Block Island Sound are different and therefore have underwater acoustic propagation conditions. 3) The wind conditions in Utgruden and Block Island are different.

We can use the measured transmission loss characteristics for Block Island Sound which address the first difference. However, we have no data on noise from wind turbines mounted on lattice jacket structures. The wind speed probability density function for the waters south of Block Island was derived from US Army Corps of Engineering WIS Station 76 and shown in Figure 15. (Spaulding, 2010)

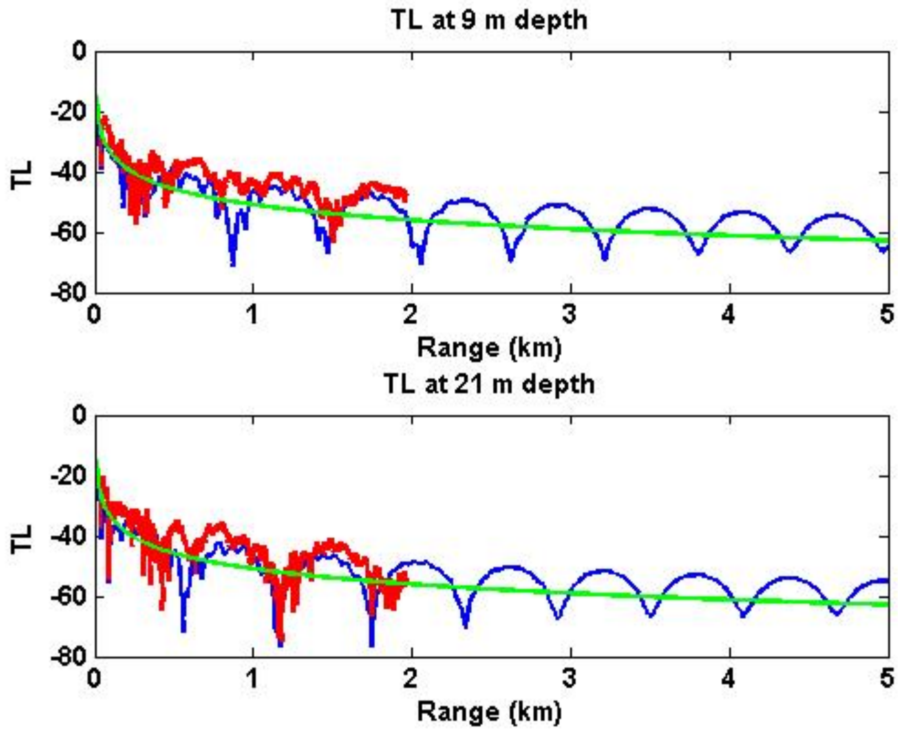

Figure 12: Measured transmission loss (red), modeled transmission loss using MMPE (blue) and 17log(r) (green). Upper plot is TL at 9 meter depth and lower plot is at 21 meter depth. The frequency is 200 Hz and the depth of the water is 35 meters. Sediments parameters were adjusted to match the measured and predicted TL. The units of TL are dB.

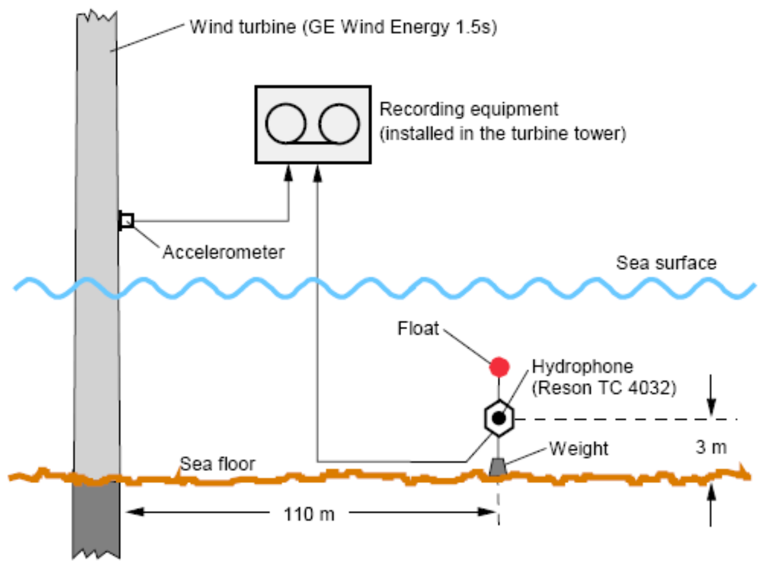

Figure 13: Measurement setup for monitoring underwater noise induced by an offshore wind turbine. Water depth was about 10 m. (Betke, 2004)

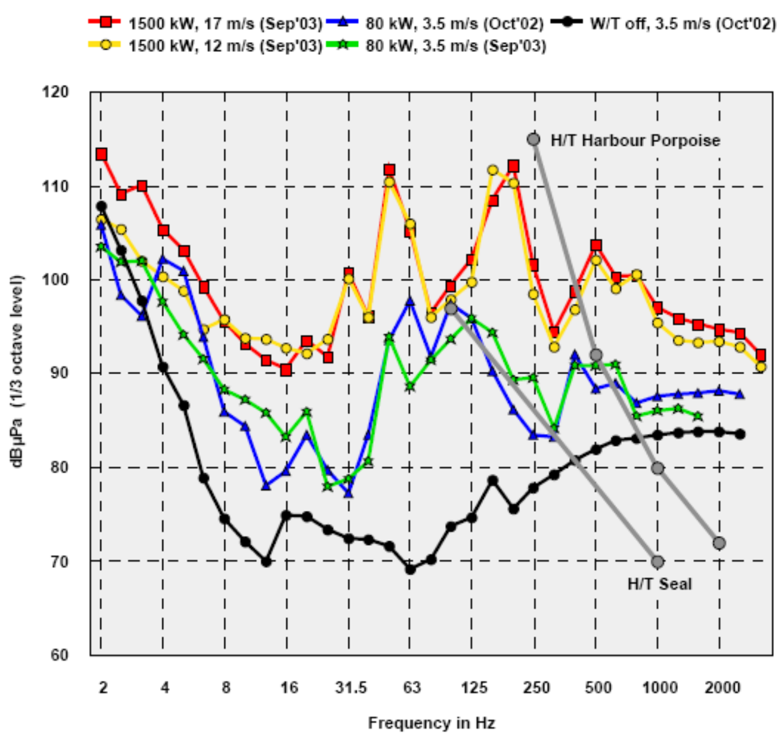

Figure 14: Measured underwater noise spectra in a 1/3-octave band for various wind speeds and power production. Also shown are the hearing thresholds for harbor porpoise and harbor seal. (Betke, 2004)

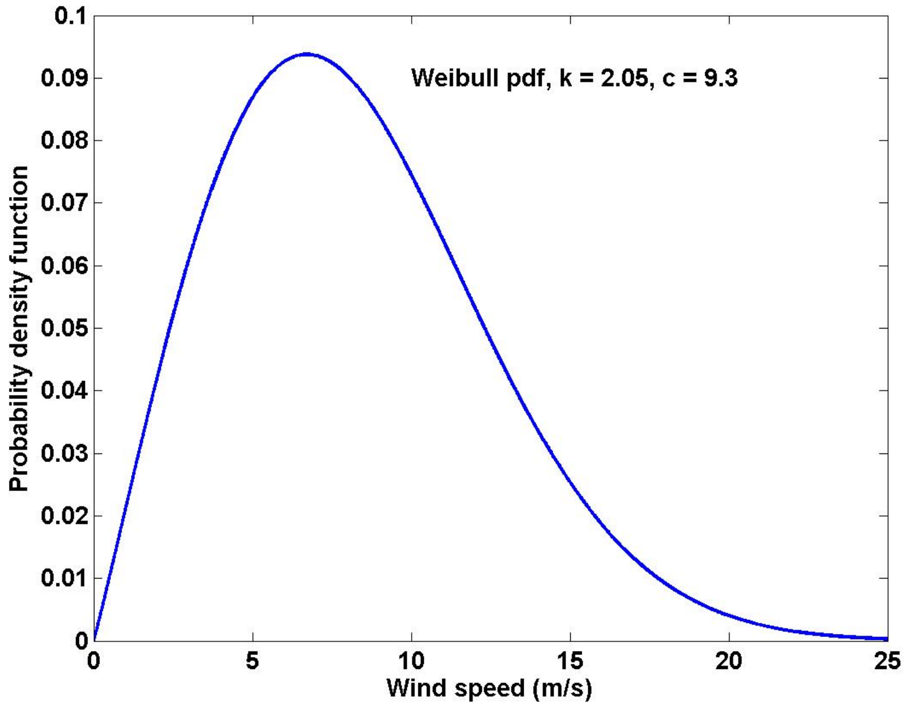

Figure 15: Probability density function for wind speed in the waters just south of Block Island. The Weibull pdf has a k-value of 2.05 and mean wind speed of 9.3 m/s.

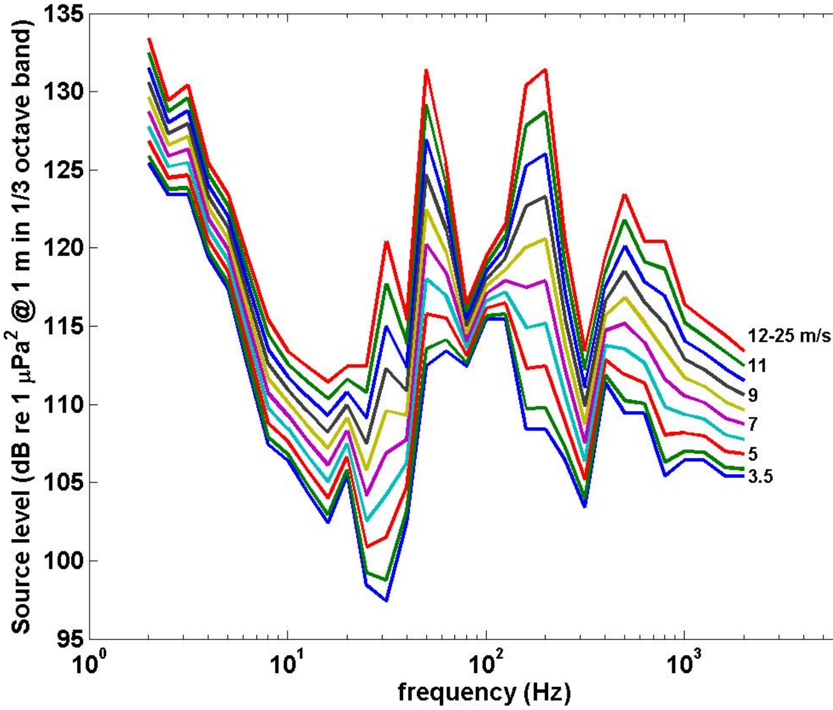

Figure 16: Calculated source level for a single wind turbine for various wind speeds from 3.5, and 4 to 25 m/s in steps of 1 m/s. Noise source levels for wind speeds from 12-25 m/s are the same.

Figure 16 shows the interpolated source levels from a single 1.5 MW wind turbine for various wind speeds from 3.5 to 25 m/s as interpolated from the Betke data in Figure 14. The levels for 12 to 25 m/s are the same. Using the levels in Figure 16, we are now able to calculate the additional noise from wind turbines in the noise budget originally presented in Figure 9. One final assumption needed is a location to determine the noise budget.

To find a reasonable location for the noise budget, we refer to the work of Robert Kenny and Kathleen Vigness Raposa. Figure 17 was developed by Kenney Vigness Raposa for the Ocean SAMP study using all available sources of information on the occurrence (Kenney & Vigness Raposa, 2010) and shows the relative abundance of the North Atlantic right whale in the region south of New England. Within the Ocean SAMP region, the principal areas of northern right whale habitat are south of Block Island. We therefore computed the noise budget for a location 10 km south of the proposed experimental wind turbines near Block Island, in the area of high relative abundance of the northern right whale. Propagation conditions were calculated using the sediment parameters estimated in our sea test. We assume that eight turbines will be in operation oriented east to west on a line 3 nm directly south of Block Island. We assume that the noise conditions at this location were the same as the data collected on the PAL. We also assume that the turbines are operating at the highest possible power setting for the wind conditions. The effect of the additional noise from these 8 wind turbines located near Block Island is shown in Figure 18 where the wind turbine noise is predicted to contribute 424 pW/m^2 or 88 dB re 1 μPa^2 in a 1/3-octave band. The noise from the eight turbines is combined together incoherently. The additional noise from the wind turbines is significantly less than noise from shipping, wind and rain for the period covered by these measurements (5 weeks in October and November, 2008). Also, the wind turbine noise is, on average, approximately the same as the biological noise in the budget.

We expect to have data from two PALs (one deployed within the state waters (3nm SE of Block Island and one deployed to the east in deeper water) that will have been in the water for one year.

For a larger wind farm (e.g. 70 turbines), the operational noise from all the turbines would add incoherently. There is no evidence of offshore wind turbines operating in resonance which could violate the incoherent assumption. Figure 19 shows three panels that illustrate the effect of two radiated noise levels at 100 meters. We chose 100 meters to diminish the effects of water depth. The left panel shows the noise in a 1/3 octave band at 200 Hz for a 70 turbine wind with 1 km spacing and a source level of 112 dB re 1 μPa^2 in a 1/3 octave band at 100 m. The middle panel is the radiated noise for a source level of 100 dB. The right panel is the measured ambient noise histogram from the Eider PAL deployed south of Block Island. The lowered radiated noise from the wind turbines brings the levels within the wind farm below the average ambient noise already present in the area. Human studies have shown that existing ambient noise levels affect the response to an additional noise source (Ontario Ministry of Environment, 2009).

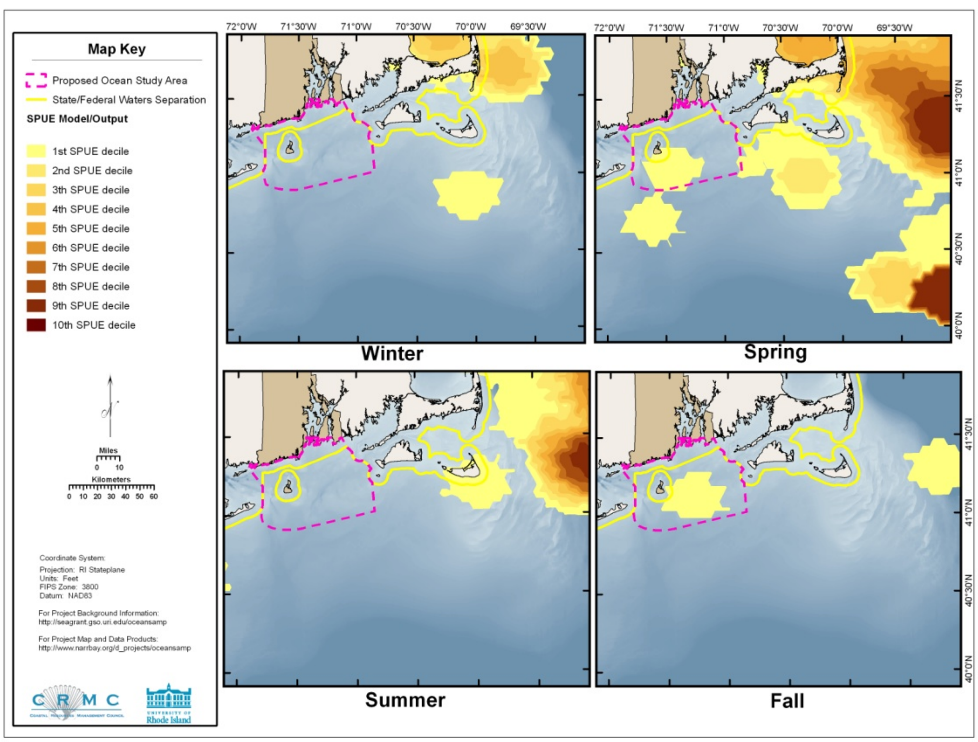

Figure 17: Relative northern right whale abundances are indicated by the yellow and brown in the region south of New England. The deciles ranged from 0.5 sightings per unit effort (SPUE) to 1200 SPUE.

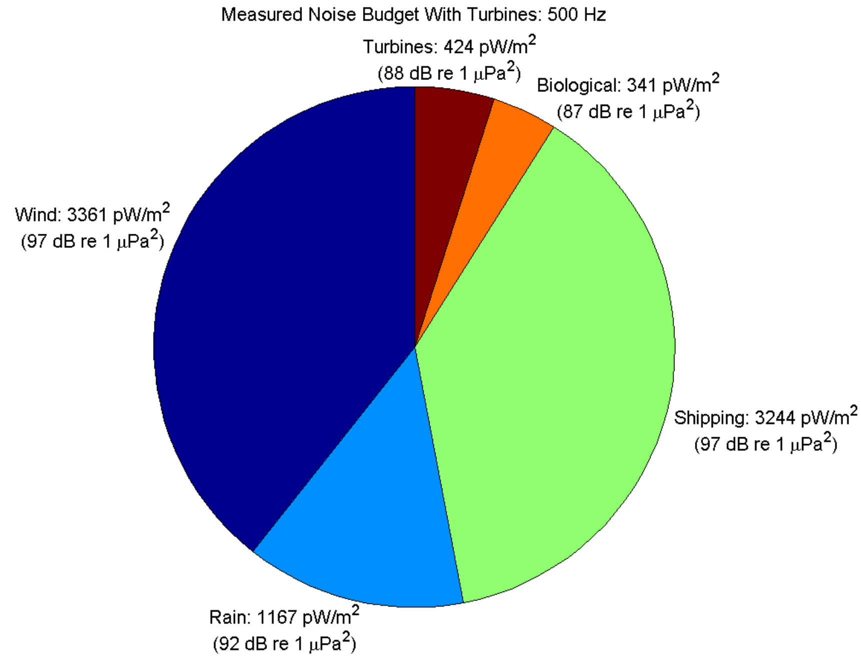

Figure 18: Noise budget as measured by the Eider PAL south of Block Island in the 1/3-octave band centered at 500 Hz with modeled turbine noise added for eight turbines measured 10 km south.

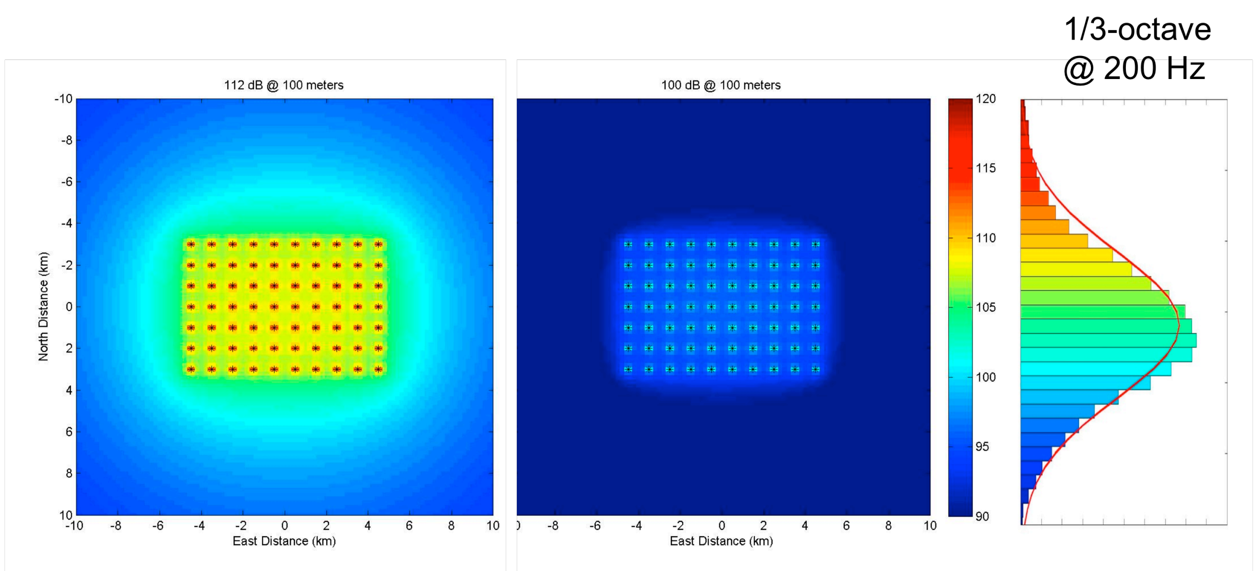

Figure 19: The left panel shows the noise in a 1/3 octave band at 200 Hz for a 70 turbine wind with 1 km spacing and a source level of 112 dB re 1 μPa^2 in a 1/3 octave band at 100 m. The middle panel is the radiated noise for a source level of 100 dB. The right panel is the measured ambient noise histogram from the Eider PAL deployed south of Block Island.

Prediction of pile driving noise

Using the propagation modeling approach discussed in the previous section, TL was modeled along tracks in all directions from the center of the proposed location of the wind farm. The approximate location is 41.1167 (N latitude); 71.5250 (W longitude) or 4554781 m (northing); 288009 m (easting). The tracks were spaced at 10 degrees apart. The ranges at which the received level exceeds 180 dB, 160 dB and 120 dB were picked based on the predicted received levels along each of these directions. The receive level at any range is calculated as the source level (@ 1m) minus the predicted TL at the range. Since no measurements of pile driving source levels were available at the location, we used published data from piles with comparable size in similar water depths. Data (Andrews, 2009) show measured sound pressure levels at 10 m for a similar size pile as 210 dB. We back calculated the sound pressure levels at 1 m to estimate the source level and used that to calculate the receive levels. Contours of received levels corresponding to 180 dB, 160 dB and 120 dB were then constructed and mapped into a GIS layer as shown in Figure 20. These received levels correspond to the *Zone of Responsiveness* for cetaceans and pinnipeds, and the *Zone of Masking* for all species, respectively, as previously presented in Table 1.

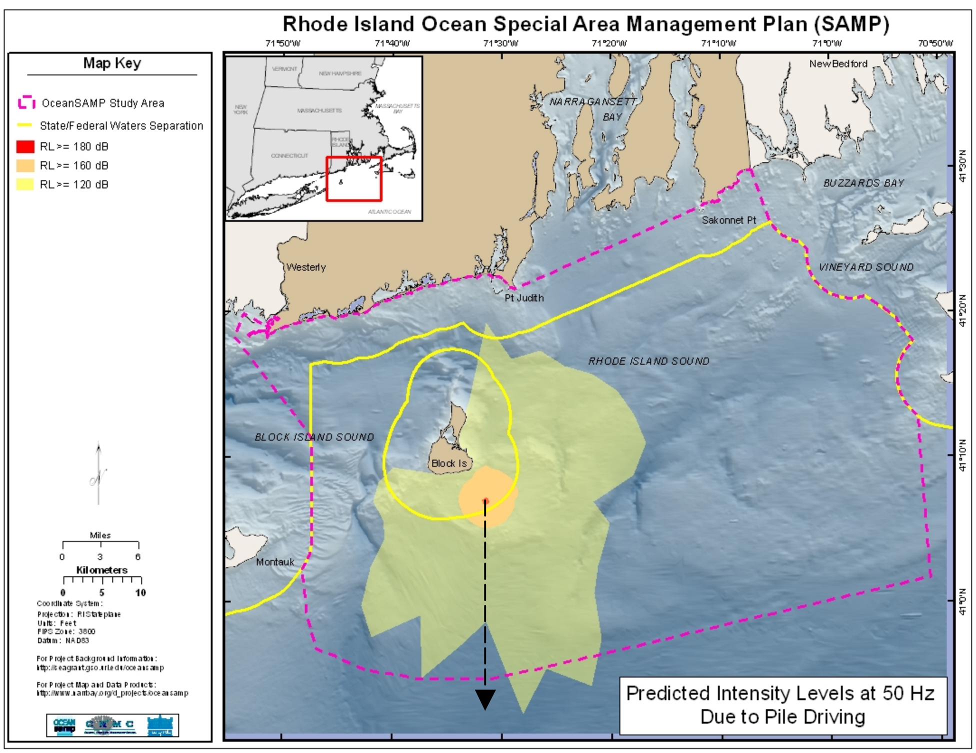

Figure 20: Estimates of the affected areas in the vicinity of proposed pile driving, location indicated by the start of the arrow. Received levels greater than 180 dB are indicated in red, 160 dB in orange, and 120 dB in yellow. The dashed arrow indicates the transect selected for modeling the broadband transmission loss.

Broadband acoustic modeling was carried out using the PE code MMPE. Calculations were made for a track as shown in Figure 20 out to a range of 30 km. Transmission loss was calculated for frequencies from 5 Hz to 1000 Hz. Figure 21 shows the transmission loss in dB as a function of depth (y-axis) and arrival time (x-axis) at 30 km. The ETOPO1 Global Relief Model provided the bathymetry along the propagation path. Measured temperature and salinity data were used to calculate the sound speed profile at the location. The sound speed and sediment geoacoustic properties were assumed range independent in these calculations.

Figure 21 provides the results of the calculation of broadband transmission loss (TL) on a transect directly to the south of the candidate turbine location southeast of Block Island. The minimum TL of 85 dB is associated with peak intensity of the pile driving noise waveform. The peak SPL can then be calculated as SPL = SL – TL. Measured data (Andrews, 2009) show sound pressure levels at 10 m for a similar size pile to be 210 dB re 1 μPa. If we assume cylindrical spreading near the pile, this corresponds to a source level of 220 dB re 1 μPa at 1 meter. Therefore the peak SPL at 30 km is 135 dB re 1 μPa. This predicts that the pile driving noise would be detectable by animals at these ranges. This level is less than the Level A Injury Criterion or the Level B Behavioral Criterion presently being used by NMFS.

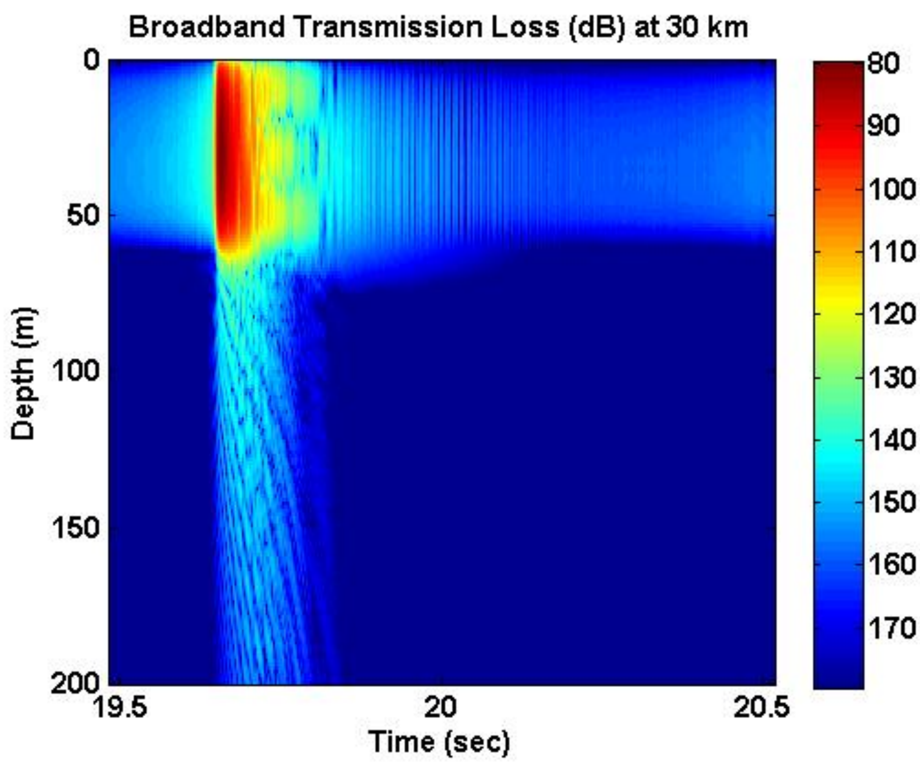

Figure 21. Broadband transmission loss on the transect to the south from candidate site out to a range of 30 km. The bandwidth of the transmission loss calculation using MMPE was 1 Hz to 10000 Hz.

Collected EM field data using calibrated systems in air in the fall of 2009

The electromagnetic field was measured at the underwater/underground cables from Newport to Jamestown and the data are shown in Figure 22. While this work is in progress, it is clear that these levels of magnetic field will also be present underwater near the power cable. This power cable is rated for 26 kVA and is similar to the cable to be installed for the 8 turbine farm near Block Island. Elasmobranches (sharks, rays and skates) respond to magnetic fields in the range of 25 to 100 μTesla (.25 to 1 milliGauss).(Gill & Kimber, 2005) Reactions to EMF can be attraction or avoidance depending on species, levels, distance from transmission cable and other factors. However, it is clear that these effects will be confined to within 10's meters from the power transmission cables envisioned for the Block Island wind farm.

We expect to have underwater EMF measurements completed in the next few months. These measurements will be taken at the Newport to Jamestown cable in Narragansett Bay.

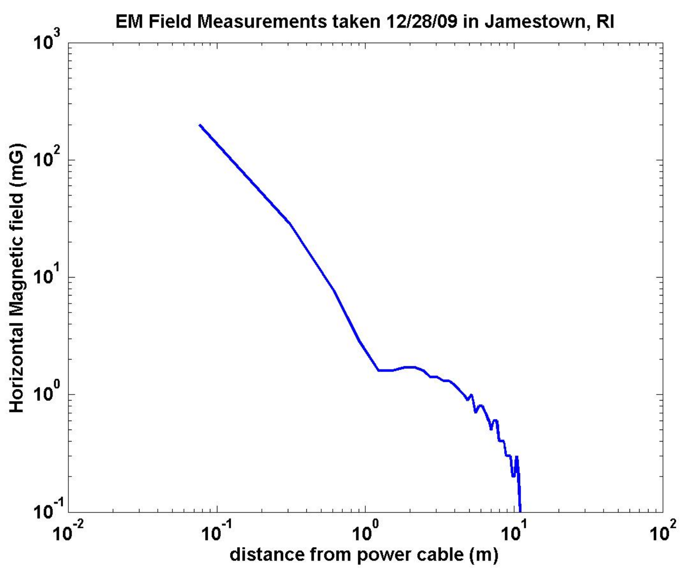

Figure 22: Horizontal magnetic field strength measurements taken on 12/28/2009 in Jamestown, RI near the underwater/underground power cable connecting Jamestown to Newport.

Conclusions and Recommendations

1) Pile driving impulses during construction may have significant physiological effects on marine life including whales and dolphins within 500 meters of the pile and pinnipeds within 150 meters of the pile.

Mitigation Recommended: Pile driving should start slowly with at least a 2 minute ramp-up before maximum pile driving. The piles should be driven with pile caps made of wood or synthetic material to reduce the pressure pulse and increase the pulse rise time.

Observers should be utilized to assure that no whales or dolphins are in an area of radius 500 meters from the pile driving (150 meters for pinnipeds). A monitoring system should be in operation during the pile driving to assure ramp up and measure the impulse time series on appropriate hydrophones and geophones. We recommend that construction be delayed until after the spring migration of North Atlantic right whales past Block Island.

2) Pile driving impulses during construction may have observable behavioral effects on marine life including marine mammals, fish, turtles, and lobsters within 4000 meters of the pile.

Mitigation Recommended: The piles should be driven with pile cushions made of wood or synthetic material to reduce the pressure pulse and increase the pulse rise time. A monitoring system should be in operation during the pile driving to assure ramp up and measure the impulse time series on appropriate hydrophones and geophones.

3) Underwater noise from offshore wind turbines has been measured in Europe at 118 dB re 1 μPa^2 in any 1/3 octave band at a range of 100 meters at full power production. The noise is due to gear noise and transmitted in to the ocean through the monopile support structure. This noise would be greater than the ambient noise present within 1 km of the wind turbines. It is likely that the operational wind turbine noise at ranges of 10 km would be below the ambient noise in the region.

Mitigation Recommended: Reducing the levels of noise from the wind turbines to below the ambient noise level in the area nearest to the wind farm may able to be achieved using the lattice jacket structure (which should reduce the noise level as compared to a monopile structure), appropriate isolation technology in the design of the structure, and lower noise drive systems. A monitoring system deployed to measure the operational noise time series on appropriate hydrophones and geophones. In addition, accelerometers should be installed on at least one of the turbines to monitor structural vibration. A goal for the wind farm developer and operator is to have operational noise from wind turbines average less than or equal to 100 dB re 1 μPa^2 in any 1/3 octave band at a range of 100 meters at full power production.

4) Airborne noise from the offshore wind turbines for the Block Island site (~3 nm south of the island) will not be detectable by humans or animals on Block Island. Airborne noise from the turbines will be detectable by humans and animals within 200 meters of the turbines.

Mitigation Recommended: The developer and manufacturer should endeavor to minimize the radiated airborne noise from the wind turbines.

5) Noise from decommissioning of the wind turbine structures using explosives could have serious impact on marine life within 500 meters of the structure.

Mitigation Recommended: The minimum possible amount of explosives should be used for the structure removal and all charges should be set to detonate at least 3 meters below the seafloor. A monitoring system should be in operation during the explosive removal to measure the operational noise time series on appropriate hydrophones and geophones.

6) Electromagnetic fields from transmission lines may have behavioral effects on marine life within 20 meters of the 26 kVA power lines likely to be used in the Block Island wind farm. The effects could include both attraction and repulsion.

> Mitigation Recommended: A monitoring system including acoustical, optical and other sensors should be established near these facilities to quantify the effects.

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