An Analysis of the Potential Acoustic Effects of Cape Wind's Offshore Wind Farm on Marine Mammal Populations

by

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List of Acronyms

a	area
AEP	auditory evoked potential
BCE	before common era
c	speed of light
°C	degree Celsius
dB	decibels
EEZ	exclusive economic zone
EIS	Environmental Impact Statement
ESA	Endangered Species Act
f	frequency
F	power
Hz	Hertz
I	intensity
kg	kilograms
kHz	kiloHertz
km	kilometers
kW	kilowatts
m	meters
MEPA	Massachusetts Environmental Protection Act
MMPA	Marine Mammal Protection Act
ms	milliseconds
mW	megawatts
NEPA	National Environmental Protection Agency
p	pressure
NOAA	National Oceanic and Atmospheric Administration
ppt	parts per thousand
PTS	permanent threshold shift
s	seconds
SPL	sound pressure levels
T-POD	timing porpoise detector
TTS	temporary threshold shift
v	velocity
µPa	microPascal
λ	wavelength

I. Abstract

Offshore wind farms are an appealing form of renewable energy that are common in Europe but have yet been developed fully in the United States. The Cape Wind project in Massachusetts has proposed the construction of 130 turbines in the Horseshoe Shoal of Nantucket Sound. Despite the potential local benefits of the development, many Cape Cod residents oppose construction of the wind farm. Opposition to this development includes concerns that the noises emitted during all phases of the wind farm's life cycle will adversely affect populations of marine mammals. In my Master's project I review and analyze information regarding the acoustic effects of offshore farms and other relevant anthropogenic sound sources. It is difficult to predict fully what effects the Cape Wind project will have on marine mammals in Nantucket Sound. Nevertheless, it is clear that the construction phase would have the greatest potential acoustic impact, including possible displacement; operational sounds are less intense and more likely to result in habituation. Ultimately, however, marine mammals within Horseshoe Shoals do not face any greater risk from Cape Wind than from other anthropogenic sound source in the region.

II. Introduction

In today's world, we worry about a possible energy shortage as oil resources become scarce and, in the process, become a target of political turmoil. Coupled with growing concern over global warming and the need for "green" alternative to our everyday living, emphasis has been put on developing new sources of energy: cleaner, safer sources for the environment that would also contribute to the United States energy autonomy. Such potentials include solar, nuclear, and wind sources. Today, established land based wind farms have the potential to contribute up to 30% of an overall energy budget (Soder and Ackermann 2005). Looking to Europe to set the stage, proposed offshore wind farms in the United States such as the Cape Wind project in Massachusetts are believed by many to be the next important alternate energy source.

The human species has been harnessing the power provided by wind since the 7th century BCE, when Afghani highlanders built vertical axis mills to grind grain (Ackermann 2005). Not until 1891 did anyone think of designing a wind turbine to harvest electricity. As the wind spins the blades of the turbine, they in turn spin a shaft connected to an electrical generator that transforms the kinetic energy of the wind into harvestable electric energy (Soder and Ackermann 2005). Due to shortages of electrical power during the World Wars, the Danish engineers worked on improving the design into the modern day predecessor. The first offshore turbine farm appeared approximately fifty years later at Vindeby, Denmark. The eleven 450 kilowatt (kW) turbines on this farm are capable of producing 11,200 to 11,730 megawatts (mW) of electricity a year (Barthelmie and Pryor 2001). Overall, previous studies have shown that offshore winds are higher, less turbulent, and more persistently occurring than onshore winds and capable of generating electricity at a steady and efficient rate (Barthelmie and Pryor 2001).

While offshore wind farms have become prevalent in Europe since their inception in Denmark, they have yet to become a reality in the United States. So far, seven projects have been announced within the United States: Long Island Power Authority/Florida Power and Light in the Long Island Sound, Wind Energy Systems Technologies off of Galveston, TX, Bluewater Wind LLC in Delaware, Southern Company off of Savannah, GA, Hull Municipal in the Boston Sound, Patriot Renewables LLC in Buzzards Bay, MA, and Cape Wind Associates in the Nantucket Sound (US Department of Energy 2008). Of all these initiatives, Cape Wind opts to be the first and largest offshore wind farm in the nation (Figure 1).

Specifically, Cape Wind plans on building 130 turbines within Horseshoe Shoal, each 16 feet in diameter and 258 feet tall from the water's surface to the center of the blades, and mounted to the seabed with a steel pipe driven 80 feet underneath the ground (Cape Wind Associates, LLC 2009). These turbines will produce of 170 megawatts per year on average, with a maximum of 468 megawatts per year. The energy will be wired to the Barnstable Substation on Cape Cod and provide about 75% of Cape Cod's energy demands for the twenty one years following its inauguration (Cape Wind Associates, LLC 2009).

III. Relevant Environmental Statures

The National Environmental Protection Act (NEPA), established in 1970, provides the policy, goals, and regulations utilized by agencies to promote and preserve the enhancement and status of the environment. Most importantly, NEPA requires any new initiative that possesses the possibility of adversely affecting nature to file an Environmental Impact Statement (EIS) or Environmental Assessment. This comprehensive report analyzes the total environmental impact the project, such as the construction and operation of Cape Wind, may have and provides any alternate strategies for significant alteration of the natural environment (US EPA 2009). Cape Wind filed their draft EIS in November 2004, a 3,800 page report that ultimately deemed that the positive impacts held more weight than any potential negative effects. Namely, Cape Wind cites that the overall reduction in greenhouse gas emissions due to the implementation of the wind farm will curb pollution and improve health quality, which will improve public health in addition to environmental circumstances (Cape Wind Associates, LLC 2009).

The Endangered Species Act (1973) requires that the planned wind farm must not threaten or harm listed species, nor affect critical habitat necessary for their conservation. The Marine Mammal Protection Act (1972) protects marine mammals from harm within American territorial waters. However, unlike the ESA, this act does not possess any stipulation regarding critical habitat. Cape Wind claims that marine mammals will not be disturbed during construction or operation of the turbines (Cape Wind Associates, LLC 2009). Finally, the Magnuson-Stevens Fishery Conservation and Managements Act (1976) requires the protection of essential fish habitat and review thereof of any project that may threaten fishing areas (Feder 1996). In response, Cape Wind's studies claim that fishing activity in the Shoal should not be altered given the wide spacing of turbines. Furthermore, they believe that the turbine bases will provide new habitat for many commercial ground fish species – something that may ultimately be beneficial to marine mammals as well (Cape Wind Associates, LLC 2009).

Many of the state laws that apply to the Cape Wind project are similar to the federal laws previously described. This list of laws includes the Massachusetts Environmental Policy Act, a state-specific version of NEPA that requires a state version of an Environmental Impact Report which may be issued in conjunction with the federal EIS (Santora et al. 2004). Like NEPA, the overall goal of MEPA is to make sure that agencies such as Cape Wind determine and investigate the possible environmental effects their projects may possess and to control any damage that may occur (Executive Office of Environmental Affairs 2009). In neither case does the Act ensure anything more than requiring that the proper research is done. A subsection of the MEPA, the Oceans Sanctuary Act of 2003, prevents building of structures or any activities that may alter the ecology of these areas (Massachusetts Office of Coastal Zone Management 2008). Included are structures built on or under the seabed, such as those Cape Wind could affect in construction of their turbines and the under seabed cables that will bring the generated electricity back to shore. This Act was amended in 2008 by the Oceans Act to control the sites of offshore renewable energy facilities. The Oceans Act also set up a number of committees to which Cape Wind will be accountable, as discussed in the next section of this paper (Massachusetts Office of Coastal Zone Management 2008).

Finally, the Electric Restructuring Act of 1997 was enacted to deregulate electricity industry and recreate it with the goal of cleaner and fairer energy supply. As a part of this act, the state government implemented the renewable portfolio standard, monitored by the Department of Energy Resources, and requires a minimum of 10% of the state's energy to come from a renewable source (Commonwealth of Massachusetts 2009). The wind energy that will be generated through projects such as Cape Wind counts towards this requirement, and thus becomes quite important for the state as a whole.

The Massachusetts Energy Facility Siting Board, part of the Department of Public Utilities, is responsible for making sure the 10% reusable energy goal as dictated by the Electric Restructuring Act is met each year (Commonwealth of Massachusetts 2009). So, although not directly responsible for Cape Wind outside of giving its initial approval of the project, opinions and trends set by this committee could affect the project's popularity in state. Finally, on a more local level, the Cape Cod Commission, established by the Cape Cod Commission Act, ensures that a project like Cape Wind will not be detrimental to the public and environmental health of the Cape.

IV. The Social Issue

People who live on Cape Cod are both the benefactors and the strongest opponents of the Cape Wind development plan, and therefore they become an important part of the human ecology surrounding this project, given that these individuals could put a stop to this project. As Cape Wind continues to meet the legal mandates set out by governmental agencies, opposition from the people will become one of the only ways left to halt its construction and operation.

A 2005 survey conducted among a 400 person sample of Massachusetts voters by Opinion Dynamics Corporation on behalf of Cape Wind indicated that 47% of voters in Massachusetts were in favor of the project, 39% against, and 13% undecided (Opinion Dynamics Corporation 2005). Yet, a 2007 study of 1500 residents by researchers at the University of Delaware indicated opposite results when only surveying Cape citizens. On the Cape, 42.4% were opposed, with only 26% in support and 33% undecided. Of those undecided, 55% were leaning towards opposing the Cape Wind project and 43% were likely to support the project (Firestone and Kempton 2007).

Cape Wind has stated publicly that the energy output of the turbines will be routed to the Barnstable Station for use by residents of the Cape. That output alone will reduce energy costs for the majority of residents, not to mention reduce the fossil fuel emissions that affect air quality on the cape (Cape Wind Associates, LLC 2009). During construction, about five hundred to a thousand new jobs will be created, with approximately 150 permanent jobs when Cape Wind reaches operational phase (Cape Wind Associates, LLC 2009). In the long run, it is projected that the investment will most likely yield local and state economic boons, and certainly no losses.

Yet, despite the number of benefits Cape Wind will provide, the prospect of visual aesthetics being compromised by the wind farm remains the most important factor for Cape Cod citizens to object to the building of the wind farm. Approximately 72% of the individuals questioned by Firestone and Kempton stated aesthetics to be their primary concern, because the development of a wind farm in the Horseshoe Shoals would ruin their pristine view of the Atlantic, even if the turbines will only rise an inch from the horizon when looking outward from the closest beach. Aesthetics, however, remains a subjective issue difficult to quantify and upon which to determine rulings.

Residents of Cape Cod who oppose this project have found alternative methods of attacking Cape Wind. The Alliance to Protect Nantucket Sound, INC has repeatedly looked for more substantial grounds in which to bring Cape Wind to court. In one such case, the Tauro Decision of 2003, the Alliance claimed Cape Wind lacked a necessary state permit to build their monitoring station on the continental shelf. However, the company possessed a permit from the U.S. Army Corps of Engineers, issued under the Outer Continental Shelf Lands Act, which allowed them to construct the station for scientific purposes. The station would allow conditions to be continuously monitored for the proposed site and data could be gathered for the EIS. Judge Tauro ruled in favor of Cape Wind (US District Court of Massachusetts 2003). Ultimately, this attempt by the Alliance to interfere with construction of the turbines, like others, fell through. So far, there has been nothing Cape Cod citizens have been able to do to prevent the construction of the turbines.

However, disruption of Cape Wind's goals may still occur if individuals are capable of presenting a strong and conclusive case for the negative environmental impacts of an offshore wind farm, such as the effects of anthropogenic noise created during construction and operation on marine mammals. Low frequency sounds within the hearing threshold of many species of cetaceans and pinnipeds are produced by turbines during both these stages (Koschinksi et. al. 2003). The extent of propagation and intensity remains mostly unknown despite the fact that low-frequency sounds tend to travel long distances (Koschinksi et. al. 2003).

Given the popularity of offshore wind farms in Europe, a number of risk assessments and related studies have been conducted. Public concerns persist regarding the creation of navigation obstacles for birds and noises that might scare away the marine mammal population (Blew et. al. 2006). Although the environmental conditions of the Baltic and North Seas differ from that of the Nantucket Sound, the data collected from these studies provide a background from which to work.

V. Sound Transmission

While the definition of sound incorporates any mechanical disturbance (typically in the form of a wave) through a medium, noise is best categorized as sound that is unwanted and capable of interfering with the normal processes of said medium (Wartzok and Ketten 1999; Ross 1976). Noise is considered unavoidable: all processes in which mechanics are involved create noise of some sort. As in air, sound travels as a wave underneath the water. However, differences in wavelength, intensity, and frequency exist of a sound travelling within the different mediums (McCarthy 2004).

How, specifically, do the mechanics of sound and noise work? Sound is usually defined by its frequency (f), speed (c), wavelength (λ), and/or its intensity (I), where frequency is measured in cycles/second or Hertz (Hz) and is equal to the speed of sound (in m/s) divided by the sound's wavelength (in m/cycle) or:

$$f = c/\lambda.$$

The speed in which a sound travels is dependent upon the density of the medium. The denser a medium, the faster a sound is capable of travelling. Thus, the same acoustics heard in air and water will travel faster in water, at an average of 1530 m/s.

Yet, the aforementioned characteristics of sound cannot stand alone when discussing their affects upon marine mammals. Similarity to ambient noise and the hearing sensitivity of a specific species must also be taken into account (McCarthy 2004). Furthermore, salinity, temperature, and pressure of water also alter the physical properties of a sound, giving any region a diverse and complex sound profile. Every 1% increase in salinity is equivalent to an increase in sound speed of 1.5 m/s. Every drop of 1°C in temperature will decrease sound speed by 4 m/s and after every 100 meters in depth, speed will increase by 1.8 m/s (Wartzok and Ketten 1999).

Radiated noise is such created from a specific source in the water whereas ambient noise is used to describe natural background sounds (Ross 1976). In addition, noise can also be classified based on the source from which it is transmitted: source-point or transient.

Even without the effects of humans, the ocean is a noisy system, which is perhaps one of its defining characteristics (Orenstein and Langstaff 2006). Wind, waves, seismic activities, precipitation, thunder, and lightening all contribute to oceanic acoustics, with wind and wave activity being the most dominant of the physical processes. Without taking biological noises into account, most natural marine sounds occur between frequencies of 100 to 50,000 Hz (McCarthy 2004). Thus, the auditory systems of many marine animals have evolved to possess functional hearing at levels outside the noisiest frequencies. This adaptation serves as an attempt to prevent masking.

IV. Marine Mammal Hearing

Before delving into the specifics of pinniped and cetacean hearing, a basic understanding of mammalian hearing mechanics will be reviewed. Despite specialized adaptations for the oceanic environment, a marine mammal's hearing process works in a similar way to that of land mammals.

On land, the smaller the animal, the better they are at hearing higher frequencies. This trend remains true among marine mammals, despite the hearing diversity created by their size, habitat, and evolutionary development. What an ear primarily receives and interprets is not the frequency, however, but the intensity of a sound measured in watts/meter squared. Intensity is equal to the power ($F \cdot v$) of a sound spread across a certain area (a), or the pressure (p) of a sound multiplied by the velocity (v) at which it is applied:

$$I = F \cdot v / a = p \cdot v.$$

Calculations of the above equation indicate that the same sound requires approximately 60 times the pressure needed in air to produce the same sound intensity within an aquatic environment. Therefore, an animal that hears equally well in both environments will need a greater sound pressure when underwater to receive the sound at the same intensity, despite the faster speed.

Sound pressure levels (SPL) in decibels (dB) are used as a measurement for comparison of sound intensities.

Mammalian ears are generally divided into three sections: the outer ear that collects the sound, the middle ear that then transforms this acoustical energy into mechanical energy, and the inner ear, capable of detecting the mechanical energy from the previous chamber and reforms it into neural impulses for the brain to interpret. Like with hearing capabilities, a wide variety of ear size and shape exists among marine mammals. With the exception of otariids pinnipeds, one of the most noticeable characteristics of many marine mammalian ears is the absence of external pinnae: an adaptation to reduce drag when diving and swimming. Other differences in structure also exist in a manipulation of the basic ear framework to adapt for higher or lower frequency reception. Differences in hearing ranges also exist between members of the same species.

To represent the acoustic capabilities of an animal, an audiogram is plotted to represent the sensitivity of an individual (in dB SPL for air based measurements and dB re 1 µPa for water based measurements) to a certain sound against its frequency (Figure 2). For mammals, including cetaceans and pinnipeds, the general audiogram is U-shaped. This hearing curve represents a high sensitivity for a narrow range of frequencies, with a distinct decrease in sensitivity on either side of these narrow ranges. Specific audiograms and hearing thresholds for pinnipeds and cetaceans are discussed later.

In contrast to cetaceans, pinnipeds lead amphibious lifestyles. Although the time spent on land versus the time spent in the ocean varies amongst the different species, the general hearing scheme for a pinniped must deal with the two different media. Sound must be sensed and interpreted whether the animal is in air or water, as observed by watching a pinniped call for its pup on land or forage underwater. Two premises have been hypothesized to explain the auditory abilities of pinnipeds in water and on land. The first involves independently operating hearing systems, one which picks up and transmits frequencies pertinent for an underwater sensory system and the other which interprets the frequencies important for land based hearing. Another possibility is that pinnipeds have adapted their acoustical capabilities towards one specific environment and possess more limited abilities in the other (Wartzok and Ketten 1999).

Within their aquatic environment, marine mammals rely on the production and reception of sounds for communication, orientation, predator avoidance, and foraging (Madsen *et. al.* 2006). Thus, the frequencies in which these animals are most sensitive depend greatly upon the frequencies generated by the animals themselves. Mysticetes produce sounds between 10 Hz and 10 kHz, while odontocetes produce sounds between 1 to 150 kHz in frequency (sounds that include echolocation as well as vocalizations for communication). Pinnipeds, meanwhile, are known to produce sounds between 50 Hz to 60 kHz (Madsen *et. al.* 2006). Hearing capabilities in marine mammals have evolved to overlap with the specific frequency ranges of sound production for each species.

Audiograms, in air and in water, exist for a limited number of pinniped species. For phocids, individuals from the harbor seal (*Phoca vitulina*), harp seal (*Phoca groenlandica*), ringed seal (*Phoca ispida*), gray seal (*Halichoerus grypus*), elephant seal (*Mirounga angustirostris),* and the Hawaiian monk seal (*Monachus schauinslandi*) species have been tested (Mohl 1968, Terhune and Ronald 1972, Turhune and Ronald 1975, Schusterman 1981). Only two species of otariids possess audiograms, the California sea lion (*Zalophus californianus*), Steller sea lion, (*Eumetopias jubatus*), and the northern fur seal (*Callorhinus ursinus*; Schusterman *et. al.* 1981, Schusterman and Moore 1978).

From data collected, phocids appear to have peak sensitivities between 10 to 30 kHz when within water. When compared to hearing curves derived in air, the peak sensitivities of the phocids appear at 3 to 10 kHz, indicating a better adaption to the aquatic environment. Otariids follow a similar trend, with peak sensitivities in water being higher (15 to 30 kHz) than the peak sensitivities measured for aerial hearing (<10 kHz). Yet, aerial and underwater audiograms for otariids are similar enough to suggest that perhaps these pinnipeds developed a parallel hearing strategy (Wartzok and Ketten 1999). Kastelein *et. al.*'s work on the hearing sensitivity of Steller sea lions, for example, depicted U-shaped audiograms similar to that of other mammals but with significant variation between individuals (2005). Maximum sensitivity occurred at 1 kHz for the male at a level of 77 dB re 1 µPa and 25 kHz for the female at a level of 73 dB re 1 µPa when underwater (Kastelein *et. al*. 2005). Meanwhile, Kastak and Shusterman determined maximum underwater hearing sensitivity for an elephant seal at 60 dB re 1 µPa when within the frequency range of 4 to 20 kHz (1999). One must keep in mind, however, that the sample size involved in these studies typically comprises only one or two individuals and thus the values obtained are not necessarily indicative of an entire species.

As odontocetes evolved to their aquatic environment, a substantially different ear developed. External pinnae disappeared and as the middle and inner ears migrated further outward, air-filled canals were reduced. Ears became suspended by ligaments within a foam-filled cavity outside of the skull to separate hearing from the bone conduction used in echolocation. Thin layers of bone comprise air chambers necessary to regularize pressure when the animal dives (Wartzok and Ketten 1999). Odontocetes use sounds in a number of behavioral contexts, including communication and echolocation. Perception of low-frequency vibrations in animals such as the bottlenose dolphin may also come from receptors in the skin capable of detecting the changes in frequencies around the animal (Turl 1993).

As with pinnipeds, threshold experiments conducted with cetaceans have been limited in number and species, specifically: the Atlantic bottlenose dolphin (*Tursiops tursiops*), the killer whale (*Orcinus orca*), the Amazon river dolphin (*Inia geoffrensis*), the beluga whale (*Delphinapterus leucas*), harbor porpoise, (*Phocoena phocoena*), the false killer whale (*Pseudorca crassidens*), the Chinese river dolphin (*Lipotes vexillifer*), the tucuxi (*Sotalia fluviatilis guianensis*), and Risso's dolphin (*Grampus griseus*; Awbrey *et. al.* 1988, Johnson 1967, Kastelein *et. al.* 2002, Thomas *et. al.* 1983, Hall and Johnson 1972, Wang *et. al.* 1992, Nachtigall *et. al.* 1995, Jacobs and Hall 1972, Sauderland and Dehnhardt 1998). Threshold experiments are conducted in controlled situations. Due to their immense size, it currently remains infeasible to conduct such experiments with mysticetes. Peak sensitivity for most odontocetes has been determined to be between 40 to 80 kHz, although the specific thresholds vary among individuals as well as species (Wartozk and Ketten, 1999).

Data collected at sea indicate that the harbor porpoise, for example, has a particularly sensitive auditory capability (Kastelein *et. al.* 2002). Audiograms indicate maximum sensitivity between 100 to 140 kHz. Anywhere above or below those values and the porpoise's hearing ability decreased significantly (Kastelein *et. al.* 2002). Among the different animals studied, audiogram shapes were similar, the maximum sensitivities varied by a degree of 10 to 15 dB, and the frequency limits varied by 90 to 150 kHz (Kastelein *et. al.* 2002). In general, odontocete audiograms display a wider range of frequencies than any other mammal tested (Hoelzel 2002).

V. Horseshoe Shoals Marine Mammal Composition

As part of their permitting requirements, Cape Wind was required to list all the marine protected species found within Nantucket Sound. Prepared for the U.S. Army Corps of Engineers in November 2004, the group had not yet settled upon Horseshoe Shoals as their final site. Thus, the statement looked at the distribution of protected species within designated alternative areas offshore of Nantucket Sound and offshore south of Tuckernuck, as well as the eventually settled upon shoal (ESS Group, Inc. 2004). The following marine mammals were listed as possible visitors to any of the proposed sites: humpback whale (*Megaptera novaeangliae*), fin whale (*Balaenoptera physalus*), northern right whale (*Eubalaena glacialis*), minke whale (*Balaenoptera acutorostrata*), long-finned pilot whale (*Globicephala melas*), white-sided dolphin (*Lagenorhynchus acutus*), striped dolphin (*Stenella coeruleoalba*), common dolphin (*Delphinus delphis*), harbor porpoise (*Phocoena phocoena*), gray seal (*Halichoerus grypus*), harbor seal (*Phoca vitulina concolor*), harp seal (*Phoca groenlandica*), and hooded seal (*Cystophora cristata*). In addition, surveys compiled within OBIS-SEAMAP since the 1970s indicate that white-beaked dolphins (*Lagenorhynchus albirostris*) have also been sited within Nantucket Sound within recent years (Figure 3; Read *et. al.* 2010). The following sections provide a brief overview of each aforementioned species.

*i. Humpback Whale (*Megaptera novaengliae*)*

The humpback whale is a highly migratory species of baleen whale found throughout the world's oceans. North Atlantic humpbacks are divided into a number of distinct subpopulations. In 2002, the National Oceanic and Atmospheric Administration recognized the Gulf of Maine stock, the group of interest for this report, as its own distinct management unit (Waring *et. al.* 2008). The total North Atlantic population was estimated in 1997 to be comprised of approximately 7700 individuals using photographic mark-recapture techniques (Palsbøll *et. al.* 1997). Another estimate, this conducted based upon genotype analysis, estimated a population of 10400 whales (Smith *et. al.* 1999). The Gulf of Maine subpopulation was estimated to be between 359 and 847 individuals based upon line-transect surveys conducted in 2004 and 2006, respectively (Waring *et. al.* 2008). The humpback whale is currently listed as endangered under the ESA.

Humpback whales spend winters in the Caribbean mating and birthing before returning north to summer within the higher latitude feeding grounds. The whale possesses a preference for schooling prey in the northern waters, including euphausiids, herring, sand lance, and other small fish (NOAA Fisheries 2010; Waring *et. al.* 2008).

Typically, during the summer months, the humpback whales are found within areas of high prey abundance: areas of upwelling, bank edges, alternating bathymetry along the continental shelf. Preferred habitat also tends to involve frontal zones that occur between mixed and stratified regions (ESS Group, Inc. 2004). Parts of the southern New England waters constitute such compensation and thus frequented by the animals. Within these areas, whales often move around in correlation with prey abundance. Sites visited, though, must also contain certain oceanographic characteristics to make their foraging techniques, such as bubble netting, possible. All age groups visit during the summer, however in winter months, only the occasional solitary juvenile tends to be observed.

Within Nantucket Sound, few humpback whales have been recorded during scientific surveys. Although bathymetric and oceanographic features resemble that of which are found at known feeding sites such as Stellwagen Bank on the other side of the Cape, densities of prey are not high enough to support many whales (ESS Group, Inc. 2004).

Humpback whales are not typically shy of vessels and are considered by some to be the most habituated to disturbances caused by boating (Watkins 1986). They have been spotted with great frequency around fishing and whale watching boats in the Great South Channel and Stellwagen Bank (ESS Group, Inc. 2004). At the same time, however, this has caused vessel collision to become one of the leading sources of anthropogenic mortality to the species (Waring *et. al.* 2008). Work conducted by Fristrup *et. al.* among the Hawai'i humpback whale population has indicated that, within the presence of low frequency broadcasts, song length increases among individuals (Fristrup *et. al.* 2003; Miller *et. al*. 2000). Furthermore, the higher level of broadcasts was associated with longer lasting vocalizations.

*ii. Fin Whale (*Balaenoptera physalus*)*

The fin whale is the most common mysticete within the western North Atlantic, typically constituting about 46% of the large whales sighted in surveys (EES Group, Inc. 2004; Waring *et. al.* 2008). Approximately 2269 individuals are thought to exist within this population according to a conservative survey conducted in August 2006 (Waring *et. al.* 2008). The Western North Atlantic stock is defined by the IWC to include whales who feed in waters off of the eastern shore of the United States, Nova Scotia, and southeastern Newfoundland (Waring *et. al.* 2008). This species is usually found along the continental shelf in waters of less than 100 m depth throughout the year and tend to travel in groups of two to seven individuals (NOAA Fisheries 2010).

As with the humpback whale, the New England waters provide important feeding grounds during the spring and summer seasons, occupying areas of 40 to 50 m in depth (EES Group, Inc. 2004). In fact, the feeding grounds utilized are often shared with humpbacks minkes, and Atlantic white-sided dolphins. Migration patterns and feeding location preference among specific individuals appear to be of maternal lineage, as juveniles have been spotted returning yearly to spots first visited as calves with their mothers (Seipt *et al.* 1990). The feeding grounds support high prey density, areas such as the Great South Channel, Stellwagen Bank, and the eastern part of Georges Bank (Hain *et. al.* 1992). Movements within the northern latitudes are believed to be connected to prey migration. This prey includes krill, squid, capelin, sand lace, herring and other small schooling fish (NOAA Fisheries 2010).

Within the Nantucket Sound, few fin whales have been spotted despite mid-shelf areas within Nantucket forming the northernmost boundary of more southern feeding grounds (EES Group, Inc. 2004; Hain *et. al.* 1992). Although there is similarity in bathymetric and oceanographic features to the feeding grounds, the wind farm site lacks the high density of prey species. As such, Horeshoe Shoals is not considered an important area for the stock (EES Group, Inc. 2004). This species is listed as endangered under the Endangered Species Act (Waring *et. al.* 2008).

Despite little being known about mortality causes for the fin whale, the whales do react strongly to low-frequency ship sounds as they are reminiscent of their own calls (Cummings *et. al.* 1986; Watkins 1986). The fin whale produces low frequency sounds of approximately 40-75 Hz, 1-s long as well as shorter, more powerful 20-Hz pulses and minute long moans of approximately 70 Hz in frequency (Cummings *et. al.* 1986). Over the years, this species has been known to actively avoid approaching vessels but have since become neutrally habituated to the presence of small boats in their waters. Generally, though, fin whales remained quiet around the presence of a boat (Watkins 1986).

*iii. Northern Right Whale (*Eubalaena glacialis*)*

The right whale is the rarest and most endangered of all large whale species, with only approximately 350 individuals left within the North Atlantic Ocean (NOAA Fisheries 2010). Of this population, about 42% are predicted to visit Cape Cod Bay during the feeding season

(McLeod 2002). It comes as no surprise that they are listed as endangered under the ESA. They are a migratory species, birthing and mating off the coast of Florida during the winter while feeding and nursing in areas north of Cape Cod during the summer. During the spring, a number of animals arrive in Cape Cod Bay – one of the six prime feeding grounds for the whale. Massachusetts Bay, the Great South Channel, the Bay of Fundy, the Scotian Shelf, and the Georges Bank comprise the others. Typically, visited regions are temperature stratified waters deeper than 100 m (EES Group, Inc. 2004).

Movement from feeding ground to feeding ground is believed to be a result of zooplankton aggregations varying throughout the season. During spring, whales tend to move from Cape Cod Bay to the Great South Channel and then towards Georges Bank in following the zooplankton (Pace and Merrick 2008). Euphausiids, cyprids and copepods such as those in genera *Calanus* and *Pseudocalanus* make up the majority of the whale's food source. (Waring *et. al.* 2008; NOAA Fisheries 2010). Aggregation density is based upon oceanographic factors such as circulation patterns, water depth, thermal fronts, and hydrographic density gradients with the whales feeding in the patches of greater density (Pace and Merrick 2008).

Very few right whales visit the Nantucket Sound despite the close proximity to prominent habitats (ESS Group, Inc. 2004). Prey occurs in far less abundance within this area than in comparison to known feeding grounds. Aggregations must be dense in order for right whales to feed effectively (Waring *et. al.* 2008). Horeshoe Shoals also does not fall within critical habitat as defined by the ESA.

Right whales have been observed not to fully react to the noises associated with vessels, although if suddenly disturbed, they would dive quickly and silently (Watkins 1986). Individual whales observed in the Bay of Fundy indicated no significant behavior alterations when exposed to playback sounds or the baseline, but five out of the six whales responded to an alert signal of 173 dB re 1 µPa at frequencies ranging from 500 to 4500 Hz (Nowacek *et. al.* 2004). Vessel strikes do remain the greatest source of anthropogenic mortality among this species, with approximately 2.4 occurring to the Western Atlantic Stock yearly (Waring *et. al.* 2008). Different theories exist as to why the right whales do not respond to ship presence, from the ship needing to be in extremely close range for the whale to perceive its presence to a variety of environmental factors obfuscating the propagation and properties of the noise (Nowacek *et. al.* 2004).

*iv. Minke Whale (*Balaenoptera acutorostrata*)*

The Minke whale is the third most abundant whale species within the U.S. Atlantic waters and not listed under the Endangered Species Act. There are four distinct North Atlantic populations; including the Canadian East Coast stock that extends down towards Massachusetts waters (ESS Group, Inc. 2004; Waring *et. al.* 2008). The full range of the whales can reach as far south as the Gulf of Mexico. The total population size of this stock is unknown, but estimated to be at least 3000 individuals based upon a 2006 aerial survey (Waring *et. al.* 2008).

Minke whales are present off the coasts of Massachusetts during the summer feeding season. However, as the shallow waters and sandy floor of the Nantucket Sound does not support aggregations of krill, copepods, and small schooling fish the animals feed on, the whale does not visit Nantucket Sound as much as nearby areas (ESS Group, Inc. 2004; NOAA Fisheries 2010). They tend to be subject to boat strikes due to their coastal habitat but can also be found within offshore waters as well (ESS Group, Inc. 2004; NOAA Fisheries 2010). Over the years, Minke whales have been noted to change from a positive interest in vessels to a general lack there of, ignoring a passing boat rather than approaching or fleeing (Watkins 1986).

*v. Long-Finned Pilot Whale (*Globicephala melas*)*

The long-finned pilot whale is one of two pilot whale species to occur within the western Atlantic, the other being the short-finned pilot whale. As the two species are difficult to differentiate at sea, a lot of the data collected for the Western North Atlantic Stock discusses both species interchangeably (Waring *et. al.* 2008). The whale tends to range from Canada to North Carolina, within waters along the continental shelf. Typically, they appear off the northeast coast in early spring, moving towards Georges Bank and the Gulf of Maine. Preferred habitat includes areas of high relief along the continental shelf break (Waring *et. al.* 2008). Also of preference are deep waters with high squid density, as that animal is their primary prey species. Pilot whales also feed on octopus and fish (NOAA Fisheries 2010). Distribution among feeding grounds can also be attributed to food abundance (McLeod 2002). As a social species of odontocete, the pilot whale is typically found within groups of 25-50 animals (NOAA Fisheries 2010).

The total population size for whales occurring off the eastern North American coast is unknown. A survey conducted along the continental shelf in 2004 indicated approximately 31,000 individuals resided within the stock (Waring *et. al.* 2008). The species is not listed under the ESA. For the EIS, the ESS Group concluded that it was not possible to determine conclusively whether pilot whales would occur around the wind farm and thus the possibility of the occurrence had to be considered (2004).

Pilot whales are notable for their mass stranding events. Such an example occurred in the winter of 2005, when thirty three short-finned pilot whales stranded near Cape Hatteras, North Carolina. No exact cause could be given for the stranding, however, at the same time in which this event occurred, the Navy was using mid-frequency active sonar within the region (Waring *et. al.* 2005). It was not possible to determine whether the mortalities were caused by sonar or not.

*vi. White-Sided Dolphin (*Lagenorhynchus acutus*)*

The white-sided dolphin resides in temperate and polar waters within the North Atlantic, from West Greenland to North Carolina (Waring *et. al.* 2008; ESS Group Inc., 2004). Preferred habitat tends to be between the continental shelf and the 100-meter isobath although prior to the 1970s, the dolphin species was primarily found within waters offshore of the continental slope (ESS Group Inc., 2004; Waring *et. al.* 2008). Prey species also include mackerel, hake, squid and shrimp (NOAA Fisheries 2010).

The western North Atlantic stock can be divided into three smaller units: the Gulf of Maine, Gulf of St. Lawrence, and Labrador Sea populations (Waring *et. al.* 2008). Total population size is estimated to be about 63,000 individuals and it is not listed on the Endangered Species Act (NOAA Fisheries 2004). Mass strandings have been known to occur for this species, but the underlying reasons for these events remain unknown (Waring *et. al.* 2008).

In their research for the EIS, the ESS Group decided that insufficient data existed to determine whether the dolphin would occur within any of their proposed wind farm sites, they concluded that the possibility could not be dismissed (2004).

*vii. White-beaked Dolphin (*Lagenorhynchus albirostris*)*

Although the white-beaked dolphin was not listed as a species of interest on the Environmental Impact Statement for Cape Wind, the species has been reported within Nantucket Sound (Read *et. al.* 2010). Thus, this species possesses the potential to appear within the proposed wind farm site. The Western North Atlantic Stock ranges from southern New England to southern Greenland. Forays into the Gulf of Maine and Cape Cod area are thought to be the results of opportunistic feeding opportunities (Waring *et. al.*, 2007). Total population for the Western North Atlantic stock is unknown. An aerial survey conducted in summer 2006 predicted that there are at least 2,000 individuals within the population (Waring *et. al.* 2007).

Since the 1970s, a switch of habitat has been documented for this species towards the offshore continental shelf (Waring *et. al*. 2007). In addition to herring, the white-beaked dolphin also feeds on other small mesopelagic schooling fish, crustaceans, and cephalopods (NOAA Fisheries 2010). Generally, this dolphin prefers cold, shallow habitats. Although not very migratory, the white-beaked dolphin will move to its more southern limits during the winter months to avoid the formation of ice. During summer months, the dolphins will move north again, and closer in shore (NOAA Fisheries 2010). The white-beaked dolphin is not listed under the Endangered Species Act.

*viii. Striped Dolphin (*Stenella coeruleoalba*)*

The striped dolphin is found in waters throughout the globe, and one of the most abundant odontocete species (NOAA Fisheries 2010). The Western North Atlantic stock ranges from Nova Scotia to the Caribbean, typically near the 1,000 m isobath of the continental shelf (Waring *et. al.* 2007). They prefer warmer, very productive waters such as upwelling and convergence areas (NOAA Fisheries 2010). The ESS Group decided that the dolphin has a potential to occur within the proposed sites and its presence could not be ruled out (2004). However, given that the animals prefer deep oceanic waters, it is unlikely that the occurrence of the striped dolphin within Horseshoe Shoals would be common. Striped dolphins travel in groups of about 25 to 100 individuals and tends not to associate with other marine mammal species (NOAA Fisheries).

Their prey species includes small, tightly packed midwater, benthopelagic, and pelagic schooling fish and cephalopds (NOAA Fisheries). Population estimates for the total number of animals are unknown, however it is believed that about 95,000 individuals existed off the eastern United States coast in 2004 (Waring *et. al.* 2007). This species is not listed under the Endangered Species Act.

*ix. Common Dolphin (*Delphinus delphis*)*

The common dolphin occurs in temperate to tropical waters around the world. Within the northeast Atlantic, they tend to remain near the Gulf Stream or in areas of about 200-300 meters with distinct underwater features where upwelling can occur (Waring *et. al.* 2007; NOAA Fisheries 2010). During the summer and fall, the animal migrates north towards Georges Bank and the Scotian Shelf. The dolphin is found within groups of hundreds of individuals on average, with the possibility to rank up to 10,000 individuals within a pod (NOAA Fisheries 2010). Prey species includes epipelagic schooling fish and cephalopods.

The common dolphin is a highly abundant species world wide, with at least 300,000 individuals existing in the Western North Atlantic stock (NOAA Fisheries 2010). Not enough data exists to determine whether the common dolphin occurs within the proposed wind farm site, thus the ESS Group ranked it as a possibility (2004). The common dolphin is not listed under the ESA.

*x. Harbor Porpoise (*Phocoena phocoena*)*

The harbor porpoise is an inshore species that occurs within colder waters. They Gulf of Maine/Bay of Fundy stock is primarily found along the eastern coast of the United States and Canada. They spend the majority of the summer within the Bay of Fundy and Gulf of Maine region but will move southward towards New Jersey during winter months. However, no specific migration pattern has yet been discerned (Waring *et. al.* 2008). They range from the coastline to deeper waters by the continental shelf, but tend to prefer regions of 150 m deep. A 2006 survey indicated that approximately 89,000 individuals existed within this population of porpoises (Waring *et. al* 2008). They tend to be solitary in nature, with largest groups consisting of fewer than five animals (NOAA Fisheries 2010). Herring, demersal species of schooling fish, and cephalopods tend to be the main food sources for harbor porpoises.

The ESS Group decided that insufficient data existed to determine whether or not the animal would occur within the Shoals (2004). However, aside from their preference towards shallow water areas, data provided by OBIS-Seamap does indicate the presence of harbor porpoises within Nantucket Sound, thus confirming the likelihood that the animal would occur within the wind farm site (Read *et. al.* 2010). This species is not listed under the Endangered Species Act.

*xi. Gray Seal (*Halichoerus grypus*)*

The gray seals are the second most common pinniped along the Atlantic coast of the United States, occurring from Maine to the Long Island Sound (EES Group, Inc. 2004). These animals are a part of the Western North Atlantic Stock, which extends and includes animals within Canadian waters as well (Waring *et. al.* 2008). As of 2005, the total population is estimated to lie between 125,000 and 169,000 individuals (Trzcinski *et. al.* 2005). Current population models predict over 250,000 animals (NOAA Fisheries 2010). The gray seal is not listed under the ESA.

Typically, these animals haul out on exposed islands, shoals, and sandbars. They are not a migratory species despite a juvenile tendency to wander. Two main breeding colonies exist in the United States, one on scattered islands offshore of Maine and the other located within Nantucket Sound at Monomoy and Muskeget Islands (ESS Group, Inc. 2004). The Monomoy National Wildlife Refuge encompasses this breeding area but does not overlap with the designated area within Horseshoe Shoals. Winter and spring seasons tend to bring the highest populations to these islands, with a population greater than 1000 individuals (Waring *et. al.* 2008). Grey seals are opportunistic and hunt mostly fish, crustaceans, squids, and octopi (NOAA Fisheries 2010). Given this proximity to the Shoals, however, it is likely that animals will occur frequently in the wind farm area, especially given that juveniles have a tendency of dispersing over 1600 km away from their natal grounds.

*xii. Harbor Seal (*Phoca vitulina concolor*)*

Harbor seals are the most common seal along the American east coast. They typically reside at latitudes above 30° north within coastal waters and on coastal islands, ledges, and sandbars (EES Group, Inc. 2004). Over 99,000 individuals comprised the Western North Atlantic population in 2001 (Waring *et. al.* 2008).

The Western North Atlantic stock occupy waters off of Maine and Canada, and move south in New England in colder months. During the fall, many juveniles, sub-adults, and adults migrate from the Bay of Fundy to New England waters to spend the winter season. The Nantucket Sound, Horseshoe Shoals included, is only one such site visited by these animals (EES Group, Inc. 2004). Many of the remote islands and sandbars within the Sound region have been noted to be preferred haul out sites for the pinniped. By the spring, the seals move north again for pupping. Thus, Nantucket Sound is primarily utilized as a foraging region. The harbor seal is an opportunistic feeder, primarily hunting fish, shellfish, and crustaceans (NOAA Fisheries 2010). It is not listed under the Endangered Species Act.

*xiii. Harp Seal (*Phoca groenlandica*)*

According to the ESS Group research conducted, the harp seal does not primarily reside within the Nantucket Sound but in recent years, it has been pushing at the edges of its southernmost boundaries within New England (2004). Approximately 5.9 million animals are estimated to exist within the Western North Atlantic population but there are no estimates of the number of individuals within the United States (NOAA Fisheries 2010). However, the potential for the harp seal to appear in the Horseshoe Shoals does exist. Furthermore, the harp seal is not listed under the Endangered Species Act.

*xiv. Hooded Seal (*Cystophora cristata*)*

The hooded seal normally resides in deep, polar waters within the north Atlantic and Arctic Oceans. Population for the Western North Atlantic stock estimated to be approximately 592, 100 individuals in 2005 (Waring *et. al.* 2007). The extent of the United States population remains unknown and the seal is not listed under the Endangered Species Act. Birthing grounds for this group are off the coast of eastern Canada, but as a highly migratory species, the seals are known to travel far from their natal grounds. Like the harp seal, they have been noted to be pushing the southernmost boundary of their range within recent years, having been spotted as far south as Puerto Rico within the United States EEZ (EES Group, Inc. 2004). The possibility for the hooded seal to occur within the Horseshoe Shoals does exist despite any lack of empirical estimates. However, more than likely any individual to appear would just be passing through as the hooded seal possesses a preference for deep offshore waters (Waring *et. al.* 2007).

VI Horseshoe Shoals

Within the Environmental Impact Statement given by Cape Wind described the oceanographic setting of their proposed site. Horseshoe Shoals is located within the Nantucket Sound, at 41°2713.64"N, 70°15'50.59"W (Figure 1). The floor bottom is comprised of fine grain sediments, specifically clay and sand (MMS 2009). The bathymetry of the Shoal varies from as little as 0.15 m deep to up to 18.3 m deep. The area is considered a dynamic system with complex tidal currents that tend to push around the sediment composition on the seafloor. Little gradient exists in salinity measurements when moving from surface to sea floor due a high level of mixing, with levels range from 30 to 32.5 ppt depending upon seasonality. Temperature also varies seasonally with little stratification. In the summer, surface temperatures reach a high of about 24 °C and bottom temperatures reach a high of about 19°C. During the winter, temperatures can drop to lows of -1 °C and 0 °C, respectively (MMS 2009). Ambient noise levels ranged from 95 to 115 dB. However, values remain variable due to effects from surface winds and storms and other varying atmospheric and oceanic conditions (MMS 2009).

VIII. Effects of anthropogenic noise on marine mammals

As previously stated, noise is unwanted and often interfering sound introduced into an environment. When discussing the effects of noise on marine mammals, the focus is on anthropogenic sources rather than natural occurring noise (i.e., raindrops on the water's surface). The degree in severity of the effects of anthropogenic noise depends on the distance of the animal from the source. Typically, there are four zones of impact that radiate outward from the initial sound point. As these sound waves travel further, their potential threat decreases, from the zone of injury to the zone of audibility (Figure 4).

In the zone of audibility, marine mammals are capable of discerning the noise. Typically, at this point in space, the sound level matches the hearing threshold of the animal at that that specific frequency but does not surpass it (Madsen *et. al.* 2006). Of all possible effects, those caused by simply hearing the noise have the least potential to alter an animal's behavior or biology. No physical harm comes to the animal. Furthermore, a noise detected in the zone of audibility does not possess the strength to drastically alter its behavior; the animal can choose whether to ignore it or not.

Moving closer to the noise source, an animal reaches the zone of responsiveness. Here, the sound waves emitted by the noise are capable of altering an animal's behavior. While smaller than the zone of audibility, the range of the zone of responsiveness can be hard to define due to a lack of detailed information on the animal. Without knowing how exactly the animal normally acts without the outside influence of the noise, it is difficult to know if behavioral changes occur because of the sound. In the Zone of Masking, however, the noise is loud enough to overlap with the natural, significant frequencies of a species. This area is easier to designate due to relatively recent studies in understanding the hearing thresholds of key species. Masking works by diminishing the likelihood an animal will hear a signal, as the new noise may be received in place (Madsen et. al. 2006). While more of a behavioral modification, an animal's overall fitness can still be affected. For example, the calls of prey may not be received and, as a consequence, the marine mammal is unable to maintain its typical diet.

The fourth and inner-most zone of impact is the area in which it is possible that physical harm may occur. The zone of injury is the area in which sound pressure levels are high enough to cause temporary or permanent threshold shifts in hearing. In a threshold shift, the hearing level rises after exposure to a sound which leaves the animal incapable of hearing. A temporary threshold shift only lasts for a short duration and is reversible while a permanent threshold shift will leave the animal permanently altered. Generally, the more significant a threshold shift is, the longer it will take for an animal to recover back to its initial hearing range.

Specifically, pressure levels in this zone are believed to need to exceed 180 dB re 1 µPa and 190 dB re 1 µPa to be of significant danger to cetaceans and pinnipeds, respectively (Madsen et. al. 2006). However, it has been shown that exposure to noise between 4 and 11 kHz and 160 dB re 1 µPa for at least 30 minutes can also cause temporary threshold shift in bottlenose dolphins (Nachtigall et. al. 2004). Therefore, scientists cannot be certain of the exact pressure levels that result in injury. The potential of physical harm from sound depends on more than just the sound pressure. There is also need to look at frequency and noise levels of the sound and animals involved before judging whether or not harm may occur (Madsen et al. 2006).

For much the same reasons, threshold shift and masking experimentation has been conducted with as small and unvaried population as with hearing sensitivity experiments. Temporary threshold shifts (TTS) are typically the subject of interest towards researchers as not to cause any unwarranted harm to the marine mammals involved. Also conducted have been critical ratio tests, the ratio of sound pressure level of a just audible signal to that of sound pressure level of a masking signal. Among pinnipeds, such work has been conducted with harp seals (*Phoca groenlandica*), ringed seals (*Phoca hispida*), harbor seals (*Phoca vitulina*), California sea lions (*Zalophus californianus*), northern elephant seal (*Mirounga angustirostris*), and northern fur seals (*Callorhinus ursinus*; Finneran *et. al.* 2003, Southall *et. al.* 2003, Southall *et. al.* 2000, Turnbull 1994, Terhune 1991, Turnbull and Terhune 1990, Moore and Schusterman 1987, Renouf 1980, Terhune and Ronald 1975). Bottlenose dolphins (*Tursiops truncatus*) and beluga whales (*Delphinapterus leucas*) comprise the majority of masking research conducted with cetaceans (Lemonds *et. al.* 2000, Au and Moore 1990, Johnson *et. al.* 1989, Johnson 1971, Johnson 1968).

In one experiment, the critical ratios of an elephant seal, California sea lion, and harbor seal between 100 to 2500 Hz were assessed to determine the point in which masking would occur. Data collected showed a relationship of increasing critical ratio with increasing frequency for all three species (Southall *et. al.* 2000). Research conducted by Kastak *et. al.* indicated that measurable TTS could be determined at sound levels of at least 65 dB for the harbor seal, elephant seal, and elder sea lion (1999).

Exposure of a bottlenose dolphin and a beluga whale to pulse noises from a seismic air gun indicated that masked hearing thresholds shifts of about 6 to 7 dB occurred for both animals when exposed to noises of 160 kPa pressure (Finneran *et. al.* 2002). Avoidance behaviors were also observed, in which the animals would appear reluctant to return to the designated stations during sessions. Meanwhile, another experimentation exposing a bottlenose dolphin to a low frequency fatiguing nose of 179 dB re 1 µPa resulted in a 10.4 dB TTS and recovery periods of up to 45 minutes (Nachtigall *et. al.* 2003). Exposure of bottlenose dolphins and beluga whales to 1 second long tones at frequencies between 0.4 and 75 Hz and levels of 192 to 201 dB re 1 µPa resulted in threshold shifts up to 3 dB of pre-exposure capabilities for all animals (Schlundt *et. al.* 2000). Hearing thresholds also returned to their baseline norm the day following the session. Disorientation and avoidance behaviors were observed shortly after exposure to the louder of the noises tested, typically at levels between 178 to 193 dB re 1 µPa for the dolphins and 180 to 196 dB re 1 µPa for the beluga whales (Schlundt *et. al.* 2000).

IX. Wind farm noises

In general, discussion regarding the potential acoustic effects of wind farms on marine species tends to focus on the noises produced by the generator during operational stage. However, as Madsen *et. al*. pointed out, some of the loudest and most disruptive sounds come from the more transitional stages of construction and dismantling (2006). Pile driving, trenching, and dredging – all techniques used in establishing the base of the foundations – tend to have greater effect on marine mammals. The individual turbines are supported by a number of different foundations, such as steel monopile supports which are usually either imbedded through pile drivers or vibration techniques. Despite the sediment type, pile driving usually takes at least a couple of hours to complete, with blows delivered to the monopile every second. The size of the monopile and hammer used, as well as oceanic environmental variables, ultimately determine the overall frequency and pressure of the sound created. However, monopiles all tend to be very large due to the size of turbines planned. Given the 258 feet planned for height of turbines just from the surface of the water at Cape Wind, monopiles used at the site will ultimately be on the larger size. The frequencies emitted from such work vary based upon distance from the work, but recordings have been made which indicated levels underneath 500 Hz near the foundation and levels as high as 200 dB re 1 µPa at 100 m away from the monopile (Madsen *et. al.* 2006). Another measurement indicated a maximum frequency of 100-300 Hz during ramming that occurred at a rate of 40/second (Betke *et. al.* 2004). Overall, sounds emitted by pile driving can be classified as high-level and low frequency.

Acoustic measurements made at operational offshore wind farm sites in Europe demonstrate a number of commonalities among sound produced by the turbines, no matter the size or composition thereof. Most sounds emitted are below 1 kHz, many fluctuating around 700 Hz (Madsen *et. al.* 2006). Wind speed does not seem to impact the levels of sound produce. Instead, the greatest relationship comes from that between frequency and mechanical characteristics of the turbine (Degn 2000). The relationship between size of the turbine and intensity of sound emitted is considered weak at best (DEWI 2004). Still, differences persist. Measurements of Utgrunden wind farm indicated that at a wind speed of 13 m/s, noises reached a frequency of 180 Hz while at 8 m/s, they only reached frequencies of up to 60 Hz (Ingemansson Technology 2003). At those lower wind speeds, the generator runs at 1100 rpm while at higher speeds, it runs at 1800 rpm (Betke *et. al.* 2004). The sound produced is typically as a tonal noise that exceed the ambient noise of the environment by at least 10 dB (Madsen *et. al*. 2006).

How are these sounds emitted? Vibrations within the gear box and electricity generator are produced while the turbine is in operation. These vibrations echo downward throughout the entire structure and into the water column and seabed (Figure 5; Betke *et. al.* 2004). Depending upon construction and the materials used, it is believed that some turbines produce more noise than others (Masden *et. al.* 2006). As expected, the more individual turbines clustered within an area, the greater the overall noise level will be. However, even this effect is more complicated than presumed, as the arrangement and spacing of the wind farm crucially affect the overall noise levels and the influence of noise radiation by surface waves makes it even more difficult to compute (Madsen *et. al.* 2006; Betke *et. al.* 2004).

Within a closed environment, any emitted sound would distribute evenly and uniformly in a spherical motion. While vibrations still attempt to follow such a shape, the distribution within any offshore site is anything but uniform due to the varying environmental conditions of shallow waters as well as the presence of other turbines. But for at least one kilometer away from the turbine, the shape of noise distribution remains close to spherical (Madsen *et. al.* 2006). Other factors affecting the transmission of wind farm noises throughout a space include the reflection of sound at the surface and bottom, as well as the stratification of the water column, salinity, and temperature of the water (Madsen *et. al.* 2006). Overall, the exact level of noises produced by a wind farm, and the transmission of such, remains rather site specific as each environmental conditions can drastically vary from site to site (Madsen *et. al.* 2006).

X. Anthropogenic Noise Studies

i. Pinger and alarm habituation

Pingers have been used by fishing communities in an attempt to scare away harbor porpoises and reduce the amount of bycatch caught by their nets. In 1997, Kraus *et. al.* showed how pingers could reduce mortality of porpoises within the Gulf of Maine (Kraus *et. al.* 1997 in Cox *et. al.* 2001). However, since then, concerns have developed regarding habituation of porpoises to the sound of these acoustic alarms. Cox *et. al.* observed the behavior of porpoises in the Bay of Fundy, Canada from June through September of 1998, specifically looking for reactions to pingers (2001).

The pinger used in the experiment produced a repeating signal of 132 dB re 1 µPa and frequency of 10 kHz. Porpoises were studied before the pinger was turned on, during, and after. Habituation to the sound became evident after analyses occurred (Cox *et. al.* 2001). Despite any initial avoidance of the pingers, the porpoises did not continue this behavior and observed moving closer to the sound source over time.

Harbor porpoises have been shown to react more strongly to noises other than pingers, (Kastelein *et. al.* 2006). To add to existing data, Kastelein *et. al.* set up a contained experimentation using a stranded striped dolphin and stranded harbor porpoise kept in a floating pen in Neetlje Jans, Netherlands. The alarm used produced noises at levels of 145 dB re 1 µPa and frequencies between 9-15 kHz that lasted durations of 0.3 seconds with 4.0 second intervals between pulses. Sessions were comprised of 15 minute baselines and 15 minute testing periods, in which the alarm would be active (Kastelein *et. al.* 2006).

A definite reaction was noted with the harbor porpoise when the alarm was on. It surfaced far more frequently and tended to stay at the opposite end of the pool. The striped dolphin, however, did not appear to react to the alarm in any significant way, with behavior being similar in both the control and test periods (Kastelein *et. al.* 2006). A comparison to existing audiograms for each species indicated that the striped dolphin possesses a less sensitive hearing capability than the harbor porpoise – perhaps one of the reason for the differences in reaction. However, data also suggests that the frequency of the alarm was within level for both species. The odontocetes were not exposed to the alarm long enough to test for habituation, however.

Another study, conducted by Teilmann *et. al.* looked for porpoise habituation to pingers within a contained enclosure within a harbor near Fjord & Bælet, Denmark. Observations were made on two wild born porpoises that had been recovering from entanglements in fishing gear. Four to six testing sessions were conducted per day for five days, each lasting 25 minutes and including ten minutes of baseline behavior, five minutes of sound exposure, and ten minutes of post exposure observation. The noises produced varied from 100 to 140 kHz in frequency, each lasting for 200 ms. The animals were observed to move away from the sound source in all of the sessions conducted, but reactions appeared to be most significant each time the porpoises were exposed to the pinger noise anew (Teilmann *et. al.* 2006). Although different types of sounds were emitted during the experiments, the porpoises did not seem to differentiate between them. However, within a specific session, the avoidance behaviors – swimming away from the sound and reducing echolocation and surfacing - diminished.

Another pinger experiment conducted by Kastelein *et. al.* examined the effect of high frequency tonal noises on harbor seals (2006). Five captive animals were kept within a pool with an underwater loudspeaker at one end to produce the noises. Each pulse lasted for 250 ms and varied at frequencies of 8, 16, 32, and 45 kHz. Every session conducted started with a forty five minute baseline period of no transmission followed by a 45 minute test period in which the pulses were played. All five seals were present within the pool during experimentation.

While overall habituation did not occur during the two months of the study, slight habituation appeared to occur during sessions. However, no hauling out behavior was observed during any of the sessions either. The seals did not entirely avoid the area of the pool with the loudspeaker during trail sessions, but did not spend as much time in that section of the pool as during the baseline session (Kastelein *et. al.* 2006). Furthermore, the surfacing frequency increased when the noises were played in comparison to the baseline sessions.

ii. Seismic surveying

Underwater seismic surveying is conducted around the globe as humans continue to search for new sources of gas and oil. Typical surveys involve a large ship patrolling waters with air guns and hydrophone streamers that are placed at different depths. Low frequencies are typically emitted in order to penetrate the seabed so that the surveyors can obtain a better idea of what lies beneath, specifically if there is evidence of the desired gas or oil. Noises produced by air guns are loud and typically between 200-250 dB re 1µPa (Goold 1996). These studies provide good a good comparison for the effects of other impulsive noises, such as the pile driving associated with the construction of wind farms (Madsen *et. al.* 2006).

Through passive acoustic monitoring, Goold looked to assess the effects of the noises emitted in conjunction with seismic surveys on the common dolphin (*Delphinus delphis*) within the Irish Sea. During two months in which Chevron UK conducted seismic surveys, the company agreed to conduct a continuous acoustic survey to assess the presence and distribution of any passing cetaceans before, after, and during operations. A hydrophone was towed four meters behind the guard ship of the fleet to make continuous recordings. Over 900 hours of recordings were obtained and replayed in a laboratory setting to identify dolphin vocalizations. Emissions were typically of 170 dB re 1 µP at 250 Hz, with limited radius disturbance spread.

Goold identified all vocalizations by ear rather than with aid of any computer program. Common dolphin was the species most frequently identified, with the occasional bottlenose dolphin mixed in. No attempt was made to determine the number of individuals present and instead, Goold displayed his findings in a percentage of acoustics recorded. Upon analyzing the data, Goold noticed that an average of 86% of vocalizations went quiet after exposed to noise from an air gun. Overall, data suggested avoidance or silence by the dolphins to seismic related noises. These behaviors were not a result of ship presence as common dolphins are historically noted not to be shy of ships (Goold 1996).

Emissions made by air guns during seismic explorations in the Beaufort Sea were often around levels of 150 dB and could be transmitted as far as 90 km away. In addition to air gun experiments, Richardson *et. al.* were able to observe bowhead whales interact with ongoing seismic explorations for a handful of days between 1980 and 1982 (1985). Observations were made from an aircraft and compared to undisturbed whales studied within the area on days seismic exploration did not occur. Activities observed on both days with and without seismic exploration were similar and no distinct reaction to the emissions or the vessels were noted.

The air gun experiments were conducted as control tests to support the hypotheses developed as a response to the observations. An air gun was fired either 5 or 3 km away from a population of bowheads, at a depth of 6 m and a sound level of 22 dB re 1 µPa every 10 seconds for a 20 minute period. Through sonobuoys, Richardson *et. al*. were able to measure received noise levels at approximate 123-118 dB re 1 µPa and a frequency varying between 50-500 Hz (1985). In accordance to the observation stage, no significant evidence of avoidance was detected during these experiments.

iii. Drilling and Dredging

With no studies having looked at turbine effects on baleen whales, studies designed to determine the effect of other industrial activities with similar noise qualities might allow for some insight. Specifically, a comparison can be made between the acoustic affects of industrial activities and the affects of noises created during the construction phase of the wind farm.

Oil exploration activities within the Canadian Beaufort Sea coincide with a portion of the bowhead whale summer range in the Pacific. Although in most instances of observation, the bowhead does react in some way to anthropogenic noise, the degree of severity has varied (Richardson *et. al.* 1986). Short term reactions typically are observed as an interruption of activity and retreat away from the sound source by the whale. From 1980-1984, Richardson *et. al.* conducted surveys within the areas of the Beaufort Sea in which drilling activities overlapped with whale range to assess any long term affects on the animals.

Aerial studies were conducted during August and September of each year, each following the same survey route as in the prior year. Seismic operations were located along these routes, often emitting underwater noises that were best described as intense and capable of being heard up to 90 km away (Richardson *et. al. 1986).* Included in these activities were dredging, construction, drilling, and boat travel. No specific frequencies of the noises associated with these activities were provided within the paper, although it was observed that underwater noises created by seismic ships moved a greater distance than other associated activities. It was observed that the level of activity increased until 1983 when it began to level off and slowly decrease.

The distribution of bowheads varied from summer to summer. Seasonal differences were observed, with the whales shifting areas of concentration from the end of July through

September based upon the breakup of Arctic ice. However, no long term behavioral alterations or patterns could be associated with the presence of the oil industry within their waters. Short term reactions were still noticed, but all observations indicated a habituation to the activities occurring around them (Richardson *et. al.* 1986). When exposed to seismic vessels, most animals appeared to ignore the sounds when further than 7.5 km away. Around the main industrial areas, as Richardson labeled the region, the whales did not appear to actively avoid the region – either during the duration of the summer season or throughout the passing of the five years. However, the quantity of whales present varied from year to year. It could not be determined that this was because of the industrial activity alone.

Gray whales in the Pacific, however, were noted to have more abrupt and significant avoidance behaviors when exposed to air gun blasts or playback noises of recorded drilling operations and construction (Moore and Clarke 2002). Included in such behaviors were swimming away from the source – usually accompanied by a ceasing of prior activities and changes in acoustic activity. However, there was no evidence of permanent displacement, as in various experiments, whales were noted to return to prior activities when sounds ended. In their literature review, Moore and Clark did point out that responses did vary with the type of noise and the levels and frequencies of said noise (2002). In certain cases, even, habituation may occur: Richardson *et. al.* noticed that the migration patterns of gray whales have not changed despite the oil industrial activities taking place along their route by California (Richardson *et. al.* in Moore and Clark 2002).

During surveys conducted in the summer of 1980, Richardson *et. al*. looked specifically at bowhead whale behavior during periods in which dredging activity was known to be occurring (1985). Measurements from a prior study indicated that dredging noises could reach 4.6 km and still be audible, with frequencies of up to 1776 Hz. However, observations made from aircraft showed bowhead whales visiting dredge sites as near as 0.8 km to the noise source. No disruption in behavioral activities occurred (Richardson *et. al.* 1985).

iv. Explosions

Explosions occur not just in a naval context but also as a construction technique pertinent for many industries, including that of the offshore wind farm. Finneran *et. al.* exposed two captive bottlenose dolphins (*Tursiops truncates*) and one beluga whale (*Delphinapterus leucas*) to controlled sound waves similar to those produced by distant explosions (2000). Experimentation took place within San Diego Bay. The animals resided in floating net enclosures with two underwater listening stations that projected the test noises. One station emitted a tone that indicated to the cetacean that testing was about to begin while the other provided the explosion-like sounds (Finneran *et. al.* 2000). The explosion noises were 250 ms in duration, including 50 ms rise and fall stages to mimic the full spectrum of sounds produced during an explosion. A piezoelectric transducer was used to generate the sounds and pressure waves associated with underwater explosions (Finneran *et. al.* 2000). The simulations ranged from a 5-kg charge at 55.6 km to 500 kg at 1.7 km, with sound levels at 170 dB re 1 µPa to 221 dB re 1 µPa, respectively. However, sufficient pressures could not be provided at frequencies below 1 kHz, specifically at levels of which are comparable to a real world scenario. As a result, specific information on the effect of explosive noises below this frequency on bottlenose dolphins and beluga whales was unable to be determined.

For each trial, the hearing threshold of the cetacean was measured prior to any sound exposure (not including ambient noises of the Bay). Then, the animal was exposed to the test impulse and hearing threshold was once again measured immediately after exposure and again one to one and a half hours after and two to three hours after to test recovery capabilities (Finneran *et. al.* 2000). This study was the first to directly measure the effects of distant underwater explosions on marine mammal hearing thresholds. No permanent threshold shift accompanied the experiment. In fact, only a small temporary threshold shift occurred as the majority of recovery hearing thresholds measured was within 4 dB of baseline values (Finneran *et. al.* 2000). Some more significant threshold shifts did occur and in certain cases, the hearing threshold of the individual decreased after exposure to the simulated explosion. They believed that the sounds produced did not have a high enough pressure to produce a more significant temporary threshold shift. No masked hearing temporary threshold shifts (levels in which the shift was greater than 6 dB) were observed at all (Finneran 2000. Explosions, therefore, may not impact cetaceans as badly as previously so long as they remain a certain distance away from the animals.

v. Vessel presence

Human vessels are the source of one of the longest, most continuous sources of anthropogenic sound within the world's oceans. Reactions to boats have vary among species and may change within populations over time. Given that vessel presence within Horeshoe Shoals will increase with the construction of the wind farm for maintenance purposes, this section on anthropogenic effects on marine mammals is of particular relevance.

In the waters north of the Nantucket Sound, in Cape Cod Bay, whale populations have been exposed to whale watchers and research vessels for over fifty years. In 1986, Watkins looked to explore the effects such boats had on frequent whale populations, and the changes in reactions these species had within approximately a thirty year period. His study focused on the great whale species most common to the area: minke whale (*Balaenoptera acutorostrata*), fin whale (*Balaenoptera physalus*), right whale (*Eubalaena glacialis*), and humpback whale (*Megaptera novaengliae*). Sighting data collected from 1958 to 1982 was analyzed and compared, with 1976 as the cut off point for recent and past observations (Watkins 1986).

As the years progressed, each species was noted to have changed differently in their reactions to the presence of vessels. Although the results have already been mentioned within the summary of the various marine mammal species that may visit the Nantucket Sound, it does not hurt to briefly repeat: minke whales changed from showing a positive interest in boats to a lack of interest, fin whales moved away from negative reactions to an overall lack of reaction, right whales continued to show negative interest or lack thereof throughout the period of the study, and humpback whales moved away from disinterest to positive reactions. Specifically, whales more accustomed to residing nearer to shore became more quickly habituated to vessels and other human activities.

Surveys noted that whales responded to sound when within their range of hearing, at about 100 m or greater than 12 dB, especially those sounds at low amplitudes or at frequencies at or below that discernable by the individual (Watkins 1986). This frequency range was deduced to be between 15 Hz and 28 Hz. Anything possessing similar characteristics to natural ambient noise appeared to be dismissed. In no case did a sound appear to attract individuals positively, although one survey resulted humpbacks investigating a low-amplitude pulse sound (Watkins 1986). Negative reactions specifically occurred when the sound became unexpected, was too loud, suddenly changed in characteristic, or could be associated with a threat. Reaction severity also depended upon what the whale had been doing beforehand. However, habituation was noted by some whales after repeated exposure to a previously disturbing noise.

XI. Wind Farm Acoustic Studies

When analyzing the acoustic affects of wind farms on marine mammals, three main goals are typically defined. Will any permanent or temporary hearing damage occur? Will the animals be displaced from their natural habitat? What masking will occur of their communication, echolocation, and auditory systems? As construction of offshore wind farms has been prevalent in Europe for the past ten years, a number of studies have been attempted to answer some of the aforementioned questions. These studies have involved a number of different means like boat or plane or land observations, radio telemetry, and passive acoustic listening devices (Evans 2008).

During the 21st annual conference of the European Cetacean Society, specialists met to review recent studies of offshore wind farm impacts on marine mammals. Their main goal was to examine and assess effects of construction and production phase as separate entities, and provide possible mitigation schemes to reduce any harmful auditory affects. A number of trends were noticed. Most important to mention in regards to this thesis were the conclusions that studies revolved primarily around harbor porpoises, harbor seals, and grey seals and that there was a linear relationship between the conservative nature of the authors and how significant environmental impact may be (Evans 2008).

i. Acoustic monitoring of harbor porpoises using T-PODs

Research conducted by the National Environmental Research Institute of Denmark used acoustic porpoise detectors to observe whether wind farm construction in the Baltic Sea deterred the animals from the area (Carstensen 2006). The Nysted Offshore Wind Farm began construction in 2002 within a coastal area of 6 to 9.5 m deep and a glacial deposition floor composition of sand and silt. Seventy two turbines were erected within an eight by nine grid that covered a total of 24 km^2. To compensate for the sandy seabed, pebble cushion layers were added to support concrete gravitational foundations – indicating large scare change to the immediate area.

In looking at surveys conducted during the summer seasons of the early 1990s, the researchers concluded that the wind farm was placed between areas of high and low porpoise density (Carstensen 2006). Surveys conducted within the proposed site prior to construction indicated that harbor porpoises visited the area for short periods of time, mostly passing through that specific region as a part of a larger home base. To test whether such visitations continued within the same frequency during construction, Carstensen's team deployed T-PODs (porpoise echolocation detectors) continuously throughout the duration of their experiments. No information existed pertaining to the specific population concentrations within the specific study areas used.

This use of the T-POD assumes that the degree of echolocation activity is directly correlated with the density of the porpoise population within the area. Still novel, the devices have only been used within a handful of studies (Carstensen 2006). However, while the researchers relied upon the data collected by Koschinski et. al. (2003) to support their reasoning, the usage of T-PODs in this particular instance does not support the particular hypothesis as well as it could. The construction of wind turbines will have a greater acoustic impact over any other sort on the marine mammals.

The T-PODs were placed within three different positions within the wind farm and within a comparison area ten kilometers away from the wind farm of similar environmental conditions. Data collection occurred during a baseline period prior to construction for seven months and for four months during the construction period. However, rather than keeping to the same time of year to compensate for any seasonal changes, the baseline period occurred winter through spring and the construction period occurred summer through fall. Therefore, when analyzing data, a common yearly distribution of the harbor porpoise was assumed.

Through the statistical analysis, a formula was developed to convert the series of clicks per minute into porpoise encounters – which occurred if any silent period within the series was under ten minutes (Carstensen 2006). If any gap of silence over ten minutes occurred, the series of clicks before and after were counted as separate visitations. This number was derived based upon the idea that a harbor porpoise can move approximately 900 m within ten minutes. The range of the T-PODs was about 170 m and ten minutes was predicted to be enough time for a specific encounter to be recorded rather than repeatedly recording the same individual or group.

These researchers noticed that waiting times between encounters (in other words, the periods in which silence lasted over ten minutes) increased during construction in both the test and control areas. This effect was more prominent among the data recorded by the T-PODs within the construction site, with an increase in waiting times almost six times larger than that of the other area. In trying to determine the effects of the specific construction methods, waiting times between porpoise encounters were compared to the average duration of the activity. At all except for one of the reference stations, waiting time between echolocation series lasted for a longer duration than the activity itself. Despite this pattern, the effect of piling and ramming activities remained short lived. Significant increases in waiting time were only found within first exposures, not subsequent recordings. In addition, it was noticed that the effect of the activities decreased the further the T-POD station was from the occurrence, as one would predict based upon zones of acoustic impact. However, construction noises still spread over a large enough difference to even effect echolocation frequencies received by the control T-PODs.

In conclusion, Castensen and his team decided that wind farm construction activities could have a substantial effect on harbor porpoises. Their results indicated that porpoises either avoided the construction area or vocalized at a far less frequency than prior to construction.

ii. Horns-Rev and Nysted Wind farms, Denmark

A two-year joint study between researchers from Denmark and Germany focused on determining impacts of existing wind farms in the North and Baltic Sea on local marine mammals and birds. Both wind farms were within Danish territorial waters: one at Horns Rev and the other at Nysted. At the time of the study, both of the wind farms had been in operation for at least four years. This project was supported by the German Federal Ministry of the Environment to obtain a better understanding of environmental impacts prior to the construction of Germany's own turbines (Blew *et. al.* 2006).

Horns Rev is located approximately 35 km west of Esbjerg, Denmark, within an estuarine system of the North Sea. Water depths range from 6.5 m to 13.5 m. In 2002, 80 turbines, each with an electrical output of 2 megawatts, were constructed within a grid formation at the site. Operation began that fall. Nysted Wind Farm, on the other hand, is located within a lagoon of about 1-2 m deep within the Baltic Sea. Seventy-two turbines were constructed here, each producing 2.2 megawatts of energy and separated within a grid by a distance of 850 m by 480 m. Operation of this farm began in 2003.

Prior studies indicated that populations of harbor porpoises occasionally visited both sites (Blew *et. al.* 2006). To determine whether visits would continue with the wind farms in operation, the researchers examined the distribution of harbor porpoises at the two sites. T-PODs were distributed evenly inside and outside of the two wind farm sites for a six-month summer-fall period. The T-POD method was chosen to prevent survey variability and complications, as well as to prevent any additional interference a surveying vessel could cause. If harbor porpoises avoided the turbines – presumably due to the noise and vibrations – the instruments closer to the farms would log less echolocation activity overall (Blew *et. al.* 2006). It was possible to correlate porpoise activity to the recorded levels of turbine emissions within that exact moment.

Preliminary observations indicated that more activity occurred at Horns Rev than Nysted. At least one porpoise encounter occurred for 97% of days in which the hydrophones were active at Nysted and for 98% of the days the hydrophones were active at Horns Rev (Blew *et. al.* 2006). A higher density of prey species was observed in the two wind farms, due to the prohibition of fishing and creation of artificial habitat by the turbine foundations. Inconsistencies appeared when comparing the data at the two sites. For example, at Nysted, porpoise activity was determined to be greater outside the wind farm than within. However, at Horns Rev, the opposite trend persisted: in which animals were more vocal within the wind farms (Blew *et. al.* 2006).

This study documented continual usage of the wind farm sites by porpoises despite the noises emitted by turbine operations. In neither case did the researchers discover anything that would point toward a marked avoidance of the areas by the animals. However, in lacking a full history of the use of habitat by harbor porpoises in these two areas, it is difficult to determine whether or not porpoise density at Horns Rev and Nysted decreased or increased with the presence of the wind farms.

iii. Horns Rev and Nysted Wind Farm: Operational Phase

Diedrerichs *et. al.* deployed T-PODs at Horns Rev and Nysted Wind Farms from June to November 2006 with the purpose of better understanding harbor porpoise reactions to the noises produced during the operational phase of the wind farms (2007). By this point in time, Horns Rev had been operational for four years and Nysted for three. The T-PODs were placed two meters above the sea floor with the hydrophone pointing away from the sea floor. Ten T-PODs were placed in each of the wind farms, set up in two rows of five – each T-POD about 600 meters away from its neighbor. Within an individual row of five, two of the T-PODs were placed outside of the farms and two were placed within 200 m of a turbine. Porpoise positive time was considered any recording of clicks which lasted at least ten minutes. Three analyses were performed. In the first, porpoise positive time was compared between the rows within a wind farm to determine if differences within the farm itself could affect porpoise distribution. The second analysis compared data collected from outside and inside the wind farm while the third sought to look at environmental factors as an effect.

Less data was ultimately collected within the Horns Rev wind farm due to a higher amount of background noise. Weather conditions likely caused this difference, specifically higher wind speeds disrupting the sandy bottom at Horns Rev (Diedrerichs *et. al.* 2007). Yet, porpoise positive time was recorded by T-PODs at both sites almost daily. Seasonal differences in recorded porpoise time were noticed, with a higher presence of animals at both wind farms in the summer time than in the fall/winter months.

Within the specific wind farm sites itself, more variation in porpoise presence was noted among the turbines than in comparison to the variation that exists between inside and outside the specific farms. No actual pattern in spatial distribution within the farm could be discerned, however. During the experimental period, the turbines within Nysted wind farm were temporarily shut down for maintenance. This gave Diedrerichs *et. al*. a chance to record porpoise vocalizations within the farm during a period in which ship activity was the only anthropogenic sound source. Yet again, no significant difference in recorded porpoise positive time resulted between data collected during the standstill and data collected in the weeks prior and after the shut down. Based upon the frequencies recorded, the researchers were also able to determine that some of the porpoise positive time could be classified as "feeding buzzes." Thus, porpoises were also foraging within the farms aside from just passing through.

iv. Fortune Channel, Canada

While *in vivo* research allows first hand conclusions to be drawn through overall observation of wind farms and animals, *in vitro* work allows for a more controlled and simulated environment in which specific goals can be accomplished. In addition, observations can only explain so much and typically cannot explain the whys of an animal's reaction (Lucke 2008). Therefore, it is important to be able to compliment both sorts of research to get the fullest idea of what is going on.

One such study, a recording study conducted by a team of researchers from Germany, Denmark, the U.K., and Canada, used a CD recording of turbines to examine the behavioral affects of such sounds in more controlled circumstances within Fortune Channel, British Columbia, Canada (Koschinski et. al. 2003). The sound recording simulated a 2 megawatt offshore wind turbine generator and was played between 30 to 800 Hz to passing harbor porpoises and harbor seals from a depth of 35 meters. Click detectors recorded echolocation activity around the transmission and theodolite surveys of passing animals were conducted from a cliff to prevent the introduction of further anthropogenic noise into the system.

Little difference was found in the time spent by harbor porpoises within the test area between the control sessions and the sessions in which the CD was played. During the playback period, average surfacing duration of the porpoises were only ten seconds longer than during the control period. However, significant differences in distance to the player during the two different sessions were noted. Rather than staying a median of 0.7 meters away from the transducer, the animals were noted to stay approximately 4.5 meters from the device when the sounds of the turbine were played (Koschinski et. al. 2003). Furthermore, significant but undefined differences in behavior were observed when the harbor porpoises were within 60 meters of the transducer. As with harbor porpoises, harbor seals stayed a significantly greater distance away from the transducer during play periods than during control periods (Koschinski et. al. 2003).

In comparison to harbor porpoise pinger experiments, the porpoises observed in this study were less avoidant of the sound of the turbines. The pinger experiments were designed to introduce a noise that porpoises would find aversive, but this is obviously not the intent of the turbine generator sound. Harbor porpoises were more cautious and curious around the transducer when turbine sounds were played (Koschinski et. al. 2003). The increase in echolocation activity further supports the idea that exploration was a more likely response than fear.

Typical seal sound avoidance behavior has been described as lifting their head out of the water for a significant period of time. However, in this scenario, no significantly long surfacing times were noted (Koschinski et. al. 2003).

v. Harderwijk, Netherlands

At the Harderwijk Dolphinarium in the Netherlands, Lucke *et. al.* looked to determine what sort of masking effect operational turbines would have on harbor porpoises using auditory evoked potential (AEP) methods. Such methods have been used in collecting audiometric data from a number of mammalian species, including human. The AEP methodology allowed for threshold measurements to be made via electrophysiological means rather than through observation and human judgment. Upon hearing an auditory signal, a neuronal potential is generated that forms a detectable and measurable energy field that can be recorded via electrodes placed at specific positions on the skin (Lucke *et. al.* 2007). For the harbor porpoise, electrodes were placed near the blowhole and dorsal fin. Such a procedure is non-invasive and reduces the potential for bias that exists with observation-based experimentation.

An adult male porpoise was exposed to recorded click type signals ranging from 0.7 kHz to 16.0 kHz during control periods. This individual had participated in other studies previously and was trained to cooperate in this type of study. The porpoise was trained to participate in the sessions conducted: to swim to an underwater station where the acoustic signal could be played and measurements could be recorded and back to poolside for positive reinforcement in the form of fish (Lucke *et. al.* 2007). All activity was further video recorded to provide observations to back up computer readings. When examining masking effects, the sound of an operational turbine, played either at a medium and a high level, was continuously played underwater through a transmitter in addition to the clicks. The turbine sounds were based upon recorded measurements of existing turbines in the North and Baltic Seas. Neural potential was recorded via electrodes, processed via computer, and analyzed for significance through a series of complex statistics (Lucke *et. al*. 2007).

Masking was determined at a level of 128 dB and frequencies of 0.7, 1, and 2 kHz. However, no masking affect occurred at frequencies higher than 2 kHz. They concluded that while higher level masking could occur, it would only be heard at a relatively short distance of tens of meters (Lucke 2008). Even if masking were to occur, it would not necessarily occur at a great enough range to reduce the communication or echolocation capabilities of harbor porpoises. Given that turbines are, generally, spaced hundreds of meters apart, there would be enough room within for the porpoise to continue functioning with little inhibition. However, at the same time, this range could increase or decrease based upon oceanographic and geological features.

The experiment was conducted with only one individual, and in a situation in which not all the background noise could be controlled. However, this does not mean the data ought to be dismissed as rather similar situations seem to occur in the majority of literature reviewed. Instead, it only supports the need for further controlled research, as well as to confirm what has already been determined by looking at similar effects *in vivo* as well.

vi. "Gray" literature review

In 2006, a group of scientists representing American, Danish, and German universities and research institutes attempted to compile results from existing "gray" literature and unpublished data on the affects of turbine noise generation on specific species (Madsen *et. al.*).

Considering that, so far, wind farms have been constructed in shallow coastal waters, Madsen *et. al.* selected representative species from this niche prevalent to the American waters: the harbor porpoise, the bottlenose dolphin, the northern right whale, and the harbor seal. The team concluded that it is the transmission of the sound and the distance in which it can reach that is of most importance for assessing impact (Madsen *et. al.* 2006). Noises produced from the operational stage are incapable of stretching as far as those from construction. Therefore, animals greatly affected by sounds of the construction stage may have an entirely different reaction to those sounds from the turbines' operational phase.

After reviewing the different noises generated during the lifespan of a wind farm, the authors considered pile driving – a technique utilized during construction to erect turbines – as having the most potential to affect marine mammals. Unfortunately, they were unable to find many studies which dealt with this effect. From the existing literature, they decided that the effects associated with pile diving represented the worst case scenario of potential acoustic effects (Madsen *et. al.* 2006). The monopile turbines take several hours to completely drive in to the bottom of the sea floor, either by using a pile-driver or vibrations. Except for concrete foundations in closed off waters, pile driving can be used in all other sediment conditions (Masden *et. al*. 2006). The exact specifications of pile-driving have previously been discussed within Section VIII.

While a study of ringed seals (*Phoca hispidia*) in Alaska did not show significant reactions to underwater noises of received levels of 150 dB re 1 µPa, a study conducted during the pile driving stage of Nysted Wind Farm construction indicated otherwise (Madsen *et. al.* 2006). Up to a 60% reduction in haul out numbers was noticed while pile driving occurred approximate 10 km away. However, no measures were made in this study of seals within the water – nor were sound levels measured above or below water (Madsen *et. al.* 2006). A number of variables then remain: were the seals reacting to noises in water or out? Were they reacting to something else entirely?

Another study conducted at Nysted looked at the responses of harbor porpoises to pile-driving during construction. A significant decrease in porpoise vocalizations were noticed during construction (Madsen *et. al.* 2006). This was noticed both within the construction area and within the reference area 10 km away. Another study, this at Horns Rev, conducted by Tougaard confirmed the aforementioned observation. In addition, visual behaviors at Horns Rev were studied. During pile diving days, travelling was the presumed dominant activity while on non-pile driving days, feeding appeared to be (Madsen *et. al.* 2006).

Despite the experiments, Madsen *et. al.* believed that the range and strength of impact from pile driving, as well as any other associated wind turbine noise, depended upon three criteria: source level, transmission-loss habitat properties, and hearing abilities of the affected animal (2006). A conservative range of impact zones for pile driving sounds was derived based upon a pile-driver of 200 dB re 1 µPa and previously determined marine mammal hearing thresholds. The resulting ranges indicated that pile driving noises could be heard by bottlenose dolphins, harbor porpoises, harbor seals, and the northern right whale at distances of between 100 to 1000 kilometers. However, as pile driving noises are short and impulsive, masking effects are not as likely as believed.

At the time of the review, no studies had been conducted examining marine mammal reaction to operating turbines. Koschinski *et. al.*'s simulated 2 MW turbine playback experiment was criticized for having potentially introduced an extra high-frequency noise that the animals may have been responding to instead of the turbine (Madsen *et. al.* 2006). Despite this problem, Madsen's team agreed with Koschinski's conclusion that any response to operational sounds at 2 MW would occur within a very small impact zone.

A similar determination of impact zones was also conducted for noises made by operational turbines. Unlike pile driving, these noises are continuous and rather low in frequency and level, typically at most 145 dB re 1 µPa (Madsen *et. al.* 2006). Odontocetes' hearing is not attuned to discern low frequencies and thus any impact from the turbines ought to be minor. Harbor seals and right whales, however, are much more capable of determining low frequency noises and would possibly perceive sounds from an operational wind farm. The effects of the turbine, however, would be dependent on the amount of masking that would occur from similar ambient sounds in the environment. In Madsen *et. al.*'s model, the zone of audibility for mysticettes and harbor seals was thought to be under 10 kilometers in ideal environmental conditions (2006).

XII. Conclusions

The development of an offshore wind turbine farm in Nantucket Sound possesses the potential to negatively affect populations of marine mammals due to the acoustic signatures which accompany the wind farm's lifespan. These sounds can be divided into two main categories: the sounds produced during the construction and dismantling of the turbine and the generation of low frequency underwater noise during operation. A completed EIS has been submitted to the federal government and, in accompaniment, a similar report has also been approved by the Massachusetts State government. In the context of environmental legislation, Cape Wind is not considered to be a threat. Horseshoe Shoals was picked for its strategic positioning in a number of circumstances, including the low densities of marine mammal population.

Only a few marine mammal species are likely to utilize the area that will be impacted by this wind farm development. The oceanographic conditions of Horeshoe Shoals are not ideal for the dense aggregations of prey species required by foraging mysticetes (ESS Group, Inc. 2004). Humpbacks, fins, right whales, and minkes may be spotted on occasion, but these species prefer nearby areas such as Stellewagen Bay or Georges Bank where environmental characteristics support high prey densities. The shallow conditions of the shoals are suitable habitat for harbor porpoises. Given that the turbine bases may create artificial reef habitat to further the number of benthic species in the area, populations of porpoises may very well increase (Diedrerichs *et. al.* 2006). The gray seal remains the other species most likely to be found within the wind farm, given the proximity to one of its main breeding colonies in the United States.

Data collected from acoustic studies of existing coastal farms in Europe suggests that marine mammals, including the harbor porpoise, do not abandon habitat after the construction phase is complete. Acoustic studies stress the important of classifying the construction/dismantling stages of a wind farm’s lifespan as separate from the auditory properties associated with the operational phase. The most intense, and dangerous, noises will be produced during the construction period.

Of particular consequence will be any pile driving which might be conducted to construct the turbines. Although sound intensity is dependent upon sediment type, pile driving can reach intensity levels as high as 200 dB re 1 µPa and frequencies ranging from 100-500 Hz (Madsen *et. al.* 2006; Betke *et. al.* 2004). This frequency range falls within estimated sensitivities for pinnipeds and odontocetes. Noises produced by air guns fall within similar intensities and frequency ranges as those produced in pile driving and provide a good comparison. Reactions have varied from species to species: Goold noticed a significant response by common dolphins to air guns in the Irish Sea while Richardson *et. al.* observed no discernable reaction by bowhead whales to air guns in the Beaufort Sea (Goold 1996; Richardson *et. al.* 1985). Observations collected by Catensen *et. al.* depicted behavior alterations by harbor porpoises during pile driving work at Nysted that resembled avoidance (2006). It is likely that construction of Cape Wind will result in displacement of any species which frequents the Shoal, whether it be because of the noise intensity, the suddenness of the noise, or some combination of both. However, the continued presence of harbor seals and porpoises at the wind farms of Europe indicate that this displacement is not permanent.

Many previous studies have shown that animals will habituate to anthropogenic noises if exposed at a great enough regularity. Despite the presence of oil and gas exploration in the Beaufort Sea, migrating mysticetes still frequent the same regions and routes (Richardson *et. al.* 1985; Moore and Clark 2002). Nevertheless, other reports indicate deviation in normal migratory paths to avoid sources of anthropogenic sounds (Romano *et. al.* 2004). Although of higher frequency than noises connected to wind farms, pinger studies have shown harbor porpoises and seals becoming more accustomed to the noise the longer the duration of exposure (Cox *et. al.* 2001; Kastelein *et. al.* 2006; Teilmann *et. al.* 2006). Likewise, similar situations have been noted in regards to increasing vessel exposure (Watkins 1986; Nowacek *et. al.* 2004). As of the latest study, Nysted and Horns Rev have reached approximately five years into their operational lifetime. Both sites are still being used by harbor porpoises and harbor seals that had inhabited the region prior (Carstensen 2006; Blew *et. al.* 2006; Diedrerichs *et. al.* 2007).

In the case of Nysted and Horns Rev wind farms, little baseline data existed for the occurrence of marine mammals in the waters occupied by the wind farms prior to their construction. Thus, it is not possible to conclude definitively whether usage of these areas has increased or decreased. However, controlled playback studies do indicate some avoidance of the noise by harbor porpoises and harbor seals (Koschinski *et. al.* 2003). While initial disturbance caused by the introduction of a new noise to the environment might be a problem initially, it appears unlikely that the nose generated by operational turbines will cause major displacement of species despite operating at levels between 700-1000 Hz and intensities as high as 250 dB. Watkins' 1986 study regarding marine mammal adaptation to vessel presence in Cape Cod Bay showed that the whales involved were more likely to display negative reactions to vessel presence when the sound came unexpectedly, was of too high an intensity, suddenly changed in characteristics, or seemed threatening. In this regard, such outcomes could imply that a continuous sound, as that produced by turbines, will not cause the same level of alarm. The reactions observed in Koschinski's playback experiment could have resulted more from the sudden introduction of a new noise into the environment rather than because of the frequency or intensity of the noise. While avoidance may be an initial problem after Cape Wind starts operation, it is unlikely that it would be a continuing one.

The aforementioned studies on the acoustic affects of wind farms on marine mammals provide a substantial amount of background information that can be utilized to formulate opinions as to how a wind farm in Horseshoe Shoals will the marine mammal population there. But it is highly important to keep in mind the fact that the Baltic and North Seas are different in environment from Horseshoe Shoals. Acoustic properties will vary between locations based upon the different physical characteristics and, consequently, noises produced by a collection of turbines in Horseshoe Shoals could feasibly be more or less extreme in their affect on marine mammals.

In addition, little research has been conducted on species aside from the harbor porpoise and harbor seal. Particularly, wind farm sounds could have an effect on mysticetes (whose vocalization frequencies are more on par with the sounds produced by wind farms). The hearing thresholds of other odontocetes and pinnipeds can be compared to frequencies emitted by wind farms through existing audiograms in order to develop general conclusions regarding influences. Such an opportunity does not exist with mysticetes.

The small sample size in the majority of research discussed in this paper is also of note. Variations in audiograms and other auditory data between individuals of the same species is a common occurrence which ultimately makes it difficult to form solid conclusions. Nevertheless, work with marine mammals often precludes large sample sizes from due to the difficulty in harboring the animals and the numerous legal restrictions involved.

No evidence of physical harm to marine mammals has yet to be detected from the construction or presence of wind farms. Persistent anthropogenic sound does, however, does possess the potential to cause higher levels of stress in these mammals. Consistent stress can lead to weakened immune systems. Also, continuous exposure leads to the possibility of hearing damage occurring. Exposure of a beluga whale and bottlenose dolphin to an air gun resulted in increased levels of neural-immune chemicals which tend to be correlated to higher stress levels (Romano *et. al*. 2004). Although a greater number of variables are involved – the response and physiology of the individual concerned, environmental properties, and sound characteristics – the possibility does exist that consistent exposure to the frequencies and levels produced by the turbines may eventually do greater harm to resident animals. Such a possibility will take years to determine and thus the matter becomes the lesser of two evils: should offshore wind farm construction continue knowing that the noise levels may ultimately, and permanently, alter the auditory capabilities of habituating marine mammals however much we currently have no evidence in support?

Mitigation techniques currently being developed may offer an opportunity to prevent such a decision from being made. Advancements in technology will lead to quieter generators within the turbines. In other cases, innovations such as the bubble curtain may contain underwater noise within a small area surrounding the turbine or construction site. Experimentation has shown that implementing a bubble curtain around a sound source does lead to lower perceived levels depending upon the distance away from said source (Wursig *et. al.* 2000). Furthermore, careful monitoring of any marine mammals during construction will allow for further mitigation through careful planning of what is constructed where and when.

A sufficient lack of peer-reviewed information regarding acoustic effects of offshore wind farms on marine mammals persists, and there is a need for better compilation of the studies conducted (Madsen et. al. 2006). Sound is an unavoidable inevitability of living life outside of a vacuum. Even without human presence, the background levels of sound in the ocean remain vast and diverse. Marine mammals have adapted to these natural noises throughout their evolutionary processes. We should not necessarily conclude that marine mammals will adapt to artificial anthropogenic noises, but past research suggests some level of acclimation to these sounds.

The possibility does exist for Cape Wind to produce noises at levels which will disturb marine mammals, especially during the construction phase. However, Cape Wind will also provide a number of benefits to Cape Cod residents despite all their protests. New jobs and other economic incentives will be created, and the United States will take another step towards energy independence and cleaner, greener production methods. Further studies are needed to explore the acoustic affects of wind turbines on marine mammals, especially as the duration of exposure becomes longer. Offshore wind farms have, after all, only become a reality during the last two decades. If and when Cape Wind begins construction, they too should conduct further experimentation and observation on this topic. The information provided within this Master's Project is just the start of what must be conducted to fully comprehend offshore wind farm acoustics some day.

XIII. Acknowledgements

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Appendix A

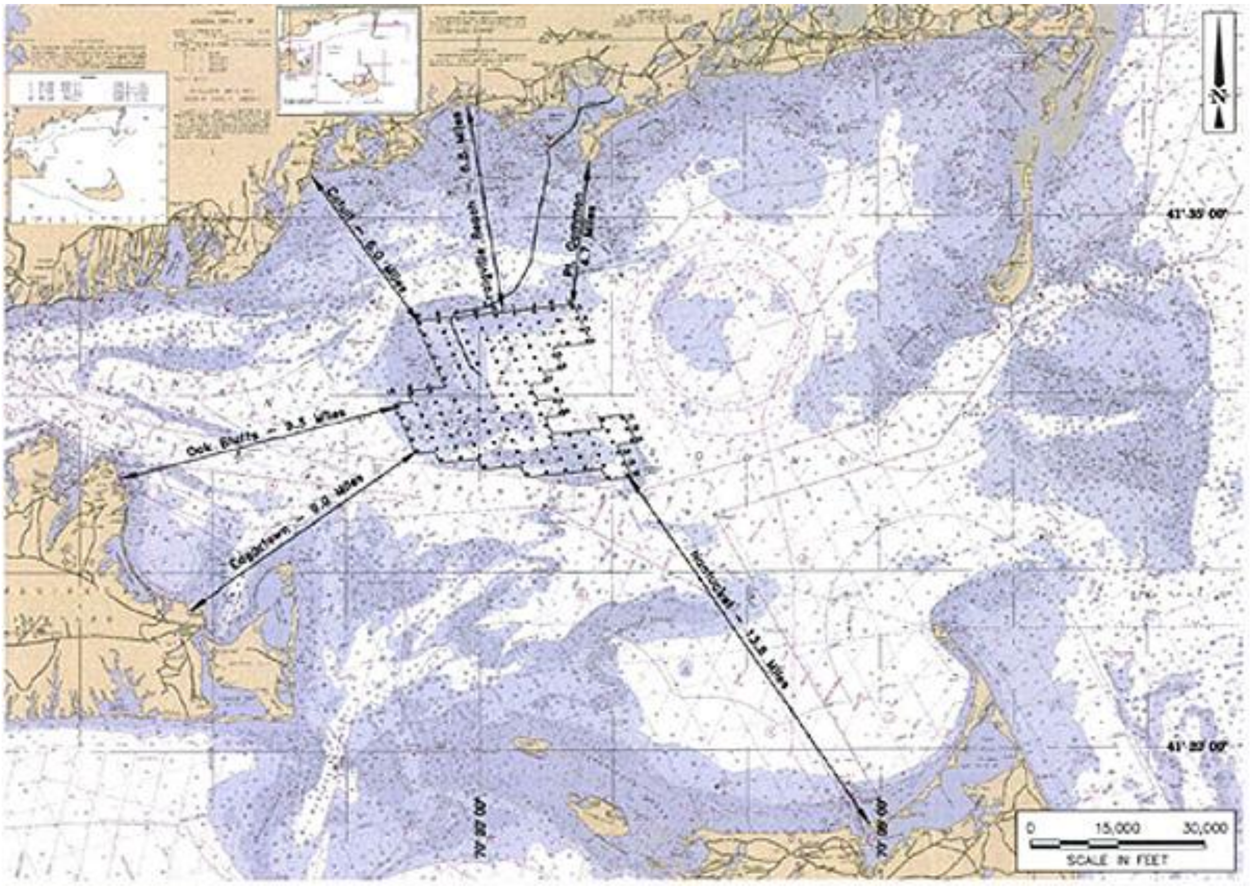


Figure 1. A map of Nantucket Sound depicting the projected location of Cape Wind's offshore wind farm. (Courtesy of the US Army Corps of Engineers and Cape Wind Associates, LLC.).

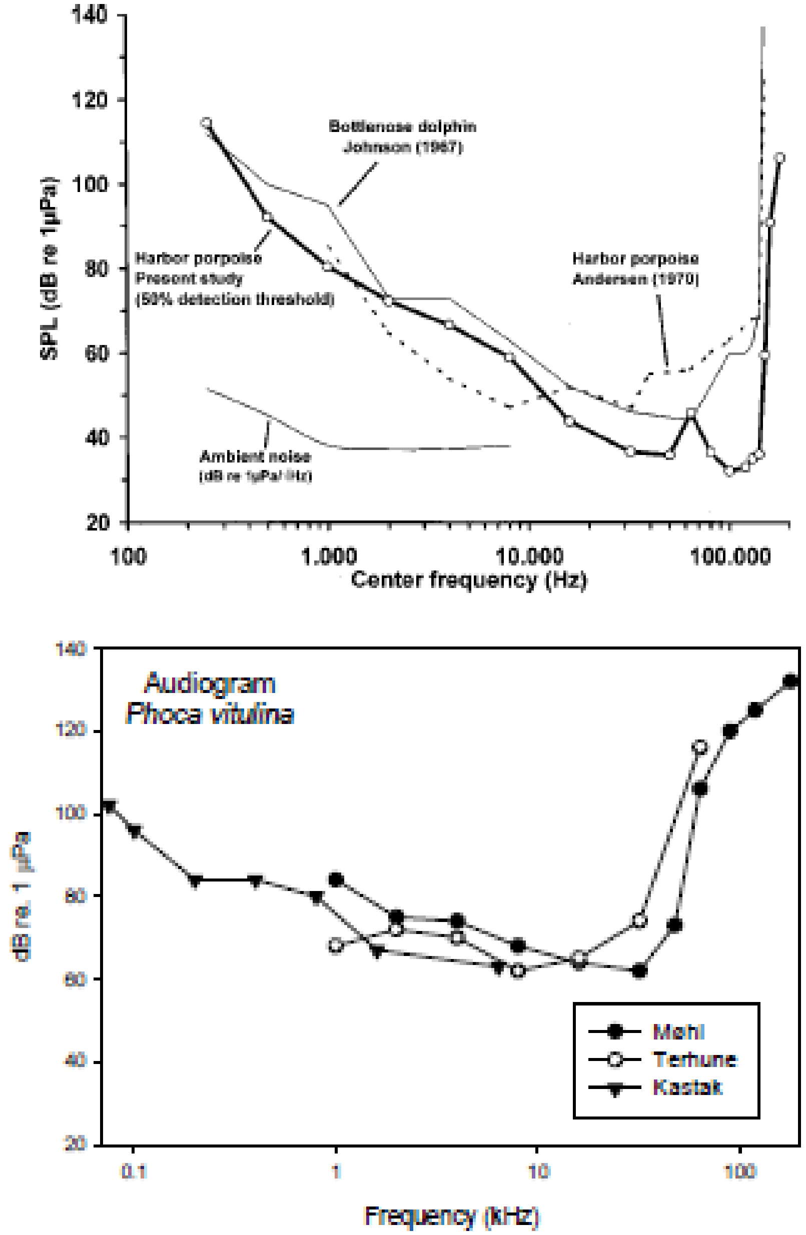
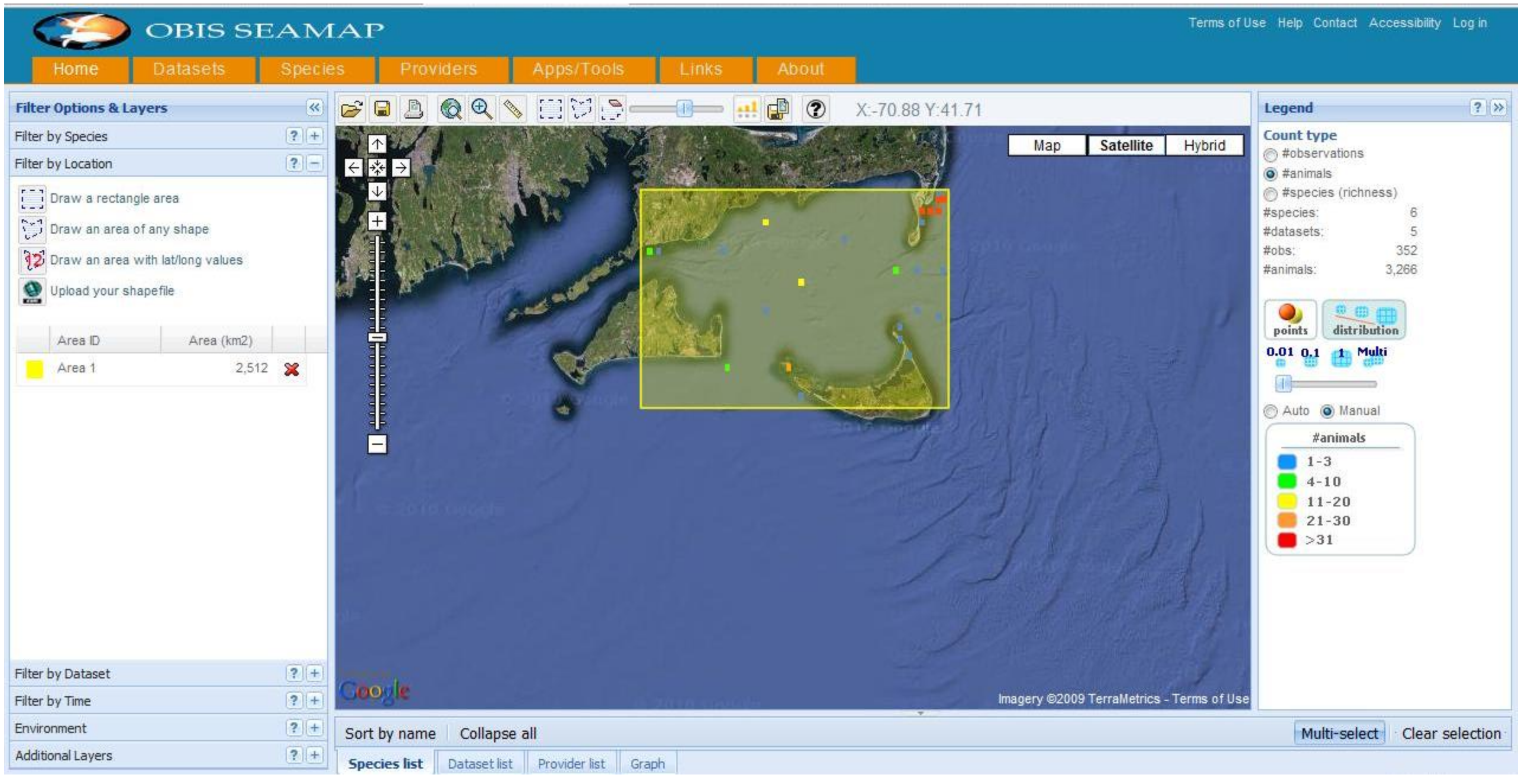


Figure 2. A comparative set of audiograms depicting hearing sensitivities for the harbor porpoise, bottlenose dolphin, and harbor seal. (Upper graph courtesy of Kastelein et. al. 2002 and lower graph courtesy of Tougaard et. al. 2006).



Area ID	Area (km2)
Area 1	2,512

○ #observations
● #animals
○ #species (richness)

#species: 6
#datasets: 5
#obs: 352
#animals: 3,266

○ Auto ● Manual

Figure 3. A screen capture of OBIS-Seamap used in determining further marine mammal visitations in Nantucket Sound. (Read *et. al.* 2010).

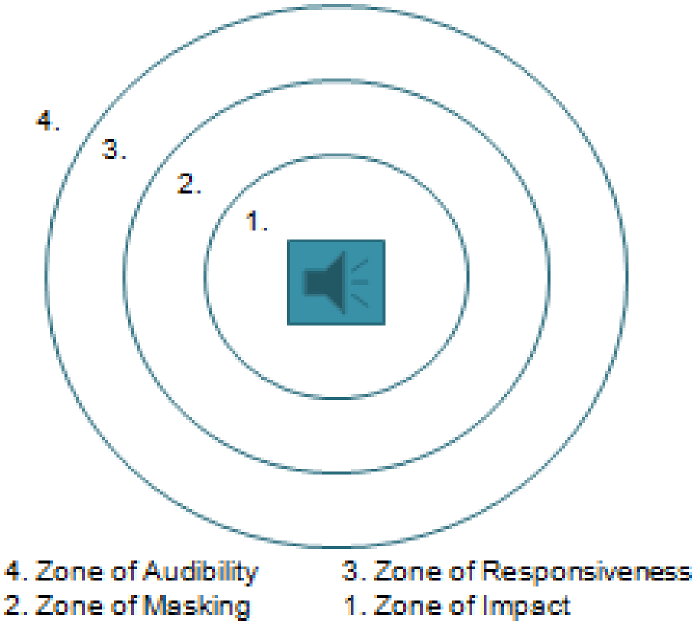


Figure 4. A depiction of the four zones of acoustic impact on marine animals as they radiate outward from the center noise source.

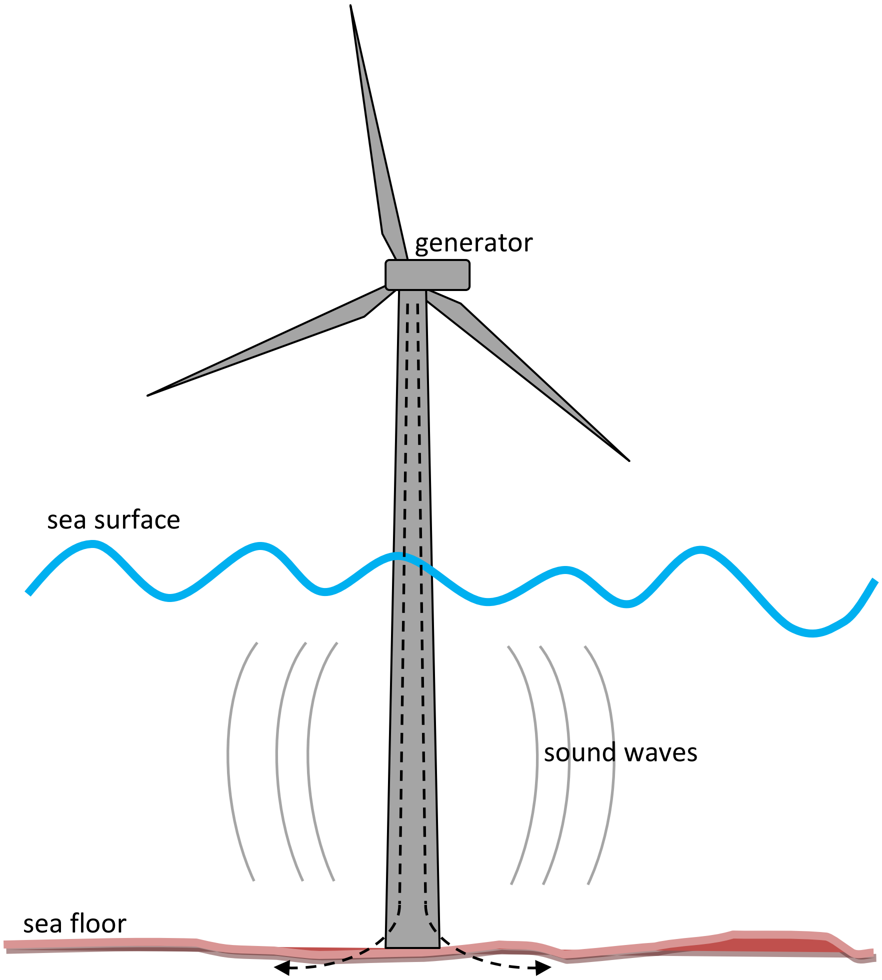


Figure 5. As sound is produced in the generator of the turbine, vibrations move through the turbine (as indicated by dotted lines) and radiate out into the surrounding environment: that of the sea itself and of the sea floor.