HARBOR PORPOISE RETURN TO THE SOUTH PUGET SOUND: USING BIOACOUSTIC METHODS TO MONITOR A RECOVERING POPULATION

by

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ABSTRACT

Harbor porpoise return to the South Puget Sound: using bioacoustic methods to monitor a Recovering population

David Anderson

Harbor porpoise began returning to the Puget Sound during the early 2000s after several decades of absence, becoming established in the South Puget Sound by 2008. This study deployed a C-POD ultrasonic click detector from March through May 2013 off Steilacoom, Washington. Porpoise detections were compared to a variety of environmental and temporal factors, including rate of tidal change, wind speed, hour of the day and month of the year. A limited set of visual observations were used to check the accuracy of the acoustic data. Harbor porpoise were detected all hours of the day, with acoustic detections peaking in the morning. The rate of detection was highest in the month of May, and lowest during April. Acoustic detections were highest during slack water and slow incoming tides, compared to faster tides and slower outgoing tides. The acoustic data showed that harbor porpoise did not leave the area when vessels operating echo sounders transited the study site, though it is not possible to determine with acoustic data if diving was used as an avoidance response. Given the proximity of the site to a ferry terminal, there is a possibility that harbor porpoise have become habituated to the ferries, which accounted for greater than 80% of the traffic using echo sounders. The C-POD has proven to be a useful tool in monitoring the harbor porpoise population, with an ability to monitor day and night in all weather conditions.

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1 Introduction

After World War II, harbor porpoise (*Phocoena phocoena*) were one of the most common cetaceans in the Puget Sound (Scheffer and Slipp 1948), yet by the time the Marine Mammal Protection Act (MMPA) was passed in 1972, harbor porpoise had been extirpated from the waters south of Admiralty Inlet. It is unknown for certain what led to the loss of habitat use by the harbor porpoise, though it was likely due to a combination of habitat degradation, fisheries bycatch, and recreational human takes which resulted in unsustainable losses to the population. High levels of pollution were present in the Puget Sound during this time period and may have contributed to the decline in the population, as toxins bioaccumulate in higher trophic level animals like the harbor porpoise (Calambokidis et al. 1985). The bycatch from gillnet fisheries, a common commercial and tribal fishing method in the Puget Sound, is also considered to have contributed to the extirpation from the South Puget Sound waters. Diving seabirds saw a decline over the same time period; the birds have a similar diet to the harbor porpoise and are also subject to by catch issues (Bower 2009), suggesting a probable systemic problem.

Occasional reports of harbor porpoise sightings were received between the 1970s and early-2000s, but these were always isolated incidents with no more than a few animals reported, with no animal sighted during surveys in the 1980s and 1990s (Flaherty and Stark 1982, Calambokidis et al. 1985, 1993). During this time period, the most common cetacean in the Puget Sound was the Dall's porpoise (*Phocenoides dalli*). Dall's porpoise are noticeably larger than harbor porpoise and have different coloration and diving behavior, factors which make species identification straightforward in the field.

It is unknown precisely when harbor porpoise started returning to the Puget Sound south of Admiralty Inlet. As the harbor porpoise population in the San Juan Islands and the Strait of Juan DeFuca increased through the 1990s and early-2000s, there were increased sightings of animals within the Puget Sound. By 2007 harbor porpoise had gradually expanded through much of the North and Central Puget Sound, with a small group of porpoise regularly sighted in the South Puget Sound by 2008 (Calambokidis, personal communication). Four porpoise were spotted off the west side of Anderson Island in the South Puget Sound in April 2008 by the author during a kayak trip, with many additional sightings later in that year. The population has continued to grow throughout the Puget Sound and harbor porpoise are frequently seen by boaters. While the harbor porpoise population has been increasing in Washington's estuarine waters, Dall's porpoise sightings have dropped drastically, and it is unknown if the decline is related to the increase in harbor porpoise or other factors. It is also unknown what factors contributed to the return of the harbor porpoise to the Puget Sound waters, though reduction in levels of some pollutants or changes in fisheries many have played a part. Some animals may have expanded their range into southern Puget Sound as a result of habitat changes or having exceeded the carrying capacity in areas they previously occupied.

Although the National Marine Fisheries Service (NMFS) is responsible for conducting periodic surveys to determine population size and distribution of marine mammals, no aerial or boat based surveys have been conducted of small cetaceans in the Puget Sound since harbor porpoise have returned. Congressional budget cuts have led to the reduction or elimination of many of the research and management activities related to these and other protected species. Without these surveys we lack the ability to monitor the recovery of harbor porpoise populations, or determine if any management decisions are necessary to protect them.

Conservation of harbor porpoises in the South Puget Sound requires abundance estimates as well as knowledge about how porpoises move throughout their range and make use of the habitat. A variety of environmental factors, such as tidal flow and time of day have been shown to influence porpoise presence and behavior (Johnston et al. 2005, Todd et al. 2009). Tidal flows cause eddies or convergent fronts in the water that can concentrate food species at different times in the tidal cycle and attract porpoises to the area. Differences in harbor porpoise presence and behavior vary from site to site depending upon how the tidal current interacts with the local bathymetry to concentrate prey. Diel variations in behavior can often be attributed to the daily migration of zooplankton from the depths to the photic zone and back. Studies in different regions have shown consistent diel feeding patterns in harbor porpoise on a site by site basis, but patterns vary between studies (Todd et al. 2009, Haarr et al. 2009). Determining the distribution and timing of harbor porpoise behaviors within the South Puget Sound is important inform management decisions and to minimize anthropogenic disturbance in critical habitat areas.

Traditionally, harbor porpoise have been studied using visual observations from land, sea, and air. Their small size, dark coloration, and brief surface time are significant challenges to the study of this animal through visual observations. Unlike some of the dolphins and the Dall's porpoise that are often attracted to vessels or human activity, harbor porpoise are considered to be a rather shy species, often seen fleeing vessels and avoiding areas of high activity (Embling et al. 2010). Even though harbor porpoise are known to react to human activity, it is unclear from the literature whether they leave the area for an extended length of time, or if it is a short-term response. In recent years, there has been increased interest in finding ways that remote sensing technology, such as passive acoustic monitoring (PAM) could be used to monitor small cetaceans. Acoustic monitoring can be used to augment visual observation, capture echolocation clicks, and collect data about underwater activity of porpoises during the day or night, in all weather conditions, without introducing human induced disturbance.

This study considered how PAM equipment, combined with traditional visual methods, could be used to monitor harbor porpoise presence and behavior in the South Puget Sound. A location in the South Puget Sound off Steilacoom, Washington was chosen to deploy a C-POD (Cetacean POrpoise Detector, Chelonia Ltd., UK) ultrasonic monitor, from March through June 2013, to detect harbor porpoise echolocation clicks. This location was chosen due to known harbor porpoise presence, favorable bathymetry and observation points that provide a view of the deployment site as well as approximately 30 km^2 of the surrounding basin. Visual observations were recorded whenever possible to corroborate acoustic data, as well as recording cetacean presence and behavior in the greater basin.

In this study, passive acoustic monitoring was shown to provide detailed information about harbor porpoise presence, distribution and behavior that will be useful for informing management decisions to protect the Puget Sound harbor porpoise population in the future, while limiting impacts on human activities. Acoustic monitoring is not a replacement for visual monitoring, it provides a low cost method of long-term monitoring of trends in abundance, distribution and behavior that is not restricted by the time of day or weather conditions, but it also has many limitations, such as limited range and the inability to detect silent animals. With proper monitoring and management, harbor porpoise can successfully inhabit their traditional habitat in South Puget Sound.

2 Literature Review

This literature review will address issues related to the return of harbor porpoise to the South Puget Sound and the use of acoustic monitoring methods to complement traditional visual methods to gain a better understanding of harbor porpoise behavior. Harbor porpoise are an important high trophic level predator throughout the coastal waters and estuaries of the temperate and boreal waters of the northern hemisphere. As with many high level predators, harbor porpoise and other marine mammals are considered a sentinel species for the ecosystems they inhabit (Bossart 2011). Harbor porpoise are one of the most numerous species of cetaceans in the world, and they inhabit coastal waters that are often near population centers of the temperate northern hemisphere, making them an easily accessible study subject. This proximity to human population also leads to conflict with anthropogenic usage of the coastal ecosystem, which has led to a great deal of research into human activities and their impact on the porpoise populations.

While, as a species, harbor porpoise are not endangered, many populations and subspecies are in decline due to human activity, with the Baltic Sea population and the Black Sea subspecies considered endangered or critically endangered (Hammond et al. 2008b). Harbor porpoise have also returned to Dutch waters in 1990 after three decades of absence (Boonstra et al. 2013), and they have recently returned to the San Francisco Bay after 65 years of absence (Keener et al. 2011). The reestablishment of populations in these areas provide an opportunity to study the factors that might influence the return of porpoise to these and other regions, and to develop management plans to protect these animals in a way that will allow their populations to recover.

Even with their numbers and accessibility, harbor porpoise research is subject to the same difficulties encountered in any cetacean research. Cetaceans are only visible at the surface for a small fraction of their lives with underwater behaviors and movement patterns hidden from view. Before the last few decades, studies of harbor porpoise were restricted to visual observations of behavior at the surface and examination of dead animals that were stranded, caught in fisheries or killed in a lethal sampling program (Scheffer and Slipp 1948). With recent developments in passive and active acoustic technology, as well as the development of wildlife tracking tags, many new opportunities have emerged for advancing our knowledge of marine mammals. Additionally, the use of remote sensing data by physical and biological oceanographers has informed research into marine mammals and other top ocean predators by providing information about bathymetry and ocean productivity that was unavailable until recent decades.

This literature review will provide a general overview of the harbor porpoise, including information about its biology, range, taxonomy and echolocation; cover a variety of threats to the harbor porpoise including both natural predators and anthropogenic factors; examine methods used for monitoring harbor porpoise and other small cetaceans, both visually and acoustically; and the analysis of the effect of environmental factors and anthropogenic disturbance on harbor porpoise distribution and behavior.

2.1 The Harbor Porpoise

2.1.1 Species Description

Harbor porpoise are the smallest cetacean found in the waters of the United States, measuring 1.5-1.7 m and 60-75 kg at maturity. The small triangular dorsal fin, without any white on the trailing edge, along with the characteristic rolling surface motion aids in differentiating harbor porpoise from other small cetaceans within the harbor porpoise's range (Bjorge and Tolley 2009). Coloration is a dark gray on dorsal surfaces, becoming light gray to white ventrally, without a distinct demarcation line between colors (Figure 2-1). A study of pigmentation patterns within and between different populations showed that there are variations between individuals in a population, and that there are trends within populations, but that pigmentation cannot be used as a morphological way to differentiate between populations (Koopman and Gaskin 1994). Though they are extremely rare, white porpoise with only small areas of pigmentation have been sighted in populations in both the Pacific and Atlantic Oceans (Keener et al. 2011).

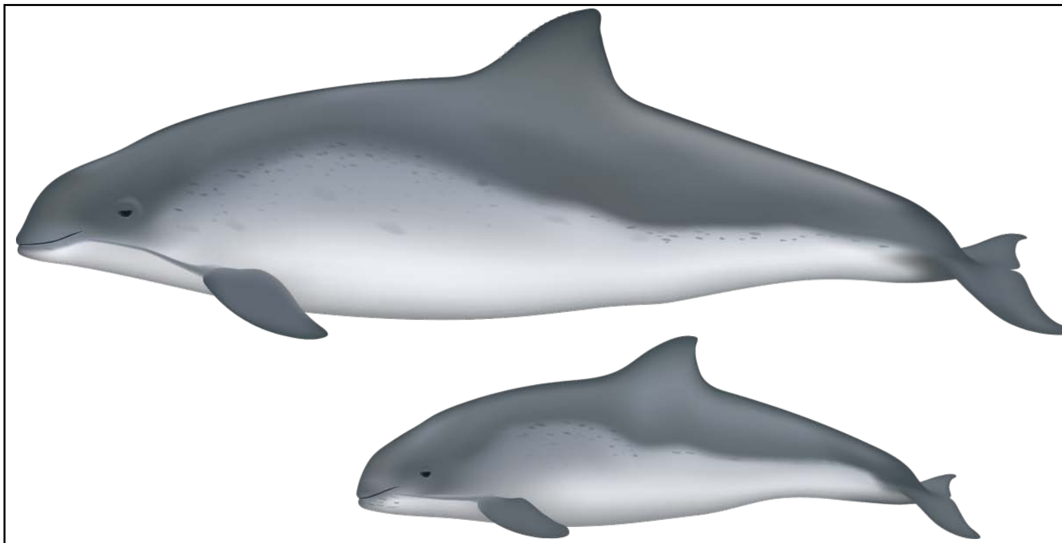

Figure 2-1: Harbor porpoise adult and calf. (Copyright Uko Gorter)

2.1.2 Taxonomy and evolution

Taxonomic Classification	
Order:	Cetacea
Suborder:	Odontoceti
Superfamily	Delphinoidea
Family:	Phocoenidae
Genus:	*Phocoena*
Species:	*Phocoena phocoena*

Harbor porpoise, along with all other whales, dolphins and porpoises of the order Cetacea, are descended from land dwelling ungulates, with the hippopotamus being their closest extant relative, splitting off around 53-54 million years ago (Ma) (Berta et al. 2006). All cetaceans retain the four-chamber stomach of their graminivore ancestors (Mead 2009). Mesonychians, an extinct taxa believed to be closely related to early cetaceans, had dentition suggesting that a change to a carnivorous diet could have occurred before protocetaceans returned to a semi-aquatic life (Berta et al. 2006).

Cetaceans are divided into two suborders, Mysticeti or the baleen whales, which filter feed using baleen plates made of keratin instead of teeth, and Odontoceti, or toothed whales, which includes dolphins and porpoises. It is believed that the split between mysticetes and odontocetes happened around 35 Ma, though there is some disagreement about the time frame (Berta et al. 2006, Fordyce 2009). The ability for odontocetes to echolocate is believed to have evolved within a few million years of the split between mysticetes and odontocetes. Fossils of an extinct branch that diverged approximately

32 Ma showed adaptations indicative of the ability to echolocate (Geisler et al. 2014).

The increasing availability of low cost genetic testing has enabled geneticists to reexamine and propose changes to the branches of the phylogentic tree of the porpoise and dolphin species. The Delphinoidea clade that includes ocean dolphins (Delphinidae) and porpoises (Phocoenidae) diverged approximately 19 Ma (Chen et al. 2011). Several lines of genetic study have shown that porpoises are most closely related to belugas and narwhals (Monodontidae), having diverged from ocean dolphins approximately 16 Ma, with the porpoises diverging from the narwhals approximately 11 Ma (Waddell et al. 2000, Chen et al. 2011). Riverine dolphins are called "dolphins" due to their morphological similarities to ocean dolphins, yet they are not part of Delphinoidea, nor are they a monophyletic group. They are members of ancient odontocete lineages that were protected from the competition for resources by true delphids due to their selection of a freshwater habitat (Cassens et al. 2000).

There are six extant species of porpoise, four of which are in the genus *Phocoena*, including the harbor porpoise, *Phocoena phocoena*. The relationships between the porpoise species is the subject of continuing genetic research, some of which suggests that harbor porpoise are most closely related to Dall's porpoise, which is currently classed in a different subfamily and genus (Rosel et al. 1995b). Mating between harbor porpoise males and Dall's females have been known to produce viable, hybridized offspring (Willis et al. 2004). This raises interesting questions, not yet covered in current literature, about genetics, morphology, genus differentiation and the role of hybridization between these two species.

There are four recognized subspecies, *P. p. relicta* in the Black, Marama and Adriatic Seas; *P. p. phocoena* in the North Atlantic; *P. p. vomerina* in the eastern North Pacific; and an unnamed subspecies in the western North Pacific (Rosel et al. 1995a, 2003, Rice 1998, Frantzis et al. 2001). The division into subspecies was conducted using morphological characteristics and analysis of mitochondrial DNA. Additional DNA analysis has been conducted to identify separate breeding populations, with 14 identified groups in the North Atlantic and Black Sea (Andersen 2003). There has been limited work on genetically defining harbor porpoise population structure within the North Pacific Basin, though mitochondrial DNA studies in the 1990s suggest that there is some gene flow between populations along the west coast of North America (Rosel et al. 1995a).

As recently as the 1970s the terms "porpoise" and "dolphin" were used interchangeably in the scientific literature for any small odontocete (Renaud and Popper 1975), and the lack of distinction continues in common usage. Porpoise are distinguished from dolphins by the lack of a prominent rostrum, smaller mouths, stouter bodies, triangular dorsal fins and spade shaped instead of conical teeth (Read 2009). Porpoise make a much more limited range of sounds, most of which are above the frequency of human hearing, unlike the lower frequency whistles and clicks of dolphins that are audible to humans (Frankel 2009).

2.1.3 Distribution and Abundance

Harbor porpoise are distributed throughout the temperate and boreal coastal waters of the Northern Hemisphere (Figure 2-2), preferring the shallow waters of bays and estuaries, as well as the near-shore region along the coast (Bjorge and Tolley 2009). A

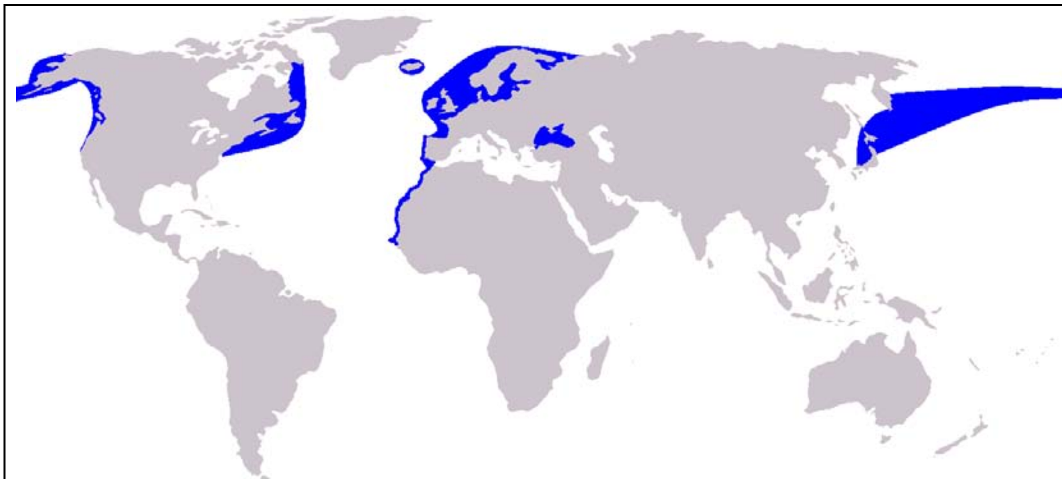

Figure 2-2: Worldwide harbor porpoise distribution. **(Copyright Wikipedia user BloodIce (CC BY-SA 3.0) http://commons.wikimedia.org/wiki/File:Cetacea_range_map_Harbour_Porpoise.PNG)**

geographically and genetically distinct population is located in the Black Sea, separated from the porpoise in the Atlantic by the Mediterranean Sea and the Bosphorus Strait, where porpoise are rarely sighted (Frantzis et al. 2001, Reeves and Notarbartolo di Sciara 2006). It is thought that harbor porpoise have avoided the Mediterranean Sea for several thousand years due to the increase in temperatures since the last ice age, separating the Black Sea population from those in the Atlantic Ocean. Tests were run on 5 bycaught animals in the Agean Sea showing that they were part of the Black Sea population (Rosel et al. 2003). The only harbor porpoise population known to venture into tropical waters are those along the west coast of Africa, which can be found as far south as Mauritania (19° N) (Smeenk et al. 1992, Boisseau et al. 2007),

Globally, the harbor porpoise population is thought to be greater than 700,000 animals, and the species is listed as Least Concern (LC) on the International Union for Conservation of Nature (IUCN) Red List of Threatened Species (Hammond et al. 2008b). The North Sea supports almost half the world population, with an estimated population of 335,000 animals (Hammond et al. 2002). While the global population is not considered to be under threat, in many parts of the world the population is in decline, and some of the distinct populations are threatened or endangered. In the Baltic Sea, where porpoise density once rivaled the neighboring North Sea, it is thought that the population is down to a few hundred individuals (Hammond et al. 2008a). The Black Sea is seeing a large decline in abundance, though no current estimates exist (Birkun Jr. and Frantzis 2008).

In Washington State, harbor porpoise are found on the Pacific coast as well as in the Strait of Juan DeFuca. Once common in the waters of the Puget Sound (Scheffer and Slipp 1948), they were extirpated south of Admiralty Inlet and east of the San Juan Islands sometime before surveys began in the 1970s (Calambokidis et al. 1992). There is no additional information available on harbor porpoise abundance in the Puget Sound before extirpation other than the Scheffer and Slipp (1948) reference to harbor porpoise as being “common” in the 1940s. Harbor porpoise began returning to the Puget Sound in the early 2000s (Calabokidis, personal communication), but no surveys have been conducted since their return to determine abundance. Aerial surveys of the coastal waters of Washington State and the Strait of Juan DeFuca were conducted in the 1990s, producing an abundance estimate of 15,000 harbor porpoise in these waters (Calambokidis et al. 1993). High concentrations of harbor porpoise were found in the central and eastern portions of the Strait of Juan DeFuca and the northern San Juan Islands during aerial surveys of those areas in 2003 (Chandler and Calambokidis 2003). These high concentrations might have led some of those animals to expand their range into the Puget Sound.

2.1.4 Life History

Timing of harbor porpoise birth varies by population, with the females in most areas giving birth from May through August after a 10.5 month gestation period. Females are capable of giving birth annually, though not all females produce a calf every year, in some populations the annual birth rate in reproductive age females can run lower than 0.75 (Read 1990). One study suggests that the females in the population off Central California reproduce every second year, instead of annually as do the populations studied in the Atlantic Ocean (Read and Hohn 1995). Size at birth is approximately 65-80 cm and around 5 kg, though this can vary by population group and food availability. Weaning is thought to occur between 8 and 12 months, which means that females spend much of their time both weaning and pregnant. Sexual maturity occurs at 3-4 years, with first parturition at 4-5 year. Harbor porpoise have been shown to live for more than 20 years, though fewer than 5% of adults are believed to live longer than 12 years (Lockyer 2003).

2.1.5 Social Structure

Little is known about the social structure within and between harbor porpoise populations. Harbor porpoise are usually sighted in foraging groups of one to three individuals, though groups of up to 12 are not uncommon (Flaherty and Stark 1982). When combined with their coastal habitat and cryptic behavior, the small group sizes favored by the harbor porpoise might play a role in predator avoidance (Gygax 2002). Other than cow-calf pairs, it is believed that groups are rather fluid in their members and structure (Flaherty and Stark 1982, Saana 2006). Larger groups have been reported at times in the literature, most of which are thought to be loosely associated feeding aggregations (Hoek 1992, Saana 2006). Tracking studies, using position reporting satellite tags and follow-up acoustic surveys, have shown that there are areas of seasonal high density, but some animals are found outside these aggregations (Sveegaard et al. 2011b, 2011a).

2.1.6 Behavior

Harbor porpoise spend most of their time foraging in groups of 1-3 individuals though it is not uncommon to have multiple small groups foraging in the same area. Normal foraging behavior consists of a surface series of 3-5 breaths followed by an extended foraging dive. Surface events are generally quick consisting of a simple forward roll that lasts about 2 seconds, with an audible puff as they breathe out, though in rough water they rise higher out of the water without their normal rolling motion (Scheffer and Slipp 1948). Aerial and splashing displays such as breaching and porpoising are rare in harbor porpoise, and mostly occur in larger groups, suggesting a possible social significance to those behaviors (Flaherty and Stark 1982, Hall 2011)

Few studies have been conducted regarding harbor porpoise dive depth and duration. A study in the Bay of Fundy, New Brunswick, Canada was conducted using time and depth recording tags showing that while foraging harbor porpoise made an average of 30 dives per hour, with a mean dive depth of 25 ± 30 m, and a mean dive time of 65 ± 53s. The maximum dive time recorded was 321 s, and the maximum depth by the same animal was 226 m. The maximum depth of the study area was 230 m, which may have limited the ability to determine their full diving capabilities (Westgate et al. 1995). A study currently underway off the west coast of Greenland is using time and depth recording satellite tags to monitor travel and dive profiles of harbor porpoise. Seven of the tagged animals recorded dives of 200 m, with two porpoise recording dives to a depth of 400 m (Nynne Hjort Nielsen, personal communication). Puget Sound has a maximum depth of 284 m; the results of the Greenland study suggest that harbor porpoise are able to utilize the entire Puget Sound for benthic foraging.

Harbor porpoise are active during all hours, though individual animals do have periods where they rest at the surface (called "logging"). Unlike terrestrial animals, cetaceans have developed a unique sleep system where one side of their brain sleeps at a time while the other side remains awake, but in a lower-energy state that allows them to monitor for potential danger (Lyamin et al. 2008).

While dolphins and the Dall's porpoise are known for riding the bow wave of boats and participating in other interactions with people, harbor porpoise are considered quite shy. Several studies have noted avoidance behavior in relation to survey vessels (Flaherty and Stark 1982, Barlow 1988, Polacheck and Thorpe 1990, Palka 1995), though some studies have noted a lack of reaction to some boats and even an apparent attraction at times (Evans et al. 1994, Raum-Suryan 1995).

2.1.7 Feeding

As with most other marine mammals, harbor porpoise feeding events are rarely observed directly. Most of what is known about harbor porpoise diets comes from studying the stomach contents of stranded or bycaught animals. Recent studies have used fatty acid (FA) analysis or stable isotope analysis to determine important information about the diet of harbor porpoise (Jansen et al. 2012). Each of these methods enables the investigation of dietary trends over different timelines, ranging from hours (stomach contents), to weeks or months (fatty acids), or even years (stable isotopes). Examination of stomach contents can identify taxa and estimate the size of recently ingested prey items by teasing out otoliths (fish ear bones), skeletal bones, and the beaks and eyes of squid and octopus (Pierce et al. 1991, Santos and Pierce 2003). Fatty acid analysis compares levels of different fatty acids that are passed from prey species and stored in the tissues of a predator (Budge et al. 2006). By knowing FA signatures of the important forage fish, it is possible to analyze blubber samples to determine the predominant prey of the harbor porpoise over the past few weeks or months. Analyzing stable isotopes can reveal the trophic level of an animal based on the concentration of the stable isotopes of carbon and nitrogen (Jansen et al. 2012). Body tissues have differing rates of turnover providing the opportunity to analyze diet over different time scales. The liver turns over very quickly with isotopes representing evidence of recent diet, while bones and other hard tissue turn over very slowly providing a longer term nutritional record (Phillips and Eldridge 2006).

Harbor porpoise are a high trophic level predator, with an estimated average tropic level of 4.1 based on stomach samples collected from bycaught animals (Pauly et al. 1998). In the North Sea and Dutch coastal waters, stable carbon and nitrogen isotopes ($\delta^{13}C$ and $\delta^{15}N$) from the muscle and bone of stranded harbor porpoise have been used to assess differences in tropic level between animals of different ages, genders, and feeding areas (Jansen et al. 2012). The ^{15}N becomes enriched with each additional trophic level so animals with higher $\delta^{15}N$ are consuming higher trophic level prey. Neonates were found to be eating at the highest level, because they are feeding exclusively on their mother's milk, which is one level higher than the mother is eating. Adult females ate at a slightly higher trophic level than males, and smaller adults ate at a higher level than larger adults. It was also found that animals in shallower coastal waters ate at a higher trophic level than those living in deeper water.

Unlike some of the larger whales with thick blubber, that can have annual prolonged fasts during their migrations, the harbor porpoise's small body size and thinner blubber layer requires them to eat regularly, with starvation a constant threat when food is scarce (Koopman et al. 2002). Harbor porpoise are opportunistic feeders, eating a variety of small fish and cephalopods (squid and octopus) (Gaskin et al. 1974, Pauly et al. 1998). Additionally, the neonates and juveniles are known to eat euphasiids (krill). Krill shells have been found in the stomachs of adults, but it is unclear whether the adults consumed the krill directly, or if the krill had been consumed by prey eaten by the porpoise. Harbor porpoise are generalists when it comes to their food, able to eat a wide variety of species, though it is unknown whether their diet is completely opportunistic or if they selectively eat high quality prey when it is available (Santos and Pierce 2003). Studies in the Gulf of Maine show seasonal difference in the harbor porpoise diet and suggest some selectivity of prey. Porpoise fed primarily on Atlantic herring in the summer months, while in the autumn, the diet was more varied. Herring still made up a majority of calories consumed, but porpoises also consumed pearlsides and red and white hake. Lactating females consumed more hake and less herring when compared to the diet of non-lactating females. (Gannon et al. 1998).

The literature on the diets of harbor porpoise in the Eastern Pacific Ocean is fairly limited, and only a few published studies have covered the inland waters of British Columbia and Washington State. A study examining the stomach contents of 26 stranded harbor porpoise collected along the eastern side of Vancouver Island, British Columbia and the San Juan Islands in Washington State found prey numbers were divided almost equally between fishes (52.2%) and cephalopods (46.5%). Findings indicated the fishes included species from ten families and cephalopod species from three families. Juvenile blackbelly eelpout (*Lycodopsis pacifica*) represented the greatest number of prey (49.6%), though this result is likely biased by 61.5% of the harbor porpoise in this study having been collected in the spring, which coincides with the seasonal availability of the juvenile eelpout. (Walker et al. 1998). A more recent study analyzed 36 stranded harbor porpoise from the Salish Sea (the Strait of Juan DeFuca, Puget Sound and the Strait of Georgia), and found evidence of 7 families of fishes along with cephalopods and polychaetes (which were not identified to taxa) in the stomach contents (Nichol et al. 2013). Both studies found Pacific herring (*Clupea pallasi*) to be an important food source, along with a mix of benthic and midwater species.

2.1.8 Sound production, hearing, communication and echolocation

Unlike the terrestrial environment, much of the marine environment is light limited, so animals often adapt to rely more on senses other than sight to monitor their environment. For marine mammals, sound and vibration play an important role in foraging, predator avoidance, mapping their environment and communicating (Frankel 2009).

As odontocetes, harbor porpoise produce sounds by moving air through a structure known as the phonic lips, located in the nasal passage near the blowhole. Dorsal bursae are lipid filled structures attached to the phonic lips that act as a resonator, amplifying the sounds. The dorsal bursae lay at the back of the melon, a special structure unique to odontocetes, which sits on top of the skull and forms the distinctive forehead of toothed whales. The melon contains special fats that act as acoustic lenses, focusing most of the sound energy in a cone directly in front of the animal (Au et al. 1999)(Figure 2-3).

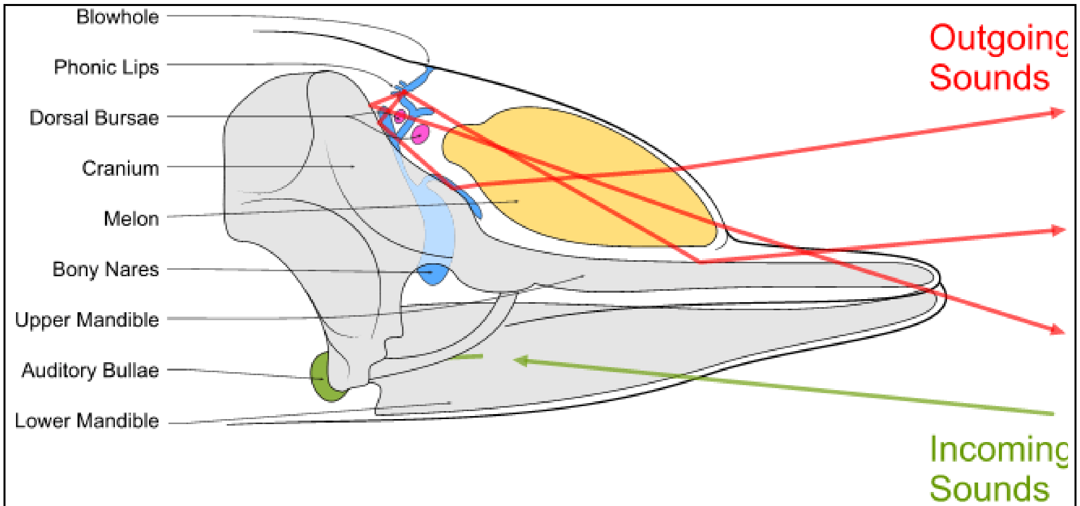

Figure 2-3: Odontocete head, showing sound path from phonic lips, reflecting off bone and being focused in the melon. Incoming sounds, including echolocation returns, are received through channels of fatty tissue in the lower mandible, and transmitted to the auditory bullae. (Copyright Wikipedia user Emoscopes (CC BY-SA 2.5) http://commons.wikimedia.org/wiki/File:Toothed_whale_sound_production.png)

Over 50% of the energy produced in a harbor porpoise echolocation click is directed within a 16° cone directly in front of, and slightly above the centerline of the head (Au et al. 1999, 2006, Kastelein et al. 2005, Madsen et al. 2010). Porpoise produce high frequency sounds in the form of clicks in the frequency range of 100-160 kHz (Madsen et al. 2010) at sound pressure levels (SPL) that can exceed 205 dB re 1 μPa pp[1] as was measured in foraging wild porpoise (Villadsgaard et al. 2007). It is believed that porpoise evolved to use such high frequency sonar to avoid detection by killer whales (*Orcinus orca*) who only hear up to 100 kHz (Andersen and Amundin 1976). While high frequency clicks provide protection from predation, they do not travel as far as lower frequency sounds thus limiting the range of echolocation and communication.

Odontocete hearing follows a different sound pathway than that found in terrestrial mammals. Instead of having an outer ear that channels sound through the ear canal, porpoise and other odontocetes receive sound using their lower jaw. Thin C-shaped mandibles hold a special acoustical fat, which receives sounds and directs them to the inner ear (Nummela et al. 2007). Harbor porpoise are thought to have a hearing range from 250 Hz through 180 kHz with maximum sensitivity in their echolocation click range of 100-140 kHz (Kastelein et al. 2002).

Harbor porpoise primarily produce high frequency clicks and are unable to make the wide range of lower frequency vocalizations that dolphins are known to produce (Frankel 2009). Research on harbor

[1] Standard shorthand for acousticians used to determine exactly how the dB level was calculated. "pp" means "Peak to Peak", which measures maximum energy, "RMS" is the other common reporting unit, which means "Root Mean Squared" and is more concerned with the average energy. "re 1 μPa" is "reference of 1 micro-Pascal", the standard in water, where dB in air are measured "re 20 μPa".

porpoise communication is limited, but preliminary investigations suggest that porpoise communicate using variations in the inter-click interval and frequency of their click trains. A study of four captive harbor porpoise, including a cow and her calf, demonstrated that certain click patterns were not used for echolocation, but represented communication between individuals. The high frequency of harbor porpoise clicks limits their effective communication range to around 1000 m (Clausen et al. 2012).

Harbor porpoise use echolocation while foraging to find and track their prey, to navigate and orient themselves spatially within their environment (Verfusß et al. 2005, Au 2009). To echolocate, animals first produce sound waves, which are transmitted into the environment. The waves then encounter objects (such as the sea floor, prey or other porpoise) and bounce back, forming an echo which returns to the animal. The strength of the echo depends on the difference in density between the object and the water, with a greater difference leading to a stronger echo. The timing of the echo lets the porpoise know the distance to the target, while the amplitude, frequency and the shape of the returning sound envelope reveal information about the prey species and its angle relative to the porpoise (Au et al. 2009). As animals close in on their targets, the return time of the echoes decrease, allowing a decreasing inter-click interval (ICI), eventually becoming what is referred to as a "buzz" with over 300 clicks per second (Deruiter et al. 2009, Nuuttila et al. 2013).

The anatomy of the prey species will influence the strength and envelope shape of the echo that is produced. Ray-finned fishes that have swim bladders produce a stronger acoustic signature than other fish, due to the large difference in density between the gas in the swim bladder and the flesh of the fish (Foote 1980). While squid lack a swim bladder or skeleton to produce a strong echo, experiments have shown that their bodies do produce a sufficient echo which can be detected by odontocete clicks (Madsen et al. 2007).

The development of echolocation has enabled odontocetes, such as the harbor porpoise, to thrive in their marine environment. By depending on sound rather than vision, they are able to efficiently locate prey, navigate in complete darkness, and avoid predators (Au 2009).

2.2 Threats

Harbor porpoise face a variety of threats throughout their range. Marine mammal eating killer whales have accounted for most known predation events on harbor porpoise, though other species have also caused documented porpoise mortality. Anthropogenic factors, such as fisheries bycatch, can have a direct impact on harbor porpoise populations. Other factors, such as pollution or vessel noise, can cause indirect impacts such as susceptibility to disease or reduced fertility.

2.2.1 Natural predators

Due to their small size and large numbers, harbor porpoise are an important prey item for larger predators. The greatest natural predatory threat to harbor porpoise are the mammal eating ecotypes of the killer whale, such as the Bigg's or transient killer whales (*Orcinus orca*) of the eastern North Pacific Ocean (Jefferson et al. 1991, Baird and Dill 1996). Large lamnid sharks, such as the great white (*Carcharodon carcharias*) and Greenland sharks (*Somniosus microcephalus*), are also major predators of harbor porpoise (Long and Jones 1996, Heithaus 2001). Recent accounts from Belgium and France have documented gray seals (*Halichoerus grypus*) killing and feeding on harbor porpoise, possibly due to declines in the lesser sandeel, which are a major source of high-energy forage for the seals (Haelters et al. 2012, Bouveroux et al. 2014).

Some fatal interactions with other species are not easily explained by the predator-prey dynamic. Bottlenose dolphins (*Tursiops truncatus*) have been known to attack and kill harbor porpoise in the United Kingdom (Ross and Wilson 1996) and Central California

(Cotter et al. 2012). It is assumed that dolphins consider porpoise to be competitors for a limited food supply, though an alternative hypothesis is that bottlenose populations with a tendency towards infanticide confuse harbor porpoise with juvenile dolphins (Patterson et al. 1998). Similarly, fish eating southern resident killer whales have been known to occasionally chase harbor porpoise with at least one case that led to the death of the porpoise. The killer whales left the body without consuming it, allowing its recovery by researchers (R. W. Baird, personal communication, May 7, 2014).

2.2.2 Fisheries interactions

Human fisheries are thought to be the greatest anthropogenic threat to harbor porpoise populations worldwide due to entanglement with fishing gear (bycatch). In the Eastern North Pacific Ocean, documentation of harbor porpoise caught in fisheries include takes in halibut setnets in California, salmon gillnets in the Pacific Northwest and a variety of fisheries in Alaska (Jefferson and Curry 1994). Tribal and commercial salmon fisheries are the most common net fisheries in the Puget Sound. No published information on bycatch of harbor porpoise is available due to the recent return of this species to this area. A study of bycatch in salmon fisheries in nearby southern British Columbia indicated an average annual mortality of 80 harbor porpoise from this fishery alone (Hall et al. 2002). Gillnets represent the greatest threat to harbor porpoise throughout their range and are indicated in their decline in many areas (Jefferson and Curry 1994, Stenson 2002).

It was originally thought that porpoise could not acoustically detect gillnets and that most porpoise swimming in close proximity to the nets were in danger of entanglement. Recent studies have shown that porpoise are able to detect the presence and location of nets from greater than ten meters, with the harbor porpoise successfully avoiding contact with the net (Nielsen et al. 2012). The results suggest that bycatch is a problem of attention shifts on the part of the harbor porpoise or acoustic masking of the echolocation returns from the gillnets. New materials and designs are being studied to increase the acoustic signature of gillnets so that marine mammals will find it easier to avoid entanglement. Gillnets made out of denser and stiffer material are being tested to reduce entanglement risk for non-target animals that make contact with the net (Larsen et al. 2002, Mooney et al. 2004, 2007). Research has been conducted into the use of acoustic deterrents, commonly called "pingers", to alert harbor porpoise to the presence of the nets, or to alternatively scare them away (Culik et al. 2001, Johnston 2002, Carlström et al. 2009). While they show some initial success in reducing porpoise bycatch, habituation appears to be a problem requiring cycling of the sounds (Cox et al. 2001).

Lost or abandoned fishing gear, including gillnets, have been shown to continually kill wildlife for years or decades (Good et al. 2009, Gilardi et al. 2010). As with many other fishery areas around the world, the Puget Sound is subject to this issue of "ghost nets". Cooperation from numerous government organizations have resulted in the removal of over 1,200 nets from the Puget Sound and Northwest Straits (Good et al. 2009). According to the Northwest Straits Initiative, between 2002 and 2013, 4,605 derelict fishing nets have been removed from Puget Sound, with the entangled remains of at least 270 species including 5 harbor porpoise (Northwest Straits Initiative 2013).

Fisheries can also impact the availability of food through competition for some of the common forage fish including herring, sardines and anchovies. In the North Pacific, few of these fisheries have been brought close to the point of collapse, so this is not likely to be a factor affecting local porpoise populations (Trites et al. 1997).

2.2.3 Noise pollution

There are many anthropogenic sources of noise pollution in the marine environment that have been shown to affect harbor porpoise.

Extremely high energy sound sources, such as airguns that are used for seismic explorations, can cause avoidance behavior in harbor porpoise at distances >70 km from the source (Bain and Williams 2006) and pile driving can cause reactions >20 km from the source (Tougaard et al. 2009). Lower energy sources, such as acoustic harassment devices (AHD) intended to keep seals away from salmon farms, also exclude harbor porpoise from the vicinity. A study in the Bay of Fundy found that porpoise maintained a distance of at least 645 m from the AHD equipped salmon pens (Johnston 2002). Noise from vessel traffic has also been shown to cause harbor porpoise to leave the area, though their behavior can vary with the vessel type and the habituation of the local population (Evans et al. 1994).

The construction and operation of offshore tidal and wind energy installations are of concern in areas of high harbor porpoise density. Currently, offshore wind farms need to be located in shallow coastal waters in order to secure the tower structures by sinking support pilings into the seabed. Tidal energy projects will also be located in shallow coastal waters, in locations with high rates of tidal flow such as bays and inlets. The areas for both of these types of energy projects coincide with the preferred habitat of harbor porpoise.

There are concerns about the impact of loud, repetitive, long term sound impacts on marine mammals during both the construction and operational phases of these projects. Pile-driving during construction produces high energy broadband sounds that are loud enough to cause porpoise to leave the area, with behavioral responses detected at distances greater than 20 km from the source (Tougaard et al. 2009). During the energy-producing operational phase, repetitive lower frequency sounds can influence behavior. A study of acoustic masking using simulated low-frequency wind turbine sounds on captive harbor porpoise suggests that a localized effect on echolocation ability does occur (Lucke et al. 2007). Additional research is necessary to determine the impact of energy infrastructure projects upon wild porpoise populations.

There are no current plans for marine based energy production in the South Puget Sound. There is a pilot tidal flow generation project that will be installed in Admiralty Inlet in the North Puget Sound (Snohomish County PUD 2014). This equipment has been designed to be installed without pile driving or any other percussive sound and is intended to assess the viability of tidal driven electrical generation from an environmental and technological standpoint.

2.2.4 Hunting

Hunting of harbor porpoise has historically occurred in many areas throughout their range, including the Puget Sound. Most porpoise fisheries are now closed, with the notable exception of Greenland, where Inuit porpoise hunting continues, with current catches in excess of 1000 animals per year (Hammond et al. 2008b). Hunting of harbor porpoise is thought to have contributed to the population decline in the Black Sea. Though it was outlawed in 1983, illegal hunting in the Black Sea continued through 1991 (Birkun Jr. and Frantzis 2008). Historically, some Washington tribes hunted harbor porpoise for food. Fisherman and hunters have been known to shoot porpoise for sport or because they were seen as pests in fish nets and traps (Scheffer and Slipp 1948). Harbor porpoise are now protected by the MMPA, which has made hunting of harbor porpoise in the United States illegal.

2.2.5 Pollution

Marine mammals are exposed to many anthropogenic sourced organic and inorganic pollutants, with coastal species, such as the harbor porpoise, having even higher exposure rates. Many of these pollutants are lipophilic, bioaccumulating in the fat through each trophic level. Harbor porpoise and other cetaceans are predators near the top of the food chain and have extensive fat stores in the form of blubber, where high concentrations of many pollutants have been detected (Bossart 2011).

Heavy metal pollution is often highest in coastal areas with runoff from regions that conduct industrial or mining activities (Ruilian et al. 2008). Cetaceans seem to be able to manage exposure to many of these metal pollutants, such as copper (Cu) and zinc (Zn) without apparent problem. All age classes of stranded animals had similar concentrations of these metals, suggesting that they are able to clear excess quantities from their systems. Porpoise tend to accumulate mercury (Hg) in their livers over time, often reaching much higher Hg levels than commonly found in terrestrial mammals at a similar trophic level (Law et al. 1991). A study of stranded harbor porpoise in Britain and Wales examined the livers of stranded animals. The livers of animals that died from infectious agents had higher levels of Hg than those killed by physical trauma, suggesting that the Hg may have weakened the immune systems (Bennett et al. 2001).

Organochlorides are a class of chemical compounds that includes some pesticides such as dichlorodiphenyltrichloroethane (DDT) and the electrical insulator polychlorinated biphenyl (PCB), which are known to cause reproductive issues in a variety of species. Production and use of DDT and PCB have been banned since the 1970s and 1980s in most industrialized countries. These persistent chemicals have remained in the environment and continue to be detected, though at reduced levels. PCBs in particular have been implicated in affecting both harbor porpoise immunity and reproductive success (Calambokidis et al. 1985, Berggrena et al. 1999, Hall et al. 2006). Polybrominated diphenyl ethers (PBDE) are a group of organobromide compounds that have been used since the 1970s as a fire retardant in a wide variety of materials including building materials and household goods. Several populations of harbor porpoise have been found to have high levels of PBDE in their blubber. This chemical compound has a similar structure to PCB, and is thought to have comparable impacts on reproduction, the immune system and the endocrine system (Ikonomou et al. 2002, Law et al. 2002, Weijs et al. 2009)

Polycyclic aromatic hydrocarbons (PAH) are released into the environment through petroleum spills or seeps, as well as the burning of wood, coal and petroleum products. High levels of PAH have been associated with a variety of toxic responses in aquatic wildlife, including harbor porpoise. PAH is known to damage the immune system and have possible carcinogenic effects (Law and Whinnett 1992, Fair et al. 2010).

Many of these pollutants have been detected in marine life within the Puget Sound, including the heavy metals lead and mercury; PCB; DDT and its metabolite DDE; and PAH (West 1997). It has been suggested that high pollution levels, specifically PCBs, might have caused lower reproduction rates in harbor porpoise in the South Puget

Sound, contributing to their extirpation (Calambokidis et al. 1985). Studies of harbor seals (*Phoca vitulina*), which are at a similar trophic level to harbor porpoise, revealed much higher concentrations of PCBs in the blubber of seals within the South Puget Sound as compared to animals in the North Puget Sound or nearby Hood Canal (Calambokidis et al. 1984).

2.2.6 Climate change

Climate change is expected to have a major impact on many marine mammal species, including the harbor porpoise, though the extent of the impact remains unknown. Several papers address the potential issues, but only a few studies have been conducted to date. Increased water temperature is a predicted impact of climate change and is likely to affect harbor porpoise prey distribution (Learmonth et al. 2006). The west coast of Greenland is now experiencing longer ice-free periods. A recent study examined the improvement of harbor porpoise body condition as they are able to remain in prime foraging areas for a longer period of time (Heide-Jørgensen et al. 2011). Climate change has also been cited as a probable cause of increased starvation among harbor porpoise in Scottish waters. It has been suggested that climate change has reduced sandeel populations, which are a major component of the harbor porpoise diet (MacLeod et al. 2007b). Some controversy exists in regards to the small sample size used in this study and a potential bias in the data, however it is one of the few studies on this topic and suggests areas for future research (MacLeod et al. 2007a, Thompson et al. 2007).

Ocean acidification is another aspect of climate change that could affect harbor porpoise. It has been suggested that squid, a common prey item for many harbor porpoise populations, will be especially vulnerable to acidification, because lower blood pH levels will reduce the ability to transport oxygen to their tissues. Acidification will also impact the carbonate shells of some species of phytoplankton, which can have effects up through the food chain (Simmonds and Isaac 2007).

There has been a great deal of study regarding the impacts of climate change on the lower trophic levels of marine ecosystems. However, little research has been conducted on the potential impacts on marine mammals.

2.2.7 Threats conclusion

Numerous natural and anthropogenic threats have been implicated in the decline of harbor porpoise populations in various parts of the world. While a few populations have been increasing in recent years, such as those in the inland waters of Washington State, many populations are in decline and the status of others remains unknown. Monitoring of populations, through abundance estimates, fisheries observer programs and necropsies on stranded animals, provide important information on the impacts of these threats to local populations.

2.3 Visual monitoring

Visual monitoring of harbor porpoise can be conducted using a variety of methods and platforms. This technique is essential to the estimation of population abundance, as acoustic methods have not advanced to the point where they can match the precision of a visual survey. Boat or ship based surveys can be used to estimate distribution and abundance through either line transect methods or using photo-ID for mark-recapture studies. Aerial surveys are conducted using line transect methods to estimate abundance and determine distribution. Shore based survey methods use point transect methods to estimate abundance, though they are more commonly used to conduct focal follows, which track a group of animals to study their behavior over time and to monitor animal presence. Visual methods excel at determining group size, detecting the presence of calves, and can cover a far greater area than can be achieved with acoustic methods (Evans and Chappell 1994).

While visual methods have a long history and remain the best method for many aspects of research, they are fraught with many difficulties when studying cetaceans due to the large percentage of time that the animals spend beneath the surface. These complications are more pronounced when studying a small, shy animal such as the harbor porpoise with their dark coloration and quick surface action. During their normal foraging behavior, a harbor porpoise surface series consists of a few surface breaths when their rolling back is only visible for about two seconds each time, followed by a foraging dive that can last for several minutes (Scheffer and Slipp 1948). Even during ideal conditions, visual methods compare poorly to acoustic methods for detecting animal presence, detecting animals before they are detected acoustically about 15% of the time, and they completely miss animals that are detected by acoustics about half the time (Evans and Chappell 1994). Sightings from vessels, shore or aerial surveys are also limited to daytime hours and times with low winds and clear weather conditions, which limits their usefulness during large portions of the year and (Evans and Chappell 1994, Palka 1996).

Untrained observers can confuse harbor porpoise and Dall's porpoise, which is the only other common black small cetacean in the Puget Sound. The Dall's porpoise has a larger dorsal fin that is slightly falcate (sickle shaped) with a more vertical trailing edge that often has some white pigmentation, and they also have a bump on their back near their tail that leads to a different surface motion than that of the harbor porpoise (Figure 2-4). Dall's porpoise also have a distinct separation of the white and black coloration on their flank, instead of the gradation seen on the harbor porpoise (Gaskin et al. 1974, Jefferson 1988). Dall's are much more acrobatic, demonstrate different surfacing behavior and are more likely to be drawn towards human activity than harbor porpoise (Jefferson 2009). Though rare, several dolphin species have been sighted in the Puget Sound. Dolphins are easily differentiated from harbor porpoise by their larger falcate dorsal fins, different coloration and much showier surface behavior.

2.3.1 Vessel surveys

Ship and small boat line or strip transect surveys are often used to produce abundance estimates for a number of cetacean species, including harbor porpoise (Barlow 1988). During line transect surveys, a vessel travels along a predetermined route called a transect line. Observers count animals that are spotted along that line and within narrow strips off to each side. A probability function is then used to determine species density in the survey area (Buckland et al. 2001). Many surveys are conducted for multiple species and will continue even during higher sea states, as a result, sightings of small cetaceans can be missed during inclement weather (Barlow and Forney 2007). A

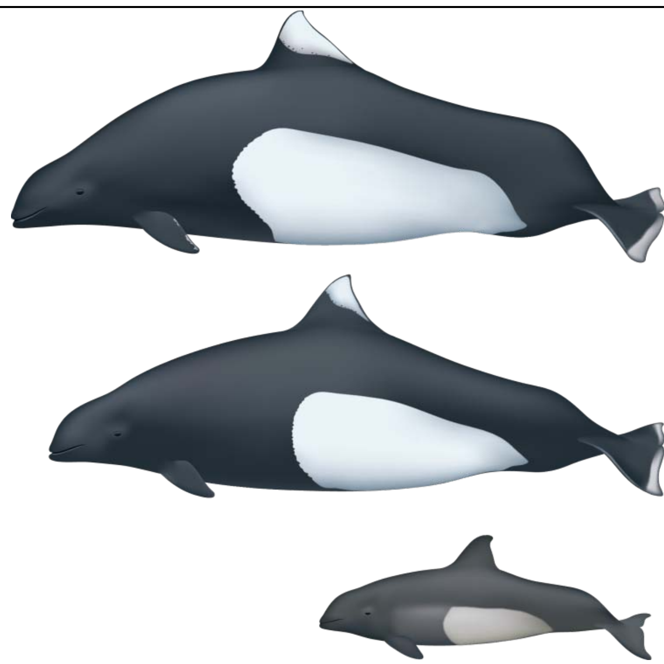

Figure 2-4: Dall's porpoise have distinctly different body shape and coloration, allowing for easy differentiation by observers. (Copyright Uko Gorter)

study of observation teams on a ship transect survey showed that researchers were found to miss porpoise on the track line approximately 22% of the time (Barlow 1988). The presence of the survey ship may cause harbor porpoise to leave the vicinity skewing the population density estimates by a factor of 1.4 to 2.7 (Palka and Hammond 2001). Even with these limitations, it is believed that a reasonable abundance estimate can be obtained through the use of vessel surveys.

Photo-identification (photo-ID) is another method used to produce abundance estimates and learn about the social structure of a population using a mark-recapture framework. Small boats are used to collect photographs of animals and record information about their location and behavior. The photo-ID process involves the comparison of these photographs to image catalogs of known individuals. Images of specific parts of animals that are likely to have distinctive markings, such as dorsal fins or flukes, are used for comparison. The first time an animal is sighted, it's considered a "mark" and the individual is entered into the catalog and assigned an identification number. If the individual has been previously sighted, it's considered a "recapture" and the sighting information is added to the animal's history enabling long term study of population abundance and social structure (Hammond et al. 1990). Due to the difficulty in consistently obtaining high quality, high definition photographs of harbor porpoise (Flaherty and Stark 1982, Gaskin and Watson 1985), few attempts have been made to produce photo-ID catalogs of the species.

2.3.2 Shore surveys

2.3.2.1 Theodolite tracking

Theodolites are surveying instruments that have been repurposed for ecological studies. Researchers often use theodolites as a non-invasive method for tracking marine mammals, boat traffic and other anthropogenic activity (Würsig et al. 1991, Emery et al. 1993, Harzen 2002). They are used to obtain accurate position data, or “fixes”, on animals and other objects moving through a study area. An observer looks through a telescope, usually 30X power, and places the target animal in the crosshairs of the scope. High-precision measurements of the horizontal and vertical angles are recorded either on paper or through a connection directly to a computer.

Given the latitude, longitude and elevation of the theodolite, the horizontal and vertical angles can then be used to calculate the position of the target animal to within a few meters by using basic trigonometry (Gailey and Ortega-Ortiz 2002) (Frankel et al. 2009). Theodolites have a range of several kilometers depending on weather conditions and target size. In favorable weather conditions, it is possible to track larger marine mammals, such as baleen whales, out to distances of 10 km (Würsig et al. 1985). For smaller animals, such as dolphins and porpoises, the useful range is reduced to about 5 km (Würsig et al. 1991). Refraction can skew the determination of the fix position near the horizon, however, this should not be an issue in the present study (Kinzey and Gerrodette 2003).

Electronic digital theodolites connect to a computer via a data cable so that angular measurements can be automatically entered into tracking software. This enables researchers to quickly record data points with no transcription errors. Software packages use input from a digital theodolite to record and calculate the fix position as well as information about species, group size, behavior, weather and other factors (Gailey and Ortega-Ortiz 2001).

2.4 Passive acoustic monitoring

Passive acoustic monitoring (PAM) involves using underwater equipment to detect sounds in the marine environment. In the biological sciences, it is primarily used by researchers to study the ecology of marine animals, though it also reveals information about anthropogenic activity. PAM devices can be deployed for long periods of time, enabling researchers to monitor animal sounds continuously throughout the day and in all weather conditions. These devices capture acoustic evidence of the presence and behavior of marine mammals, with minimal impact on animal behavior (Zimmer 2011). Certain animal behaviors that are difficult to detect using surface observation, such as communication or echolocation, can be monitored through the use of acoustic techniques (Villadsgaard et al. 2007).

While there are many advantages to the use of PAM, it also has its limitations. In order to be detected, animals must be producing sounds of sufficient strength to be discernible from the background noise. Depending on the frequency and directionality of the sound, the range of detection could be hundreds of kilometers in the case of blue whales (Širović et al. 2007), or just a few hundred meters for species such as porpoises which focus their high frequency sounds in a narrow beam (Kyhn et al. 2012). Using current technology, it is difficult to produce abundance estimates using PAM. Unless individual animals of a species make signature sounds, it is not possible to identify specific animals; therefore it is difficult to estimate group size or study population structures (Marques et al. 2013).

There are a variety of PAM devices ranging in size from large permanently deployed arrays down to small portable units that weight less than one kilogram and are easily carried to remote sites (Sousa-Lima et al. 2013). They can be simple hydrophones which allow realtime monitoring of sounds, acoustic recorders which store the data for later analysis, or they can be devices that conduct some onboard processing before the data is recorded. These versatile devices allow for a broad range of deployment options, including monitoring from shore (Thomas and Fisher 1986) or ship (Nielsen and Møhl 2006, Borchers and Burt 2007); mooring devices within the water column (Sousa-Lima et al. 2013); or attaching equipment to autonomous robot gliders (Wiggins et al. 2010, Klinck et al. 2012) or including small devices in animal tags (Sousa-Lima et al. 2013).

2.4.1 Hydrophone

Hydrophones are sealed underwater microphones and are the most basic form of acoustic monitoring device (Gordon and Tyack 2002). All acoustic monitoring devices include some kind of hydrophone to capture sound from the marine environment. The output from the hydrophone can be used for real time monitoring, recorded for later analysis or used as a source of input for more advanced PAM devices.

Shore based stations can be connected to fixed hydrophones through cable or radio links providing real time monitoring of the audio stream (Thomas and Fisher 1986, Marques et al. 2013). These sites are often permanent installations that utilize undersea cables to power the equipment and provide a data link back to shore. By using multiple hydrophones deployed in an array, many sites are able to track individual animals as they move thorough the study area (Marques et al. 2013). Shore based studies may also include the deployment of smaller temporary hydrophones which require less infrastructure or portable units used by researchers for short term sampling (Gordon and Tyack 2002).

Ships and small boats are versatile platforms for the use of hydrophones. Keel mounted hydrophones are permanently secured to the ship, which allows for acoustic sampling without having to deploy additional equipment and can be used even in rough sea states (Nielsen and Møhl 2006, Borchers and Burt 2007). Hydrophones towed behind ships, often in arrays, position the equipment away from the noise of the ship. This enables research teams to monitor for acoustic evidence of marine mammals while running transect lines (Thomas and Fisher 1986, Borchers and Burt 2007, Sveegaard et al. 2011a, Marques et al. 2013). Small dipping hydrophones can be deployed from vessels of any size to quickly sample for the presence of animals (Thomas and Fisher 1986, Gordon and Tyack 2002). Ship based transect surveys are key tools in determining areas of high porpoise density, however, the presence of a vessel may cause changes to porpoise behavior which could influence the results (Sveegaard et al. 2011a).

Unlike ship and shore based systems, autonomous hydrophones are self-contained and are deployed for extended periods, recording their data for later analysis. Other than during times of deployment, these devices substantially reduce concerns regarding the impact of the research vessel on animal behavior. Autonomous hydrophones are ideal for deployment where there is limited ability to service the devices, such as in remote locations or for projects that have limited funding for ship time and equipment. Some devices are designed to be deployed at the surface, in the form of freely floating buoys, and others can be moored throughout the water column using a variety of ground tackle options (Sousa-Lima et al. 2013).

The extended deployment times of autonomous hydrophones lead to large demands on data storage. In an attempt to conserve storage capacity, researchers adopted the idea of duty-cycling in which the device records only a few minutes out of each hour (Sousa-Lima et al. 2013). Early versions of autonomous hydrophones were often assembled by the researchers themselves and consisted of tape recorders triggered by mechanical timers that activated the device according to the duty-cycle (Thomas and Fisher 1986). Innovations in batteries, digital recording methods and storage have greatly increased the possible deployment periods, though duty-cycling is still commonly used as a method to increase deployment time (Sousa-Lima et al. 2013).

Other autonomous devices can include hydrophones in their design to record acoustic activity. Short-term recording tags can be attached to marine mammals to track their movement and dive patterns for periods ranging for a few hours to a few days (Sousa-Lima et al. 2013). Tags such as the D-tag and Acousonde include a tiny hydrophone to provide researchers with audio that accompanies the movement data. In additional to vocalizations, it has been found that the movements of the fluke while swimming can be identified (Sousa-Lima et al. 2013).

Seagliders and Wave Gliders are small, low power, autonomous robot vehicles that can be equipped with recording hydrophones. These vehicles are often deployed for several months on low-cost, low impact transect surveys. Unlike other autonomous devices, gliders are able to transmit data through satellite links back to the researchers in near real time. These mobile platforms allow for economical monitoring of remote sites without the expenses related to using a ship while reducing disturbance to the study population (Wiggins et al. 2010, Klinck et al. 2012, Marques et al. 2013).

An issue common to all these platforms is that the high frequency sounds produced by harbor porpoise requires sampling at greater than 400 kHz, which will generate more than 30 TB of acoustic data per year (Tregenza 2013). Due to these high volumes of data, recording hydrophones are better suited to short-term experiments rather than long-term monitoring of harbor porpoise. They are most commonly used to study aspects of sound production, such as SPL, ICI, and directionality of their sonar (Au et al. 1999, Kastelein et al. 2005). Ultrasonic click detectors, such as the C-POD, provide a solution to data storage issues during long-term deployments.

2.4.2 The POD, T-POD and C-POD ultrasonic sound detectors

The desire to economically monitor for the presence of dolphins and porpoises on long-term deployments, led to the development of ultrasonic click detectors. The audio input from the hydrophone is pre-processed before storage; only metadata about certain tonal sounds is recorded. Since the entire waveform is not recorded, this method allows for much longer deployment times with moderate levels of onboard storage.

The first iteration of the POD (POrpoise Detector) was developed in the in the late 1990s and was simply a data logger that recorded the number of clicks detected each minute (Tregenza 1998, Baines et al. 1999). The POD worked by comparing sound levels in the band used by porpoise (120-150 kHz) to sound levels in three other bands below 100 kHz. By comparing these bands, it was possible to determine whether it was a broadband sound or one that was likely to have been produced by a porpoise. Porpoise clicks were only counted when the energy in the upper band was greater than in the lower bands, thus limiting false positives (false detections) (Chelonia Ltd. 2013a). This design was based on previous work that used automatic click detectors attached to a towed hydrophone array (Chappell et al. 1996). Only aggregate counts of clicks detected per second were recorded by this early device, no data about individual clicks or click trains were recorded. In addition to porpoise data, noise level, water temperature and dolphin click counts, were also logged. The peak energy within the lower "dolphin" band was used to discriminate between dolphin and porpoise clicks, which allowed the device to be used for dolphin research as well. This first generation POD provided aggregate counts of detected clicks, however, without additional information on individual clicks and click trains the ability to further filter data to reduce false detections was limited (Chelonia Ltd. 2013a).

The T-POD (Timing POrpoise Detector, Chelonia Ltd., U.K.) was the next generation porpoise detector, which changed from recording the clicks detected per second to recording the time and duration of each click within the filter range. Clicks were still identified by comparing the energy level within the click band to the energy level in the lower-bands, and only recording metadata about the target sounds. Each stored click received a timestamp which allowed post-processing software on a computer to be used to identify characteristic click trains. Clicks that did not match the duration of an echolocation click or spurious clicks that were not part of a train were discarded. The T-POD advanced through five versions before the design was retired in 2008 due to difficulty and expense of obtaining some of the older electronics as the design neared a decade in service (Chelonia Ltd. 2013a, Dähne et al. 2013).

The most recent design is the C-POD (Cetacean POD, Chelonia Ltd., U.K.), which was used in the current study. Unlike the earlier PODs, which performed much of the detection through the use of analog filters, the C-POD detection logic is an all-digital design. While the digital design allows for more complex analysis of the detected sounds, it retains the core concept of using filters to detect tones in the NBHF range that are at a higher energy level than tones in the lower bands and background noise. The C-POD differs by its ability to digitally separate the different tone frequencies, rather than being limited to the predefined frequency bands in the analog filters. In addition to the timestamp and duration of the clicks recorded by the

T-POD, the digital design enabled the C-POD to record much more information about each click, including the dominant frequency, the bandwidth of the sound, how the sound changes over time and limited information about the sound envelope. This additional metadata improves the ability of the post-processing software to identify the sound source (Chelonia Ltd. 2013a). The broad ultrasonic bandwidth of the C-POD, from 20 kHz through 160 kHz is able to detect echolocation clicks produced by all odontocetes other than sperm whales, which have peak echolocation frequencies of 400 Hz to 2 kHz in the males, and 1.2 kHz to 3 kHz in the females, which is below the 20kHz minimum frequency of the C-POD (Goold et al. 2000).

Each generation of POD has improved significantly upon the previous generation in the ability to detect and filter data. The current C-POD has been used successfully in many studies because of its ability to record data through long-term deployments in a wide variety of conditions. The limitations of recording only metadata restricts C-POD usefulness in animal behavior studies intended to identify specific animals in a group, such as work with dolphin signature whistles, or for other in-depth acoustic analysis. Recording hydrophones are still the preferred method for gathering data for these applications.

2.4.2.1 Calibration

POD devices can vary in sensitivity, therefore when multiple click detectors are used, it is important to calibrate the devices so that data can be compared accurately. The differences can be attributed to variability of piezoelectric transducers used to pick up the sound, the plastics used in the end caps and final assembly. When different version of detectors are used in the same study, these differences in sensitivity are even greater as many parts are replaced and upgraded with each revision (Simon et al. 2010, Chelonia Ltd. 2013a).

Techniques that are commonly used to calibrate click detectors include tank tests and field calibration. Tank tests are conducted by placing the POD in small tanks containing sound sources and several hydrophones to monitor actual sound levels (Kyhn et al. 2008). The tanks are designed to reduce the impact of echoes on the device being tested (Dähne et al. 2013). Field calibration tests are conducted by deploying several devices in close proximity to each other so they are in the same sound environment. The SPL received by the different devices are then compared to determine their relative sensitivity (Kyhn et al. 2008).

As part of their quality assurance procedures, the manufacturer tank tests every C-POD, rotating the device through 360 degrees, and recording the SPL received. The minimum threshold for recording the click is set to a median value, where 50% of the positions during the rotation could detect the test tone. A calibration file is created for each C-POD and this data is used by the CPOD.exe software to account for differing levels of sensitivity (Chelonia Ltd. 2013b).

2.4.2.2 Range of detection

Determining the range of detection of an acoustic monitoring device is an important factor for many aspects of acoustic research such as attempts to use acoustic methods to estimate animal abundance. The high frequencies used by harbor porpoise are quickly attenuated in water, limiting their range of detection when compared to species that vocalize at lower frequencies. Clausen et al. (2012) modeled the maximum range of harbor porpoise communication based on known parameters of their sound production and hearing. Due to the highly directional nature of their click production and hearing, it was determined that their maximum communication range is 1200 m when facing each other though it drops to 200 m when facing in opposite directions. The reception distance is also affected by natural and anthropogenically produced ambient noise, bathymetry, temperature gradients and obstacles in the sound path. The sensitivity of the C-POD is much lower than the auditory system of the harbor porpoise, especially when the porpoise are on-axis to the sound source (Clausen et al. 2012, Dähne et al. 2013). Therefore, the range of detection of the C-POD will be considerably reduced as compared to the above estimates of harbor porpoise communication range.

There are a limited number of studies that have attempted to determine the range of detection of various POD devices. One study used nine T-PODs in an attempt to develop a method of estimating abundance and found considerable variation in the sensitivity between devices. It was found that harbor porpoise had to be within 22 to 104 m to ensure detection (Kyhn et al. 2012). It is thought that the maximum on-axis range for the C-POD is 300-400 m (Hardy et al. 2012).

Studies of this nature require visual observers to use a theodolite to map porpoise transits as they pass the POD. This requires a considerable amount of additional effort in the field and few study sites provide appropriate, accessible shore based locations necessary for this work.

2.4.2.3 Detection error rate

As with all studies, the error rate is of concern when using any sort of automated method to process data. The click train classifier used by the CPOD.EXE software is designed to be very conservative, producing few false-positive (false detection) results, which leads to having a high rate of false-negatives (missed detections). The rate of false detections is dependent on the background noise level at each individual site. Settings can be changed in the software to limit detections based on the quality of the click trains. Researchers can visually check several hundred click trains to determine the false detection rate caused by background noise and adjust the quality settings in the software (Tregenza 2013).

Missed detections are common when using the click train classifier, both for NBHF species and dolphins. Entire encounters can be missed due to a lack of any click trains meeting the conservative requirements of the classifier, especially at the higher quality settings, though it is unknown what percentage are actually missed. At present, the only way to reduce the number of missed detections beyond setting the output to accept all qualities of detections, is to visually review potential click trains, marking those that appear to be valid. An analysis of both false detections and missed detections were conducted in a study of dolphins at Camp Lejeune (Read et al. 2012), by deploying C-PODs along with DMON autonomous digital recorders (Woods Hole Oceanographic Institution, Woods Hole, MA, USA). The acoustic recordings were analyzed by a trained technician and the results were compared to the results produced by the C-POD and the CPOD.exe software. When used to detect dolphins, the C-POD was found to have a between 0.53% and 3.67% false detection rate, and a 50.49% to 82.74% rate of missed detections.

2.4.2.4 Abundance estimates

Due to the expense of conducting traditional aerial or ship based line transect surveys and mark-recapture studies, there is a great deal of interest in using acoustic methods to produce abundance estimates. This is a rapidly advancing field within cetacean ecology, but many difficulties remain (Marques et al. 2009, 2013). A study using T-PODs, spaced in an array, proved successful in making abundance estimates for the study area, with the caveats that the estimates required theodolite tracking from shore to develop the probability of detection function for each T-POD as the porpoise swam through the site, and to also determine the average group size (Kyhn et al. 2012). Kyhn et al. made it clear that their estimation was only valid within the detection area of the array of the T-PODs, and estimates were only considered accurate to an order of magnitude (i.e.$10^{(\log_{10} estimate \pm 0.5)}$). For example, a density estimate of 67 animals using acoustic data could represent between 21 and 212 individuals. While research will continue to advance the use of acoustic monitoring to estimate absolute abundance, the lack of precision limits its usefulness at this time.

A more established method of analysis involves the monitoring of changes of relative abundance over time in a population. This method is being used as part of Mexico's vaquita (*Phocoena sinus*) recovery plan. Approximately 50 C-PODs have been deployed within the Vaquita Refuge, an area of 1271 km^2 within their small home range at the northern end of the Sea of Cortez (Rojas-Bracho et al. 2010). Vaquita are a close relative of the harbor porpoise, and are considered the most endangered extant species of marine mammal with fewer than 200 individuals. Any decline in the population needs to be quickly detected and addressed. Though the Mexican government has implemented many measures to protect the vaquita, including buying back licenses from fishermen in the area, and banning gillnet fishing within the reserve, the acoustic data suggests that the population is continuing to decline.

An attempt to monitor the critically endangered Baltic Sea harbor porpoise population is using similar methods to those used in the vaquita protect. The SAMBAH (Static Acoustic Monitoring of the Baltic Sea Harbour porpoise, http://www.sambah.org/) project has deployed 300 C-PODs throughout the shallower areas of the Baltic Sea over a two year period, from May 2011 to May 2013, with reports due at the end of 2014. The goals of the study are to estimate porpoise population density, abundance and distribution throughout the Baltic Sea; determine habitat preferences; locate frequently used areas; and identify areas at high risk of adverse human-porpoise interactions.

2.5 Environmental analysis

Implementing conservation management strategies requires an understanding of how animals use their environment, and how environmental factors affect their behaviors. It is believed that most harbor porpoise movements are based on their constant search for food, therefore most studies examine factors that are known to influence harbor porpoise prey species. Seasonal migrations of prey such as herring or squid, or concentrations of other prey can lead to seasonal changes in distribution of harbor porpoise (Gaskin and Watson 1985, Gannon et al. 1998). While harbor porpoise don't feed directly on zooplankton, the diel vertical migration of zooplankton can affect the availability of prey species that feed on the zooplankton (Alldredge and King 1985, Ohman 1990). Similarly, tidal changes can cause fronts to develop downstream of obstructions, which will concentrate plankton and draw harbor porpoise prey species (Johnston et al. 2005). There are other environmental factors that could influence harbor porpoise behavior, yet many of these require measurements that are outside the realm of most porpoise research studies.

2.5.1 Seasonal patterns

Understanding seasonal patterns of harbor porpoise abundance and distribution is important, not only to inform biological research, but also from conservation and management perspectives. Harbor porpoise are a species of concern throughout much of their range, with many populations in decline. The listing of the harbor porpoise as a species of conservation importance under the EU Habitats Directive has led to numerous studies that considered seasonal density as an important factor when assessing sites for marine protected areas (Embling et al. 2010).

Knowledge of harbor porpoise seasonality helps to inform management decisions regarding the regulation of human activities, and to strike a balance that allows for the greatest level of protection with the least economic impact. Gilles et al. (2011) produced a predictive model of the German Bight as part of a program to assess proposed wind farm locations. It was noted that seasonal population shifts can occur and if decisions were based solely on summer surveys, other seasonal hotspots of high porpoise density would be missed. Higher seasonal abundance can also lead to either closures in certain fisheries, or the requirement that nets use acoustic pingers to alert porpoise to their presence (Trippel et al. 1999).

As a species, harbor porpoise are not known for conducting long seasonal migrations, though many populations do display seasonal movements and there are a few know instances of longer migrations to follow prey. These movement patterns can alter the distribution of the porpoise population, with animals favoring different locations throughout the course of a year. Seasonality of populations in northern waters is often related to sea ice. When sea ice melts in the spring, porpoise will move into formerly frozen areas in search of nutrient-rich food, such as herring in the Baltic Sea (Koschinski 2001) or cod off the west coast of Greenland (Heide-Jørgensen et al. 2011). When the ice returns during fall and winter months, porpoise leave the area for open waters.

When ice is not a driver of porpoise movement, it is assumed that seasonal changes are due primarily to food availability. Harbor porpoise along the northeast coast of the United States and Canada move into areas such as the Gulf of St. Lawrence and the Bay of Fundy during the summer months to feed on abundant supplies of herring (Palka et al. 1996, Gannon et al. 1998). During the fall and winter, the majority of these populations are believed to move onto the continental shelf in search of other prey, though some animals are occasionally sighted on their summer feeding grounds year-round (Gaskin and Watson 1985).

Populations such as those in the inland waters of Washington State are known to maintain a year-round presence throughout their range, with areas of higher density varying through the seasons (Flaherty and Stark 1982). Much of this variability can be explained by changes in food supply, such as herring or squid moving into a region to spawn, or juvenile eelpouts growing to a size where they become worthwhile prey for the porpoise to pursue (Flaherty and Stark 1982, Hall 2004, Nichol et al. 2013). Some changes in density can also be attributed to females showing a preference to calve in certain area (Lockyer and Kinze 1995, Gilles et al. 2011). It is unknown what the criteria are for the selection of calving grounds, though availability of abundant nutrient dense food is thought to play a role (Gilles et al. 2009).

2.5.2 Diel patterns

Patterns of diel behavior in harbor porpoise have been addressed by several studies that used visual and acoustic methods, as well as telemetry from tagged animals. Diel patterns have often been noted; however, there is little consistency to porpoise presence and behavior patterns between study locations.

PODs have been used in a number of studies that have noted diel patterns in harbor porpoise detections. North Sea gas platforms show more echolocation activity at night (Todd et al. 2009), as did aquaculture cage sites in the Bay of Fundy (Haarr et al. 2009). Two C-PODs were deployed in Minas Passage in the Bay of Fundy to determine if a tidal turbine was impacting the presence of porpoise. One C-POD was deployed at the turbine and the other in a control location away from the turbine. At both sites, the times of greatest porpoise presence were in the middle of the night and lowest at midday (Tollit et al. 2011). T-PODS were deployed at two sites in the Blasket Islands, Ireland as part of a project to assess locations for a marine protected area. Unlike most other studies, these results indicated that porpoise were more active at night at one site and more active during the day at the other (Berrow et al. 2009). At a proposed wind farm site in the Netherlands little variation was found for much of the year, though detections during the winter months were the lowest in the afternoon and the highest at night. (Brasseur et al. 2004).

Data retrieved from tags can also provide information on porpoise activity levels. A study using radio tracking tags in the Bay of Fundy found that porpoise activity was lowest between midnight and 0600 (Read and Gaskin 1985). This is an interesting contrast to the findings of both Haarr et al. (2009) and Tollit et al. (2011) which indicated a higher level of porpoise echolocation activity during the night in the Bay of Fundy. The work by Read and Gaskin (1985) used the best technology available at that the time. It will be interesting to see the results of studies that are currently underway which use more advanced tag and satellite technology.

Danish researches used towed hydrophone arrays to assess possible locations for a marine protected area in the Danish Straits and the Kattegat, between Denmark and Sweden. There was no significant difference between daytime and nighttime harbor porpoise echolocation activity. It was suggested that porpoise may have been reacting to the survey ship which could influence the results (Sveegaard et al. 2011a). This was the only study found that used towed hydrophone arrays and addressed diel activity.

Visual techniques are limited by their nature to daytime hours, yet some visual studies were still able to determine diel patterns of abundance. Harbor porpoise were observed most frequently in a near-shore feeding area in Monterey Bay, California, between 0700 and 1000 (Sekiguchi 1995). During strip transects of southwestern Ireland, active feeding on pelagic fish was observed in the morning and evening hours (Leopold et al. 1992). Line-transect boat surveys conducted off the Northern San Juan Islands, Washington, observed more porpoise in the mornings and evenings, with fewer sightings at midday (Raum-Suryan and Harvey 1998). A study in southwest Britain using focal-follows showed no significant difference in porpoise presence throughout the day, though one area showed a diel influence on group size and distance from shore (Goodwin 2008). Boat and shore based observations off Vancouver Island, British Columbia revealed no significant difference in diurnal activity (Hall 2011).

Many diel patterns of marine behavior are thought to be driven by the vertical migration of zooplankton. This migration is believed to be a predator avoidance mechanism which consists of an ascent of zooplankton into the photic zone in the evening, followed by a decent back to the aphotic zone in the morning (Lampert 1989, Ohman 1990). This diel migration draws planktivores, which in turn draw higher level predators, including harbor porpoise (Robertson and Howard 1978, Alldredge and King 1985). During the morning downward migration of zooplankton, benthic predators have been found to swim several meters up into the water column to feed (Genin et al. 1988). Harbor porpoise are likely to seek out areas where their benthic prey becomes easier to forage in the early morning hours.

2.5.3 Tidal patterns

Currents generated by the changing tides also cause fronts and eddies, which concentrate plankton and attract animals up through the food chain (Owen 1981). Fronts are a line of lateral convergent flow between two bodies of water and are generated by currents moving across underwater obstructions. Eddies are the rotational motions of water that occur as currents flow past underwater obstructions, or they can be caused by the Coriolis effect on waters moving in a horizontal system. Both fronts and eddies have vertical components that concentrate biology, making it a productive area for predators to forage.

A study of seasonal variability of harbor porpoise in the German Bight found that porpoise preferred areas with strong fronts produced by currents or upwelling (Gilles et al. 2011). A study off the northern end of Grand Manan Island in the Bay of Fundy found greater localized concentrations of harbor porpoise during the flood than ebb tides (Johnston et al. 2005). This study used satellite imagery to determine the length of the island's wake during incoming tides, and then used active acoustic sonar to map the distribution of prey species. Areas that developed fronts during flood tides were found to have the greatest concentration of prey species as well as a high density of harbor porpoise.

2.6 Vessel avoidance

Harbor porpoise are generally perceived to be relatively shy animals that avoid moving vessels. Their reactions to survey vessels have been shown to introduce a negative bias which needs to be accounted for when estimating abundance (Carretta et al. 2009). A variety of methods have been used to determine whether porpoise were reacting to survey vessels, including observations from the survey vessel itself (Raum-Suryan 1995), shore based survey observers (Flaherty and Stark 1982), and even the use of a helicopter to scout ahead and monitor the behavior of the porpoise as the survey vessel approached (Barlow 1995). In most cases, the harbor porpoise exhibited avoidance behavior (Flaherty and Stark 1982, Barlow 1988, Polacheck and Thorpe 1990, Palka 1995), but a survey using a slower boat (Raum-Suryan 1995) and one using a kayak (Gaskin and Watson 1985) noticed no avoidance behavior as they approached the porpoise.

When studies have observed porpoise behavior as they relate to a variety of vessels in an area, the results become much more interesting. A shore based observation site in the Shetland Islands was used to monitor harbor porpoise reactions to a variety of vessel types, revealing differing reactions to different types of vessels (Evans et al. 1994). Encounters with yachts caused porpoise to move towards the vessel 2/3 of the time, while encounters with speed boats always caused an avoidance reaction. Reactions to fishing vessels appeared to be a relatively even mix of all three conditions: no response, positive and negative reactions. A large ferry that rarely entered the study area caused avoidance behavior two out of four times, while the small ferry that made up to 8 crossings each day, had only 22% negative reactions, 46% no response, and 32% positive response. Such a low level of negative reactions to the ferry suggests that the porpoise may have habituated to the regular ferry traffic.

An extensive survey with shore based and boat based components was conducted in the San Juan Islands of Washington State in the early 1980s (Flaherty and Stark 1982). One aspect of the study examined the reaction of porpoise to vessels, including the survey boat. A negative correlation was found between the number of boats in the area and the number of porpoise observed, with no porpoise observed during times of heavy boat traffic. This study found that animals changed their behavior during 11 out of 13 encounters with boats. Unlike Evans et al. (1994), only once did porpoise approach a vessel, all other encounters involved some sort of avoidance behavior. The boat that was approached was a slowly drifting or trolling fishing boat which would have made minimal noise. The researchers concluded that porpoise behavior is affected by vessels, perhaps because of the heavy use of small boats and the noise produced by outboard engines.

Flaherty and Stark note that in addition to fleeing the area, porpoise may use diving as an avoidance behavior. Observations included incidents in which porpoise dove for up to 7 minutes before resurfacing. Porpoise sometimes resurfaced quite a distance from the initial point where the vessel passed, and at other times resurfaced very close to their original position. During times when the survey boat was floating quietly among a widely spread group of porpoise, some would occasionally surface within 10 m of the boat.

While it is clear that harbor porpoise often react to vessels in their vicinity, their reaction is not always to leave the area. Their response seems to be related to the boat noise, size, speed and behavior. Evans et al. (1994) noted possible porpoise habituation to ferry traffic, which is an important consideration in the Puget Sound due to the extensive ferry system in Washington State.

3 Methods

3.1 Study area

The primary study area is located at the north end of Cormorant Passage, in the South Puget Sound of Washington State (Figure 3-1). Separated from the main channel by Ketron Island, the bathymetry of Cormorant Passage offered near-shore deployment depths of 45 m, without the steep slope leading down into the deep basins that characterize this area of the Puget Sound. Visits to the area at the south end of Steilacoom, Washington revealed several potential observations locations, down near the waterline as well as on high

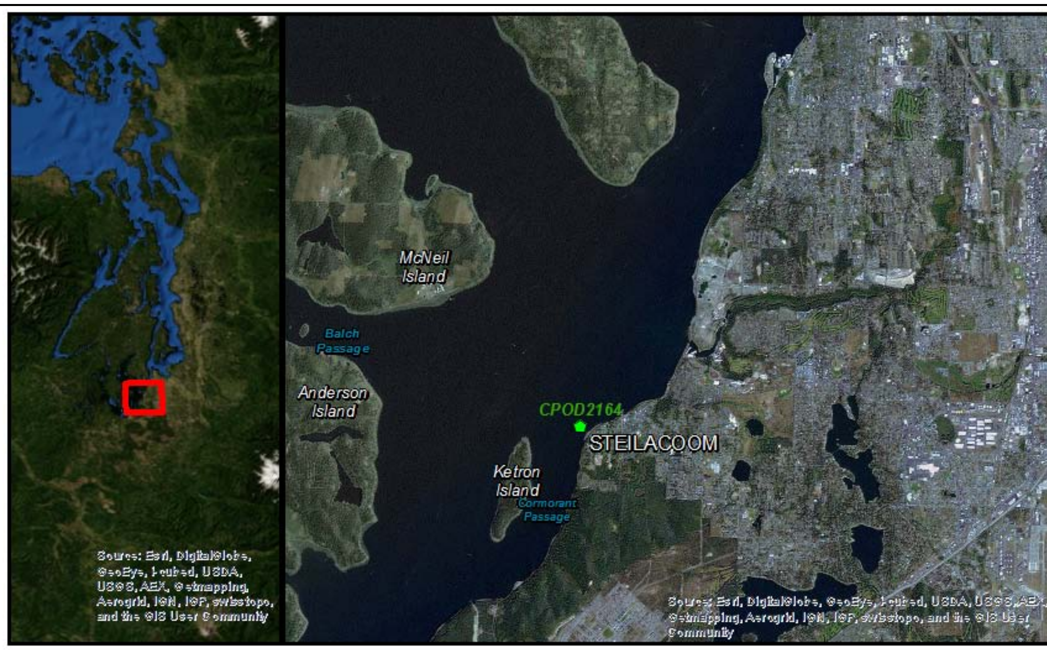

Figure 3-1: The study site, located off Steilacoom in the South Puget Sound. The C-POD was located approximately 200 m off Saltar Point, at the north end of Cormorant Passage in water approximately 45 m deep.

banks with unobstructed views. Harbor porpoise were observed on these visits, and discussions with residents suggested that porpoise are regularly sighted in the area.

The selected deployment location was approximately 200 m off the beach at Saltar's Point Park in Steilacoom, Washington (47.1698° N, 122.6147° W). The C-POD was deployed from March 10 through May 31, 2013. A utility lot (47.1697° N, 122.6017° W, 15 m elevation) with public access to the east of the deployment site was used for visual surveys from July, 2012 through June, 2013. The utility lot was closed to public access at the end of June, 2013 so a new observation site was located in a vacant lot (47.1681° N, 122.6127° W) to the southeast of the C-POD.

Both high-bank locations were within 300 m of the C-POD deployment site and allowed tracking and behavioral observations of harbor porpoise throughout the detection range of the C-POD. The high-banks allowed for monitoring the greater basin to a visual detection range of 5 km, covering an area of approximately 30 km^2.

3.2 Acoustic Survey Methods

3.2.1 C-POD Click Detectors

Passive acoustic monitoring for harbor porpoise was conducted using C-PODs, manufactured by Chelonia, Ltd.

(http://www.chelonia.co.uk), which are autonomous ultrasonic tonal click detectors. Unlike regular recording hydrophones, which record the sounds throughout their range, C-PODs record metadata about each tonal sound between 20 kHz and 160 kHz, allowing for much more efficient use of memory, greatly increasing the deployment time. A sound is considered to be "tonal" when a narrow frequency band of sound contains more energy than the rest of the broadband range of sounds. The C-POD is powered by 10 D-cell batteries and click data is stored on a 4GB secure digital (SD) flash memory card, allowing for quick data recovery and redeployment in the field (Tregenza 2013).

The C-POD (POD2164) was successfully deployed on March 9, 2013 and recovered and redeployed April 14, 2013. The second deployment ended when the equipment got tangled in fishing gear on May 31, 2013, and was returned by the fisherman with data intact.

3.2.2 Deployment and Mooring

The C-POD was deployed and retrieved by hand from small boats. A location with a depth of approximately 45 m was selected, and marked on the GPS, before dropping the ground tackle and the C-POD. The ground tackle consisted of a 6 kg Danforth anchor, 4.5 m of anchor chain, a 6.8 kg pyramid anchor and 60 m of anchor line. A large crab float was attached at the surface, with a 20 m tag line attached to two smaller floats The C-POD was attached to the anchor line 25 m off the seabed.

3.2.3 Processing C-POD Data

SD cards containing data from the C-PODs are read onto the PC and processed using the Windows based CPOD.exe program, which is supplied with the C-POD, for processing click train data and providing graphical analysis tools. The CPOD.exe program uses a click train classification algorithm, the KERNO classifier, to identify probable click trains. Click trains are categorized as ‘high’, ‘mod’, ‘low’ or ‘?’

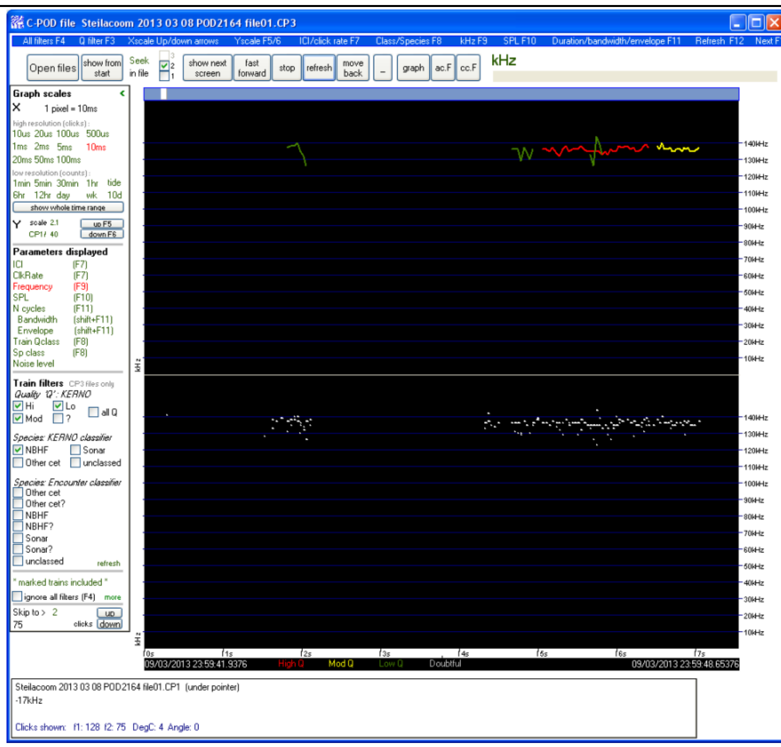

Figure 3-2: Harbor porpoise click trains. The lower panel shows the raw tonal sound data, including individual clicks. The upper panel shows click trains identified by the KERNO classifier.

according to how well they fit the expected parameters of a click train: frequency and duration of the clicks, number of clicks, shape of the sound and the inter-click intervals (Figure 3-2).

Sound sources of interest categorized by the KERNO algorithm include porpoise, other cetaceans, or SONAR from the echo sounders of passing vessels. Harbor porpoise clicks are high-frequency narrow-band (HFNB) sounds over 100kHz of short duration that occur in quick succession. Other cetaceans, such as dolphins, have click trains that cover a broader band of frequencies and include a component under 100kHz. Echo sounders from passing vessels are easily distinguished

Figure 3-3: Echo sounder sonar as detected by the KERNO classifier. Regularly timed pulses at a consistent frequency are easily identified.

due to their consistent frequency and pulse pattern over extended periods (Figure 3-3).

Inspections of the graphical displays were used to determine the background noise levels at the site. Estimates of the rate of false detections were made by comparing frequency, inter-click intervals and possible noise sources to the expected parameters for harbor porpoise click trains. The visual displays were also used to manually review porpoise presence for 10 minutes before and 10 minutes after the passage of a vessel using an echo sounder, and checking for missed detections during these periods when the KERNO classifier failed to identify a click train.

Upon completion of classification and analysis in CPOD.exe, data were exported to a .txt file that could be read into Microsoft Excel and R. Output was created in both an hourly and daily format to allow for analysis with environmental data of differing time scales.

3.3 Visual Survey Methods

Visual survey methods were used to validate presence and behavior of porpoise in close proximity to the C-POD, as well as to log data about harbor porpoise over a much larger geographic area than is covered by the detection range of acoustic equipment. Visual survey methods are limited to daylight hours during times of clear visibility, with a Beaufort Sea State of 2 or less, which corresponds to wind speeds of less than 8 knots (4 m/s). Visibility was also affected in the evening by sun glare to the west. Attempts were made to conduct at least one observation session each week when possible.

Two methods were used to collect the visual observation data on harbor porpoise, scanning with compass binoculars and tracking with a theodolite. Due to the wet maritime weather in the spring, most observations were conducted using compass binoculars and data was recorded on paper data collection forms. Information included group size, behavior and approximate position of harbor porpoise, as well as the start and end times of each sighting and any changes in weather conditions. The theodolite was used to more precisely track harbor porpoise in relation to the C-POD when there was no risk of precipitation and there were at least two observers available to act as spotters and operate the equipment. Due to these limitations, the theodolite was only used three times during the study period.

Opportunistic sighting reports were also collected from residents of the area indicating dates and times when they noticed harbor porpoise near C-POD mooring float. Several times each week, one of the volunteers would stop for 10 or 15 minutes on her way to work in the morning in order to observe porpoise activity and take notes.

3.4 Environmental Data

Environmental variables recorded on an hourly basis were used as independent variables for analysis with detection positive minutes (DPM) per hour as the dependent variable. Analyses were conducted using hurdle regression analysis (from the pscl package) using R v. 3.02. A common problem with environmental count data, such as DPM in this study, is a high percentage of zero-count data, which is known as "zero-inflated". The hurdle model was developed to deal with zero-inflated data by splitting the analysis into two separate models. The zero counts are analyzed in the zero hurdle model which determines whether the independent variable influences the likelihood of there being a non-zero count. In the zero-hurdle model counts only have two states, zero and non-zero. If there is a non-zero count it is considered to have hurdled into the positive count state. The second part of the model is the zero truncated model, where only the non-zero counts are analyzed against a negative binomial distribution. The negative binomial distribution was selected due to the over-dispersion of the data. Results from these two tests are reported separately and are not dependent on each other.

Hourly weather data was retrieved from the Tacoma Narrows Airport weather station (KTIW, 47.2675°N, 122.57611°W Elev: 315ft) located approximately 10 km north of the observation site in

Steilacoom. The Tacoma Narrows Airport station was selected over the slightly closer station at Joint Base Lewis McChord due to its close proximity to the water. Exploratory analyses were conducted on air temperature, wind speed and precipitation. High levels of correlation were found between the air temperature and both the time of day and the season, therefore air temperature was excluded from analysis. Precipitation was not independent of wind speed and did not achieve significance, so it was excluded from the hurdle model. The only weather variable to be included in the hurdle model was wind speed. Water temperature was recorded every minute by the C-POD, with the water temperature also acting as a proxy for the season and was excluded from analysis.

There are no tidal gauges in the South Puget Sound, with the nearest water level monitoring site in Commencement Bay, Tacoma, WA, where it will be influenced by the Puyallup River. Tidal data was calculated for the site using the WXTtide32 program (http://www.wxtide32.com/), which uses station data provided by NOAA for Cormorant Passage where the C-POD is located. Change in tide height is used as a proxy for tidally driven currents, and were calculated from the beginning to the end of each hour. The hourly relative change in tide height was used as one of the independent variables in the hurdle model.

To determine if there were diel trends in presence at the study site the hour of the day was analyzed as an independent variable in the hurdle model. Seasonal variability was analyzed using DPM per day as the dependent variable and the month as the independent variable using a non-parametric Kruskal-Wallis one-way analysis of variance by ranks. Pairwise comparisons between months was conducted using the Kruskalmc (R package pgirmess). All environmental analysis was conducted using R v. 3.02.

3.4.1 Anthropogenic Impact Data

Vessel echo sounders are the most readily identified anthropogenic data available in the acoustic record. Analyses were conducted to determine if echo sounders had any impact on harbor porpoise detections at the site. Echo sounder detections were analyzed for harbor porpoise presence during the 10 minutes immediately prior to the initial sonar reception by the C-POD, and for the 10 minutes after echo sounder activity ceased to be detected.

Echo sounder detections were identified by the KERNO classifier in CPOD.exe. The classifier only detects the strongest portion of the echo sounder activity during the middle of the train; it does not classify the beginning and ends of the train properly due to weak signal strength. Every echo sounder detection was verified via the graphical interface to extend the start and end points of the echo sounder train and remove any echo sounder false detections. Periods of 10 minutes before the start of the echo sounder signal and 10 minutes after the end of the signal were checked for porpoise click trains detected by the classifier. If no porpoise click trains were detected, a manual check for missed detections was conducted. A McNemar's chi-squared test was used to assess whether vessels with active SONAR were affecting harbor porpoise presence as they transit the study site.

4 Results

4.1 Acoustic results

Acoustic data at the Steilacoom site from 10-Mar-2013 through 31-May-2013 had a total of 59,955 detected click-trains. There were 10,104 DPM out of 119,640 minutes of recording, with porpoise presence detected 8.5% of the time. During the deployment, NBHF click trains were detected during 906 out of 1994 hours, with 1088 zero-DPM hours (Figure 4-1). Hourly DPM ranged from 0 to 60 with a mean of 3.94 and a median of 0. The high proportion of zero counts necessitated the use of a hurdle model when analyzing hourly

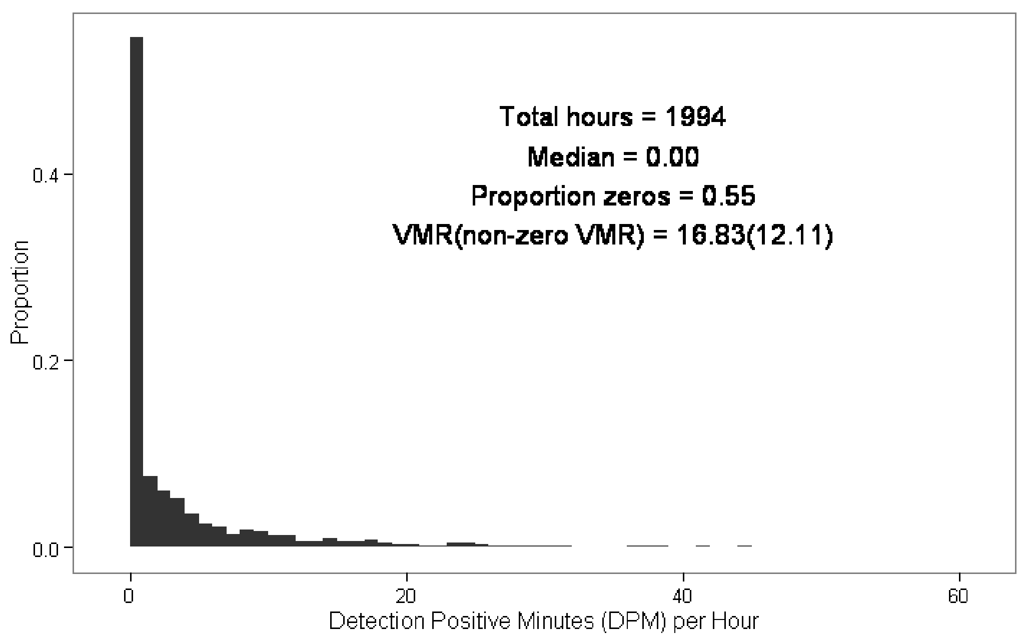

Figure 4-1: Histogram of detection positive minutes (DPM) per hour recorded by the Steilacoom C-POD illustrates the excess of zeros in the count data, requiring the use of an appropriate zero-inflated model.

environmental data, and the variance to mean ratio (VMR) of the nonzero counts (VMR = 12.11) required the use of a negative binomial distribution during analysis. Daily DPM ranged from 7 to 471, with a mean of 121.7 DPM (SD = 104), which corresponds to 8.5% of the minutes in a day (1440), and a median of 96 DPM (Figure 4-2).

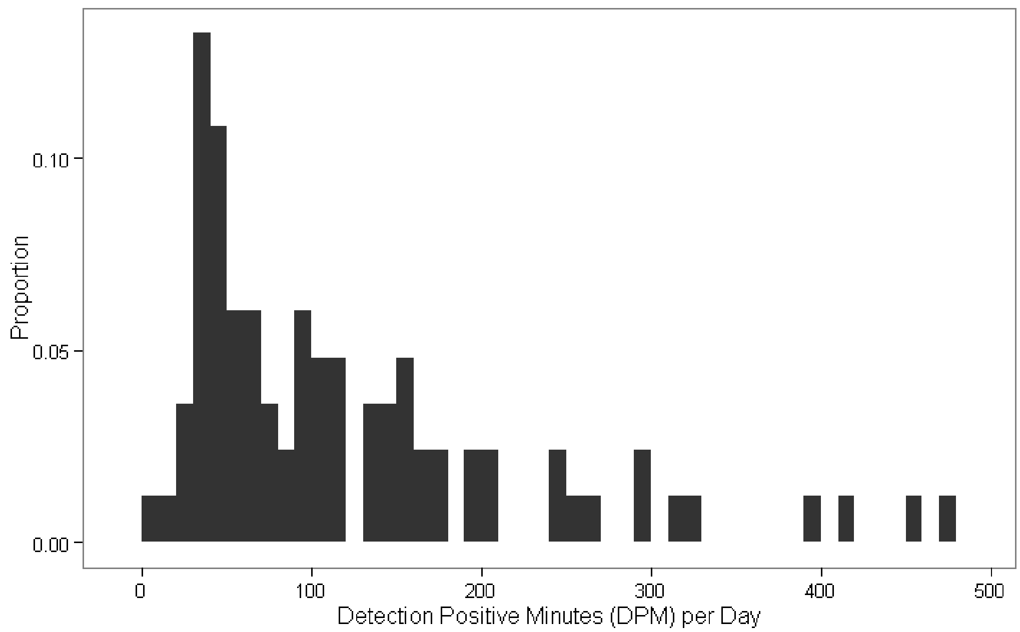

Figure 4-2: Histogram of the detection positive minutes (DPM) per day. The daily DPM ranged from a low of 7 to a high of 471, with a mean of 121.7 and a standard deviation of 104.

4.2 Click train analysis

Background noise levels at the Steilacoom site proved to be low enough that any NBHF click trains that were classified as “low quality” or better could be used for analysis. A selection of 900 NBHF click trains were checked for possible false detections, with only two questionable results that occurred during broadband ship noise, yielding a false-positive rate of <0.23%. While checking for false detections, it became apparent that there were far more missed detections than false detections, though no effort was taken to quantify the missed detections due to the difficulty of identifying each individual click train. The level of missed detections appeared to be consistent throughout the results with most encounters generating at least one detection.

All high, moderate and low quality results for other cetaceans, such as dolphins, were checked and all results were considered to be false detections or questionable as to whether they represent actual detections due to their occurrence during periods of high environmental or vessel traffic noise. On days when Risso's dolphins were known to be in the area, some potential low quality click trains were detected, though the results are brought into question due to the high levels of false detections in the other cetacean category. Many of the false detections in the dolphin range were produce by echo sounders or other vessel noise. There were a few cases of false echo sounder detections, which were caused by harbor porpoise click trains, though these were easily identified and corrected.

4.3 Environmental results

The factors included in the hurdle analysis were rate of tidal change, wind speed and hour of the day (Figure 4-3). Tidal change per hour had a range of -1.09 to 1.23 m hour^{-1} (*M = 0.00 m hour^{-1}, SD = 0.55 m hour^{-1}*). Wind speeds were in the range of 0 to 9.8 m s^{-1} (*M = 2.6 m sec^{-1}, SD = 2.1 m sec^{-1}*), with 449 out of 1994 hours having calm wind.

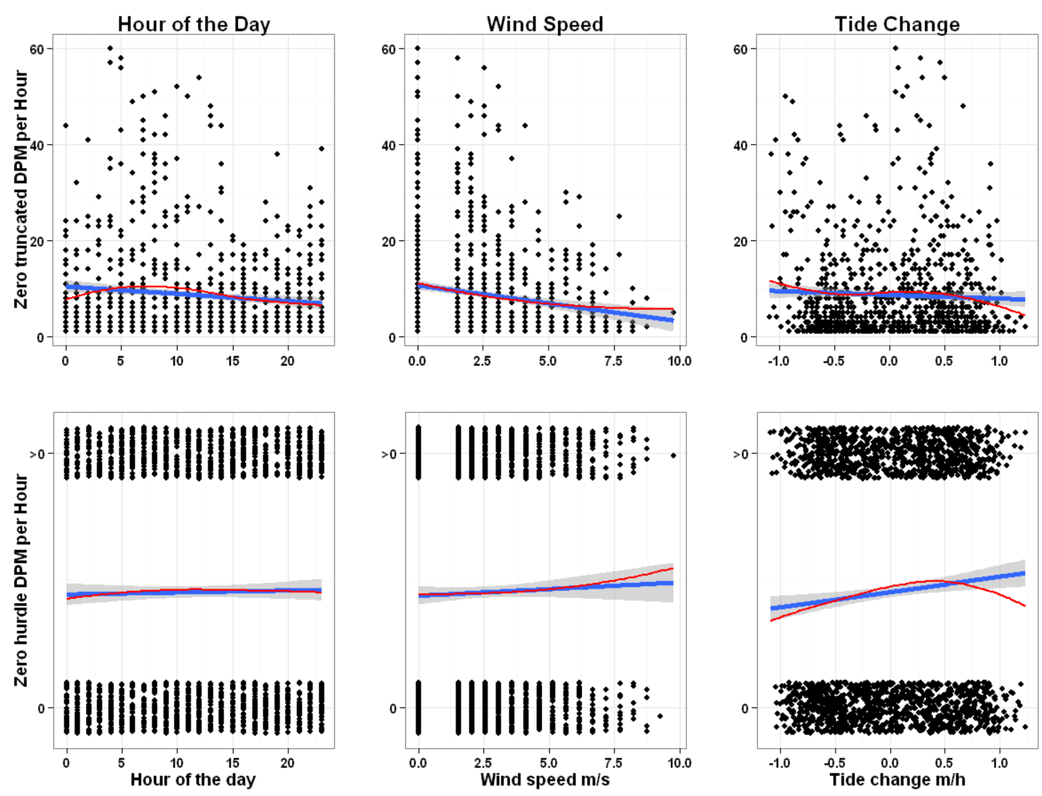

Figure 4-3: Hurdle model results comparing environmental variables to detection positive minutes per hour. The top plots show the zero truncated portion of the hurdle model, and the bottom plots show the zero hurdle portion, where zero counts are compared to non-zero counts (results are jittered for clarity). Regression lines are in blue, with LOESS local regression lines in red. Hour of the day and wind speed were found to be significant in the zero truncated portion of the model, and tide change was significant in the zero hurdle portion of the model.

Hourly DPM data were analyzed against the hour of the day, wind speed and the tidal change over the course of the hour using a negative binomial hurdle model due to the zero-inflation of the dataset (

). Tidal change was the only independent variable tested to have a significant impact on the zero hurdle section of the model (*p=0.004*). The zero-truncated count section of the model had significant results from both the hour of the day (*p=0.025*) and the wind speed (*p < 0.001*).

The Steilacoom C-POD recorded a significant difference in the mean DPM per hour count when compared to the hour of the day (*p = 0.025*). Detections peaked in the morning between 0700-0759, with a

Table 4-1: Hurdle model results from Steilacoom, with hour of the day and wind speed having a significant influence on the zero-truncated count of detection positive minutes (DPM) per hour, and tide change having a significant impact on the zero hurdle binomial model.

Count model					
	Coefficient	Std. Err.	z value	p value	
Hour	-0.0167	0.0074	-2.24	0.025	*
Wind speed	-0.0957	0.0230	-4.17	< 0.001	*
Tide change	-0.0500	0.0898	-0.56	0.577	
Zero hurdle model					
Hour	0.0015	0.0066	0.226	0.821	
Wind Speed	0.0174	0.0221	0.79	0.429	
Tide Change	0.2374	0.0830	2.86	0.004	*

Log-likelihood: -4116 on 9 Df

mean of 7.1 DPM $hour^{-1}$ ($SD = 12.4$) , with the lowest detection level occurring in the afternoon between 1700-1759, with a mean of 2.1 DPM $hour^{-1}$ ($SD = 3.9$) (Figure 4-4).

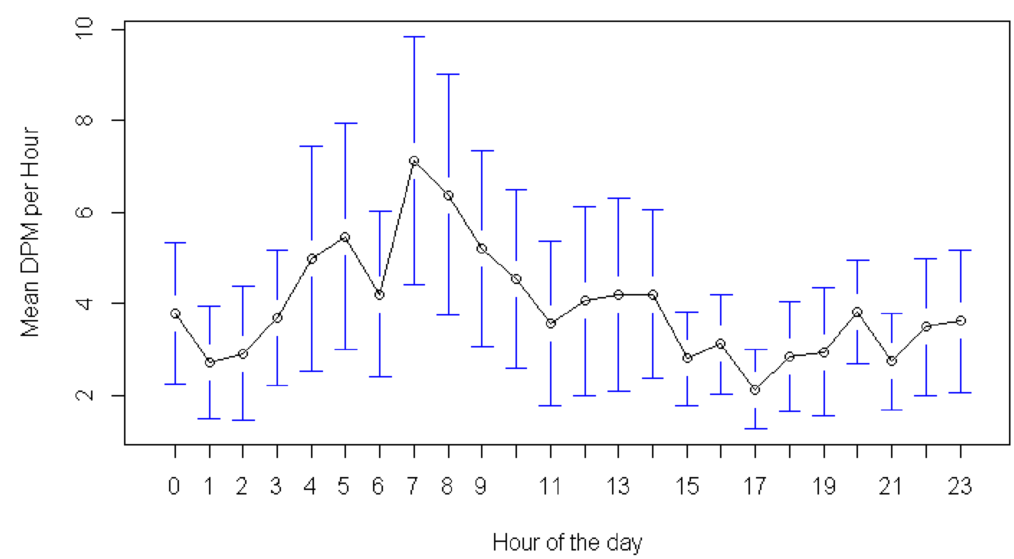

Figure 4-4: There is significant variation in the mean of the DPM per hour throughout the day, with the highest detection levels in the morning hours. The bars represent the 95% confidence interval (CI).

The wind speed was found to have a significant impact on the zero-truncated hourly DPM count data ($p < 0.001$), with decreasing detections as wind speed increased (Figure 4-5). The mean zero-truncated DPM $hour^{-1}$ during calm winds (n=198) was 11.2 (SD=12.9), while wind speeds greater than 6 m sec^{-1} (n=83) had a mean of 6.6 (SD=6.3). Even though wind speed appeared to have an inverse relationship with the mean DPM $hour^{-1}$, out of 161 hours with wind speed greater than 6 m sec^{-1}, there were 83 hours where click trains were detected, and 11 of those hours had more than 15 DPM.

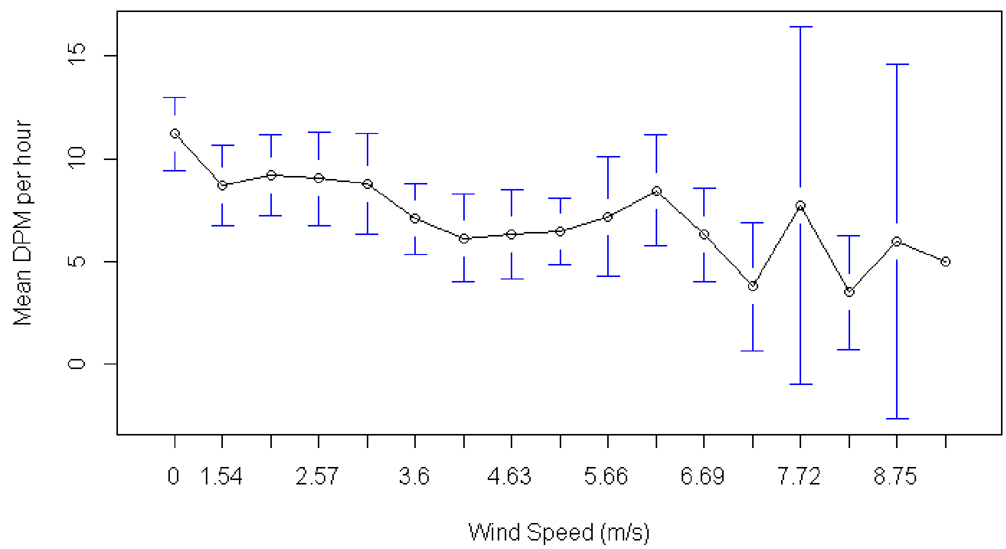

Figure 4-5: There is significant variation (p < 0.001) in the zero-truncated means of the DPM per hour at different wind speeds, with decreasing acoustic activity levels detected at higher wind speeds. The bars represent the 95% confidence interval (CI).

The magnitude and direction of the change in tide height over the course of an hour was found to cause a significant difference in the zero hurdle portion of the model ($p = 0.004$), though it had little effect on the mean DPM counts in the zero-truncated portion of the model. Positive DPM hours were most likely to occur during slowly incoming tides, with a tidal change rate of approximately +0.4 m $hour^{-1}$. This suggests that the current produced by the change in tide plays a role in porpoise choosing to use this area, but it plays little role in how long they stay within the detection range.

4.4 Seasonality

Daily detection positive minutes varied on a monthly time scale (Figure 4-6) with the highest level of porpoise presence during the month of May (*n=31*) with a range of 35 to 471 DPM day^{-1} (*m=201.5, SD=123.7*). A moderate porpoise presence was recorded in March (*n=22*) with 28 to 209 DPM day^{-1} (*m=108.5, SD=49.4*), and decreased throughout the month. The lowest levels were in April (*n=30*) with 7 to 114 DPM day^{-1} (*m=49.0, SD=25.4*). A Kruskal-Wallis analysis of variance (ANOVA) was conducted to compare the effect of the month of the year on detection positive minutes (DPM) per day from March

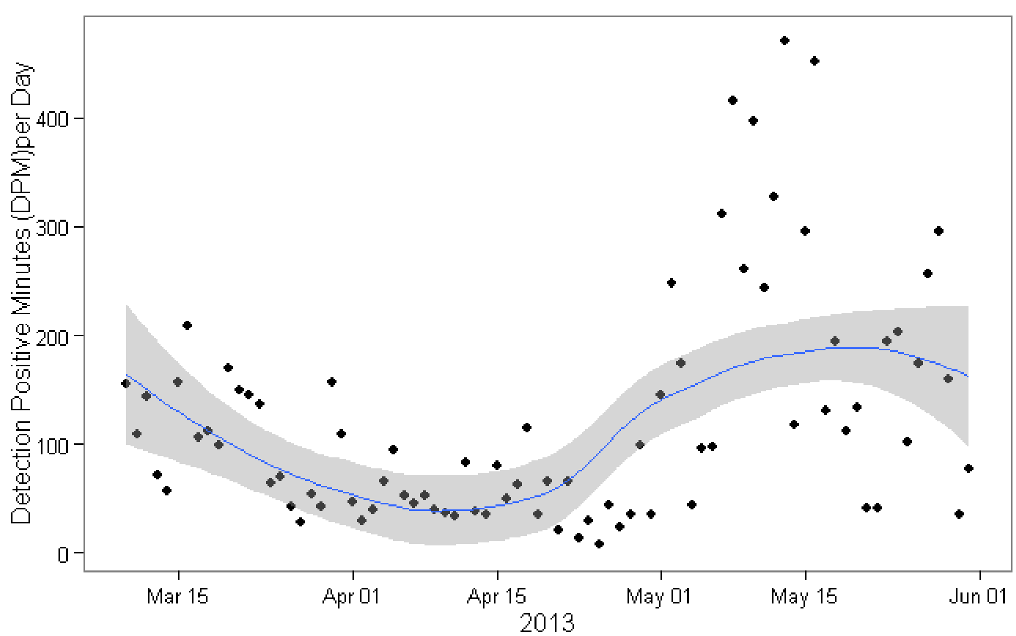

Figure 4-6: Detection positive minutes (DPM) per day throughout the Steilacoom C-POD deployment. Lowest levels are in late April, and highest in Early May. March and April experience much smaller variance from the mean, with most counts within or close to the 95% CI.

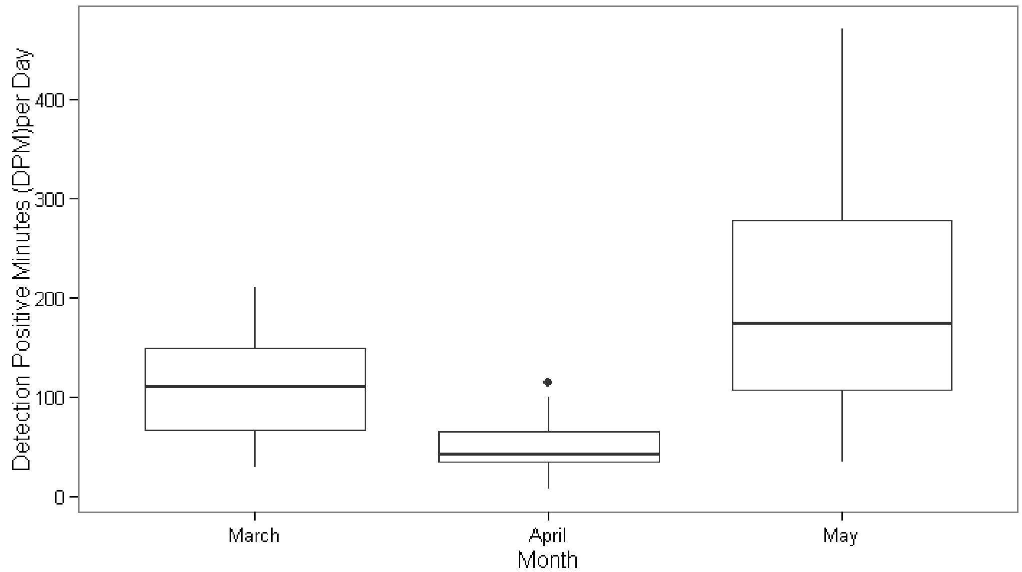

Figure 4-7: Significant differences were detected between months (P < 0.001), with very few detections during April, followed by a spike in detections during May.

through May, 2013. There was a significant effect of the month on the DPM day^{-1} at the p<.05 level for the three months ($\chi^2(2) = 38.96, p < 0.0001$).

Pairwise comparisons of the mean ranks between months were conducted using Kruskalmc post hoc test, with the results shown in Table 4-2. Significant differences were found in the March-April and

Table 4-2: Results of Kruskalmc post hoc pairwise test. Significant differences were found in the March-April and April-May tests, but not in the March-May test.

	Observed difference	Critical diff.	Significant
March-April	24.268	16.197	Yes
March-May	13.932	16.086	No
April-May	38.200	14.779	Yes

April-May pairwise tests, with no difference detected March-May. These results show that harbor porpoise density in a portion of their range within the South Puget Sound can vary on a temporal scale of weeks to months.

4.5 Interaction with vessel echo sounders

Review of the Steilacoom C-POD data revealed 155 echo sounder events logged during the March-May 2013 deployments. The majority of these events (82%) matched the schedule for the Steilacoom-Ketron Island ferry and presented a similar 4-6 minute 50 kHz echo sounder signature, so those were all assumed to be the ferry. Other vessels had echo sounders operating in the 50 kHz, 80 kHz and 120 kHz bands, with the 50kHz band being the most common. The research boat used to deploy the C-POD was equipped with a dual-band echo sounder, but upon review only the lower band was apparent in the record. This is a probable artifact of the attenuation of higher frequency signals, combined with the detection algorithm of the C-POD, which only records metadata about the highest energy tonal sound that it detects. It is probable that other vessels, especially fishing boats, also had dual-band systems with only the lower band showing up.

Table 4-3: Truth table of porpoise presence/absence during the 10 minutes before and 10 minutes after 155 echo sounder events recorded by the Steilacoom C-POD.

Porpoise presence before and after SONAR events			
	Absent after	Present After	Sum
Absent before	79	21	100
Present before	8	47	55
Sum	87	68	155

All echo sounder events identified by the KERNO classifier were checked for NBHF click trains that were consistent with harbor porpoise presence for 10 minutes before the start of the echo sounder, and for 10 minutes after the echo sounder ended, with the results summarized in Table 4-3. A McNemar's chi-squared test determined that there was a significant difference between periods when porpoise were not detected before the echo sounder event then they were detected afterwards, and periods when their presence was detected before the echo sounder and not detected after ($\chi^2 = 4.97$, $df = 1$, $p = 0.026$). Contrary to their reputation for shying away from vessels, 85% of the time when porpoise were detected before the period of echo sounder activity, they were also detected after as well, with only 15% of the periods showing a lack of detections after the echo sounder activity. When no porpoise were detected before the echo sounder activity, they remained absent afterwards 79% of the time, with detections showing up 21% of the time after an occurrence of echo sounder activity.

One notable echo sounder event occurred on May 2, 2013 starting at 1728 and continuing until 2036, with few gaps in the 80 kHz signal. During that time there were also some instances of vessels with 50 kHz systems also operating in the area. Detections of porpoise remained at moderate to high levels throughout this period, extending about half an hour after the vessels with the sonar departed.

4.6 Visual results

Poor viewing conditions interfered with most attempts to conduct visual observations during March and April, which only had two short sessions each. A total of 18 visual observation sessions were conducted during the C-POD deployment, for a total time of 911 minutes. Harbor porpoise were sighted within the detection radius of the C-POD during 12 sessions, these sightings included 22 animals in 14 groups (*m=1.57*). On one occasion, two groups were foraging in the area for overlapping periods, which will be treated as one acoustic encounter. Porpoise were detected by the KERNO classifier during 12 out of the 13 encounters. The one missed encounter was a fast traveling porpoise, while all other encounters were of foraging animals. Visual review of the acoustic data during the period of the missed encounter revealed that many clicks were recorded, but few well ordered click trains were occurring.

During six of the encounters porpoise were already present at the start of the survey period. The remaining six encounters were evenly divided between those that were detected first by the observers, before porpoise entered the acoustic detection zone, and those which were detected by the C-POD before the animals were sighted. There were two periods when the C-POD detected click trains of porpoise, yet only animals outside the standard 400 m range of detection were observed. During only one instance, no porpoise were sighted in the area when the C-POD detected several click trains.

5 Discussion

The use of a C-POD acoustic porpoise detector has proven to be an effective complement to the use of visual observation in the study of harbor porpoise behavior and distribution in the South Puget Sound. While the number of visual observations was limited by the weather, the C-POD was able to detect all the visually confirmed foraging encounters within the detection radius, only missing a fast traveling porpoise. Acoustic data revealed associations between porpoise presence and seasonal, diel, wind speed and tidal variables that would have been impossible to gauge with visual methods alone. Data from the C-POD also produced surprising results when porpoise presence was compared to echo sounder activity from fishing boats and the passing Steilacoom-Ketron Island ferry.

5.1 Visual observation

Even though the poor weather conditions made it difficult to collect sufficient visual data to conduct any meaningful quantitative analysis, the C-POD detected all foraging groups of animals within 200 m. The one encounter that was not acoustically detected was of a single animal that was traveling through the site, while all detected encounters involved foraging animals. It is likely that traveling porpoise only click often enough to ensure that they do not swim into anything, while foraging porpoise will ensonify their surroundings in all directions in an attempt to locate food. This idea is supported by a study which found that when porpoise are not actively foraging, they produce click trains far less often. Porpoise send out a high energy, long distance click train to assist in navigation, followed by a longer interval between click trains than occurs during foraging (Akamatsu et al. 2007). Foraging behavior was studied in finless porpoise (*Neophocaena phocaenoides*) and unlike traveling dives, foraging dives were found to involve rolling and scanning the environment during 31% of the dive time, and echolocating over 4 times more frequently than during dives without searching behavior (Akamatsu et al. 2010)

There were three acoustic detections that occurred when no porpoise were sighted within 200 m of the C-POD. These simply could have been missed by the observers. It is also possible that the porpoise were outside the 200 m range, but if they were on-axis with the C-POD it would have extended the range of detection (Clausen et al. 2012)com. A much larger sample of matched visual and acoustic observations need to be collected before it is possible to draw any meaningful conclusions.

5.2 Environmental analysis

Understanding seasonal distribution and abundance is important to inform future research and management decisions. Seasonality is of particular importance when considering measures to protect harbor porpoise populations, such as the efforts being undertaken in the EU to define marine protected areas (Sveegaard and Teilmann 2008, Berrow et al. 2009, Sveegaard et al. 2011b). If it is determined that restrictions on human activities need to be implemented to protect the harbor porpoise in the South Puget Sound, such as limitations on gillnet fisheries, knowledge of the times and locations of the highest porpoise density will allow for the most effective protection while limiting impact on the restricted activities.

Even though harbor porpoise were acoustically detected during every day of the deployment, there was significant temporal variability in the use of the site. On a monthly timescale, the difference between the moderate and low levels of detections during March and April respectively, were followed by the much higher level of acoustic activity during May, with the greatest peak happening during the first two weeks of the month. This suggests that there are some longer-term factors, such as an increase in the availability of prey at the site, which influenced the porpoise to spend more time foraging in the area.

On a diel timescale, it was found that harbor porpoise were most acoustically active at the site in the morning, between 0400 and 1000, with a peak during the 0700 hour. The acoustic results showed high levels of morning activity in the area which was supported by volunteer observations with near-shore harbor porpoise activity observed most mornings within a short 15 minute window, often within the detection range of the C-POD (Laurie Shuster, personal communication). Much lower levels of detection occurred in the late afternoon, with the lowest levels during the 1700 hour. The higher rates of detection during the morning hours roughly corresponded to sunrise, which occurs on March 10 at around 0630 Pacific Standard Time (PST) and 0420 PST on May 31. Peak activity closely associated with sunrise suggests that harbor porpoise presence at the site is related to the morning descending vertical migration of zooplankton, which happens during the hours after sunrise. The zooplankton attract benthic planktivorous fish that are common prey species of the harbor porpoise (Alldredge and King 1985, Genin et al. 1988). The relatively shallow shelf area at the north end of Cormorant Passage, where the C-POD was deployed, would allow for easier predation by the porpoise on these benthic species than in the deeper waters of the main channel. While PAM is able to reveal these trends in diel behavior, other techniques such as the use of multi-frequency sonar to map biomass migration (Genin et al. 1988, Johnston et al. 2005) would provide a more complete picture of what is likely to be driving harbor porpoise presence during the morning hours.

Harbor porpoise are known to congregate and feed along fronts and in eddies that form on the leeward side of islands and headlands, suggesting that swiftly moving tidally driven currents might play a role in porpoise's site selection (Johnston et al. 2005). The rate of detection at the C-POD site showed that harbor porpoise were more likely to be present during the relatively slack waters of slowly incoming tides, and the lowest chance of detection occurred during the times of greatest tidal change. This suggests that harbor porpoise are not drawn to this site by strong currents. A possible explanation for the higher probability of porpoise detections during slack water lies in the local bathymetry of the region. Strong fronts develop off the north side of Ketron Island and at the mouth of Balch Passage, between Anderson and McNeil Islands, on outgoing tides, where porpoise are often observed feeding for extended periods (personal observation). During incoming tides, the strongest fronts develop mid-channel, with only weak fronts developing in the near shore location of the C-POD (personal observation). Porpoise may be drawn away from the study site, to the areas where fronts are developing during times of stronger tidal flow, spending more of their time foraging in the study site during times of slack water.

Wind speed could be influencing porpoise detections in a number of different ways. As wind speed increased, there was a decline in the mean number of DPM hour^{-1}. Wind waves at the water surface are a major source of broadband noise in the marine environment, which can mask the porpoise echolocation clicks, making detection more difficult (Clark et al. 2009, Hildebrand 2009). At a deployed depth of greater than 20 meters, the surface noise should be somewhat attenuated, though it would still affect the detection radius of the C-POD. While the counts were lower during periods of high wind, the percentage of hours with at least one detection was higher than the mean for the deployment period and many hours had greater than 15 DPM. It can be concluded noise from wind waves had no more than a moderate effect on the rate of detections.

Wind also affects water movement, mixing surface water layers, driving currents and causing upwelling in some areas, which could affect the distribution of prey species (Koseffl et al. 1993, McManus et al. 2005). Increases in wind waves could also have a direct effect on harbor porpoise, requiring more energetic surface behavior instead of their normal low rolling surface activity (Scheffer and Slipp 1948). Harbor porpoise might choose to forage in more protected areas during high winds to minimize their energy expenditures. Even though the winds are having an effect on porpoise detections by the C-POD, the detection rate is much better than would be expected from visual techniques under the same conditions.

5.3 Anthropogenic disturbance

The examination of the time periods before and after echo sounder activity produced a surprising result; vessels transiting this portion of the Puget Sound do not necessarily cause harbor porpoise to flee the area. Harbor porpoise were found to remain in the area 85% of the time when vessels passed close enough to the study site for their echo sounder to be detected. During most of these events, porpoise echolocation continued throughout the vessel passage, suggesting that they stay in the area and continue foraging, rather than leaving and returning when the vessel has passed. When porpoise were in the area and a vessel with an echo sounder passed, they left the area 15% of the time; 21% of the time, porpoise were not detected in an area until after a vessel with an echo sounder passed through the study area. The difference between animals leaving the area and those arriving is sufficient to suggest that porpoise might be attracted to some aspect of vessel passage. Evans et al. (1994) showed that harbor porpoise reacted to vessels in different ways depending on the vessel type, speed and behavior. While the expected avoidance response did occur, there were many instances where no reaction was recorded and some occasions where the porpoise moved towards the vessel.

Visual observations of porpoise feeding when vessels transited the area suggest that diving for several minutes is a common avoidance behavior. Instead of fleeing the area, they often reappear in the same general vicinity after the vessel has passed. Porpoise that are traveling through the area appeared to be more likely to leave the area and not be seen again when a vessel encounter occurs (personal observation). Similar behavior was noted in Flaherty and Stark (1982) where many porpoise were witnessed using diving as a preferred method of vessel avoidance. While acoustic methods excel at determining porpoise presence, they do not reveal details about porpoise surface behavior or dive length, which would be necessary for assessing whether the porpoise are using dives as an avoidance behavior.

The sample size of echo sounder activity is relatively small, and collected from a single site in close proximity to regular ferry lanes. With greater than 80% of the detected echo sounder events attributable to the Steilacoom-Ketron Island ferry, and additional ferry runs from Steilacoom that service Anderson and McNeil Islands, it is reasonable to infer that harbor porpoise in the waters off Steilacoom may have become habituated to the regular presence of these vessels.

A similar situation was discussed in Evans et al. (1994), where one of the vessels was a small ferry that transited the site as many as 8 times per day. In that study, harbor porpoise were found to move closer to the ferry 32% of the time, away 22% of the time and showed no response 46% of the time. More research needs to be conducted at a variety of sites, using both visual and acoustic methods in order to determine the impact of different forms of vessel traffic on porpoise behavior and the possibility of habituation occurring.

5.4 Passive acoustic monitoring

The C-POD has proven to be a useful tool for monitoring harbor porpoise presence in conditions that make other forms of observation unworkable. With the ability to deploy the C-PODs for several months at a time, then quickly recover the data and redeploy the equipment within a matter of minutes, they provide an excellent long-term monitoring solution.

The customized software developed to detect and classify click trains in the C-POD data are can save a significant amount of time processing the acoustic data. It provides a graphical interface for easy review of data, classifies the source of click trains and outputs data in a format that can be used by Microsoft Excel or statistical packages. The detection algorithms are quite conservative, providing very low rates of false detections, which unfortunately leads to a high rate of missed detections. A cursory examination of missed detections found that well over half of the porpoise click trains remained undetected, even during encounters with large numbers of detected click trains. In many cases the high rate of missed detections is not an issue because it is rare that an entire encounter will go undetected even if every click train is not accounted for. During analyses when the high rate of missed detections is unacceptable, such as during the echo sounder analysis, the identification and marking of the missing click trains is a fairly simple, yet time consuming, process.

While the C-POD has many advantages, it is not without its limitations. Instead of capturing full recordings of sounds, the device only stores metadata describing the sound. The single omnidirectional hydrophone also limits the ability to determine the number of animals in a group, making it difficult to come up with reasonable abundance estimates. Furthermore, its range of detection is limited to only a few hundred meters which limits the size of the study area to a smaller range than covered by visual observation techniques.

While this study has addressed the usefulness of C-PODs in monitoring harbor porpoise in the South Puget Sound, and has produced some baseline data, a proper monitoring program will require multiple C-PODs to gain an understanding of the changes in harbor porpoise habitat selection, range, seasonal distribution and behavior. To understand whether apparent changes in relative abundance are actually occurring or if the changes have more to do with shifts in yearly or seasonal distribution, visual and acoustic monitoring is needed at additional long term study sites throughout the South Puget Sound region.

5.5 Conclusion

The Puget Sound is a remarkable ecosystem that has seen considerable abuse over the years. We have overfished and polluted the waters and dammed the rivers that make the Sound such a productive estuarine environment. Marine mammals in the region were killed for their furs, their oil and because they were seen as competition for resources, with several species brought to the point of near extinction. When one of these species returns to an ecosystem where they haven't been seen for several decades, it is cause for a certain amount of optimism that conditions are improving. We don't know for certain why porpoise disappeared from the South Sound, nor do we know what led to their return, yet we continue to pollute our waters and we short-change environmental education and conservation.

Passive acoustic methods used in this study have proven to be useful for monitoring several key behavioral aspects of the harbor porpoise population that has reestablished in the South Puget Sound. The timing of this study, during the normally stormy late winter and spring months, demonstrated the ability to collect acoustic data during times when visual data collection is often not possible. Even with limited ability to conduct visual observations during much of the deployment period, the C-POD continued to collect data about the use of the site by harbor porpoise during all hours of the day and night, in all weather conditions. The ability to collect data at night enabled analysis of diel activity levels around the clock, not just during daylight hours. With the high winds and rain that is very common during April and May, it is unlikely that the limited visual observations would have revealed the extent of the seasonal variation that was evident in the acoustic record. The apparent lack of response by harbor porpoise within the acoustic record to the passage of vessels operating an echo sounder was one of the more surprising results of this study and is worthy of future research.

The use of passive acoustic monitoring devices, like the C-POD, is providing many new opportunities to improve our understanding of the marine environment that we all depend on. These tools are being used throughout the world to monitor a wide variety of marine species and represent a large step forward in our ability to collect new forms of data that were previously unavailable. Researchers don’t need to be physically present in remote locations during data collection and the equipment gathers information throughout the day and night in all weather conditions. Passive acoustic monitoring provides a cost effective method of gathering information about species of concern, especially as human pressure on marine resources continues to expand.

Harbor porpoise are a high trophic level sentinel species whose abundance and success reflects the health of the ecosystem. By monitoring the continuing viability of the porpoise in South Puget Sound, it expands our understanding of human impacts on our marine ecosystem. Harbor porpoise, along with salmon, killer whales, and harbor seals, can serve as living reminders of our past mistakes and the need to protect the marine environment.

6 An interdisciplinary study with broad impact

The return of the harbor porpoise into the waters of the Puget Sound is an important ecological event that suggests that the environment of Washington's inland waters have improved to a level that can once again support a harbor porpoise population. While we will never know precisely what led to their extirpation, by studying their return, we can monitor porpoise health and growth rates as a benchmark for the health of the marine environment. The results of this and future studies will provide valuable information to support conservation and resource management decisions by policy makers.

The deployment of a single C-POD has shown that it can be a useful tool for monitoring behavior, but a device in a single location does not reveal much about the spatial and temporal use of the South Puget Sound by the porpoise, nor can it tell us about the health of the population. Deploying an array of C-PODs on permanent moorings throughout the area would provide important information about changes in porpoise abundance over time, as well as their movements throughout the South Puget Sound. The data from multiple C-PODs would be useful for informing policy and management decisions as well as providing an opportunity for scientists to expand on behavioral studies about the species.

As a protected species under the Marine Mammal Protection Act, policy decisions can have a wide ranging impact on a variety of industries. Fisheries policies might need to take porpoise presence into account if bycatch or other fisheries interactions increase to a level that the population cannot support. Pollution from runoff, heavy industry, the proposed coastal coal train route, and other anthropogenic sources may need to be regulated if pollutants are found at dangerous levels in samples of marine mammal tissues.

Resident marine mammal populations act as excellent sentinel species for monitoring anthropogenic impacts to our marine waters (Bossart 2011). Porpoise are long-lived, high trophic level predators, therefore toxins bioaccumulate in their fatty tissues to levels which are easily detectable. The heavy subdermal blubber layer accumulates many of the fat soluble toxins which the animal has ingested. These tissues are easily sampled using nonlethal biopsy darts, which enables researchers to monitor toxin levels without relying solely on stranded animals. This can serve as another measure of the presence of toxins in the marine environment, some of which may have accumulated to the point of becoming a concern.

Marine mammals are considered to be charismatic megafauna and are much loved by the people of the Puget Sound region. On many occasions, members of the public stopped by the research site and expressed interest in the harbor porpoise story. Most people were unaware of the existence of harbor porpoise in these waters and wanted to learn more about these animals and their return to the Puget Sound. This provides an excellent opportunity to educate people about issues related to the health of our local waters. Recent articles covering the return of the harbor porpoise have appeared in several local newspapers spurring additional public interest in the topic.

Citizen scientist groups are forming throughout the world around a variety of environmental issues. With increasing public interest in the harbor porpoise, Puget Sound provides an excellent opportunity for citizen scientists to contribute observations about porpoise location and behavior and to help educate the general public. Some citizen scientists volunteer their time to assist professional researchers with data collection in the field or office based work with analysis projects. Professional mariners spend a considerable amount of time on the water and frequently contribute invaluable information regarding location and behavioral patterns of many marine mammal species.

Harbor porpoise have returned to the South Puget Sound after an absence of several decades. Careful monitoring of the range and abundance of these animals is essential to conservation efforts. Acoustic monitoring, when combined with visual surveys, can provide essential information to properly monitor and manage this population within the South Puget Sound. Further study and published research is needed in order to document the recovery of this population and to contribute to the global knowledge base and conversation regarding this widely distributed species.

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