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FINAL PROJECT REPORT

EVALUATION OF A PASSIVE ACOUSTIC MONITORING NETWORK FOR HARBOR PORPOISE TO ASSESS MARINE RENEWABLE PROJECTS IN CALIFORNIA

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PREFACE

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Evaluation of a Passive Acoustic Monitoring Network for Harbor Porpoise to Assess Marine Renewable Projects in California is the final report for the Exploratory Studies of Potential Environmental Issues with Alternative Energy Futures for California project (contract number 500-11-033) conducted by Moss Landing Marine Laboratories. The information from this project contributes to Energy Research and Development Division's Energy-Related Environmental Research Program.

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ABSTRACT

Harbor porpoise *(Phocoena phocoena)* are found in coastal waters of the temperate northern hemisphere, where they are subjected to a variety of anthropogenic impacts including pollution, noise, and fishery interactions. Marine renewable energy projects currently in development in California have the potential to disturb, displace, and damage the hearing of harbor porpoises. Effective monitoring strategies are necessary to establish baseline data prior to the installation of marine renewable energy structures, to determine the impacts of construction activities, and to assess long-term impacts from marine renewable energy site operation. Along the U.S. West Coast, harbor porpoise populations are monitored using line-transect aerial surveys, which are costly, weather-limited, and provide coarsely resolved data. However, passive acoustic monitoring is a promising new tool for more effective monitoring of this species along the U.S. West Coast. The authors proposed to establish a trial passive acoustic monitoring network for harbor porpoise and evaluate the feasibility of a passive acoustic approach to monitoring harbor porpoise during marine renewable energy site development in California. The authors sought to describe the relationship between acoustic and visual observations of harbor porpoise and to evaluate the optimal spatial and temporal sampling scales for an effective monitoring network. The authors found that a passive acoustic monitoring network for harbor porpoise is feasible to implement and is an improvement over traditional visual survey methods due to increased temporal sampling. Substantially more simultaneous visual and acoustic surveys would be required to characterize this relationship accurately. The data suggest that the spatial distribution of harbor porpoises shifts over periods of weeks and can be highly variable between years, and therefore collecting baseline data at the population level for several years prior to potential disturbance (as well as during and after) will be critical for accurately assessing the impacts of marine renewable energy installations on harbor porpoise populations.

Keywords: Harbor porpoise, cetaceans, passive acoustic monitoring, marine renewable energy, echolocation.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

Introduction

Harbor porpoise *(Phocoena phocoena)* are found in coastal waters of the temperate northern hemisphere, where they are subjected to a variety of anthropogenic impacts including pollution, noise, and fishery interactions. Marine Renewable Energy (MRE) projects currently in development in California have the potential to disturb, displace, and damage the hearing of harbor porpoises. Effective monitoring strategies are necessary to establish baseline data prior to the installation of MRE structures, to determine the impacts of construction activities, and to assess long-term impacts from MRE site operation. Along the U.S. West Coast, harbor porpoise populations are monitored using line-transect aerial surveys, which are costly, weather-limited, and provide coarsely resolved data. However, passive acoustic monitoring (PAM), which involves using underwater microphones to detect vocalizing marine mammals, is a promising new tool for more effective monitoring of this species along the U.S. West Coast.

Project Purpose

The researchers proposed to establish a trial passive acoustic monitoring network for harbor porpoise and evaluate the feasibility of a passive acoustic approach to monitoring harbor porpoise during MRE site development in California. The researchers sought to describe the relationship between acoustic and visual observations of harbor porpoise and to evaluate the optimal spatial and temporal sampling scales for an effective monitoring network.

Project Results

The researchers found that a passive acoustic monitoring network for harbor porpoise is feasible to implement and is an improvement over traditional visual survey methods due to increased temporal sampling. The relationship between visual and acoustic porpoise detections is difficult to quantify due to mismatched temporal and spatial sampling between the two survey approaches. Substantially more simultaneous visual and acoustic surveys would be required to characterize this relationship accurately. However, findings suggest that passive acoustic monitoring networks can be fully functional as a standalone assessment approach and therefore precise pairing to visual observations may be unnecessary. The data suggest that the spatial distribution of harbor porpoises shifts over periods of weeks and can be highly variable between years, and therefore collecting baseline data at the population level for several years prior to potential disturbance (as well as during and after) will be critical for accurately assessing the impacts of MRE installations on harbor porpoise populations.

Project Benefits

This exploratory project represents the first implementation of a passive acoustic monitoring network for harbor porpoise outside of Europe and is a major step towards realizing passive acoustic monitoring for harbor porpoise populations in California. The researchers have developed effective mooring designs, documented the temporal and spatial variability in harbor porpoise distributions, and provided guidelines for future passive acoustic monitoring network development. The work to develop functional mooring designs and analysis approaches will be directly applicable to monitoring, assessment, and mitigation during future MRE development.

CHAPTER 1: Motivation for Using Fixed Passive Acoustic Networks to Monitor Harbor Porpoises During MRE Development

There is growing interest in the development of Marine Renewable Energy (MRE) projects along the California coastline (Forney et al. 1991, California Energy Commission 2011). Wind and waves are particularly promising sources of renewable energy in this region and proposed sites include target water depths of 0 to 200 meters for wind (Forney et al. 1991, Forney 1995, Dvorak et al. 2010) and less than 50 meters for wave energy installations (Previsic 2006, Brandt et al. 2011). Several of these potential MRE locations occur within the core habitat of harbor porpoises *(Phocoena phocoena)* in shallow coastal waters.

Along the California coast, harbor porpoises occur in four distinct populations (Calambokidis and Barlow 1991, Chivers et al. 2002, Benke et al. 2014). Harbor porpoises are commonly distributed throughout waters up to 100 meters deep, with the greatest densities in depths from 10-40 meters (Barlow 1988, Carretta et al. 2001, Rojas Bracho et al. 2010). Due to their nearshore distribution, harbor porpoises are exposed to a diverse array of lethal and sublethal anthropogenic impacts including pollution, noise, and fishery interactions (Barlow and Forney 1994). In some areas, cumulative anthropogenic impacts have led to the decline or disappearance of harbor porpoise populations. For example, harbor porpoises disappeared from San Francisco Bay and the Puget Sound in the mid-twentieth century and have only recently re-populated these areas (Calambokidis et al. 1985, Raum-Suryan and Harvey 1998).

The most significant threat to harbor porpoises from MRE development is the noise generated by construction activities, particularly pile driving (Madsen et al. 2006). Harbor porpoises, like many marine mammals, use sound to forage and to communicate. Noise from construction activities has the potential to disrupt harbor porpoise behavior, displace them from core habitat, and, at close range, may cause injury or death (Madsen et al. 2006). Given the well-documented sensitivity of harbor porpoise populations to human activities in the nearshore environment (Jefferson et al. 1994, Forney 1995, Benke et al. 2014), it is be important to develop effective techniques to assess the potential impacts of MRE projects on these populations in California.

Harbor porpoises produce highly-directional echolocation clicks with peak frequencies around 130 kHz (Au et al. 1999). These clicks attenuate rapidly in seawater which results in a variable passive acoustic detection range of several hundred meters (DeRuiter et al. 2010). Because these clicks are well described and do not travel long distances, they can be used as a proxy for animal density around a passive acoustic sensor. Networks of passive acoustic monitoring devices have been used to monitor the population stability of the critically-endangered Baltic Sea harbor porpoise (Gallus et al. 2012) and the closely-related and critically endangered vaquita *(Phocoena sinus)* in the Gulf of California (Rojas Bracho et al. 2010). Passive acoustic monitoring schemes have also been used to assess the short- and long-term impacts of MRE installations on harbor porpoises in the North and Baltic Seas (Teilmann and Carstensen 2012).

At the Horns Rev II wind farm in the Danish North Sea, researchers used porpoise click detectors (T-PODs or C-PODs; Chelonia Ltd., www.chelonia.co.uk) to monitor the impact of construction activities on harbor porpoise presence in a before-after control-impact (BACI) framework. They detected decreased harbor porpoise presence for one to three days at distances up to 18 km following pile-driving activity and an increase in harbor porpoise presence at a site 22 km away from the construction activity, indicating an influx of refugee animals (Brandt et al. 2011). Similarly, at the Nysted offshore wind farm in the Danish Baltic, researchers used T-PODs to document that the time between consecutive encounters of echolocation activity increased from six hours to three days after the onset of wind farm construction (Carstensen et al. 2006). Long-term passive acoustic monitoring of echolocation activity at this site has demonstrated that porpoise presence declined significantly since the baseline, pre-construction period and as of 2011 had not recovered to pre-construction levels (Teilmann and Carstensen 2012). These studies have demonstrated the value of baseline data collection in determining the impact of MRE construction activities and the utility of passive acoustic methods for both short- and long-term monitoring at MRE sites.

The success of these previous studies in detecting MRE impacts on harbor porpoise populations using passive acoustic methods is encouraging; however, harbor porpoise along the California coast often occur in higher densities than in the Baltic and North Seas, and therefore monitoring methods that have been successful in low-density areas may not translate well to California. Furthermore, the continental shelf along the California coast is much narrower than in other areas where harbor porpoise occur and harbor porpoise are found only within 10-30 km from shore. These differences in density and habitat structure demand the development of different passive acoustic monitoring schemes. This project aims to determine the feasibility of using passive acoustic monitoring devices for both long-term monitoring of harbor porpoise populations and impact assessments during MRE site development.

In the proposal to evaluate the feasibility of a passive acoustic monitoring network for harbor porpoise in California, two main research questions were outlined. First, what is the relationship between acoustic and visual observations of harbor porpoise? Second, what are the optimal spatial and temporal sampling scales for an effective monitoring network? This report describes the progress made towards answering these questions and advancing the use of passive acoustic monitoring for harbor porpoises along the California coast.

CHAPTER 2: Comparing Simultaneous Visual and Acoustic Observations of Harbor Porpoises

2.1 Introduction

2.1.1 Background

Populations of harbor porpoises along the California coast have been monitored using aerial surveys since the late 1980s (Forney et al. 1991). These surveys are effective for long-term monitoring of large-scale trends in abundance, but are not well suited to detect impacts to harbor porpoise populations on small temporal and spatial scales. Additionally, aerial surveys are expensive and weather-limited. Passive acoustic monitoring methods provide a powerful alternative to aerial surveys and are increasingly used to monitor small cetaceans both to assess long-term population trends (Benke et al. 2014) and to monitor before, during, and after potentially harmful human activities (Teilmann and Carstensen 2012). The researchers simultaneously conducted aerial and passive acoustic surveys to describe the relationship between visual and acoustic observations of harbor porpoises and to link historical aerial surveys to future passive acoustic monitoring efforts to maintain coherent trends in abundance.

2.1.2 Objectives

Objective 1: Describe the relationship between simultaneous visual and passive acoustic detections of harbor porpoises.

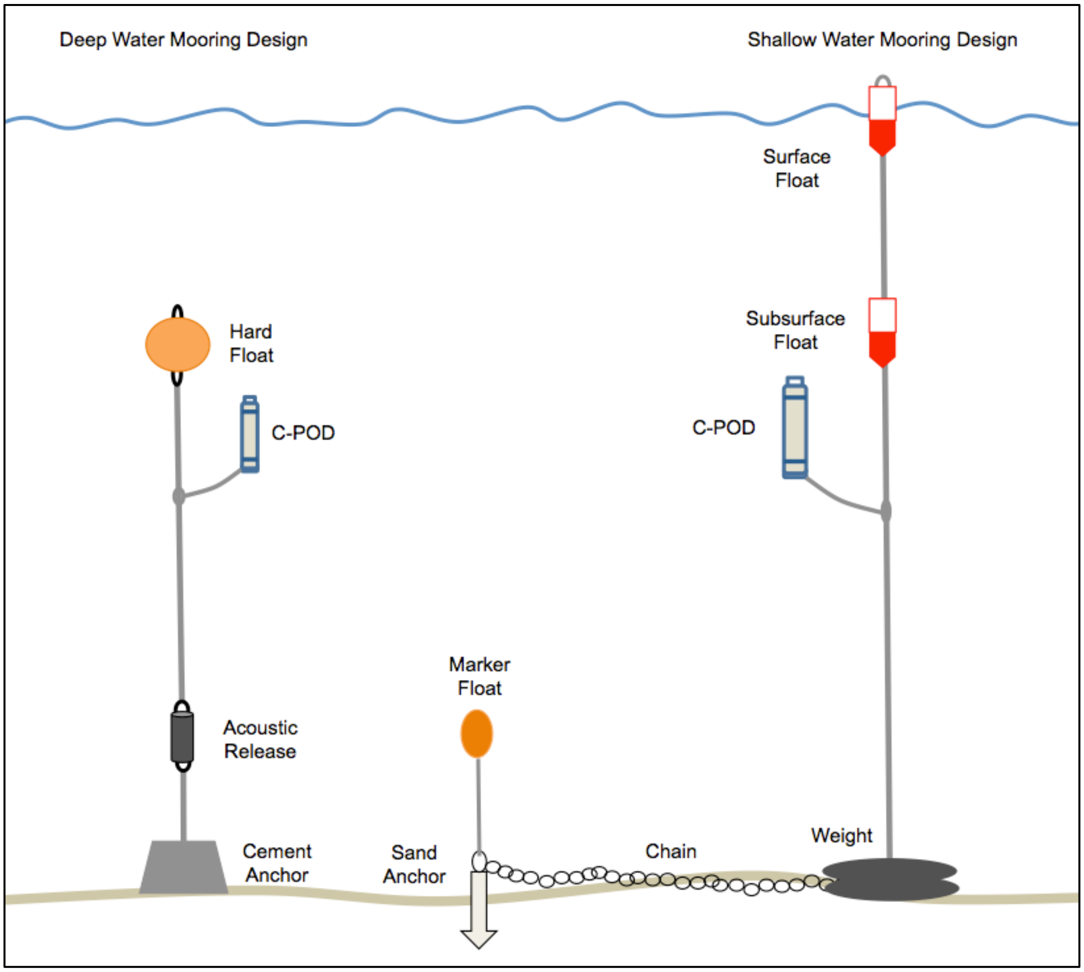
2.2 Methods

2.2.1 Field Methods

The researchers deployed a network of passive acoustic monitoring devices (C-PODs) in northern Monterey Bay (Fig. 1). Northern Monterey Bay was chosen for initial network deployment because the bathymetry in this area results in a rapid spatial gradient of harbor porpoise densities, with relatively high densities in the nearshore areas and relatively low densities near the deep Monterey Canyon. The study area included waters from 10 m to 100 m depth, north of Moss Landing (36.48° N) and east of Terrace Point (122.10° W), with a total area of 295 sq. km. The network design was a systematic, randomly positioned grid of 11 C-PODs spaced 5 km apart and oriented to mimic the shape of the coastline.

Scientific divers installed C-PODs at locations with water depths of less than 30 m. These moorings were L-shaped (Fig. 1) and included a surface marker, subsurface floats to keep the line taut, 50 lbs of weight at the vertex of the mooring, approximately 10 m of chain along the sea floor, and a sand anchor to hold the mooring in place. This mooring design allowed the mooring to lift partially off the sea floor during extreme wave events. C-PODs in water more than 30 m deep incorporated an acoustic release and did not require diver installation. These moorings (Fig. 1) included a 150 lbs cement weight, an acoustic release, and a large subsurface float. When the acoustic releases were triggered, the float, line, C-POD, and acoustic release returned to the surface, while the cement weight remained on the sea floor.

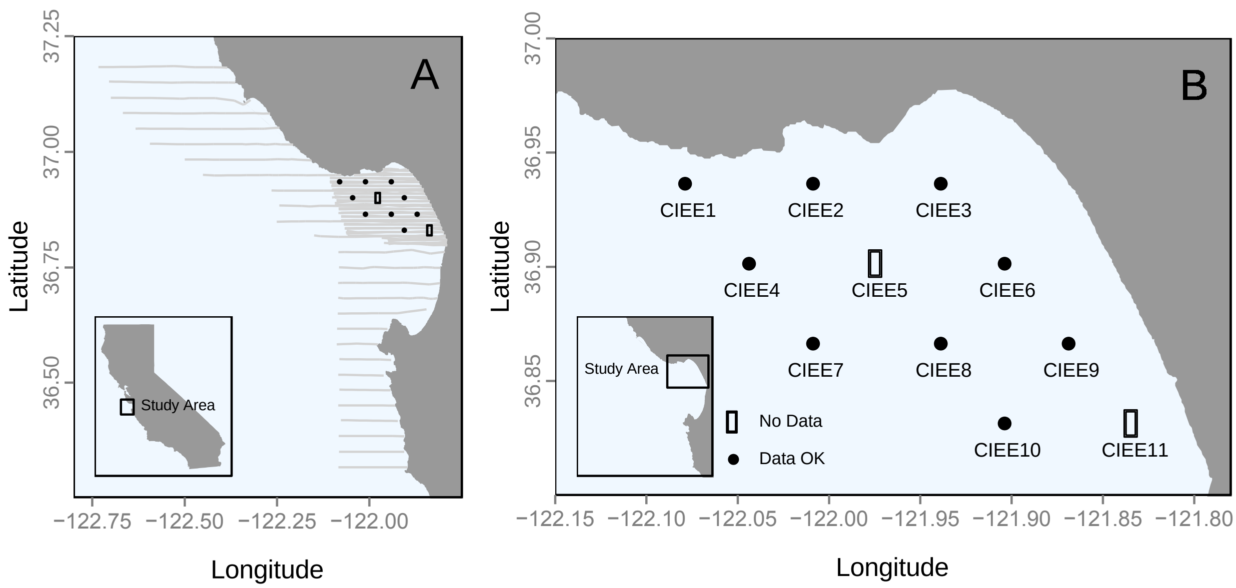
Figure 1: Passive Acoustic Mooring Designs



Schematic diagram of C-POD mooring designs (not to scale). Moorings at locations with water depths greater than 30 m were installed using the deep water (left) design, while moorings at locations with water depths less than 30 m were installed using the shallow water (right) design. The shallow water design required scientific diver installation and retrieval, while the deep-water design required the use of acoustic releases.

Simultaneous aerial surveys for harbor porpoise were conducted during the C-POD network deployment in 2013 (Fig. 2). One survey was flown over the entire Monterey Bay harbor porpoise population range and three replicate surveys were flown over the northern Monterey Bay study area. Surveys were conducted from a Partenavia high-wing twin-engine aircraft using standard aerial survey methods (Forney et al. 1991). In summary, two observers searched from bubble windows on either side of the aircraft while a third observer searched from a belly window in the rear of the aircraft. A data recorder transcribed verbal sighting information for cetaceans, turtles (including declination angle, species, and number of animals), and environmental (visibility conditions) information from the observers into a custom-written software program on a laptop computer.

Figure 2: Aerial Survey and Passive Acoustic Monitoring Effort in Monterey Bay



The left panel shows the entire range of the Monterey Bay harbor porpoise population with aerial survey transects (gray lines) and C-POD mooring locations (circles/rectangles). Right panel shows only the northern Monterey Bay study area, with C-POD mooring locations (circles) and station names. In both panels, filled circles indicate instruments from which data was retrieved, while hollow rectangles indicate instruments that failed to collect data as intended during the 2013 field season.

2.2.2 Data Analysis

Aerial survey data were filtered to include only effort segments flown in good survey conditions (Beaufort Sea States Code 0-2) because porpoise detectability drops off markedly in higher sea states. To compare aerial and acoustic datasets, aerial survey effort was extracted from a radius of 2.5 km around each C-POD mooring location. This radius corresponds to half the distance between C-POD moorings and was chosen so that aerial survey data was associated with a single C-POD mooring. Effort-normalized values of harbor porpoise seen per kilometer surveyed, PPK, (Forney et al. 1991, Forney 1995) were calculated for each day of aerial survey effort within these radii. This metric was chosen because absolute densities of harbor porpoises would be difficult to calculate within such small geographic areas. PPK per day provides a relative abundance of harbor porpoise presence comparable to the average number of echolocation clicks per hour during daytime hours.

To compare harbor porpoise detection rates in the aerial and acoustic datasets, the researchers calculated the total PPK across all ~70 km of aerial survey effort within 2.5 km of C-PODs and the mean number of echolocation clicks per hour during daytime hours across the 111to133 continuous days acoustic record of each C-POD mooring. The researchers used generalized linear models (GLMs) to model the aerial detection rate as a function the acoustic detection rate. In the simplest model, the researchers fit a linear model without an intercept term. In the second model, the predictor variable was log-transformed because the aerial detection rate appeared to increase non-linearly with increasing acoustic detection rates. An intercept term was also included to force the second model to include the origin because when few porpoises are present both aerial and acoustic detection rates are expected to approach zero.

2.3 Results

2.3.1 Summary of Data Collected

The network of 11 C-POD moorings was deployed for four months from August 2013 to January 2014 and each mooring collected between 111 and 133 continuous days of click data (Table 1). Aerial surveys were conducted on four days for a total of 1,930 km of aerial survey effort in good weather conditions within the Monterey Bay region.

Table 1: Summary of Aerial Survey and Passive Acoustic Monitoring Data Collected

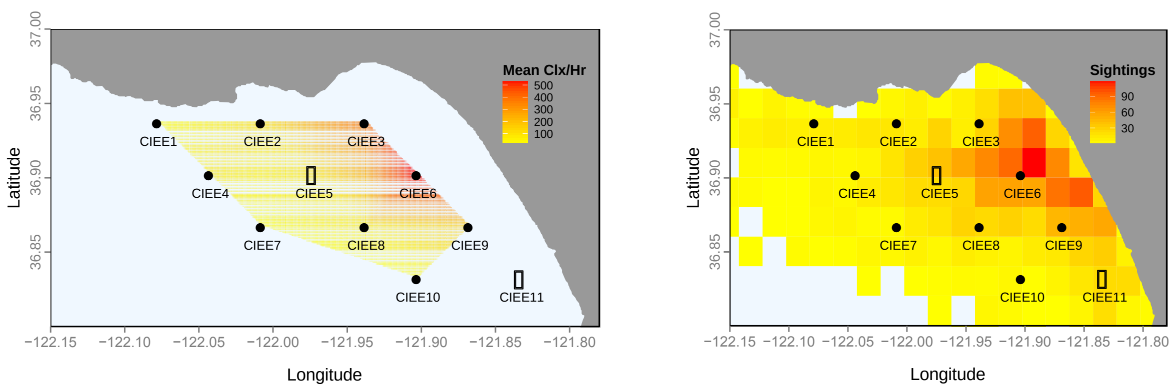
Mooring	Depth (m)	Deployment Length in days	Aerial Effort (km)	Mean Clicks per Hour	Total PPK
CIEE1	28	133	53	27	2.38
CIEE2	19	133	67	81	1.81
CIEE3	20	133	69	318	2.56
CIEE4	47	133	70	61	1.18
CIEE5	32	133	NA	NA	NA
CIEE6	24	133	69	532	3.16
CIEE7	67	111	68	24	0.53
CIEE8	60	133	69	62	0.88
CIEE9	29	132	70	127	1.80
CIEE10	74	132	69	26	0.13
CIEE11	29	132	NA	NA	NA

The depth reported is the depth of the water column at each mooring location. Acoustic detection rates are reported in mean clicks per hour during daytime hours. Visual detection rates are reported in total porpoise per kilometer (Total PPK) over all aerial survey effort flown within 2.5 km of each C-POD mooring in 2013.

2.3.2 Comparisons of Aerial and Acoustic Detection Rates

The aerial survey dataset showed considerable within-site variability in daily mean PPK across all harbor porpoise densities. Encouragingly, the lowest density site according to both metrics was CIEE10 and the highest density site according to both metrics was CIEE6 (Fig. 2). The difference in harbor porpoise presence at these two sites is a four-fold difference in total PPK and a 50-fold difference in mean clicks per day. The linear and non-linear models both found mean clicks per day to be a significant ($P < 0.05$) predictor of total PPK (Fig. 3). The non-linear model had slightly lower residual deviance than the linear model (3.07 versus 3.37 on 7 degrees of freedom) but based on a quantile-quantile plot seemed to fit the data less well.

Figure 3: Heatmaps of Passive Acoustic and Visual Harbor Porpoise Detections

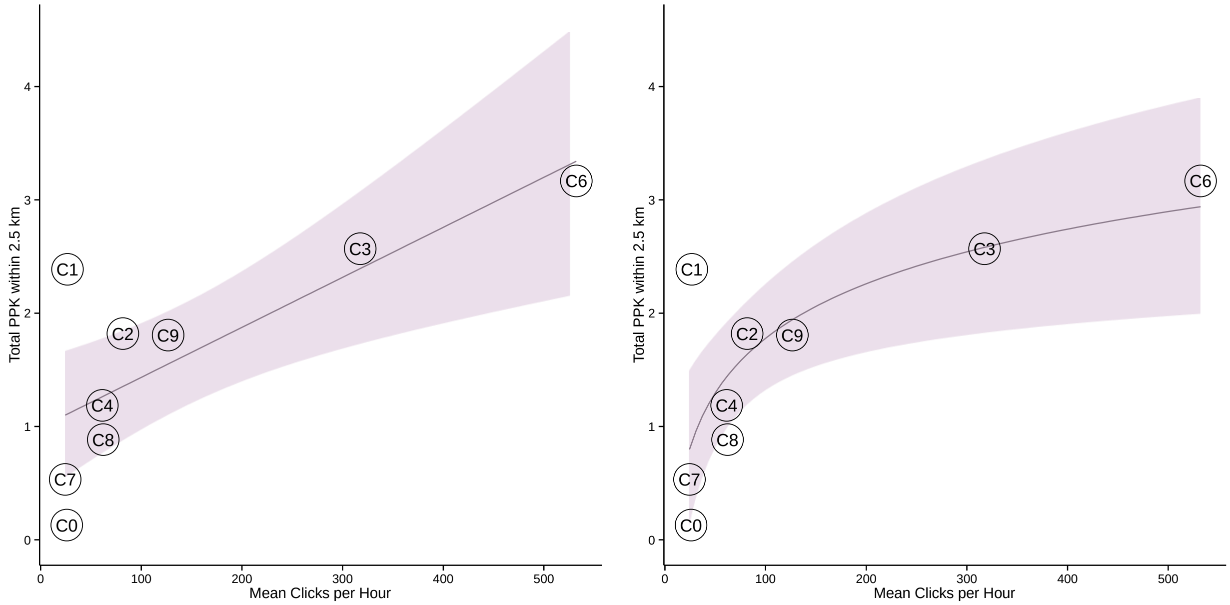


Passive acoustic (left panel) and visual (right panel) detection rates of harbor porpoises in 2013. Daytime acoustic detection rates (mean clicks per hour) were interpolated across the C-POD network study area. Visual detections (number of harbor porpoise sightings) were summed within 0.02 by 0.02 degree bins across the aerial survey area. Note that this map of sightings is not normalized by survey effort and does not account for group size.

2.4 Discussion

The range of harbor porpoise detection rates from the lowest to the highest density sites was a four-fold increase in PPK and a 50-fold increase in click rates. This may indicate that PPK saturates more quickly than click rates due to observer limitations or porpoise diving behavior. Comparisons of aerial and acoustic datasets proved challenging because these metrics are capturing different dimensions of true harbor porpoise density. Aerial surveys provide excellent spatial coverage at the expense of temporal resolution. Conversely, passive acoustic data can be collected continuously for months or years at a time, but individual sensors have limited detection ranges and thus the density of the passive acoustic network determines the spatial resolution of the passive acoustic dataset. The paired data collected during the 2013 field season were not sufficient to describe the relationship between passive acoustic and visual observations of harbor porpoises, and it is clear from analyses conducted to date that aerial survey data are not a sufficiently accurate approximation of true harbor porpoise abundance to be used as a standard for validation. Future work to index aerial and acoustic datasets may need to focus on linking trends in abundance rather than absolute densities.

Figure 4: Relationship Between Passive Acoustic and Visual Harbor Porpoise Detection Rates



Two possible relationships between passive acoustic (mean clicks per hour) and visual (porpoise seen per kilometer surveyed, PPK) harbor porpoise detection rates. Both panels show the acoustic (x-axis) and visual (y-axis) detection rates at individual moorings (circles with abbreviated mooring names), the model-predicted values (black line), and the 95 percent confidence intervals (purple shading).

Left Panel: linear GLM constructed without an intercept term.

Right Panel: nonlinear GLM.

Mean clicks per day were log-transformed and an intercept of zero was specified to force the model through the origin.

CHAPTER 3:
Developing Design Criteria for Passive Acoustic Monitoring of Harbor Porpoises

3.1 Introduction

3.1.1 Background

Although C-PODs have been used extensively to document the impacts of MRE installations on harbor porpoises in Europe, previous studies have primarily utilized linear before-after control-impact (BACI) array designs (Brandt et al. 2011). Additionally, one large-scale study unrelated to MRE development has attempted to estimate the absolute abundance of harbor porpoises in the Baltic Sea (Benke et al. 2014) and another has focused on estimating trends in abundance of the closely related vaquita (Rojas Bracho et al. 2010). In this project, the researchers have attempted to synthesize these different approaches to C-POD network design and objectives, with the goal of developing design criteria for passive acoustic monitoring networks of harbor porpoises in California.

3.1.2 Objectives

Objective 1: Determine appropriate spatial and temporal scales for monitoring harbor porpoise populations.

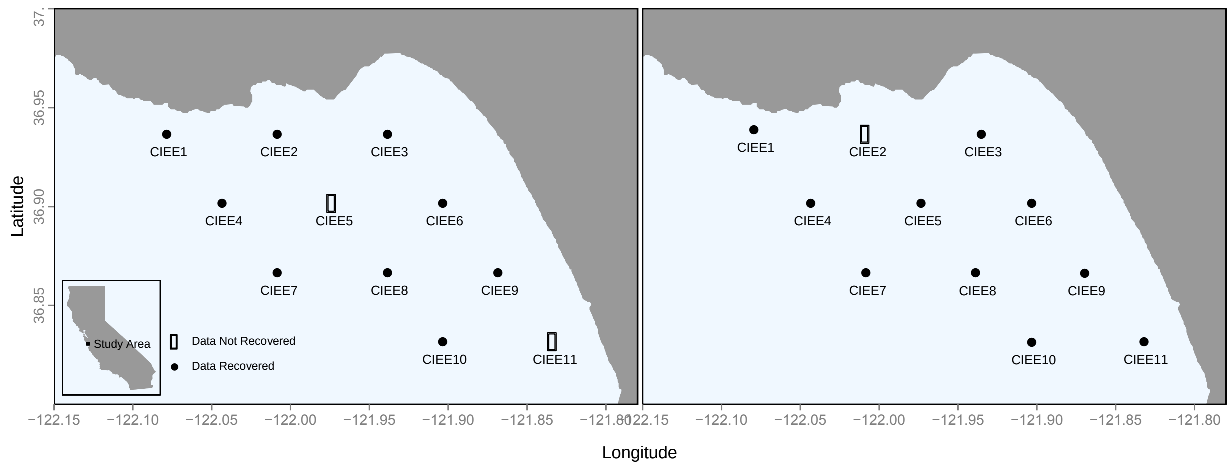
Objective 2: Evaluate whether passive acoustic networks can capture simulated trends in harbor porpoise abundance.

3.2 Methods

3.2.1 Field Methods

The researchers deployed a trial network of echolocation click detectors in northern Monterey Bay in 2013 and 2014 (Fig. 4). As reported in Chapter 2, northern Monterey Bay was chosen because the bathymetry in this area results in a rapid spatial gradient of harbor porpoise densities, with very high densities in the nearshore areas and relatively low densities near the deep Monterey Canyon. For this pilot study, the researchers chose to deploy a dense network of C-PODs over a small geographic area to better evaluate the optimal spatial sampling required to adequately characterize harbor porpoise presence. Like the areas of impact around potential MRE installations, the study area comprises only a portion of the range of the Monterey Bay harbor porpoise population and therefore the study population is not closed to individual movements in or out of the study area. The study area included waters from 10 m to 100 m depth, north of Moss Landing (36.48° N) and east of Terrace Point (122.10° W), with a total area of 295 sq. km. The network design is a systematic, randomly positioned grid of 11 C-PODs spaced 5 km apart and oriented to conform to the shape of the coastline (Fig. 5).

Figure 5: Monterey Bay Study Area in 2013 and 2014



C-POD mooring network in 2013 (left panel) and in 2014 (right panel). Filled circles indicate instruments from which data were recovered as planned while hollow rectangles indicate moorings from which no data were recovered because of equipment loss or failure.

3.2.2 Data Analysis

C-PODs detected individual echolocation clicks and stored information about each click in text format on an SD card. No waveform data were collected. In post-processing, clicks were classified as likely to have been produced by harbor porpoise using characteristics including the peak frequency, duration, and inter-click interval. Using the KERNO classification algorithm in the specialized program CPOD.exe, all high-quality harbor porpoise echolocation clicks were extracted from the C-POD records. For most analyses, the mean number of echolocation clicks per day was used as the acoustic metric. All analyses were carried out in R v. 3.1.0.

To compare harbor porpoise echolocation click rates across the two field seasons, the R package ggplot2 was used to display time series of each mooring in each year with local smoothing (LOESS) to improve readability. The researchers also constructed descriptive box-and-whisker plots to illustrate the median, first and third quantiles, minimum and maximum values, and outlier values of echolocation clicks per day at each mooring in each year. These plots were combined with rotated kernel density plots (violin plots) that illustrate the distribution of data across values of echolocation clicks per day. The change in the mean number of echolocation clicks per day at each mooring was calculated, as well as a total change for the study area using only data from moorings that collected data in both survey years.

To examine spatial differences in relative harbor porpoise density in 2013 and 2014, heatmaps of mean echolocation click rates were constructed across the study area. Values were interpolated across the study area using the R packages rgdal, akima, and sp and plotted using ggplot2. A heatmap of the difference in mean echolocation rates between 2013 and 2014 was also constructed to more clearly illustrate spatial differences in relative harbor porpoise density.

3.2.2.1 Temporal and Spatial Correlations

To quantify the spatial and temporal correlations within and between moorings, the researchers used autocorrelation and cross-correlation functions within the R package stats and plotted relationships using the R package ggplot2. Lag time (in days) was compared to an autocorrelation of mean echolocation clicks per day for each individual C-POD record in both years. The researchers also examined the relationship between the distance between C-POD moorings and the degree of cross-correlation with no lag time, between the distance and maximum cross-correlation when lag time was allowed to vary, and between the distance and the lag time that produced the maximum cross-correlation. Linear models were constructed to describe these relationships and model predictions and standard errors were plotted.

3.2.2.2 Simulated Scenarios of Disturbance

To evaluate the ability of the C-POD network to detect changes in harbor porpoise density, the researchers simulated disturbances and calculated the statistical power to detect the simulated change. Statistical power was defined as 1-β, or the probability of correctly rejecting the null hypothesis, where β is the probability of incorrectly failing to reject the null hypothesis (Type II Error). The null hypothesis is that there is no change and the alternative hypothesis is that there was a change. Cohen's d (the difference in means between the two samples divided by their pooled standard deviation) was used as the effect size. Statistical power was determined using a paired, two-sided t-test in the R package pwr with alpha levels of 0.05, 0.10, and 0.20. In the simplest scenario, the researchers uniformly decreased and increased the mean number of echolocation clicks per day by known percentages across the entire study area. Data were averaged by mooring and month to increase sample size and evaluate if seasonal changes in harbor porpoise distribution could result in variable network power. In a more complex scenario, an epicenter for a simulated disturbance was randomly chosen. Mean click rates were decreased by 75 percent at the epicenter, by 50 percent at moorings within a 7.5 km radius of the epicenter, and by 25 percent at moorings within a 20 km radius of the epicenter. This simulation was conducted iteratively for all possible epicenter locations within the study area.

3.3 Results

3.3.1 Summary of Data Collected

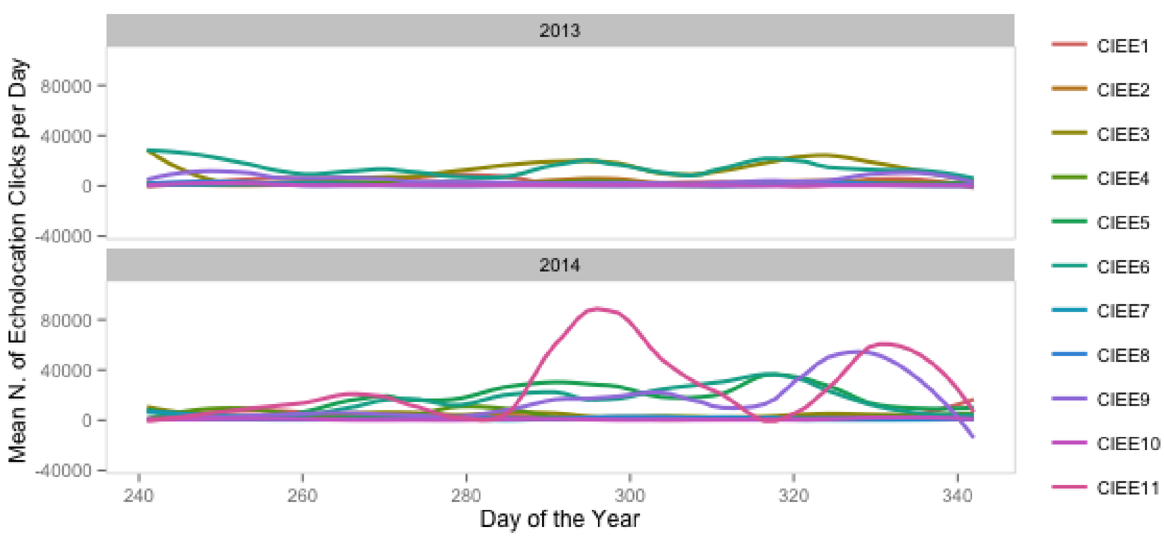
The network of 11 C-POD moorings was deployed for four months from August 2013 to January 2014 and each mooring collected between 111 and 133 continuous days of click data. The network from August 2014 to January 2015 was redeployed and each mooring collected between 134 and 157 continuous days of click data. All instruments were deployed in both years between August 29th and December 8th. Across instruments that were deployed in both years, the click rate increased 11 percent between 2013 and 2014 (Table 2) though the rate of change ranged from -66 percent at station CIEE3 to +165 percent at station CIEE9. This calculation is likely biased because it does not include data from moorings CIEE2, CIEE5, or CIEE11. No strong seasonal patterns were observed in 2013, but in 2014 click rates increased in the second half of the monitoring period (Fig. 6).

Table 2: Summary of Echolocation Clicks Recorded in 2013 and 2014

Mooring	Mean Clx/Day in 2013	Mean Clx/Day in 2014	Percent Change
CIEE1	3,963	3,314	-16 percent
CIEE2	2,505	NA	NA
CIEE3	12,334	4,175	-66 percent
CIEE4	2,078	4,212	+103 percent
CIEE5	NA	17,748	NA
CIEE6	14,673	15,593	+6 percent
CIEE7	660	1,479	+124 percent
CIEE8	1,374	1,284	-7 percent
CIEE9	5,567	14,762	+165 percent
CIEE10	524	784	+49 percent
CIEE11	NA	26,340	NA
Total			**+11 percent**

Mean Clx/Day is the mean of all echolocation clicks recorded from August 29th to December 8th in each year. The total percent change was calculated only from instruments that collected data in both years.

Figure 6: Smoothed Time Series of Mean Echolocation Rates



Time series of mean echolocation clicks per day at each mooring location in 2013 and 2014. Data were locally smoothed using a LOESS model with alpha = 0.3.

In 2013, two instruments (CIEE5 and CIEE11) failed and did not return any data. One failure was due to corrosion from battery leakage, while the cause of failure in the second case remains unknown. Additionally, one C-POD (CIEE5) was incidentally entangled in crab pot fishing gear and returned to the researchers by a local fisherman approximately three weeks before the planned mooring retrieval. Two additional moorings (CIEE2 and CIEE11) were found to be missing their surface floats, but all instruments and anchors were successfully recovered via diver searches. It is likely that the floats on these two moorings became entangled in boat propellers, as they were near the Santa Cruz and Moss Landing harbors. In 2014, one C-POD mooring (CIEE7) was incidentally entangled in crab pot fishing gear and returned to the researchers by a local fisherman within two days of the planned retrieval. Additionally, mooring CIEE2, located near the Santa Cruz harbor, was completely missing from its anchor, presumably due to entanglement in a boat propeller. The instrument and data recovery rate was 82 percent in 2013 and 90 percent in 2014.

3.3.2 Analytical Results

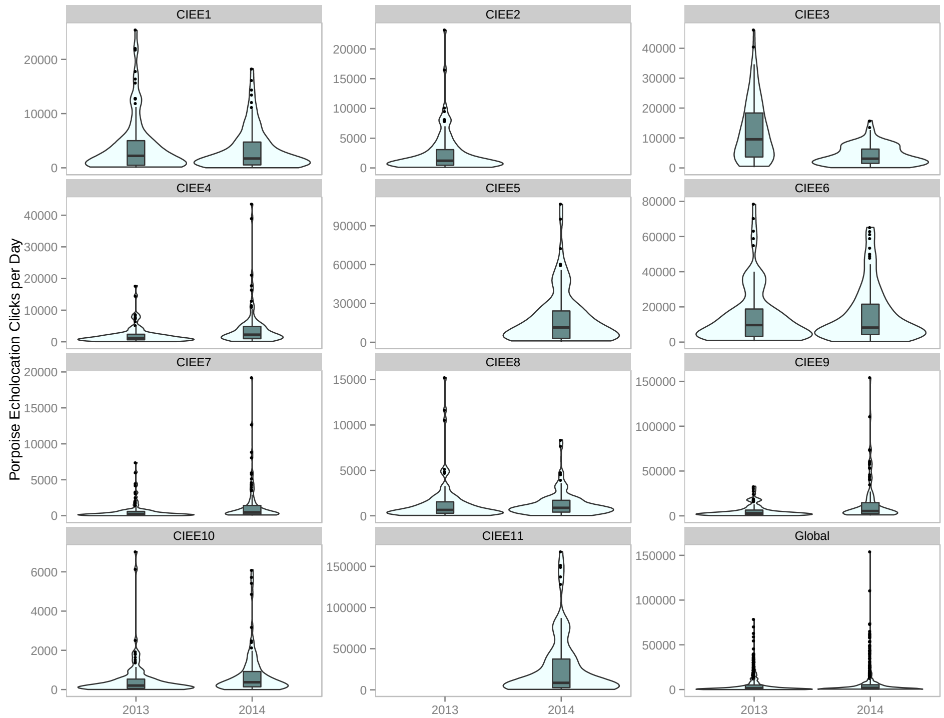
As reported previously, echolocation click rates were 11 percent higher in 2014 than in 2013. At some locations, the distribution of echolocation click rates was consistent between years while others were not (Fig. 7). For example, stations CIEE1 and CIEE6 showed very similar distributions in the two survey years, while at station CIEE3 click rates were higher in 2013 than in 2014. Examining these differences in a spatial context, there is an apparent southward shift in distribution between 2013 and 2014 (Fig. 8 and 9). The highest density site was CIEE3 in 2013 (mean 14,673 clx/day) and CIEE11 in 2014 (mean 26,340 clx/day).

3.3.2.1 Temporal and Spatial Correlations

The autocorrelation within individual mooring records drops dramatically within five days (Fig. 10). The first zero crossing of the mean autocorrelation was 16 days in 2013 and 12 days in 2014, indicating that harbor porpoise distribution patterns are shifting on timescales of about two weeks. These findings are consistent with previous aerial surveys which have observed shifts in harbor porpoise distribution on the order of weeks to months. These patterns appeared broadly consistent across the two years sampled.

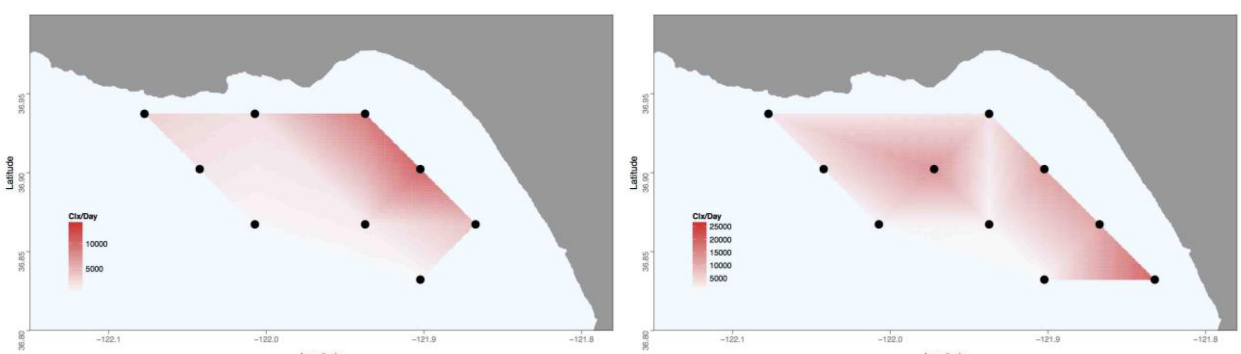
When the degree of correlation between instruments at varying distances from one another with no time lag was examined, the researchers found a weak negative relationship between distance and degree of correlation (Fig. 11), which was similar in both years. Using a simple linear GLM to describe this relationship, the researchers found that distance was a significant predictor of correlation strength ($P < 0.0001$). The model predicted a correlation of zero at a distance of 8.75 km. Correlations beyond this distance were generally negative rather than zero, indicating movements of harbor porpoises between different regions within the study area. When the time lag between records was allowed to vary by up to 30 days (Fig. 12), the researchers found that the maximum cross-correlation was also significantly negatively related to distance ($P < 0.01$) and that the lag time producing the maximum cross-correlation was significantly positively related to distance ($P < 0.001$). There was considerable scatter in all of these comparisons but trends were consistent with expectations for temporal and spatial correlation between moorings.

Figure 7: Comparison of Echolocation Rates in 2013 and 2014



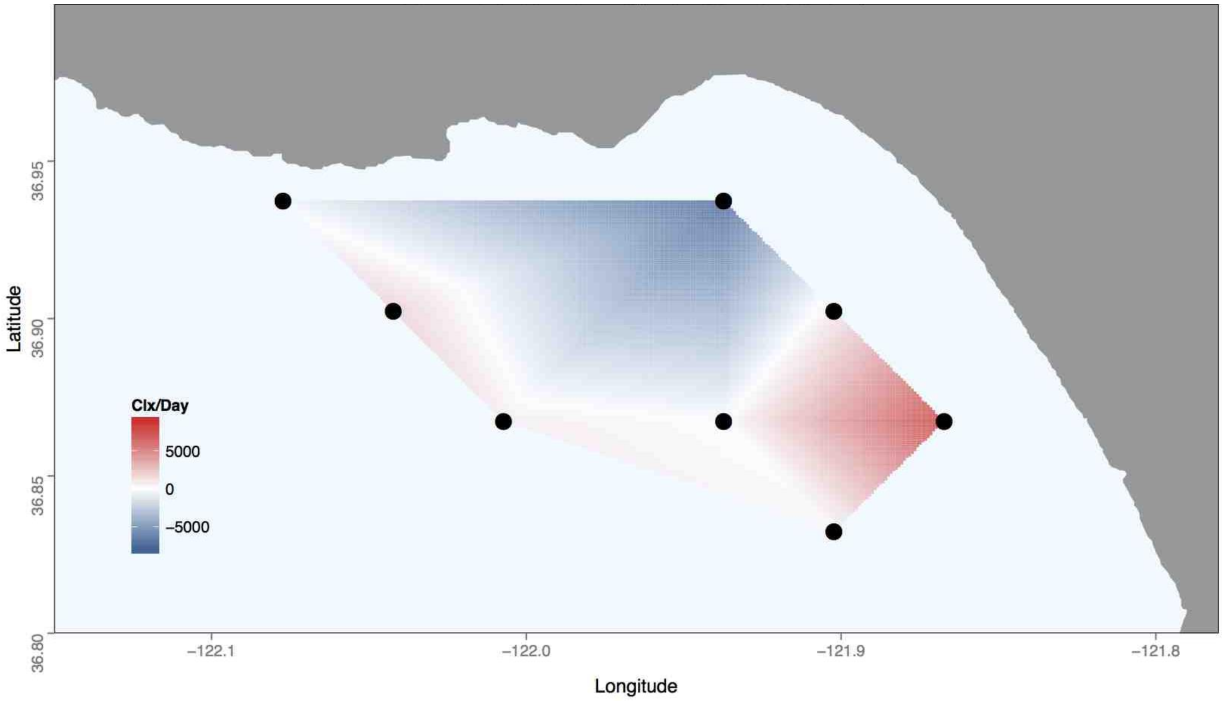
Box-and-whisker (green) and violin kernel density (blue) plots illustrating the distributions of echolocation clicks per day recorded across all monitoring stations in 2013 and in 2014.

Figure 8: Spatial Differences in Echolocation Click Rates in 2013 and 2014



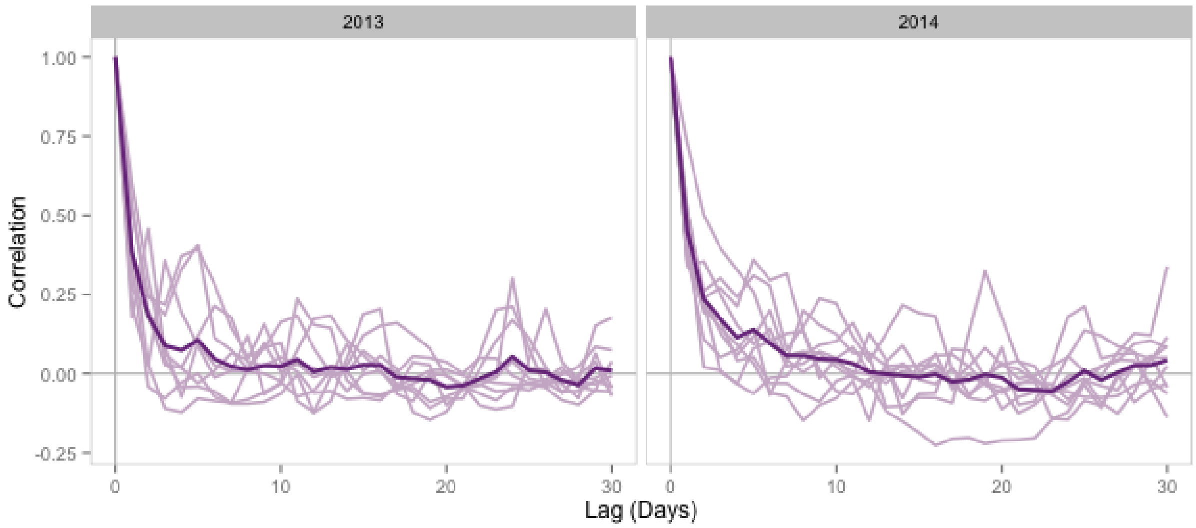
Interpolated mean harbor porpoise echolocation clicks per day in 2013 (left panel) and in 2014 (right panel).

Figure 9: Spatial Differences in Echolocation Click Rates between 2013 and 2014



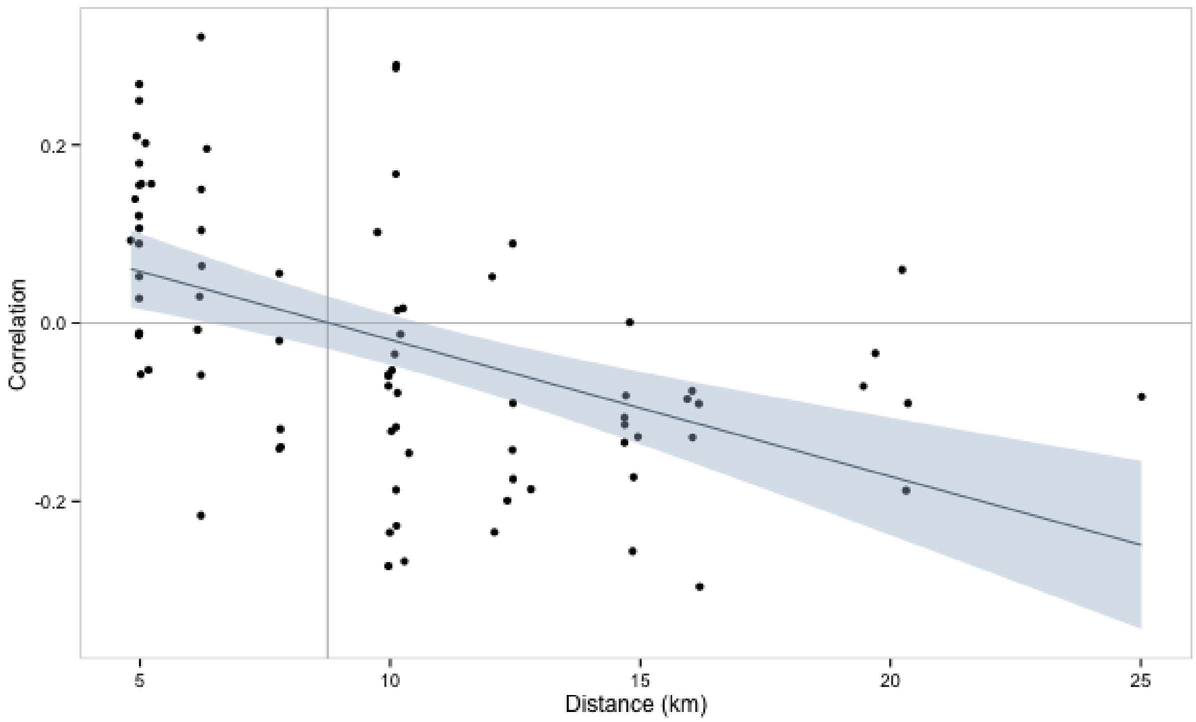
Interpolated difference between mean harbor porpoise echolocation clicks per day observed in 2013 and in 2014. Blue areas indicate a negative difference (lower click rates in 2014 than in 2013) while red areas indicate a positive difference (higher click rates in 2014 than in 2013). Only moorings for which data were available in both years were included.

Figure 10: Autocorrelation within Passive Acoustic Records



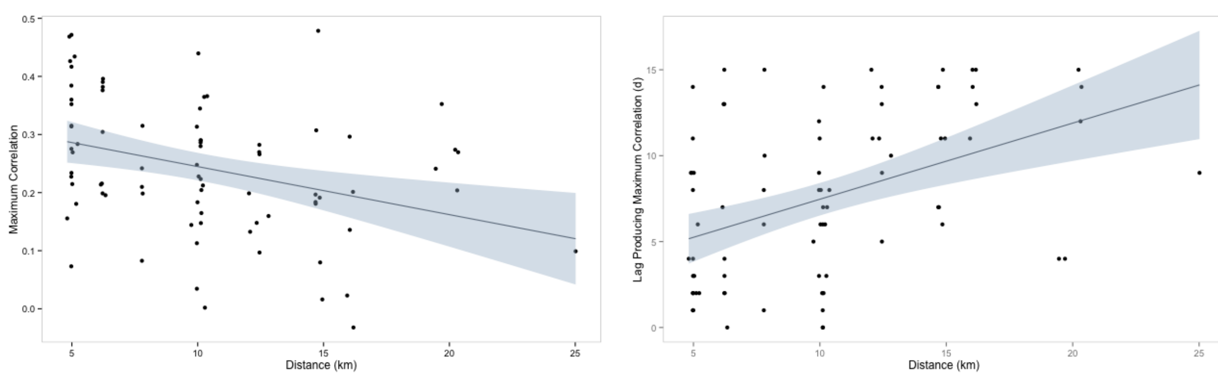
Lag (in days) versus correlation for all C-POD records in 2013 and 2014. Pale purple lines show autocorrelation at individual moorings, while the dark purple line shows mean autocorrelation. The first zero crossing of the mean autocorrelation occurs after 16 days in 2013 and after 12 days in 2014.

Figure 11: Spatial Cross-Correlation Between Instruments



Distance between moorings versus cross correlation with no temporal lag. All possible pairs of moorings were evaluated in both 2013 and 2014 and each pairing is represented by a single black point. A linear model (dark blue line) with standard error (light blue shading) illustrates the negative relationship between distance and degree of correlation between instruments. The model predicts a correlation of zero at a distance of 8.75 km (gray lines).

Figure 12: Maximum Cross-Correlation Between Instruments

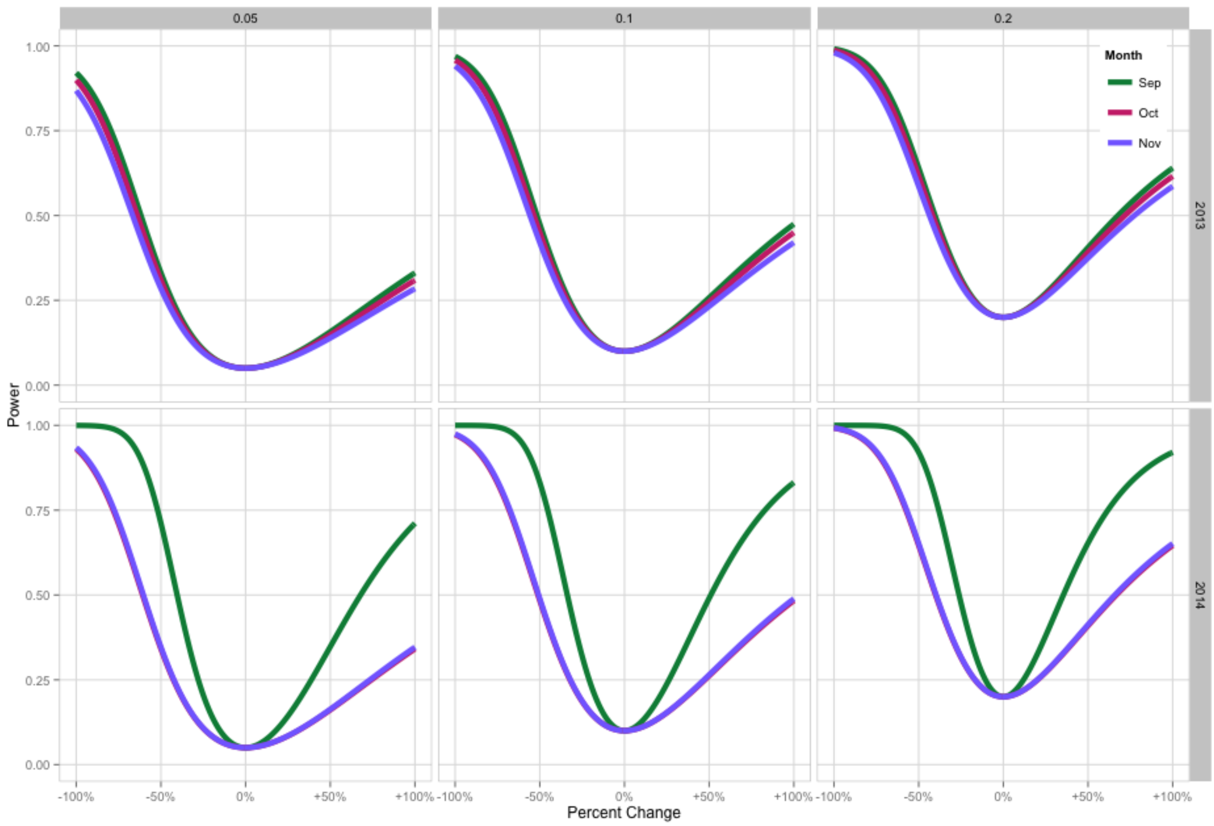


The left panel shows distance between instruments versus maximum possible correlation when the temporal lag was allowed to vary. All possible instrument pairs for both years are shown. The right panel shows the distance between instruments versus the temporal lag (in days), which produced the maximum correlation between instruments. Linear models (dark blue lines) with standard errors (light blue shading) indicate the negative relationship between distance and maximum correlation (left panel) and the positive relationship between distance and the lag time producing the highest correlation (right panel).

3.3.2.2 Simulated Scenarios of Disturbance

The results of the simulated uniform reduction in harbor porpoise echolocation click rates indicate that statistical power is low (<0.25) for changes less than 50 percent, but high (>0.75) for changes exceeding 75 percent (Fig. 13). As expected, statistical power increased with significance level. In 2013, statistical power was similar across the three months sampled. In 2014, statistical power was higher in September than in October or November. This is due to the lower variance in click rates across the study area in September compared to other months.

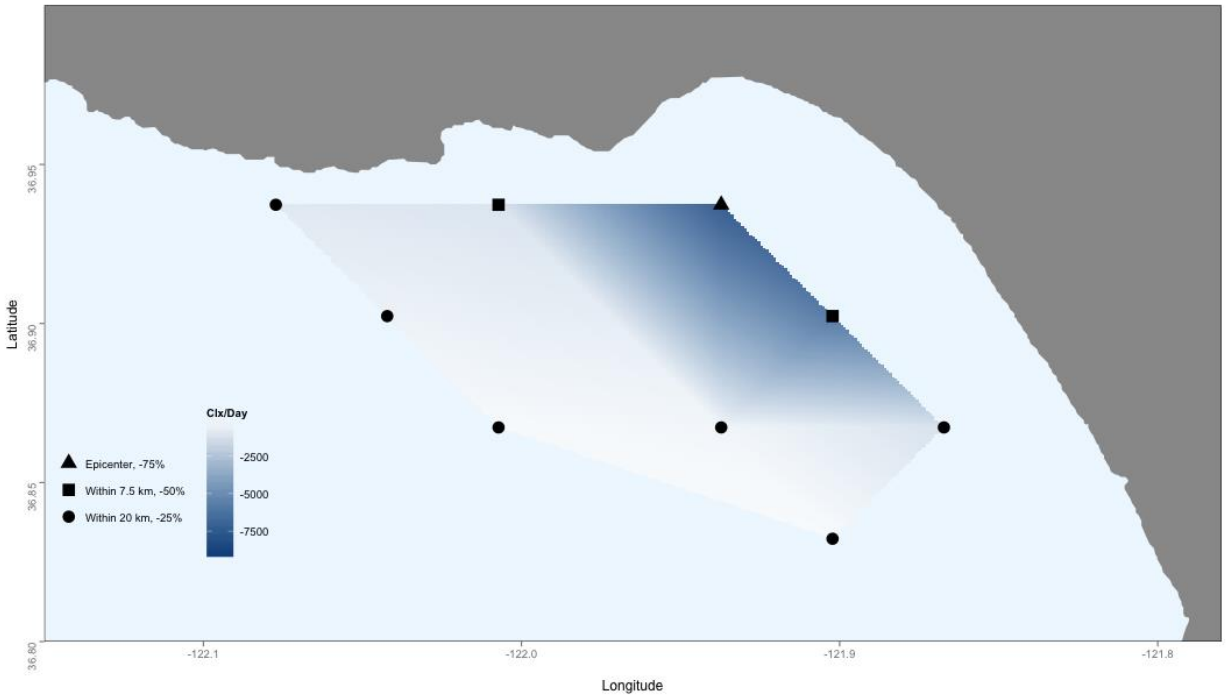
Figure 13: Statistical Power to Detect Simulated Uniform Disturbances



Simulated percent change (x-axis) versus calculated statistical power (y-axis) at three different significance levels (vertical panels) in 2013 and 2014 (horizontal panels).

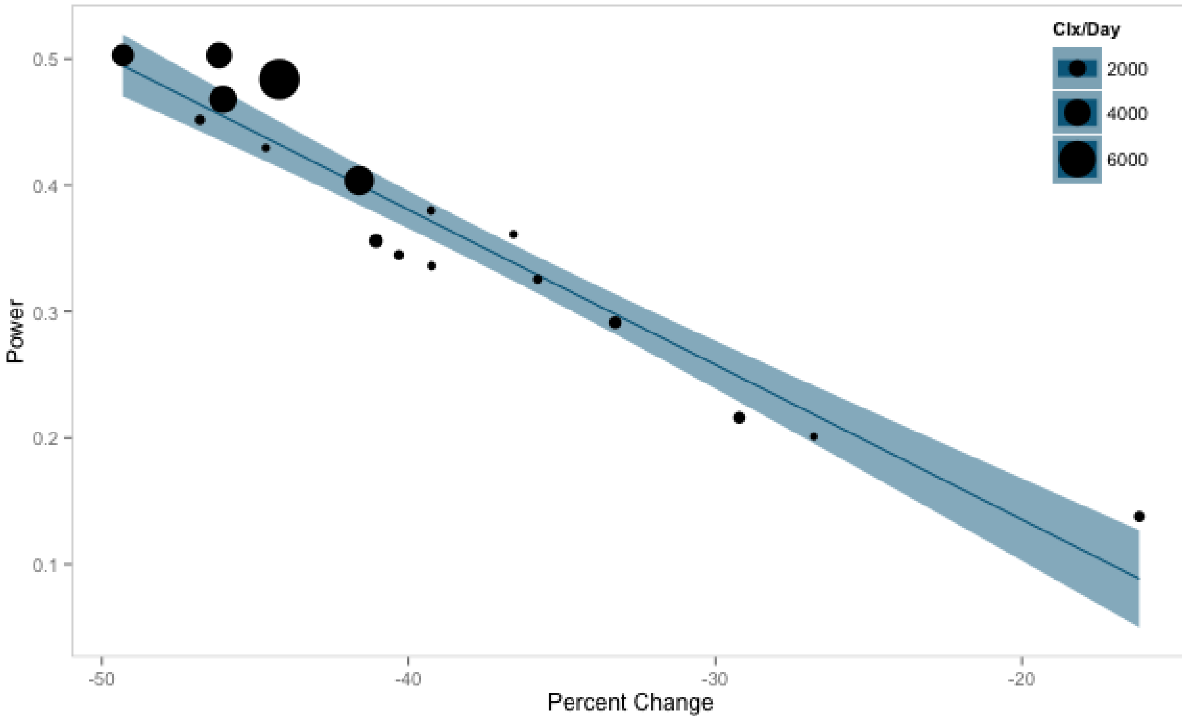
A more complex scenario of disturbance is illustrated in Figure 14 with a simulated disturbance in the northeast corner of the study area. The effective percent change in click rates across the study area varied depending on the simulated location of the disturbance. Disturbance locations along the edges of the study area generally resulted in lower effective percent changes due to fewer neighboring moorings being impacted. The power to detect simulated disturbances was negatively related to the effective percent change (Fig. 15), which was influenced by both the location of the disturbance relative to other moorings and the relative density of harbor porpoises at the disturbance location. Disturbances at locations with higher densities of porpoises resulted in higher effective percent changes and higher statistical power.

Figure 14: Example of a Simulated Disturbance



Simulated disturbance (triangle) and resulting reduction in echolocation click rates (blue shading).

Figure 15: Statistical Power to Detect Simulated Complex Disturbances



Effective percent change of simulated disturbances across the monitoring network (x-axis) and resulting statistical power (y-axis). Individual scenarios are represented by black dots scaled by the original number of echolocation clicks per day at the simulated epicenter. The blue line and shading represent model-predicted power and standard error.

3.4 Discussion

The researchers successfully collected two years of passive acoustic data on harbor porpoises in northern Monterey Bay. The C-POD mooring designs functioned well, though the researchers found that moorings with surface markers were at risk for entanglement in boat propellers while moorings without surface markers were at risk for entanglement in fishing gear. Based on experience, when designing future monitoring networks it will be important to consider the spatial distribution of local fisheries, boat traffic, and large whales to design moorings appropriately. When deciding on the number of C-PODs necessary for effective monitoring, a minimum loss rate of 10-25 percent should be expected.

The 11 percent observed increase in harbor porpoise echolocation rates in the study area between 2013 and 2014 is certainly due to animal movement into the study area. The maximum reproductive rate for this species is 5-7 percent per year (REF) but is likely lower for the Monterey Bay population since it is near carrying capacity. The high within- and between-year variability in harbor porpoise echolocation rates observed over the course of this study indicates that short, one-year baseline monitoring periods prior to MRE installation will be insufficient to adequately characterize harbor porpoise distribution and abundance in areas of potential impact. The apparent southward shift in the distribution of animals from 2013 to 2014 (Fig. 9) was especially visible in October and November of 2014, when a substantial increase in harbor porpoise echolocation rates was observed at stations located towards the southern end of the study area (Fig. 6). These observations highlight the importance of monitoring at the population level to distinguish animal movements from true changes in abundance. In the context of MRE, monitoring at large spatial scales before, during, and after MRE installation will allow managers to discriminate avoidance behaviors from true decreases in harbor porpoise abundance.

Through analysis of the temporal autocorrelation within C-POD records, the researchers found that changes in harbor porpoise distribution are occurring on timescales of approximately two weeks (Fig. 10). The cross-correlation between instruments fell to zero at a distance of 8.75 km (Fig. 11) suggesting that future monitoring networks should be designed with inter-instrument spacing on the order of 5-10 km. However, given expected instrument loss rates of 10-25 percent, it may be prefereable to design monitoring networks with slightly redundant spatial sampling to avoid large data gaps due to missing instruments.

The simulated reductions in harbor porpoise echolocation click rates demonstrated that, as expected, statistical power is relatively low for small changes in abundance and relatively high for large changes in abundance (Fig. 13). At an alpha level of 0.05, the power to detect a 50 percent uniform decrease across the study area was between 0.28 and 0.71. Similarly, in a more complex simulated disturbance, where echolocation rates were reduced drastically at the epicenter of the simulated disturbance and more moderately at greater distances (Fig. 14), a 50 percent effective reduction in click rates resulted in a statistical power of 0.46 at an alpha level of 0.05. To put these results in perspective, reported power to detect a 50 percent decrease in harbor porpoise populations over a 15 year period using visual survey methods ranges from 0.14 to 0.33 (Taylor et al. 2006). Although these simple simulations likely represent a best case scenario for statistical power to detect changes in harbor porpoise abundance, the researchers believe that these results indicate that a passive acoustic approach to monitoring harbor porpoise populations will have greater power to detect trends than traditional visual survey methods. However, the documented variability between years at this study site suggests that for passive acoustic monitoring to be effective, it will be necessary to conduct multi-year baseline studies to fully characterize natural variability in harbor porpoise acoustic activity before using passive acoustic monitoring to infer trends in abundance.

In conclusion, this two-year pilot study demonstrated the feasibility of a passive acoustic monitoring network for harbor porpoise in California. This exploratory project has led to the development of effective mooring designs, documented the temporal and spatial variability in harbor porpoise distributions, and provided guidelines for future passive acoustic monitoring network development. This project represents the first implementation of a passive acoustic monitoring network for harbor porpoise outside of Europe and is a major step towards realizing passive acoustic monitoring for harbor porpoise populations in California. The work to develop functional mooring designs and analysis approaches will be directly applicable to monitoring, assessment, and mitigation during future MRE development.

REFERENCES

Au, W. W. L., R. A. Kastelein, T. Rippe, and N. M. Schooneman. 1999. Transmission beam pattern and echolocation signals of a harbor porpoise (Phocoena phocoena). The Journal of the Acoustical Society of America 106:3699.

Barlow, J. 1988. Harbor porpoise, Phocoena phocoena, abundance estimation for California, Oregon, and Washington: 1. Ship surveys. Fishery Bulletin 86:417–432.

Barlow, J., and K. A. Forney. 1994. An Assesssment of the 1994 Status of Harbor Porpoise in California. US Department of Commerce, National Oceanic and Atmospheric Administration, National Marine Fisheries Service, Southwest Fisheries Science Center.

Benke, H., S. Bräger, M. Dähne, A. Gallus, S. Hansen, C. G. Honnef, M. Jabbusch, J. C. Koblitz, K. Krügel, and A. Liebschner. 2014. Baltic Sea harbour porpoise populations: status and conservation needs derived from recent survey results. Mar Ecol Prog Ser 495:275–290.

Brandt, M., A. Diederichs, K. Betke, and G. Nehls. 2011. Responses of harbour porpoises to pile driving at the Horns Rev II offshore wind farm in the Danish North Sea. Marine Ecology Progress Series 421:205–216.

Calambokidis, J., and J. Barlow. 1991. Chlorinated hydrocarbon concentrations and their use for describing population discreteness in harbor porpoises from Washington, Oregon, and California. Page 101 *in*. US Dept. of Commerce, National Oceanic and Atmoospheric Administration, National Marine Fisheries Service.

Calambokidis, J., S. M. Speich, J. Peard, G. H. Steiger, J. C. Cubbage, D. M. Fry, and L. J. Lowenstine. 1985. Biology of Puget Sound marine mammals and marine birds: population health and evidence of pollution effects. US Department of Commerce, National Oceanic and Atmospheric Administration, National Ocean Service.

California Energy Commission, T. 2011. Renewable Power In California: Status And Issues. Pages 1–336.

Carretta, J. V., B. L. Taylor, and S. J. Chivers. 2001. Abundance and depth distribution of harbor porpoise (Phocoena phocoena) in northern California determined from a 1995 ship survey. Fishery Bulletin 99:1–11.

Carstensen, J., O. Henriksen, and J. Teilmann. 2006. Impacts of offshore wind farm construction on harbour porpoises: acoustic monitoring of echo- location activity using porpoise detectors (T-PODs). Marine Ecology Progress Series 321:295–308.

Chivers, S. J., A. E. Dizon, P. J. Gearin, and K. M. Robertson. 2002. Small-scale population structure of eastern North Pacific harbour porpoises (Phocoena phocoena) indicated by molecular genetic analyses. Journal of Cetacean Research and Management 4:111–122.

DeRuiter, S. L., M. Hansen, H. N. Koopman, A. J. Westgate, P. L. Tyack, and P. T. Madsen. 2010. Propagation of narrow-band-high-frequency clicks: Measured and modeled transmission loss of porpoise-like clicks in porpoise habitats. The Journal of the Acoustical Society of America 127:560–567.

Dvorak, M. J., C. L. Archer, and M. Z. Jacobson. 2010. California offshore wind energy potential. Renewable Energy 35:1244–1254.

Forney, K. 1995. A decline in the abundance of harbor porpoise, Phocoena phocoena, in nearshore waters off California, 1986-93. Fishery Bulletin 93:741–748.

Forney, K. A., D. A. Hanan, and J. Barlow. 1991. Detecting Trends in Harbor Porpoise Abundance from Aerial Surveys Using Analysis of Covariance. Fishery Bulletin 89:1–11.

Gallus, A., M. Dähne, U. K. Verfuß, S. Bräger, S. Adler, U. Siebert, and H. Benke. 2012. Use of static passive acoustic monitoring to assess the status of the "Critically Endangered" Baltic harbour porpoise in German waters. Endangered Species Research 18:265–278.

Jefferson, T. A., B. E. Curry, and N. A. Black. 1994. Harbor porpoise mortality in the Monterey Bay halibut gillnet fishery, 1989. Rep. Int. Whaling Comm. Spec:445–448.

Madsen, P. T., M. Wahlberg, J. Tougaard, K. Lucke, and P. L. Tyack. 2006. Wind turbine underwater noise and marine mammals: implications of current knowledge and data needs. Marine Ecology Progress Series 309:279–295.

Previsic, M. 2006. California Ocean Wave Energy Assessment. energy.ca.gov. California Energy Commission, PIER Renewable Energy Technologies Program Area.

Raum-Suryan, K. L., and J. T. Harvey. 1998. Distribution and abundance of and habitat use by harbor porpoise, Phocoena phocoena, off the northern San Juan Islands, Washington. Fishery Bulletin 96:808–822.

Rojas Bracho, L., A. Jaramillo Legoretta, G. Cardenas, E. Nieto, P. Ladron de Guevara, B. Taylor, J. Barlow, T. Gerrodette, A. henry, N. Tregenza, R. Swift, and T. Akamatsu. 2010. Assessing trends in abundance for vaquita using acoustic monitoring: within refuge plan and outside refuge research needs. Workshop report -- October 19-23, 2009. Pages 1–43. U.S. Department of Commerce.

Taylor, B. L., M. Martinez, T. Gerrodette, J. Barlow, and Y. N. Hrovat. 2006. Lessons from monitoring trends in abundance of marine mammals. Marine Mammal Science 23:157–175.

Teilmann, J., and J. Carstensen. 2012. Negative long term effects on harbour porpoises from a large scale offshore wind farm in the Baltic—evidence of slow recovery. Environmental Research Letters 7:045101.