UNIVERSITY OF CALIFORNIA, SAN DIEGO

Blue Whale Response to Underwater Noise from Commercial Ships

A dissertation submitted in partial satisfaction of the

requirements for the degree Doctor of Philosophy

in

Oceanography

by

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The Dissertation of Megan Frances McKenna is approved, and it is acceptable in quality and form for publication on microfilm and electronically:

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None of us got where we are solely by pulling ourselves up by our bootstraps. We got here because somebody - a parent, a teacher, an Ivy League crony or a few nuns - bent down and helped us pick up our boots. ~Thurgood Marshall

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ABSTRACT OF THE DISSERTATION

Blue Whale Response to Underwater Noise from Commercial Ships

by

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The extent to which low-frequency noise from large vessels is a part of the coastal marine environment and the ramifications of this for blue whale (*Balaenoptera musculus)* communication ranges and vocal behavior was investigated in the Santa Barbara Channel (SBC), a region off the coast of southern California. Analysis of noise from individual ships transiting the region, identified unique spectral characteristics, and radiated noise levels related to ship-type. Predicting radiated underwater noise from container ships under normal operating conditions proved to be challenging given the high dimensionality of the problem. Generalized additive models of radiated ship noise in relation to design characteristics, operational conditions, and oceanographic features revealed the most relevant parameters associated with ship noise. The statistical approach provided a comprehensive view of radiated ship noise in a coastal environment. Increased background noise levels from commercial ship traffic altered the low-frequency acoustic environment in which large whales are communicating. A comparison of long term averages of ambient noise at different sites revealed that blue whales utilizing this region are exposed to diverse acoustic environments and ranges at which they can communicate acoustically. A significant reduction in average noise levels in the SBC, related to changes in the economy and unintended consequences of an air quality improvement rule, was observed from 2007 to 2010. The decrease in ocean noise provided direct evidence for the impact on the ecosystem from the human activity and presented a unique opportunity to understand the magnitude of change necessary to improve the acoustic habitat quality for blue whales. Although the vocalizations of blue whales continued in the presence of ships, changes in call level and rate were observed. Understanding the interactions between human activity and the marine ecosystem is vital to its sustainability. The results of this research advance scientific understanding of human produced noise in the marine environment, and serves as a model for addressing noise pollution in a coastal region on both an ecosystem and individual species basis.

CHAPTER 1

Introduction

Few, if any regions of the ocean are unaffected by human influence (Halpern *et al.* 2008) and marine animals are increasingly forced to contend with the presence of human activity in their environments. Quantifying the pervasiveness and consequences of human disturbance is critical for understanding the link with species survival and ecosystem health (Gill *et al.* 2001). Commercial ships are distributed throughout the world's oceans and are one of a myriad of impacts interacting synergistically to alter marine habitats. A major challenge in marine conservation is developing an understanding of the spatial extent and impact of these different threats and, ultimately, working to alleviate the stressors. Prioritizing is difficult but any reduction in impact has the potential to increase the resilience to other more globally induced threats (Nystrom *et al.* 2000, Hughes *et al.* 2005).

Behavioral change is often considered one of the most sensitive measures of the effects of human disturbance on animals (Carney & Sydeman 1990) and examples of behavioral response studies to human presence are widespread in the scientific literature. Animals may respond to anthropogenic disturbances by reducing their use of certain areas (Morrison *et al.* 1995), altering movement patterns, and reducing the amount of time foraging (Knight 1995, Aguilar Soto *et al.* 2006), all potentially leading to a decrease in energetic gains (Tyler 1991, Siemers & Schaub 2010). Behavioral responses to human disturbances can vary in magnitude and depend on the value of the habitat (*i.e.,* resource quality) and the increased vulnerability to other threats (*e.g.* predation) and the nature of the disturbance (*i.e.,* acute, chronic) (Gill *et al.* 1996, Beale & Monaghan 2004).

Commercial shipping is central to globalization; the low economic cost of transporting goods via the ocean has allowed a burgeoning in global trade (Rodrigue *et al.* 2009). As much as 90 percent of world trade is transported by commercial vessels (IMO 2009). The history of shipping is one of increasing numbers, size, and sophistication. Along with the steady growth in the number of commercial vessels there has been a quadrupling in average gross tonnage (GT) from 160 million GT in 1965 to 605 million GT in 2003 and a similar increase in propulsion power (Ross 1993, Mazzuca 2001). With the increase in global commercial ship traffic, come increasingly apparent negative environmental consequences.

The relationship between increased shipping, and increased ocean noise is well-established (Andrew *et al.* 2002, McDonald *et al.* 2006, Chapman & Price 2011). During standard operation, surface ships generate a significant amount of underwater noise mainly from propeller cavitation (Ross 1976). Dramatic increases in low-frequency ambient noise have been documented at numerous sites throughout the world's oceans. Previous studies of ocean ambient noise, particularly in deep-water sites beyond the continental margins, showed a steady rise in low-frequency ambient noise (Curtis *et al.* 1999, Andrew *et al.* 2002, McDonald *et al.* 2006). Sites on the continental shelf, in relatively shallow waters have revealed geographic differences in low-frequency noise levels related to the presence of human activity. For example, a bathymetrically complex southern California coastal site with minimal local ship traffic revealed little increase in background noise compared to 50 years ago (McDonald *et al.* 2008). In contrast, a site off the coast of Boston, Massachusetts with high-traffic showed a doubling in acoustic power compared to less trafficked locations (Hatch *et al.* 2008). Similarly, Parks *et al.* (2009) found variability in low-frequency ocean noise off the east coasts of the Unites States and Canada, with highest levels near major shipping routes. Low-frequency noise levels in estuary waters of Long Island, NY fluctuated with different levels of recreational boating activity (Samuel *et al.* 2005). Although measured noise levels in these coastal habitats correlated with the presence of and distances to major shipping routes, distant ship traffic can also contribute to noise levels (Bannister 1996, Wagstaff 1981). In order to model ocean noise accurately, considerations of all propagation mechanisms are necessary (Hamson 1997, Kuperman *et al.* 1997).

It is clear from numerous scientific investigations of marine mammals that the perception and production of sound is critical to various aspects of their life history (Richardson *et al.* 1995). Because sound conducts well in water, the use of sound has been capitalized upon as an efficient mode of biological communication in the ocean. Many marine organisms have evolved complex auditory systems including: cognitive and anatomical capacities to exploit this property for navigation, habitat selection, sensing and tracking prey, mating, and social interactions (Tavolga 1964, Au 1993, Edds-Walton 1997, Simpson *et al.* 2005). Rising levels of ocean noise may negatively impact marine mammals by interfering with their ability to detect sounds, from either conspecifics for social or mating purposes or natural (*e.g.* rain, waves) sounds that aid in navigation or foraging.

The environment in which signals are produced plays an important role in determining how these acoustic signals are perceived or received by conspecifics and predators (Marten & Marler 1977). The ability to communicate is limited by the distance over which a signal can be perceived by a receiver over a given background of noise and the propagation characteristics from the caller to the receiver. In environments with increased low-frequency noise from transiting ships, it is likely that communication space for low-frequency specialist, like the blue whales, is reduced by masking effects (Clark *et al.* 2009). Acoustic interference, or masking, is defined as the failure to recognize a signal as a result of the interfering presence of other sounds, either natural or anthropogenic. Although acoustic masking is well documented in literature on human hearing (Wegel & Lane 1924, Fletcher 1940), quantifying the effects in marine mammals is inherently difficult (Richardson *et al.* 1995). However, masking is a key concern regarding the impact of sound on marine mammals, and implicated as a potential long-term effect of anthropogenic noise.

Reports on the effects of man-made noise on the behavior of marine mammals varies, depending on the species investigated, the level of noise to that of ambient, degree of naiveté of the animals to the noise sources, and activity of the animal during the exposure (Myrberg 1989). Some changes in large whale vocalizations have been observed in the presence of anthropogenic noise (Fristrup *et al.* 2003, Miller *et al.* 2000). The exposure of right whales to ship noise elicited no response in the dive behavior (Nowacek *et al.* 2004), suggesting a possible habituation to vessel noise common in their environments. Most studies examining marine mammal behavior in the presence of ships have involved both smaller vessels and smaller marine mammals; notable modifications in behavior included a change in surfacing patterns, an increase in intensity of calls, and cessation of foraging (Janik & Thompson 1996, Lesage *et al.* 1999, Erbe 2002, Jahoda *et al.* 2003, Aguilar Soto *et al.* 2006, Jensen *et al.* 2009, Holt *et al.* 2009).

The main objective of my dissertation is to examine the extent of underwater noise from commercial ships and the impact on the communication and foraging behavior of endangered blue whales. The motivation for my dissertation research is to further our understanding of two environmental threats of commercial shipping (*i.e.,* underwater noise and whale-ship collisions) on an endangered species. Broadly, my dissertation research falls into two categories, first is to characterize and quantify the underwater noise radiated from commercial ships, on an individual ship level and across different spatial and temporal scales; and second, to evaluate the biological consequence of the noise on blue whale communication and foraging behavior. To accomplish this research commercial ship traffic information was combined with long-term passive acoustics data and blue whale behavior. The results provide insight on the extent and consequences of noise from commercial ships on the marine environment.

Geographic and Oceanographic Setting

My dissertation research took place in the northern part of the Southern California Bight (SCB), an area encompassing the Northern Channel Islands and surrounding waters. This region is considered an urban coastal environment (Crowder *et al.* 2006); yet home to a diversity of marine organisms, providing an ideal setting to investigate the interactions between human activities and marine ecosystems.

The SCB is geographically defined as the region south of Point Conception, where the California land mass curves eastward, north of approximately 30°N, and incorporating the Channel Islands (Dailey and Reish 1993). The bathymetry is a complex matrix of deep basins, shallow ridges, offshore islands, and a steep slope along the 2,000 m isobath. The Santa Barbara Basin, the main region under investigation in this research, is bordered to the north by the California coastline and to the south by the Northern Channel Islands. The slope of the basin bordering the mainland is gentler than the region bordering the islands; the maximum depth of the basin is 600 m (Emery, 1958). The bathymetry south of four of the Northern Channel Islands (Anacapa, Santa Cruz, Santa Rosa, and San Miguel) includes the deep Santa Cruz Basin (>1,000 m), and a sloping region that extends to the continental shelf. The complex bathymetry of the region creates areas of entrapment for phyto- and zoo-plankton that attract fish and top predators like marine mammals (Hui 1979, Selzer & Payne 1988, Baumgartner 1997). Furthermore, the bathymetric features complicate the sound propagation in the region, creating a unique environment to understand spatial variability in ambient noise.

Oceanographically, this region is part of the California Current System (CCS), the eastern limb of the large-scale, anticyclone North Pacific gyre. The waters of the CCS are characterized by a variety of seasonal circulation patterns which are a complex mix of cold water upwelled off Point Conception and warm, saline SCB waters (Harms and Winant, 1998). The dominant current is the equatorward flowing California Current, a cool, low saline, subarctic water current. Its strength is mediated by the Aleutian Low and North Pacific High pressure systems (Checkley Jr. & Barth 2009). There are also two poleward flowing currents present in this region, the California Countercurrent, also called the Davidson Current (Strub & James 2000**)**, and the California Undercurrent, both of which bring warm, saline Equatorial waters north (Reid *et al.* 1958, Hickey 1993**)**. Seasonally, the California Current is strongest and closest to shore in spring, when there is predominantly equatorward flow. In contrast, in summer and fall the California Countercurrent dominates, bringing warmer water further north and west into the SCB and pushing the California Current further offshore (Hickey 1993, Hickey *et al.* 2003, Caldeira *et al.* 2005). The meeting of these currents forms strong mesoscale eddies, which have been shown to play an important role in zooplankton and fish larvae retention (Logerwell *et al.* 2001, Logerwell and Smith 2001), creating hotspots for predators. Eddies and other mesoscale features are strongest in summer and fall (Strub & James 2000, Checkley Jr. & Barth 2009). Finally, productivity in the SCB is high due to equatorward winds in the late spring and summer that force an offshore flow and create upwelling of cold, nutrient-rich water near the coast (Checkley Jr. & Barth 2009). The high productivity of the region has led to diversity and species richness in zooplankton, fish and squid (Star & Mullin 1981, Dailey & Reish 1993, Checkley Jr. & Barth 2009), as well as marine mammals, including at least ten species of delphinid, seven mysticete species, nine beaked whale species, and four pinniped species.

Interacting with this high degree of biological diversity is a myriad of human activities (Crowder *et al.* 2006). And not surprisingly, coastal ecosystems near high human population density are the most heavily impacted by human activity (Halpern *et al.* 2008, 2009). One of these stressors, and the focus of my dissertation, is the presence of large commercial ships. The primary access route into one of the world's largest ports, Port of Los Angeles-Long Beach (POLA) travels through this region. POLA is the second busiest port in North America (CINMS, 2009). Until recently, an estimated 75% of vessel traffic departing from, and 65% of traffic arriving at, POLA and Port Hueneme traveled through the Santa Barbara Channel (SBC) (CINMS, 2009). Commercial vessel traffic in the SBC is concentrated in the designated shipping lanes, with an average of 18 ships transiting per day (McKenna *et al.* 2009). The majority of traffic is categorized as cargo ships (*e.g.* container ships, bulk carriers and vehicle carriers), traveling at average speeds of 10 ms^{-1} (19 knots).

Given the high levels of impact, protected regions have been established to help maintain the biological diversity. Channel Islands National Marine Sanctuary (CINMS) was granted a special protected status in 1980 and includes numerous marine protected areas that limit human activities (CINMS 2009). The CINMS is a 1,110-square-nautical-mile region off the coast of Ventura and Santa Barbara and encompasses the waters that surround Anacapa, Santa Cruz, Santa Rosa, San Miguel, and Santa Barbara Islands, extending from mean high tide to six nautical miles offshore around each of the five islands.

Endangered Eastern North Pacific Blue Whale

Blue whale (*Balaenoptera musculus)* populations were depleted in the North Pacific by commercial exploitation that continued until 1966 (Rice 1978, Clapham *et al.* 1999). An estimate of post-whaling populations in the North Pacific was 1,400 animals (Gambell 1976). More recent estimates of the abundance of blue whales in the eastern North Pacific using both line-transect and mark-recapture methods, showed an increase in abundance off the coast of California, likely from changes in distributions and overall population growth (Barlow 1995, Calambokidis & Barlow 2004, Calambokidis *et al.* 2009). Currently, the eastern North Pacific stock estimates are around 2,000-3,000 animals (Calambokidis and Barlow 2004). Blue whales in the eastern North Pacific appear to be separated from populations in the central and western North Pacific based on difference in call types (Stafford *et al.* 1999, 2001). This blue whale population feeds off California from May through November (Calambokidis *et al.* 1990, 2000, 2007) and migrates to waters off Mexico and as far south as the Costa Rica Dome (6°N) in winter and spring (Calambokidis *et al.* 1990, Stafford *et al.* 1999, Mate *et al.* 1999).

Aggregations of eastern North Pacific blue whales found off the coast of California, including the SCB, are feeding on dense patches of krill (Calambokidis *et al.* 2000, 2007). High densities of krill, the primary food source of blue whales, are associated with areas of high primary productivity, and consequently, influence whale distributions (Mate *et al.* 1999, Croll *et al.* 2005). Local topography and regional upwelling zones largely determine the distribution of krill within the California current (Brinton 1976, Feidler *et al.* 1998, Brinton & Townsend 2003, Ressler *et al.* 2005, Croll *et al.* 2005). *Euphausia pacifica* and *Thysanoessa spinifera* dominate the aggregations of krill found in the region. Both species congregate in areas downstream from upwelling centers and in close proximity to regions of steep topographic relief and continental shelf waters (Croll *et al.* 1998, Feidler *et al.* 1998).

Blue whales targeting this prey source engage in lunge feeding; a foraging strategy characterized as energetically costly, but highly efficient, particularly if the prey densities are sufficient (Goldbogen *et al.* 2011). Lunge feeding in blue whales and other Balaenopterids, is a form of suspension feeding in which large volumes of water that contain dense aggregations of prey are engulfed and filtered through baleen plates (Goldbogen *et al.* 2008, 2007, Friedlaender *et al.* 2009). Lunge feeding in Balaenopterids occurs where prey is dense and abundant, from the surface waters (Friedlaender *et al.* 2009) to more than 500 m in depth (Panigada *et al.* 1999).

Blue whales, like most baleen whale species, vocalize in low-frequency ranges (15-100 Hz). Blue whales in the north Pacific are known to produce at least four call types (McDonald *et al.* 1995, Thompson *et al.* 1996, Oleson *et al.* 2007b): A and B calls (16 Hz, ~20 second duration), D calls (down-sweep from 90-25 Hz, 1-4 second duration), and highly variable amplitude and frequency modulated calls (FM). Blue whale A and B calls occur in repeated sequences and are only produced by males and likely function in mate attraction and long-range communication. Previous studies have identified two unique patterns in song: BBB song defined as an interval of 48 seconds between consecutive calls, and BAB song with 128 seconds between B calls with an interspersed A call. Singular or irregular B calls are also produced by males (McDonald *et al.* 2001, Oleson *et al.* 2007a). Blue whale D calls are recorded from both males and females (Oleson *et al.* 2007a) and appear to have an identifiable behavioral context related to social interaction, particularly when animals are foraging. Previous studies that found supporting evidence for social function showed that calling whales are often paired or in close association with other whales, and alternating patterns in calling has been observed between individuals (Thode *et al.* 2000, McDonald *et al.* 2001, Oleson *et al.* 2007a). Furthermore, the calls are produced at depths of 15-35 m where visual identification of conspecifics is possible and the calls have spectral characteristics that might enhance detectability (Marler 1955, Edds-Walten 1997).

Little is known about the natural causes of mortality of blue whales, although rake marks and observations of killer whale (*Orcinus orca*) attacks indicate predation occurs (Jefferson 1991). Human-related mortality continues despite protection from commercial whaling, as there have been numerous observations of blue whales on the bows of ships (Norman *et al.* 2004). Ship strikes are a significant mortality factor - between 1988 and 2007, 21 blue whale deaths were reported along the California coast and strandings are spatially associated with locations of shipping lanes (Berman *et al.* 2010).

Management Context

The commercial shipping industry is complex, and perhaps the most international of the world's industries. Management is centralized through the International Maritime Organization (IMO), a United Nations agency tasked with the responsibility for the safety and security of shipping and the prevention of marine pollution by ships. Effective management of environmental threats from marine transportation is challenged by the complex and spatially overlapping set of other interests, particularly in the coastal environment (Crowder *et al.* 2006).

Given the established environmental threat of underwater noise from shipping, numerous meetings and workshops have been held to discuss methods to mitigate the problem. In 2004, the U.S. Department of Commerce's National Oceanic and Atmospheric Administration (NOAA) and numerous other government, industry, and academic partners convened the first formal meeting to consider the effects of sound from large vessels on marine life. The meeting was entitled "Shipping Noise and Marine Mammals: A forum for Science, Management, and Technology". A second meeting on this topic, in May 2007, sponsored by NOAA discussed the potential application of vessel-quieting technologies. In April 2008, Okeanos, a non-profit organization, held a workshop to engage members of the international maritime transport industry, including the IMO. The workshop entitled "International Workshop on Shipping Noise and Marine Mammals" brought together a diverse group of stakeholders from around the world. All participants, including myself, called for the coordination of action at the international level through the IMO. Since this workshop, considerable efforts have been made to engage the international shipping community to adopt strategies to reduce underwater radiated noise from commercial ships.

In addition to this degradation of habitat quality from the noise produced by ships, there is also the potential for direct interaction with marine organisms, particularly large endangered cetaceans (Jensen and Silber 2003). Ship-strikes occur worldwide and in some cases strikes are occurring frequently enough to have a significant impact on a population scale (Vanderlaan *et al.* 2008, Vanderlaan *et al.* 2009, Williams and O'Hara 2010, Berman *et al.* 2010). In the fall of 2007, five blue whale mortalities due to ship strikes occurred off the coast of southern California, an abnormally high number of incidents in this small region over a short period of time (Berman *et al.* 2010). During this period, researchers observed one of the highest counts of individual whales present in the SBC and more whales distributed in the vicinity of the shipping lanes, compared to previous years (Berman *et al.* 2010). The spike in mortalities did not provoke a regulatory response, but it raised concern in the community. Regional managers took action to avoid the re-occurrence of these events by implementing a voluntary speed reduction in the SBC and called for further research to understand behaviors that might put whales at additional risk to collision.

Managing the environmental threats of commercial shipping involves not only an understanding of the complexity of governing and interest groups, but also the biological implications of the threat. My research focuses on addressing some of the biological implications of commercial shipping in a coastal environment. First, my analyses of ship noise in Chapters 2-3- provide some of the necessary information to develop effective mitigation strategies (*i.e.,* how to quiet ships). Chapters 4-6 provide direct evidence of the effect of noise from ships on blue whale communication. The behavioral analysis in Chapter 7 furthers our understanding of how blue whales are responding to the presence of ships to better evaluate efforts to reduce ship strikes.

Dissertation Outline

<u>Chapter 2: Underwater Radiated Noise from Modern Commercial Ships</u>

In chapter 2, I took an opportunistic approach to measuring radiated noise from ships by combining continuous seafloor acoustic data recordings with passage information from commercial ships transiting the SBC. Three metrics of ship noise measured during normal operating conditions are presented for seven merchant ship-types: container ships, vehicle carriers, bulk carriers, open hatch cargo ships, and chemical, crude oil and product tankers.

Aims and Objectives

2.1 To characterize the underwater radiated noise from seven commercial ship-types

2.2 To compare spectral characteristics of radiated noise from the different ship-types

2.3 To develop metrics useful for comparisons and understanding the impact on marine mammals

Hypotheses

2.1 Spectral characteristics of radiated ship noise will vary between ship-types.

2.3 Faster and larger ships will radiate more noise into the marine environment.

2.3 The spatial extent of noise from a passing ship will depend on the size and speed of the ship.

<u>Chapter 3: Modeling Container Ship Underwater Radiated Noise</u>

In chapter 3, seafloor acoustic measurements of container ship passages are combined with ship design characteristics, ship operational conditions, and oceanographic features to determine the variables relevant to observed ship radiated sound levels. Statistical models are developed for different frequency bands using the predictor variables.

Aims and Objectives

3.1 To determine the variables and conditions that predicts higher levels of radiated ship noise

3.2 To evaluate noise levels in different frequency bands

Hypotheses

3.1 Multiple acoustic measurements from the same ship will differ depending on the unique passage.

3.2 Different frequency bands will have different predictors of underwater radiated noise.

3.2 Speed of the ship will have the highest predictive power.

3.3 Statistical models will explain the majority of the observed variability in radiated noise levels.

<u>Chapter 4: Quieter Ocean- Unintended Consequence of Recent Ship Traffic Trend</u>

In chapter 4, I show how recent changes in commercial ship traffic along the west coast of the US, near the Channel Islands, had the unintended consequence of quieting a biologically important, yet urbanized coastal region. Long-term acoustic recordings (2005-2010) were combined with ship traffic information.

Aims and Objectives

4.1 To measure temporal changes in long-term average noise levels in a coastal region, related to regional ship traffic patterns

4.3 To correlate changes in average noise levels with ship traffic patterns using two independent metrics of ship traffic

4.4 To determine the change in ship traffic needed to decrease average levels by 1 dB

Hypotheses

4.1 A decline in regional traffic from the "great recession" will correlate with a decrease in average noise levels.

4.2 A shift in traffic related to air quality policy will correlate with additional decreases in average noise levels in the Santa Barbara Channel.

Chapter 5: Underwater Noise in a Blue Whale Habitat Near the Channel Islands National Marine Sanctuary

The goal of chapter 5 is to use long time-series data of ambient sound, combined with knowledge of ship traffic to understand the variability of the low-frequency sound fields in an important blue whale habitat. Both spatial and temporal comparisons at six sites in a coastal region off the coast of southern California are investigated. Differences in both the average ambient noise levels and the observed variability in levels between sites are quantified using three metrics: percentiles, empirical cumulative distribution functions and noise pollution levels. Furthermore, the variability in ambient noise levels at each site, are used to quantify the communication ranges for blue whale calls. For sites close to major shipping routes, temporal differences in noise levels related to ship traffic patterns are examined, including daily patterns and a recent shift in traffic in the region.

Aims and Objectives

5.1 To describe the low-frequency ambient noise environment in relation to distance from commercial shipping lanes

5.2 To relate daily patterns in ship traffic to variability in noise levels

5.3 To assess changes in blue whale communication ranges related to ambient noise levels

Hypotheses

5.1 Average low-frequency ambient noise levels will relate to both distance to major shipping routes and exposure to distant ship traffic noise.

5.2 A coastal region isolated from distant ship traffic noise, but close to a major shipping route will have the highest variability in daily noise level that relate to daily ship traffic patterns.

5.3. Detection ranges of blue whale calls will be reduced in regions closest to major commercial shipping lanes.

Chapter 6: Blue Whales Change their Calls in the Presence of Large Ships

In chapter 6, I investigate the response of vocalizing blue whales to the presence of commercial ships. Four potential vocal responses are investigated. First, changes in song are explored by quantifying inter-call intervals of the blue whale B calls during the seasonal peak of song. Second, patterns in song type in different average background noise levels were compared between October 2008 and October 2009. Third, changes in contact calls during foraging are examined by comparing the call interval of D calls in the seasonal peak in foraging (July 2008). Lastly, modifications to amplitude, frequency range and duration are measured for D calls.

Aims and Objectives

6.1 To characterize blue whale calling patterns related to ship traffic noise

6.2 To identify changes in calling behavior related to the presence of ship noise

6.3 To run simulations of the Lombard effect and evaluate if a response can be measured

6.3 To relate call modifications to potential biological implications

Hypotheses

6.1 If blue whale song type is related to the presence of a ship, then song type relative frequencies will shift to a higher proportion of irregular song type when ships are present.

6.2 If blue whale foraging/ contact call intervals are related to the presence of ships, then an increase in contact calling will occur when a ship is present.

6.3 If blue whales change call amplitude in the presence of ships, then an increase in call amplitude (Lombard effect) will occur when ships are present.

6.4 If calling behavior is related to the density of ship traffic, then a decrease in ship passages will results in increased presence of song.

Chapter 7: The Response of Deep-Foraging Blue Whales to the Presence of Large Ships

The goal of chapter 7 is to determine the response of individual deep-foraging blue whales to the close passage of large ships. The deployments of suction cup tags on individual blue whales within the shipping lanes provide acoustic and kinematic data. The behavioral reaction of the whale to the ship is then evaluated based on the tag data and previous descriptions of deep-foraging dives, while considering the characteristics of the passing ship (*i.e.,* range to animal, size, speed, and source level), the individual animal (*i.e.,* sex, behavior at close approach), and prey.

Aims and Objectives

7.1 To identify the behavioral response of foraging blue whales to the close passage of a ship

7.2 To determine the threshold of response (*i.e.*, distance to ship)

7.3 To examine the potential energetic and social costs of observed behavioral changes

Hypotheses

7.1 During the close passage of a ship, blue whale foraging behavior (*i.e.,* dive duration and number of lunges) will decrease compared to other dives in the profile and stereotyped foraging dives.

7.2 During the close passage of a ship, blue whale surface behavior (*i.e.,* surface time and number of breaths) will increase compared to other dives in the profile and stereotyped foraging dives.

7.3 The degree of the response will relate to the distance of the close approach. At distances greater than 1 km ships will not elicit a behavioral response.

Dissertation Structure

This thesis contains six empirical data chapters. Each of the chapters is intended to stand alone as a publishable unit, and the reader may encounter some redundancy in the introduction and methods for each chapter.

Chapter 2, entitled "*Underwater Radiated Noise from Modern Commercial Ships"*, has been submitted for publication in the Journal of the Acoustical Society of America and is presented as part of this dissertation with acknowledgement to the co-authors in the study, Donald Ross, Sean M. Wiggins and John A. Hildebrand.

Chapter 3, entitled "*Modeling Container Ship Underwater Radiated Noise",* is in preparation and formatted for publication in the Journal of the Acoustical Society of America and is presented as part of this dissertation with acknowledgement to the co-authors in the study, Sean M. Wiggins and John A. Hildebrand.

Chapter 4, entitled "*Quieter Ocean- Unintended Consequence of Recent Ship Traffic Trends*", is in preparation and formatted for publication in the Journal of the Acoustical Society of America Express Letters and is presented as part of this dissertation with acknowledgement to the co-authors in the study, Donald Ross, Sean M. Wiggins, John A. Hildebrand, Steve L. Katz, T.J. Moore, and Jessica Redfern.

Chapter 5, entitled, "*Underwater Noise in a Blue Whale Habitat Near the Channel Islands National Marine Sanctuary*", is in preparation and formatted for publication in the Journal of the Acoustical Society of America and is presented as part of this dissertation with acknowledgement to the co-authors in the study, Donald Ross, Sean M. Wiggins, and John A. Hildebrand.

Chapter 6, entitled, "*Blue Whales Change their Calls in the Presence of Large Ships",* is in preparation and formatted for publication in Endangered Species Research and is presented as part of this dissertation with acknowledgement to the co-authors in the study, Sara Kerosky, Sean M. Wiggins, and John A. Hildebrand.

Chapter 7, entitled, "*The Response of Deep-Foraging Blue Whales to the Presence of Large Ships",* is in preparation and formatted for publication in Biology Letters and is presented as part of this dissertation with acknowledgement to the co-authors in the study, John Calambokidis, Jeremy A. Goldbogen, and Erin M. Oleson.

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CHAPTER 2

Underwater Radiated Noise from Modern Commercial Ships

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Abstract

Underwater radiated noise was measured for seven types of modern commercial ships: container ships, vehicle carriers, open hatch cargo ships, bulk carriers, and chemical, crude oil and product tankers. Calibrated acoustic data (<1,000 Hz) from an autonomous seafloor-mounted acoustic recorder were combined with ship passage information from the Automatic Identification System for ships transiting in the Santa Barbara Channel off the coast of southern California. Metrics describing ship noise included source level, sound exposure level and transmission range. A 54kGT container ship had the highest broadband source level at 188 dB re 1µPa@1m; a 26kGT chemical tanker had the lowest at 177 dB re 1µPa@1m. Within each ship-type group, evidence for increased source level with larger size and faster speeds was found. However, across ship-types differences were likely related to design characteristics. Compared to other ship-types, bulk carriers radiated less acoustic energy less than 50 Hz and tankers radiated less acoustic energy greater than 300 Hz. Asymmetry in radiated noise was observed (*e.g.* as a container ship approached the recorder, noise was above background at a distance of 12 km and at the stern aspect the distance was 20 km). The presented metrics provide a method for quantifying ship noise in coastal marine environments.

Introduction

The underwater acoustic output generated by commercial ships significantly contributes to ambient noise in the ocean (*e.g.* Wenz, 1962; Ross, 1976; Wagstaff, 1981; Hildebrand, 2009). Commercial ships generate underwater noise during normal operation and most notably from propeller cavitation, peaking at 50-150 Hz, but extending up to 10,000 Hz when operating at high speeds (Ross, 1976). The history of commercial shipping is defined not only by increases in the number of ships to support burgeoning global trade, but also increases in ship size, propulsion power, and sophistication. The total gross tonnage (GT) of ships quadrupled between 1965 and 2003, at the same time the number of commercial ships approximately doubled **(**Ross, 1993; NRC, 2003; Hildebrand, 2009). The expansion of shipping and ships over the past 4 decades produced about a 12 dB re 1 μPa^2/ Hz increase in deep ocean ambient noise at 30-50 Hz; a doubling in acoustic energy every decade (Ross, 1993; Andrew *et al.,* 2002; McDonald *et al.,* 2006). The effect of commercial ship traffic on ambient noise levels measured on the continental shelf correlates with the density of local ship traffic, bathymetry, and sound propagation characteristics (Hodgkiss, 1990; Hatch *et al.,* 2008; McDonald *et al.*, 2008; Hildebrand, 2009; McKenna *et al.,* 2009).

What is lacking are measurements of radiated noise from individual ships in normal operating conditions to understand how different ship-types and operating conditions contribute to local ambient noise levels. Surveys of underwater noise from ships in the last few decades provided information about noise from individual ships operating under various conditions; however, these controlled measurements were made on a limited number of ships and most measurements were from older ships (Ross and Alvarez, 1964; Arveson and Vendittis, 2000; Heitmeyer *et al.*, 2003; Trevorrow *et al.,* 2008). Bahtiarian (2009) provided a standard for measuring underwater noise generated by ships which provided specific guidelines for measurement set up, instrumentation and data processing; however this standard can be applied only to a limited number of ships and operating conditions because of the expense of removing a ship from operation to conduct the noise measurements.

We took an opportunistic approach to measuring radiated noise from ships by combining continuous seafloor acoustic data recordings with passage information from commercial ships transiting the Santa Barbara Channel (SBC) off the coast of southern California (Fig. 2.1). Ships use the shipping lanes that pass through the SBC while traveling to and from the combined ports of Los Angeles and Long Beach. This region has one of the busiest shipping lanes in the world, with at least 6,500 vessels (43% of all U.S. shipping trade) passing through the area in 2008 (CINMS, January 2009).

Three metrics of ship noise measured during normal operating conditions are presented for seven merchant ship-types: container ships, vehicle carriers, bulk carriers, open hatch cargo ships, and chemical, crude oil and product tankers. Acoustic measurements near the seafloor were collected using an autonomous long-term passive acoustic recorder and were combined with ship passage information from the Automatic Identification System (AIS). Received sound levels during the passage of a ship at known distances were compared to average background noise levels. Estimates of source level and sound exposure level were calculated from the received levels and propagation loss typical of the region and season.

Merchant ship-types

The world merchant fleet of modern ships over 100 GT is composed of approximately 100,000 ships totaling 830 million GT and with an average age of 22 years (UNCTD, 2008). This global fleet is composed of a variety of vessel types; ships are categorized based on goods carried, such as cargo (dry, liquid, or contained) or passengers. The cargo transported influences designs and operating conditions of different ship-types (Eyres, 2007).

Ships designed to carry bulk goods include both bulk carrier and tanker ship-types. Tankers and bulk carriers transport heavy, high density commodities and operate at relatively slower speeds. Bulk carriers account for 14% of the global merchant fleet and transport unpacked bulk cargo (*e.g.* grains, coal, cement, and ore) in cargo holds below the water level and are sometimes outfitted with cranes, derricks, and conveyors for loading and unloading cargo (Eyres, 2007; UNCTD, 2008). Tankers transport liquids in the cargo holds and are categorized as crude oil tankers, product tankers, or chemical tankers and account for 21% of the world merchant fleet (UNCTD, 2008). Crude oil tankers transport unrefined crude oil from the location of extraction to refineries, and are generally the largest of the tankers. Product tankers carry refined petrochemicals from refineries to various processing ports. Chemical tankers are similar in size to product tankers, but carry chemical products (*e.g.* ammonia and chlorine) and are sometimes outfitted with sophisticated heating systems for their cargo.

General cargos occupy the largest single category (32%) in the world merchant fleet (UNCTD, 2008). Open hatch cargo ships are one of the many groups of general cargos, which transport forestry products or any unitized cargo (*i.e.,* pallets) in cargo holds. Container ships, designed to carry cargo pre-packed into containers, did not exist prior to the 1960s; however, since 1990 container trade has increased by a factor of five. Currently, these ships make up 13% of the world's fleet in terms of deadweight tonnage (UNCTD, 2010). Container ships carry cargo in rectangular containers units within the fuller portion of the hull, arranged in tiers stacked on the deck of the ship (Eyres, 2007). Vehicle carriers, a specialized group of container ships, transport automobiles in compartments. These ships have a high box-like form above the waterline to accommodate as many vehicles as possible. Loading and discharging vehicles on and off the ships is accomplished via large ramps at the stern quarter and stern of the ship. These ships are usually equipped with bow thrusters to aid in maneuverability in ports (Eyres, 2007). The remainder of the world fleet includes passenger ships (8%) and a variety of other specialized vessel types (UNCTD, 2008).

Methods

Acoustic Recordings

During 2009, a high frequency acoustic recording package (HARP) was deployed in the SBC at 34º16.2'N and 120º1.8'W at a depth of 580 m (Fig. 2.1). HARPs are bottom-mounted instruments containing a hydrophone, data logger, low drift rate clock, battery power supply, ballast weights, acoustic release system, and flotation (Wiggins and Hildebrand, 2007). The hydrophone sensor is tethered to the instrument and buoyed approximately 10 m above the seafloor. The hydrophone sensor includes two transducers: one for frequencies below 2 kHz and one for frequencies above 2 kHz. All acoustic data used in this study were corrected based on hydrophone sensitivity calibrations performed in at Scripps Whale Acoustics Laboratory and at the U.S. Navy's Transducer Evaluation Center facility in San Diego, California.

All acoustic measurements were taken along the right side of ships transiting in the northbound shipping lanes of the SBC (Fig. 2.1). The closest point of approach (CPA) of a ship to the HARP was measured as the slant range to the HARP, based on the depth of the HARP hydrophone (570 m) and the surface distance of the ship to the HARP. Only northbound ships were analyzed to minimize the ranges from the ships to the HARP; at CPA, northbound ships are approximately 3 km from the HARP compared to southbound ships that are 8 km at CPA. The bow aspect of the ship is defined as the time period during which the ship is approaching the CPA.

The stern aspect is defined as the time after CPA as the ship travels away or retreats from the HARP.

The acoustic data corresponding to periods near CPA derived from ship passage information were evaluated for the presence of a single ship. Data were eliminated based on the passage of another ship within 1.5 hours of CPA or if vocalizing marine animals (*e.g.* whales, fish) were present.

Ship Passage Information

Commercial vessel activity was monitored in the SBC using the Automatic Identification System (AIS) (Tetreault, 2005). An AIS receiving station was located on the campus of the University of California at Santa Barbara (34°24.5'N and 119°52.7'W) (Fig. 2.1). AIS signals from vessels in the region were received using a very high frequency (VHF) omni-directional antenna and a radio (Icom IC-PCR1500 receiver, 1 channel) connected to a computer. The software program *ShipPlotter* (ver. 12.4.6.5, COAA) was used to decode the VHF signal and archived daily logs. All archived AIS data were downloaded and imported into a *PostgreSQL* database. Queries were designed to extract information on northbound ships passing the HARP during the recording period. The information extracted from the AIS database for each ship included a time stamp, speed, heading, latitude and longitude, unique ship identification, ship name, general ship-type, total length and draft.

Additional information for each ship (*i.e.,* ship-type, gross tonnage, engine specifics, and horse power) was extracted from the World Encyclopedia of Ships from Lloyd's Registry of ships. The surface current speed and direction during the passage of each ship were obtained from archived data at the University of California Santa Barbara surface current mapping project

(ICESS, 2009). The speeds over ground from the AIS data were adjusted to actual speed by removing the effect of surface current speed and direction.

Received Levels, Ambient Noise Levels, and Distance Estimates

Received levels (RLs) during one hour ship passages were compared to estimates of ambient noise in different frequency bands. Ambient noise levels in the SBC were previously measured when ships were not present, providing a baseline for the region. Ambient sound levels from the HARP at the same site as this study were reported to be 80 dB re 1 $\mu Pa^2/Hz$ at 40 Hz, 68 dB re 1 $\mu Pa^2/Hz$ at 95 Hz, and 63 dB re 1 $\mu Pa^2/Hz$ at 800 Hz (see Fig. 2 McKenna *et al.*, 2009). RLs during the one hour ship passages were measured at CPA and every 60 seconds for 30 minutes prior to CPA and 30 minutes after CPA. Ambient noise levels were compared to the measured RL during the ship passages. The differences between ship RLs and ambient noise levels for the three frequency bands were reported as a function of distance from the receiver to the ship.

The distances to the ships as they approached and retreated from the HARP did not change linearly. To calculate the ship's distance from the HARP at each 60 second measurement, the distance at CPA and the distance the ship traveled in 60 seconds were used. The speed reported by AIS, corrected for water current speed, was used to calculate distance traveled in 60 seconds. The ranges from the receiver to the transiting ship positions were calculated as the square root of the sum of each distance (*i.e.,* CPA range and distance traveled in 60 seconds) squared.

Transmission Loss

To investigate sound transmission loss (TL) from the ships to the HARP, a model using a range dependent parabolic equation was created, using the Acoustic Toolbox User Interface and Post Processor (Duncan and Maggi, 2005). The model required seabed (*i.e.,* bathymetry and sediment) and water column (*i.e.,* salinity and temperature) properties. Core samples from the seafloor near the HARP site showed sediments of silty layers deposited on an annual cycle (Emery, 1960; Hulsemann and Emery, 1961). The sediment characteristics used in the propagation models were based on literature descriptions of the sediment from these studies and the geo-acoustic properties associated with that sediment type (Hampton, 1973). We also included a bottom roughness in the models to dampen reflections.

A water column sound speed profile was generated from temperature, salinity and pressure measurements (Mackenzie, 1981) taken at a location close to the HARP (34º15.0'N and 119º54.4'W). The measurements were collected on 21 April 2009, the same month and year the ships in this study transited the region. Water column data were collected as part of the Plumes and Blooms Program at the Institute for Computation Earth System Science at the University of California, Santa Barbara. Water column data were collected only from the sea surface down to 200 m. Previous studies in this region showed a constant sound speed profile at depths below 200 as both temperature and pressure increased (Linder and Gawarkiewicz, 2006).

The modeled sound source was placed at 7 m and 14 m below the sea surface, typical depths of ship propellers. Source frequencies ranged from 22-177 Hz. Horizontal ranges extended from 100 to 5,000 m and depths ranged from the sea surface to the seafloor (580 m). The model's spatial resolution was 50 m in depth and 50 m in horizontal range. Acoustic loss at the depth of the hydrophone and ranges from the ships to the HARP were reported. Transmission loss models were generated in three octave bands centered at 31.5, 63 and 125 Hz.

Ship Source Levels

Source levels (dB re 1 μPa^2 @ 1 m) were estimated for all ships measured. For each ship-type category, the mean source level and standard error were calculated. The amount of acoustic data used for the source level estimate was set to the time it took the ship to travel its length. AIS provided the speed and length of the ship needed for this calculation. Source levels were estimated from the RLs at CPA and the TL at the CPA distance. The horizontal range from the ship to the receiver was calculated from coordinates of the HARP and the ship and a TL model at this distance was added to the measured RL.

Source level estimates are presented in 1-octave and 1/3-octave bands, using the standard center frequencies, and in1-Hz bands. To determine the 1-octave and 1/3-octave band levels, the mean squared pressure values were summed across the frequencies, and converted back to sound pressure levels expressed as decibels referenced to a unit pressure density.

Sound Exposure Levels

Sound exposure levels (SELs) were estimated for all ships at their CPA distance (~3 km). The SEL for each ship passage at this distance was calculated by integrating the square of the received pressure waveform over the duration of the passage. The duration of the passage was determined from a cumulative sum of RL up to a 30 minute period after CPA. The integration time cutoff was when the difference in RL cumulative summation was less than 0.1 dBs The duration of the passage, or integration time, is dependent on the distance from the ship to the receiver and the speed of the ship; closer and faster ships have shorter integration time compared to ships at slower speeds and greater distances (Table 2.1).

An equation for calculating SEL at various ranges from the sound source (*i.e.,* ship) was determined. Ranges of interest (ROI) were 500 m to 15 km from the specific ship. First, RLs at the ROIs were calculated from the ship source level (SL) estimates minus TL from the source to the ROIs. Second, the distances of the HARP to ship locations during the 30 minutes stern passage (at a 60 second interval) were determined based on a ratio of the CPA distance to the ROI distance. RLs during this passage were then calculated (SL-TL(ROI)) and the integration time and SEL were set to when the cumulative sum did not change by more than 0.1 dBs Last, SEL, as a function of range, was fit to an exponential equation with constants reported for each ship investigated.

Results

A total of 29 ships that transited the northbound shipping lane in the Santa Barbara Channel in April 2009 were analyzed. The ships were divided into seven ship-type categories as designated by the World Shipping Encyclopedia from Lloyd's Registry of ships. Table 2.1 summarizes the design and operational conditions as well as the measured and estimated sound levels for each transiting ship. Within each of the seven ship categories, the vessels had similar sizes and traveled at similar speeds.

Received Levels

The CPA distance from the ships to the HARP ranged from 2,637 m to 3,461 m (Table 2.1). At these distances, bulk carriers and container ships had higher broadband RLs (~116 dB re 1 μPa^2 at 20-1,000 Hz) than the other types of ships (Table 2.1). The tankers, open hatch cargos, and vehicle carriers all had similar broadband received levels (~111 dB re 1 μPa^2 at 20-1,000 Hz).

One-hour spectrograms of a container ship, bulk carrier and product tanker RLs are illustrated in Fig. 2.2 (selected ships are designated in Table 2.1 by *). These spectrograms show changes in noise levels over a broad frequency range, 10- 1,000 Hz. Tonal lines below 100 Hz are propeller blade cavitation lines and their harmonics, but the interference pattern at the higher frequencies is caused by constructive and destructive interference of sound from a dipole source. These interference patterns also are dependent on water column properties.

During the one-hour passage, the container ship traveled a total of 40 km. The RLs from the container ship were highest at frequencies below 100 Hz (Fig. 2.2A); although higher frequency noise also was produced during the passage. RLs were highest at CPA with measured levels about 20 dB above background at 95 and 40 Hz, and about 15 dB above background at 800 Hz (Fig. 2.2A- bottom graph). As the container ship approached the HARP, the RLs at 40 Hz rose above background near 16 km from the receiver (Fig. 2.2A). As the ship traveled away from the receiver, noise levels at 40 Hz stayed above background for over 30 minutes (*i.e.,* > 20 km distance from the receiver). At 95 and 800 Hz, container ship noise levels were above background symmetrically at the bow and stern aspects, approximately 8.5 km away from the receiver (Fig. 2.2A).

The bulk carrier traveled a total of 27.2 km during a one hour passage. The RLs from the bulk carrier were highest at frequencies near 100 Hz (Fig. 2.2B). At CPA, the levels were about 30 dB above background at 95 Hz and around 20 dB above at 800 Hz, but only ~10 dB above background at 40 Hz. As the ship approached CPA, noise levels in the 95 Hz band were elevated above background first, and at a distance of 11 km from the receiver. At the stern aspect, noise levels in all bands remained above background for the entire 30 minute period, with the 95 Hz band having the highest levels.

The product tanker traveled a distance similar to the bulk carrier (27.6 km) during the one hour passage. However, unlike the bulk carrier, most of the acoustic energy was below 100 Hz (Fig. 2.2C). Low-frequency noise levels for the product tanker were above background for almost the entire 1-hour passage of the ship, with more acoustic energy at the stern aspect. The levels at 800 Hz rose above background by < 5 dB, resulting in the lowest RLs for high frequency compared to the other two ship-types.

Ship Source Levels

The water column properties in April 2009 were dominated by cold upwelled water observed throughout the region (McClatchie *et al,* 2009) (Fig. 2.3A). Based on these and sediment properties for the basin, propagation model TL curves for the 63 Hz octave band and two source depths are shown to be similar to spherical spreading model where TL = 20·log(range[m]) (Fig. 2.3B). Propagation loss models for the 1/3-octave frequency bands investigated were found to be similar at ranges comparable to the CPA distance (~3 km); however, TL variability was found to be related to source depth. Decreasing the source depth from 14 to 7 m increased TL bands by 2-4 dB re 1 μPa^2 at the ranges of interest (Fig. 2.3B). The effects of seawater absorption can be ignored at these short ranges and low frequencies (Fisher and Simmons, 1977; Jensen *et al.,* 1993).

Based on this modeling, we used the simple spherical spreading model to estimate source levels from the received levels at the HARP for the full band 20-1000 Hz (Table 2.1) and for 1-octave, 1/3-octave and 1-Hz bands (Fig. 2.4). A container ship traveling at 11.2 ms^{-1} (21.7 knots) had the highest estimated broadband source level (188.1 dB re 1 μPa^2 20-1,000 Hz); whereas, a chemical product tanker traveling at 6.2 ms^{-1} (12.1 knots) had the lowest estimated source level (176.6 dB re 1 μPa^2 20-1,000 Hz). On average, the container ships and bulk carriers had the highest measured source levels (186 dB re 1 μPa^2 20-1,000 Hz), despite differences in size and speed (Table 2.1). The container ships traveled seven knots faster than the bulk carriers and are on average 20 kGT larger.

There were differences in container ship and vehicle carrier source levels and operational speeds (Fig. 2.4A): container ships traveled faster and had higher levels. The bulk carriers had higher source levels than the open hatch cargos, yet both traveled at speeds of 7 ms^{-1} (Fig. 2.4B). The distinct 100 Hz peak of the bulk carriers was observed in 1-octave, 1/3-octave, and 1-Hz band spectral averages. There were minimal differences in the estimated source levels for the three types of tankers (Fig. 2.4C), except for a greater drop in level above 200 Hz for the product tankers.

One-octave band source levels provided the best means for averaging over the interference patterns present in the 1/3-octave and 1-Hz bands, yet still captured differences in acoustic signatures of different ship-types (Fig. 2.4). For example, the bulk carriers clearly have a different acoustic signature compared to container ships, with a distinct peak at 100 Hz. This difference is lost in a broadband (20-1000 Hz) source level estimate for bulk carriers and container ships where the broadband levels are similar for these ships-types (Table 2.1).

Sound Exposure Levels

Because SELs are integrated over a specific duration in which noise energy is above a certain level and contributes to the cumulative sum, as opposed to an instantaneous measurement at CPA, sound exposure levels at 3 km were on average 9 dB greater than those received level at the same distance (Table 2.1). At a distance of 3 km SELs were highest for a bulk carrier traveling at 7.4 ms^{-1} and lowest for a vehicle carrier traveling at 8.5 ms^{-1}, 127 and 117 dB re 1 μPa^2 ·second respectively. The integration time for exposure level at 3 km varied with ship-type;

in general ships traveling faster (*i.e.,* container ships) had shorter integration time (Table 2.1). The longest integration time for the sound exposure above background levels at 3 km was for a chemical product tanker (19 minutes), the slowest ship in this study (6.2 ms^{-1}).

Using the equation in Table 2.1, the SELs at 1 m are significantly higher than the estimated source level (>30 dB), but it is unlikely that a receiver will be 1 m from the ship over the entire integration time. Instead, the equations are useful for estimating the total acoustic energy at a given distance from the ship while assuming the receiver remains stationary over the integration time. For example, using the equation in Table 2.1 the broadband SEL at 1 km for a 54.6 kGT container ship would be 166.2 dB re 1 $\mu Pa^2 \cdot$second; the same ship at a distance of 5 km the SEL would be 148 dB re 1 $\mu Pa^2 \cdot$second.

Discussion

Using a seafloor acoustic receiver and known ship passage information, differences in spatial extent, source level and sound exposure level related to ship-type and frequency were observed. Broadside radiated ship noise showed that tankers and container ships radiated noise predominantly in the lower frequencies; while bulk carriers had a distinct acoustic signature centered at 100 Hz. Container ships, bulk carriers, and tankers displayed an asymmetry in radiated noise, with more acoustic energy at the stern aspect. Bulk carriers and container ship-types had the highest broadband source levels compared to the five other ship-types. This pattern was also observed in our cumulative exposure estimates. The differences observed in underwater radiated ship noise for modern ships are likely related to differences in operating conditions, as previously reported, but also differences in design characteristics specific to newer ship-types, and some unknowns related to cargo load.

For WWII merchant ships, Ross (1976) reported a positive relationship between ship noise and the size and speed of a vessel: radiated ship noise from most ship-types was dependent on the square of the length and the fifth power of the speed (Ross and Alvarez, 1964). A more specific derivation for overall noise level (L_s) above 100 Hz proposed by Ross (1976) was:

$$L_s = 112 + 50\log\frac{U_a}{10kt} + 15\log DT$$

where, DT is displacement tonnage and U_a is speed of advance.

However, the author expressed caution in the use of this estimation formula for ships over 30 kGT, as is the case for most ships in this study. Below the variability in radiated noise found for modern ship-types are discussed in terms of the operational and design characteristics, while addressing some of the unknowns.

Received Levels, Ambient Noise Levels, and Distance Estimates

A ship's radiated noise measured during a one-hour passage provided an estimate of the spatial extent at which noise around a ship is elevated above background levels. An asymmetrical pattern was observed in radiated noise for all ship-types, with more noise radiated at stern aspects resulting in a larger spatial acoustic footprint aft of the ship. This was anticipated given that previous studies showed that source levels were generally higher at stern aspects compared to the bow (Arveson and Vendittis, 2000; Trevorrow *et al.,* 2008).

A difference in the dominant frequency of the radiated noise was shown to be related to ship-type. Compared to container ships and tankers, bulk carriers radiated less acoustic energy below 50 Hz. Near CPA, levels in this band were above background levels by about 10 dB during the passage of the bulk carrier, compared to 15-20 dB during the passage of a container ship and product tanker. The product tanker had less acoustic energy in frequencies above 300 Hz, unlike the container and bulk carrier (Fig. 2.3).

The source of the distinct spectral characteristics related to ship-type is unknown, but might be related to differences in operation, propeller type or hull design specific to the ship-type (Arveson and Vendittis, 2000; Matveev, 2005). The exact mechanisms causing the spectral characteristics are beyond the scope of this study, but a few possibilities can be eliminated. First of all, tankers and bulk carriers traveled at similar speeds, therefore, speed is unlikely the sole explanation (Table 2.1). Fouling or damage on the propeller is also unlikely the cause because the same unique characteristics were observed in all ships of a given type.

Ship Source Level Estimates

Within each of the seven ship-types, ships with the highest broadband source levels were either traveling at the highest speeds or were the largest ships, a relationship previously found for older merchant ship-types (Ross and Alvarez, 1964; Ross, 1976). For container ships, vehicle carriers, and bulk carriers the fastest ships had the highest levels, even though they were not the largest ships. For the crude oil and product tankers, the highest source levels were measured for largest ships (length and GT), although not the fastest. The only ship-type that did not fit the size or speed correlation was the chemical tanker; however, the oldest ship had the highest estimated source level in this category (Table 2.1).

The container ship had the highest broadband source level at 188 dB re 1µPa @1 m. Compared to all other ships measured in this study, this vessel was traveling at the fastest speeds (11.2 ms^{-1}) and was the longest ship (289 m). Although this suggests that the relationship with size and speed holds across all ship-types, similar source levels were found for bulk carriers and container ships (Table 2.1) - ships with different sizes and speeds (Table 2.1). Bulk carriers travel slower and are generally smaller than container ships which would suggest lower radiated noise from bulk carriers compared to the larger and faster container ships (Ross and Alvarez, 1964; Ross, 2005; Hildebrand, 2009).

Specific features of ship-types (*e.g.* source depth) might provide insight into the reason for similar estimated source levels, despite differences in size and speed. A shallower source depth will decrease the effect of the dipole, thereby decreasing the amount of radiated sound from the ship. The closer the distance between the dipole sources, the less strength of the dipole (Ross, 1976), as presented in this study's propagation models, when the source was moved from a depth of 14 m to 7 m (Fig. 2.3B).

An unloaded ship likely results in a shallower depth of the propeller, thereby radiating less noise. Unfortunately, AIS does not provide information on the load of a particular ship during its transit; therefore, it is not possible to evaluate fully differences in radiated noise related to the ship load. However, the holds in bulk carriers must be full at all times to maintain the immersion of the propeller and prevent structural damage as required by a 2004 law passed by the Maritime Safety Committee of the IMO (Eyres, 2007). Container ships, on the other hand, do not always carry a full load, particularly ships traveling on a northbound route, as those measured in this study. A comparison of the spectral features of the same ship with varying cargo loads would help evaluate possible differences in radiated noise related to load.

Hull design is specific to each ship-type (Gillmer and Johnson, 1982; Eyres, 2007) and might also result in a difference in source depth between ship-types. Hull fullness, shape, and dimensions are optimized for efficient transfer of the goods carried. Hull design must balance the minimization of drag with structural integrity, stability and practicality for transfer of goods at ports (Gillmer and Johnson, 1982; Ellefsen, 2010). Bulk carriers are full-form ships and have a lower volumetric coefficient (*i.e.,* ship displacement divided by the length between the perpendiculars cubed), compared to container ships (Gourlay and Klaka, 2007). In addition, hull design in container ships has been refined to promote efficient travel at faster speeds. Another feature of the container ships that might results in a shallower source depth is that they carry 60% of their cargo on deck, compared to all cargo below deck in bulk carriers (Eyres, 2007).

Vehicle carriers had the lowest source levels compared to the other ship-types in this study, but were larger and traveled faster than the open hatch cargo ships and chemical tankers. Vehicle carriers have a high boxlike form that sits above the waterline to accommodate as many vehicles as possible on deck, resulting in a shallow draft and a shallow propeller depth (Eyres, 2007), possibly explaining the lower measured source levels.

Predicting Ship Noise in a Coastal Marine Environment

The metrics presented in this study provide a means of predicting noise and exposure levels from ships in coastal environments. Noise from commercial ship traffic is a dominant component of the low-frequency ambient noise in the deep ocean; yet, the contribution of ship noise in coastal regions is more difficult to predict because of environmental variables and varying contributions of ship noise (McDonald *et al.*, 2008; Hildebrand, 2009). The variability in ship noise is related to the proximity to shipping lanes and local sound propagation conditions, unlike deep water sites where distant shipping dominates ambient noise levels (Wagstaff, 1981; Bannister, 1986; Andrew *et al.*, 2002; McDonald *et al.,* 2006). Distant shipping does not contribute to ambient noise at many coastal sites because of sound scattering and shadowing effects from bathymetric features. The level of noise radiated by an individual ship or ship-type and the spatial extent are important factors to consider when evaluating the contribution of ship noise to sites on the continental shelf. As described above, noise levels from an individual ship do not simply correlate with the size and speed of the ship; therefore the noise levels in a coastal region will depend on the types of ships present and the variables that will influence propeller (source) depth.

Combining acoustic measurements of ship noise with ship traffic composition and temporal and spatial patterns within a particular coastal region allows for predictions of local noise levels. For example, the majority of ship traffic in the Santa Barbara Channel is composed of cargo ships, particularly container ship traffic. The traffic in this region is concentrated in the designated lanes with peaks in traffic occurring at noon and midnight related to port activity (McKenna *et al.,* 2009). Long-term averages of noise levels show large daily variations related to these peaks in traffic while average noise levels decrease as the distance from the shipping lanes increases. Since container ships dominate the traffic in this region, the long-term averages should reflect the spectral characteristics of container ships noise (*i.e.,* dominate energy in the 31.5 Hz octave band with a higher frequency component). If ship traffic in a coastal region was dominated by the same number of tankers, one would expect average noise levels to increase, and the variability in ambient noise levels to decrease, due to the large spatial extent of the low-frequency (<40 Hz) noise radiated from a tanker. If ship traffic in a coastal region was dominated by bulk carriers, one would expect ambient noise levels to have a peak around 100 Hz and minimal increases below 50 Hz.

Metrics for Accessing Noise Impact

Acoustic pollution from ship noise is considered one of the major factors affecting habitat quality for marine organisms (NRC, 2005**)**. Concerns regarding acoustic noise pollution from ships arise because of the potential to disrupt natural habitat or cause injury to marine animals. In this study, radiated ship noise over a one-hour passage provided an estimate of both the spatial extent at which ship noise is elevated above background levels (Fig. 2.2) and the region within which potential impact of ship noise on marine organisms can be evaluated.

Increased noise levels from ship traffic will interfere with marine organisms' ability to communicate and interpret acoustic cues in their environment; this is particularly relevant to baleen whales which call at frequencies similar to ship noise for mating-related and long range communication (Richardson *et al.,* 1995; Clark *et al*, 2009). Acoustic masking compromises the receiver's ability to detect important acoustic signals in the same frequency range as the noise. By raising the background noise levels, ships will decrease the ranges at which animals can perceive calls from con-specifics (Clark *et al.*, 2009).

The effect of high sound levels from ships on hearing requires knowledge of both the frequency range of the masker and the hearing threshold of the masked. Marine mammal hearing thresholds have been measured in a limited number of marine species (Fay, 1988; Gerstein *et al.*, 1999); assumptions can be made, however, based on the frequency range of the calling animals and the anatomy of the inner ear (Richardson *et al.,* 1995; Parks *et al.,* 2007). Low-frequency calling baleen whales common to this coastal region include humpback (*Megaptera novaeangliae*), fin (*Balaenoptera physalus)* and blue whales (*Balaenoptera musculus*). Ship noise frequencies are in the same band as the call repertoires of these animals (Payne and McVay, 1971; McDonald *et al.*, 1995; Stafford *et al.*, 1998; Fristrup *et al.*, 2003). Noise levels during ship passages coupled with characteristics of the animal calls provide estimates of the decrease in communication ranges caused by masking from ship noise.

There is also the potential for animals within acoustic range of a ship to exhibit behavioral responses in the presence of ship noise (see Table 14 in Southall *et al.,* 2007). Combining the results of this study (*i.e.,* the spatial extent of the ship noise and SEL) with information on the behavior of animals during ship passages provides a technique for evaluating changes in animal behavior. The attachment of biological tags outfitted with sensors to measure kinematic data provides an effective tool to obtain both baseline and response behavioral data (Aguilar-Soto *et al.,* 2006; Goldbogen *et al.,* 2011). Future noise impact studies combining tag and acoustic recording data in the absence and presence of ships will provide valuable information on potential behavior responses to ship noise.

The SEL equations presented in this study provide a tool to estimate sound exposure levels of a passing ship. SEL assumes that the source is moving away at a given speed and the receiver remains stationary over the integration time. For marine animals that have limited mobility, or in some cases highly mobile animals engaged in a site specific behavior, this is an accurate estimate of SEL. For organisms that are moving through this sound field, the SEL equations for each ship also allows SEL to be estimated if an animal moves towards or away from a ship during its passage.

Limitations

The estimates of source levels presented in this study relied on accurate descriptions of the environment in which the sounds were generated. Some variability was expected related to differences in water column properties during the passage of each ship (Jensen *et al.,* 1993). To minimize error in the measurements, all ships were measured during the same time of year and using the same instrumentation. The use of AIS provided precise positions of the ship, which were used to determine the distance of each ship to the HARP. The differences in CPA distances were small, resulting in minimal fluctuations in transmission loss (<3 dB).

A few limitations of the descriptions of ship noise presented in this study are related to the opportunistic approach. Measurements were only made at broadside angles to the ship- at distances of 3 km. This restricts descriptions of the directionality of radiated noise from individual ships. Previous studies with control over the movement of the ship relative to the acoustic receivers indicated that the radiation pattern was generally dipole in form. Some departures in this pattern in frequencies above 300 Hz suggest interactions with the hull, specifically a decrease in the fore and aft directions by 3-5 dB (Arveson and Vendittis, 1996). This pattern has been widely observed and explained by others: bow radiation is blocked by the hull and stern radiation is partially absorbed in the bubble wake of the ship. Trevorrow *et al.* (2008) quantified this difference for a small coastal oceanographic vessel (560 GT). They reported a broadside maximum in source level, with a 12 dB reduction in the bow and a 9 dB reduction at stern aspect for large angles (>40 degrees). These studies suggest that the estimates of the spatial extent of ship noise from broadside measurements in this study may be an overestimate for directly forward and aft of the ship.

The ship acoustic measurements were made near the seafloor and received levels are not necessarily representative of the levels throughout the entire water column. At these ranges and low frequencies, acoustic interference effects the radiated noise at a given range and depth. Both the depth of the sources and water column properties will influence this radiation pattern, as seen in the propagation models (Fig. 2.3). Autonomous hydrophone arrays with simultaneous water column sound speed profiles would improve these methods and provide a more comprehensive picture of radiated ship noise, using this same opportunistic approach.

Lastly, this study only measured ship noise during one month. The motivation for this was to allow comparisons across ship-types, without adding variability related to seasonal water column variability. Future studies should measure the same ship and ship-type over multiple passages and oceanographic conditions to quantify variability in radiated ship noise.

Summary

This study presents opportunistically measured radiated noise from modern commercial ships under normal operating conditions which allowed for presentation of metrics describing the level of ship noise in coastal regions and potentially providing a means to evaluate the noise impact on the marine environment. In addition to using long-term, calibrated acoustic measurements, a key component in this analysis was the use of the Automatic Identification System to provide accurate distances from the transiting ships to the acoustic receiver. Descriptions of radiated noise for seven different ship-types using three metrics are presented and compared. Within each ship-type group, evidence for the predicted relationship with source level and size and speed of the vessel were found. However, across ship-types the differences in radiated noise levels more likely correlate with difference in hull design and depth of the propeller.

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Table 2.1: Summary of commercial ship characteristics
(*ships in Fig. 2.3, **dB re 1 μPa^2 (20-1000 Hz), ***dB re 1 μPa^2 (20-1000 Hz)*second,
r = range in m).

Lloyd's Registry of ships						Measured							
Ship Type	MMSI Number	Length *[m]*	Year Built	Gross Tonnage *[10^3]*	Horse Power *[10^3]*	Speed *[ms^{-1}]*	Range at CPA *[km]*	Received Level @CPA **	Source Level @1 m**	Sound Exposure Level @3 km ***			
										dB	*mins*	$a*(r)^b$ *a*	*b*
Container Ships	636090869	294	2005	54.6	62.2	10.6	3.1	114.9	184.7	123.1	12	217.4	-0.071
	352919000	294	1994	53.1	42.1	10.7	2.6	116.1	184.5	122.3	11	216.8	-0.072
	235007500	294	2004	53.5	55.9	10.7	3.0	117.0	186.6	124.9	12	218.8	-0.070
	353287000	294	2003	53.8	67.2	10.9	3.2	114.9	185.0	123.4	12	217.6	-0.071
	548719000*	294	1993	53.4	42.1	11.0	3.0	114.6	184.2	122.5	12	216.9	-0.072
	211207740	298	1993	53.8	49.6	11.2	2.9	118.9	**188.1**	126.1	12	219.7	-0.070
Vehicles Carriers	413075000	173	1984	33.1	10.7	7.8	2.9	110.6	180.0	119.3	14	214.5	-0.074
	353788000	180	1989	47.6	14.7	8.5	3.0	108.6	178.1	117.1	14	213.0	-0.075
	232872000	199	2006	61.3	16.5	8.5	3.0	111.3	180.8	119.9	14	215.0	-0.073
	636011280	175	2000	37.9	12.2	9.1	3.3	111.8	182.2	121.4	14	216.1	-0.072
Bulk Carriers	576915000	189	2004	29.7	9.3	7.1	3.4	115.2	185.8	125.9	16	219.5	-0.070
	371978000	229	2006	42.9	13.3	7.1	3.2	114.9	185.1	125.0	16	218.9	-0.070
	240537000	225	2005	40.0	12.7	7.3	3.1	116.0	185.9	125.7	15	219.3	-0.070
	371940000	190	2007	30.7	11.0	7.3	2.7	115.6	184.2	123.4	14	217.6	-0.071
	440223000*	167	1997	16.3	9.1	7.4	3.0	117.9	187.4	127.0	15	220.4	-0.069
Open Hatch Cargo Ships	477657600	199	2007	29.8	12.9	6.7	3.4	111.2	181.8	122.1	16	216.6	-0.072
	257313000	197	1986	27.2	10.1	6.7	3.1	109.0	178.8	118.8	16	214.2	-0.074
	477653500	190	2007	20.2	9.0	7.3	2.8	114.8	183.8	123.2	14	217.4	-0.071
	563496000	213	1995	37.2	14.1	7.3	3.0	111.5	181.1	120.7	15	215.6	-0.073
Chemical Products Tankers	355799000	148	1985	10.8	6.9	4.6	3.4	114.9	184.9	124.3	14	218.3	-0.071
	636010515	181	1996	26.2	11.3	6.2	3.3	106.0	**176.6**	118.0	19	213.6	-0.074
	235007540	182	2004	30.0	12.9	7.1	3.4	111.9	182.4	123.0	17	217.3	-0.071
	352329000	149	1993	10.8	8.2	8.0	3.2	112.5	183.1	123.2	16	217.4	-0.071
Crude Oil Tankers	564924000	241	2003	56.4	16.0	6.5	3.5	108.7	179.4	119.9	17	215.0	-0.073
	636012853	243	2006	57.2	18.4	6.6	3.1	112.1	182.1	122.2	16	216.7	-0.072
	636090885	229	2000	37.0	13.0	7.5	2.9	112.1	181.3	120.7	14	215.6	-0.073
Products Tankers	371604000	182	2005	28.1	12.6	7.1	2.9	109.3	178.5	118.0	15	213.6	-0.074
	319768000*	228	2007	42.4	18.4	7.5	3.1	112.7	182.7	122.4	15	216.8	-0.072
	371924000	180	2006	28.8	12.9	8.0	3.4	111.2	181.8	121.5	15	216.2	-0.072

Figure 2.1: Map of the Santa Barbara Channel. The north and southbound shipping lanes and 100 m bottom contours are shown. (HARP = black star, AIS station = white dot).

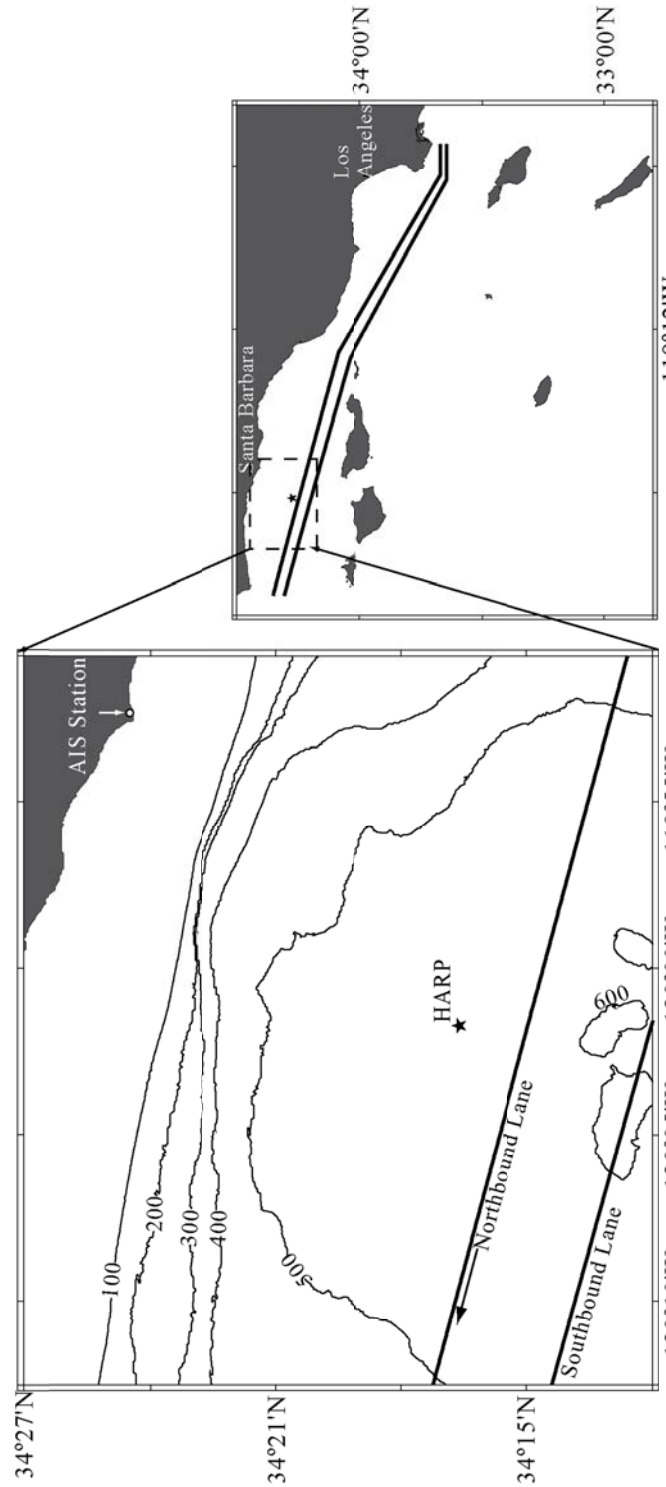
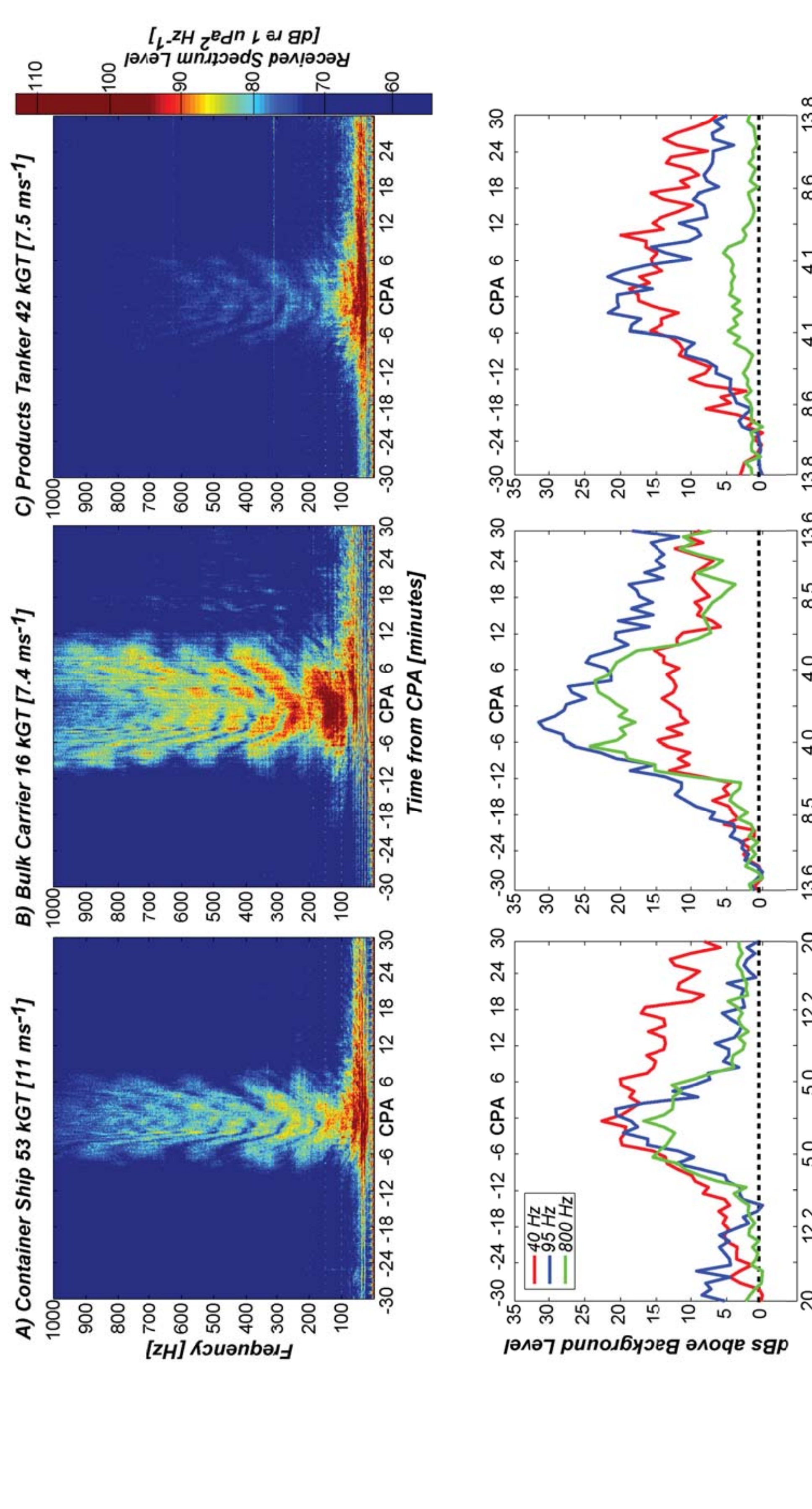

34°00'N
33°00'N
Los Angeles
Santa Barbara
119°12'W
AIS Station
119°55'W
120°00'W
120°05'W
120°10'W
HARP
600
Northbound Lane
Southbound Lane
100
200
300
400
500
34°27'N
34°21'N
34°15'N

Figure 2.2: Received sound levels during 1-hour passages of three different ship-types: A) Container ship (MMSI 548719000). B) Bulk carrier (MMSI 440223000). C) Product tanker (MMSI 319768000). Figures are centered at CPA of the ship to the HARP. Top figure series shows the received levels as color (dB re 1 $\mu Pa^2/Hz$) during a one hour window around the passage of the ships, using a 5 second spectral average. Bottom figure series show the difference in RL from an estimate of background noise level. The corresponding distance traveled over that 1-hour period is shown on the x-axis on the bottom graphs; this scale is dependent on the speed of the ship.


A) Container Ship 53 kGT [11 ms-1]
B) Bulk Carrier 16 kGT [7.4 ms-1]
C) Products Tanker 42 kGT [7.5 ms-1]
Frequency [Hz]
Time from CPA [minutes]
Received Spectrum Level [dB re 1 uPa2 Hz-1]
dBs above Background Level
Distance from HARP to Ship [km]
40 Hz
95 Hz
800 Hz

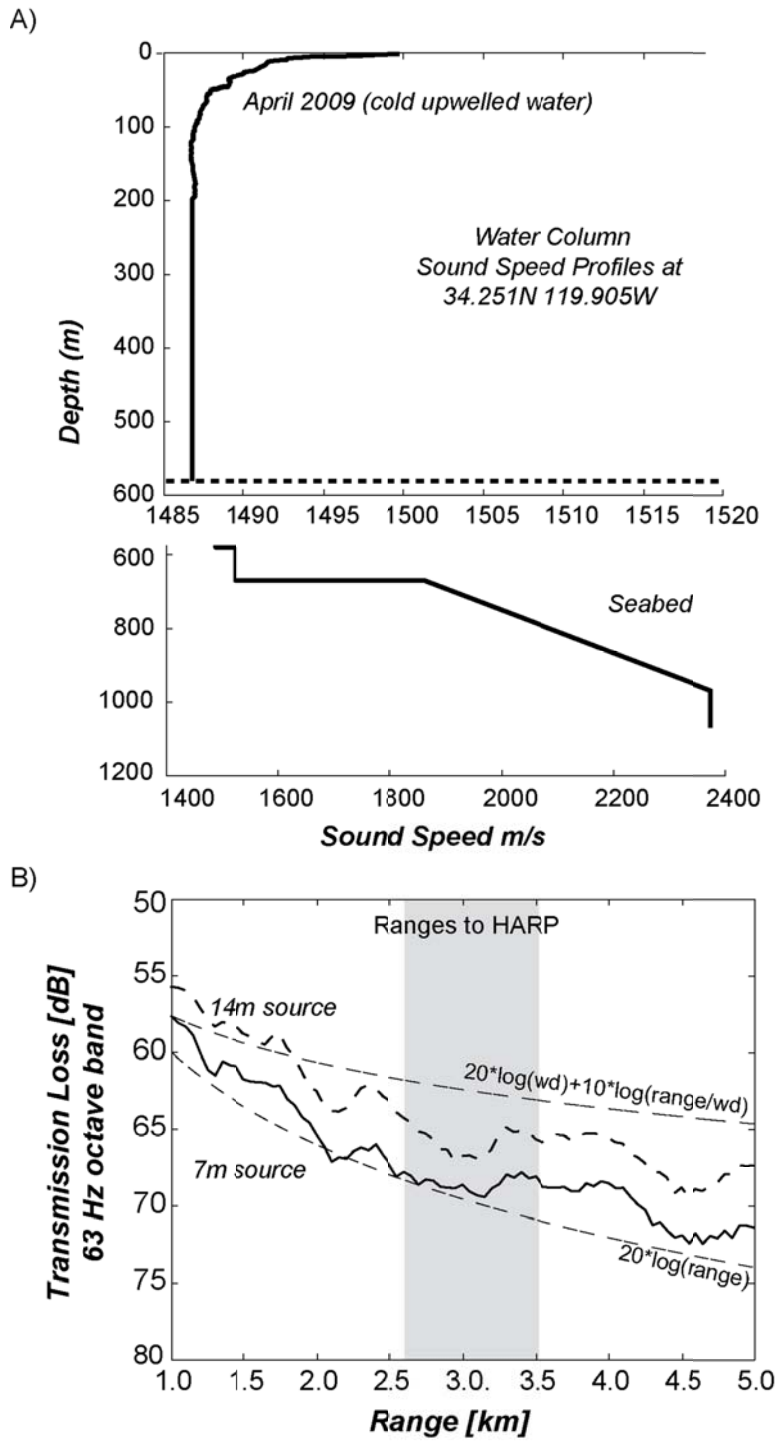
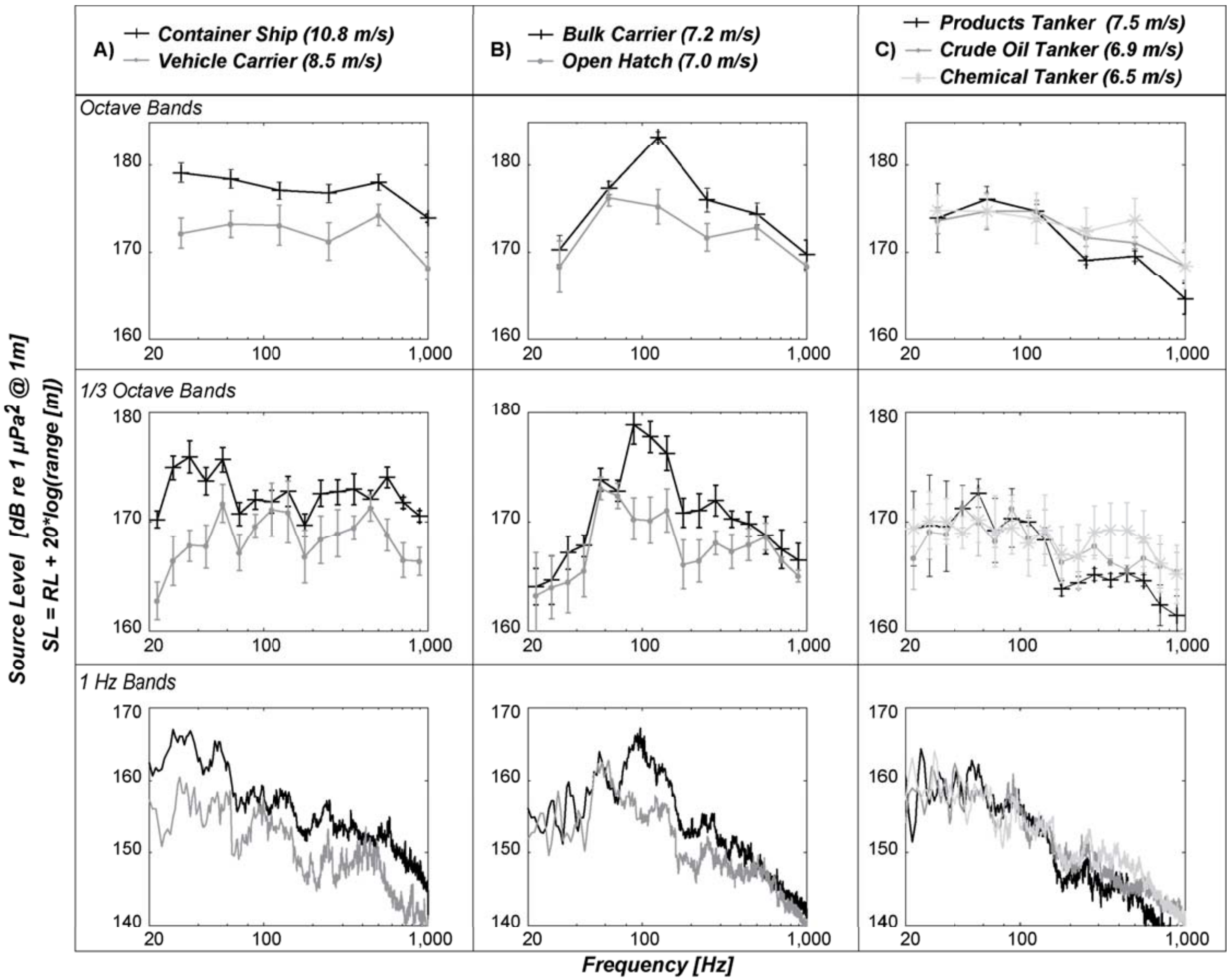


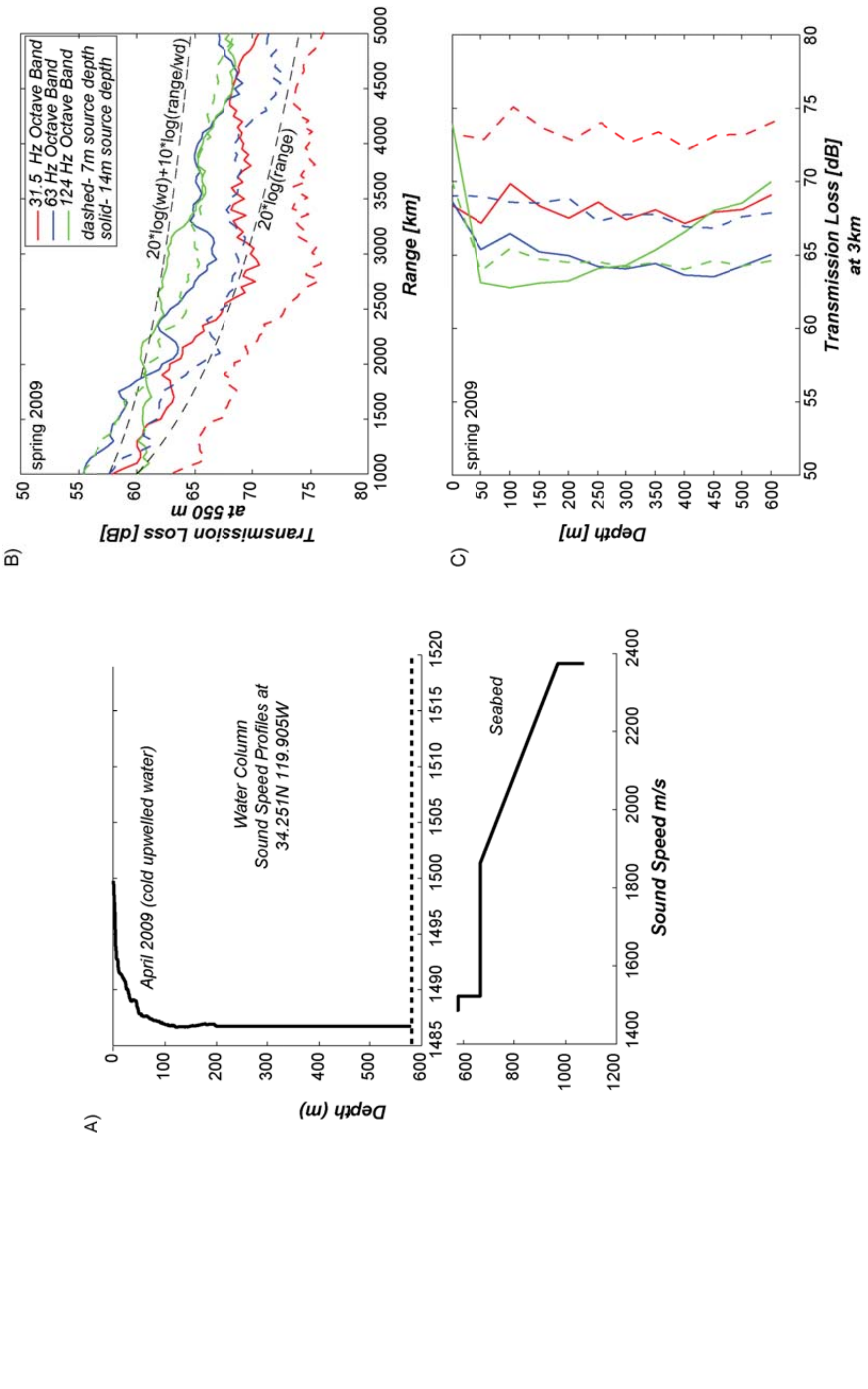
Figure 2.3: Region specific transmission loss model. A) Sound speed depth profile for water column and sediment during April 2009. B) Sound propagation loss for 63 Hz octave band at depths of 510-570 m for different source depths (14 and 7 m). The ranges from the ships to the HARP are shaded in gray (wd = water depth at acoustic receiver).

Figure 2.4: Ship source levels for A) container ships and vehicle carriers, B) bulk carriers and open hatch cargos, and C) three types of tankers. Top two series of figures show octave and 1/3 octave bands, with mean and standard errors. Bottom series shows the 1 Hz band levels.



A) Container Ship (10.8 m/s)
Vehicle Carrier (8.5 m/s)
B) Bulk Carrier (7.2 m/s)
Open Hatch (7.0 m/s)
C) Products Tanker (7.5 m/s)
Crude Oil Tanker (6.9 m/s)
Chemical Tanker (6.5 m/s)
Octave Bands
1/3 Octave Bands
1 Hz Bands
Source Level [dB re 1 μPa² @ 1m]
SL = RL + 20*log(range [m])
Frequency [Hz]

Appendix I: Transmission loss model results in the Santa Barbara Channel for April 2009. A) Sound speed depth profile for water column and sediment during April 2009. The water column properties were representative a period of cold upwelled water. These variables were used in the propagation models. B) Sound propagation loss for three octave bands at depths of 510-570 m for different source depths (14 and 7 m). wd = water depth at acoustic receiver. C) Sound propagation in the water column at a distance of 3.5 km from the source at depths of 7 and 14 m.


A)
Depth (m)
April 2009 (cold upwelled water)
Water Column
Sound Speed Profiles at
34.251N 119.905W
Seabed
Sound Speed m/s
B)
spring 2009
31.5 Hz Octave Band
63 Hz Octave Band
124 Hz Octave Band
dashed- 7m source depth
solid- 14m source depth
20*log(wd)+10*log(range/wd)
20*log(range)
Transmission Loss [dB]
at 550 m
Range [km]
C)
spring 2009
Depth [m]
Transmission Loss [dB]
at 3km

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CHAPTER 3

Modeling Container Ship Underwater Radiated Noise

by Megan F. McKenna

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Abstract

Statistical models of radiated underwater noise from container ships (20 - 1,000 Hz) were developed and evaluated using vessel design characteristics, operational conditions, and oceanographic features. A total of 593 container ship passages and 18 predictor variables were used to build generalized additive models. Ships in the analysis transited a 600 m basin off the coast of southern California where seafloor acoustic recorders, 3 km from a commercial shipping lane, measured radiated noise from the transiting ships. In an analysis that only included ships with four or more transits, individual ship identification did not improve explained variability when operational and oceanographic variables were also incorporated into the model. Underwater noise levels from container ships were partially explained by ship design characteristics, but the addition of operational and oceanographic variables improved explained deviance to 56%. In the step-wise selection procedure, speed had the highest predictive power in all frequency bands, ship size had the second highest, and various oceanographic conditions (*i.e.,* month, wave height, current direction) added to the deviance explained. The presence of intense tones (10% of ships in this study) resulted in higher predicted levels in frequencies above 250 Hz. Uncertainty in sound propagation and sound source depth likely accounts for unexplained variability in the models.

Introduction

Merchant shipping constitutes a major source of low-frequency noise in the ocean (Wenz, 1962; Ross, 1976; Wagstaff, 1981; Hildebrand, 2009), particularly in the northern Hemisphere where the majority of ship traffic occurs. In frequencies below 300 Hz, natural background noise levels are elevated by 15-20 dB when ship noise is present (Ross, 1993; Andrew *et al.,* 2002; McDonald *et al.,* 2006; McKenna *et al.*, 2009). Concerns have been raised over the impact of these increased noise levels on marine animals dependent on sound for life functions (NRC, 2003; Clarke *et al.,* 2009). However, few studies exist for predicting ship noise or identifying specific conditions that result in higher underwater radiated noise levels.

Container ships, a specific classification of large commercial vessels, are designed to carry manufactured cargo pre-packed into containers. These ships were introduced in the 1950s, and since 1990 container trade increased by a factor of five (the fastest growth of any ship-type) and currently these ships constitute a major component of the global shipping fleet with almost 90% of general cargo transported in containers (IMO, 2009). In this study we focus on container ships and present a statistical method to explain the variability in the observed underwater radiated noise.

Seafloor acoustic measurements of container ship passages are combined with ship design characteristics, ship operational conditions, and oceanographic features to determine the variables relevant to observed ship radiated sound levels. Statistical models are developed for different frequency bands using the predictor variables. Estimated sound levels from individual ships on different transits are also evaluated.

Background

Underwater radiated noise is an incidental by-product from standard ship operations, with the highest sound levels at the lowest frequencies (< 300 Hz). The sound generated by a ship consists of a broad-band component generated by propeller cavitation and narrow band components generated by both propeller cavitation and internal machinery (*e.g.* engine, generators, pumps). The broad-band noise results from the collapse of cavitation voids generated on the lifting side of each propeller blade as it passes through the low-flow velocity region near the top of its cycle of rotation (Ross, 1976). The blade lines in the propeller cavitation spectrum are produced by the changing volume of the region occupied by cavitation voids; this volume varies in a cyclic fashion, reaching a peak as each propeller blade nears the top of rotation. Previous research mainly focused on propeller cavitation and the hydrodynamic process related to the generation of the cavitation bodies (ten Wolde and de Bruijin, 1975; Blake, 1984; Fish and Blanton, 1988). These studies focused on improving propeller efficiency and relied on significant knowledge of the physical parameters of the inflow, making them largely impractical for predicting the cavitation volumes across a variety of ships and operating conditions. Furthermore these studies rarely report radiated noise levels. Efforts to predict source levels and frequencies generated by propeller cavitation from modern ships were developed (Gray and Greeley, 1980) and proved useful for predicting blade rate radiation, but not blade rate harmonics (Arveson and Vendittis, 2000).

Early studies of radiated ship noise from operating ships reported an increase in radiated noise related to the length and speed of a ship for a variety of merchant and naval ship-types (Ross and Alvarez, 1964; Ross, 1976). These ships, however, were less than 200 m long with speeds of less than 5 ms^{-1} (10 knots) and are not representative of modern merchant ship fleet. Furthermore, the engine and propulsion systems of older ships (*i.e.,* direct-drive diesels, steam turbines, and reciprocating steam-plants) have been replaced with geared medium-speed diesels and with low-speed direct-drive motor diesel propulsion systems to improve energy efficiency. Predictions of underwater radiated noise based on these modifications in ship design and operating conditions exist, and were extrapolated to explain the increases in ambient noise in the ocean. Ship noise measurements of these new ship-types are needed to validate these predictions (Ross, 2005).

Estimates of modern radiated ship noise are limited to just a few examples because ship time as well as measurement costs are high. Air-dropped sonobuoys have been used to collect acoustic measurements of ships-of-opportunity. Results of these studies were widely reported (Wright and Cybulski, 1983), but were later found inaccurate when compared with seafloor acoustic measurements (Arveson and Vendittis, 2000). An ensemble of broad-band source spectra of sound generated by 54 individual ships reported differences in radiated noise unrelated to speed and length as previously predicted. Instead, the authors attributed the variability in noise to inappropriate propagation models and the presence of local ship noise (Wales and Heitmeyer, 2002; Heitmeyer *et al.,* 2003). However, these sonobuoy measurements likely were not calibrated properly and the environmental conditions were not recorded during the acoustic measurements. Furthermore, the predictive power decreases when a variety of modern ship-types are combined into a single analysis because each ship-type has its own unique spectral characteristics (McKenna *et al.,* submitted).

Extensive seafloor measurements of underwater radiated noise of a modern cargo ship characterized both the broad-band and narrow band noise (Arveson and Vendittis, 2000). At low speeds, the acoustic signature is dominated by the tones of the ship's service diesel generator. The dominant source of noise at high speeds is propeller cavitation observed as a series of harmonics at multiples of the blade rate. Although these results are useful, measurements need to be collected from a significant number of ships to have predictive power.

Study Setting

The study site was located in the Santa Barbara Channel (SBC); a region on the continental shelf, off the coast southern California, bordered to the north by the California coastline and to the south by the Northern Channel Islands (Fig. 3.1). The slope of the basin bordering the mainland is gentler than the region bordering the islands; the maximum depth of the basin is ~600 m (Emery, 1958). Core samples of the basin sediments contained silty layers believed to be deposited on an annual cycle (Emery, 1960; Hulsemann and Emery, 1961).

Oceanographically, this region is within the California current system, the eastern limb of the large-scale, anticyclone North Pacific gyre. The waters of the California current are characterized by a variety of seasonal circulation patterns which are a complex mix of cold water upwelled off Point Conception and warm, saline Southern California Bight waters (Harms and Winant, 1998). In the summer, a persistent cyclonic feature is found in the western SBC which mixes these water masses. During the spring, upwelling events occur, introducing nutrient-rich, cold water (Huyer, 1983). Late winter storms introduce sediment laden waters from river input (Toole and Siegel, 2001). This variability in water masses can have an effect on the sound transmission in the area (Kuperman and Ingenito, 1980).

Two major ports serve ships traveling through the Southern California Bight: Port Hueneme; and the Port of Los Angeles-Long Beach (POLA). POLA is the second busiest port in North America (CINMS, 2009). Until recently, an estimated 75% of vessel traffic departing from, and 65% of traffic arriving at, POLA and Port Hueneme traveled through the SBC (CINMS, 2009). Commercial vessel traffic is concentrated in the designated shipping lanes (Fig. 3.1), with an average of 18 ships transiting per day (McKenna *et al.*, 2009).

Methods

Statistical Model

Models of container ship noise as a function of a suite of design, operational and oceanographic variables were constructed separately for specific frequency bands within the framework of generalize additive models (GAM: Hastie and Tibshirani, 1990). All models were created using *R* (version 2.12, 2010), a readily available statistical software package. Generalize additive models are a nonparametric extension of the more familiar linear models (GLM; McCullagh and Nelder, 1989), where a response variable (y) is modeled as the sum of linear functions of the variables (x_1, x_2, . . x_n). In the case of GAMs, y is modeled as the sum of non-linear functions of the variables plus constants (ε_i):

$$y = \sum f_i(x_i) + \varepsilon_i \qquad (1)$$

Generalize additive models share many of the same statistical properties of GLMs, but do not constrain the relationship between y and x to be linear or of any particular function. Nonparametric functions can be fit to the predictor variables using smoothing functions such as Loess or spline smoothers to define the relationship between the predictor and the response variables. GAMs are ideal for modeling distribution data since the constraint of linearity is lifted and a more flexible approach to the relationship between variables can be taken. Both GLMs and GAMs utilize a link function, relating the predictor variables to the distribution of the response variable.

For this analysis, a Gaussian distribution of estimated source levels was used with an identity link function. The link function was chosen based on the distributions of the source levels within each frequency band (Fig. 3.2). Seven frequency bands were evaluated separately: broad-band (20-1,000 Hz) and octave bands centered at 16, 31.5, 63, 124, 250 and 500 Hz. Eighteen potential predictive variables were included and are detailed below.

A forward/ backward step-wise model fitting procedure (*i.e.,* step.gam) was carried out for each frequency band to determine which variables had the most explanatory power in predicting the measured ship source levels. Each predictor variable was tested in the model on its own as well as using a smoothing spline with up to three levels of degrees of freedom. The best model was selected using Akiake's Information Criterion (AIC):

$$\mathrm{AIC} = -2*\log(L(\Theta \mid y) + 2*P \qquad (2)$$

where, ($L(\Theta \mid y)$ is the likelihood of the parameters given the data y, and P is the number of parameters. The best fit model minimizes AIC by maximizing the log-likelihood, with penalties for the number of parameters included (Akaike, 1976). In addition to using AIC, the best model was also verified using an analysis of deviance, comparing the residual deviance of several models using a Chi-Square method. The best fit model was one that minimized both AIC and residual deviance.

The first set of models included only a subset of all the unique ship transits, specifically ships that had four or more transits during the analysis period. Only operational and oceanographic predictors were included; design variables were excluded because they directly correlate with the individual ship variable. The models were implemented to determine if the specific ship (as a categorical variable) improved the model fit. If not, the ship transits used in the following models were considered independent events.

Some of the ship design predictor variables were highly correlated (Fig. 3.3); therefore we removed uncertainty in our results by transforming highly correlated variables. First, we ran the step-wise GAMs separately for each frequency band. The variable with highest explanatory power was used to transform the correlated variables into the residuals of the linear relationships between the two variables. Once the correlated variables were transformed, the models were re-run to determine all the ship design variables that had predictive power. The relevant predictor variables were included in the next model with the relevant operational and oceanographic variables. These models were used to evaluate predictability of ship noise in different frequency bands and determine the parameters important for predicting container ship noise levels.

Response Variable

Acoustic recordings: High frequency acoustic recording packages (HARPs; Wiggins and Hildebrand, 2007) were deployed in the SBC from October 2008 to October 2009 to measure acoustic noise levels of passing ships (Fig. 3.1; Table 3.1). The HARPs were located approximately 3 km from the northbound shipping lane providing a good site for obtaining acoustic measurements of transiting ships (Fig. 3.1).

HARPs are bottom-mounted instruments containing a hydrophone, data logger, battery power supply, ballast weights, acoustic release system, and flotation. The hydrophone is tethered to the instrument and buoyed approximately 10 m above the seafloor. The hydrophone includes two transducers: one for frequencies below 2 kHz and one for frequencies above 2 kHz. All acoustic data used were corrected based on hydrophone calibration performed in our laboratory and at the U.S. Navy’s Transducer Evaluation Center facility in San Diego, CA.

The HARPs were configured to record continuously for 55 days at 200 kSamples second^{-1}. To sample the entire year, approximately every two months the HARPs were recovered and serviced with new batteries, recording media and ballast weight. In some cases a new hydrophone was fitted and the instrument was re-deployed. Table 3.1 summarizes the acoustic data analyzed in this study. Personnel and ship time were limited for servicing the acoustic recorders; therefore, some months were not recorded continuously and these periods were not included in the analysis.

Ship locations: To estimate ship source levels (*i.e.,* response variable for the model) from the recorded HARP data, the times corresponding to ship locations were needed to estimate range from the ship to the HARP. Ship position data from the Automatic Identification System (AIS) were used to determine the range to the HARP. Ships greater than 300 gross tons (3.05×10^5 kg) are required to broadcast their position and unique identification information while underway via AIS. This system was originally conceived for ship-to-ship communication, allowing large vessels to increase their awareness of surrounding large vessel traffic and for ship to shore communication to aid in marine traffic safety (Tetreault, 2005). The AIS message, transmitted via very high frequency (VHF) radio approximately every 30 minutes, includes dynamic positional information tagged with general ship information. A second message, sent less frequently (*i.e.,* 6 minutes) provides additional ship information, and voyage specific details.

AIS signals from large commercial vessels transiting the SBC were collected using a marine VHF antenna connected to a radio and transferred to and recorded by a standard personal computer. The AIS receiving station was located on the campus of the University of California at Santa Barbara (34°24.5'N and 119°52.7'W; Fig. 3.1). The program, *ShipPlotter* (ver. 12.4.6.5, COAA, 2008), was used to decode the signal and archive daily logs. All archived AIS data were remotely downloaded and imported into a *PostgreSQL* database (ver. 8.4, 2009). Queries extracted AIS messages sent during the acoustic recording periods (Table 3.1). The salient information to match ship passages with the acoustic recordings included time of transmission, speed, heading, latitude, and longitude.

Estimated ship source level: The position of each transiting ship relative to the acoustic receiver was determined from the AIS data and the position and depth of the HARP. Received sound levels (RLs) were calculated for each ship at its closest point of approach (CPA) to the HARP. The RLs were expressed as the distribution of mean square pressure per unit frequency, on a logarithmic scale (dB). The amount of time used for the sound spectrum level calculation was equal to the time it took the ship to travel its length, as suggested by Bahtiarian (2009) and detailed in the ASA standard (ANSI/ASA S12.64-2009/Part 1).

Source spectrum levels at 1 m are presented as total broad-band energy (20-1,000 Hz) and energy in standard octave bands, centered at 31.5, 63, 124, and 500 Hz. To determine the octave band levels, the mean squared pressure values were summed across the frequency bands, and converted back to sound pressure levels expressed as decibels referenced to a unit pressure density in sea water. To estimate the source level for each transiting ship, the expected loss at the CPA distance was added to the measured RL. A spherical spreading loss model was used (see McKenna *et al.,* submitted). Because source levels are expressed on a logarithmic scale, the response variable in the statistical models are considered log transformed.

Predictor Variables

Eight variables characterizing the specific design of each transiting ship were unique ship identification (ID), gross tonnage (GT), service speed (SSPD), length overall (LOA), average draft (DFT), horse power (HP), and year built (YB) (Table 3.2). Design variables were gathered from the World Encyclopedia from Lloyd's Registry of ships. Only ships classified as container ships greater than 100 m were included in this analysis.

The AIS data provided information on the operating conditions of each ship transit; four specific parameters included were speed (SPD), distance to the receiver (RAN), time to the next passage of the ship (OTH), and the proportion of the service speed the ship was traveling at (PSPD) (Table 3.2). The speeds reported by AIS, are speeds over ground, not actual speed of the ship relative to surface currents. The AIS speeds were adjusted to actual speed based on the surface current speed and direction. This information was obtained from archived data at the University of California Santa Barbara, surface current mapping project (ICESS, 2009).

The sea conditions during the passage of each ship were obtained from archived data at the National Oceanic and Atmospheric Administration (NOAA), station 46053 (32°14.9’N 119°50.5’W). The six oceanographic conditions measured during the same hour as the passage of each ship were matched to each ship passage were current direction (CDIR), wind direction (WDIR), wind speed (WSPD), significant wave height (WVHT), dominant wave period (DPD), and the direction from which the waves at the dominant period are coming (MWD) (Table 3.2).

An additional predictor variable from the acoustic data included the presence of strong frequency tones (TONE). This was a simple categorical variable- present or absent. The final predictor variable included was the month of the acoustic measurement.

All acoustic data matching the CPA times were evaluated for the presence of a single ship. Ships were eliminated if another ship passed within 1-hour or if vocalizing marine mammals were present. Shortest time from the previous or next ship passage was included in the statistical analysis to highlight any potential contamination from other distant ships in the region.

Results

A total of 593 container ship transits were included in this study. Of the 331 unique ships that made these transits, 149 ships (45%) made two or more transits, of these, 29 ships had four or more transits, the remaining 182 ships only transited past the recorder once. Using a subset of the data (29 ships that made four or more transits), we tested if unique ship was important for predicting the source level. Individual ship identification did not improve explained variability when operational and oceanographic variables were also incorporated into the model. This is not unexpected given the variability in the measured source levels for each individual ship; however, there was a trend of larger ships having higher measured source levels (Fig. 3.4). Based on these results, ship identification was not included in our analysis of all ship passages and each transit was considered an independent event.

All models significantly improved with the addition of operational and oceanographic variables. For all frequency bands, the explained deviation using the best fit model with design predictors was never greater than 25%; when operating conditions were included in the models explained deviance increased to >40% (Table 3.3; Fig. 3.5). Ship speed had the highest predictive power for all frequency bands; however, the important design and oceanographic predictors differed depending on octave band. For frequencies below 44 Hz (*i.e.,* 16 Hz and 31.5 Hz octave bands) the length of the ships and the month of the measurement had the next highest predictive power (Table 3.3; Fig. 3.5). For octave bands centered at 250 and 500 Hz, the presence of tones resulted in higher predicted source levels (see example of the tones in Fig. 3.6). Narrowband tones were present in 10% of the measured ships.

Below are summaries of the best models and relevant predictor variables for each frequency band model of container ship noise; equations are shown in Table 3.3 and Table 3.4 lists the delta AIC values for each predictor included in the models. Delta AIC values were generated from the step-wise selection procedure. For all models, the greatest model improvement occurred with the addition of ship speed.

Broad-band Model (20-1,000 Hz)

For ship source level in a broad frequency band, the step-wise selection procedure with design, operational, and oceanographic variables resulted in 8 covariates explaining 56% of the deviance (Table 3.3); operational speed had the highest predictive power and the greatest delta AIC value (Table 3.4). Broad-band radiated noise levels increased with speed, ship length, when the service speed was faster than predicted by ship length, and when tones were present. The oceanographic conditions which predicted higher noise levels were high wave height and water current traveling in the opposite direction of the ship. The month of the measurement also had predictive power, with higher radiated ship noise in the spring, likely water column properties that affect sound propagation. Most of the relationships predicted were linear, with the exception of residual service speed and wave height (Table 3.3; Fig. 3.5).

Octave Band Centered at 16 Hz Model

For ship source levels in the lowest octave band (16 Hz), the step-wise selection procedure with design, operational and oceanographic variables resulted in 8 covariates explaining 54% of the model deviance: speed, length of ship, month, wave height, distance to the HARP, residual proportion of service speed, the direction from which the waves at the dominant period are coming, and the current direction (Table 3.3). The three variables with the most predictive power (speed, length, and month) were the same for the broad-band noise model (Fig. 3.5A&B). Ship noise levels in the 16 Hz band increased with increasing ship length and speed. When the proportion of the ship speed relative to the service speeds was less than expected, noise levels increased. Similar to broad-band noise levels, the month of the measurement resulted in higher estimated source levels in the spring (April-June). The oceanographic conditions that predicted higher radiated noise levels were high wave heights and current and dominant waves traveling in the opposite direction of the ship.

Octave Band Centered at 31.5 Hz Model

For ship source levels in the octave band centered at 31.5 Hz, the step-wise selection procedure with design, operational and oceanographic variables resulted in 8 covariates explaining 53% of the deviance. Vessel speed had the highest predictive power and the greatest delta AIC value (Table 3.4). The three variables with the most predictive power (speed, length, and month) were the same for the broad-band and 16 Hz octave band models (Fig. 3.5A-C). Most of the relationships predicted were linear, with the exception of current direction and time from the next ship passage (Table 3.3). In the 31.5 Hz octave band, ship noise levels increased with increasing speed, ship length, when the proportion of the ship speed relative to the service speeds was less than expected and age of the ship. The month of the ship passage predicted higher levels in the spring compared to late fall. The ships that passed that area less than 13 hours from the passage of the measured ship resulted in higher measured levels. The oceanographic conditions that predicted an increase in ship noise levels were higher wave heights and surface currents in the opposite direction of the ship.

Octave Band Centered at 63 Hz Model

For ship source levels in the octave band centered at 63 Hz, the step-wise selection procedure with design, operational and oceanographic variables resulted in 6 covariates explaining 43% of the deviance. The four variables with the most predictive power (speed, residual HP, range to HARP, and month) were different from the broad-band, 16 Hz and 31.5 Hz octave band models (Fig. 3.5A-D). Ship noise levels increased with increasing speed, when HP was greater than expected based on GT, when ships were closer to the HARP and when gross tonnage increased. The month of the ship passage predicted higher levels in the spring compared to late fall. The ships that passed that area less than 13 hours from the passage of the measured ship resulted in slightly higher predicted noise levels.

Octave band centered at 124 Hz Model

For ship source levels in the octave band centered at 124 Hz, the step-wise selection procedure with design, operational and oceanographic variables resulted in 5 covariates explaining 38% of the deviance. The four variables with the most predictive power were speed, month, gross tonnage, and distance to the HARP (Fig. 3.5E). Ship noise levels increased with increasing speed. The relationship with gross tonnage was complicated with higher levels for the smaller and larger ships, and a minimum at the medium sized ships (64 kGT). When ships were shorter than expected based on gross tonnage, noise levels were higher. Ships at closer ranges to the HARP had higher noise levels. No oceanographic conditions were included in the models.

Octave Band Centered at 250 Hz Model

For ship source levels in the octave band centered at 250 Hz, the step-wise selection procedure with design, operational and oceanographic variables resulted in 7 covariates explaining 44% of the deviance. The four variables with the most predictive power were speed, month, gross tonnage, and the presence of tones (Fig. 3.5F). Ship noise levels increased with increasing vessel speed, gross tonnage and the presence of tones. When the service speed was greater than expected based on the gross tonnage noise levels were higher. Likewise, when ships were shorter than expected based on gross tonnage noise levels were higher. Similar to other frequency bands, predicted source levels were higher in the spring compared to late fall and when the ships were closer to the HARP. No oceanographic predictors were included in this model.

Octave Band Centered at 500 Hz Model

For ship source levels in the octave band centered at 500 Hz, the step-wise selection procedure with design, operational and oceanographic variables resulted in 4 covariates explaining 39% of the deviance. The four variables with the most predictive power were speed, month, the presence of tones, and gross tonnage (Table 3.3; Fig. 3.5G); a result that was similar to the 250 Hz band. Ship noise levels increased with increasing speed, gross tonnage, and the presence of tones (Fig. 3.5G). Source levels were higher in the spring compared to late fall. No oceanographic predictors were included in this model.

Discussion

Predicting radiated underwater noise from container ships under normal operating conditions was found to be dependent on the varying relationships of the predictors and on the frequency band. The modeling approach allowed the importance of some of these relationships to be ranked. No previous studies of underwater radiated container ship noise exist to compare our measured source levels. However, in previous work using the same opportunistic method to measure radiating noise (McKenna *et al.,* submitted), the results of this study were similar to previous controlled measurements for a bulk carrier (Arveson and Vendittis, 2002).

Ship design parameters alone do not accurately predict the levels of radiated noise from a transiting ship. Individual ship identification lacked predictive power when multiple transits of the same ship were compared and the explained deviance increased with the addition of operational and oceanographic conditions. Based on these initial findings, the final statistical models included design, operational, and oceanographic variables for 593 ship transits with each ship transit treated as an independent event.

Broad-band source level (20-1,000 Hz) and source levels in the two lowest frequency bands were predicted with the most deviance explained. Increased uncertainty was found in higher frequency bands. Overall, vessel speed had the most predictive power in all frequency band models, a representation of ship size (length or GT) had the second highest predictive power, and then various oceanographic conditions significantly factored into the predictive power (Tables 3.3&3.4). Previous studies have quantified the relationship between radiated noise and ship speed and size for older merchant ships (Ross and Alvarez, 1964; Ross, 1976). Our results corroborate these findings for a modern ship-type, the container ship.

Our statistical approach left some unexplained variability (Table 3.3), which was likely related to the depth of the sound source (propeller and hull draft). Arveson and Vendittis (2000) highlighted the importance of including this measurement in any analysis of radiated ship noise because source depth will change the propagation of radiated noise. A shallower source depth will decrease the effect of the dipole source, thereby decreasing the amount of radiated sound from the ship. The closer the distance between the source and the sea surface the lesser the strength of the dipole (Ross, 1976). Source depth varies depending on the particular design of a ship and the load conditions during a specific transit. Unfortunately, AIS does not provide source depth information and was therefore not included in the models. Instead, we included the average draft of the ship from Lloyd's registry of ships as a proxy for the depth of the source. Yet, this variable did not have high predictive power in the models, suggesting that draft was not a good proxy for the actual depth of the source. Perhaps other metrics, such as the number of loaded containers, might be more accurate. In general, container ships leaving the ports of Los Angeles and Long Beach (*i.e.,* northbound) are not as fully loaded as when they enter the ports. Since we only measured ships leaving the ports, the source depth for the partially loaded ships might be similar; however, our estimates of container ship noise would be an underestimate of radiated noise from a fully loaded ship with a deeper source.

Ship operational speed had the highest predictive power in explaining the level of radiated noise from container ships (Fig. 3.5), similar to Ross and Alvarez (1964) for various types of merchant and military ships. The relationship increased linearly (on a dB scale) with some deviations at higher speeds. For example, the 63 Hz octave band showed a flattening of the relationship when speeds were above 10 ms^{-1}. Of the design parameters, ship length provided the highest predictive power in the low-frequency octave bands (16 and 31.5 Hz) and the broad-band; the relationships were all linear- increased predicted levels with increased ship length (Fig. 3.5; Table 3.3). Ross and Alvarez's (1964) predicted noise was dependent on the square of the length.

The age of a ship also had predictive power in the 31.5 Hz band model and predicted that older ships produced more low-frequency noise. Most of the ships analyzed were built between 2000 and 2005 (47%), 19% were built after 2005, and the remaining ships were built prior to 2000; the oldest container ship included in this study was built in 1971. Although the newer ships traveled faster and were on average larger, there have been continued improvements in reducing ship resistance and increasing propulsion and machinery efficiency, particularly after the 1973 and 1979 oil crisis (Okumoto, 2009). Improvements included dampening of engine vibrations, changes in hull design and fewer cylinder engines (Okumoto, 2009). Furthermore, the propeller exciting frequency has shifted higher, related to the increase in engine revolutions per minute (RPM). The ship built in 1971 had a 90 RPM turbine engine, and likely 5 blades resulting in a 7.5 Hz propeller exciting frequency; the newer ships with higher RPM diesel engines and 5 blades would produce a higher propeller exciting frequency (9.1 Hz) (Okumoto, 2009). These changes to the propulsion would potentially result in a decreased amount of low-frequency radiated noise in newer builds of container ships. Some of these older ships might also have propeller damage or fouling that would result in higher levels of radiated noise.

For the 63, 124, 250 and 500 Hz octave band models, gross tonnage explained the most variability of all the design variables; therefore, the design predictors included in the models were added as residuals of a direct linear relationship with gross tonnage (Fig. 3.3B). In these frequency bands, unlike the lower bands, the parameters with predictive power were not consistent. Gross tonnage was the only design variable included in the 500 Hz octave band model. For 63 Hz octave band model, when HP was greater than expected (given ship gross tonnage), noise levels were predicted to be higher (Fig. 3.5D). There was an inverse relationship with ship length. When a ship was shorter than predicted give the gross tonnage, noise levels were predicted to increase in the 124 and 250 octave band models. This result might be confounded with differences in ship speeds related to size.

Of the seven possible oceanographic conditions, the month of the ship passage was the only covariate included in all the models (Fig. 3.5; Table 3.3). This predictor was intended to capture differences in radiated noise related to water column properties, specifically sound speed profiles. All models tended to show an increase in predicted radiated noise during the spring months (April, May and June), with the exception of the 124 Hz model. The water in this region is characterized by a variety of seasonal circulation patterns that results in a complex mixture of cold water upwelled off Point Conception and warm, saline Southern California Bight water (Harms and Winant, 1998). During the spring, strong upwelling events occur, introducing nutrient-rich, cold water (Huyer, 1983). Although there appears to be an increase in radiated ship noise during the spring, not all months are represented in this study and limit this comparison.

Excluded months were August, December, January, and February and significantly fewer transits in July and September. Furthermore, ephemeral coastal oceanographic features such as internal waves could also influence the propagation, influencing the results of the monthly comparisons (Zhou *et al.,* 1991).

Surface current direction was another important predictor of ship noise in all lower frequency models (broad-band, 16 Hz, and 31.5 Hz; Table 3.3). When the surface current was opposite to the ships' direction of travel, predicted noise levels were higher. This was expected given that for a ship to achieve the same speed an increase in engine power is needed resulting in increased radiated noise. In the lower frequency models, the wave height, dominant wave period, and direction of the dominant wave period also influenced predicted noise levels. Higher wave height and a decrease in wave period create rougher seas, which would influence the motion of the ship at the surface. If the ship rolling and pitch of the ship changes, the dynamic movement likely causes the increase in cavitation and the predicted radiated ship noise levels in these conditions. Weather will also influence the ambient noise levels at these frequencies; however, when a ship was close to the receiver (<4 km) the measured noise levels were dominated by ship noise and wind speed and direction were not included in any of the models of radiated ship noise.

We did not expect the range of the ship to the HARP to have any explanatory power. The variable was included to account for possible measurement error. However, for some frequency bands (16, 63, 124, and 250 Hz), an increase in ship source level was predicted for ship transiting closer to the HARP. Ship behaviors might explain why levels were higher when ships were closer to the HARP. A spatial analysis of ship speed in the region showed that faster ships travel on the outside of the lanes (closer to the HARP; McKenna *et al.,* submitted). Based on this observation, this variable more likely relates to ship speed. The inclusion of the time between the passing ships was another important predictor suggesting that there might be some contamination from low-frequency distant ship noise in the region, as suggested by Heitmeyer *et al.* (2003). Only the 31.5 Hz and 63 Hz octave bands included this variable in the predictive model (Table 3.3). Ships with tones present had higher predicted noise levels in both the total energy band and higher frequency octave bands (250 and 500 Hz). The cause of these tones is unknown, but might be related to propeller damage not only increasing radiated noise, but decreasing efficiency of the propulsion system (Ross, 1976).

Conclusion

The statistical approach of this study reduced the number of ship noise predictors to just a few from 18 ship design parameters, operating conditions and oceanographic features. Our results corroborate previous studies and predicted higher levels of noise from larger and faster ships. Unique to our study are the inclusion of oceanographic variables (water column properties, wave height, dominant wave period, and current direction) and the presence of high intensity tones when predicting the level of underwater radiated noise. Only models for container ships are presented, however these methods could be applied to other ship-types.

This study shows that levels of radiated noise are not simply a function of a particular ship or ship design, but also operating conditions and environmental variables. These predictors should be considered when quantifying the level of ship noise in a particular region and the potential impact on marine organisms.

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Chapter 3, in full, is currently in preparation for submission. McKenna, M.F., Wiggins, S.M., and Hildebrand, J.A. Modeling Container Ship Underwater Radiated Noise. The dissertation author was the primary investigator and author of this material.

Table 3.1: Summary of acoustic data for analysis of container ship noise

Year	*Month*	*Days sampled*	*Hydrophone*	*Latitude*	*Longitude*	*Depth*	*Number of ships*
2008	October	15-31	471	34°16.617 N	120°01.492 W	576	75
2008	November	1-30	471	34°16.617 N	120°01.492 W	576	100
2009	March	13-31	412	34°16.528 N	120°01.129 W	577	77
2009	April	1-31	412	34°16.528 N	120°01.129 W	577	115
2009	May	13-31	412	34°16.667 N	120°01.613 W	580	64
2009	June	1-31	412	34°16.667 N	120°01.613 W	580	101
2009	July	1-6	412	34°16.667 N	120°01.613 W	580	13
2009	September	2-30	412	34°16.634 N	120°01.506 W	580	15
2009	October	1-27	412	34°16.634 N	120°01.506 W	580	33

Table 3.2: Descriptions of predictor variables

Predictor Variable	*Abbreviation*	*Description*
Ship Design		
Length	*LOA*	total length of ship in meters
Gross tonnage	*GT*	a unitless index related to ships overall internal volume
Horsepower	*HP*	measurement of engine power
Service speed	*SSPD*	speed the ship was designed to travel at for maximum efficiency
Draft	*DFT*	the average vertical distance between the waterline and the bottom of the hull
Identification	*ID*	Maritime Mobile Service Identity (MMSI), a series of 9 digits to uniquely identify ships
Year built	*YB*	Year the ship was constructed
Ship Operational		
Speed	*SPD*	actual ship speed over ground
Range	*RAN*	distance of the ship to the HARP at closest point of approach
Proportion of speed	*PSPD*	proportion of the service speed the ships is travelling (SPD/SSPD)
Other ship	*OTH*	time to the next ship passage (>1 hour)
Tones	*TONE*	presence of spectral tones
Environmental		
Month	*MTH*	month of the year
Wave height	*WVHT*	significant wave height (meters) is calculated as the average of the highest one-third of all of the wave heights during the 20-minute sampling period
Wave direction	*MWD*	mean wave direction corresponding to energy of the dominant period (DPD). The units are degrees from true North.
Current direction	*CDIR*	direction the ocean current is flowing toward. 0-360 degrees, 360 is due north, 0 means no measurable current.
Wave period	*DPD*	dominant wave period (seconds) is the period with the maximum wave energy
Wind direction	*WDIR*	wind direction measurements in degrees clockwise from true North.
Wind speed	*WSPD*	wind speed values in m/s.

Table 3.3: Summary of generalized additive model results for each frequency band

EQUATION- in the order of predictive power	***AIC***	***Residual deviance***	***Deviance explained***	***Highest predictive power***	***No. predictors included***
BROAD-BAND (20-1,000 Hz)					
TE ~*SPD + LOA + MTH + s(rSSPD,3) + TONE + MWD + s(WVHT,2) + CDIR*	2834.5	3826.3	0.56	Speed	8
OCTAVE BAND CENTERED AT 16 Hz					
OB16 ~ *SPD + LOA + MTH + WVHT + s(RAN,3) + rPSPD + MWD + CDIR*	3341.9	9003.2	0.54	Speed	8
OCTAVE BAND CENTERED AT 31.5 Hz					
OB31 ~ *SPD + LOA + MTH + WVHT + YB + s(CDIR,2)+ s(tOTH,3) + rPSPD*	3294.3	8252.7	0.53	Speed	8
OCTAVE BAND CENTERED AT 63 Hz					
OB63 ~ *s(SPD,2) + rHP + s(RAN,3) + MTH + s(GT,3) + s(OTH,3)*	3109.4	6021.7	0.43	Speed	6
OCTAVE BAND CENTERED AT 124 Hz					
OB125 ~ *SPD + MTH + s(GT,3) + s(RAN,2) + rLOA*	2992.9	5083.2	0.38	Speed	5
OCTAVE BAND CENTERED AT 250 Hz					
OB250 ~ *SPD + MTH + GT + TONE + s(rSSPD,3) + rLOA + s(RAN,2)*	3022.0	5284.7	0.44	Speed	7
OCTAVE BAND CENTERED AT 500 Hz					
OB500 ~ *s(SPD,2) + MTH + TONE + GT*	3192.9	7146.0	0.39	Speed	4

Table 3.4: Comparison of delta AIC values from the step-wise GAM procedure

Model Predictor		***delta AIC***						
Ship Design		*Broad-band*	*16 Hz*	*31.5 Hz*	*63 Hz*	*124 Hz*	*250 Hz*	*500 Hz*
Length	*LOA*	30.6	40.7	52.8		6.1	3.1	
Gross tonnage	*GT*				12.5	50.0	16.5	11.9
Horsepower	*HP*				24.9			
Service speed	*SSPD*	32.9					39.1	
Draft	*DFT*							
Identification	*ID*							
year built	*YB*			13.6				
Ship Operational		*Broad-band*	*16 Hz*	*31.5 Hz*	*63 Hz*	*124 Hz*	*250 Hz*	*500 Hz*
Speed	*SPD*	323.7	291.9	257.9	203.4	173.2	206.8	181.4
Range	*RAN*		10.5		17.2	6.4	2.3	
Proportion of speed	*PSPD*		9.2	1.9				
Other ship	*OTH*			2.6	4.9			
Tones	*TONE*	11.8					10.0	30.6
Environmental		*Broad-band*	*16 Hz*	*31.5 Hz*	*63 Hz*	*124 Hz*	*250 Hz*	*500 Hz*
Month	*MTH*	25.9	37.8	46.5	11.0	12.2	18.8	36.9
Wave height	*WVHT*	4.8	15.5	13.4				
Wave direction	*MWD*	4.8	3.9					
Current direction	*CDIR*	3.8	3.0	4.7				
Wave period	*DPD*							
Wind direction	*WDIR*							
Wind speed	*WSPD*							

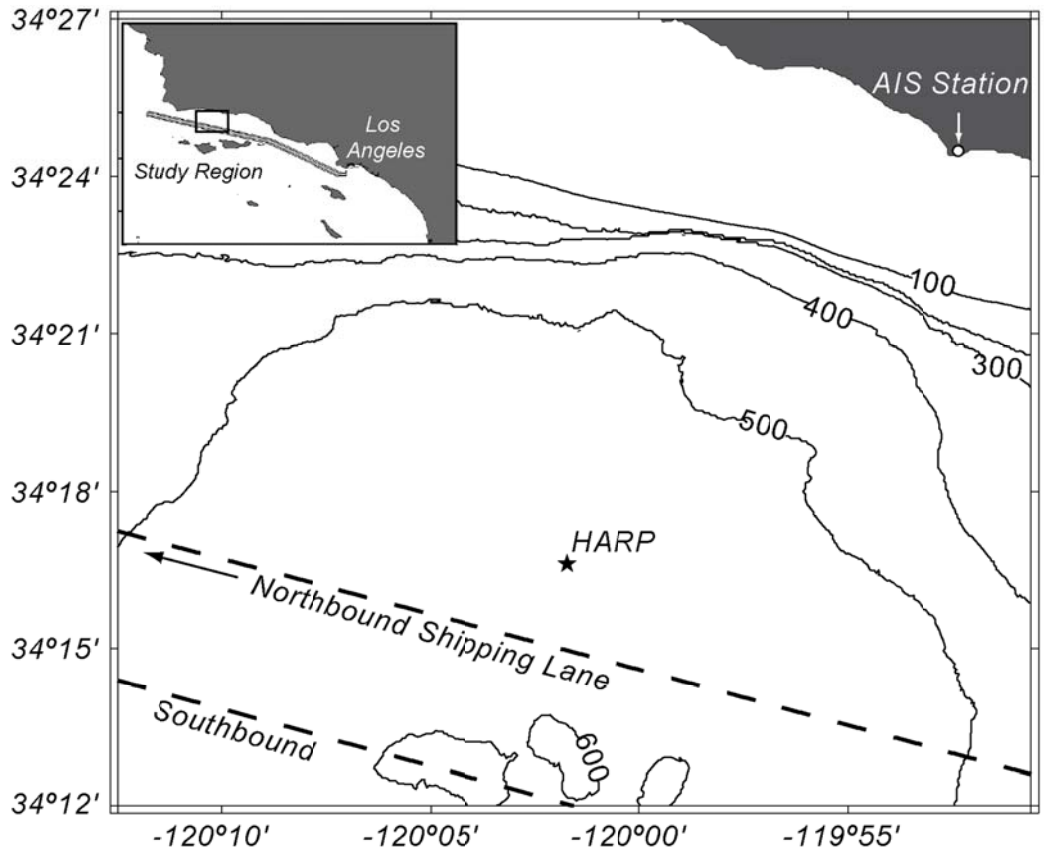
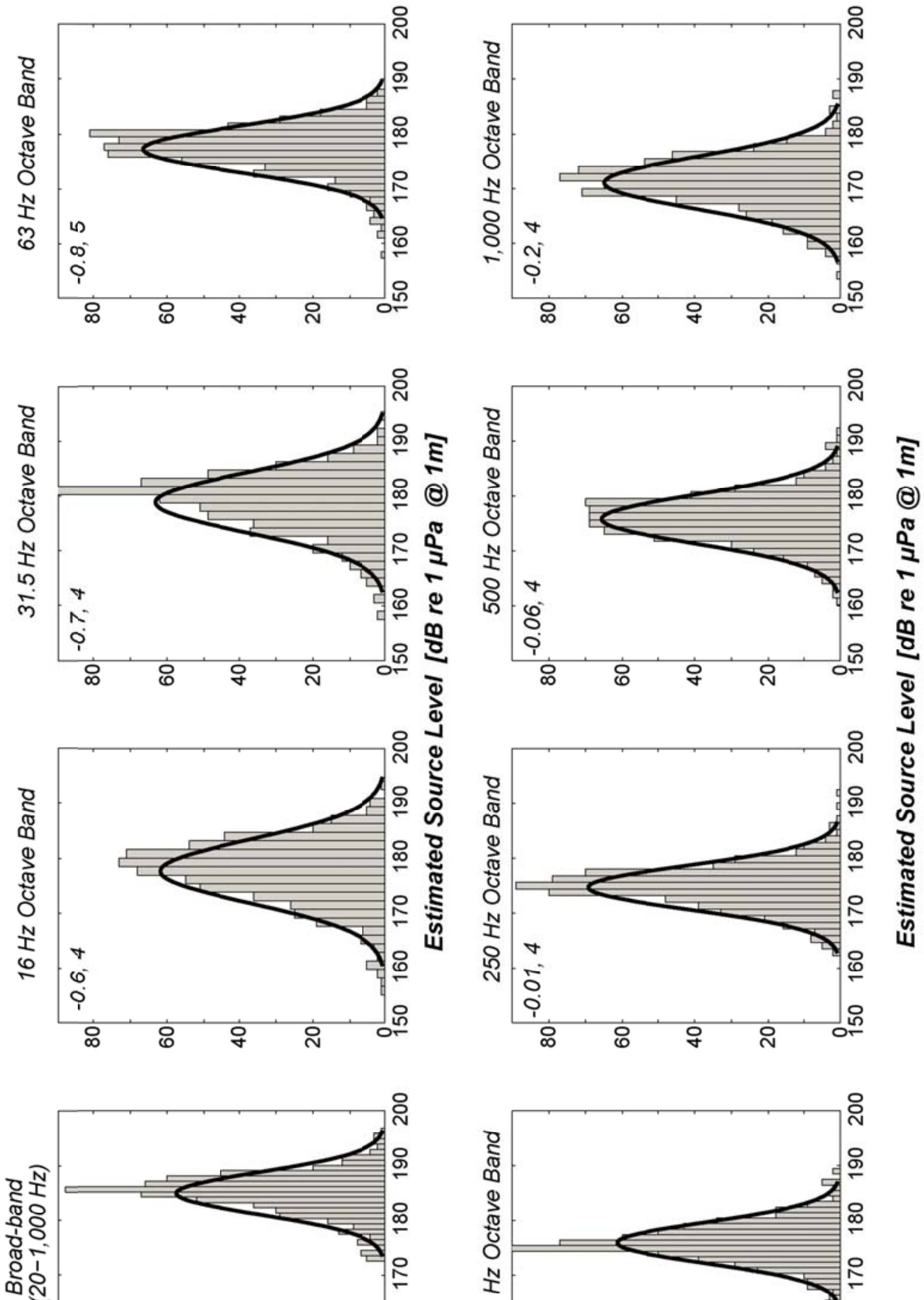


Figure 3.1: Map of Santa Barbara Channel, a region off the coast of southern California. The locations of the HARP (black star), AIS receiving station (white dot), north and southbound shipping lanes, and 100 m bottom contours are shown.

Figure 3.2: Distributions of container ship source levels. Estimated source levels are plotted by frequency band of interest. The broad-band is a sum of the squared pressures from 20-1,000 Hz. The remaining bands are standard octave bands, with the center frequencies shown in the title. The 1,000 Hz octave band is shown, but not analyzed in this study due to our sampling frequency of 2,000 Hz. The number of bins is equal to the square root of the number of transits, with a fitted normal distribution. The skewness (measure of asymmetry of the data around the mean, negative indicated left skew) and kurtosis (measure of outliers, where 3 is considered normal) are shown in the upper left corner.



Broad-band (20–1,000 Hz)
-0.5, 4
16 Hz Octave Band
-0.6, 4
31.5 Hz Octave Band
-0.7, 4
63 Hz Octave Band
-0.8, 5
124 Hz Octave Band
-0.1, 4
250 Hz Octave Band
-0.01, 4
500 Hz Octave Band
-0.06, 4
1,000 Hz Octave Band
-0.2, 4
No. of ship transits
Estimated Source Level [dB re 1 µPa @ 1m]
0
20
40
60
80
150
160
170
180
190
200

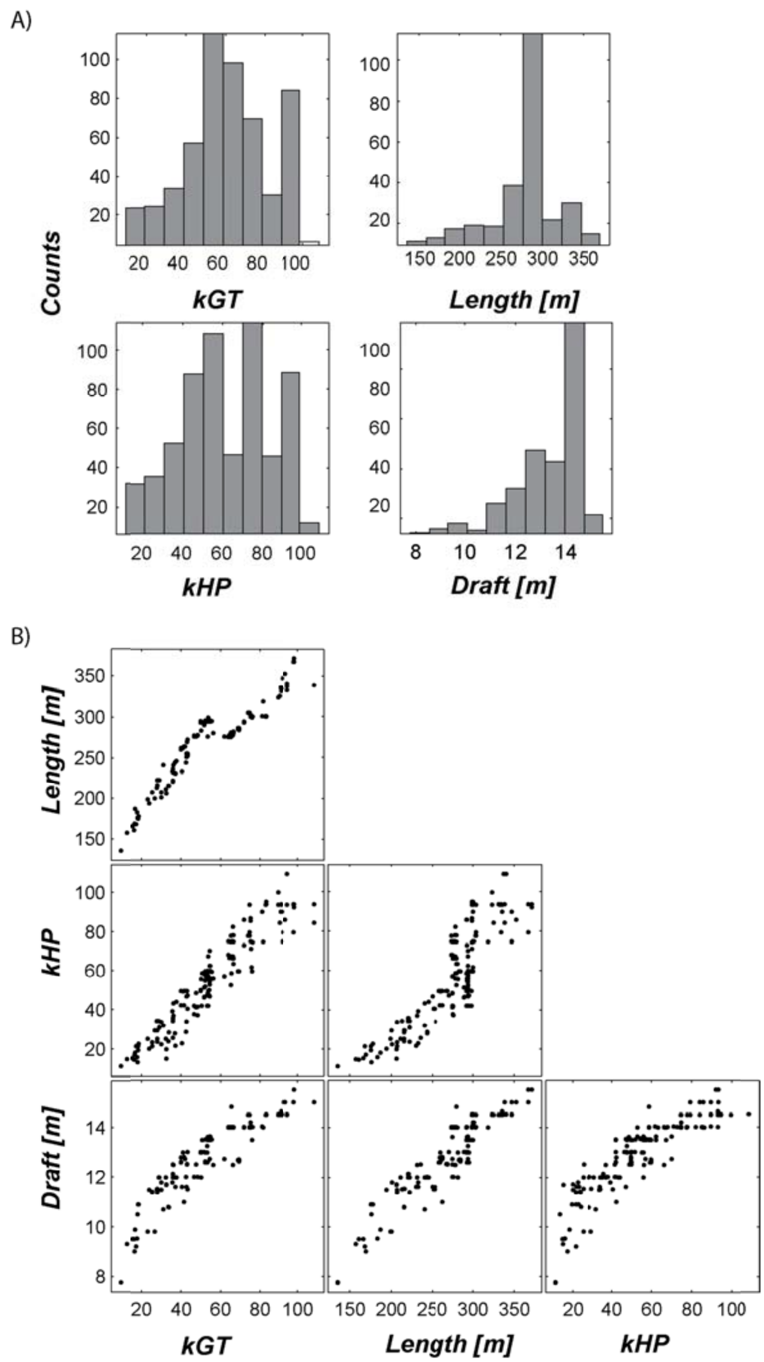


Figure 3.3: Container ship design characteristics. A) Distributions of design variables. B) Correlations of the different design characteristics, including gross tonnage (kGT), ship length, horse power (kHP), and drafts are shown.

Figure 3.4: Variability in container ships source level for individual ships. Ships plotted transited on four or more different occasions. The boxes bound the 25th and 75th percentiles, with the center line at the median. The ends of the whiskers are highest and lowest values of the data set that are within 1.5 times the inter-quartile range of the box edges. The plus signs represent data outside the range of the whiskers.

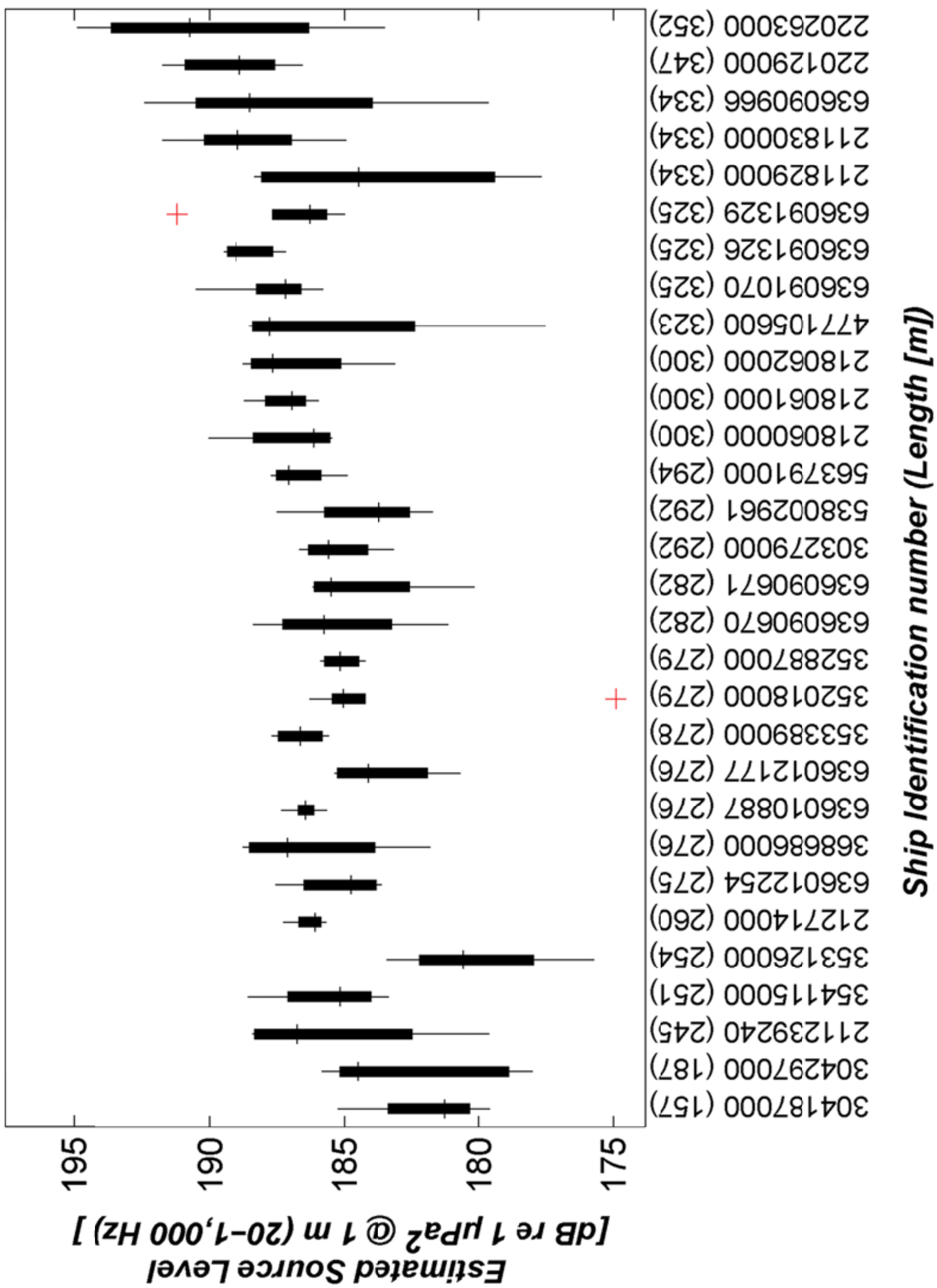
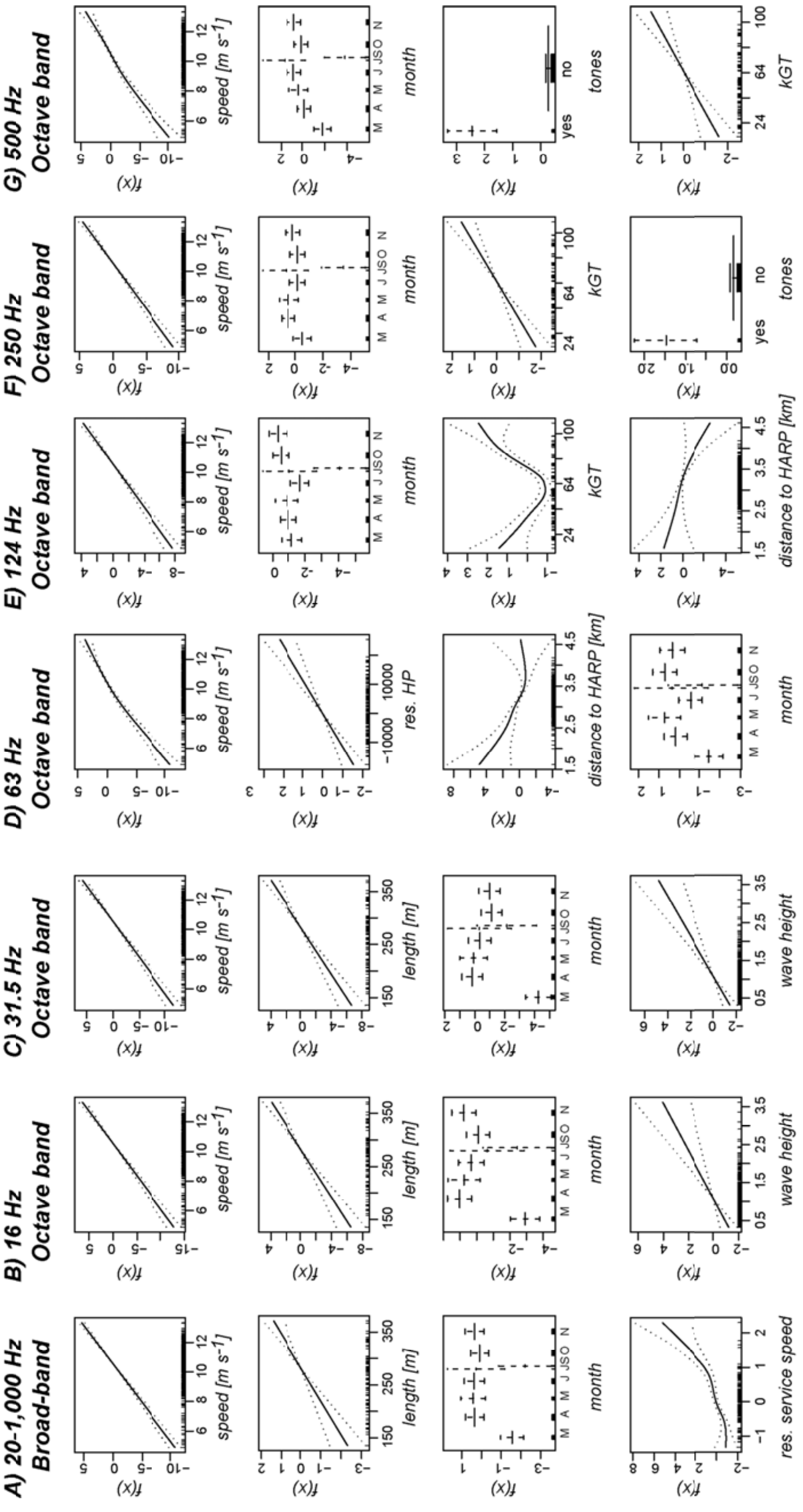

Estimated Source Level
[dB re 1 μPa² @ 1 m (20–1,000 Hz)]
195
190
185
180
175
Ship Identification number (Length [m])
30418700 (157)
30429700 (187)
211239240 (245)
354115000 (251)
353126000 (254)
212714000 (260)
636012254 (275)
368986000 (276)
636010887 (276)
636012177 (276)
353389000 (278)
352018000 (279)
352887000 (279)
636090670 (282)
636090671 (282)
303279000 (292)
538002961 (292)
563791000 (294)
218060000 (300)
218061000 (300)
218062000 (300)
477105600 (323)
636091070 (325)
636091326 (325)
636091329 (325)
211829000 (334)
211830000 (334)
636090966 (334)
220129000 (347)
220263000 (352)

Figure 3.5: Generalized additive model functions for container ship source level. For each frequency band model (A-G), functions are for the 4 variables with the most predictive power. The rows are ordered according to predictive power (*i.e.*, the first row are the predictors that had the highest predictive power in the step-wise model selection procedure). Functions are scaled relative to the model mean (note the different y-axis scales). Month and tone were modeled as a categorical variable and the width of each function bar represents the sample size. Dashed lines are two standard error bands.


A) 20-1,000 Hz Broad-band
B) 16 Hz Octave band
C) 31.5 Hz Octave band
D) 63 Hz Octave band
E) 124 Hz Octave band
F) 250 Hz Octave band
G) 500 Hz Octave band
f(x)
speed [m s-1]
length [m]
month
res. service speed
wave height
res. HP
distance to HARP [km]
kGT
tones
yes
no
M A M J JSO N

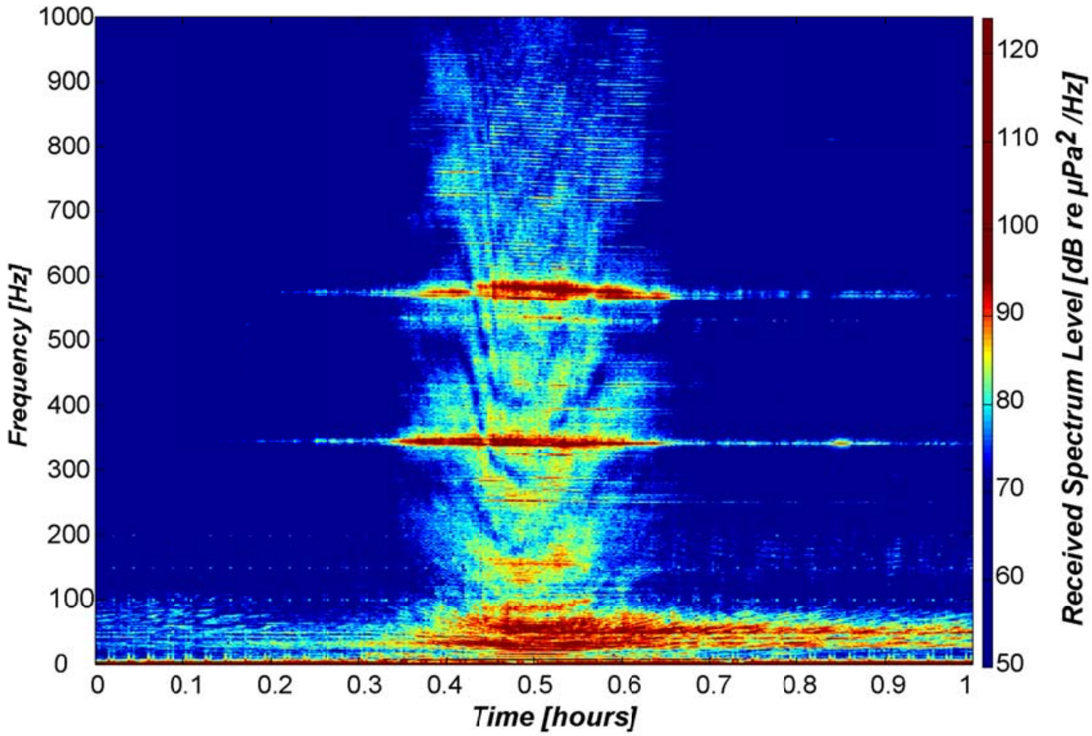
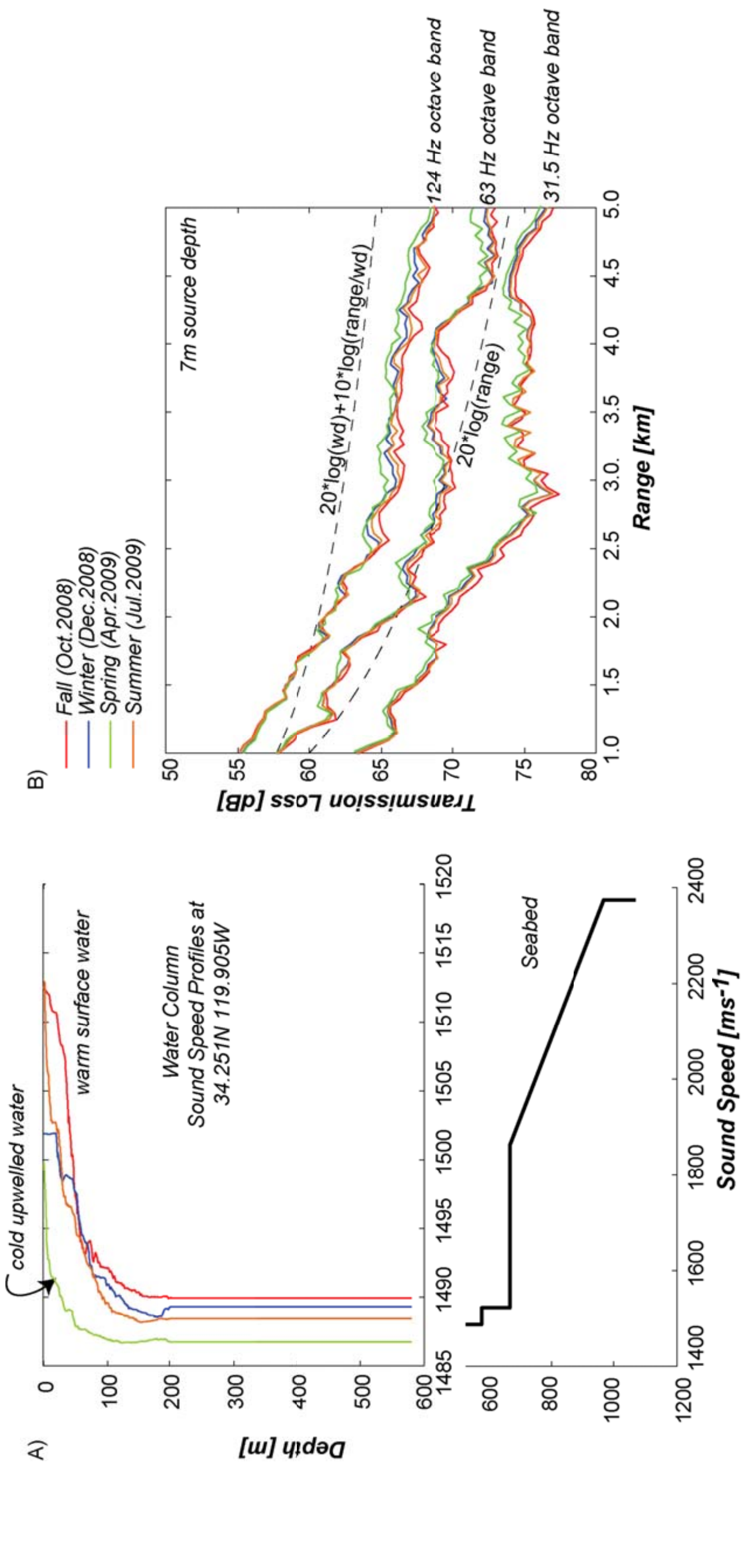


Figure 3.6: Received sound spectrum levels during a 1-hour passage of a container ship (294 m). The spectrogram is centered on the closest point of approach of the ship to the HARP, a distance of 3 km. The intense tones present in the higher frequency bands are representative of the tones seen in 10% of the container ships in this study.

Appendix II: Seasonal propagation in the Santa Barbara Channel. A) Sound speed depth profile for water columns representative of December 2008, April 2009, July 2009, and October 2009. Bottom graph shows the seabed properties. These properties were used in the propagation models. B) Sound propagation loss for three octave bands at depths of 510-570 m for a source depth of 7 m. wd = water depth at acoustic receiver.


A)
Depth [m]
cold upwelled water
warm surface water
Water Column
Sound Speed Profiles at
34.251N 119.905W
Seabed
Sound Speed [ms-1]
B)
Fall (Oct.2008)
Winter (Dec.2008)
Spring (Apr.2009)
Summer (Jul.2009)
Transmission Loss [dB]
7m source depth
20*log(wd)+10*log(range/wd)
20*log(range)
124 Hz octave band
63 Hz octave band
31.5 Hz octave band
Range [km]

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CHAPTER 4

Quieter Ocean- Unintended Consequence of Recent Ship Traffic Trends

by Megan F. McKenna

Donald Ross, Sean M. Wiggins, John A. Hildebrand, Steve L. Katz, Thomas J. Moore, and Jessica Redfern

Abstract

Underwater ambient noise levels measured off the coast of southern California were correlated with regional changes in commercial shipping trade. The results provide an example of the magnitude of change required to reduce acoustic impact from shipping on a coastal marine habitat. Between 2007 and 2008 two events occurred that resulted in a decrease in ship traffic in the Santa Barbara Channel: the economic recession and a coastal air-quality improvement rule. From October 2005 to February 2010, monthly low-frequency ambient noise levels at a site 3 km from a major shipping route from were compared to regional traffic levels. The results of two independent metrics of ship traffic both showed that a 1 dB reduction in average low-frequency noise resulted from a decrease in traffic by 1 ship.

Introduction

At low-frequencies, ambient noise in most areas of the ocean is dominated by noise from commercial shipping[1]. Underwater radiated noise is an incidental by-product from standard ship operations, with highest sound levels at low frequencies (<100 Hz). The sound generated by ships consists of a broad-band component from propeller cavitation and narrow band tones from propeller cavitation and internal machinery[2]. This low-frequency noise can propagate long distances depending on where the ship transits[3,4].

Sound is recognized as a critical, if not primary, sensory system for many marine organisms[5]. Sound energy travels efficiently through the ocean medium, and marine animals have evolved systems to exploit this property for communication during social and breeding activities, navigation, habitat selection, and sensing and tracking prey or predators[6-8].

The introduction of man-made sound into the marine environment threatens these basic life strategies by masking signals from conspecifics and predators, altering behavior, and inducing negative physiological responses[9]. On an ocean basin scale, low-frequency background noise attributed to bourgeoning commercial shipping has been increasing by three decibels per decade (a doubling in acoustic energy)[10,11], raising concerns about the impacts on marine life.

The world’s oceans are threatened by complex and interacting anthropogenic activities; few areas are unaffected by humans[12]. Examples are needed to demonstrate the magnitude of change necessary to reverse or even reduce these impacts. Here we show how recent changes in commercial ship traffic along the west coast of the US, near the Channel Islands, had the unintended consequence of quieting a biologically important, yet urbanized coastal region (Fig. 4.1).

Recent Trends in Regional Commercial Trade (2007-2010)

One of the world’s major shipping routes transits the Santa Barbara Channel (SBC), carrying a significant portion of the US trade. Containerized goods moved by ships, measured as the number of twenty-foot equivalent units (TEU)[13], showed the most dramatic decrease compared to previous years in both 2008 and 2009 (Fig. 4.2), corresponding to the *great recession* that officially lasted from December 2007 to June 2009[14].

A second change in regional commercial ship traffic began on July 1, 2009, when the California Air Resources Board (CARB) passed an air quality improvement rule- requiring all ships within 24 nautical miles of the coastline to use low-sulfur fuel. The majority of ships responded by transiting on a more southerly route to minimize the use of higher cost fuel (Fig. 4.3).

Based on these changes in ship traffic patterns, three distinct time periods were defined for the purpose of comparisons in this study: *pre* (February 2007 to July 2007), *recession* (April 2008 to June 2009), and *CARB* (July 2009 to February 2010). The long-term underwater ambient noise measurements during these time periods were compared to data on ship traffic.

Low-frequency Ambient Noise Measurements

High frequency acoustic recording packages (HARPs) were deployed in the SBC (34º19.2'N and 120º1.8'W) from February 2007 to February 2010. HARPs are bottom-mounted instruments containing a hydrophone, data logger, battery power supply, ballast weights, acoustic release system, and flotation. The hydrophone is buoyed 10 m above the seafloor and includes two transducers: one for frequencies below 2 kHz and the other for frequencies above 2 kHz. To sample the entire period, the HARPs were recovered, serviced with new batteries and in some cases a new hydrophone, and re-deployed. All acoustic data were corrected based on hydrophone calibration performed in the laboratory and at the U.S. Navy’s Transducer Evaluation Center facility in San Diego, California.

The acoustic data were processed to determine monthly spectral averages of ambient noise. Continuous data with no overlap between spectral averages were processed using a Hanning window. A total of 225 seconds were used for each spectral average. All spectra were calculated in 1 Hz bins. Monthly sound levels at 40 Hz from February 2007 to February 2010 were compared. The 40 Hz band captured the dominant frequency of ship noise and avoided frequencies dominated by blue and fin whale calls.

Regional Ship Traffic

Two metrics were used to measure levels of shipping activity. The total number of loaded outbound TEU were compiled from data collected at the Port of Long Beach[13] and represented regional traffic trends. To measure traffic trends within the Santa Barbara Channel, vessel traffic was monitored using the Automatic Identification System (AIS). AIS transponders onboard ships greater than 300 gross tons automatically broadcast transit information via a VHF signal. The AIS messages include dynamic position information and general ship information (*i.e.,* speed, longitude, latitude, true heading, and unique ship identifier). A second message includes more static information about the ship (*e.g.* the unique vessel identifier, vessel name, ship-type, dimensions, and destination).

The AIS VHF radio signals were received at a shore station located on the University of California, Santa Barbara west campus (34°24.5'N 119°52.7'W). The typical receiving range for the AIS station was 73 miles, based on the height of the receiving antenna and the typical ship AIS transmission range. The AIS signals received at the shore station were fed through a radio and into a PC computer. *ShipPlotter* software (ver. 12.4.6.5, COAA) decoded the AIS signal and archived daily lists of all AIS transmissions. The archived data were downloaded remotely and imported into a *PostgreSQL* database (ver. 8.3). Data extracted for this analysis included position, time, unique ship identification, ship-type, ship length, and ship speed. Data analyzed were from 15 September through February 2010. Only ships designated as cargo and tanker and more than 100 m in length were included.

The average number of ships per day in the channel was calculated for each month, when AIS data were available (Table 4.1). A second spatial metric was used to quantify the change in traffic during the *recession* and *CARB* periods: the total kilometers traveled in a 2 km by 2 km grid (Fig. 4.3). Only data from 15 September to 30 November in 2008 and 2009 were used. The total kilometers traveled in each cell served as the estimate of ship traffic density.

Shadow zones introduce a negative bias when using AIS point transmissions to calculate ship traffic density. To minimize this bias, the AIS point transmissions were converted to unique linear transits. The linear transits were defined as a sequence of AIS transmissions from a ship without gaps greater than 24 hours or gaps of more than one hour and a concurrent change in heading of greater than 30 degrees. It was important to separate these transits because a straight line between these transmission locations is unlikely to accurately represent a ship's transit. Ship transit calculations were conducted in *ArcInfo* (version 10.0) and *ArcView* (version 3.2a).

Changes in Low-frequency Underwater Ambient Noise in a Coastal Region

An analysis of seafloor acoustic recordings in the region revealed differences in ambient noise related to the observed declines and shifts in commercial ship traffic (Table 4.2, Fig. 4.4). AIS data was not available prior to September 2008; therefore total monthly loaded outbound TEU in the *pre* and *recession* periods were compared to measured average monthly noise levels. As expected, the *pre*-period had higher numbers of TEU and higher average noise levels compared to the *recession* (Fig. 4.2). A Pearson's correlation test showed a strong relationship between average noise levels and TEU (*coeff=0.7, p=0.001*). In a comparison of June 2007 (*pre*) to June 2009 (*recession*), a 20% decrease in TEUs resulted in a 5% decrease in average sound levels in the SBC (Table 4.2). In other words, a decrease of 1 dB per 5,518 TEU was observed. Individual ship built between 1988 and 2000 are between 4,000 and 5,000 TEU[15].

Because the TEU metric is representative of the entire region, data compiled from AIS data were used to quantify just the change in traffic within the channel. Both the average number of ships per day and total kilometers traveled, showed a dramatic change in traffic within the channel- nearly a 70% decrease. A Pearson's correlation test between the average noise levels and average number of ship per day showed a strong relationship (*coeff=0.96, p=0.001*). In a comparison of February 2009 (*recession*) to February 2010 (*CARB*), a decrease of 11 ships per day resulted in 8 dB decrease in low-frequency ambient noise (Table 4.2, Fig. 4.4). In this example, a 1dB reduction in noise resulted from a decrease of 1 ship per day in the Channel.

Summary and Conclusion

Recent economic trends have reversed an increasing trend in ambient noise for a coastal region; moreover air quality legislation, which caused ships to change routes, reduced sound levels in the SBC to those measured in the 1960s[10]. This decrease in ocean noise improves the acoustic habitat quality for marine organisms in this region. The unintended noise reduction provided direct evidence of the impact on the ecosystem from human activity and offers a unique opportunity to understand the magnitude of change necessary for a reduction. We observed that a 1 dB reduction in ambient noise resulted from a decrease of 1 ship passage per day and 5,518 reduction in TEU.

Although these results showed a clear decrease in human impact in a coastal environment related to the economy, the change in noise related to the CARB rule simply shifted the noise to another region. Managing for a single environmental concern, in this case air quality runs the risk of magnification of another threat; a potential cost to both the environment and shipping industry. The new traffic pattern, for example, has the potential unintended consequence of bringing ships and certain species of large whales into greater proximity, presumably increasing the risk of whale-ship collision. Comprehensive studies quantifying multiple environmental threats are needed to provide managers with a more explicit understanding of the inevitable trade-offs or compatibilities within management decisions[16].

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Table 4.1: Summary of data analysis for ambient noise and ship traffic (* minutes recorded out of total minutes).

Time Period	Acoustic Data					Ship Traffic Data		
	Month	*Recording days*	*Sample Rate**	*No. 225s averages*	*Sound Level dB re uPa @40Hz*	*Loaded Outbound TEU*	*Avg. No. ships per day in SBC*	*Avg. speed of ships in SBC*
pre	Oct-05	5-31	5/10	3,207	79.26	103,422	-	-
	Nov-05	1-30	5/10	3,750	78.29	107,147	-	-
	Dec-05	1-31	5/10	2,810	78.72	104,184	-	-
	Jan-06	1-24	5/10	5,640	78.41	99,740	-	-
	Feb-07	25-28	continuous	1,240	80.80	108,215	-	-
	Mar-07	1-31	continuous	11,900	80.07	125,529	-	-
	Apr-07	1-21	continuous	7,692	81.81	121,191	-	-
	May-07	10-31	continuous	7,972	81.94	127,061	-	-
	Jun-07	1-30	continuous	11,516	82.24	140,967	-	-
	Jul-07	1-4	continuous	1,344	82.05	135,089	-	-
recession	Apr-08	17-30	5/7	3,834	81.91	163,577	-	-
	May-08	1-31	5/7	8,504	81.66	158,798	-	-
	Jun-08	1-5	5/7	1,332	82.73	160,180	-	-
	Jul-08	23-31	5/7	2,462	80.97	153,364	-	-
	Aug-08	1-31	5/7	8,504	80.03	153,467	-	-
	Sep-08	1-30	5/7	8,222	79.61	129,630	22.3	18.3
	Oct-08	15-31	continuous	6,148	79.21	132,521	19.9	18.2
	Nov-08	1-31	continuous	8,914	79.21	109,850	18.9	18.0
	Dec-08	5-31	5/10	5,178	79.21	94,009	18.9	17.9
	Jan-09	1-31	5/10	9,834	78.18	88,510	17.7	17.6
	Feb-09	1-21	5/10	4,336	77.53	92,781	15.8	17.5
	Mar-09	13-31	continuous	7,300	78.35	117,674	18.4	17.9
	Apr-09	1-31	continuous	11,518	77.72	112,976	17.2	18.2
	May-09	13-31	continuous	7,290	76.83	121,065	17.7	18.1
	Jun-09	1-31	continuous	11,518	78.24	114,107	16.0	18.4
CARB	Jul-09	1-6	continuous	2,014	75.89	108,420	12.1	15.9
	Sep-09	2-30	continuous	10,756	72.50	109,337	6.2	15.7
	Oct-09	1-27	continuous	10,076	71.64	119,194	6.1	15.7
	Nov-09	4-30	5/10	5,186	70.00	114,283	5.9	14.9
	Dec-09	1-31	5/10	5,950	67.90	123,084	5.7	14.5
	Jan-10	1-31	5/10	5,950	68.28	113,183	5.2	14.7
	Feb-10	1-20	5/10	3,714	69.21	123,208	5.3	13.7

Table 4.2: Comparisons of the change in average noise levels and ship traffic metrics.

Metrics	*pre to recession* Jun 07 vs. Jun 09	*recession to CARB* Feb 09 vs. Feb 10
Ambient Noise	-4 dB -5%	-8 dB -11%
Regional Traffic	-26,860 TEU -19%	
Channel Traffic		-11 ships per day -67%
1 dB change equals	5,518 TEU	1 ship per day

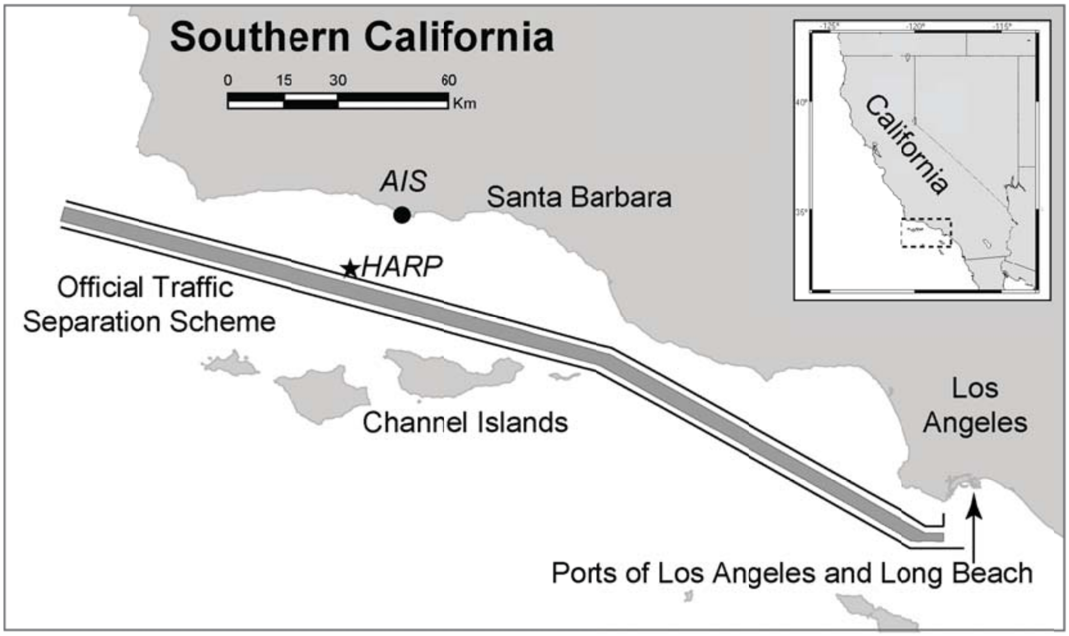

Figure 4.1: Map of the study region off the coast of southern California. The underwater acoustic recorder (HARP), AIS receiving station and the official traffic separation scheme are shown.

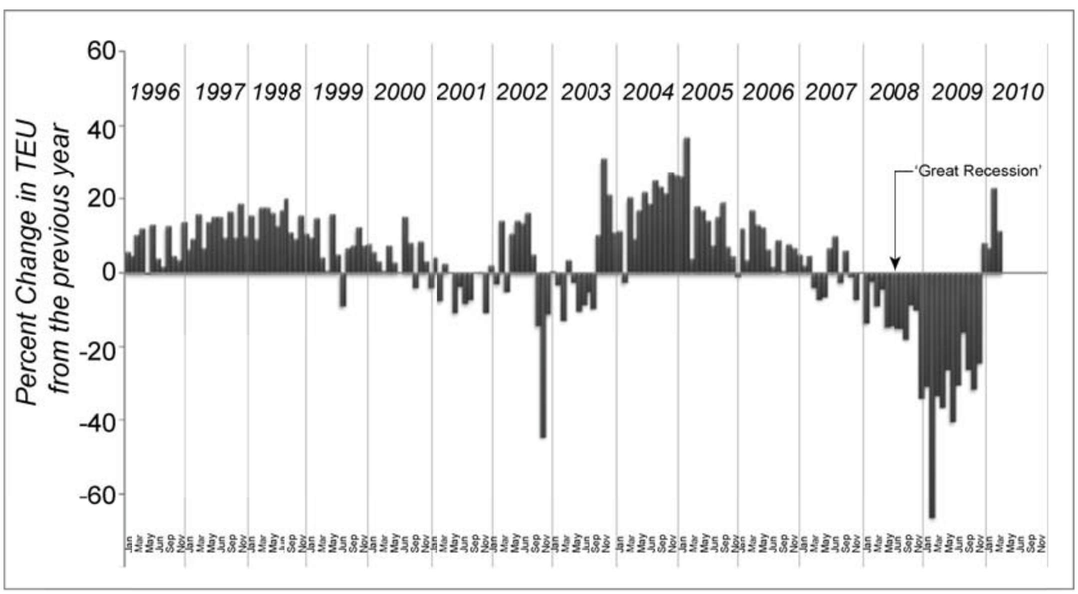

Figure 4.2: Percent change in TEUs (Twenty-foot equivalent units) from the previous year (1996 to 2010).

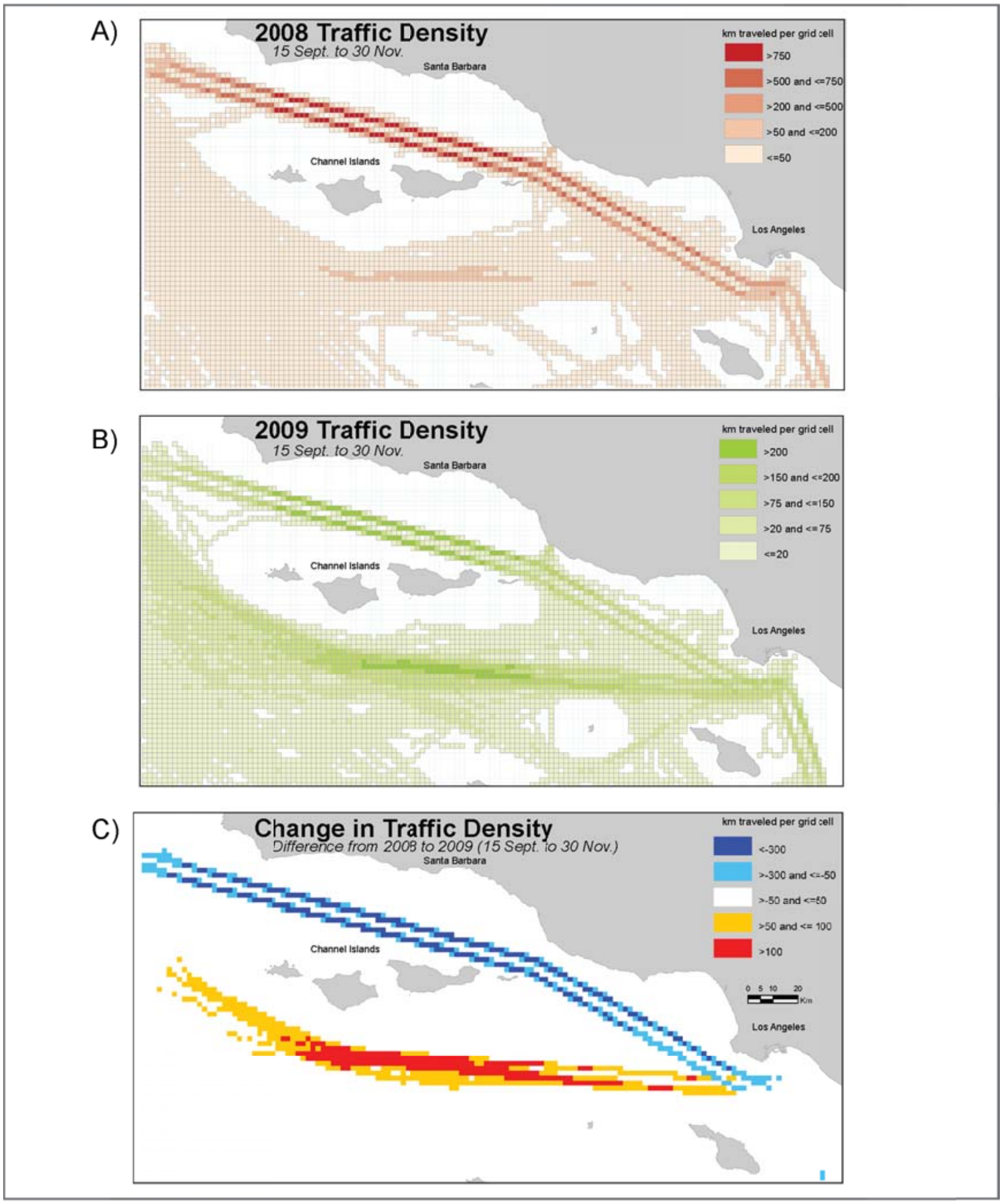

Figure 4.3: Comparison of ship traffic density A) 2008 B) 2009 derived from cumulative km traveled in each 2 km by 2 km grid cell (note the difference in the scales) C) The difference in kilometers traveled from 2008 to 2009.

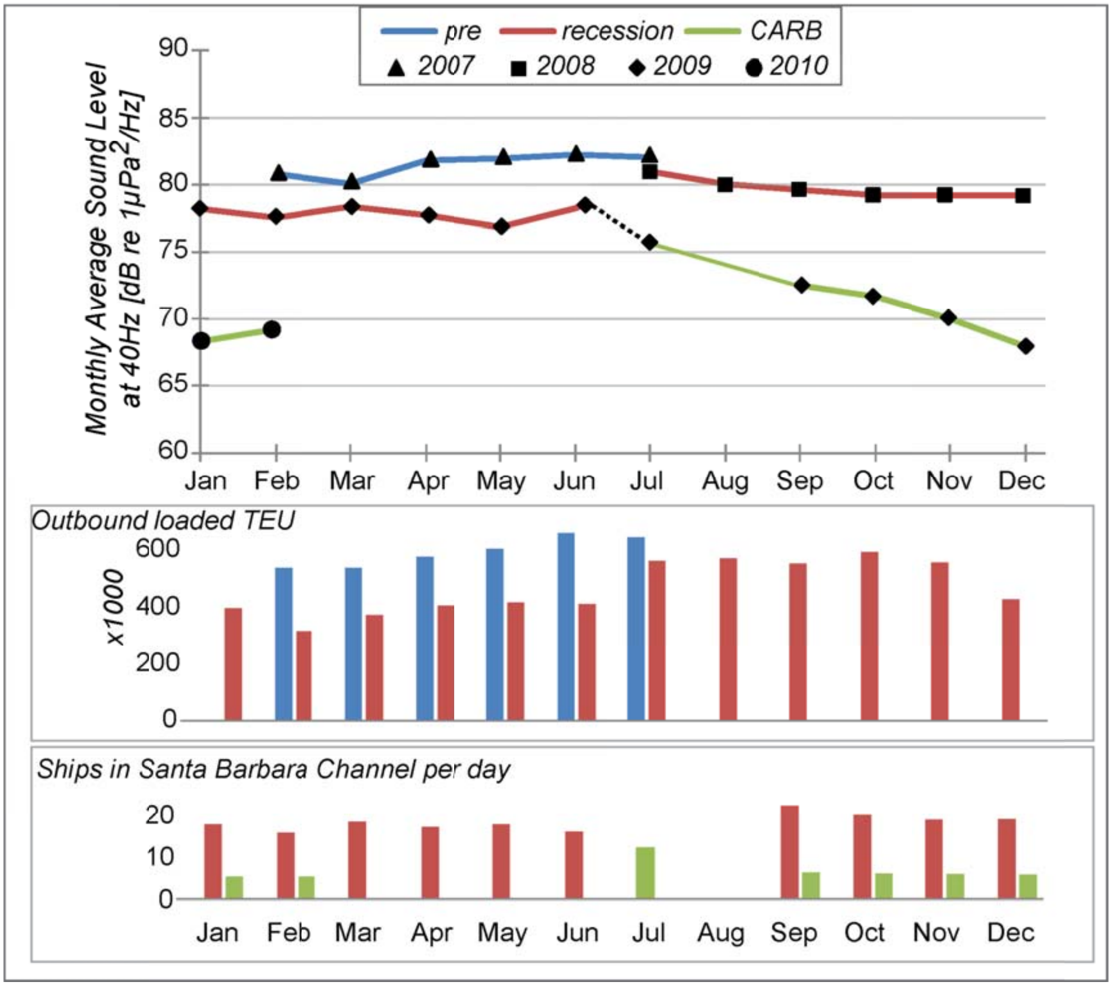

Figure 4.4: Comparison of monthly average sound levels in the SBC (2007-2010). The symbols represent the different years and colors indicate the three different time periods. The bottom graphs depict the corresponding monthly number of loaded outbound TEUs and the average number of ships in the channel from AIS data.

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CHAPTER 5

Underwater Noise in a Blue Whale Habitat Near the Channel Islands National Marine Sanctuary

by Megan F. McKenna

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Abstract

Long-term statistics of ambient noise in a coastal region off southern California combined with ship traffic data were used to understand the variability of low-frequency noise in an important blue whale habitat. Results revealed distinct patterns in low-frequency ambient noise related to both local and distant ship traffic and highlighted the importance of complex bathymetric features when predicting low-frequency noise levels. Sites closest to shipping lanes did not have the highest average noise levels; a site further offshore had the highest average sound levels (86 dB re 1μPa^2/Hz at 40 Hz). The nearshore sites, closest to the shipping lanes, had the greatest variability in noise levels. Highest average noise level were measured during the night (87 dB re 1μPa^2/Hz at 40 Hz); lowest levels were measured in late afternoon (69 dB re 1μPa^2/Hz at 40 Hz). These daily patterns in noise levels correlated with the average number of ships that transited the region. Theoretical models of blue whale communication ranges based on measured sound levels showed that at the site with the highest average noise levels, blue whale call ranges on average were reduced to less than 25 km for B calls and less than 5 km for D calls. This represents a greater than 90% reduction in potential communication ranges. A decreasing

temporal trend in ambient noise was observed at all sites, likely related to recent declines in commercial shipping trade.

Introduction

A variety of sources, both natural and anthropogenic, are known to contribute to low-frequency ambient noise in the ocean (Wenz 1962, Hildebrand 2009). Dramatic increases in low-frequency ambient noise have been documented at sites throughout the world's oceans, attributed to the global expansion of commercial shipping (Ross 1993, Andrew *et al.* 2002, McDonald *et al.* 2006). Given the evidence for increasing sound in the ocean, concerns for the impact on marine life dependent on sound for basic life functions have been raised (Payne and Webb 1971, Richardson 1995, NRC 2003). Rising levels of ocean noise likely negatively impact marine mammals by interfering with their ability to detect sounds, from either conspecifics for social or mating purposes or natural sounds that aid in navigation or foraging. Understanding the spatial and temporal variability of ambient sound and relative contribution of anthropogenic sources in important marine habitats is essential for evaluating the potential impacts on marine life.

Previous studies of ocean ambient noise, particularly in deep-water sites beyond the continental margins, documented a steady rise in low-frequency ambient noise (Curtis *et al.* 1999, Andrew *et al.* 2002, McDonald *et al.* 2006). However, sites on the continental shelf, in relatively shallow waters have revealed geographic differences in low-frequency noise levels, related to the presence of human activity. For example, a bathymetrically complex southern California coastal site with minimal local ship traffic revealed little increase in background noise compared to 50 years ago (McDonald *et al.* 2008). In contrast, a site off the coast of Boston, Massachusetts with high-traffic showed a doubling in acoustic power compared to less trafficked locations (Hatch *et al.* 2008). Similarly, Parks *et al.* (2009) found variability in low-frequency ocean noise off the east coasts of the Unites States and Canada, with highest levels near major shipping routes. Low-frequency noise levels in estuary waters of Long Island, NY fluctuated with different levels of recreational boating activity (Samuel *et al.* 2005). Although measured noise levels in these coastal habitats correlated with the presence of and distances to major shipping routes, distant ship traffic can also contribute to noise levels. To accurately model ocean noise, considerations of multiple propagation mechanisms are necessary (Hamson 1997).

The Southern California Bight (SCB) is an ideal place to investigate the effect of ship traffic on ambient noise levels given the complex bathymetric features and known distributions of regional commercial ship traffic. Two major ports serve ships traveling through the region: Port Hueneme, and the Port of Los Angeles-Long Beach (POLA). POLA is the second busiest port in North America (CINMS 2009). Until recently, an estimated 75% of vessel traffic departing from, and 65% of traffic arriving at, POLA and Port Hueneme traveled through the Santa Barbara Channel (CINMS 2009). Commercial vessel traffic was concentrated in the designated shipping lanes (Fig. 5.1), with an average of 18 ships transiting per day (McKenna *et al.* 2009). A portion of the shipping lanes travel through the Channel Islands National Marine Sanctuary (CINMS). The CINMS is a 1,110-square-nautical-mile region off the coast of Ventura and Santa Barbara and encompasses the waters that surround Anacapa, Santa Cruz, Santa Rosa, San Miguel, and Santa Barbara Islands. The Sanctuary was established in 1980 and granted a special protected status, including numerous marine protected areas that limit human activities (CINMS 2009).

This region is also an important summer foraging ground for the endangered eastern North Pacific blue whale. The whales tend to aggregate in cold, up-welled coastal waters to feed primarily on subsurface concentrations of euphausiids (Croll *et al.* 1998, Fiedler *et al.* 1998). Blue whale populations, world-wide, were decimated by commercial whaling from around 300,000 to fewer than 10,000 and are slowly recovering (Barlow 1995). The current eastern north

Pacific stock estimates are around 2,000 (Barlow 1995, Calambokidis and Barlow 2004, Calambokidis *et al.* 2009).

Blue whales, like most baleen whale species, vocalize in low-frequency ranges (15-100 Hz), similar to the dominant acoustic energy band of ships (Ross 1976, Richardson *et al.* 1995, Arveson and Vendittis 2000, McKenna *et al.* submitted). Blue whales in the north Pacific are known to produce at least four call types (McDonald *et al.* 1995, Thompson *et al.* 1996, Oleson *et al.* 2007b): A and B calls (16 Hz, ~20 second duration), D calls (down-sweep from 90-25 Hz, 1-4 second duration), and highly variable amplitude and frequency modulated calls (FM calls). Blue whale A and B calls occur in repeated sequences, are only produced by males, and likely function in mate attraction and long-range communication. Singular or irregular B calls are also produced by males (McDonald *et al.* 2001, Oleson *et al.* 2007a). The D calls are produced by both males and females and are usually associated with feeding activity (Oleson *et al.* 2007a).

The environment in which acoustic signals are produced plays an important role in determining how these signals are perceived or received by conspecifics or predators (Marten and Marler 1977). Sound is an efficient way to propagate energy through the ocean, and many marine organisms, including blue whales, have evolved communication systems to exploit this property (Edds-Walton 1997). The ability to communicate is limited by the distance over which a signal can be perceived by a receiver over a given background of noise and the propagation characteristics from the caller to the receiver. In environments with increased low-frequency noise from transiting ships, it is likely that communication space for low-frequency specialist, like the blue whales, is reduced by masking effects (Clark *et al.* 2009). Acoustic interference, or masking, is defined as the failure to recognize a signal as a result of the interfering presence of other sounds, either natural or anthropogenic. Although acoustic masking is well documented for human hearing (Wegal and Lane 1924, Fletcher 1940, Yost 2000), quantifying the effects in marine mammals is difficult (Richardson *et al.* 1995). However, masking is a key concern regarding the impact of sound on marine mammals, and is implicated as a long-term effect of anthropogenic sound. Analytical approaches have been implemented to explore the potential effects of masking on marine mammals (Clark *et al.* 2009).

This study focuses on long-term regional comparisons of ambient noise levels in a bathymetrically complex region of blue whale foraging habitat. The goal of this study is to use long time-series of ambient sound, combined with knowledge of ship traffic to understand the variability of the low-frequency sound fields. Both spatial and temporal comparisons at six sites in a coastal region off the coast of southern California were investigated (Fig. 5.1). Differences in both the average ambient noise levels and the variability between sites were quantified using three metrics: percentiles, empirical cumulative distributions functions and noise pollution levels. We found distinct spatial patterns in low-frequency ambient noise related to both local and distant ship traffic and highlighted the importance of complex bathymetric features when predicting underwater low-frequency noise levels. This study also revealed temporal differences in noise levels related to ship traffic patterns for sites close to major shipping routes. Finally, using theoretical models variations in detections ranges of blue whale calls were observed.

Methods

Acoustic Recordings 2008-2009

All acoustic recordings were made using calibrated archival seafloor acoustic recorders, known as high frequency acoustic recording packages (HARPs, Wiggins and Hildebrand 2007). HARPs are bottom-mounted instruments containing a hydrophone, data logger, battery power supply, ballast weights, an acoustic release system, and flotation. The hydrophone sensor is tethered to the instrument and buoyed approximately 10 m above the seafloor. The hydrophone includes two transducers: one for frequencies below 2 kHz and one for frequencies above 2 kHz. All acoustic data used in this study were corrected based on hydrophone sensitivity calibrations performed in our laboratory and at the U.S. Navy's Transducer Evaluation Center facility in San Diego, California.

HARPs were deployed at six sites around the Northern Channel Islands, a region off the coast of southern California (Fig. 5.1). Overlapping recording periods between sites were selected for analysis (Table 5.1). Analysis periods were divided into separate months: July 2008, October 2008, January 2009, May 2009 and July 2009. The locations, depths, dates, and duration for each dataset are summarized in Table 5.1. All sites remained at the same location, except for the HARP south of the island (*STH*) which was moved to three different locations within the southern portion of the CINMS (Fig. 5.1).

The distance from major shipping lanes varied across monitored sites. One HARP in the channel was 3.5 km from the northbound shipping lane (*SBC*). A second site in the channel was 5.5 km from the southbound shipping lane, and was located in shallower water (250 m) on the self-edge between Santa Rosa and Santa Cruz Islands (*GAP*). This site was in the boundaries of the CINMS. A site further west, offshore of Point Conception (*PTC*) was also close (6.5 km) to the southbound shipping lane. Three sites were located south of the islands. These sites were not close to any major shipping lane.

Acoustic Data Processing

Acoustic recordings from each site were decimated to a sampling frequency of 2,000 Hz and sorted into monthly time periods (Table 5.1). The decimation process filters the data in forward and reverse directions with an eighth-order low-pass Chebyshev Type I filter and then resamples the resulting smoothed signal at a lower rate. For each month and site, spectral averages in 1-Hz bins were calculated from continuous acoustic data with no overlap using a Hanning window. A total of 225 seconds of data were used for each spectral average. Frequencies ranged from 10 to 1,000 Hz, with particular interest in 40 Hz, a low-frequency band that avoids blue whale A or B calls so, the calls are not part of the long-term averages.

To compare the spectral averages across sites and time periods, both percentiles and cumulative distributions were implemented in *MATLAB* (ver. 2010b). Percentiles were calculated for each frequency bin and were useful for comparing long-term averaged acoustic data to transient acoustic events (*e.g.* ship passages).

The 90th, 50th, and 10th percentiles were used to calculate noise pollution level (NPL) in each frequency band using the formula:

$$NPL_{freq} = L_{50} + (L_{10} - L_{90}) + \frac{(L_{10} - L_{90})^2}{60} \quad (5.1)$$

where, L_{50} is the mean spectrum level, L_{90} is the level exceeded 90% of the time and L_{10} is the level exceeded 90% of the time. The NPL is based on methods for measuring traffic noise and incorporates both average levels and the degree of fluctuations in noise. It is assumed that sites with greater variances in noise are more disruptive based on research with humans (Robinson 1971).

One of the simplest ways to quantify variability is with probability density functions. The Kaplan-Meier estimate of cumulative distribution function (CDF), also known as the empirical CDF (ECDF) was calculated for the frequency band of 40 Hz using the following formula:

$$Fn(x) = \frac{1}{n} + \sum_{i=1}^{n} I(X_i \le x) \quad (5.2)$$

where, x is a given spectrum sound level measurement, and X_i are all the measurements less than x, and n is the number of measurements in the time period of interest. The result is a matrix of probabilities for each sound level, or in other words, the proportion of time each site experienced an ambient noise level above a particular value.

The shape of the low-frequency noise distributions at each site were evaluated using two metrics: skewness and kurtosis. Skewness is a measure of the asymmetry in the data around the sample mean. A skewness of zero indicates a normal distribution, negative values indicate data spread more to the left of the mean, and a positive value indicates data are spread more to the right of the mean.

$$s = \frac{E(x-\mu)^3}{\sigma^3} \quad (5.3)$$

where, μ is the mean, σ is the standard deviation of the data x, and *E*(t) represents the expected value. The second metric used to describe the ambient noise levels was kurtosis, a measure of how outlier-prone a distribution is. For normal distributions, kurtosis is 3 and when values are less than 3 distributions are less prone to outliers,

$$k = \frac{E(x-\mu)^4}{\sigma^4} \quad (5.4)$$

where, μ is the mean, σ is the standard deviation of the data x, and *E*(t) represents the expected value. A one-sample Komogorov-Smirnov test was used to compare the ambient noise values to a standard normal distribution. A rejection of the null, that the data is normally distributed, was tested at a 5% significance level.

Theoretical Communication Ranges

The measured ambient noise levels (ANLs) at each site were used to estimate potential communication ranges of blue whales (*i.e.*, distances at which an individual at a recording site would receive a call from a conspecific). Ranges were estimated for blue whale B and D calls.

Spectral averages at 40 Hz were used as the ambient noise levels. Theoretical communication ranges (TCRs) were estimated at each ANL using the following formula:

$$TCR_{ANL} = 10^{\left(\frac{SL-(ANL+SNR)}{20}\right)} \qquad (5.3)$$

where, *SL* is the broad-band call source level based on literature, ANLs are the measured 40 Hz spectrum levels at the acoustic receiver, and *SNR* is an estimated signal to noise ratio (*i.e.*, the level the call needs to be above background noise to be perceived by a whale). The equation is repeated for all spectral averages at a given site and time period. Distributions of ranges at each site were assessed using ECDF, as described above in equation (5.2).

There are a number of assumptions made in the *TCR* calculation and the goal is not to provide an absolute measure but offer a simplified method to understand the variability and compare communication ranges between sites using measured background noise levels. This method assumes spherical spreading loss from the caller to the receiver in a given background noise environment and does not account for the depth of the whale. The second assumption is that source level of the caller is constant in all background noise levels. The third assumption is the SNR of the call at the receiver and in this study 10 dB SNR was used. This is based on masking research on humans which estimated a 5-15 dB SNR for a signal to be detected (Yost 2000). This equation does not take into account potential processing gain by the animal. And, lastly, the 40 Hz ANLs are likely an underestimate of the total acoustic energy in the critical band of blue whale hearing, resulting in an underestimate of the masking effect (Yost 2000). A critical band is defined as the auditory filter or the bandwidth a human processes around a signal (Fletcher 1940). The critical band determines the level of masking for a signal, in other words, the detection of a tonal signal is determined by the total amount of acoustic energy in the critical band. For humans, critical bands are a function of the center frequency of the signal, and for frequencies below 500

Hz critical bandwidths are 100 Hz (Zwicker and Fastl 1999). Broad-band ambient noise levels in this 100 Hz band could be as much as 20 dB greater than a 40 Hz band when a ship is present.

Ship Traffic Patterns

Vessel traffic in the region was monitored using the Automatic Identification System (AIS). AIS transponders onboard ships >300 gross tons automatically broadcast transit information via a VHF signal. The AIS messages include dynamic position information and general ship information (*i.e.,* speed, longitude, latitude, true heading, and unique ship identifier). A second message includes more static information about the ship (*i.e.*, the unique vessel identifier, vessel name, ship-type, dimensions, and destination).

The AIS VHF radio signals were received and decoded at a shore station located on the University of California, Santa Barbra west campus (34°24.5'N 119°52.7'W). The typical range for the AIS station was 73 miles, based on the height of the receiving antenna and the typical ship transmission range. The AIS signals received at the shore station were fed through a radio and into a PC computer. *ShipPlotter* software (Ver. 12.4.6.5, COAA, 2008) decoded the AIS signal and archived daily lists of all AIS transmissions. The archived data were downloaded remotely and imported into a *PostgreSQL* database. Data extracted for this analysis included position, time, unique ship identification, ship-type and ship length from 15 September to 30 November in 2008. Only ships designated as cargo and tanker and more than 100 m in length were included.

Shadow zones introduce a negative bias when using AIS point transmissions to calculate ship traffic density. To minimize this bias, the AIS point transmissions were converted to linear transits. The linear transits were defined as a sequence of AIS transmissions from a ship without gaps greater than 24 hours or gaps of more than one hour and a concurrent change in heading of greater than 30 degrees. It was important to separate these transits because a straight line between these transmission locations is unlikely to accurately represent a ship's transit. The total kilometers traveled in each cell served as the estimate of ship traffic density in the region. Ship transit calculations were conducted in *ArcGIS* (ver.10 ESRI, 2010).

Results

Regional Variability in Noise Levels

Distinct spatial differences in low-frequency ambient noise levels were observed across the region. A summary of the ambient noise levels are, over space and time is shown in Fig. 5.2. For all sites in each time period, the median and mean values were similar in all frequencies (10-1,000 Hz), indicating a Gaussian distribution in sound levels. Comparisons of monthly ECDF at each site (*i.e.*, the percentage of time each site experienced a noise level above a particular value) indicated minimal temporal variability in noise levels at SBC, *PTC* and *GAP* (Fig. 5.2). However, there was a noticeable decrease in average noise levels by 6 dB at both sites in the channel (*SBC* and *GAP*) in July 2009, compared to July 2008 (Table 5.2).

Although commercial ship traffic in the region is concentrated in the Santa Barbara Channel shipping lanes (Fig. 5.3), the sites in the channel closest to the shipping lanes did not have the highest average noise levels (Table 5.2, Fig. 5.2). The sites closest to the shipping lanes, however, experienced the greatest variability in ambient noise levels- as indicated by the broad ECDFs and histograms (Fig. 5.4) and reported variances in Table 5.2. At the site closest to the northbound shipping lane (*SBC*), measured sound levels were below 70 dB 0.20 or 20% of the time, with a maximum level of 110 dB; at the site closest to the southbound shipping lane (*GAP*), measured sound levels were below 70 dB only 0.10 or 10% of the time, with a maximum level of 119 dB (Fig. 5.4, Table 5.2). Levels exceeded 90 dB at both these sites 11% of the time.

The site about 7 km from the southbound lane, but offshore (*PTC*) had the highest average low-frequency sound levels (86 dB re 1μPa^2/Hz at 40 Hz) (Table 5.2). Measured sound levels at this site were never below 72 dB re 1μPa^2/Hz at 40 Hz and only 0.25 or 25% of the time were levels below 80 dB (Fig. 5.4). Maximum levels were 117 dB (Fig. 5.4B, Table 5.2).

The sites south of the islands were not near any major shipping route, although a small proportion of traffic did travel south of the islands (Fig. 5.3). Despite the similar relationships to traffic routes, noticeable differences in average levels and variability in noise levels were observed (Fig. 5.4, Table 5.2). For example, 50% of the time sound levels exceeded 80 dB at *STH*-1, 76 dB at *STH*-2 and 73 dB at *STH*-3. The site south of the islands with the highest average levels (*STH*-1) had also the lowest variability, and noise levels were never below 75 dB re 1μPa^2/Hz at 40 Hz. The lowest average ambient noise levels of any site was also the deepest site (*STH*-3), located in an offshore canyon, and experienced levels above 90 dB, less than 5% of the time.

The NPL metric captured both average noise levels and the variability in the levels, and sites classified as having the greatest NPLs, experienced both high average noise levels and greater variability (Fig. 5.5). As expected, *PTC* had the highest NPL. If sites had similar average levels, a site with greater variability resulted in a higher NPL, as seen in a comparison between *SBC* and *STH*-1.

Daily Pattern in Ship Traffic

High variability in noise levels was observed at *SBC* site and appeared to relate to daily patterns in ship traffic (Fig. 5.6). Highest average noise level were measured during the night (87 dB re 1μPa^2/Hz at 40 Hz), while lowest levels were measured in late afternoon (69 dB re 1μPa^2/Hz at 40 Hz). These daily patterns in noise levels correlated with the average number of ships that transited the region. The same patterns were observed at the *GAP* site, but shifted in time slightly, given the differences in peaks in southbound traffic compare to northbound traffic

(Fig. 5.6B). These large differences in low-frequency ambient noise levels were not observed at *PTC*, a site also close to a commercial shipping lane, but located further offshore.

Theoretical Communication Ranges

Using the known spatial differences and within site variability in underwater low-frequency ambient noise levels, theoretical detection ranges for blue whale calls were investigated. As laid out in the methods section, a number of assumptions were made to complete this analysis, and the results offer a way to understand how the variability in noise might impact communication ranges for animals dependent on signals from conspecifics. Given that the blue whale B calls are known to have higher source levels, compared to the D call, this call type will propagate greater distances. This is illustrated by the different scales on the x-axes of Fig. 5.7. As expected, the site with the highest noise levels had the lowest average ranges of call detection. For example, at *PTC* 50% of the time ranges were less than 25 km for B calls and less than 5 km for D calls. For all other sites, ranges were greater than or equal to 50 km for B calls and 10 km for D calls 50% of the time (Fig. 5.7).

When interpreting these results it is important to consider the potential ranges of communication, particularly at the inshore sites. For example, the Santa Barbara Channel is only about 25 km in the north-south direction and 80 km in the east-west direction. B call ranges are less than 25 km for sites in the channel 20% of the time and less than 80 km 55 to 68% of the time. In the channel, potential D call ranges are 25 km or less 65-80% of the time and 80 km or less 98% of the time.

Discussion

The main objective of this study was to describe spatial patterns in ambient noise in an important habitat for the endangered eastern north Pacific blue whale. The results revealed distinct patterns in low-frequency ambient noise related to both local and distant ship traffic patterns and highlight the importance of complex bathymetric features when predicting underwater low-frequency noise levels. Whales communicating in this region will experience different acoustic environments, both in terms of average sound levels and variations in levels. The theoretical models developed to understand how these ambient noise levels change detection ranges of calls from conspecifics add to our understanding of the biological implications of increased ocean ambient noise levels.

Spatial Variability in Ambient Noise Levels

Long-term ambient noise levels measured on these regional-spatial scales show that there is variability both at each site and between sites, related to temporal and spatial patterns in ship traffic. One important result is that the highest average (and median) sound levels were not measured at the sites closest to one of the world's busiest commercial shipping lanes, as might be expected. An offshore site (*PTC*), 6.5 km from a major shipping lane, had the highest average low-frequency noise levels (86 dB re 1µPa^2/Hz at 40 Hz) and these levels are consistent with values from other regions of high ship traffic (Wenz 1964, Hildebrand 2009). Furthermore, a site south of the Northern Channel Islands (*STH*-1) not located near any major shipping routes, had the same average (and median) noise levels as a site 3 km from a major traffic lane (*SBC*, Table 5.2).

These results suggest that underwater low-frequency average noise levels are not simply a function of the distance to major shipping routes, and that propagation characteristics specific to each site will affect the noise characteristics. As observed with other sites on the continental slope, distant ship noise contributes to average noise levels and relates to global patterns in ship traffic (McDonald *et al.* 2006). When ships transit along the continental slope, the radiated noise can enter the deep sound channel, by a process commonly known as down-slope conversion (Wagstaff 1981). Another way for ship noise to enter the deep sound channel occurs at high latitudes, where the sounds channel shoals to intersect the sea surface (Bannister 1986). Underwater low- frequency ambient noise levels at regions on the continental slope are generally more predictable than coastal ambient noise level because distant shipping from the deep sound channel dominates the measured noise levels. In this study, a site exposed to distant ship traffic and close to a major shipping route had the highest measured sound levels.

Temporal Variability in Ambient Noise Levels

Noise from distant ship traffic does not contribute to ambient noise at sites on the continental shelf (McDonald *et al.* 2008). The level of noise radiated by individual ships and the patterns in traffic are important factors to consider when evaluating ambient noise levels at sites on the continental shelf. Daily ship traffic pattern in this region are concentrated at specific times of the day, and correlate with port activities (McKenna *et al.* 2009). During the hours when traffic was at a minimum, average sound levels in the Santa Barbara Channel were below 70 dB re $1\mu Pa^2/Hz$ at 40 Hz (Fig. 5.6), but reached almost 90 dB during peak traffic hours. Therefore, the site closest to known commercial shipping lanes (*SBC*) had the highest variability in noise levels (difference between the maximum and minimum levels was 82 dB), and the variance decreased as the distance from the shipping lanes increased (Table 5.2).

Even within the channel, average ambient noise levels were not correlated with the distance to major shipping lanes. Site *GAP* had higher average noise levels and was 1 km further from the shipping lanes than site *SBC*. This difference might relate to the propagation characteristics specific to each site; however it is possible that the difference is related to the characteristics of ships transiting the southbound lane versus the northbound lane. Given that more loaded containers enter the port of POLA, compared to containers leaving port (POLA 2010), ships on a southward transit are more loaded, increasing the amount of radiated noise into the marine environment (Ross 1976, McKenna *et al.* submitted). Another possible explanation is that the higher levels were measured at the shallower site and fish sounds might be present (Širović *et al.* 2009).

It is important to note that weather conditions also contribute to noise levels in these low frequencies (Knudsen *et al.* 1948, Wenz 1962), unless the heavy ship traffic dominates the spectra (Hildebrand 2009). At the inshore sites, it is likely that surface agitation contributed to the observed patterns in ambient noise in the absence of ships. The relationship with surface agitation is complex and related to sound-speed profile and bottom characteristics unique to each site (Kuperman and Ingenito 1980).

A deep-water site (*STH*-3) south of the Northern Channel Islands had the lowest average noise levels, 74 dB re 1µPa^2/Hz at 40 Hz; however in July 2009 average levels increased to 78 dB re 1µPa^2/Hz at 40 Hz and likely the increased is related to a shift in regional ship traffic. The implementation of the low-sulfur fuel regulation on July 1, 2009 changed the pattern of ship behavior substantially in the region (CARB 2011). The cost and feasibility of using low-sulfur fuel within the Channel caused many commercial ship operators to transit on the south side of the Northern Channel Islands, substantially decreasing traffic within the channel. Consistent with this change, average sound levels in the channel were 6 dB lower, in July 2009 compared to July 2008.

For sites monitored between 2008 and 2009, prior to the 2009 traffic shift described above, a slight decreasing trend in ambient noise levels was observed (2-3 dB). This overall decrease in regional noise levels might be related to the global economic downturn (POLA 2008), resulting in diminished commercial ship traffic.

Acoustic Habitat Quality

The NPL metric used in this study to characterize the acoustic environment, assumes that annoyance or disturbance correlates with higher variability in noise levels. Although this phenomenon is well known for humans (Scholes 1970, Robinson 1971), it is less understood in non-human animals. However, NPL provides a metric to investigate how animals might respond to habitats with different types of noise disturbances. For example, in habitats with periods of both high and low levels of acoustic disturbance (medium NPL, *SBC*), short-term adjustments in behavior might be the more likely response; whereas in regions of high NPL (*PTC*), either long-term adjustments or habitat avoidance might be more likely. It is possible to test these hypotheses by investigating calling patterns in the different acoustic environments, and by including noise metrics as parameters in habitat modeling efforts.

Difference in theoretical communication ranges in the region depended on the variability in background noise levels and directly related to the average background noise levels at each site, using our simplified approach. For example, the offshore site (*PTC*) exposed to both distant and local ship traffic had the smallest potential communication ranges (< 25 km for B calls and < 5 km for D calls 50% of the time). Besides the offshore site having the largest reduction in communication ranges, it is important to consider the potential communication ranges at a given site. For example, at offshore sites long-range communication might be more important than within more coastal regions, like the Santa Barbara Channel. Ranges in the Santa Barbara Channel are at the maximum distance in the channel 68% of the time; whereas maximum detection range for the offshore site (*PTC*) is never greater than 150 km, considerably less than expected for B calls which are thought to function in long range communication.

The validity of these estimates depends on many factors that were not considered or assumed to be constant in this study. For example, the intensity with which the sender vocalizes is important and assumed constant; however there is evidence that animals will increase call intensity in the presence of increased background noise (Warren *et al.* 2006). At these ranges the background noise levels at the caller will not necessarily be the same as the receiver. For simplicity, transmission loss from the caller to the receiver was assumed to follow spherical spreading, but complex bathymetric features and sound speed profiles can alter the sound propagation pathways (Jensen *et al.* 1994). Furthermore, the range estimates assume that both call types have the same detection thresholds, even though they differ in both bandwidth and harmonic structure and these features might change the detection thresholds (Lohr *et al.* 2003). And, lastly, the reported detection ranges are likely an over-estimate, given the use of a narrow band metric for background noise. A broad-band measurement would be as much as 20 dB greater when a ship is present, which would further decrease communication ranges.

Summary

The goal of this study was to quantify the spatial and temporal patterns in ambient noise levels within an important coastal marine habitat. The results provide a comprehensive spatial analysis of ambient noise useful for both understanding the contribution of ship noise in a complex bathymetric environment and the potential impacts on marine organisms that depend on the low-frequency sound environment. A site exposed to both distant ship traffic noise and close proximity to a major traffic lane (6 km range) had the highest average low-frequency noise levels and the greatest reduction in blue whale long-range communication. Sites within a nearshore basin had the most variability in ambient noise related to the daily patterns in ship traffic. The difference in hourly average noise levels at these sites provides a way to evaluate how ship traffic density will change noise levels. Mitigation strategies to reduce the noise in an inshore habitat could utilize these traffic densities to achieve a specific noise reduction. Overall, decreasing temporal trends in ambient noise was observed at all sites, likely related to recent declines in commercial shipping trade. Furthermore, a shift in regional traffic patterns out of the Santa Barbara Channel to the region south of the Channel Islands, changed ambient noise levels throughout the region.

Acknowledgments

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Chapter 5, in full, is currently in preparation for submission. McKenna, M.F., Ross, D., Wiggins, S.M., and Hildebrand, J.A. Underwater Noise in a Blue Whale Habitat Near the

Channel Islands National Marine Sanctuary. The dissertation author was the primary investigator and author of this material.

Table 5.1: Summary of acoustic recordings in the region

SITE	LATITUDE	LONGITUDE	DEPTH	DAYS	SAMPLING (% of time)	TOTAL TIME (hrs)
SBC						
Jul-08	34-16.621	120-01.661	580	23-31	71	154
Oct-08	34-16.617	120-01.492	576	15-31	100	408
Jan-08	34-16.528	120-01.132	580	1-31	71	528
May-09	34-16.667	120-01.613	580	13-31	100	456
Jul-09	34-16.667	120-01.613	580	1-6	100	144
PTC						
Oct-08	34-19.110	120-48.333	700	14-31	100	432
Jan-08	34-18.902	120-48.370	700	1-31	71	531
May-09	34-18.885	120-48.367	802	1-5	100	120
GAP						
Jul-08	34-08.399	119-59.349	238	1-23	100	552
Oct-08	34-08.405	119-59.316	238	1-4	71	69
Jan-08	34-08.364	119-59.336	483	1-31	71	531
May-09	34-08.365	119-59.346	250	29-31	100	48
Jul-09	34-08.365	119-59.346	250	1-22	100	528
STH						
Jul-08	33-50.207	120-07.270	305	23-31	71	154
Oct-08	33-50.200	120-07.275	300	15-30	100	384
Jan-08	33-59.956	120-32.432	556	1-31	50	372
May-09	33-54.722	119-33.793	1000	28-31	100	96
Jul-09	33-54.722	119-33.793	1000	1-22	100	528

Table 5.2: Summary of ambient noise levels at 40 Hz

Site and Month	*Mean*	*Medial*	*Standard Deviation*	*Maximum Level*	*Minimum Level*	*Number of Samples*
Jul-08						
SBC	81.0	81.6	9.5	110	63	2,462
GAP	81.1	81.1	7.9	119	64	8,462
STH-2	80.6	78.6	7.5	110	70	2,152
Oct-08						
SBC	79.2	79.0	8.9	109	62	6,148
PTC	87.5	86.6	7.3	117	74	6,530
GAP	81.2	80.6	7.8	103	65	864
STH-2	78.7	77.1	6.5	112	66	6,148
Jan-09						
SBC	78.2	78.0	8.9	106	62	9,834
PTC	84.8	84.4	7.1	111	72	9,834
GAP	80.1	80.6	8.2	109	61	9,836
STH-2	80.5	79.6	3.7	105	74	9,824
May-09						
SBC	76.8	75.7	9.0	109	62	7,290
PTC	85.4	84.8	7.3	106	74	1,824
GAP	79.5	78.6	8.1	116	63	1,160
STH-3	73.8	72.1	7.5	113	61	1,160
Jul-09						
SBC	75.9	75.1	8.2	99	63	2,014
GAP	75.6	74.4	7.4	122	65	8,154
STH-3	78.1	76.5	8.2	105	61	8,154
All days						
SBC	78.3	78.0	9.0	110	62	25,734
PTC	85.9	85.3	7.3	117	72	18,188
GAP	80.5	80.7	8.1	119	61	20,322
STH-2	79.2	77.5	6.8	112	66	8,300
STH-1	80.5	79.6	3.7	105	74	9,824
STH-3	73.8	72.1	7.5	113	61	1,160

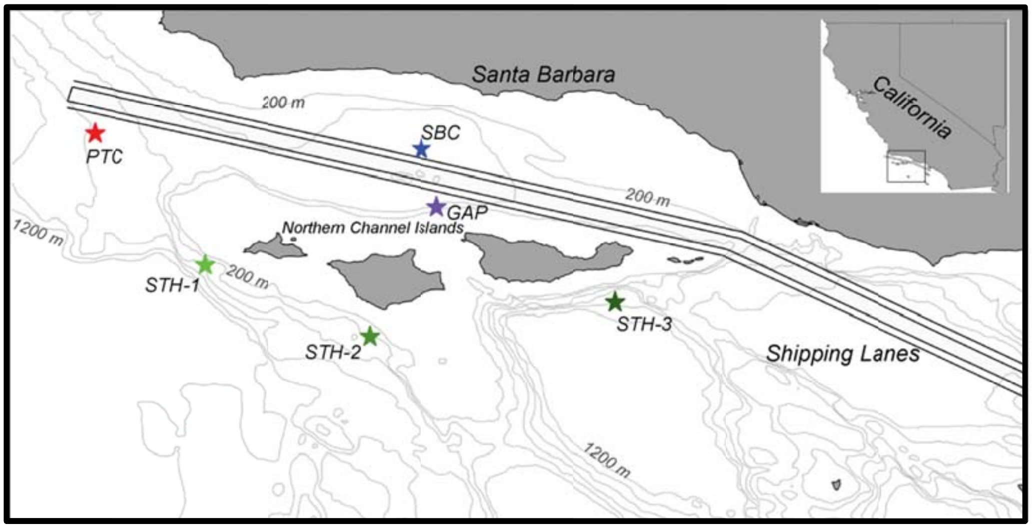
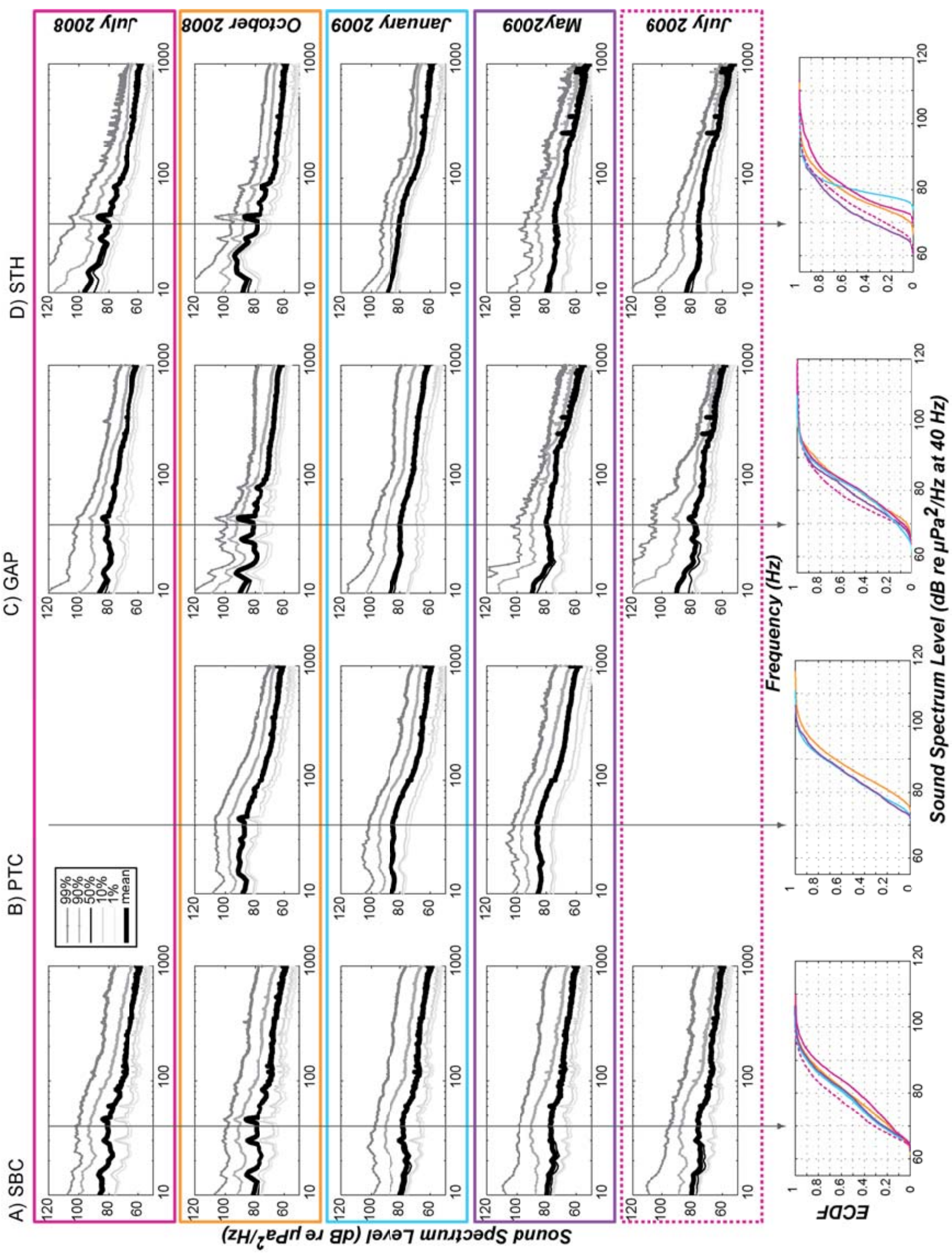


Figure 5.1: Study region off the coast of southern California, including the northern Channel Islands. Bathymetric features are shown as gray lines plotted every 200 m to a depth of 1,200 m. The stars represent the locations of the HARPs. The black lines in the Santa Barbara Channel indicate the commercial shipping lanes.

Figure 5.2: Low-frequency sound spectrum levels in the region, from July 2008 to July 2009. Spectral plots show the statistical properties of the measured sound levels as percentiles or the sound levels below which a certain percent of the observations fall. Bottom graph shows the empirical cumulative distributions for each month at 40 Hz, as indicated by the vertical arrow. A) Monthly sound levels for *SBC*, an inshore region near the northbound shipping lane. B) Monthly sound levels for *PTC*, an offshore region 6.5 km from the commercial shipping lanes. C) Monthly sound levels for *GAP*, an inshore region near the southbound shipping lane. D) Monthly sound levels for sites south of the islands.


A) SBC
B) PTC
C) GAP
D) STH
July 2008
October 2008
January 2009
May2009
July 2009
99%
90%
50%
10%
1%
mean
Sound Spectrum Level (dB re µPa²/Hz)
Frequency (Hz)
ECDF
Sound Spectrum Level (dB re µPa²/Hz at 40 Hz)

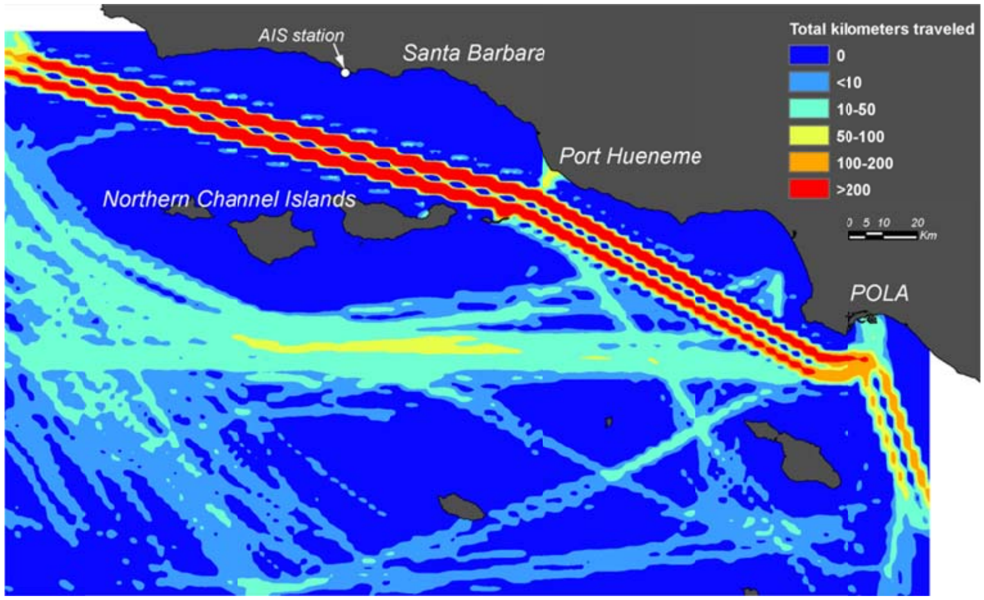


Figure 5.3: Density of ship traffic in the study region. Data from AIS ship tracks are summed in each 2 km by 2 km grid cell and smoothed using a spline interpolation. Ship tracks from 15 September 2008 through 30 November 2008 are represented. Only ships greater than 100 m in length and designated as either cargo or tanker are included.

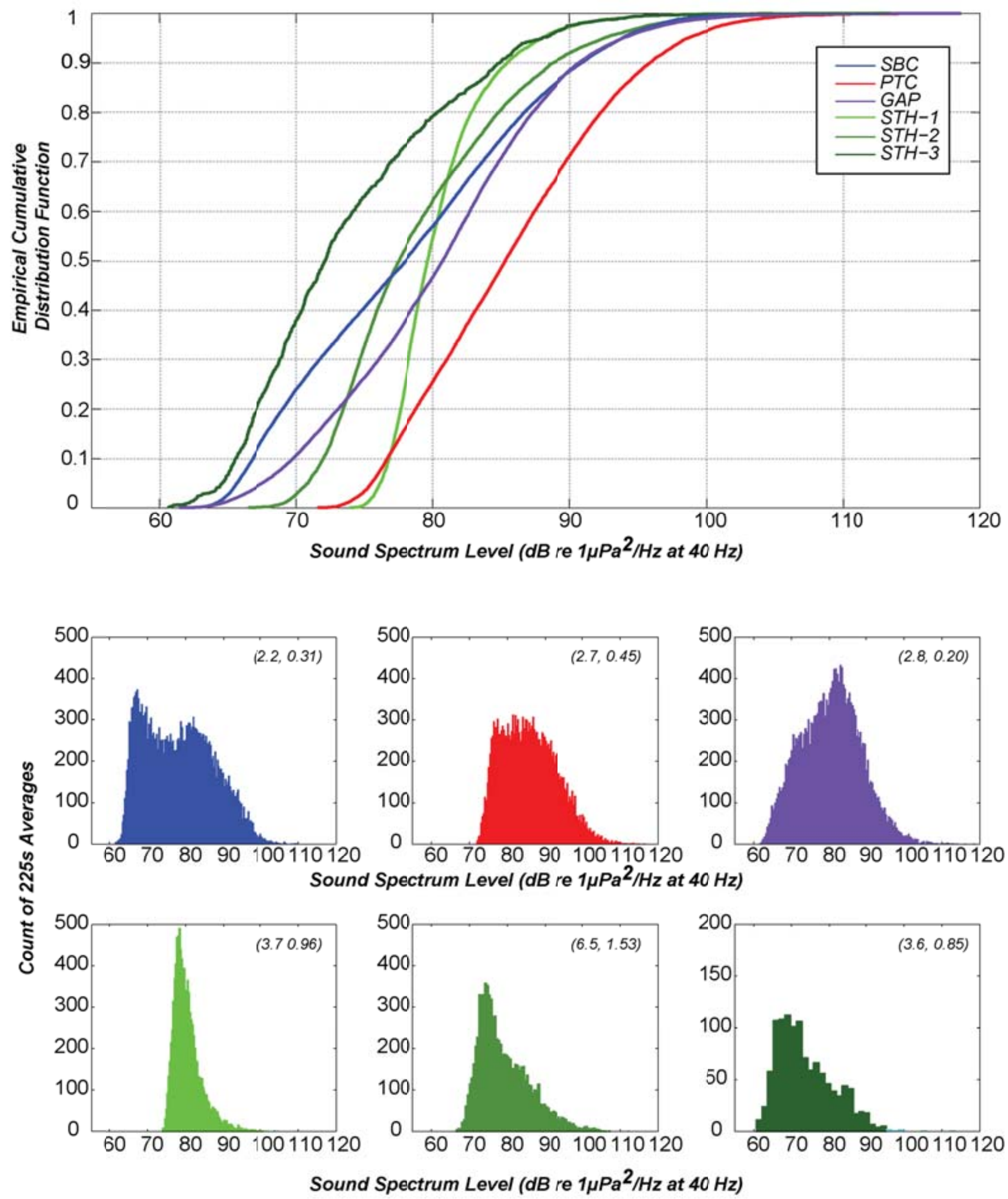


Figure 5.4: Distributions of sound spectrum levels at 40 Hz for all acoustic data collected at six sites. A) Empirical cumulative distribution function curves. B) Histograms of noise levels. The number of bins equal to the square root of the number of 225 seconds averages in data. The kurtosis and skewness of each distribution of the 40 Hz noise levels are shown in the upper right corner of each graph. Y-axis scales are dependent on the number of 225 seconds samples taken at each site.

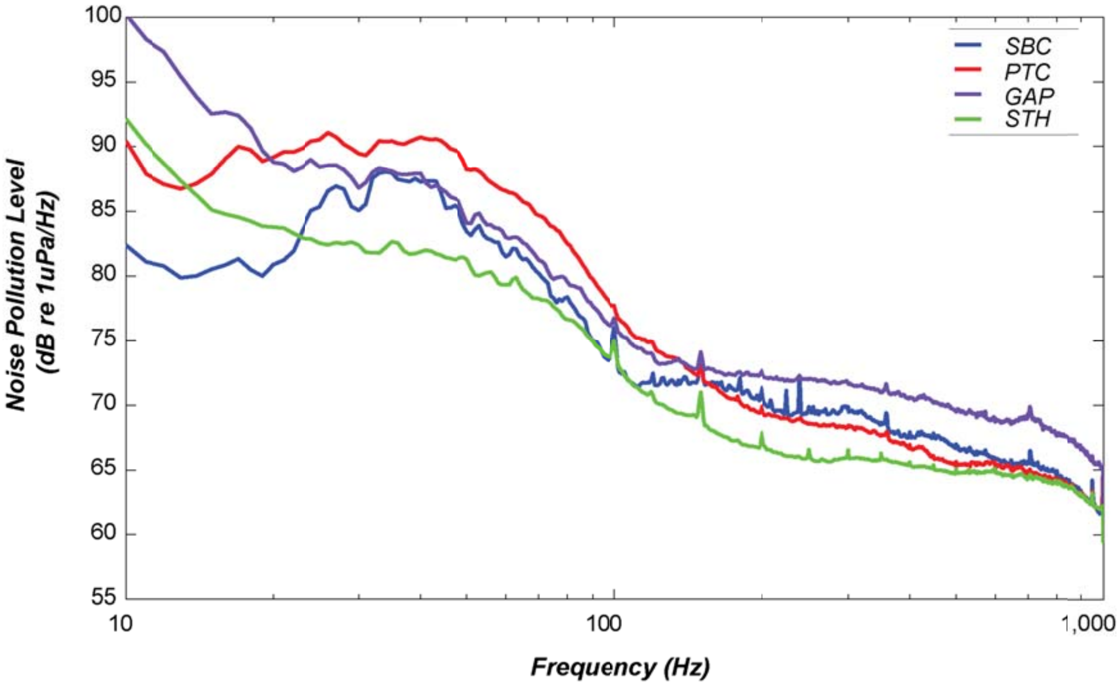


Figure 5.5: Noise pollution level metric for acoustic data collected at each site in January 2009.

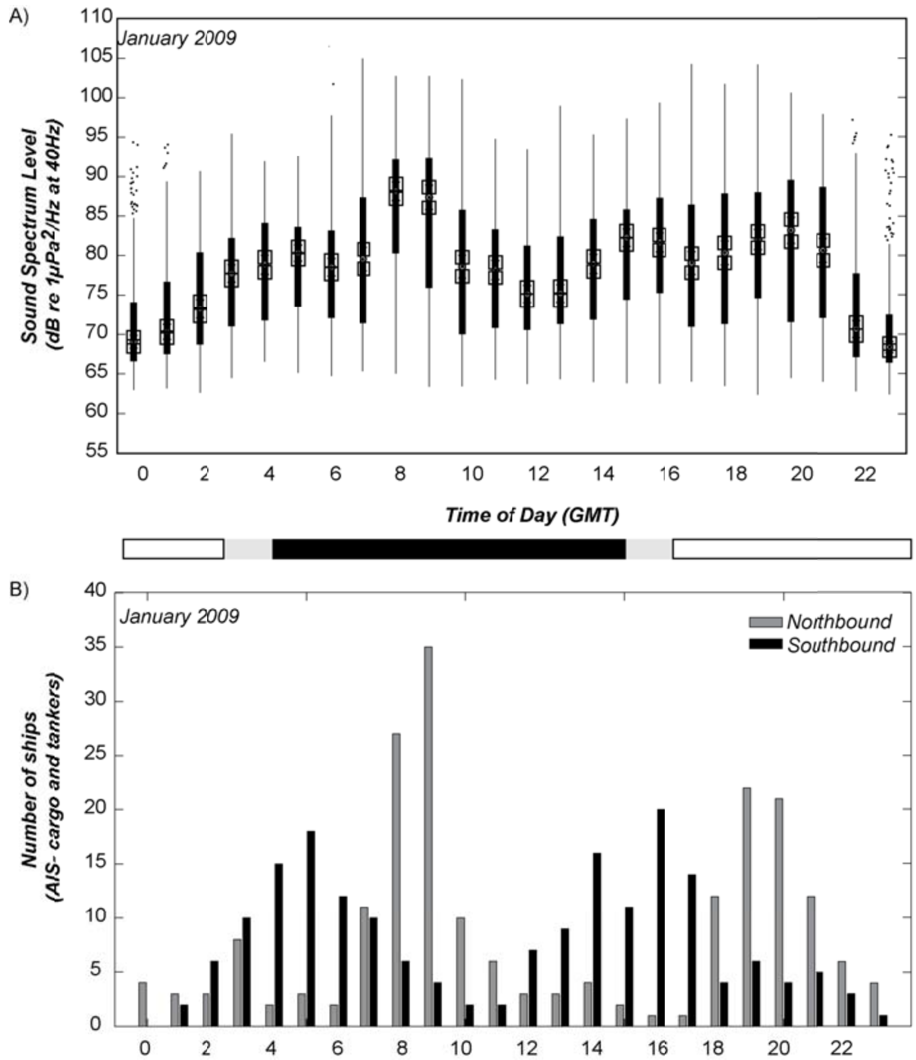


Figure 5.6: Daily patterns in sound levels and ship passages at the Santa Barbara Channel site for January 2009. The bars in the center of the figure indicate the local daylight hours (white=day, grey= dawn and dusk, black=night). A) Acoustic data divided into hours of the day. On each box, the central mark is the median, the edges of the black boxes are the 25th and 75th percentiles, the whiskers extend to the most extreme data points, and outliers are plotted individually as black dots. Two medians are considered significantly different at the 5% level if the unfilled boxes do not overlap. B) Total number of ships passages from AIS data collected in January 2009. Both northbound and southbound ships are shown. Only ships greater than 100 m in length and designated as either cargo or tanker are included in the totals.

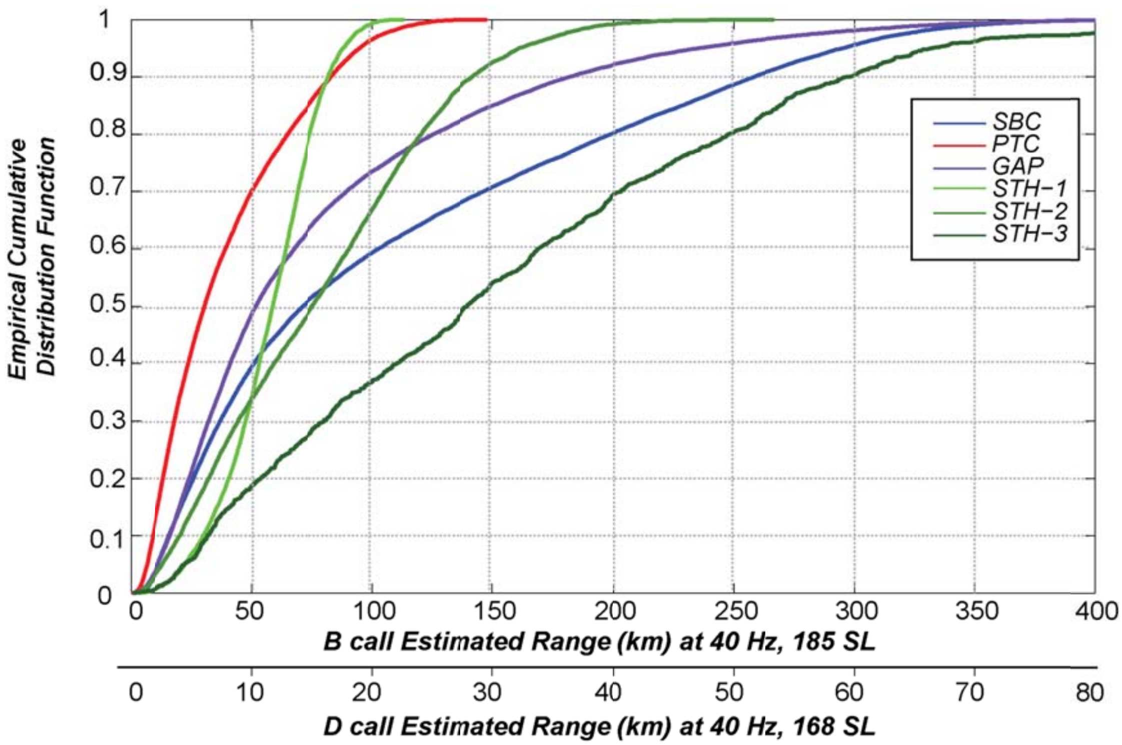


Figure 5.7: Distributions of the theoretical communication ranges for two types of blue whale calls, B and D. The empirical cumulative distribution functions are derived from all the acoustic data collected at each site. The x-axes show the theoretical ranges as calculated from equation (5.3).

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CHAPTER 6

Blue Whales Change their Calls in the Presence of Large Ships

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Abstract

Increases in background noise can interfere with the detection and discrimination of vocal signals among members of a species. Here we investigate the vocal behavior of the endangered North Pacific blue whale (*Balaenoptera musculus*) in the presence of commercial ships in the Santa Barbara Channel off the coast of southern California. Passive acoustic monitoring data were combined with ship passage information to evaluate changes in calling related to the presence of ship noise. We found evidence for modifications in call interval, type, and amplitude related to the increase in noise from transiting ships. A significantly greater proportion of irregular B call detections occurred when ships were present, signifying a possible disruption of song in the presence of ships. Variability in intervals between blue whale D calls was observed-related to both time of day and presence of ships. A partial Lombard effect was identified for D calls and verified with simulations. For each decibel increase in background noise level, the amplitude of the D calls increased by 0.4 dBs These findings add to a growing body of literature identifying how animals are adjusting to the increased background noise from the urbanization of their habitats. Given that blue whales continue to produce calls in these noisy environments,

understanding the biological implications of the observed modifications in their calling is necessary to evaluate potential impacts and improve management of this endangered species.

Introduction

Ambient sound is an important aspect of habitat. Organisms, both aquatic and terrestrial, have evolved complex communication systems related to the characteristics of background sound and propagation in their environments (Wiley and Richards 1978, Hauser 1997, Lugli *et al.* 2003). Alteration of the acoustic habitat by human activities threatens the effectiveness of these communication systems (Warren *et al.* 2006). As with any modification to habitat, knowledge of animal response is critical for evaluating the potential impact on the survival of the species.

Increases in ocean ambient noise from human activity has received considerable attention from researchers concerned about the health of marine species sensitive and dependent on sound for basic life functions (Richardson *et al.* 1995, Tyack 2008). The efficient propagation characteristics of sound energy in water likely influenced the evolution of a diversity of uses of sound by marine organisms. For example, fish and some invertebrate species utilize sound for selection of habitat (Simpson *et al.* 2004&2005, Vermeij *et al.* 2010). Odontocetes (toothed whales) produce high frequency, high intensity echolocation sounds to sense and track prey (Au 1993). Long-range communication to facilitate mating and social interactions is used by baleen whales, through the production of low-frequency calls (Edds-Walton 1997).

Sources of anthropogenic noise in the ocean include commercial shipping, oil and gas exploration, development and production (*e.g.* air guns, drilling, and ships), naval operations (*e.g.* sonars, communications, and explosives), research (*e.g.* sonar, telemetry, communication, navigation, and air guns), and other activities such as construction, icebreaking, and recreational boating (Hildebrand 2009). Studies of noise effects on animal communication systems fall into two broad categories: effects of noise on signal design and effects of noise on animal distributions and reproductive success. This study investigates the effect of ship noise on signal characteristics of blue whales (*Balaenoptera musculus*).

High levels of noise mask acoustic signals and certain adjustments of animal signals can help mitigate the effects of masking noise. Although short-term responses are well documented, evidence for long-term or evolutionary responses are less understood. One well known response to elevated noise is the Lombard effect, an increase in signal amplitude, in order to maintain high signal to noise ratios (SNRs) (Lombard 1911). A variety of species have exhibited this response, including toothed whales exposed to noise from small vessels and whale-watching boats (Scheifele 2005, Holt *et al.* 2008). Other potential signal modifications to compensate for increased noise include a shift in frequency, longer call durations, and increased call rates. Examples of these changes have also been documented in marine mammal species (Miller *et al.* 2000, Fristrup *et al.* 2003, Foote *et al.* 2004, Di Iorio and Clark 2009). Potential modifications in call amplitude, interval, and type were investigated in this study.

Transiting ships radiate a significant amount of low-frequency underwater noise during normal operating conditions, with most acoustic energy below 100 Hz, (Ross 1976, Arveson and Vendittis, 2000, McKenna *et al.* submitted). The intensity of radiated ship noise in a particular region depends on the ship-type, the operating conditions of the ship and sound propagation characteristics (McKenna *et al.* submitted). Blue whales vocalize at these same low-frequencies (<100 Hz), and are likely sensitive to sound from large ships (Payne and Webb 1971, NRC 2003). Detection of individual ships by blue whales might occur at ranges of 10s of kilometers or more.

As the global commercial shipping fleet increases its size and speed, noise added to the marine environment is intensifying; background levels are now elevated at some sites by at least 10 times what they were in the 1960s, and have doubled in intensity every decade for the past 40 years (Andrew *et al.* 2002, McDonald *et al.* 2006). In the Pacific basin where low-frequency sounds can propagate for hundreds of kilometers, this trend is attributed to noise from local and distant ships. However, because of the complex bathymetry in coastal regions like the Southern California Bight, noise from distant ships will not propagate into the shallow regions (McDonald *et al.* 2008). Thus, local shipping traffic is the dominant source of ship noise in coastal areas like the Santa Barbara Channel (SBC, McKenna *et al.* 2009).

Two major ports serve ships traveling through the SBC: Port Hueneme and the Port of Los Angeles-Long Beach (POLA). POLA is the second busiest port in North America (CINMS 2009). Until recently, an estimated 75% of vessel traffic departing from, and 65% of traffic arriving at, POLA and Port Hueneme traveled through the SBC (CINMS 2009). Commercial vessel traffic in the SBC is concentrated in the designated shipping lanes (Fig.6.1), with an average of 18 ships transiting per day (McKenna *et al.* 2009). The majority of traffic is categorized as cargo ships (*e.g.* container ships, bulk carriers and vehicle carriers), traveling at average speeds of 10 ms^{-1} (19 knots).

The SBC includes not only one of the busiest shipping lanes in the world, but is also an important summer foraging region for the endangered North Pacific blue whale population. The whales tend to aggregate in cold, up-welled coastal waters to feed primarily on subsurface concentrations of euphausiids (Croll *et al.* 1998, Fiedler *et al.* 1998). World-wide blue whale populations were decimated by commercial whaling from approximately 300,000 to fewer than 10,000 and are slowly recovering (Barlow 1995). The North Pacific stock estimates are around 2,000 and may be one of the largest populations in the world (Barlow 1995, Calambokidis and Barlow 2004, Calambokidis *et al.* 2009). During the feeding months (late summer/fall), whales forage in the presence of both commercial and recreational vessels in the channel.

The proximity of shipping routes in the SBC with predictable blue whale foraging grounds provides a study area to test for changes in blue whale vocalizations in the presence of ships. Blue whale calls are predominantly in the low frequencies (15-100 Hz); a frequency range similar to the dominant acoustic energy of ships (Ross 1976, Richardson *et al.* 1995, McKenna *et al.* submitted). Blue whales in the North Pacific are known to produce at least four call types (McDonald *et al.* 1995, Thompson *et al.* 1996): A and B calls (16 Hz, ~20 second duration), D calls (down sweep from 90-25 Hz, 1-4 second duration), and highly variable amplitude and frequency modulated calls. A and B calls are songs produced by males and possibly function in mate attraction (McDonald *et al.* 2001, Oleson *et al.* 2007a). The D calls are recorded from both males and females and are usually associated with feeding activity (Oleson *et al.* 2007a).

The goal of this research is to quantify the response of vocalizing blue whales in the presence of commercial ships. Four potential vocal responses were investigated. First, changes in song were explored by quantifying inter-call intervals of the blue whale B calls during the seasonal peak of song (October 2008 and 2009). Changes in contact calls during foraging were examined by comparing the inter-call interval of D calls in the seasonal peak in foraging (July 2008). Modifications to amplitude, frequency range and duration were also measured for D calls. Lastly, due to a shift in shipping traffic out of the SBC in 2009, patterns in song type in different average background noise levels were compared between October 2008 and 2009.

Methods

Acoustic Recordings

To monitor calling blue whales in a region of regular commercial ship traffic, high frequency acoustic recording packages (HARPs) were deployed in the SBC off the coast of southern California. HARPs are bottom-mounted instruments containing a hydrophone, data logger, low drift rate clock, battery power supply, ballast weights, acoustic release system, and flotation (Wiggins and Hildebrand 2007). The hydrophone sensor is tethered to the instrument and buoyed approximately 10 m above the seafloor. The hydrophone includes two transducers: one for frequencies below 2 kHz and one for frequencies above 2 kHz. HARPs sampled at 200 kHz and recorded continuously for approximately 55 days. All acoustic data used in this study were corrected based on hydrophone sensitivity calibrations performed in our laboratory and at the U.S. Navy's Transducer Evaluation Center facility in San Diego, California.

Two sites in the channel were acoustically monitored in 2008; one site (site B) was located in Santa Barbara Basin at a depth of 580 m and a second site (site J) was located on the shelf edge (250 m), north of the Channel Islands (Fig. 6.1, Table 6.1). Site B was also monitored in 2009. Continuous acoustic data collected at these sites during peaks in blue whale calling periods (*i.e.*, July and October) were analyzed.

Ship Traffic Data

Commercial vessel activity was monitored in the SBC using the Automatic Identification System (AIS, Tetreault 2005). An AIS receiving station was located on the west campus of the University of California at Santa Barbara (34°24.5'N and 119°52.7'W) (Fig. 6.1). AIS signals from vessels in the region were received using a high frequency (VHF) omni-directional antenna and a radio connected to a computer. The software program *ShipPlotter* (ver. 12.4.6.5, COAA) was used to decode the VHF signal and archived daily logs. All archived AIS data were downloaded and imported into a *PostgreSQL* (ver. 8.4) database.

To compile information on ships transiting the north and southbound shipping lanes in the SBC, the database was queried for ships transiting during HARP recording periods (July and October 2008, and October 2009). Ship data gathered for cargo ships and tankers included a time stamp, speed, heading, latitude and longitude, unique ship identification, ship name, general ship-type, total length and draft.

B Call Detection and Classification

In October 2008 and 2009, blue whale B calls were detected using an automatic detection algorithm on continuous acoustic data decimated to 2 kHz sampling frequency. For this analysis, only acoustic data from site B were analyzed (Fig. 6.1, Table 6.1). The B call third harmonic (Fig. 6.2A) was selected for detection because of its high signal to noise ratio. Custom software developed in *MATLAB* (ver. 2007b, Mathworks, Inc.) automatically detected the B calls using a spectrogram correlation method (Pfeil *et al.* submitted). Application of this method for detection of blue whale calls has proven successful in previous studies (Mellinger and Clark 2000, Wiggins *et al.* 2005, Oleson *et al.* 2007b, McDonald *et al.* 2009).

To calculate the spectrograms used with the detection algorithm, fast Fourier transforms (FFTs) of the time series waveforms were performed with 2,048 samples, 50% overlap, and Hamming windows. These spectrograms were cross-correlated with a synthetic kernel, or reference function, representing the B call third harmonic. The parameters of synthetic kernel were based on characterization of known B calls. The kernel only represented the first 10 seconds of the call, which included a down-sweep portion starting at approximately 49.2 Hz and ending 10 seconds later at 46.9 Hz (Fig. 6.2A).

The spectrogram cross-correlation output is a score function. When this function was above a user-defined detection threshold, the detection score and time of the call were tabulated. Detector performance resulted from comparisons of the detector results with manually selected calls (Pfeil *et al.* submitted). Using the results of this evaluation, a detection threshold which produced <8.5% false detections and <12.2% missed calls was adopted.

Blue whale B call detections were further processed to categorize the detections into song types based on intercall intervals. Previous studies defined song as a sequence of stereotypical calls or phrases occurring in a repeated pattern (McDonald *et al.* 2006, Oleson *et al.* 2007b). Conversely, singular B calls are those occurring irregularly, without a recognizable pattern. Song interval was based on previous studies (Oleson *et al.* 2007b) and verified in this dataset. The consistent intervals identified included a consecutive B interval (BBB song) of 47.5 ± 8 seconds and B calls interspersed with an A call interval (BAB song) of 127.5 ± 9 seconds. These intervals were used to automatically sort B call detections. Each B call detection was compared to all detections that occurred within 200 seconds. If one of the song intervals occurred, the calls in the sequence were labeled as the corresponding song type. Once a call was classified, the classification procedure moved to the next detection. If no calls occurred within the 200 seconds, or the interval did not fall in the designated categories, the detection was categorized as irregular.

D Call Detection and Classification

Blue whale D calls were manually selected from continuous acoustic data collected at site J in July 2008. This site was located on the shelf edge, north of the Channel Islands, a known blue whale foraging area. Acoustic data were decimated to 2 kHz sampling frequency. The program Triton developed in *MATLAB* (ver. 2007b, Mathworks, Inc.) was used to visualize the data and log the calls. For each call the start and end frequencies and corresponding times were noted. Standardized spectrogram parameters when detecting calls were set to 120 second plot lengths, 0 to 200 Hz frequency range, and an FFT length of 10,000 with 80% overlap, and a hamming window. A spectrogram equalizer was used at times of very high or intense background noise and contrast settings were adjusted to detect faint calls.

D calls were classified based on the number of calls present in a 120 second period after each call and the intervals to the next calls. For the purposes of this study, a calling series was defined as period when more than one call occurred in the 120 seconds period; otherwise a call was labeled as singular. If the interval of any of the calls in the series were less than 2 seconds, the calls in that period were classified as a multiple caller series. This is a minimum classification estimate for multiple caller series. It is possible that multiple animals could be calling at intervals of more than 2 seconds, but this was not addressed in this study.

Co-occurrence of Ships and Calling Whales

Ship passage periods were defined as the time period in which a ship traveled within a distance of 10 km from the HARP, both before and after the closest point of approach of the ship to the HARP. To determine distances, the geographic coordinates of the ship (from AIS data) and the depth and geographic position of HARP were compared. The passage duration varied depending on the speed of the ship (*i.e.*, slower ships had longer passage durations). If blue whale B or D call detections occurred during these ship passage periods they were designated as occurring in the presence of a ship; otherwise the calls were categorized as occurring when a ship was not present. Background noise level measured before each call verified the acoustic presence of ships. Call rates, or calls detected per hour, were determined for each category (ship and no ship). The number of calls that occurred in each category was divided by the total hours sampled in each category.

In October 2008 and 2009, the proportion of B song types (*i.e.*, BBB, BAB, or B irregular) that occurred during a ship passage were compared to the proportion of call types when a ship was not present. The specific null hypothesis tested was whether the call type relative frequencies were the same when a ship was present compared to when a ship was not present. A contingency table for testing the independence of call type and ship presence was used, and evaluated using a Chi-square statistic:

$$x^2 = \sum\sum\frac{(f_{ij}-\dot{f_{ij}})^2}{\dot{f_{ij}}} \tag{6.1}$$

where, f_{ij} are the observed frequency for a given call type and ship category, and $\dot{f_{ij}}$ are the expected frequencies. Expected frequencies for each category and call type were calculated using the following formula:

$$\dot{f_{ij}} = \frac{(R_i)(C_j)}{n} \tag{6.2}$$

where, R is the total number of calls in either the ship or no ship category (i) and C is the total number of calls in each call type (j) and n is the total calls in the analysis. The significance of the x^2 tested against critical values (see Appendix Table B.1 in Zar 1999). The test statistic was set at a .05 critical alpha level with two degrees of freedom.

The same statistical approach was used to test the difference in relative frequencies of B call types between October 2008 and October 2009. The test was also employed to compare relative frequencies of the three D call interval types (*i.e.*, single, multiple caller series, or single caller series) that either occurred during a ship passage, or not during a ship passage.

Because the proportion of call types and ship passages can vary depending on the time of day, all call types were sorted into hourly bins for investigations of temporal patterns. Categorized calls were divided into 1-hour bins to examine when the events occurred. Hours that had calls categorized as both ship present and ship not present were included in the analysis; hours biased towards one category were removed.

Call Received Level

To test if call amplitude changed with background noise level (*i.e.*, ship noise) D call received levels (RLs) were compared to measured background noise levels (BLs). Given the high variability in D calls, the duration and bandwidth specific to each call were used to calculate the call received level. The mean squared pressure values were summed across the call frequencies, and converted back to sound pressure levels expressed as decibels referenced to a unit pressure density. Background sound pressure levels were measured 5 seconds prior to the start time of the call. This time was adjusted if another call was present. The sound spectrum levels at 40 Hz were used to quantify the level of ship noise. A linear correlation between call RLs and BLs was determined.

Given the unknown distance of the calling animals and the overlap in frequency of blue whale calls and ship noise, there was a potential to mask calls in higher background noise levels. This would lead to a biased representation of the call RLs related to BLs. To test the masking potential and determine under what conditions a change could theoretically be measured, simulations with known sound level distributions and call responses were performed. The call responses modeled included: perfect Lombard effect (1:1, *i.e.*, for every 1 dB increase in noise, there is a 1 dB increase in call level), two partial Lombard effects (1:0.5 and 1:0.3), and no response (1:0). Two different underlying sound level distributions were tested: one with normally distributed data and equal means for the call RL and BL and, the second simulation tested normally distributed call RLs with a mean of 100 dB and BLs with a mean of 80 dB and right skewed. The second simulation closely represented the data collected in this study. The actual call RL distribution was derived from a sub sample of the calls that occurred when background levels were below 70 dBs This distribution represented the distances of the callers to the acoustic receiver, given a constant source level.

Results

Co-occurrence of Ships and Blue Whale Calls

Analysis of hourly averages of blue whale calls revealed distinct diel patterns. In October 2008, daily peaks in the number of B call detections occurred at dawn and dusk (Fig. 6.3A). In October 2009, call detections remained elevated during the night time and the maximum number of calls h^{-1} was lower (80 h^{-1} in 2009, compared to 100 h^{-1} in 2008, Fig. 6.3A, Fig. 6.4A). Overall, average daily calling rates were similar between 2008 and 2009, approximately 1,500 B call detections per day (Table 6.1).

The average number of D calls peaked around dawn (8 h^{-1}, Fig. 6.5A). D calls remained relatively high throughout the day (6 h^{-1}), peaked again just after dusk, and were lowest during the night hours (Fig. 6.5A). The average D calling rate in July 2008 was approximately 122 calls per day (Table 6.1).

The daily patterns in traffic were similar across all months and years with distinct peaks around midnight and mid-day. The peaks in southbound traffic occurred earlier than the northbound traffic (Fig. 6.3B, Fig. 6.4B, and Fig. 6.5B). Commercial ship traffic in the SBC differed in October 2009 compared to July and October 2008 (Table 6.1, Fig. 6.3B, and Fig. 6.5B). A greater number of ships transited the SBC in 2008, approximately 16 ships d^{-1} in July and 15 ships d^{-1} in October, compared to 5 ships d^{-1} in October 2009.

The co-occurrence of ships and calls varied depending on the hour of day, and as expected correlated, with the patterns in calling and ship traffic. In October 2008, the co-occurrence of B calls and ships was distributed across all hours of the day, given the high volume of ship traffic (Table 6.1, Fig. 6.3D). In October 2009, given the decrease in ship traffic, two hours did not have the co-occurrence of ships and B call detections (Fig. 6.4C). Because D calls are less frequent compared to B calls, some of the hours in July 2008 did not have examples of D calls occurring with ships present (Fig. 6.5C). Only a subsample of hours was analyzed: 4 hours at night (3-6 GMT) and 4 hours during the day (16-19 GMT). The removal of hours without the co-occurrence of calls and ships prevented confounding results related to diel patterns in call types.

Relative Frequencies of Call Types

In both 2008 and 2009, B call type relative frequencies were significantly different when a ship was present compared to when a ship was not present ($\chi2= 464$, $p< 0.001$; $\chi2= 142$, $p< 0.001$). An increase in the proportion of B detections categorized as occurring at an irregular, non-song interval when ships were present was observed (Fig. 6.6). Song type BAB did not show any change in relative frequency. A comparison of call type relative frequencies between 2008 and 2009 when ships were not present resulted in a significant difference ($\chi2= 11.5$, $p=0.005$), with a slightly higher frequency of BAB song in 2009.

A comparison of D call types detected when ships were present to when ships were not present revealed significant shifts in relative frequencies (Fig. 6.7). This shift varied depending on the time of day analyzed (night: $\chi2= 10.8$, $p=0.006$; day: $\chi2= 51.1$ $p<0.001$). When ships were not present, a greater number of detections were categorized as multiple caller series during the night, compared to day time (Fig. 6.7A, $\chi2= 9.6$, $p=0.01$). The proportion of multiple caller series significantly increased when ships were present, from 56% to 72% during the night, and 31% to 54% during the day. This increase in calls categorized as multiple caller series during the night hours when ships were present resulted in a decrease in the number of single calls and single caller series. During the day time hours, only the single caller series decreased and the proportion of single D calls remained the same.

Call Received Level and Ship Noise

An increase in the received levels of D calls was observed when the background noise increased (Fig. 6.8A). The change was not a perfect Lombard effect, increasing only at about 0.4 dB for every 1 dB increase in background noise. Given the underlying distributions of D call received levels and background noise levels (Fig. 6.8B), the observed increase in call RL provided at least a 5-10 dB signal to noise ratio (SNR), even at high BL of noise. When the call RLs were binned according to the number of ships present, a significant increase in call RL was observed with the increase in the number of ships present (Fig. 6.8C).

The results of the Lombard effect simulations allowed for evaluation of the observed changes in RLs with BLs. Simulations with distributions of RLs and BLs with equal means resulted in inaccurate characterizations of the Lombard effect, when RL that were less than the corresponding BL were removed (Fig. 6.9). This inaccuracy depended on the degree of the simulated Lombard effect. No Lombard effect (random samples) resulted in an incorrect effect of 0.5 dB increase in RL per 1 dB increase in noise (Fig. 6.9B). However, as the correlation between RL and BL increased, the inaccuracies decreased. A simulated "perfect" Lombard resulted in an accurate estimate of the effect (Fig. 6.9C, Fig. 6.11).

Simulations using the observed distributions of RLs (at low BLs) and BLs in this study (Figs. 6.8B, Fig. 6.10A) resulted in increased accuracy when measuring the Lombard effect (Fig. 6.10, Fig. 6.11). The percent error for the observed 0.4 dB increase in D call RLs with 1 dB increase in BL was ~3% based on the simulation results (Figs. 6.11).

Discussion

Comparisons of blue whale call type, interval and amplitude revealed modifications related to the increase in noise from transiting commercial ships. A greater proportion of irregular B call detections occurred when ships were present, resulting in a possible disruption of song in the presence of ships. Variability in intervals between blue whale D calls was observed and related to both time of day and presence of ships. Calls occurred more rapidly in the presence of ships. A partial Lombard effect was identified for D calls and verified with model simulations. Given that blue whales continue to produce calls in noisy environments, understanding the biological implications of the observed changes in vocalizations is necessary to evaluate potential impacts and improve management for this endangered species.

Few, if any, studies have specifically addressed the costs to vocal adjustments in terms of individual fitness and population stability (Patricelli and Blickley 2006). Some of the potential costs discussed in the literature include decreased recognition or incorrect interpretation by receivers if vocalizations are adjusted. Furthermore, calling at higher amplitudes (increased SNR) may lead to energetic costs (Brumm 2004, Oberweger and Goller 2001). Below the implications for the observed blue whale calling modifications are discussed.

Opposing Diel Patterns in Calling and Ship Traffic

The diel patterns in B and D calling appeared to negatively correlate with ship traffic (*i.e.,* a decrease in calling when traffic was highest) (Fig. 6.2, Fig. 6.5A, and Fig. 6.5B). It is possible this pattern relates to a decrease in detections with increased ship noise, particularly at the site close to the northbound shipping lane (site B). However, similar daily patterns in calling were observed at other sites in the Southern California Bight, not close to a commercial shipping lane (Wiggins *et al.* 2005, Oleson *et al.* 2007b). This argues against the hypothesis that calling decreases when ships are present and supports the hypothesis that the observed diel patterns likely serve a biological function, as suggested in previous studies (McDonald *et al.* 2001, Wiggins *et al.* 2005, Oleson *et al.* 2007a&2007b).

General patterns of behavior in association with specific call types have been observed and help explain the daily patterns in calling. Behavioral observations of individual calling blue whales using suction-cup tags and visual-acoustic tracking indicated an apparent separation in calling related to foraging and singing activities (McDonald *et al.* 2001, Oleson *et al.* 2007a). D calls were observed between day time deep foraging dives and as observed in this study, peaked during the day (Oleson *et al.* 2007a, 2007b) when prey sources are more concentrated (Schoenherr 1991, Fielder *et al.* 1998). Although it is unlikely that D calls facilitate prey capture, the association of these calls with feeding behavior does suggest a relationship with foraging. They may serve as a contact call for locating conspecifics, as seen in right whales (Clark 1982). In contrast to D calls, B calls, particularly song, were heard from solitary travelling males and likely serve a mating function (McDonald *et al.* 2001, Oleson *et al.* 2007a). Dawn and dusk peaks in B calling suggest a transition to singing behavior when prey is dispersed.

The patterns in ship traffic in the SBC relate to port schedules (McKenna *et al.* 2009). Although this pattern seems ideal for minimizing the overlap with calling whales, blue whales are distributed throughout the region and ship passages in regions further north and south will overlap with peaks in blue whale vocalization patterns.

Disruption of Song

Seasonal patterns in the occurrence of blue whale song in the Southern California Bight showed a peak in the presence of song in October (Oleson *et al.* 2007b). Therefore, patterns in blue whale song were only compared in October 2008 and October 2009 to avoid potential confounding relationships with seasonal occurrence. When ships were not present, the proportion of call types was similar to previous observations with more calls categorized as song compared to singular B calls (Oleson *et al.* 2007b). When song was separated into the two types (*i.e.*, BAB or BBB), in both years, BBB song type was more common.

An increase in the frequency of irregular B calls when ships were present was observed in both October 2008 and October 2009 (Fig. 6.6). Consequently, the frequency of BBB song type significantly decreased when ships were present, in both 2008 and 2009. No change in song type BAB was observed when ships were present. The cause of this change in call rate is unknown and might result from either an increase or decrease in call interval. There was more evidence for a decrease in the interval suggesting the animals might be responding to the increased ship noise by enhancing the probability of signal reception by an increased call rate. This vocal response would likely incur energetic costs. In some cases the interval increased between calls and might reflect extended surface time, as suggested in previous studies (McKenna *et al.* in prep) when an animal was in close proximity to a ship. Regardless of the specific response, a shift to irregular calling pattern in the presence of ship noise represents a disruption of song and might result in temporary communication breakdown, especially if conspecifics are relying on the interval to interpret the signals.

Although the presence of ships resulted in a decrease in the blue whale BBB song type, no change in the BAB song type was observed in either year. It is unknown why only one song type would change, but might relate to a difference in function of these two song types. A calls are lower in amplitude suggesting the BAB song might function in shorter range communication, whereas BBB song is for longer range communication. Therefore, the disruption of the BBB song type suggests a change related to long range communication, and not shorter range AB calling.

Additional evidence for this response was a higher proportion of BAB song type, compared to BBB song type in 2009, when there were fewer overall ships present.

There is a possibility that observed shifts in B calling in the presence of ships relates to the detection of the calls. For example, if calls are masked during the closest point of the ship passage to the HARP, the interval between calls would change, but would likely mask a series of calls, instead of a select number of calls during the ship passage. Furthermore, the BAB song did not change and if the patterns were related to the detector, both song types would exhibit a similar pattern of masking.

Increase in Contact Calls

A greater proportion of D calls classified as part of a multiple caller series (*i.e.*, 2 or more calls occurring at interval of 2 seconds or less) occurred during the night time hours compared to mid-day, and further increased when ships were present. The increased proportion of multiple caller series suggests an increase in contact calling between blue whales in the presence of ships.

Blue whale D calls appear to have an identifiable behavioral context related to social interaction, particularly when animals are foraging. Supporting evidence from previous studies showed that both sexes produce this call type, calling whales are often paired or in close association with other whales, and alternating patterns in calling has been observed between individuals (Thode *et al.* 2000, McDonald *et al.* 2001, Oleson *et al.* 2007a). Furthermore, the calls are produced at depths of 15-35 m where visual identification of conspecifics is possible and the calls have spectral characteristics that might enhance detectability (Marler 1955, Edds-Walten 1997).There appears to be a premium on maintaining acoustic contact, and the results of this study suggest that when acoustic contact is disrupted (in this case by ships), multiple animals will call to potentially regain contact. Previous studies quantifying changes in blue whale contact calling in the presence of seismic surveys, showed a similar increase in calling in the presence of seismic noise (Di Iorio and Clark 2010).

D call parameters, including call duration, bandwidth, and start and end frequencies when ships were not present were compared to calls detected when ships were present. No evidence for a change in call structure was found. Slight adjustments in frequency may provide only marginal improvements in call detection in broadband high level noise, such as ship noise. Furthermore, shifting call parameters comes with potential consequences, such as decreased recognition by a conspecific (Warren *et al.* 2006, Patricelli and Blickley 2006).

Partial Lombard Effect

A partial Lombard effect was observed for blue whale D calls: as background noise level increased with the presence of ships, call amplitude increased to maintain a high SNR. The Lombard effect is a well-known short-term response to elevated noise levels and has been demonstrated to occur in numerous species experiencing increases in background noise (Warren *et al.* 2006). Studies that attributed the increase in noise to a specific source (*i.e.*, whale watch boats, road traffic) reported increased amplitudes positively correlating with the number of sources (Brumm *et al.* 2004, Scheifele *et al.* 2005, Holt *et al.* 2008). This same pattern was observed in this study, that is, increased call amplitude with a greater number of ships (Fig. 6.8C).

In this study, the relationship of call amplitude to background noise was not 1 to 1, and the SNR decreased with increasing background noise (Fig. 6.8A). At maximum background noise levels, SNR was only 5 dB, whereas at low background noise levels, the SNR was 30 dBs This might imply that blue whales may only have a limited ability to increase call amplitude.

In studies of the Lombard effect, repeated measures of call amplitude at known distances and simultaneous measures of ambient noise are needed to detect an effect. Unique to this study is that the distance of the calling whales relative to the HARP were unknown. Although this would seem impossible to measure a Lombard effect because call RL that are below BLs would not be detected and therefore skew the relationship, simulations were run to evaluate what the error on the measured effect would be. The results of the modeling suggest that it is possible to detect a Lombard effect in a population of callers at different distances, but the underlying distributions of the callers must be considered. The ability to detect a response decreases if the means of the call RLs and BLs are the same (Fig. 6.9), unless it is a perfect Lombard effect (Fig. 6.11). In this study, the distribution of RLs had a higher mean than the background noise levels; therefore it was possible to measure the effect with a ~3% error (Fig. 6.11). One assumption of the model is that the distances of the calling whales to HARP would remain constant. In other words, the presence of a ship would not systematically cause animals to move closer to the instrument, resulting in increased call RL related to distance to the receiver, not call amplitude. There is no evidence that this behavioral response would occur. However, there is some evidence that the blue whales actually move closer to a passing vessel (McKenna *et al.* in prep), which would result in a position further from the HARP.

Decrease in Ship Traffic in the SBC

The implementation of the low-sulfur fuel regulation on July 1, 2009 changed the pattern of ship behavior substantially in the SBC (CARB 2011). The cost and feasibility of using low-sulfur fuel within the Channel caused many commercial ship operators to transit on the south side of the Northern Channel Islands, substantially decreasing traffic within the channel (Fig. 6.2, Fig. 6.4B).

Despite the reduction in traffic, only minor changes in blue whale B calling was observed between October 2008 and October 2009. Daily calling rates were similar (~1,500 d^{-1}) and hourly rates showed only minor changes. In 2009, when traffic was reduced, calling was slightly higher at night, 70 calls h^{-1} compared to 60 calls h^{-1} in 2008. However, the number of calls in the peak calling period (dawn) was greater in 2008 (more ships), compared to 2009. The relative frequencies of the types of B calls were slightly different in 2009 compared to 2008 (Fig. 6.6). A higher proportion of BAB song type, compared to BBB song type occurred in 2009, when there were fewer overall ships present. A shift to the lower amplitude song type might suggest a shift to shorter range communication in an environment with fewer ship passages.

The similar results of song calling patterns in 2008 and 2009 supports the hypothesis that blue whales are compensating for increases in background noise with short-term vocal adjustments - instead of modifications specific to the average noise levels of a region. Short-term vocal adjustments are commonly observed in species exposed to variable increases in background noise (Brumm and Slabbekoorn 2005, Warren *et al.* 2006, Patricelli and Blickley 2006).

Other factors (*e.g.* oceanographic conditions, prey availability) might also influence patterns in blue whale calling rates (Oleson *et al.* 2007b). If the underlying conditions varied between October 2008 and October 2009, detecting significant changes related to ship traffic patterns might be confounded by calling behavior related to oceanographic conditions.

Conclusion

In this study, we have provided evidence for short-term modification of vocalizations of the endangered North Pacific blue whale off the coast of Southern California, with a high density of ship traffic. Passive acoustic monitoring data were combined with ship passage information to evaluate changes in calling related to the presence of commercial ships. Despite the high levels of ship traffic in the region and subsequent increase background noise level, blue whales continued to call; therefore we developed techniques to investigate calling rate and call amplitude to provide additional insight on the potential vocal responses to ship noise.

This study adds to a growing body of literature on responses of animals to an increasingly urbanized ocean environment (Miller *et al.* 2000, Fristrup *et al.* 2003, Foote *et al.* 2004, Sun and Narins 2005, Holt *et al.* 2008, Di Iorio and Clark 2009). Animals that remain in these high noise environments must contend with the trade-offs. Maintaining communication for group cohesion, mate selection, or finding resources can be accomplished with some modifications to signals (*i.e.*, call amplitude, call rate, frequency shift); however, neither the consequences nor the effectiveness of these responses are fully understood. Direct metrics linking the response to survival are needed to effectively evaluate and develop conservation strategies related to these responses.

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Chapter 6, in full, is currently in preparation for submission. McKenna, M.F., Kerosky, S., Wiggins, S.M., and Hildebrand, J.A. Blue Whales Change their Calls in the Presence of Large Ships. The dissertation author was the primary investigator and author of this material.

Table 6.1: Acoustic Recordings, Ship Passages, and Blue Whale Call Detections at HARP sites in the SBC.

Deployment	***Site***	***J***	***B***	***B***
	Latitude	34º08.406 N	34º16.617 N	34º16.528 N
	Longitude	119º59.340 W	120º01.492 W	120º01.129 W
	Depth	245	576	577
	Year	2008	2008	2009
	Month	July	October	October
	Days Sampled	1-23	15-31	1-27
	Total Hours	527	384	623
Ships	***Total ships***	386	445	125
	Hours with ships	109	132	41
	Proportion of hours with ships	0.21	0.34	0.07
Calls	***Call Type***	D	B	B
	Total calls	2,816	24,643	41,534
	Calls occuring with ships	549	3,704	1,767

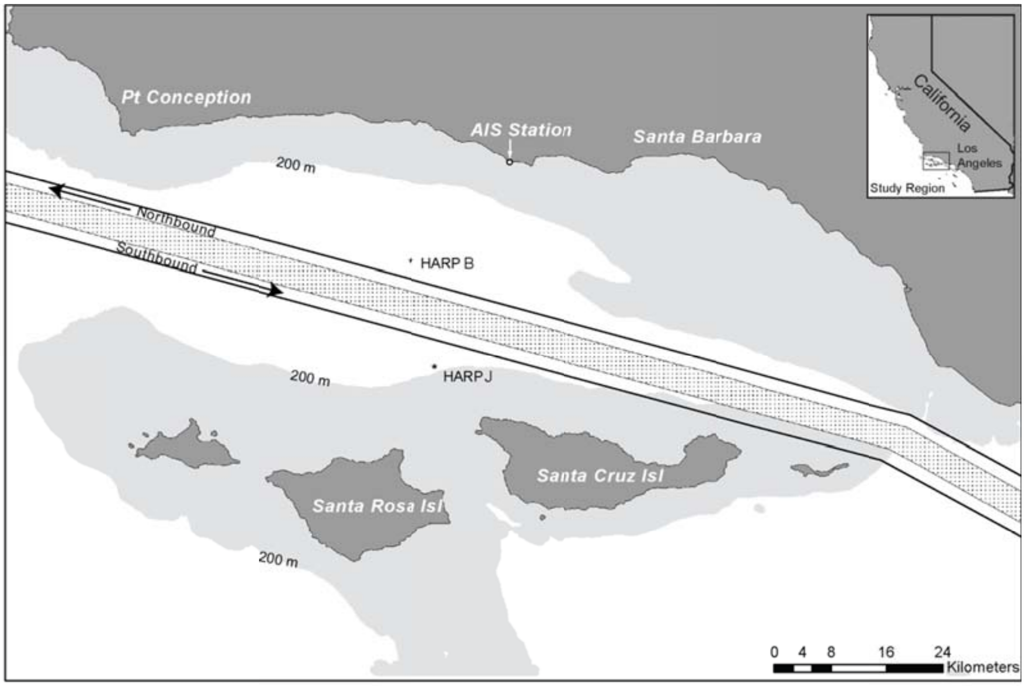


Figure 6.1: Santa Barbara Channel and Northern Channel islands with 200 m contour. The two stars represent the locations of the HARPs (B and **J**). The black lines indicate the commercial shipping lanes and the shaded area between designates the traffic separation area. The white dot just west of Santa Barbara identifies the location of the AIS shore station.

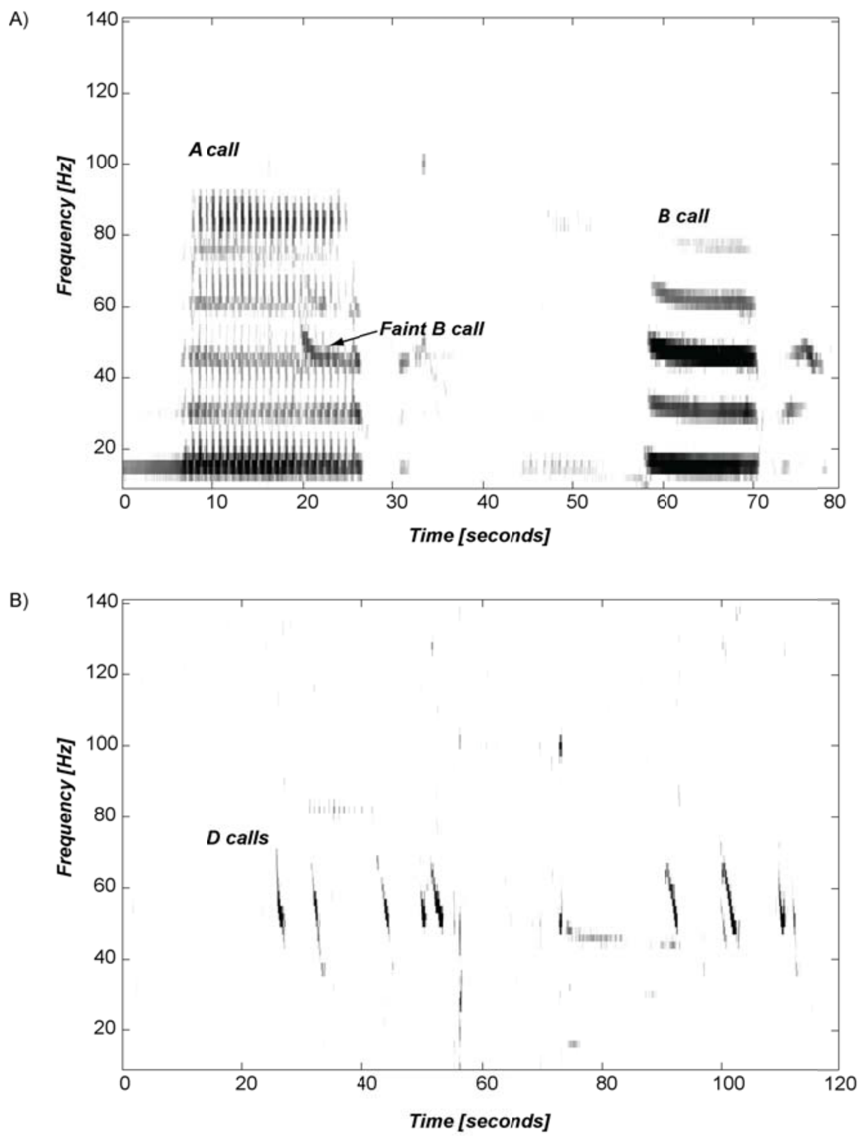


Figure 6.2: Spectrograms of HARP data showing blue whale call types. A) Blue whale A (pulsed) and B (tonal) calls. The B calls have a series of harmonically related components. The B third harmonic is detected because of its high SNR. B) A sequence of blue whale D (down-sweep) calls. These calls exhibit more variability in frequency range and duration than the A and B calls.

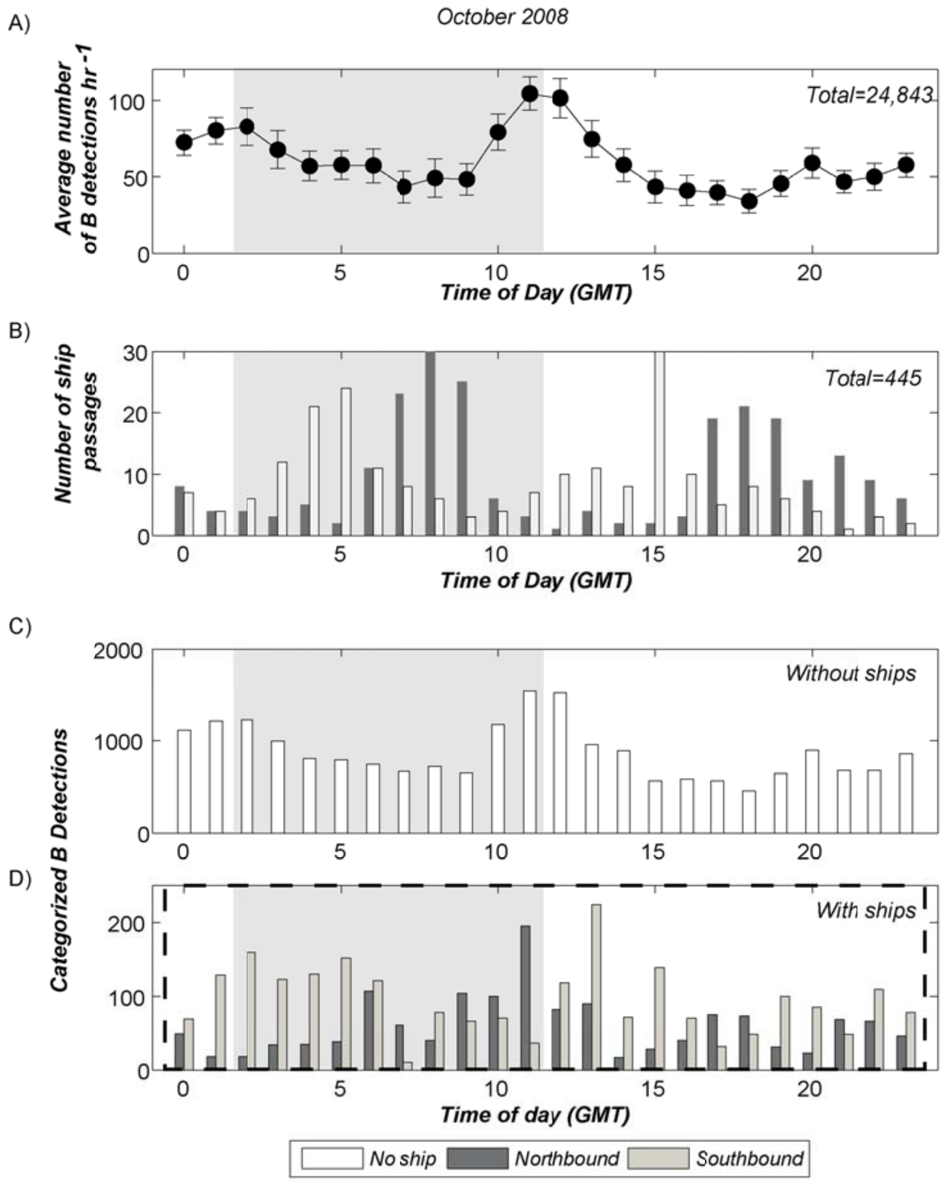


Figure 6.3: Occurrence of B calls and ships in October 2008 at site B in the SBC. A) Average number of B calls per hour. B) Sum of all AIS ship passages in each hour bin. Both the southbound and northbound ships are shown. C) Hourly distribution of B calls that occurred when ships were not present. D) Hourly distributions of B calls that occurred when ships were present, in either the north or southbound lane. The dashed box indicates the hours used in the call analysis. Shaded areas in all graphs represent night hours.

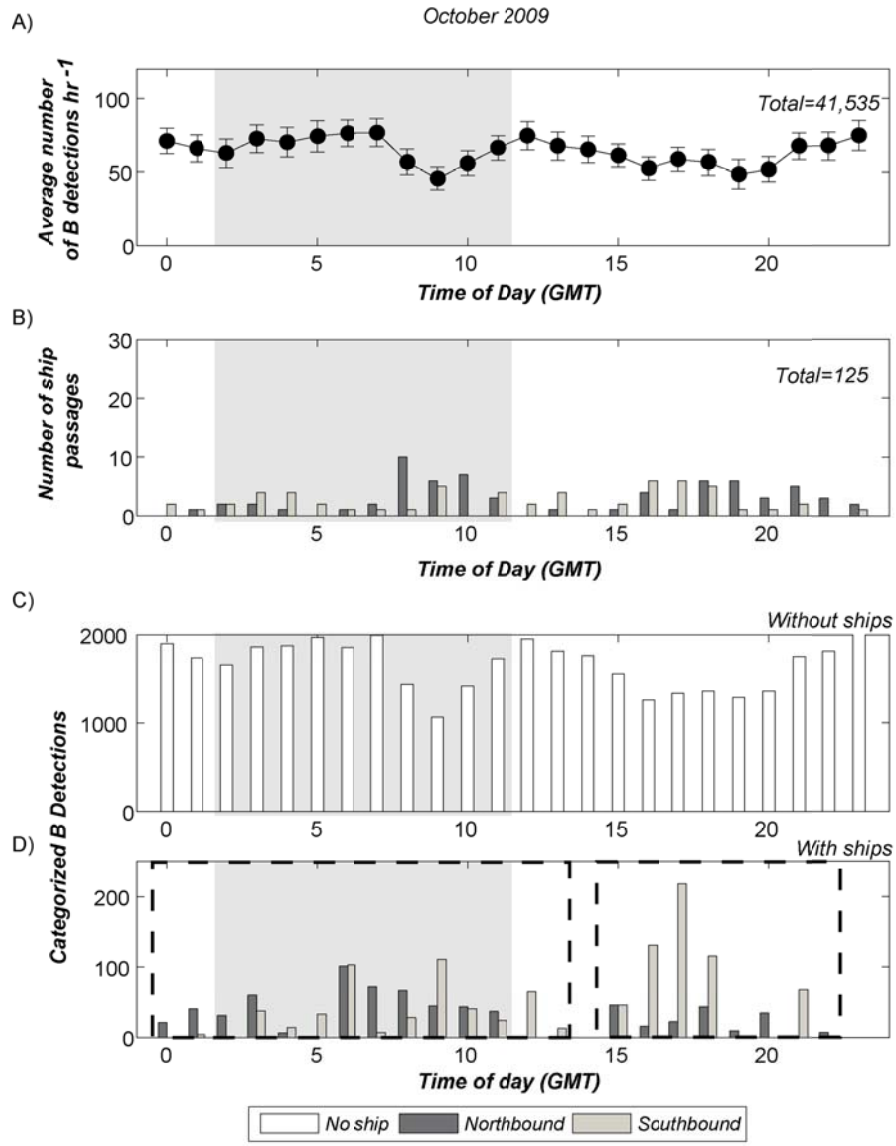


Figure 6.4: Occurrence of B calls and ships in October 2009 at site B in the SBC. A) Average number of B calls per hour. B) Sum of all AIS ship passages in each hour bin. Both the southbound and northbound ships are shown. C) Hourly distribution of B calls that occurred when ships were not present. D) Hourly distributions of B calls that occurred when ships were present, in either the north or southbound lane. The dashed boxes indicate the hours used in the call analysis. Shaded areas in all graphs represent night hours.

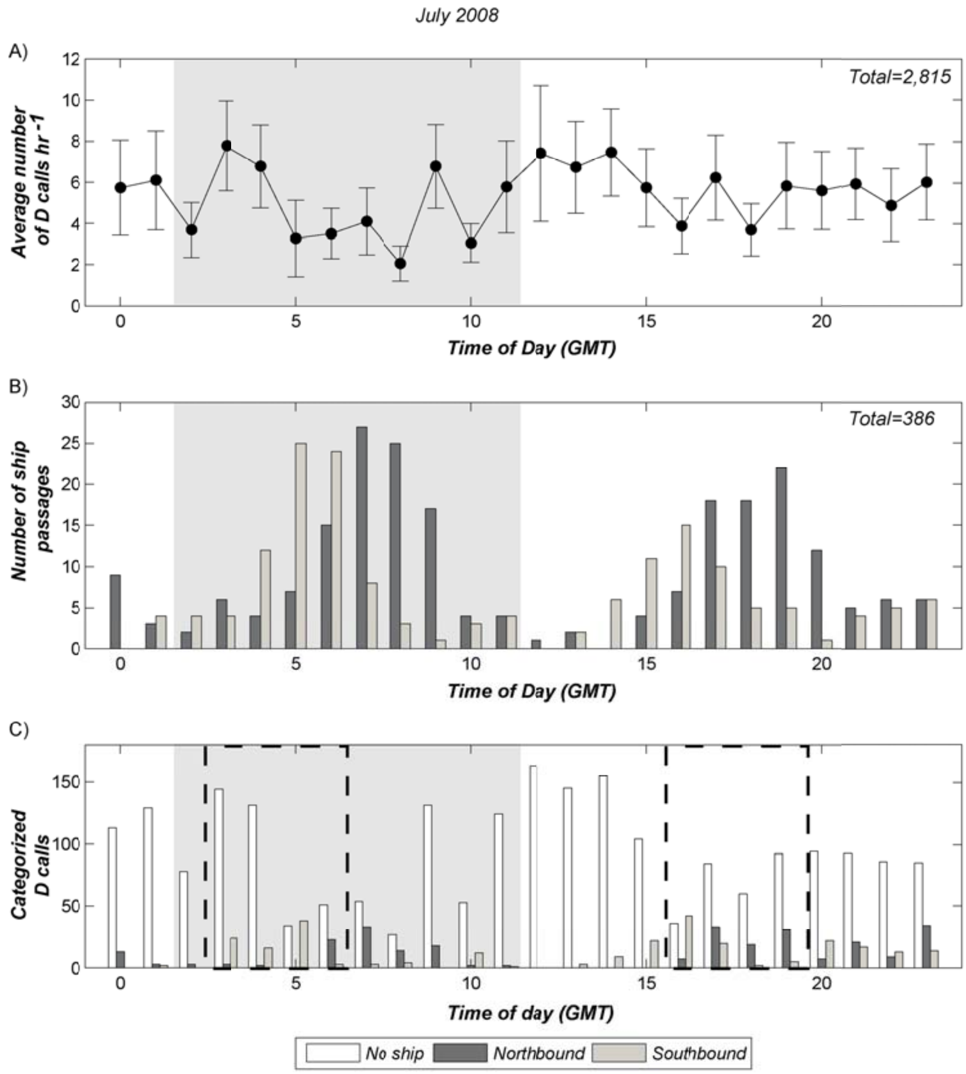


Figure 6.5: Occurrence of D calls and ships in July 2008 at site J in the SBC. A) Average number of D calls per hour. B) Sum of all AIS ship passages in each hour bin. Both the southbound and northbound ships are shown. C) Hourly distribution of D calls that occurred when ships were not present and when ships were present, in either the north or southbound lane. The dashed boxes indicate the hours used in the call analysis. Shaded areas in all graphs represent night hours.

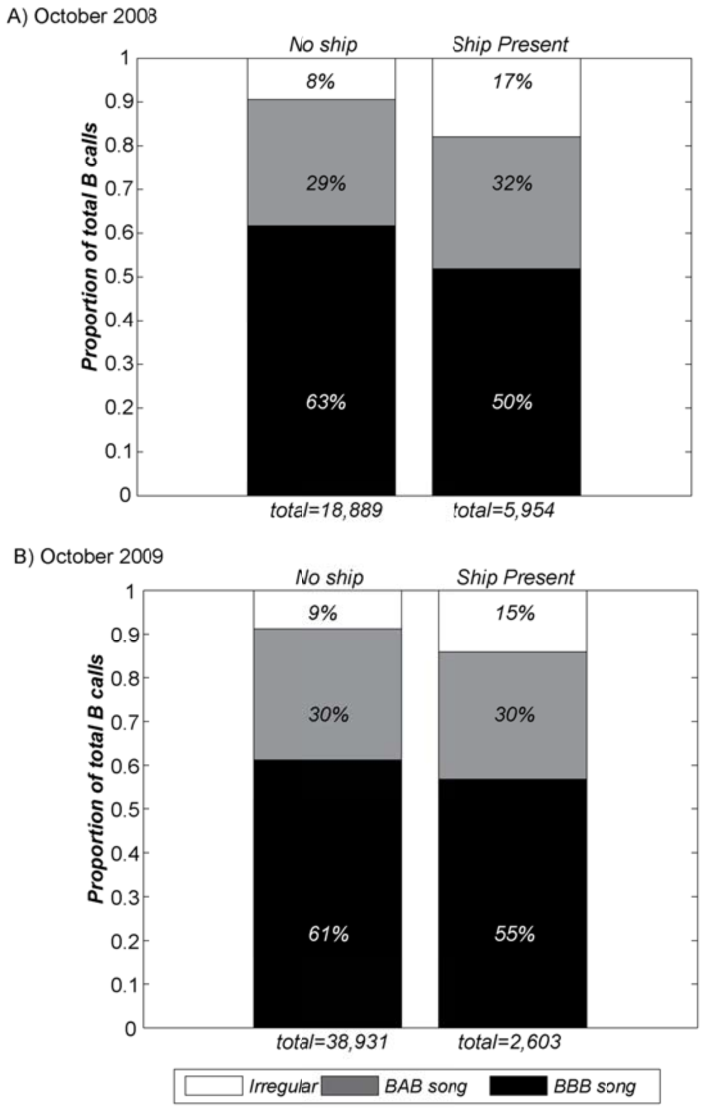


Figure 6.6: Relative frequencies of B call types. Total numbers of calls in each category are indicated on the x-axis. A) Comparison of call types in 2008. Call types relative frequencies were not the same for the two categories ($\chi2= 464$, $p< 0.001$). B) Comparison of call types in 2009. Call types relative frequencies were not the same for the two categories ($\chi2= 142$, $p< 0.001$). Call types relative frequencies when ships were present were not the same for 2008 and 2009 ($\chi2= 13.5$, $p=0.002$).Call types relative frequencies when ships were not present were not the same for 2008 and 2009 ($\chi2= 11.5$, $p=0.005$).

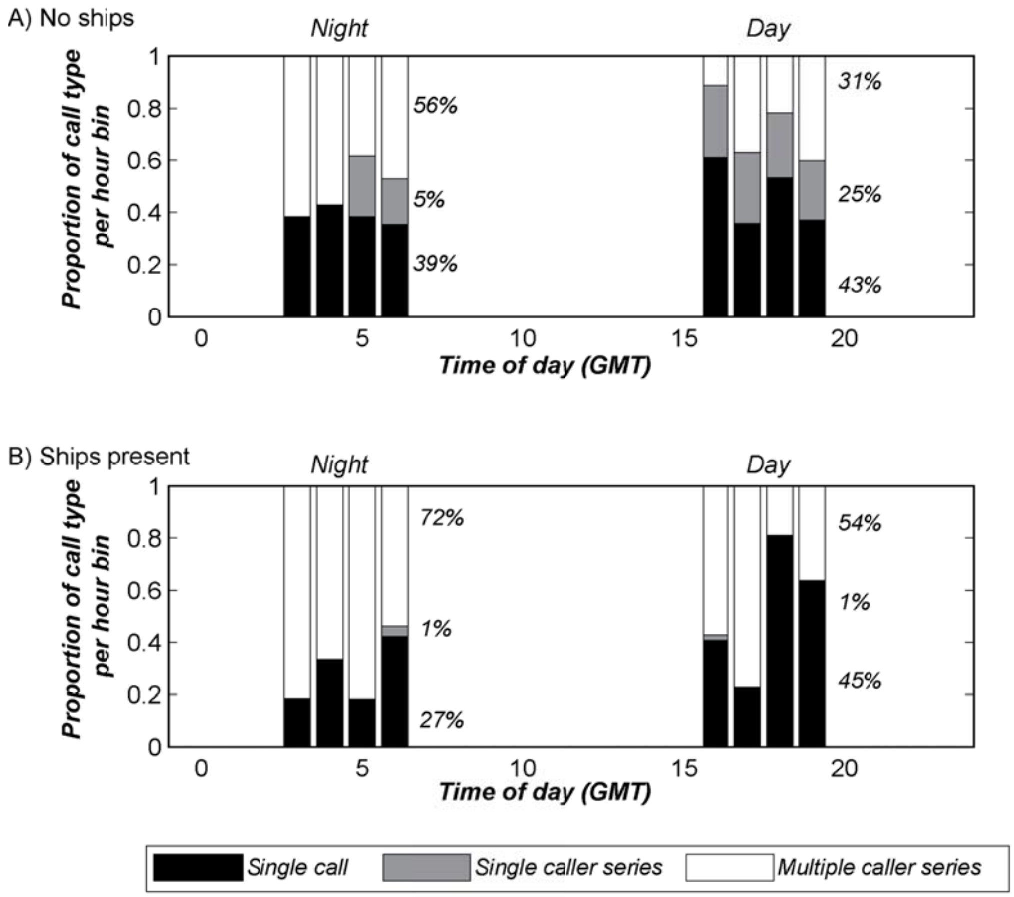
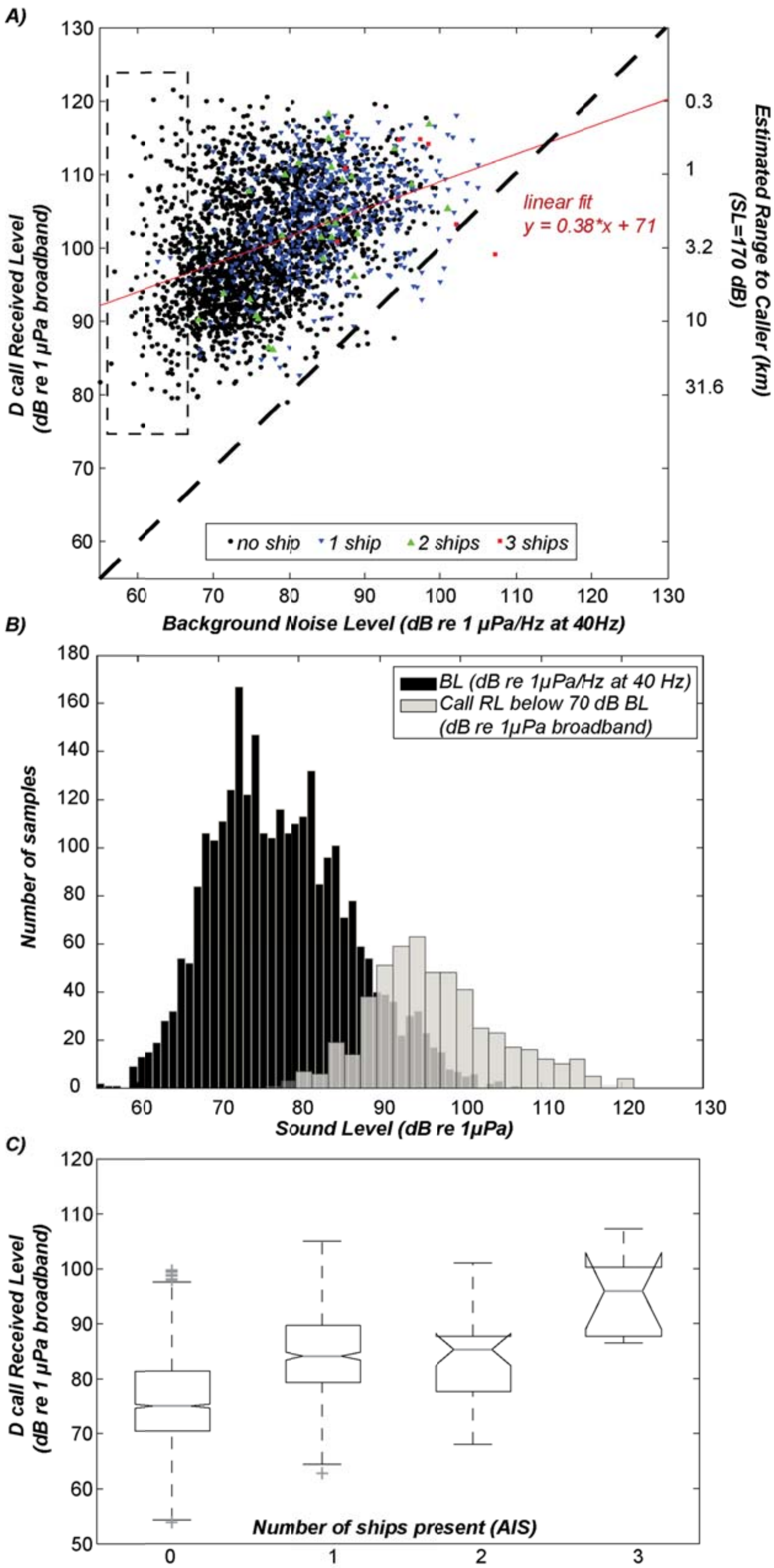


Figure 6.7: Relative frequencies of D call types in July 2008 at site J. Data are shown in hour bins- the percentages are for all 4 hours. A) Relative frequencies of D call types when no ships were present (360 calls in the night, 272 calls in the day). Call type relative frequencies were significantly different in the two categories ($\chi2= 9.6$, p=0.01). B) Relative frequencies of D call types when ships were present (109 calls in the night, 159 calls in the day). Call type relative frequencies were only slightly significantly different in the two categories ($\chi2= 69.8$, $p<0.001$). Comparisons between calls when ships were present to when ships were not present, relative frequencies were significant for both categories (night: $\chi2= 10.8$, p=0.006; day: $\chi2= 51.1$ $p<0.001$).

Figure 6.8: D call received sound levels and background noise levels. A) Call RLs versus BLs, with a linear fit. The color of the dots represents the category of when the call occurred (*i.e.*, no ship, 1 or more ships). The dashed line indicates the threshold for which calls can be detected. The dashed box, enclosing all calls that occurred when BLs were below 70 dB, designates the calls plotted in Fig.6.8B. B) Distributions of BLs measured at 40 Hz, and RLs measured over the frequency band of each call. Only calls that occurred in BL of 70 dB re 1µPa/ Hz are included in the distribution plot. The number of bars for each distribution is equal to the square root of the number of samples. C) Distributions of call RLs that occurred in each category- no ships, or 1 or more ships. On each box, the central line is the median, the edges of the box are the 25th and 75th percentiles, the whiskers extend to the most extreme data points, and outliers are plotted individually as pluses. Interval endpoints are the extremes of the notches. Medians are significantly different at the 5% significance level if their intervals do not overlap.


A)
D call Received Level (dB re 1 μPa broadband)
Estimated Range to Caller (km) (SL=170 dB)
0.3
1
3.2
10
31.6
linear fit
y = 0.38*x + 71
no ship
1 ship
2 ships
3 ships
Background Noise Level (dB re 1 μPa/Hz at 40Hz)
B)
Number of samples
BL (dB re 1μPa/Hz at 40 Hz)
Call RL below 70 dB BL (dB re 1μPa broadband)
Sound Level (dB re 1μPa)
C)
D call Received Level (dB re 1 μPa broadband)
Number of ships present (AIS)

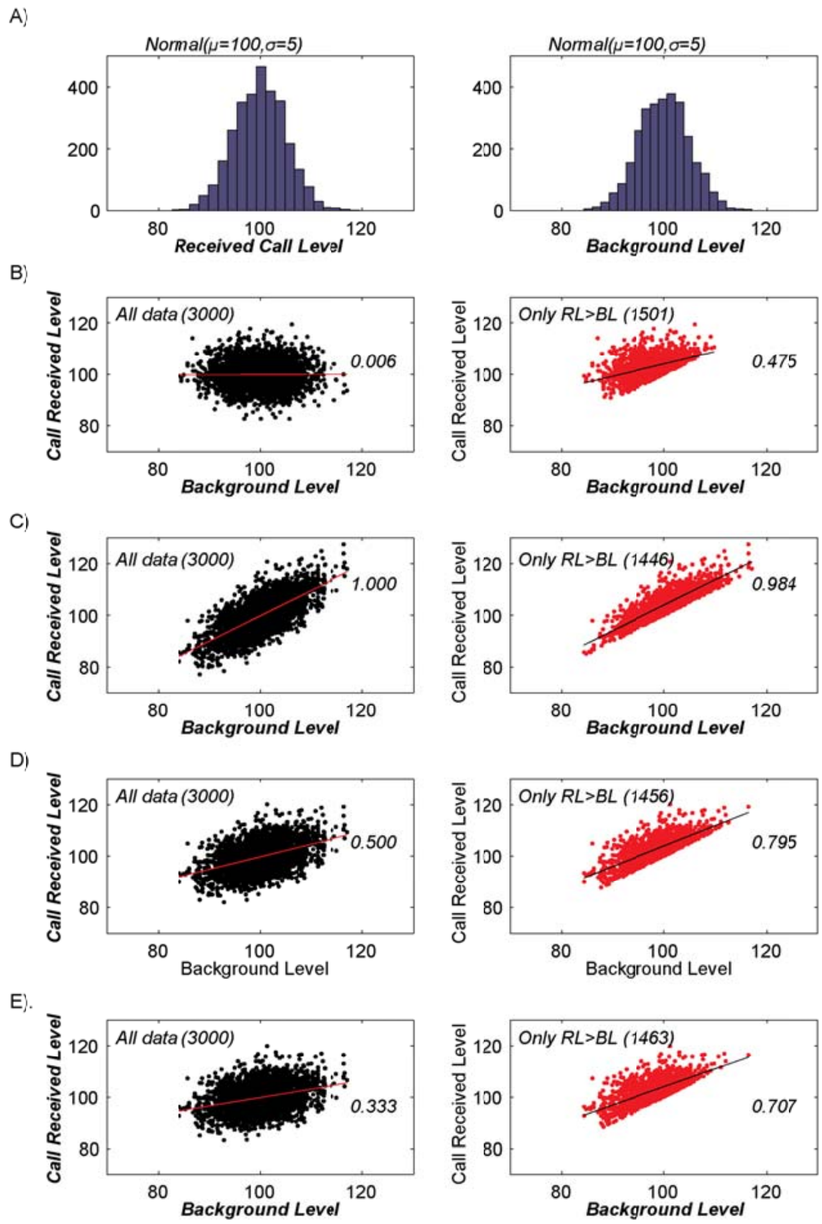


Figure 6.9: Simulated Lombard effects for normal distributions with equal means. A) The underlying distributions which points were randomly selected from. B) Results if no Lombard effect is present- first graphs shows the linear relationship of all the randomly selected data points; the second graph displays only selected points above the BL. C) Results of the perfect Lombard (*i.e.*, for every 1 dB increase in noise, call RL increases by 1 dB). D) Results of a partial Lombard effect- for every 1 dB increase in noise there is a 0.5 dB increase in signal level. E) Results of partial Lombard- for every 1 dB increase in noise there is a 0.3 dB increase in signal level. The total number of signals is noted in the upper left-hand corner of each graph. Linear correlations are shown in each graph and the slopes are used in the error analysis.

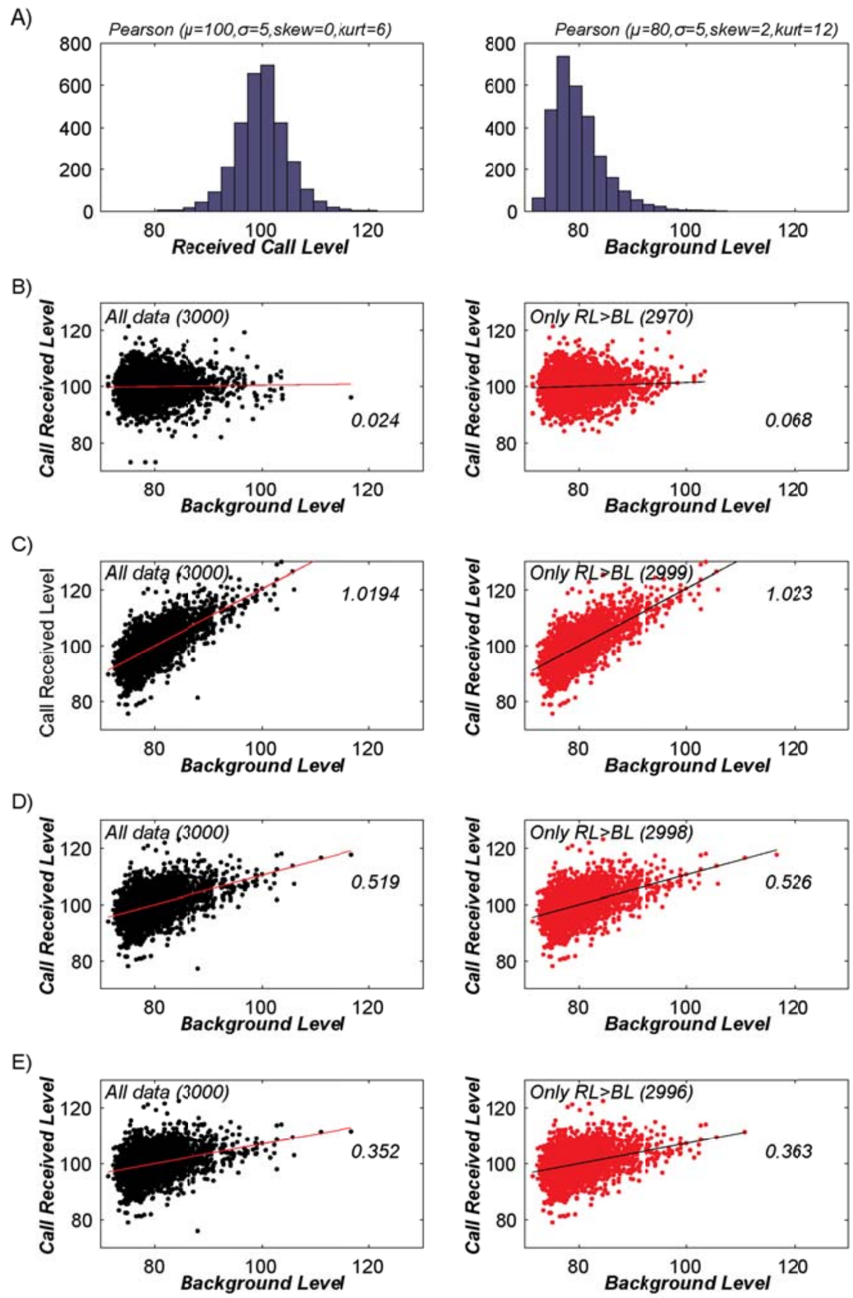


Figure 6.10: Simulated Lombard effects for distributions with unequal means and skewed distributions. A) The underlying distributions which points were randomly selected from. B) Results if no Lombard effect is present- first graphs shows the linear relationship of all the randomly selected data points; the second graph displays only selected points above the BL. C) Results of the perfect Lombard (*i.e.*, for every 1 dB increase in noise, call RL increases by 1 dB). D) Results of a partial Lombard effect- for every 1 dB increase in noise there is a 0.5 dB increase in signal level. E) Results of partial Lombard- for every 1 dB increase in noise there is a 0.3 dB increase in signal level. The total number of signals is noted in the upper left-hand corner of each graph. Linear correlations are shown in each graph and the slopes are used in the error analysis.

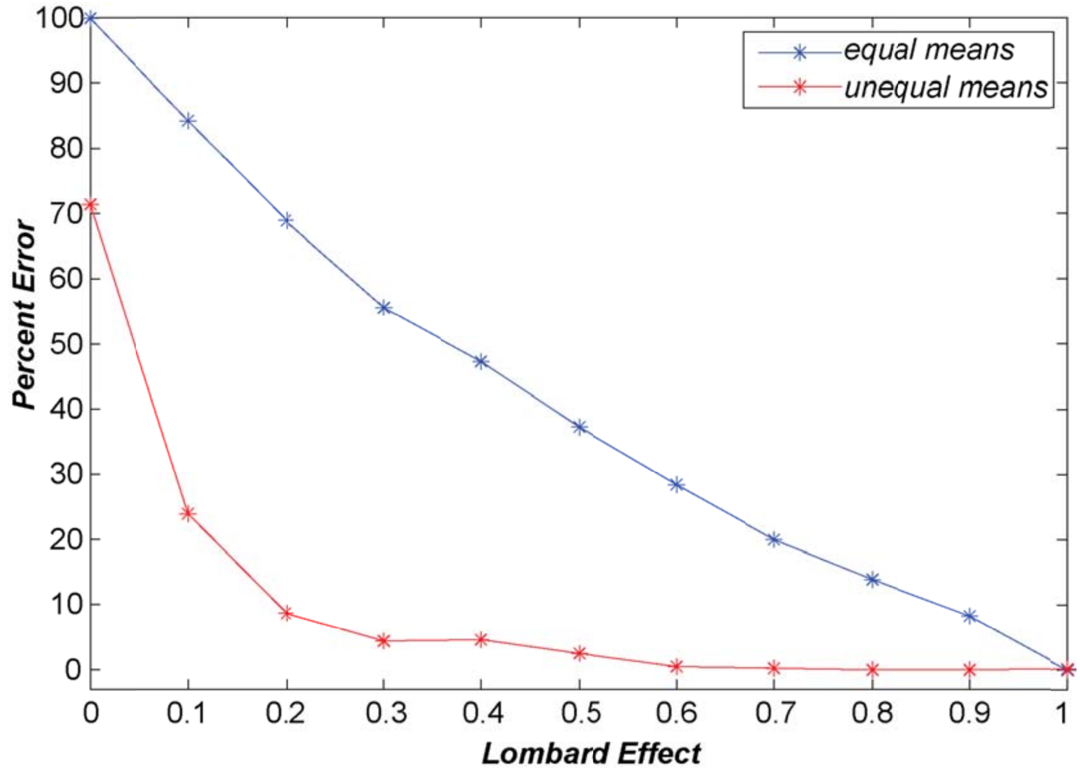


Figure 6.11: Error analysis results for detecting the Lombard effect. Simulated distributions for equal and unequal means are shown. The distributions correspond to the results shown in Figure 6.9A and 6.10A, respectively.

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CHAPTER 7

The Response of Deep-Foraging Blue Whales to the Presence of Large Ships

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Abstract

Deployments of suction-cup tags on individual blue whales (*Balaenoptera musculus*) within commercial shipping lanes off the coast of southern California provided acoustic and kinematic data to evaluate the behavioral response to the close passage of large ships. Eight close approaches of large ships at distances less than 3,600 m were observed for five deep-foraging individual blue whales. This study identified behavioral responses of foraging blue whales to the transiting vessels which resulted in a decrease in foraging time and increased risk of ship strike. The response was dependent on the distance to the vessel- no response was observed at ranges greater than 900 m. In some cases, detecting change in behavior was complicated by short-term variability in diving behavior, potentially unrelated to the large vessel disturbance. Further research addressing these confounding conditions is needed to quantify the fitness consequences of blue whales behavioral response to large ships. Implications for the population survival might be high given that these animals continue to forage in disturbed regions, particularly if resource quality is inadequate in undisturbed regions. The conclusions of the research are considered preliminary but provide insights on the potential impacts of anthropogenic activities.

Introduction

No region of the ocean is unaffected by human influence (Halpern *et al.*, 2008) and marine organisms are increasingly forced to contend with the presence of human activity in their environments. Quantifying the consequences of human disturbance is critical for understanding the link with survival and reproductive success of populations, particularly for endangered species (Gill *et al.*, 2001; NRC, 2003). Behavioral change is often considered the most sensitive measure of the effects of human disturbance on animals (Carney and Sydeman, 1990) and examples of behavioral response studies to human presence are widespread in the scientific literature. Animals may respond to anthropogenic disturbances by reducing their use of certain areas (Morrison *et al.*, 1995), altering movement patterns, and reducing the amount of time foraging (Knight, 1995; Aguilar Soto *et al.*, 2006), all potentially leading to a decrease in energetic gains (Tyler, 1991; Siemers and Schaub, 2011). However, behavioral responses to human disturbances can vary significantly in magnitude and depend on the value of the habitat (*i.e.,* resource quality) and the increased vulnerability to other threats (*e.g.* predation) and the nature of the disturbance (*i.e.,* acute, chronic) (Gill *et al.*, 1996; Beale and Monaghan, 2004). All these variables must be considered to accurately evaluate the significance to survival, both for the individual and the population.

This study investigates modifications in deep foraging behavior of blue whales (*Balaenoptera musculus*) in the presence of large commercial vessels (<150 m) operating at speeds greater than 7 ms^{-1} (14 knots). Blue whales and other species of Balaenopterids feed in bulk by engulfing large volumes of water that contain dense aggregations of prey, a behavior known as lunge feeding (Sanderson and Wassersug, 1993; Goldbogen *et al.*, 2008, 2007; Friedlaender *et al.*, 2009). Lunge feeding in Balaenopterids occurs where prey is dense and abundant, from the surface waters (Friedlaender *et al.*, 2009) to more than 500 m in depth

(Panigada *et al.*, 1999). High densities of krill, the primary food source of blue whales, are associated with areas of high primary productivity, and consequently, influence whale distributions (Croll *et al.*, 2005; Fiedler *et al.*, 1998).

The North Pacific blue whale population aggregates in the Southern California Bight, including the Santa Barbara Channel (SBC), from late June to October to feed on dense patches of krill (Calambokidis *et al.*, 2000; 2007) (Fig. 7.1). Local topography and regional upwelling zones largely determine the distribution of krill within the California current, which flows through the SBC (Croll *et al.*, 2005; Fiedler *et al.*, 1998). *Euphausia pacifica* and *Thysanoessa spinifera* dominate the aggregations of krill found in the SBC. Both species congregate in areas downstream from upwelling centers and in close proximity to regions of steep topographic relief and continental shelf waters (Croll *et al.*, 1998; Fiedler *et al.*, 1998). Blue whales targeting this prey source engage in deep-lunge feeding; a behavior characterized as energetically costly, but highly efficient, particularly if the prey density is sufficient (Goldbogen *et al.*, 2011).

The proximity of shipping routes in the SBC with these predictable blue whale feeding grounds introduces the potential for both acute and chronic disturbances to foraging whales. Two major ports serve ships traveling through the SBC: Port Hueneme; and the Port of Los Angeles-Long Beach (POLA). POLA is the second busiest port in North America (CINMS, 2009). Until recently, an estimated 75% of vessel traffic departing from, and 65% of traffic arriving at, POLA and Port Hueneme traveled through the SBC (CINMS, 2009). Commercial vessel traffic in the SBC is concentrated in the designated shipping lanes (Fig. 7.1), with an average of 18 ships transiting per day (McKenna *et al.*, submitted). The majority of traffic is categorized as cargo ships (*e.g.* container ships, bulk carriers and vehicle carriers), traveling at average speeds of 10 ms^{-1} (19 knots).

Transiting ships radiate a significant amount of low-frequency underwater noise during normal operating conditions, with most acoustic energy below 100 Hz, (Ross 1976; Arveson and Vendittis, 2000; McKenna *et al.*, submitted). The intensity of radiated ship noise in a particular region depends on the ship-type, the operating conditions of the ship and sound propagation characteristics (McKenna *et al.*, submitted). Blue whales vocalize at these same low-frequencies (<100 Hz), and are likely sensitive to sound from large ships (Payne and Webb 1971; NRC, 2003). Detection of individual ships by blue whales might occur at ranges of 10s of kilometers or more.

The behavioral response of large whales to commercial ship traffic is not well understood. Reports on the effects of man-made noise on the behavior of marine mammals varies, depending on the species investigated, the level of noise to that of ambient, degree of naiveté of the animals to the noise sources, and activity of the animal during the exposure (Myrberg, 1989). Some changes in large whale vocalizations have been observed in the presence of anthropogenic noise (Miller *et al.*, 2000; Fristrup *et al.*, 2003). The exposure of right whales to ship noise elicited no response in the dive behavior (Nowacek *et al.*, 2004), suggesting a possible habituation to vessel noise common in their environments. Most studies examining marine mammal behavior in the presence of ships have involved both smaller vessels and smaller marine mammals; notable modifications in behavior included a change in surfacing patterns, an increase in amplitude of calls, and cessation of foraging (Janik and Thompson 1996; Lesage *et al.*, 1999; Erbe, 2002; Jahoda *et al.*, 2003; Aguilar Soto *et al.*, 2006; Jenson *et al.*, 2009; Holt *et al.*, 2009).

The goal of this research is to quantify the response of individual deep-foraging blue whales to the close passage of large ships. The deployments of suction cup tags on individual blue whales within the shipping lanes provide acoustic and kinematic data. The behavioral reaction of the whale to the ship is then evaluated based on the tag data and previous descriptions of deep-foraging dives (Goldbogen *et al.*, 2011), while considering the characteristics of the passing ship (*i.e.,* range to animal, size, speed, and source level), the individual animal (*i.e.,* sex, behavior at close approach), and prey. The specific research questions we addressed: (1) What is the form of the response to close passage of large vessels? (2) Is there a threshold of range to the ship that elicits a response by blue whales? (3) What are the potential energetic and social costs to these animals?

Methods

Behavioral Data

The behavior of blue whales in the presence of ship noise and close ship approach was studied using suction-cup attached acoustic recording tags (B-Probe: Greeneridge Sciences) and GPS Fastlock location tags (MK-10: Wildlife Computers). Tags were deployed on blue whales in the shipping lanes in the SBC; attachment using a long pole from a small boat occurred when the animal surfaced. The B-Probe acoustic sensor, sampling at 2,048 Hz, recorded animal vocalizations and in some cases ship noise and was used to determine swim speed from flow noise (Goldbogen *et al.*, 2006). The tag also recorded temperature, depth, and 2-axis acceleration at a 1 Hz sampling rate. The MK-10 tag recorded pressure and GPS positions during surface periods.

Dive depth and body orientation were measured by the sensors on the tag, and additional behavioral variables were derived from the auxiliary sensors. Dive behavioral parameters measured included: (1) dive duration, descent time, angle, speed, and gliding phase of the dive; (2) bottom time, number and angle of lunges, and maximum dive depth; (3) ascent time, angle, and speed; and (4) surface time and number of breaths. In addition, the acoustic data were manually scanned for the presence of vocalizations. If present, the call type and received levels were determined. The pressure data recorded on the MK-10 tag were used to determine dive depth, times and presence of possible lunges.

The tagged whales' position and surface behavior were visually monitored by observers onboard the research vessel. The whale was photographed for individual ID, and genetic material (*i.e.,* skin) present on the recovered tag was collected for sex determination. The presence of prey was qualitatively confirmed using 200 kHz sonar on board the tagging vessel. The acoustic backscatter was visually monitored and depth and thickness of the highest intensity were recorded at the last surfacing before the whale began a deep dive.

Statistical Analysis

Only animals that were engaged in deep foraging were included in this analysis. Each dive in a sequence from a single deployment was compared to previously collected stereotyped deep-lunge feeding dive records (see Goldbogen *et al.*, 2011), and to the mean of all the dives in the individual tag deployment. Differences were noted when values fell outside one standard deviation of the mean. These deviations from the mean were evaluated based on distance of the passing ship, and characteristics of the animals, prey source, and ship-type.

When multiple ship passages occurred within 1- hour, dive behaviors were compared using a random intervention analysis (RIA; Box and Tiao, 1975; Carpenter *et al.*, 1989) implemented in *MATLAB* (R2010b). Statistical tests like RIA do not rely on a random sampling assumption, do not require that data are sampled from a specific probability distribution, and allow valid statistical inference from small data sets, as is the case in this study. The ability to detect a change decreases with sample size- less than 30 samples are not recommended (Carpenter *et al.*, 1989). This approach facilitates the analysis of studies that include unreplicated or non-randomly selected treatments, using a before-after sampling coupled with computerintensive permutations of the data. The basic analysis subtracts the mean before intervention, from the mean after the intervention. This difference statistic is evaluated against many (*i.e.,* 100,000) possible sequences of before-after differences, by randomly shuffling the data and recalculating the difference statistic. A result is deemed significant if the probability of obtaining the difference statistic is less than 5%. Essentially, this test confirms whether a difference in samples collected before and after intervention is greater than expected by chance, but it does not confirm that the intervention was the cause of the change (Carpenter *et al.*, 1989).

Ship Information

Ship locations were monitored using a real-time Automatic Identification System (AIS) receiver installed aboard the tagging boat and from a shore station near Santa Barbara. Ships over 300 GT are required to transmit information on their position, speed, and unique identification information via AIS (Tetreault, 2005). The shore station provided the entirety of the ship passage in the region. The boat-mounted AIS provided real-time information to the tagging team on the closest point of approach to the tagged whale and the speed and track of the approaching vessel.

Measurement of underwater noise radiated from passing ships on the B-probe was only possible in specific conditions, given the high levels of flow noise generated as the whale moved through the water. Flow noise masked noise produced by passing ships, unless the ship was at close ranges (<200 m) and the animal was engaged in low flow behaviors (*i.e.,* after a deep lunge). Ship source levels were, therefore, estimated from seafloor instruments (Fig. 7. 1. HARP) in the area (for description of methods see McKenna *et al.*, submitted).

Results

Eight close approaches (CAs) of large commercial ships at distances less than 3,600 m were observed for five individual blue whales engaged in deep-lunge foraging (Fig. 7.1; Table 7.1). The transiting ships were either large container ships or vehicle carriers, travelling at speeds of 7 ms^{-1} (14 knots) to 12 ms^{-1} (23 knots). Ship source levels estimated from the seafloor instrument were higher for the container ships (180-185 dB 1 μPa) compared to the vehicle carriers (175 dB 1 μPa; Fig. 7.2), as found in previous research (McKenna *et al.*, submitted).

There were two main regions in the SBC where the close approaches occurred, north of Santa Cruz Island (SCI) and near Hueneme Canyon (HC). In 2008, three of the CAs occurred where the 200 m bathymetric contour intersected with the southbound shipping lane, north of SCI (SCI; Fig. 7.1). On two separate days (14 and 16 August 2008), two pairs of blue whales were observed foraging in this region. The trail animal of one pair and the lead of another were tagged (Table 7.1). The sex of these animals was undetermined, but based on previous research, the lead animals are usually female and the trail animals are male (Oleson *et al.*, 2007). Krill patches were confirmed at this location during the deployments and the main concentration was at 150-200 m.

Five of the CAs occurred near HC, where the northbound shipping lane intersects the canyon (Fig. 7.1). On three separate days in 2009 (4 and 5 August and 16 September), foraging blue whales were tagged. The tagged animals included the trail of a pair (likely a male), a single female animal, the trail of a pair (male), and the lead of a pair (female) (Table 7.1). Patches of krill concentrated near the bottom (300 m) were confirmed with a 200 kHz depth sounder.

Tag attachment time varied; therefor the total number of deep-dives differed for each animal (Table 7.1). Kinematic behaviors right after the close approach were compared to all other dives in the sequence and to previously reported averages. Differences from the mean for dive duration, number of lunges, surface time, and number of breaths were observed (Figures 7.3 and

7.4) and in some cases the behaviors were one standard deviation from the mean. Only one deployment (16 August 2009) had enough dives (n=36) before and after the close approach to perform the RIA (Fig. 7.5).

Observed behavioral changes

The closest approach (1,300 m) with a 63 kGT vehicle carrier occurred when the animal was at the bottom of a foraging dive (252 m). All dives in this deployment were deeper than those reported by Goldbogen *et al.* (2011); therefore all the dives in the series, including the one at the CA, had a maximum depth, gliding percentage of the decent, and time to ascend that were greater than previously reported averages. During the dive and the subsequent surface period when CA occurred a faster descent speed was observed, but there was no change in the number of lunges, surface time or number of breaths compared to stereotyped dives or the other dives in the individual deployment (Fig. 7.3B-D).

Two CAs occurred during a single tag deployment on 16 August 2008: a 38 kGT vehicle carrier passed at 690 m when the animal was at the surface, and a 75 kGT container ship passed 58 minutes later at a distance of 197 m when the animal was descending on a deep dive. The surface time and the number of breaths right after both CAs and the next surfacing period were greater than the maximum observed during stereotyped deep foraging dives (Fig. 7.3C&D), and the longest surfacing periods observed in the entire dive profile for this individual (Fig. 7.4C; Fig. 7.5). The dive time and number of lunges were lower during the CAs compared to the average of the entire deployment (Fig. 7.3A&B), but not significantly different from the other dives in the profile, based on the RIA analysis. The RIA resulted in two behaviors, surface time ($p<0.01$) and descent angle ($p<0.02$), that were statistically different during the two close approaches (6 dives) compared to before (17 dives) (Fig. 7.5). An almost significant increase ($p=0.06$) in descent speed was also observed. Compared to the stereotyped deep foraging dives, all dives in this deployment had longer surface times, greater number of breaths, and greater ascent time. The dive time, number of lunges, and maximum depth were all similar to previous studies.

The blue whales observed near HC foraged at depths of 300 m, greater than SCI and previous studies; therefore some of the deep diving characteristics deviated from those previously reported (*i.e.,* maximum dive depth, proportion of decent spent gliding, dive time and descent time). One interesting pattern observed in these deep foraging animals was a significant increase in the proportion of gliding during descent, as predicted by a decrease in buoyancy with depth.

A close approach at a distance of 1,000 m occurred while an animal was at the surface, just after a deep dive (Table 7.1). Slightly fewer lunges were observed during that dive, although within the range of stereotyped deep-foraging dives and the other dives in the deployment (Fig. 7.3B). Unfortunately, the tag fell off at the end of the next surface period after the close approach, so it was difficult to evaluate any changes in surface behavior after the CA. Calls were detected on this tag, with received levels high enough to suggest that they were from the tagged animal. The calls occurred during the surface periods, at depths of 20-25 m. When the ship approached, there was no change in the rate or received levels of the calls (Fig. 7.6).

Two close ship approaches occurred with a single female foraging at HC. The first close approach with a 54 kGT container ship occurred at a distance of 300 m when the animal was on the ascent after a deep foraging dive (Table 7.1). The dive profile of this animal included a variety of deep dive types: both dives with no lunges and longer dives with lunges. During the dive before the close approach, only one lunge was observed (below average), and the ascent angle was more gradual (29 degrees compared to an average of 53 degrees). In addition, the time spent at the surface and the number of breaths both increased after the close approach, compared to the stereotyped dive and mean of all the dives in the deployment (Fig. 7.3C&D). Calls were detected on this tag, although likely from another animal based on the call received levels.

The trail animal of the near-by pair was at depth during this same ship passage (54 kGT container ship), at a distance of 55m at CA. The surface period after the close approach was shorter than the mean of all the dives, opposite to the pattern observed for the other individuals (Fig. 7.3C&D). However, during the next surfacing, a longer surface period and more breaths were observed (Fig. 7.3C&D).

The second close approach (3,600m) of the single whales was a 40 kGT vehicle carrier and passed when the single animal was ascending from a deep dive. At this distance, the dive time and number of lunges were above average and there was no difference in the surface time or the number of breaths (Fig. 7.3C&D).

During the close approach (900 m) of a 10 kGT Roro ship, the foraging dives did not deviate from the stereotyped deep-foraging dive or any of the other dives in the deployment (Fig. 7.3). As seen with other animals foraging at deeper depths, more gliding on the descent was observed.

Discussion

This study identified behavioral responses of foraging blue whales to transiting vessels; the consequences of the observed disturbances are discussed below. The observed responses were dependent on the distance to the passing ship. At distances less than 900 m- changes in surface and dive behaviors were found. All whales analyzed were engaged in deep-foraging during the passages of known ships; however, detecting change in behavior is complicated by short-term variability in dive behaviors, potentially unrelated to the disturbance. The grouping category of the animals varied (lead, trail, and single). Repeated samples in each of these categories are needed to fully detect alterations in behaviors related to ship passage. Although the prey source was qualitatively confirmed, it was not possible to quantify differences in patch quality or species composition, which might influence foraging behavior. The discussion that follows is considered preliminary but provides insights for better understanding the potential impacts of anthropogenic activities.

Increased Surface Time and Foraging Efficiency

Whales foraging in close proximity to passing ships spent an increased amount of time at the surface, a similar short-term response observed in foraging right whales to an acoustic alarm stimulus (Nowacek *et al.*, 2004). The biological explanation for increased surface time is unknown, but might be a response to a perceived threat or a movement to escape the most intense ship noise, since the surface is a location of reduced sound-pressure levels (Gerstein *et al.*, 2005). Increased number of breaths during the extended surface period suggests a recovery to a stressful event, although heart rate and glucocorticoid hormones are more accurate measurements of stress response (Reeder and Kramer, 2005).

Regardless of the explanation for the change, increased surface time directly reduced the amount of time the whales spent foraging, representing a negative energetic gain to the animals. This cost can be estimated based on the additional time spent at the surface during the close approach, and average number of lunges per dive time. For example, the 197 m CA resulted in an additional 10.5 minutes spent at the surface, compared to the average surface time (Fig. 7 3C). For this animal the average frequency of lunges per dive was 0.77 lunges per minute (3 lunges per dive; 3.9 minutes bottom time). Increasing the time spent at the surface by 10.5 minutes, would result in 3.7 fewer possible lunges. Multiply that by the average number of ships that pass through the region during the day (4) and foraging close to a major shipping lane results in a 14% decrease in foraging time.

A decrease in the number of lunges was also observed after the passage of the ship (Fig. 7. 3B), further decreasing foraging time. Goldbogen *et al.* (2011) emphasized the importance of prey density on foraging efficiency to maintain large body size and high rates of lipid deposition. This study highlights that disturbance from ships can also decrease foraging efficiency, assuming the quality of the patch did not decrease during the passage of the ships.

Increased surface time or decreased number of lunges was not observed after the close approach at 55m, although the next surfacing was10 minutes above the mean. In this example, another tagged single whale was exposed to the same ship passage at a distance of 300 m and an increased surface period was observed. This difference in response to the same ship passage suggests that difference is related to the individual whale, not specific characteristics of the passing ship. This whale was a trail animal in a pair and possibly engaged in calling behaviors based on the presence of shallow dive bouts in between the deep foraging dives (Oleson *et al.*, 2007). Unfortunately, this whale was not tagged with an acoustic recorder; therefore it is not possible to verify calling behavior.

Response as a Function of the Range to a Ship

Although the most common response to close approaching ships was an extended surface periods, the response decreased with distance from the ship passage. Ships passing at distances greater than 900 m did not elicit a response by the whale. The intensity of ship noise would decrease as a function of range. Using a simple spherical spreading model the levels would decrease by at least 60 dB, resulting in received sound levels of 125 dB re 1µPa for container ships and 118 dB re 1µPa for vehicle carriers at a 1,000 m range. A possible explanation for the decrease in response with distance is that the animals are habituated to the presence of lower levels of vessel noise, particularly when foraging in high vessel traffic areas (Nowacek *et al.*, 2004). Furthermore, foraging at depth is energetically costly, particularly if a certain frequency of foraging events are not maintained (Goldbogen *et al.*, 2011).

Even though whales at distances greater than 900 m did not show a clear behavioral change physiological responses are possible. Physiological changes observed in other species exposed to disturbance from human activity have ranged from increased heart rate (McArthur *et al.*, 1982; Knight, 1995; Weisenberger *et al.*, 1996; Weimerskirch *et al.* 2002) and adrenocortical stress response (Fowler, 1999; Wasser *et al.*, 2000) to hearing loss (Erbe, 2002; Richardson, 1995; Smith *et al.*, 2004). All these potential responses would have significant implications for the survival of the individual and the population foraging in an environment with pervasive ship noise. Measuring such changes in physiological response is an important direction for future work.

Primary Foraging Habitat in Areas of High Ship Traffic

Behavioral responses to human disturbances are context dependent and individual responses depend on trade-offs related to the individual and the behavioral state (Gill, 2007). The consequence of human disturbance at the individual level and how it translates to population-scale impacts depends on the scale at which the disturbance occurs (*e.g.* proportion of population effected, quality of habitat affected) and the density dependence operating within the populations (Gill *et al.*, 2001). Blue whales were found foraging in areas of high ship traffic densities. A large portion of the North Pacific blue whale population returns to this region every year to forage on an abundance of krill (Calambokidis and Barlow, 2004).

The lack of apparent spatial response of foraging blue whales to environments with high levels of human activity suggests a higher vulnerability to the potential impacts of ships (*e.g.*

short-term disturbances, long term changes in fitness, risk of ship strike). Strong spatial avoidance of human presence are often considered good measures of relative susceptibility of a species; however not leaving an area of high impact might also indicate the susceptibility of a species (Gill *et al.*, 2001). The choice to stay or leave an area will be dependent on the quality of the area, availability of resources, and the predation risk. On a population level, if little suitable habitat is available elsewhere, constraining animals to disturbed areas, and the fitness costs to the animals are high the threat to the populations is the greatest (Gill *et al.*, 2001). Accurately quantifying the resource quality for the region is necessary to evaluate the availability of food in relation to shipping lanes.

Conclusion

Behavioral responses of blue whales to the close proximity of transiting ships were observed, suggesting a decrease in foraging efficiency and increase in the risk of ship strike. The response was dependent on the distance to the vessel- no behavioral response was observed at ranges greater than 900 m. Implications for the population survival might be high given that these animals continue to forage in highly disturbed regions, particularly if resource quality is inadequate in undisturbed regions. Behavioral responsiveness to disturbances in some cases is not sufficient to determine vulnerability to human presence, as the same response can result directly from opposing circumstances or different responses are possible from the same disturbance. Further research addressing these confounding situations is needed to quantify the fitness consequences of the blue whale response to large ships.

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Chapter 7, in full, is currently in preparation for submission. McKenna, M.F., Calambokidis, J., Goldbogen, J.A., and Oleson, E.M. The Response of Deep-Foraging Blue Whales to the Presence of Large Ships. The dissertation author was the primary investigator and author of this material.

Table 7.1: Summary of ship close approaches (? sex not verified with genetics, * indicates a calling animal, ** Ship source level in units of dB re 1μPa^2 (20-1,000 Hz)).

Close approach				Tag Deployment					Vessel Characteristics				
Distance (m)	***Time (local)***	***Group Type***	***Depth***	***Date***	***Latitude***	***Longitude***	***Duration (hour:min)***	***Number of dives***	***Type***	***Source Level*****	***GT***	***Length (m)***	***Speed (ms^{-1})***
2008- North Santa Cruz Island													
1,300	15:44	trail *(male?)*	252 *(bottom)*	14-Aug-08	34º09.05N	119º51.38W	01:37	7	vehicle carrier	~180	62,510	200	10.1
690	16:00	lead *(female?)*	6 *(surface)*	16-Aug-08	34º06.7N	119º37.8W	10:36	36	vehicle carrier	182.0	38,349	188	8.9
197	16:58	lead *(female?)*	151 *(descent)*	16-Aug-08	34º06.7N	119º37.8W	10:36	36	container ship	186.1	75,484	300	11.9
2009- Hueneme Canyon													
1,020	16:45	trail *(male?)*	10 *(surface)**	4-Aug-09	34º03.07N	119º14.18W	02:51	9	vehicle carrier	180.6	42,447	184	6.8
55	11:25	trail *(male)*	4 (surface)	5-Aug-09	34º02.73N	119º13.04W	06:11	17	container ship	184.4	54,152	294	0.0
300	11:25	single (female)	212 *(ascent)*	5-Aug-09	34º03.56N	119º13.66W	04:27	9	container ship	184.4	54,152	294	9.1
3,600	12:30	single (female)	157 *(ascent)*	5-Aug-09	34º03.56N	119º13.66W	04:27	9	vehicle carrier	~180	39,422	177	7.2
900	18:33	lead *(female)*	195 *(bottom)*	16-Sep-09	34º03.22N	119º13.39W	06:59	13	roro	~180	9,859	150	8.8

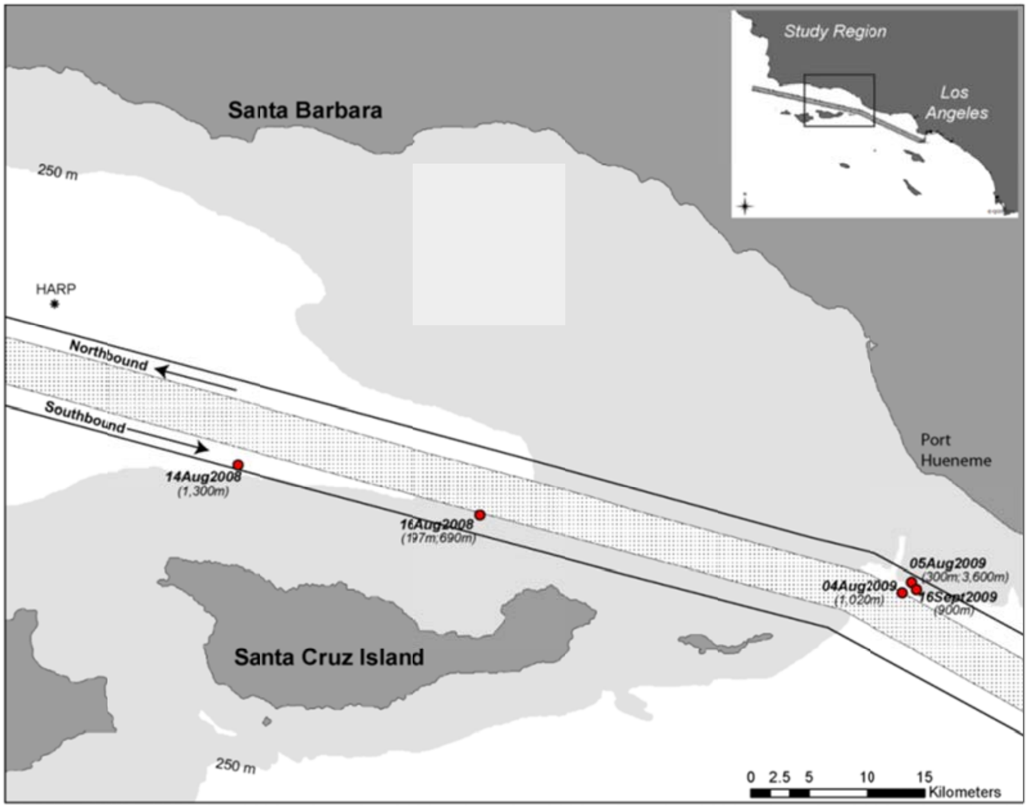


Figure 7.1: Map of the study region and location of close approaches in the SBC. HARP (*) indicates the position of the seafloor acoustic recorder used to measure ship noise.

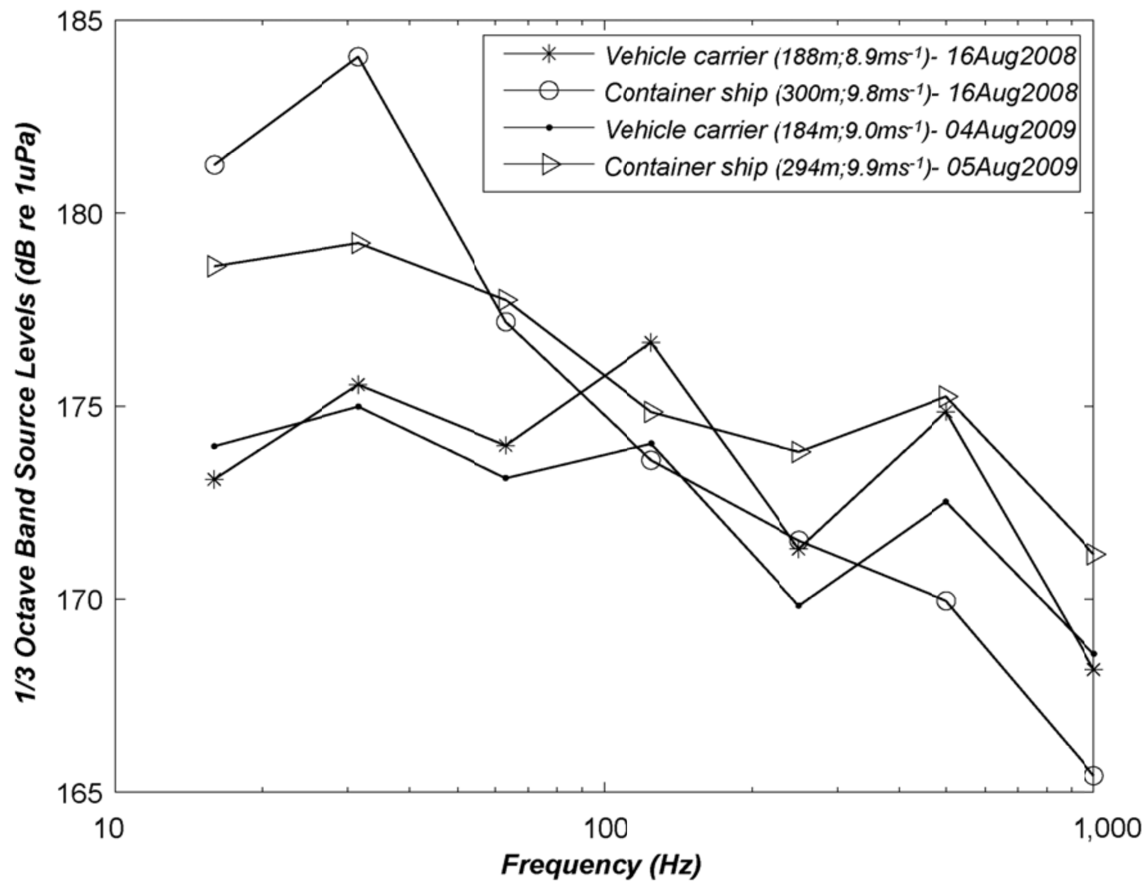
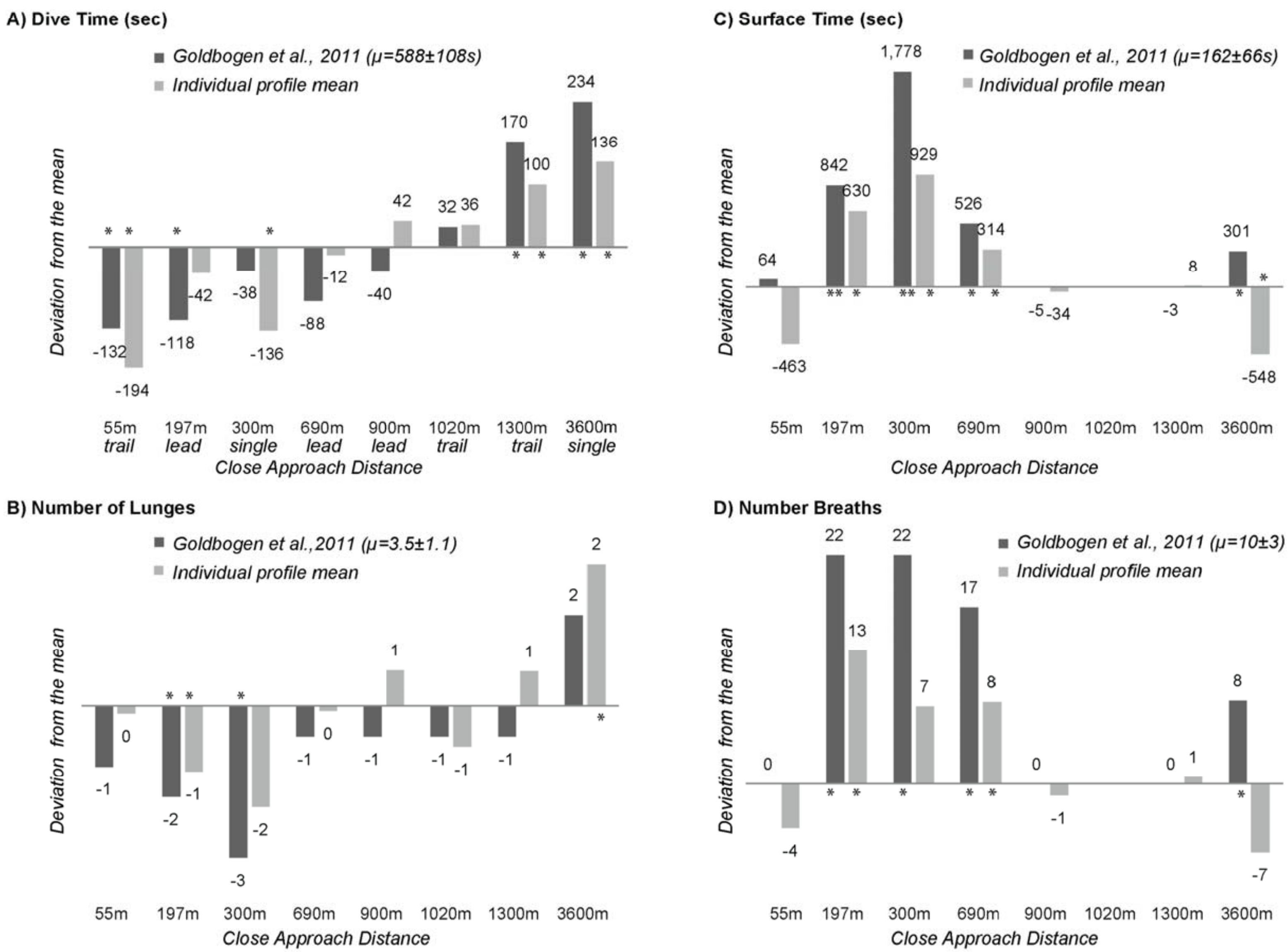


Figure 7.2: 1/3 Octave band source level estimates for the commercial ships that came in close proximity to foraging blue whales. Received levels were measured on a nearby seafloor acoustic recorder (HARP) and source levels were estimated using a spherical spreading model.

Figure 7.3: Deviations in behavior during the close approaches at various distances. The dive sequence and surface period closest to the time of close approach are shown. Four behavior parameters are plotted A) dive time (seconds); B) number of lunges; C) surface time (seconds); and D) number of breaths. Both deviations from typical deep foraging dives presented in Goldbogen *et al.*, 2011 and deviations from the mean of all the dives in the individual whale's dive profile are shown (*, ± one standard deviations of the mean; **greater than the maximum behavior observed in Goldbogen *et al.*, 2011).



A) Dive Time (sec)
Goldbogen et al., 2011 (μ=588±108s)
Individual profile mean
Deviation from the mean
-132 -194 -118 -42 -38 -136 -88 -12 -40 42 32 36 170 100 234 136
55m trail
197m lead
300m single
690m lead
900m lead
1020m trail
1300m trail
3600m single
Close Approach Distance
B) Number of Lunges
Goldbogen et al.,2011 (μ=3.5±1.1)
Individual profile mean
Deviation from the mean
-1 0 -2 -1 -3 -2 -1 0 -1 1 -1 -1 -1 1 2 2
55m 197m 300m 690m 900m 1020m 1300m 3600m
Close Approach Distance
C) Surface Time (sec)
Goldbogen et al., 2011 (μ=162±66s)
Individual profile mean
Deviation from the mean
64 -463 842 630 1,778 929 526 314 -5 -34 8 -3 301 -548
55m 197m 300m 690m 900m 1020m 1300m 3600m
Close Approach Distance
D) Number Breaths
Goldbogen et al., 2011 (μ=10±3)
Individual profile mean
Deviation from the mean
0 -4 22 13 22 7 17 8 0 -1 0 1 8 -7
55m 197m 300m 690m 900m 1020m 1300m 3600m
Close Approach Distance

Figure 7.4: Deviations in behavior as a function of time from close approach for individual whales. Four behaviors are plotted A) dive time (seconds); B) number of lunges; C) surface time (seconds); and D) number of breaths. The symbol shape indicates the distance a close approach and the color represent the individual whale (*i.e.,* blue symbols are from the same whale).

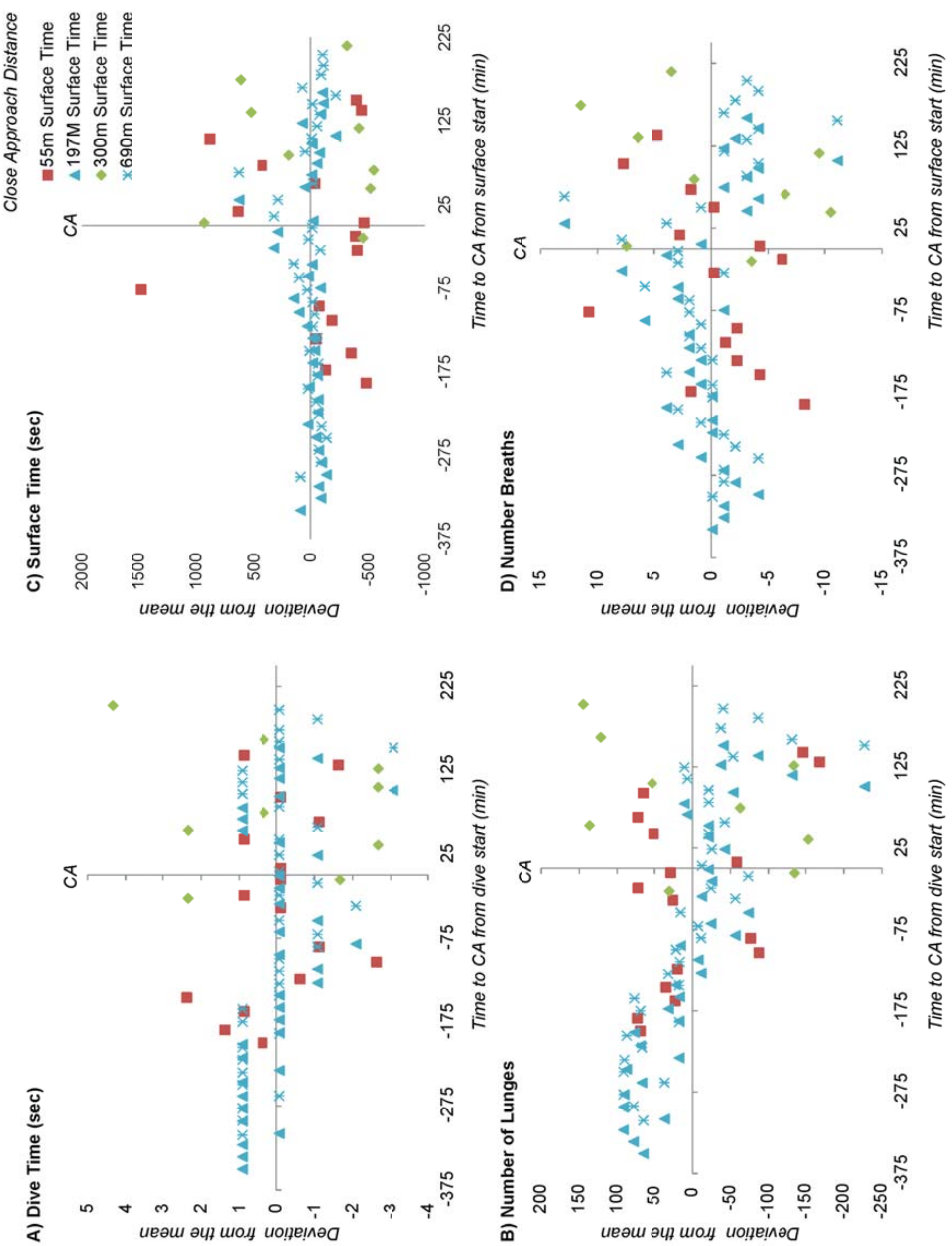
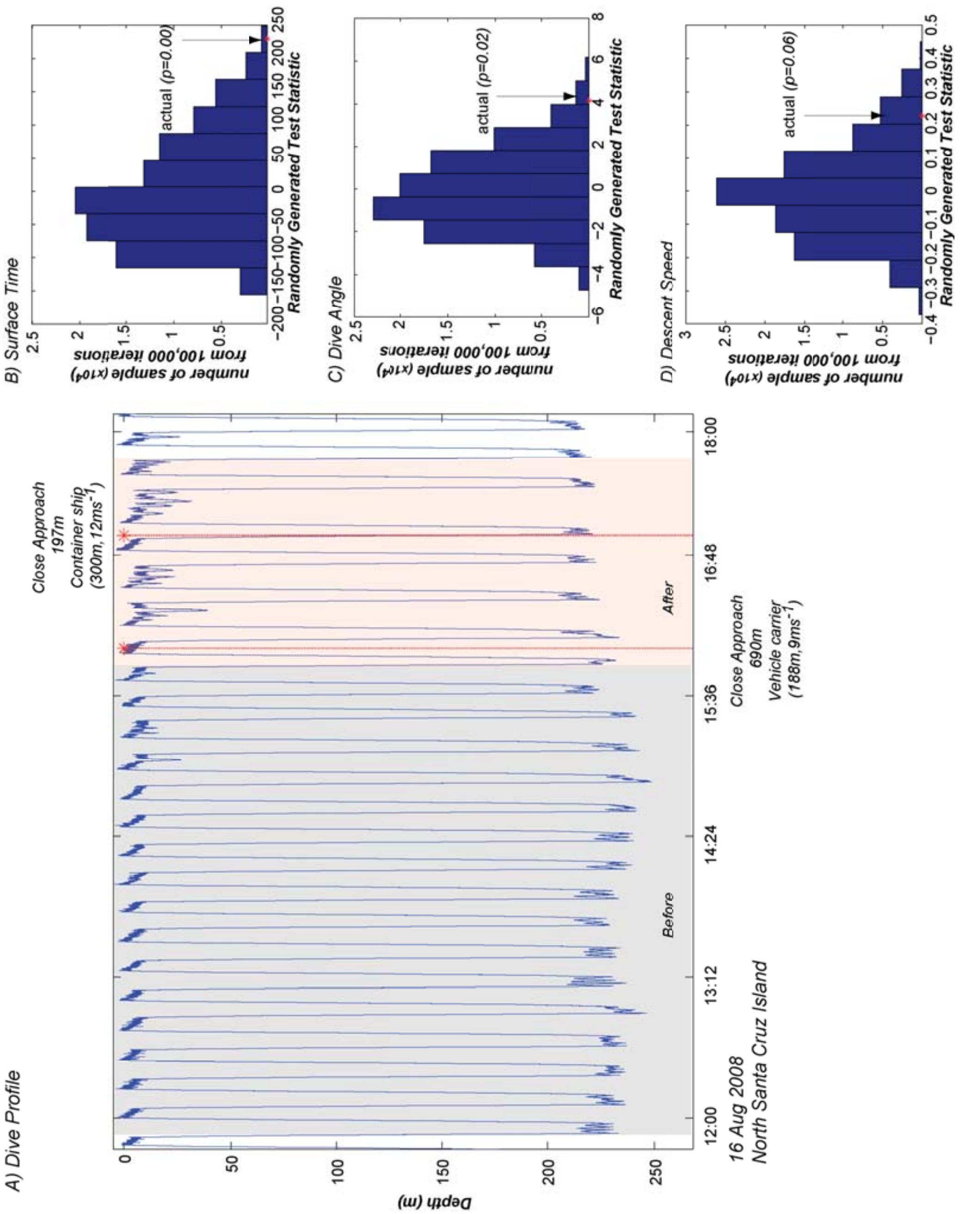

A) Dive Time (sec)
B) Number of Lunges
C) Surface Time (sec)
D) Number Breaths
Deviation from the mean
CA
Time to CA from dive start (min)
Time to CA from surface start (min)
Close Approach Distance
55m Surface Time
197M Surface Time
300m Surface Time
690m Surface Time

Figure 7.5: Random Intervention Analysis of close ship approach. A) Dive profile of deep-foraging blue whale and timing of the close approaches of two ships. The shaded areas correspond to the two time periods used in the RIA; B) RIA results for surface times; C) RIA results for dive angle; D) RIA results for descent speed. The red stars indicate the position of test static relative to the 100,000 randomly generated test statistics.


A) Dive Profile
Depth (m)
16 Aug 2008
North Santa Cruz Island
Before
After
Close Approach
197m
Container ship
(300m, 12ms^-1)
Close Approach
690m
Vehicle carrier
(188m, 9ms^-1)
B) Surface Time
C) Dive Angle
D) Descent Speed
number of sample (x10^4)
from 100,000 iterations
Randomly Generated Test Statistic
actual (p=0.00)
actual (p=0.02)
actual (p=0.06)

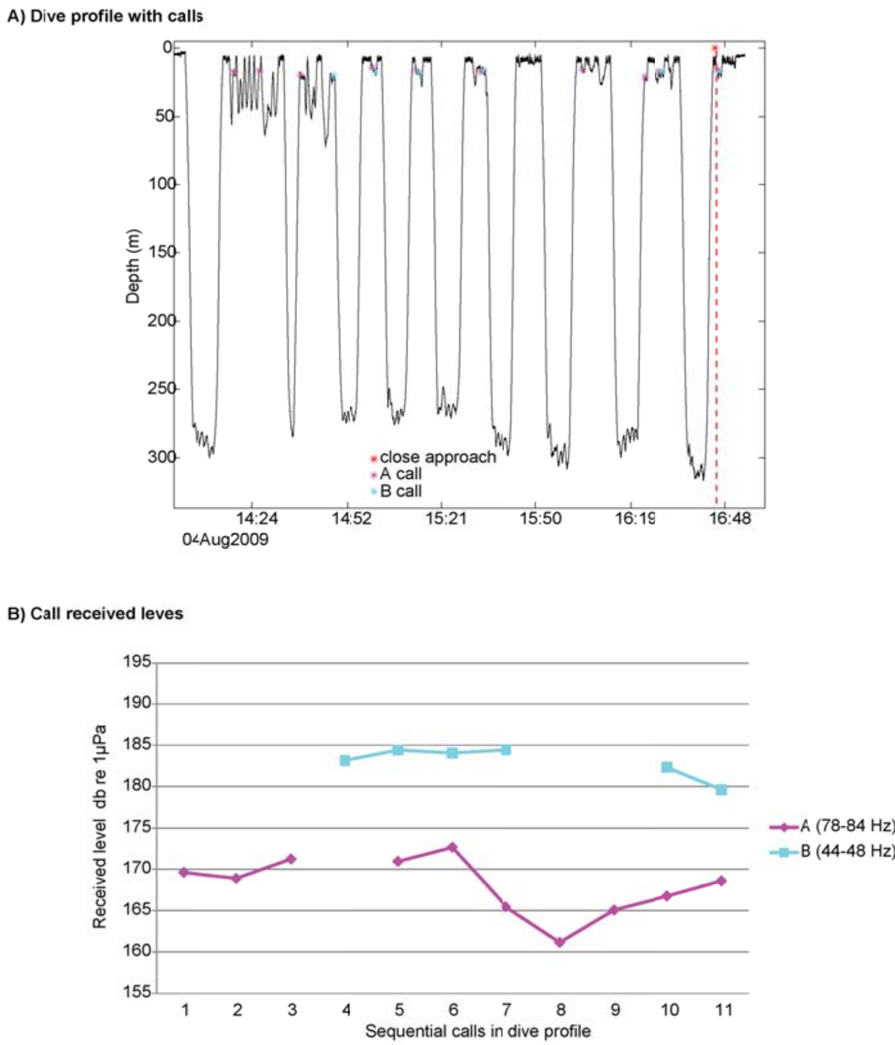


Figure 7.6: Whale calling behavior during the close approach of a ship. A) Dive profile of calling whale with depths of calls indicated. B) RL of calls measured on the tag.

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