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Assessing the risk of chronic shipping noise to baleen whales off Southern California, USA

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ABSTRACT: Low-frequency noise that is part of the acoustic environment for baleen whales has increased in many areas of the Northeast Pacific Ocean that contain whale habitat. We conducted a spatially explicit risk assessment of noise from commercial shipping to blue, fin, and humpback whale habitats in Southern California waters and explored how noise is affected by several place-based management techniques: a National Marine Sanctuary, an Area to be Avoided (ATBA), and a Traffic Separation Scheme (TSS). We used shipping data to model noise at 2 frequencies that are part of the acoustic environment for these species and capture the variable contributions from shipping to noise. Predicted noise levels in Southern California waters suggest high, region-wide exposure to shipping noise. Our risk assessment identified several areas where the acoustic environment may be degraded for blue, fin, and humpback whales because their habitat overlaps with areas of elevated noise from shipping traffic and 2 places where blue and humpback whale feeding areas overlap with lower predicted noise levels. One of the places with lower predicted noise occurs in the Channel Islands National Marine Sanctuary (CINMS). Noise has not been directly managed within the CINMS; instead, reduced noise in this portion of the CINMS is likely an ancillary benefit of the ATBA surrounding most of the Sanctuary. Areas of elevated noise in the CINMS also occur, primarily where a TSS intersects the Sanctuary's boundaries. Our risk assessment framework can be used to evaluate how shipping traffic affects acoustic environments and explore management strategies.

KEY WORDS: Anthropogenic noise · Risk assessment · Habitat modeling · Automatic Identification System (AIS) data · Commercial shipping

INTRODUCTION

Ocean noise produced by human activities has significantly increased since the beginning of the industrial era, although the changes in ocean noise have not been evenly distributed in space and time. Analyses of data collected between 2004 and 2012 at 2 locations that are not near major shipping lanes (one in the equatorial Pacific Ocean and one in the South Atlantic Ocean) showed decreases in the

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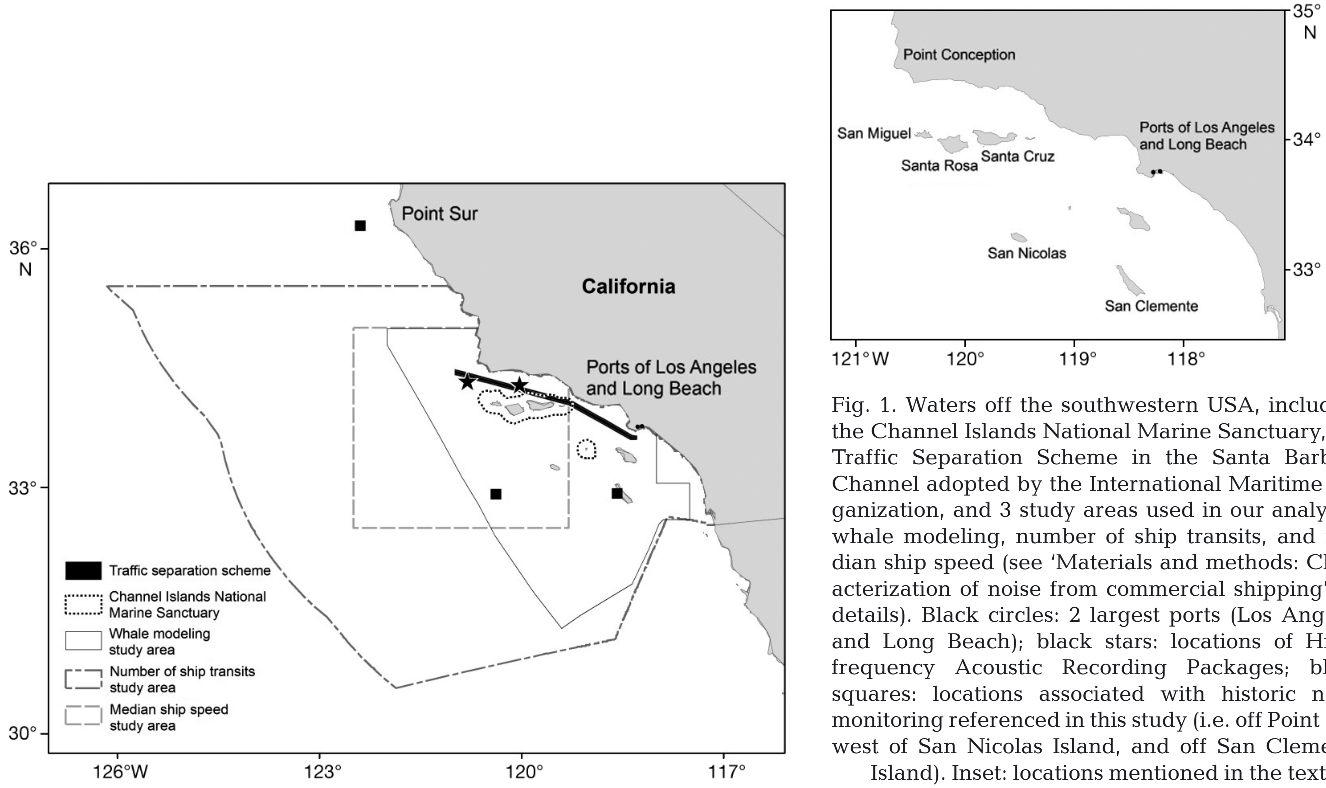


Fig. 1. Waters off the southwestern USA, including the Channel Islands National Marine Sanctuary, the Traffic Separation Scheme in the Santa Barbara Channel adopted by the International Maritime Organization, and 3 study areas used in our analyses: whale modeling, number of ship transits, and median ship speed (see 'Materials and methods: Characterization of noise from commercial shipping' for details). Black circles: 2 largest ports (Los Angeles and Long Beach); black stars: locations of High-frequency Acoustic Recording Packages; black squares: locations associated with historic noise monitoring referenced in this study (i.e. off Point Sur, west of San Nicolas Island, and off San Clemente Island). Inset: locations mentioned in the text

ambient sound floor and other sound level parameters (Miksis-Olds & Nichols 2016). In contrast, low-frequency noise has increased in the Northeast Pacific Ocean since the 1960s (Andrew et al. 2011, Chapman & Price 2011) and in the Indian Ocean over the last decade (Miksis-Olds et al. 2013). The increase in low-frequency noise observed in both locations has been linked to increases in shipping. Frisk (2012) used ambient noise measurements from the Northeast Pacific Ocean that span several decades and ambient noise measurements from areas in the South Pacific Ocean with extremely low shipping traffic to provide a theoretical explanation for the increases. He showed that the increase can be attributed primarily to commercial shipping and that shipping is linked to the global economy.

Ambient noise measurements in Northeast Pacific Ocean have also been used to assess spatial and temporal variability in noise. In particular, long-term changes (30 to 50 yr) in low-frequency noise have been observed at several locations off the coast of California (Fig. 1). At 2 sites that occur in deeper waters beyond the continental margin (one off Point Sur and one off San Nicolas Island), noise increased at approximately 3 dB re 1 μPa per decade in the 30 to 50 Hertz (Hz) band (Andrew et al. 2002, McDonald et al. 2006). This increase is likely representative of noise increases in the Northeast Pacific Ocean deep sound channel caused by increasing commercial shipping, including both increases in the number of ships and increases in their gross tonnage and horsepower (McDonald et al. 2006). Although the change in noise at these 2 sites was similar, the 4 to 8 dB higher noise levels at Point Sur than at San Nicolas Island are likely caused by the closer proximity of the Point Sur site to major shipping lanes (McDonald et al. 2006). In contrast, noise measured during periods with no local ship traffic did not change between the 1960s and the 2000s at a site near San Clemente Island, which is on the continental shelf (in waters 110 m deep) and is not directly on a commercial shipping lane. These results suggest that noise at this site is influenced more by wind, biological sources, and local shipping than distant shipping noise from the deep sound channel (McDonald et al. 2008). More recent measurements of noise (i.e. 1994 to 2007) at Point Sur and San Nicolas Island show that low-frequency noise levels are remaining constant or slightly increasing, with one exception of decreasing levels of 50 Hz noise at Point Sur (Andrew et al. 2011).

The noise monitoring locations in the Northeast Pacific Ocean overlap with important habitat for baleen whales. In particular, blue whales feed in Southern California waters from June to October (Calambokidis et al. 2015), humpback whales feed in these waters from March to November (Calambokidis et al. 2015), and aggregations of fin whales have been observed in these waters year-round (Forney et al. 1995). A 7 yr summary of blue and fin whale calls in Southern California waters detected blue whale 'B calls' (tonal calls with a downsweep in frequency) between June and January, with a peak in September (Sirović et al. 2015). The 'B calls' are 1 of 3 blue whale call types recorded in the Southern California Bight (Sirović et al. 2015). Series of 'A calls' (a series of rapid, low-frequency pulses) and 'B calls' (~16 Hz) are believed to serve a reproductive function (Oleson et al. 2007). Blue whale 'D calls' are more variable in their characteristics (~25 to 90 Hz) and are believed to serve a social function (Oleson et al. 2007). Fin whale 20 Hz calls (downsweep pulses produced in regular or irregular sequences, with regular sequences attributed to males) were detected year-round, but detection levels were highest between September and December, with a peak in November (Sirović et al. 2015). Humpback whale calls (~150 to 1800 Hz) have also been recorded in these waters over much of the fall, winter, and spring (Helble et al. 2013).

Blue whales and fin whales are currently listed as endangered under the US Endangered Species Act (ESA) 1973 and as 'depleted' and 'strategic' under the US Marine Mammal Protection Act (MMPA) 1972, as is a segment of the humpback whale population that feeds off the US West Coast. Although populations of fin whales along the California coast have been increasing since at least 1991 (Moore & Barlow 2011) and Monnahan et al. (2015) suggest that blue whales may have reached carrying capacity, all 3 species still face threats from ship strikes, entanglements, and anthropogenic noise. While poorly understood, use of sound by baleen whales is assumed to include, but not be limited to, hearing conspecific calls. In particular, baleen whales are believed to rely on low-frequency sounds for feeding, breeding, and navigation. The potential effects of noise on baleen whales have been recognized for over 40 yr (Payne & Webb 1971) and more recently, behavioral responses to shipping noise have been documented for all 3 species (e.g. Sousa-Lima & Clark 2008, Castellote et al. 2012, Melcón et al. 2012). Low-frequency noise can also result in acoustic masking, which impedes an individual's ability to effectively perceive, recognize, or decode sounds of interest (Clark et al. 2009); consequently, areas with elevated noise may represent degraded acoustic environments. The large noise increases in the Northeast Pacific Ocean have occurred within the lifetime of these baleen whales and at frequencies that form an important part of their acoustic environment.

Southern California waters were among the first areas identified in national and international discussions of management techniques to reduce chronic underwater noise impacts because the Ports of Los Angeles and Long Beach (Fig. 1) are ranked among the nation's largest for both the number of port calls and cargo capacity (MARAD 2014). The Channel Islands National Marine Sanctuary (CINMS) is located within these waters (Fig. 1) and has been a particular focus of these discussions because US National Marine Sanctuaries have unique mandates associated with managing designated areas of the marine environment. For example, CINMS regulations prohibit taking (e.g. harassing, harming, capturing, or killing) any marine mammal within the Sanctuary, except as authorized by the MMPA and the ESA. An evaluation of noise impacts in the CINMS was completed in partnership with the Office of National Marine Sanctuaries (Polefka 2004) and was followed by a formal presentation of CINMS as a policy case study to examine methods for reducing shipping noise impacts (Haren 2007). Haren (2007) concluded that pursuit of sanctuary authority to regulate noise would face obstacles and would not address the influence of shipping noise beyond the boundary of the CINMS. Haren (2007) also noted that it is possible for the US Government to request that the International Maritime Organization (IMO) designate the CINMS and surrounding areas as a Particularly Sensitive Sea Area (PSSA). A PSSA is an area that needs special protection because of its significance and vulnerability to shipping. Management measures associated with the PSSA could require or recommend that ships operate in a manner that reduces noise (e.g. travel at slower speeds or use alternative shipping routes). A better understanding of the risk of noise to marine species in this region is needed to define specific management measures (e.g. seasonal or dynamic slow speed zones and alternative shipping routes).

Estimates of the loss of acoustic communication space can be a valuable tool for assessing risk caused by low-frequency, chronic noise (Clark et al. 2009, Hatch et al. 2012). Spatially explicit risk assessments have also been conducted using spatial representations of species habitats and underwater noise generated by human activity. For example, Erbe et al. (2012) mapped cumulative underwater acoustic energy from shipping using a simple sound transmission model and Automatic Identification System (AIS) data. Erbe et al. (2014) combined these data with distribution maps for 10 species (including dolphins, porpoises, baleen whales, and pinnipeds) using audiogram weighting across a range of frequencies to identify species-specific hotspots of ship noise. Williams et al. (2015) used the same data and approach, but identified important species habitats that occur in areas with little noise.

We conducted a spatially explicit assessment of the risk of noise from commercial shipping to blue, fin, and humpback whale habitats in Southern California waters. We used AIS data to model noise at 2 frequencies that are part of the acoustic environment for these species and capture the variable contributions from shipping to noise. In particular, we selected 50 Hz to represent a peak in the contribution from shipping to noise and 100 Hz to represent the point at which contributions from shipping to noise begin to diminish (National Research Council 2003). Predicted noise was compared to noise measurements at 2 sites within the study area.

Our analyses focused on the contribution of shipping to noise in baleen whale habitats, rather than focusing on masking of specific communication signals (e.g. the techniques used by Clark et al. 2009 and Hatch et al. 2012). We assume that these species are using low frequencies for a variety of biological functions (feeding, breeding, and navigation) and that they can be broadly impacted by noise occurring at low frequencies. Our analyses identified areas where species habitat (defined using 3 sources of distribution data that capture different habitat elements) overlaps with low-frequency noise created by commercial shipping. Due to their extreme low-frequency calling activity, we assessed risk, or potential for degradation of the acoustic environment, for fin and blue whales using our lower, 50 Hz modeled noise. Our slightly higher 100 Hz modeled noise was used to assess risk to humpback whales because it better reflects frequencies used in their vocal repertoires. These noise and risk characterizations allow managers and stakeholders to identify areas where chronic noise may impact the acoustic environment of these 3 species in Southern California waters. Specifically, our assessment identified hotspots of noise in species habitats, similar to Erbe et al. (2014), and areas within species habitats that are quiet, similar to Williams et al. (2015).

MATERIALS AND METHODS

Characterization of noise from commercial shipping

The noise modeling approach that we used is described in Porter & Henderson (2013) and is briefly reviewed here. This approach was used in the NOAA Fisheries CetSound project (http://cetsound.noaa.gov), but our models used higher resolution shipping information obtained from AIS data (see below). Noise modeling requires environmental information, such as bathymetry, bottom type, and sound speed. These data are used to calculate transmission loss for noise sources distributed on a grid of the study area. Noise level is then calculated by convolving the transmission loss with source level densities estimated for specific activities (e.g. shipping, pile driving, or sonar). This 2-stage approach provides a mechanism for quickly updating noise predictions to reflect changes in source level densities. Our models currently only include noise produced by commercial shipping; however, this approach could be used to integrate noise from multiple human activities.

Our models used depth from the SRTM30_PLUS data set (http://topex.ucsd.edu/WWW_html/srtm30_plus.html; Smith & Sandwell 1997, Becker et al. 2009). The seafloor bottom was categorized using sediment thickness (www.ngdc.noaa.gov/mgg/sedthick/sedthick.html; Divins 2003) and seabed properties from Pacific States Marine Fisheries Commission (http://marinehabitat.psmfc.org/physical-habitat.html). These data sources only differentiate between 'hard' and 'soft' bottom types. We used 'bottom sediment type' (Anonymous 2003) to define 'hard' as cobbles to very coarse pebbles (phi = −6) and 'soft' as fine silt (phi = 7.9). Basalt lies below the depth of the sediments as given by the NOAA sediment-thickness database. Sound speed was calculated by averaging 'summer' and 'fall' temperature and salinity climatologies from the World Ocean Atlas (Levitus et al. 2013). Finally, the scattering loss of sound due to sea surface roughness was incorporated in the models using significant wave height for a 10-knot wind speed (e.g. H. Zhang at ftp://eclipse.ncdc.noaa.gov/pub/seawinds/SI/uv/monthly/ieee).

The source level densities used in our models were obtained from measurements of shipping traffic. Specifically, we used AIS data collected between August and November 2009 to calculate the number of ship transits in approximately 1 × 1 km grid cells. The low-frequency noise produced by ships has the potential to propagate long distances. Consequently, the number of ship transits was calculated in an area that extended farther north and offshore than the whale modeling study area (Fig. 1) to ensure that the models included noise from as many ships affecting the whale modeling study area as possible. The whale modeling study area corresponds to the extent of transects covered by NOAA Fisheries' Southwest Fisheries Science Center on systematic marine mammal and ecosystem assessment surveys. AIS data were downloaded from NOAA Fisheries' Coastal Services Center's Marine Cadastre website (www.marinecadastre.gov).

We only used AIS data that had valid Maritime Mobile Service Identity (MMSI) values (201000000 and 775999999), speed over ground >0 knots, and a navigational status of under way using engine, restricted maneuverability, under-way sailing, or undefined. The AIS data points were joined in chronological order to form a line if both points had the same MMSI and the elapsed time between points was less than 1 h. If the elapsed time was greater than 1 h and less than 6 h, points that had less than a 30° change in heading were joined. If 2 successive points failed to meet these criteria, the current line ended and another was started. The total number of transits in each grid cell was calculated using the line statistics tool in ArcGIS Desktop v.10.2.2 (ESRI, Redlands, CA) for 4 length-based ship categories: (1) ≥18 and ≤120 m; (2) >120 and ≤200 m; (3) >200 and ≤320 m and (4) >320 m. A search radius of approximately 0.5642 km was used in the calculations because the area of the resulting circle is the same as the area of the grid cells.

The number of ship transits per cell was converted to source level densities using the source levels in Carey & Evans (2011) for the 4 length-based ship categories. The source levels in Carey & Evans (2011) are based on a worldwide shipping noise model known as the Ambient Noise Directionality Estimation System (ANDES), which references vessels active during the 1970s and 1980s. As reported in Carey & Evans (2011), source levels vary from 130 dB for the smallest length category ('small tanker'; 18 to 120 m) and highest frequency (400 Hz) to 180 dB for the largest length category ('super tanker'; >320 m) and lowest frequency (50 Hz). Ships in all 4 categories were modeled using a propeller depth of 6 m. The source level densities (dB re 1 µPa^2 Hz^{-1} at 1 m) are reported by frequency in 1-Hz bands.

Noise levels produced by ships are influenced by ship size and speed (McKenna et al. 2013). We modeled noise associated with 4 ship-length categories that provide estimates appropriate for large-scale and long-term noise predictions. However, variability among individual ships within a length category was not incorporated in the noise model. The average speed for each length category was estimated to determine within-cell residency times for each transit and the associated accumulation of source levels. We obtained ship speeds from point-based AIS data collected by the US Coast Guard between August and November 2009 (accurate speed data cannot be obtained from the 2009 Marine Cadastre data). Specifically, we calculated the median speed for all ships in each length category within the bounding box shown in Fig. 1. We limited our analyses to this smaller box, rather than using all shipping data, to avoid ships traveling into and out of the main ports because ship speeds close to ports are slower and do not represent speeds throughout the broader area. Although reduced noise has been measured for some ships when traveling at slower speeds (McKenna et al. 2013), the noise reduction may be offset by the increased time ships spend in an area when traveling at slower speeds. The median speed used to model noise was 6.40 knots for ships ≥18 and ≤ 120 m, 13.50 knots for ships >120 and ≤ 200 m, 17.20 knots for ships >200 and ≤320 m, and 21.00 knots for ships >320 m.

The KRAKEN Normal Modes model (Porter & Reiss 1984, 1985) was used to model the transmission loss. Normal modes of the ocean are calculated at the center of each grid cell and the sound field is calculated along a fan of radials around the center of each grid cell using adiabatic mode theory (Kuperman et al. 1991). Resulting source level densities were convolved with transmission loss to estimate noise levels (dB re 1 µPa^2 Hz^{-1}, hereafter dB) for each cell at a discrete depth (30 m) for 2 specific 1 Hz frequency bands (50 and 100 Hz). Predicted levels are expressed as equivalent, unweighted sound pressure levels (Lzeq), which are time-averaged across a specified duration, in this case the 122 d for August through November.

Predictions from the noise models were compared to empirical underwater acoustic data collected at 2 sites in the region (McKenna 2011), one north of the Santa Barbara Channel Traffic Separation Scheme (TSS) between Santa Rosa and Santa Cruz Islands and one on the southwestern edge of the TSS (Fig. 1). Acoustic data were collected using High-frequency Acoustic Recording Packages (HARPs) developed at Scripps Institution of Oceanography (Wiggins & Hildebrand 2007). The HARP hydrophones were deployed approximately 10 m above the seafloor. Acoustic data collected in November 2009 were decimated to a sampling frequency of 2 kHz and processed to calculate monthly sound spectrum averages. Spectrum measurements (reported as root-mean-square re: 1 µPa^2 Hz^{-1}) were produced using 225 s samples of continuous data with no overlap between each spectral average using a discrete-time Fast-Fourier Transforms (FFT). All spectra were processed with a Hanning window and 2000 point FFT length, yielding 1 Hz frequency bins. We calculated the arithmetic mean of the resulting pressure squared values and converted to dB scale for each frequency bin to be consistent with the modeling methodology. Monthly sound spectrum averages for 49 and 99 Hz (offset by 1 Hz to avoid instrument system noise) were reported to represent empirical measurements of background noise that could be directly compared to 50 and 100 Hz noise level predictions. Comparisons were made between the empirical measurements from the HARP and predicted noise in the cell containing the HARP.

Modeled noise was also compared to low-frequency, pre-industrial noise levels, which are considered to represent little to no shipping traffic. McDonald et al. (2008) estimated that pre-industrial noise levels were ~55 dB at 40 Hz at a site near San Clemente Island (Fig. 1). Wenz (1962) more generally represented 'light shipping' conditions to be approximately 65 dB at 50 Hz. Drawing from this literature, we selected 65 dB to approximate an upper bound for both 50 and 100 Hz pre-industrial noise conditions in our study area. Modeled noise was summarized using the 10th, 50th (median), and 90th percentiles of predicted values. The estimate of pre-industrial noise conditions and the percentiles were used to define 5 categories for the predicted noise levels at 50 and 100 Hz: <65 dB (pre-industrial noise conditions), 65 dB to the 10th percentile, 10th to 50th percentiles, 50th to 90th percentiles, and >90th percentile. These 5 categories were compared to time series of noise measurements off California (Fig. 1) to assess their correspondence to different volumes of shipping traffic.

Co-occurrence of whale habitat and noise

Whale distribution data were available from 3 sources that capture different elements of whale habitat. Redfern et al. (2013) developed habitat models for blue, fin, and humpback whales in waters off Southern California using 7 yr of data (1991, 1993, 1996, 2001, 2005, 2008, and 2009) collected by NOAA Fisheries' Southwest Fisheries Science Center on systematic marine mammal and ecosystem assessment surveys. These surveys were conducted throughout the US exclusive economic zone from August to November; consequently, model predictions of species density (Fig. 2) capture large-scale and long-term patterns in species distributions during a single season, but do not capture fine-scale patterns, particularly near the coast, or seasonality.

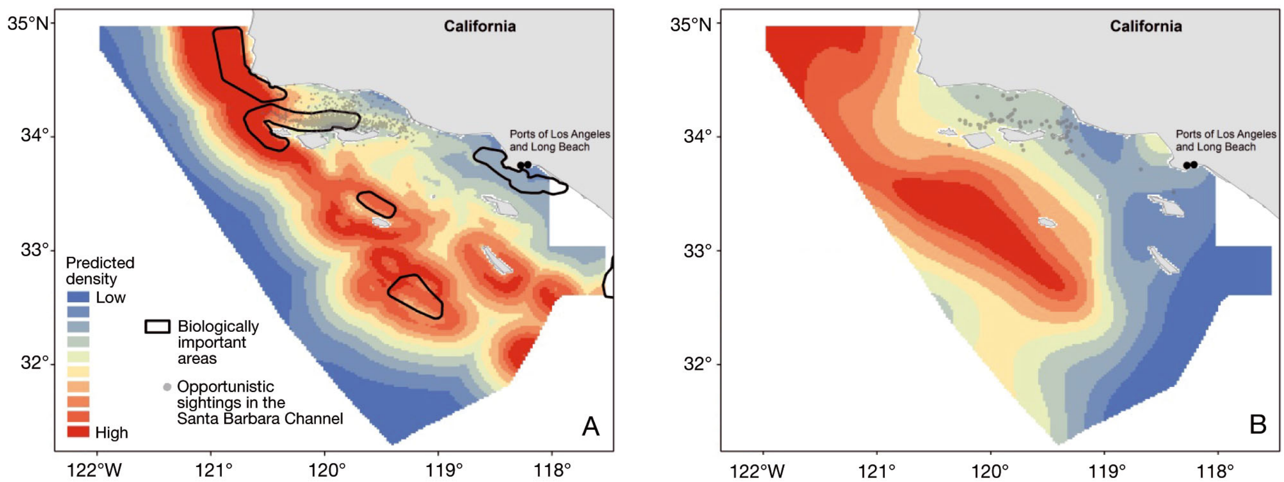
Calambokidis et al. (2015) developed boundaries for Biologically Important Areas (BIAs) in these waters (Fig. 2). The BIA boundaries were based on expert judgment and were drawn to encompass concentrations of feeding animals (direct observation of feeding or surfacing patterns suggestive of feeding) that were present in multiple years. Non-systematic, coastal (i.e. within 50 nautical miles [nmi]) surveys conducted by small boat to maximize encounters with blue and humpback whales for photo-identification and tagging studies were the primary data sources used to delineate the BIA boundaries. The BIAs for both species compare favorably to densities predicted by habitat models developed using data from the entire US West Coast, including the Southern California data used by Redfern et al. (2013). Differences occur because the 2 datasets provide complementary information: the small boat surveys used to delineate the BIAs were better able to capture nearshore, fine-scale distribution patterns and the habitat models based on the systematic surveys captured broad-scale distribution patterns throughout nearshore and offshore waters (Calambokidis et al. 2015). We compared the BIAs to the densities predicted by Redfern et al. (2013) using whale habitat models developed for just Southern California waters. Finally, the CINMS has been collecting opportunistic sightings (primarily from whale watching vessels) in the Santa Barbara Channel since 1999 (Fig. 2). These data provide information about where whales were present, but do not provide information about relative densities or absences.

We used all 3 sources of whale distribution data to estimate the co-occurrence of each species' habitat with noise. We assessed risk, or potential for degradation of the acoustic environment, for fin and blue whales using the modeled 50 Hz noise. We used the modeled 100 Hz noise to assess risk for humpback whales because humpback whale vocalizations occur at higher frequencies than blue and fin whale vocalizations. Predictions from the habitat models were made in a 2 × 2 km grid; they were extracted at the center of each 1 × 1 km cell in the noise grid. Cells in the noise grid with one or more opportunistic sightings were categorized as a presence and other cells were treated as missing data. We calculated the number of cells within the 5 noise categories for the highest 20% of predicted densities, BIAs, and presence cells.

RESULTS

Characterization of noise from commercial shipping

The 1 × 1 km grid summarizing the number of ship transits between August and November 2009 shows



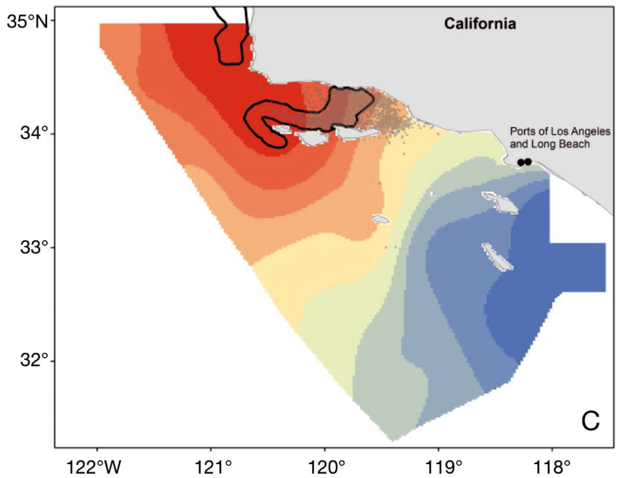


Fig. 2. Habitat representations for (A) blue, (B) fin, and (C) humpback whales between August and November from 3 data sources. A habitat model was developed from 7 yr of line-transect data and used to predict density throughout the whale modeling study area (Redfern et al. 2013). Predicted densities are shown in 10 approximately equal area categories. Biologically Important Areas (BIAs) represent areas of high concentrations of feeding animals (Calambokidis et al. 2015); BIAs have not yet been defined for fin whales. Opportunistic sightings have also been collected in the Santa Barbara Channel (the size of the dots is larger for fin whales than blue and humpback whales because there were so few fin whale sightings in the Channel)

that ships travelled in a broad area south of the northern Channel Islands and in the TSS within the Santa Barbara Channel (Fig. 3A,B). It also shows that smaller ships travel closer to the coast than larger ships. Predicted 50 and 100 Hz noise levels at 30 m depth in the whale modeling study area reflected these shipping traffic patterns (Fig. 3C,D). However, predicted noise also reflects longer-distance, low-frequency propagation from distant shipping traffic in some regions, such as offshore of Point Conception, west of San Miguel Island, and south of the northern Channel Islands. In contrast, the Santa Barbara Channel is not exposed to noise from distant shipping traffic. Median predicted noise levels in the whale modeling study area were 88 dB at 50 Hz and 77 dB at 100 Hz (Fig. 4). At the HARP north of the Santa Barbara Channel TSS between Santa Rosa and Santa Cruz Islands, predicted 50 and 100 Hz noise levels were between 5 and 12 dB higher than measured noise (Table 1). At the HARP on the southwestern edge of the TSS, predicted 50 and 100 Hz noise levels were closer to measured noise (within 3 dB) (Table 1).

We used 65 dB to approximate an upper bound for both 50 and 100 Hz pre-industrial noise conditions in our study area. Over 99 and 94 % of the whale modeling study area contained predicted 50 and 100 Hz noise levels, respectively, above pre-industrial noise conditions. Percentiles of predicted 50 and 100 Hz noise levels in the whale modeling study area corresponded to shipping traffic volumes in a time series of measurements made off Point Sur (Table 2): low (pre-industrial to 10th percentile of predicted noise levels), moderate (10th to 50th percentiles of predicted noise levels), heavy (50th to 90th percentiles of predicted noise levels), and extreme (>90th percentile of predicted noise levels).

Noise levels predicted in the CINMS spanned the range of noise levels predicted in the whale modeling study area. When considering the entire CINMS and comparing it to predicted noise levels in the

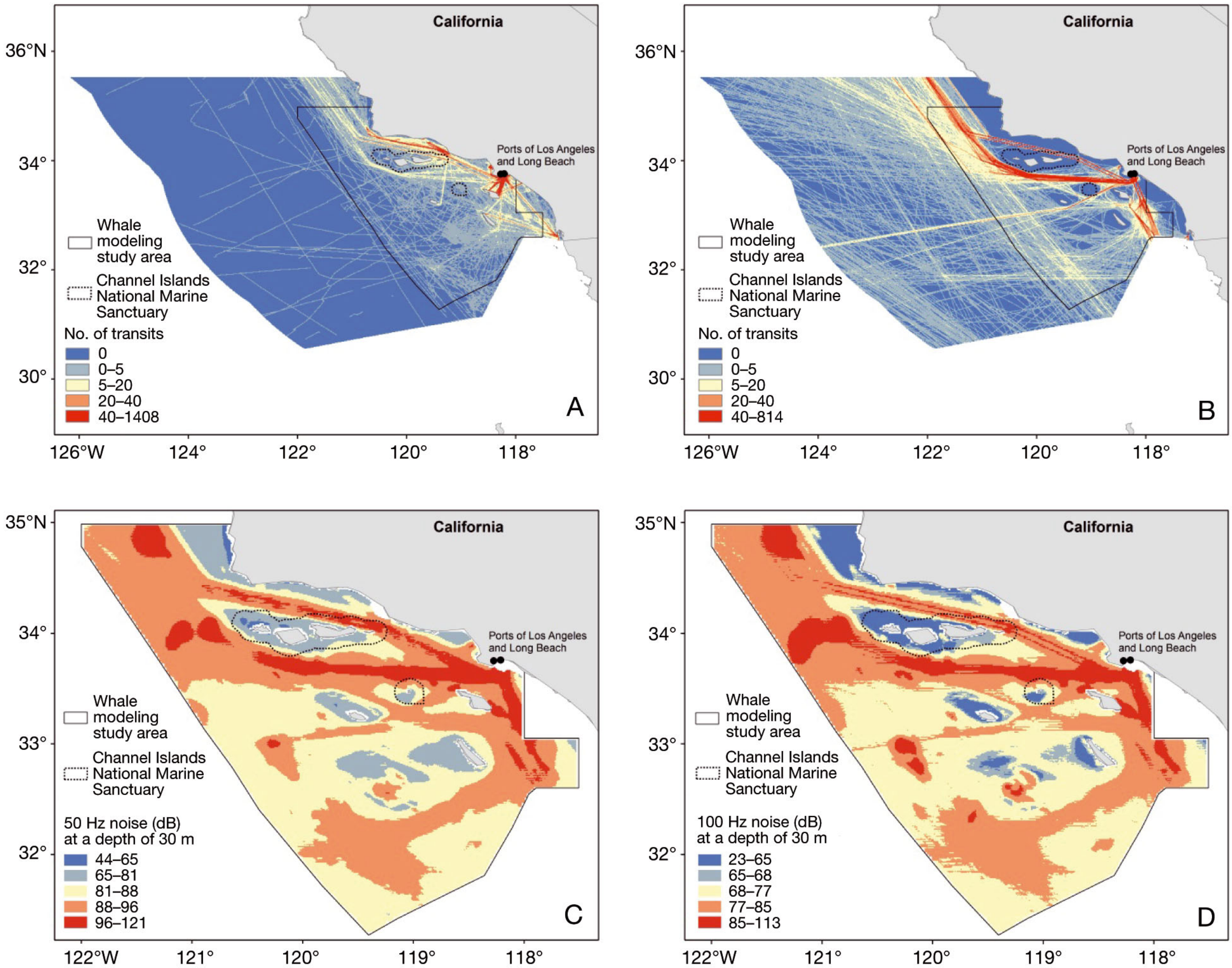


Fig. 3. Number of transits by ships (A) ≥18 and ≤120 m in length and (B) >200 and ≤320 m in length between August and November in 2009 was calculated in an area larger than the whale modeling study area to capture the influence of ships in surrounding waters in the noise predictions. Maps for the 2 other ship length categories (>120 and ≤200 m in length and >320 m in length; see 'Marterials and methods: Characterization of noise from commercial shipping' for details) are not shown because their traffic patterns are similar to the patterns seen for ships >200 and ≤320 m in length. Predicted (C) 50 and (D) 100 Hz noise levels at 30 m depth between August and November 2009. Noise predictions at both frequencies were categorized using an estimate of pre-industrial noise conditions (65 dB) and the 10^{th}, 50^{th}, and 90^{th} percentiles of the predictions. Noise predictions generally correspond to the traffic patterns for larger ships, although some influence from smaller ships can also be seen

whale modeling study area, the CINMS represents a quieter area (Table 3). It contained some of the few remaining places within the whale modeling study area that are predicted to have pre-industrial noise conditions. Although the portion of the CINMS with pre-industrial noise levels was small at 50 Hz (4%), approximately half of the CINMS was associated with 50 and 100 Hz noise levels categorized as either pre-industrial or lower traffic volumes. However, approximately 22 to 24% of the CINMS also contained predicted noise levels in or above levels associated with heavy volumes of shipping traffic.

Co-occurrence of whale habitat and noise

Blue whale habitat was associated with the 200 m isobath (Redfern et al. 2013), which represents the shelf break in this region. The blue whale BIAs generally overlap with the higher densities predicted by the habitat model; however, the model predicted higher blue whale densities throughout a much broader offshore region (Fig. 2A). Almost no blue whale habitat, regardless of the data source used to define habitat, contained pre-industrial noise conditions and the majority of blue whale habitat con-

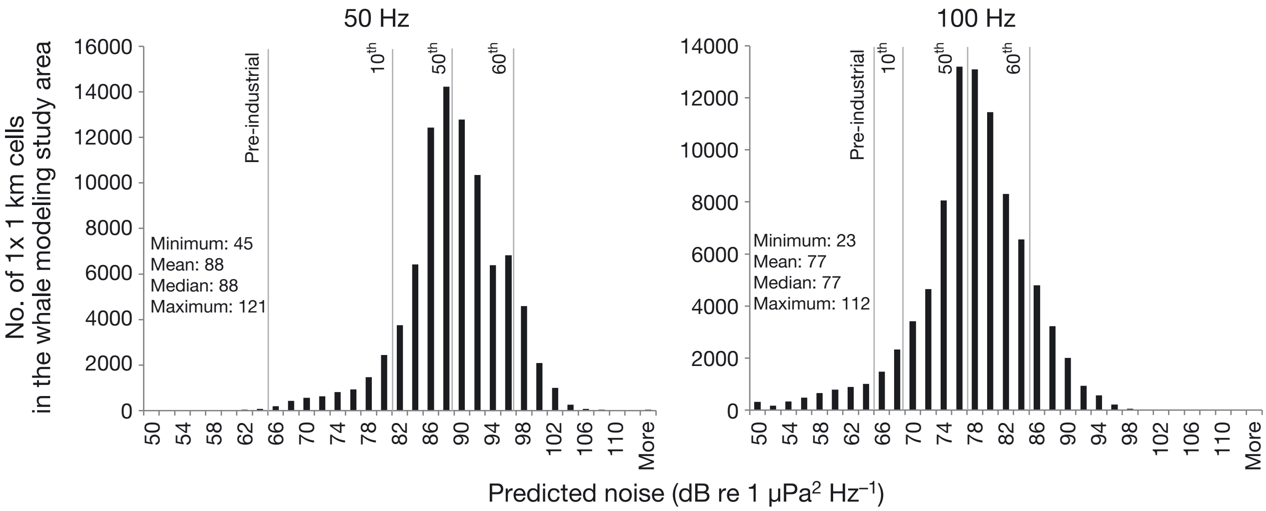


Fig. 4. Histograms of 50 and 100 Hz predicted noise levels within the whale modeling study area. The *x*-axis and summary statistics are in decibels (dBs). Thin gray lines mark the noise levels used in our analyses: pre-industrial noise below 65 dB for both frequencies and the 10th, 50th (median), and 90th percentiles of predicted noise levels. The mean and median of the predicted noise levels were the same (within rounding) at both frequencies

Table 1. Comparison of predicted 50 and 100 Hz noise levels (August to November 2009) to noise measured at 2 High-frequency Acoustic Recording Packages (HARPs) in November 2009. TSS: the traffic separation scheme adopted by the International Maritime Organization in the Santa Barbara Channel

Location	Sea floor depth (m)	Noise predicted at the HARP (dB)	Noise measured at the HARP (dB)
50 Hz			
North of the TSS between Santa Rosa and Santa Cruz Islands	578	91	80
Southwestern edge of the TSS	777	89	86
100 Hz			
North of the TSS between Santa Rosa and Santa Cruz Islands	578	80	75
Southwestern edge of the TSS	777	75	78

tained predicted 50 Hz noise levels associated with moderate, heavy, and extreme volumes of shipping traffic (Table 4). Noise risk hotspots occurred near the ports of Los Angeles and Long Beach, in the Santa Barbara Channel (including areas inside the CINMS), and in discrete offshore locations (Fig. 5A). In coastal waters off Point Conception, a blue whale BIA overlaps with a relatively quieter area associated with low volumes of shipping traffic.

Fin whale habitat (Fig. 2B) occurred in offshore waters and generally had the least overlap with predicted 50 Hz noise levels associated with pre-industrial and low volumes of shipping traffic (Table 4). In particular, no fin whale habitat contained pre-industrial noise conditions. Additionally, over

Table 2. Predicted 50 and 100 Hz noise levels in the whale modeling study area (reported in decibels rounded to the nearest whole number) corresponded to deep-water empirical measurements of shipping traffic volumes: pre-industrial, low (pre-industrial to 10th percentile of predicted noise levels), moderate (10th to 50th percentiles of predicted noise levels), heavy (50th to 90th percentiles of predicted noise levels), and extreme (>90th percentile of predicted noise levels)

Volume of shipping traffic	50 Hz	100 Hz	Reference(s)
Pre-industrial	<65	<65	Wenz (1962) 'light traffic'; McDonald et al. (2008)
Low	65–81	65–68	Wenz (1962) 'usual traffic'; Point Sur ~1960
Moderate	81–88	68–77	Urick (1984) 'moderate traffic'; Point Sur ~1980
Heavy	88–96	77–85	Urick (1984) 'heavy traffic'; Point Sur ~1995
Extreme	>96	>85	

Table 3. Percentage of the Channel Islands National Marine Sanctuary that contained predicted 50 and 100 Hz noise levels associated with different volumes of shipping traffic (see Table 2 for the range of noise levels in each category)

Volume of shipping traffic	Channel Islands National Marine Sanctuary (% area)	
	50 Hz	100 Hz
Pre-industrial	3.9	42.9
Low	49.7	12.8
Moderate	22.3	22.4
Heavy	13.2	14.3
Extreme	10.9	7.6

50% of fin whale habitat contained predicted 50 Hz noise levels associated with heavy and extreme volumes of shipping traffic (Table 4). Noise risk hotspots occurred offshore of Point Conception and to the west and south of the northern Channel Islands (Fig. 5B).

Humpback whale habitat occurred in the northernmost portion of the whale modeling study area (Fig. 2C). The humpback whale BIAs overlap with the higher densities predicted by the habitat model; however, the model predicted higher humpback whale densities farther offshore than the BIAs (Fig. 2C). Humpback whale habitat contained a larger percentage of area associated with pre-industrial noise conditions, compared to blue and fin whales (Table 4). These quiet areas occurred in the CINMS and in coastal waters off Point Conception (Fig. 5C). Noise risk hotspots occurred primarily in offshore habitat, but also occurred in the Santa Barbara Channel and the CINMS (Fig. 5C).

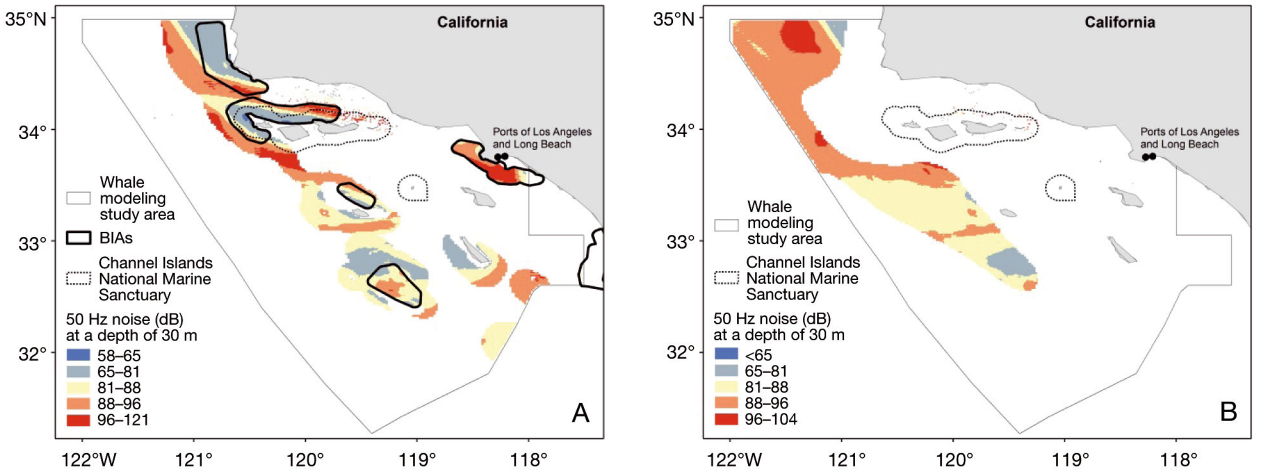
DISCUSSION

Predicted noise levels in southern California waters suggest high, region-wide exposure to shipping noise. For example, over 99 and 94% of the whale modeling study area contained predicted 50 and 100 Hz noise levels, respectively, above our approximation of pre-industrial conditions. Our risk assessment identified several areas in these waters where the acoustic environment may be degraded for blue, fin, and humpback whales because their habitat overlaps with predicted areas of elevated noise from shipping traffic. In particular, the Santa Barbara Channel contained higher predicted densities and biologically important feeding areas for blue and humpback whales that overlap with elevated noise from the TSS. The TSS separation zone was reduced from 2 to 1 nmi in 2013 to reduce the risk of ships striking whales. To understand how this change has affected the overlap between whale habitat and noise, risk assessments must be conducted using traffic data collected after this change. Areas offshore of Point Conception, west of San Miguel Island, and south of San Miguel Island and Santa Rosa Island contained higher predicted densities of all 3 species and elevated noise from commercial shipping.

In general, fin whale habitat was predicted to occur in noisier waters than blue and humpback whale habitat. The habitat models developed by Redfern et al. (2013) predict higher fin whale densities farther offshore than higher blue whale densities, resulting in a higher overlap between fin whale habitat and predicted 50 Hz noise levels. Humpback whale habitat generally occurred in waters less influenced by noise than blue and fin whale habitat because humpback whales occur closer to shore, where predicted 50 and 100 Hz noise levels were lower. In general, predicted 100 Hz noise levels were lower than 50 Hz levels because large ships produce less noise at 100 than 50 Hz (Carey & Evans 2011). Additionally, 100 Hz can be considered a lower bound for assessing noise risk to humpback whales because their conspecific vocalizations span a broad range of low

Table 4. Estimated percentage of whale habitat that contained predicted 50 Hz (blue and fin whales) and 100 Hz (humpback whales) noise levels associated with different volumes of shipping traffic (see Table 2 for the range of noise levels in each category). Whale habitat was defined using the highest 20% of densities predicted by a habitat model (Density), biologically important feeding areas (BIA; BIAs have not yet been defined for fin whales), and areas containing opportunistic sightings (Sightings)

Volume of shipping traffic	Blue whales			Fin whales		Humpback whales		
	Density	BIA	Sightings	Density	Sightings	Density	BIA	Sightings
Pre-industrial	0.3	1.3	0.1	0.0	0.0	18.9	52.4	25.4
Low	24.7	37.9	29.2	6.8	26.9	4.3	10.1	12.3
Moderate	36.8	26.2	18.3	35.9	16.4	14.2	21.2	29.0
Heavy	32.6	22.8	31.2	50.9	35.8	44.3	13.4	23.8
Extreme	5.6	11.9	21.2	6.4	20.9	18.2	2.9	9.6



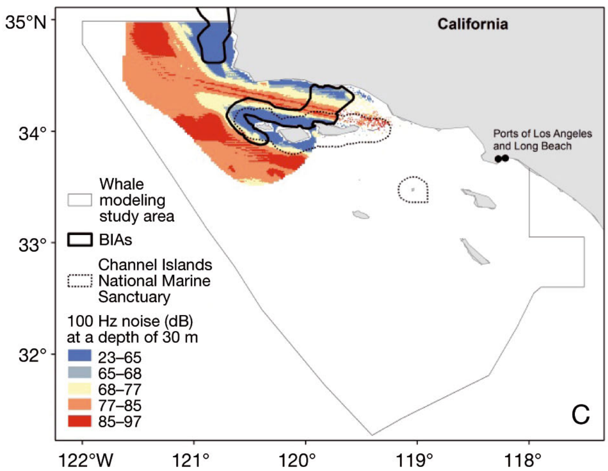


Fig. 5. Predicted noise levels at 50 Hz are shown in categories associated with different volumes of shipping traffic (pre-industrial: <65 dB; low: 65 to 81 dB; moderate: 81 to 88 dB; heavy: 88 to 96 dB; extreme: >96 dB) for (A) blue and (B) fin whale habitat. Habitat was defined as the highest 20% of densities predicted by a habitat model (Redfern et al. 2013), Biologically Important Areas (BIAs) (Calambokidis et al. 2015), and areas within the Santa Barbara Channel that contain opportunistic sightings; fin whale BIAs have not yet been defined. No fin whale habitat contained predicted noise levels below 65 dB. Noise at 100 Hz is also shown in categories associated with different volumes of shipping traffic (<65 dB: pre-industrial; low: 65 to 68 dB; moderate: 68 to 77 dB; heavy: 77 to 85 dB; extreme: >85 dB:) for (C) humpback whale habitat. Noise risk hotspots (areas where species habitat contained elevated noise) can be identified and represent areas where the acoustic environment for the species may be degraded by shipping noise. Quieter areas within species habitat can also be identified

frequencies. The co-occurrence of blue and fin whale habitat and predicted 50 Hz noise levels raises concerns about the quality of their acoustic environment and how it supports their communication at extreme low frequencies. These long-lived animals evolved to take advantage of acoustic conditions that this study estimates have been entirely (fin whales) to nearly entirely (blue whales) eliminated within the habitats most important to sustaining their presence in Southern California waters.

Our risk assessment also identified 2 places where biologically important blue and humpback whale feeding areas overlap with lower predicted noise levels: in coastal waters off Point Conception and in the CINMS. When considering the entire CINMS, it represents a relatively quieter area within the generally noisy southern California waters. In particular, approximately half of the CINMS contained predicted noise levels associated with pre-industrial and low volumes of shipping traffic. Noise has not been directly managed in the CINMS; instead, areas containing reduced noise levels in the CINMS are likely an ancillary benefit of the Area to be Avoided (ATBA) that was created around most of the CINMS by the IMO in 1991 to reduce groundings and pollution risks. Ships over 300 gross tons are also prohibited from operating within 1 nmi of any of the Channel Islands unless they are transporting people or supplies to an island or engaged in fishing or kelp harvesting. As a result of the ATBA and restrictions close to the islands, ship traffic and, concomitantly, elevated noise in the CINMS has been primarily restricted to where the TSS overlaps with the Sanctuary's boundaries (Fig. 3). This overlap results in approximately 22 to 24% of the CINMS containing predicted 50 and 100 Hz noise levels in or above levels associated with heavy volumes of shipping traffic.

The agreements and differences between predicted noise levels and the HARP measurements highlight the many sources of variability that influence predicted noise levels at a particular location, at particular frequencies, and within specific time periods.

In southern California waters, the differences between predicted and measured noise are likely strongly influenced by changes in shipping traffic. A decrease in the number of ship transits off southern California was observed as a result of the 'Great Recession' that occurred between December 2007 and June 2009 (McKenna et al. 2012a). Traffic patterns also changed when the California Air Resources Board implemented the Ocean-Going Vessel Fuel Rule (hereafter, fuel rule) in July 2009. The fuel rule was intended to reduce air pollution by requiring large, commercial ships to use cleaner-burning fuels when traveling within 24 nmi of the mainland coast (Soriano et al. 2008). A majority of ships traveled through the Santa Barbara Channel in the TSS adopted by the IMO before implementation of the fuel rule. Following implementation, a higher proportion of ships began traveling south of the northern Channel Islands to reduce the time spent using more expensive, cleaner fuels (McKenna et al. 2012a).

Our noise models were developed using the number of ship transits between August and November 2009. In contrast, the HARP measurements were made in November 2009. The much higher (5 to 12 dB) differences between predicted and measured noise at the northern HARP likely occurred because the HARP measured reduced traffic in the Santa Barbara Channel during November, compared to the higher traffic within the Santa Barbara Channel during the earlier part of time period used in the noise models (August through November). The smaller differences (<3 dB) between predicted and measured noise at the southwestern HARP likely occurred because the increased traffic traveling south of the northern Channel Islands was measured by the HARP during November and incorporated in the later part of time period used for the noise models (August through November).

The differences in predicted versus measured noise may also be the result of ship source levels. The noise models used ship source levels that were estimated from data collected in the 1970s and 1980s (Carey & Evans 2011); these source levels may overestimate the noise produced by the modern fleet. The 1 Hz-band ship source levels used in the noise models are approximately 10 to 15 dB higher than some more recent, broader-band estimates of source levels for newer ship designs (e.g. McKenna et al. 2012b). Improvements in the noise models could also be made by incorporating ship speed in predicted ship source levels. High-resolution, spatially explicit maps of vessel speed can be derived from AIS data. However, algorithms to estimate changes in source level from speed exist for a small number of vessel types and length classes (e.g. container ships; McKenna et al. 2013). Finally, the noise models could be improved by increasing the resolution of bottom-type data for waters off Southern California because sound propagation is influenced by bottom type. As more measurements of ocean noise become available in southern California waters, the comparison between predicted and measured noise should be expanded spatially and temporally.

Our risk assessment framework can be used to evaluate the consequences of potential management actions and further changes in shipping traffic. For example, noise associated with different ship routing options could be modeled and used to quantify the resulting changes in the co-occurrence of whale habitat and noise. Additionally, a time series of annual noise predictions could be developed to understand changes in risk associated with changes in shipping traffic. The next steps for the risk assessment are to incorporate uncertainty and develop metrics to estimate the consequences of the risk. Explicitly identifying uncertainty helps managers understand the degree of confidence they can place in the risk assessment and helps to prioritize future data collection efforts (Hope 2006).

There is uncertainty associated with both the predicted species densities and noise levels used in our risk assessment. The uncertainty in the predicted species densities arises primarily from interannual variability in species distributions (Redfern et al. 2013). This interannual variability is caused by changes in oceanographic conditions on annual (e.g. the El Niño Southern Oscillation), decadal (e.g. the Pacific Decadal Oscillation), and longer time scales (e.g. climate change). This uncertainty can be reduced by extending the data time series, using finer-resolution habitat data, and incorporating prey data. There is also a need to examine the seasonality of the risk estimates because fin whales are present off Southern California all year and some blue and humpback whales may have arrived before or remained after the period in which the data were collected. Finally, the risk assessment could be conducted using the maxima or minima of predicted noise levels during the August to November time period, in addition to predicted values averaged over this time period. It could also be expanded beyond the single frequencies we selected to capture the variable contributions from shipping to noise using one-third octave bands or audiogram weighting (e.g. the approach developed by Erbe et al. 2014).

The current risk assessment identifies areas of co-occurrence between whale habitat and noise from commercial ships. Metrics are needed to estimate the consequences of this co-occurrence. Previous studies have estimated the loss of potential communication opportunities among individuals (e.g. Clark et al. 2009, Hatch et al. 2012) to quantify the influence of chronic noise on large whales. Applying this metric to Southern Californian waters would further highlight frequency-specific implications of noise for transmission of specific call types. The fitness implications of locally degraded acoustic environments can also be considered within population viability models that include other environmental determinants of foraging and mating success and that account for trends in those variables (e.g. climate change). Finally, stress hormone levels and other health and demographic indicators could be compared among populations, subspecies, or sister species that occur in areas with different long-term noise conditions.

Current US regulation of noise under the ESA and MMPA does not include impacts associated with chronic noise from shipping. Consequently, new and different types of management may be needed to address low-frequency ocean noise. Place-based management focuses on a specific ecosystem and the range of activities that impact it (Hatch & Fristrup 2009). Our risk assessment highlights how noise is affected by several place-based management techniques: a National Marine Sanctuary, an IMO ATBA, and an IMO TSS. Previous evaluations concluded that pursuit of sanctuary authority to directly manage low-frequency noise would face obstacles and would not address the influence of shipping noise beyond sanctuary boundaries (Haren 2007). However, our risk assessment suggests that the IMO's designation of most of the CINMS as an ATBA has resulted in lower noise in many areas of the Sanctuary, compared to Southern California waters in general. Consequently, a variety of international management tools focused more broadly on reducing spatial overlap between human activities and vulnerable marine areas may provide opportunities for successful noise management.

Shipping traffic and noise are concentrated in a TSS. Where the TSS occurs in the CINMS, resources are exposed to high levels of low-frequency noise creating a gap in the Sanctuary's place-based protection. This gap is of particular concern due to the biologically important blue and humpback whale feeding areas that occur in this region. Offshore areas containing the highest predicted densities of fin whales were also heavily impacted by noise. Noise in heavily impacted BIAs could be reduced by designating these areas as PSSAs (highlighting their need for special protection) and implementing management measures that require or recommend that ships operate in a manner that reduces noise.

Humpback and blue whales BIAs in coastal waters off Point Conception contained some of the remaining quiet areas in Southern California waters. Areas that support feeding and breeding for these populations and that are currently quieter, relative to regional levels, could be designated as ATBA to ensure they remain free of high levels of shipping traffic. Studies of ship-strike risk have also been conducted in Southern California waters (Redfern et al. 2013). Strategies for reducing ship-strike risk have been implemented in many parts of the world and include moving or creating a TSS, moving or creating voluntary shipping routes, and reducing ship speed. These strategies may also reduce noise. Hence, the consequences of low-frequency noise should be considered with ship strikes in cumulative risk assessments and marine spatial planning. Most place-based management strategies are static in space and time. There is also a need to consider dynamic management strategies to respond to the spatial and temporal variability inherent in marine mammal distributions and human use patterns.

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