Title
Assessing approaches for ship noise reduction within critical whale habitat.

Journal
The Journal of the Acoustical Society of America, 156(5)

ISSN
0001-4966

Authors
ZoBell, Vanessa M
Hildebrand, John A
Frasier, Kaitlin E

Publication Date
2024-11-01

DOI
10.1121/10.0034455

Peer reviewed

NOVEMBER 22 2024

Assessing approaches for ship noise reduction within critical whale habitat

Vanessa M. ZoBell; John A. Hildebrand; Kaitlin E. Frasier

J. Acoust. Soc. Am. 156, 3534–3544 (2024)
https://doi.org/10.1121/10.0034455

JASA ARTICLE

Assessing approaches for ship noise reduction within critical whale habitat

Vanessa M. ZoBell,[a] John A. Hildebrand, and Kaitlin E. Frasier
Scripps Institution of Oceanography, University of California San Diego, La Jolla, California 92037, USA

ABSTRACT:
Ship noise pollution significantly overlaps with critical habitats of endangered whales in the Santa Barbara Channel, prompting the need for effective noise reduction strategies. Various ship noise reduction approaches were assessed by simulating both source-centric (e.g., speed reduction or retrofit) and space-centric (e.g., routing changes) strategies to determine which would most effectively minimize noise within important marine habitats. Reducing the speeds of all ships achieved the highest noise reduction of the source-centric methods, although solely slowing cargo ships led to similar reductions. Implementing a single-route approach on the southern side of the Channel Islands achieved the greatest reduction of the space-centric strategies. For the multi-route approaches, some noise reduction was achieved by creating a buffer zone between the proposed shipping lanes and the critical habitat boundary. This simulation framework provides a mechanism for efficient exploration and assessment of noise reduction strategies across time and space. The framework can be updated to consider new approaches to changing ocean conditions.
 https://doi.org/10.1121/10.0034455

(Received 14 June 2024; revised 30 October 2024; accepted 4 November 2024; published online 22 November 2024)

[Editor: Shima Abadi] Pages: 3534–3544

I. INTRODUCTION

Reducing underwater radiated noise (URN) pollution generated by ships has become an international priority for ocean conservation (Chou *et al.*, 2021; IMO, 2018, 2023; IWC, 2014). URN reduction techniques are beginning to be explored and implemented around the world (MacGillivray *et al.*, 2019; Malinka *et al.*, 2023; ZoBell *et al.*, 2021b; ZoBell *et al.*, 2023a). These efforts require a comprehensive understanding of the vessel's noise-generating mechanisms, as well as broad engagement with the public, ship owners, industry, maritime safety officials, naval architects, and researchers, among many more participating parties and groups. Financial resources are needed to support these efforts including funding to redesign vessels, deploy acoustic monitoring equipment, and conduct ongoing measurement, evaluation, and communication of noise reduction outcomes.

Various methods have been proposed to reduce vessel noise, both by targeting the sources and the spatial distribution of URN. Source-centric noise reduction efforts aim to reduce URN at its primary sources, which include propeller cavitation, machinery noise, and vibrations from the hull. These efforts have been implemented through vessel speed reduction (VSR) programs as well as engineering and design efforts (Aktas *et al.*, 2023; MacGillivray *et al.*, 2019; Malinka *et al.*, 2023; Smith and Rigby, 2022; ZoBell *et al.*, 2021a; ZoBell *et al.*, 2021b). Space-centric efforts to reduce ship noise, using marine spatial planning, provide a framework for diverse stakeholder activities within the ocean (Crowder *et al.*, 2006; Redfern *et al.*, 2017). Although noise reduction efforts have been discussed as a potential method to reduce noise in certain areas of concern, they can increase noise in other areas by increasing vessel speeds outside of speed reduction zones, or moving noise to other areas in marine spatial planning initiatives (IMO, 2014).

Critical habitats, marine sanctuaries, and marine monuments are of high priority for protection from noise pollution. The Santa Barbara Channel (SBC) and surrounding areas are of significance for noise reduction due to the coexistence of intensive commercial shipping and abundant wildlife (see Fig. 1; Haren, 2007; McKenna *et al.*, 2009; Redfern *et al.*, 2017). The SBC region encompasses the Channel Islands National Marine Sanctuary (CINMS), which is home to a wide array of marine biodiversity and is protected under the National Marine Sanctuaries Act (Checkley and Barth, 2009; National Marine Sanctuaries, 2000). The region is seasonally occupied by marine mammals, including blue, humpback, fin, and gray whales, among many other species, all of which are protected under the Marine Mammal Protection Act (Barlow and Forney, 2007; Marine Mammal Protection, 1972). Blue whales and humpback whales have designated biologically important feeding areas (BIAs), which are region- and time-dependent areas in which cetaceans are known to concentrate for feeding (Calambokidis *et al.*, 2015). Intersecting the boundaries of the CINMS and the BIAs is the traffic separation scheme (TSS), commonly called shipping lanes, which supports commercial vessel transits to and from the first and second

[a]Email: vmzobell@ucsd.edu

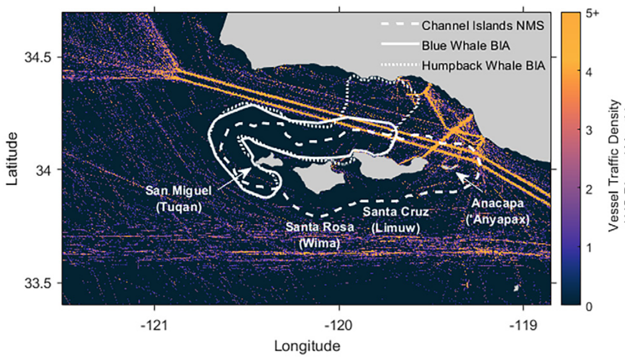

FIG. 1. (Color online) Vessel traffic density [Automatic identification system (AIS) pings / month] for August 2017. Critical habitats are delineated by white lines including the Channel Islands NMS (dashed), the Blue Whale BIA (solid), and the Humpback Whale BIA (dotted).

busiest ports in the Western Hemisphere, the Port of Los Angeles and the Port of Long Beach, respectively (UNCTAD, 2022). The volume of cargo at these ports is increasing and predicted to scale up as demand grows (Zhang *et al.*, 2019).

Potential solutions to reduce current and future noise pollution in the SBC region are continually being explored and analyzed. A VSR effort called the Protecting Blue Whales and Blue Skies program has been shown to reduce noise at the source of the vessel by 5 dB (ZoBell *et al.*, 2023b). Additionally, a vessel retrofitting (redesign) effort conducted by Maersk, a major shipping company, reported reductions in the monopole source levels of vessels post-retrofitting for certain frequency bands (ZoBell *et al.*, 2023a). Most source-centric noise reduction studies to date have focused on metrics such as radiated noise level (RNL), sound exposure level (SEL), and monopole source level (MSL), which quantify the noise generated by individual vessels (Findlay *et al.*, 2023; MacGillivray *et al.*, 2019; ZoBell *et al.*, 2021b).

In addition to source-centric efforts, marine spatial planning has been considered in this region through port access route studies (PARS). Under the United States Ports and Waterways Safety Act (PWSA), the U.S. Coast Guard (USCG) is required to conduct a PARS before establishing or modifying any fairway or TSS in the U.S. The PARS process, which occurs regionally every 10–20 years, is a transparent public process with broad stakeholder involvement (United States Coast Guard, 2023). The 2011 U.S. West Coast PARS recommended shifting a shipping lane northward to divert traffic away from CINMS to protect the marine environment (United States Coast Guard, 2011). Although the 2011 PARS was not explicitly designed to reduce noise, the framework provides the potential for noise reduction through marine spatial planning.

Marine organisms are exposed to multiple noise sources simultaneously, making biologically relevant analyses important to understand the full spatiotemporal exposure of animals to noise in a region (ZoBell, 2023). With the understanding that noise reduction is achievable, it is important to investigate which approaches are most effective in reducing noise pollution in time and space. Our study simulated source-centric and space-centric solutions for noise reduction across the SBC region to identify the most effective solutions. Reducing vessel speeds and changing shipping routes within the region were found to reduce noise pollution in critical habitats. This study demonstrated that simulating ship noise pollution under various mitigation scenarios is an effective and efficient approach to identifying promising strategies for noise reduction.

II. METHODS

The study area covered a 220×250 km grid encompassing latitude 33.26°N to 35.24°N and longitude 121.55°W to 118.83°W. This region includes three critical habitats: Channel Islands National Marine Sanctuary, Blue Whale BIA, and Humpback Whale BIA (Fig. 1). Sound pressure levels (SPLs) across this region were modeled using methods described in ZoBell *et al.* (2024), which are briefly outlined in the following. SPLs were modeled for pre-industrial and modern ocean noise as well as source-centric and space-centric simulations (Secs. II A–II D). All of the SPLs were modeled at 50 Hz, as the low-frequency acoustic environment is more affected by shipping noise than the high-frequency environment (ZoBell *et al.*, 2024). A depth of 30 m was used for modeling, both to align with past studies in this region and because it represents the nominal depth of a singing blue whale (Oleson *et al.*, 2007; Redfern *et al.*, 2017). The SPLs were computed at a 4 km spatial resolution and an hourly temporal resolution for August 2017, since the summer months coincide with peak baleen whale presence. Hourly SPLs were averaged over the month to identify trends across the region for each simulation. Changes in SPLs from the simulations were investigated across the entire region, and the distributions of the monthly SPLs from each simulation were compared across the three critical habitats.

A. Pre-industrial ocean noise

Pre-industrial SPLs were used as a baseline to estimate ocean noise levels in the region before the industrial revolution and the advent of container shipping (ZoBell *et al.*, 2024). This pre-industrial model was compared to modern SPLs and noise reduction simulations to assess the impact of anthropogenic activity. Pre-industrial SPLs were modeled by converting wind speed to SPL across the study grid. Wind speeds for August 2017 were collected from the cross calibrated multi-platform (CCMP) wind vector analysis product (Ricciardulli, 2022). The wind speed model has a spatial resolution of 0.25 degrees and a temporal resolution of 6 h. Wind speeds were interpolated to a 4 km spatial resolution to be combined with the modern noise model. An empirical model for wind-driven noise was then applied to convert wind speeds (in m/s) to 50 Hz SPL (in dB re 1 μPa^2) at 30 m depth for each grid cell (Hildebrand *et al.*, 2021).

B. Modern ocean noise

The modern ocean noise model combines wind noise with ship noise and serves as the model for presently existing noise levels within the region. Ship noise was modeled using vessel tracks from AIS data from an antenna on Santa Cruz Island (34.99°N, 119.63°W) with an average detection range of 300–400 nautical miles (Santa Barbara Amateur Radio Club Inc., 2024). Stationary ships (with ship speed of zero knots) were excluded from the model. Each ship track was interpolated to one minute resolution, and the latitude, longitude, and duration (in minutes) that a ship was in a 4×4 km grid cell was recorded. Ships were classified by ship type based on the groupings of Macgillivray and de Jong (2021). If the ship type within the AIS data message was empty, the ship type was deemed "Other." MSLs, SPLs modeled at a distance of 1 m from the source, were calculated based on vessel speed, length, and ship type using the MSL model developed by Macgillivray and de Jong (2021). The average ship length and speed from the original model were changed to the average ship length and speed of a vessel in the SBC (170.1 m, 12.6 knots) to account for the differences in ships used to develop the model and the ships within the SBC region (ZoBell *et al.*, 2024).

A range-dependent parabolic equation method (RAMGEO) was used to calculate propagation loss (PL) as a function of range and depth at 10-degree intervals around the center of each grid cell (Collins, 2001). The maximum range of each radial reached 40 km with a maximum depth of 900 m below the seafloor. Range-dependent temperature and salinity profiles from the California State Estimation at Scripps (CASE-STSE) were used to compute sound speed profiles in 1/16 spatial resolution. Sediment properties from ZoBell *et al.* (2024) as well as the Ocean Discovery Drilling Program were used to include range-dependent acoustic sediment properties in the model (ZoBell *et al.*, 2024). PL was subtracted from MSL for the grid cells activated by the presence of a ship. The duration of time (in seconds) each ship was in the grid cell was converted to dB using $10*\log_{10}$(duration), resulting in cumulative SEL for all ships within the grid cell for each hour. Hourly SPL was then calculated by subtracting the duration of a full hour in seconds, $10*\log_{10}(60*60)$, from SEL, yielding SPL values in dB re $1\mu\text{Pa}^2$ for each grid cell. Wind noise was incoherently summed with ship noise (in pressure), to generate the cumulative modern noise map for abiotic (wind-driven) noise sources and human-made (ship) noise sources.

C. Source-centric simulations

Source-centric noise reduction was simulated for two speed reduction approaches and one design approach. The original (August 2017) AIS data were used to compare original speeds from the modern ocean noise model to simulated AIS data which incorporated the same vessels but with reduced speeds and changes in design. For the first simulation, vessel speeds of all ships were reduced to a target speed of 10 knots. Vessels transiting at 10 knots or less from the original AIS data were not changed. MSLs were recalculated for each ship at the 10 knot speed. The additional time it took the vessel to transit at 10 knots was added to the duration in each grid cell to account for increases in SELs with increased time spent in the cell.

The next source-centric approach simulated the reduction in speed solely for cargo ships (AIS type 70-79). All speeds from cargo ships in this simulation were reduced to 10 knots and MSLs were recalculated. Cargo ships transiting at or below 10 knots were not changed. Subsequent increases in time with the slowdown were added to each grid cell. The original AIS data were used for ship types other than cargo ships, and no speeds or durations were altered.

Finally, source-centric noise reduction through ship design modification was simulated across the region. A container ship retrofitting effort undertaken by Maersk was shown to reduce MSL at 50 Hz by 2.9 dB (ZoBell *et al.*, 2023a). To investigate how this design, and design efforts in general, may affect the acoustic environment across space and time, a design simulation was conducted by subtracting 2.9 dB from the MSL at 50 Hz for all cargo ships within the region. Speeds and durations were not modified in this approach, and ship types other than cargo ships did not receive a simulated retrofit.

D. Space-centric simulations

A space-centric approach was investigated by analyzing existing shipping lanes and prospective modifications in the area. In 2023, the USCG initiated a PARS on the Pacific West Coast (United States Coast Guard, 2023). In the proposal, the USCG considers the addition of a fairway on the southern side of CINMS, called the Pt. Mugu Fairway. Seven space-centric simulations were performed to identify changes in SPL with the addition of the Pt. Mugu Fairway and several modifications to the lanes throughout the region.

SPLs were modeled with the implementation of the Pt. Mugu Fairway to investigate the soundscape with this alteration before it is potentially implemented. In addition to the proposed Pt. Mugu Fairway, two alterations to the fairway were simulated, both considering multi-routes and single-route options, for a total of seven simulations. The multi-route simulations allowed for 80% of the cargo transits to be on the SBC TSS and 20% on one of the southern routing options, to emulate the percentages found on these lanes in the August 2017 AIS data. The single route option removed all cargo ship transits from the SBC TSS and had 100% of the cargo ship transits on the southern routing options. Although this option has not been proposed by the USCG in the 2023 PARS, the simulation allows for this option to be considered in future marine spatial planning efforts.

The routes and the percent of cargo ships per day are displayed in Fig. 2. The first simulation reflects the original AIS data and includes the USCG approved SBC TSS and the voluntary western lanes (SBC TSS). The second multi-route option includes the TSS and the proposed Pt. Mugu

https://doi.org/10.1121/10.0034455

Fairway (Multi-route: Pt. Mugu Fairway). The third multi-route approach model includes the TSS and a slight modification to the Pt. Mugu Fairway in which the lanes extend straight, reducing the area in which the lanes are directly adjacent to the CINMS boundary (Multi-route: Modified Fairway). The final multi-route technique includes the TSS and the proposed Pt. Mugu Fairway with a 10 km buffer from the closest lanes to the CINMS boundary (Multi-route: Buffer Fairway). The three single route options included 100% of vessel transits to be on the southern lanes for the Pt. Mugu Fairway, Modified Fairway, and Buffer Fairway (Fig. 2).

Each space-centric model was developed using simulated cargo ship AIS data that supported the same number of cargo ships transiting at the same speeds to allow comparison across simulations. On average, 15 cargo ships per day transited in the region during August 2017, traveling at an average speed of 13.6 ± 3.7 knots. These metrics were used to space 15 cargo ships per day with randomly selected start times along the routes. The coordinates of the routes were modified to model transit variation by adding a value from a random normal distribution [mean = 0°, standard deviation (SD) = 0.003°]. The cargo ships were given a ship length from a random normal distribution mirroring cargo ships in this region (mean = 271.8 m, SD = 64.2 m). The original AIS data from ships other than cargo ships were incorporated to gain a more holistic understanding of the soundscape since some ship types (such as pleasure crafts and passenger vessels) will likely not be transiting on the shipping lanes at all times. MSLs for both the non-cargo ships from the original AIS data as well as the simulated cargo

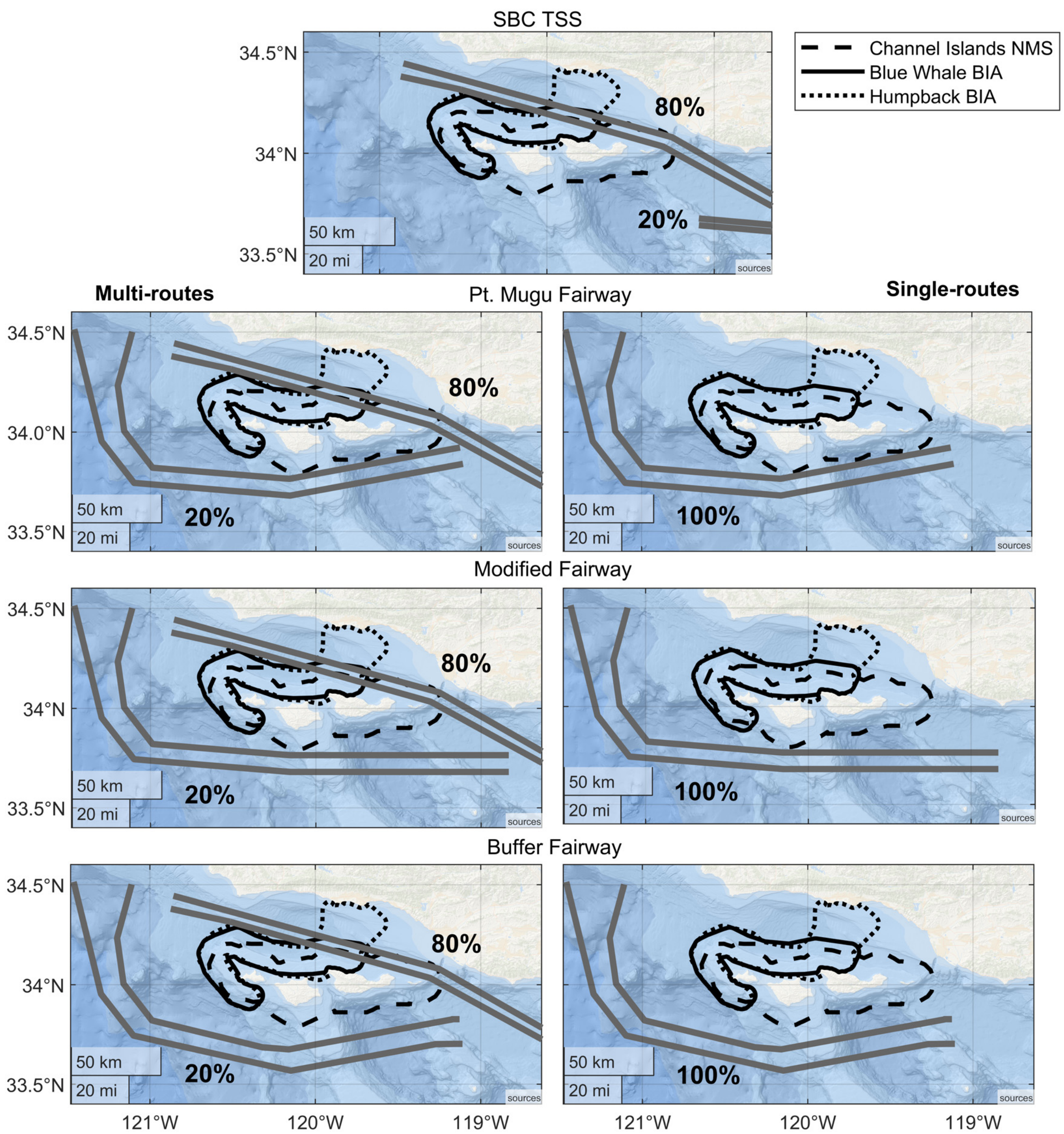

FIG. 2. (Color online) Routes and percentage of vessel transits on northern and southern lanes modeled for space-centric noise reduction simulations. Multi-route includes both the SBC TSS (80% of vessels) and the Pt. Mugu Fairway (20% of vessels), as well as two altered Pt. Mugu Fairway options. The single-routes have the proposed and altered Pt. Mugu Fairways supporting 100% of vessels.

ships were computed based on ship type, length, and speed, and subtracted from the PL grid. The SPL was then computed and extracted from within each habitat boundary.

E. Noise reduction summary statistics

PL was subtracted from MSLs for each of the source-centric and space-centric simulations. The duration of each ship's presence in each grid cell, whether original or altered based on the simulation, was then added in linear space to calculate SEL, which was then used to compute SPL in dB re $1\mu Pa^2$. SPL was calculated for each simulation across the full grid and extracted at each grid cell within the critical habitats. The distribution of SPLs within the critical habitats for each simulation was analyzed to identify differences in SPLs across simulations.

To quantify differences between simulations, the SPLs computed from the source-centric simulations were subtracted from the modern SPLs that utilized the August 2017 AIS data. For the space-centric simulations, the SPL reduction was computed by subtracting the simulations from the SBC TSS model, which emulates the same vessel distribution as the original AIS data. Larger negative values indicated higher SPL reduction, while smaller negative values indicated lower SPL reduction.

To evaluate the spatial extent of SPL reduction from the simulations, excess noise (simulated noise–wind noise) was calculated for each simulation. The percentage area within each critical habitat where excess noise was greater than 3, 6, and 9 dB was calculated. The percentage reduction in space with excess noise at each of the levels was then compared between modern SPLs (SBC TSS model for space-centric approach) and the SPL from each simulation.

III. RESULTS

Simulated SPLs were evaluated in three habitats (blue whale BIA, humpback whale BIA, and CINMS) using a previously developed model that was validated with local passive acoustic recording data (ZoBell *et al.*, 2024). Three source-centric and seven space-centric simulations were investigated to identify the most effective techniques for noise level reduction. Ship traffic speeds and routes from August 2017 served as the modern baseline for the region.

Results for all simulations were summarized as monthly SPLs and noise reductions were assessed by calculating differences in monthly SPLs per grid cell compared to the modern ocean noise model. Within each critical habitat, SPLs were extracted, and the distributions were compared across simulations and baseline conditions (modern and pre-industrial, Figs. 3–6). Further, excess noise levels—defined as simulated noise levels that exceeded pre-industrial noise levels within a grid cell—were compared across simulations by calculating the change in percentage area experiencing excess noise (Table I).

A. Source-centric: SPL analysis

Noise reduction across the full grid was evaluated for three source-centric methods: speed reduction to 10 knots for all ships, speed reduction of cargo ships only, and retrofitting (redesign of propellers and bow) of cargo ships. The difference in SPLs from the August 2017 AIS data (modern) and the simulated techniques across the full grid are shown in Fig. 3. The simulations predict a maximum noise level reduction of 4.1 dB (speed reduction of all ships), 3.5 dB (speed reduction of cargo ships), and 1.5 dB (retrofit of cargo ships). All the simulations produced a reduction in SPLs, despite an increase in the time ships spent in the grid cells during the speed reduction approaches.

Noise reduction within each habitat was investigated by extracting the monthly SPL data within the boundaries of the habitat for each simulation. All simulations demonstrated reductions in noise compared to modern levels (Fig. 4). Among

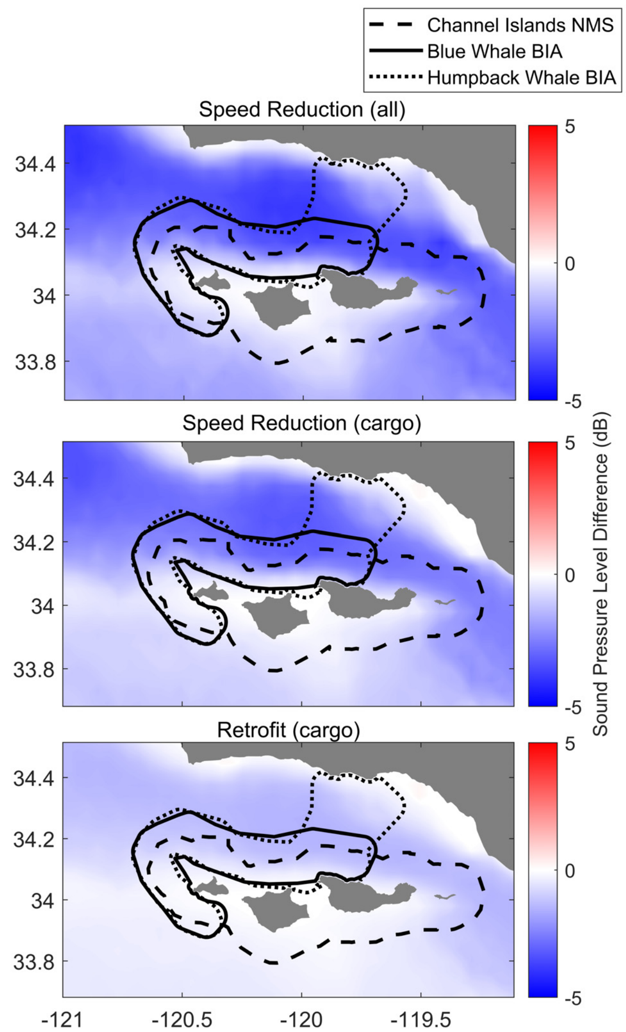

FIG. 3. (Color online) The difference in monthly 50 Hz SPL between modern sound levels from August 2017 AIS data and source-centric simulations. Blue shading indicates areas with greater reduction and white shading indicates areas with no reduction. Speed reduction of all ships is predicted to achieve the greatest reduction in SPL.

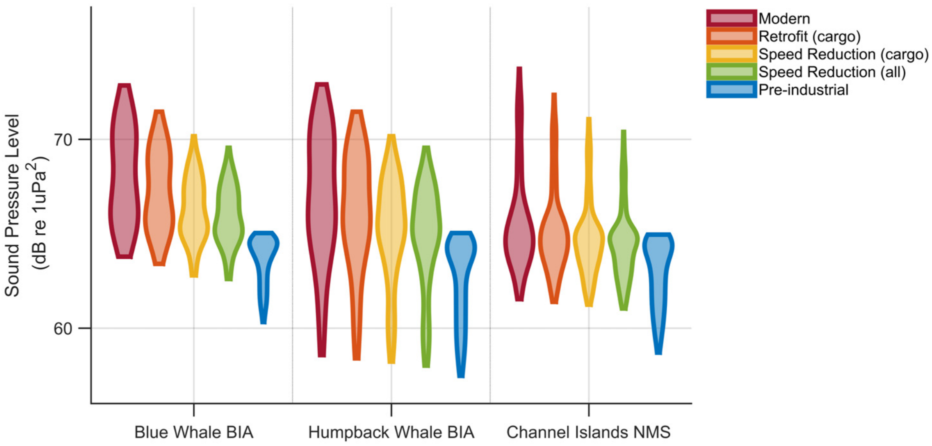

FIG. 4. (Color online) Distributions of modeled 50 Hz SPLs within each critical habitat for modern (August 2017), pre-industrial, and simulated sound levels. The speed reduction (all) simulation allowed for the greatest reduction in SPL compared to modern ocean noise levels.

the three habitats, the Blue Whale BIA had the highest median modern noise levels, with the majority of its boundary within the range of influence of ship noise emanating from traffic in the shipping lanes. CINMS had the highest maximum modern noise levels, due to a congested portion of the TSS intersecting the sanctuary boundary and situated atop narrow, steep-walled bathymetry that reflects sound, causing constructive interference, the combined intensity of coherent sound waves. In contrast, the Humpback Whale BIA had the lowest minimum modern noise values, likely

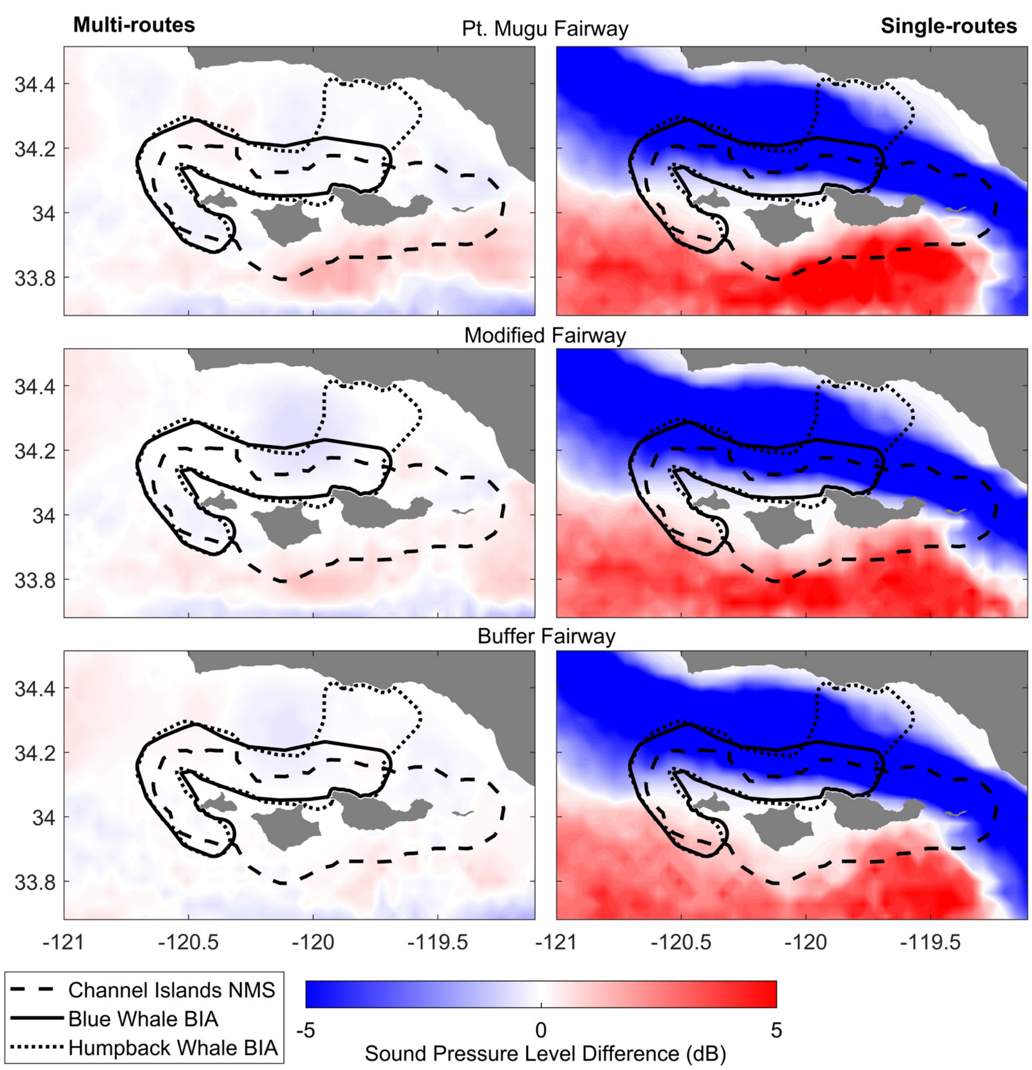

FIG. 5. (Color online) The SPL difference in dB between the SBC TSS simulation and the altered route simulations. Blue shading indicates areas with a reduction in SPLs and red shading indicates areas with increased SPLs.

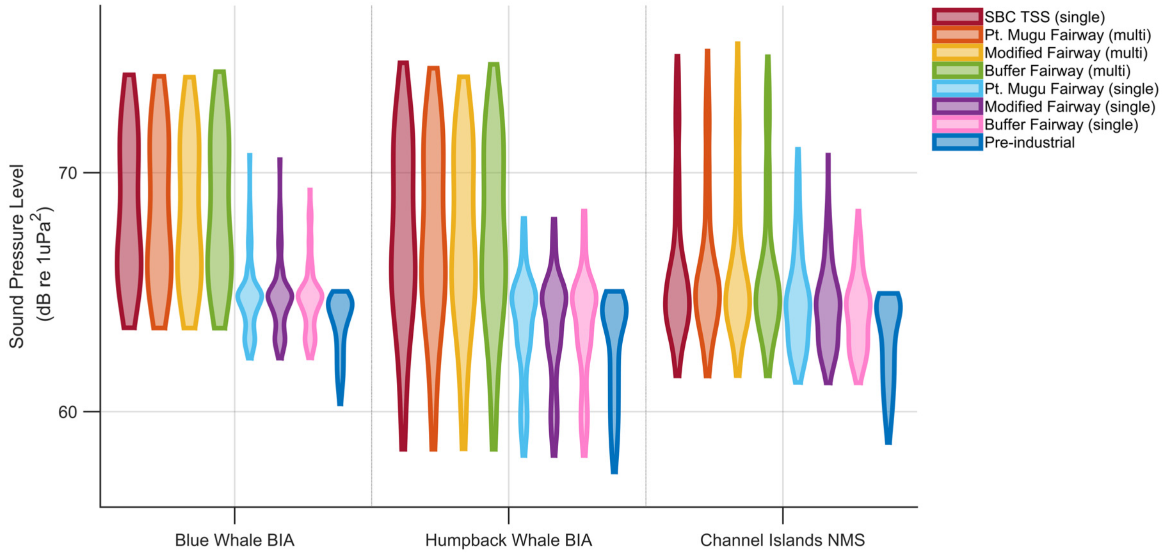

FIG. 6. (Color online) Distribution of SPLs within each critical habitat for seven space-centric simulations, in addition to pre-industrial ocean noise. The single-route techniques allowed for the greatest reduction in SPL compared to the multi-route techniques.

influenced by the portion of the area encompassing shallow, nearshore regions that are shielded bathymetrically from noise propagating from the shipping lanes and solely frequented by small boats.

The implementation of a speed reduction for all ships showed the greatest noise decrease across all three critical habitats (Fig. 4). The maximum decrease in SPL was in the Humpback Whale BIA with a 3.8 dB reduction. The SPL decrease associated with speed reduction of cargo ships was less than 1 dB different from the SPL decrease estimated if all ships reduced their speeds. The cargo retrofit approach had the smallest SPL reduction across the critical habitats with less than a 2 dB reduction across all habitats.

B. Source-centric: Excess noise analysis

Excess noise levels were defined as regions where model-predicted SPLs exceeded pre-industrial noise. Changes in the percentage area of excess noise where ship + wind noise was 3, 6, and 9 dB above pre-industrial noise are given in Table I(a). Our discussion (see the following) solely focuses on changes in excess noise of more than 3 dB. The analysis reveals that reducing source noise for all ships, or specifically for cargo ships, resulted in the most significant spatial reduction of excess noise.

The Humpback Whale BIA had the greatest decrease in area of excess noise, likely because the BIA boundary encompasses the TSS, and extends nearshore where small boats are present. The speed reduction for all ships simulation decreased the area of excess noise in the Humpback Whale BIA by up to 27% and the speed reduction for cargo ships alone decreased the area of excess noise by up to 23%. The cargo retrofit simulation resulted in the smallest decrease in area of excess noise of only 8.5%.

TABLE I. Change in the percentage area of excess noise (ship + wind noise 3, 6, and 9 dB above pre-industrial noise) for each simulation in comparison to the modern ocean noise levels across the critical habitats.

		Change in the % area of excess noise		
Simulation	Excess Noise threshold	Blue Whale BIA	Humpback Whale BIA	Channel Islands NMS
(a) Source-centric				
Speed reduction (all)	> 3 dB	24.8 ↓	27.3 ↓	12.1 ↓
	> 6 dB	21.5 ↓	22.4 ↓	5.4 ↓
	> 9 dB	12.4 ↓	12.7 ↓	5.8 ↓
Speed reduction (cargo)	> 3 dB	20.7 ↓	23.0 ↓	8.8 ↓
	> 6 dB	19.8 ↓	19.4 ↓	4.2 ↓
	> 9 dB	11.6 ↓	12.1 ↓	4.2 ↓
Retrofit (cargo)	> 3 dB	5.8 ↓	8.5 ↓	2.9 ↓
	> 6 dB	9.1 ↓	10.9 ↓	2.1 ↓
	> 9 dB	7.4 ↓	8.5 ↓	2.5 ↓
(b) Space-centric				
Pt. Mugu (multi-route)	> 3 dB	1.7 ↑	0.6 ↑	2.5 ↑
	> 6 dB	2.5 ↑	1.2 ↑	2.1 ↑
	> 9 dB	0.8 ↑	-	-
Modified Mugu (multi-route)	> 3 dB	-	1.2 ↓	-
	> 6 dB	-	-	0.4 ↑
	> 9 dB	0.8 ↓	1.2 ↓	-
Buffer Mugu (multi-route)	> 3 dB	0.8 ↑	-	0.4 ↑
	> 6 dB	1.7 ↑	0.6 ↑	0.4 ↑
	> 9 dB	1.8 ↑	0.6 ↑	-
Pt. Mugu (single-route)	> 3 dB	53.7 ↓	58.2 ↓	7.9 ↓
	> 6 dB	36.4 ↓	36.4 ↓	11.7 ↓
	> 9 dB	17.4 ↓	18.2 ↓	11.7 ↓
Modified Mugu (single-route)	> 3 dB	53.7 ↓	58.2 ↓	13.1 ↓
	> 6 dB	36.4 ↓	36.4 ↓	15.4 ↓
	> 9 dB	17.4 ↓	18.2 ↓	11.7 ↓
Buffer Mugu (Single-route)	> 3 dB	52.1 ↓	57.0 ↓	17.9 ↓
	> 6 dB	36.4 ↓	36.4 ↓	17.5 ↓
	> 9 dB	17.4 ↓	18.2 ↓	11.7 ↓

The CINMS had the least reduction in excess noise area across all scenarios, likely due to its lower baseline levels. This is attributable to its shallower bathymetry, which attenuates ship noise faster, as well as the inclusion of the backside of the Channel Islands, which is shielded from much of the shipping noise generated in the channel. Speed reduction for all ships resulted in a 12.1% decrease in the area of excess noise, while speed reduction for cargo ships alone reduced the area of excess noise by 4.2%. The cargo ship retrofit simulation decreased the area of excess noise by 2.9%.

Within the Blue Whale BIA, SPL reductions were similar to those in the Humpback Whale BIA, with the area of excess noise reduced by 24.8% (speed reduction of all ships), 20.7% (speed reduction of cargo ships), and 5.8% (retrofit of cargo ships). Overall, the speed reduction simulations proved to be the most effective in reducing SPL intensity and reducing the spatial extent of excess noise across critical habitats.

C. Space-centric: Sound Pressure Level Analysis

Sound pressure levels were simulated for seven different space-centric mitigation options. The difference in SPL between the SBC TSS technique and the simulations across the region is shown in Fig. 5. Unlike the source-centric approaches, space-centric methods resulted in a mix of reductions and increases in SPL within critical habitats, as well as regions where SPL remained unchanged. The Pt. Mugu Fairway (multi-route) approach resulted in an increase in SPL on the southern side of Santa Rosa, Santa Cruz, and Anacapa Islands, as noise generated from the proposed fairway propagates into the CINMS boundary. The Buffer Fairway (multi-route) approach exhibited the smallest increase in SPL on the south side of the islands inside CINMS.

The single-route techniques achieved maximum reductions (cell with the greatest decrease) of 11.6 dB for all simulations and a maximum increase (cell with the greatest increase) of 7.3 dB in the Pt. Mugu Fairway simulation. The SPLs on the north side of the island for all single-route techniques were reduced by > 5 dB. With an increase in the percent of traffic on the southern side of the islands in the single-route techniques, there was an increase in SPL values for all simulations.

The Modified Fairway and Buffer Fairway approaches pushed some of the increases in SPL outside of the sanctuary boundary. The Buffer Fairway option did not increase SPLs on the south side of Santa Rosa Island as much as the other scenarios. In general, the multi-route approach showed minimal difference from the current TSS scheme when compared to the single-route approaches which significantly decreased SPLs north of the islands, at the expense of increased SPLs south of the islands.

Within each critical habitat, the distribution of SPLs was extracted for each space-centric technique (Fig. 6). The multi-route SPL distributions largely mirrored the current SBC TSS distribution, while the single-route distributions were noticeably reduced. SPL distributions within each critical habitat shared the same patterns as the modern noise approach that utilized the August 2017 AIS data, with the highest median SPL occurring within the Blue Whale BIA, the highest SPL regions occurring in CINMS, and the lowest SPLs regions predicted in the Humpback Whale BIA.

Among the multi-route approaches, the modified fairway scenario achieved the greatest maximum noise level reduction across all three habitats. However, the multi-route techniques resulted in negligible changes in SPL distributions for the Blue Whale BIA and the Humpback Whale BIA (increases <0.3 dB). CINMS experienced an increase of 1.5 dB along its southern edge under the Pt. Mugu Fairway and Modified Fairway scenarios. This was reduced with the Buffer Fairway technique to an increase of 0.6 dB.

For the single-route approaches, all three techniques produced approximately a 10–12 dB reduction across habitats. All three single-route simulations were similar for the Humpback Whale BIA. The Buffer Fairway simulation had the lowest SPLs for CINMS and the Blue Whale BIA.

D. Space-centric: Excess noise analysis

To evaluate the spatial extent of noise reduction within the habitats, the percentage change in the area of excess noise was analyzed [Table I(b)]. The changes in the percentage area of excess noise where ship + wind noise was 3, 6, and 9 dB above pre-industrial noise are shown in Table I(b). Our discussion focuses on changes in the area of excess noise of more than 3 dB.

The multi-route approaches resulted in a mix of small increases, small decreases, and no changes in the percentage area of excess noise (>3 dB). The Pt. Mugu (multi-route) technique created increases in the percentage area with excess noise in all critical habitats, ranging from 0.5% to 2.5%. The Modified Fairway (multi-route) technique reduced the area of excess noise in the Humpback Whale BIA by 1.2%, with no significant changes in the other critical habitats. The Buffer Fairway (multi-route) technique slightly increased areas of excess noise in the Blue Whale BIA and CINMS by less than 1%.

In contrast, the single-route approaches consistently achieved greater reductions in percentage area of excess noise compared to the multi-route options. Pt. Mugu (single-route) reduced the excess noise area by over 50% in the BIAs and approximately 8% in CINMS. The Modified Mugu (singe-route) reduced excess noise area in CINMS to 13%. The Buffer Mugu (single-route) produced the greatest reduction in excess noise area for CINMS of approximately 18%, and over 50% for the BIAs.

IV. DISCUSSION

This paper presents a framework for modeling present-day anthropogenic noise levels and projecting future noise reduction scenarios. Our simulations of ship noise mitigation strategies (source-centric and space-centric approaches) demonstrated reductions in noise within critical habitats of endangered whale species and a protected national marine sanctuary. Multiple metrics of noise reduction are provided to include a comprehensive picture of changes in ship noise. Incorporating these results into the planning process for shipping activity in the region could benefit this important coastal marine ecosystem, especially considering anticipated increases in shipping (UNCTAD, 2022). Simulating scenarios through modeling provides a method for evaluating noise reduction strategies and tradeoffs before they are implemented, saving time and resources.

A. Effectiveness of noise reduction strategies in critical habitats

Among the source-centric options explored in this study, reducing ship speeds to a target of 10 knots for all vessels within the region resulted in the greatest reduction of SPLs and excess noise area across the region, including within the critical habitats. A speed reduction applied solely to cargo ships achieved similar reductions, albeit slightly less; cargo ships represent an average of approximately 39% of vessel transits in this study, but have some of the highest MSL measurements compared to other ship types. Retrofitting was the least effective source-centric option for reducing noise in this study. However, this strategy would have noise reduction benefits throughout the entirety of a ship's route and avoid increases in other areas, potentially contributing to more sustainable shipping at the global scale. The retrofitting design evaluated in this study was focused on increasing fuel efficiency, rather than reducing noise, although noise reduction was a co-benefit of the initiative (ZoBell *et al.*, 2023a). Future investigations could explore whether retrofitting and design changes aimed specifically at noise mitigation could be more effective. It is also noteworthy that bathymetry and propagation played a role in which areas of the critical habitat were exposed to higher levels of noise. For instance, the area immediately surrounding the Channel Islands showed lesser changes in SPL values due to bathymetry-driven attenuation in shallow waters. Conversely, constructive interference increased SPL values in regions with steep-walled bathymetry. A nuanced approach to noise reduction that considers local bathymetry and propagation effects is essential for optimizing noise mitigation in marine environments.

Based on the findings of this study, we recommend that speed-reduction programs, such as the Protecting Blue Whales and Blue Skies program consider expanding to include additional ship types into their programs to increase noise reduction across critical habitats. However, particularly targeting large ships, such as cargo ships and tankers, may allow for similar reductions. While retrofitting all cargo ships is unlikely, identifying exceptionally noisy designs for retrofitting—especially combined with a speed reduction program—could achieve greater noise reduction than either method applied alone.

B. Communicating noise reduction in coastal shipping planning processes

Routing options redistributed areas of high and low SPL within the study region and delineated habitats, yielding different net effects. The 2023 Port Access Route Study is proposing a multi-route approach to the region, including the SBC TSS and the Pt. Mugu Fairway (United States Coast Guard, 2023). Among the alterations to the multi-route techniques investigated in this study, the Modified Fairway and the Buffer Fairway had the lowest SPL values, depending on the critical habitat. These findings suggest that allowing for more space between the fairway and the critical habitat boundaries may be beneficial. The Modified Fairway approach achieved the greatest reduction in the area of excess noise among the multi-route options.

External protected area buffer zones have been reported to be beneficial in protecting critical habitats from spreading threats, such as noise (Kubacka *et al.*, 2022; Palomo *et al.*, 2013; Shafer, 1999). In these areas, beyond-boundary awareness was noted to be an important factor in deciding where threats are delimited in proximity to these protected areas. External buffers may be helpful when proposing shipping lanes in this region, with overlapping protected areas and threats (Kubacka *et al.*, 2022; Palomo *et al.*, 2013). However, it is important to note that the noise reductions achieved by the multi-route techniques were on the order of 1–2.5 dB, which was significantly less than the reductions achieved by the single-route techniques.

Although not proposed in the 2023 PARS, the removal of the SBC TSS resulted in the most significant reduction in SPL and excess noise area for both the source-centric and space-centric options. The Blue Whale BIA and CINMS showed the greatest reduction in SPL with the Buffer Fairway technique, while the Humpback Whale BIA had the greatest reduction with the Modified Fairway technique. The single-route fairway options led to reductions in excess noise area of over 50% for both the Blue Whale BIA and Humpback Whale BIA. Given these findings, we recommend that future PARS consider the removal of the SBC TSS, redirecting large commercial ship traffic exclusively to the southern side of the Channel Islands.

The routing changes examined in this study are helpful for the BIA and national marine sanctuary boundaries within the SBC region as they were defined at the time of this analysis. However, as ocean conditions change and new boundaries are designated, we recommend revisiting and updating these simulations to account for changes in species' home ranges and migration pathways resulting from global environmental change.

C. Additional considerations and next steps

While we have outlined several proposed strategies here, there are additional options that merit consideration. As mentioned earlier, this study only included habitat boundaries that were published at the time of analysis, however, many other species utilize this region during different times of the year. Eastern North Pacific gray whales migrate from their breeding grounds off Baja California, Mexico, to feeding grounds in Alaska, following the California coastline for much of their journey. Additionally, past studies indicate a year-round presence of fin whales along the West Coast. Future analyses could incorporate revised BIAs for cetaceans in the West Coast region of the U.S., as well as consider other species of concern, such as fish and invertebrates (Calambokidis *et al.*, 2024).

In addition to considering alternative habitats, future research would benefit from the investigation of additional noise reduction strategies and techniques. For instance, the current traffic patterns show that 80% of vessels utilize the SBC TSS while 20% of vessels use the southern lanes. Future forecasting analyses could investigate how varying the percentage of usage between these two routes might impact noise levels to identify the potential for reduction of SPLs and areas of excess noise within habitats. There may also be simulations in which a combination of source-centric and space-centric options are employed. For example, if vessels were required to slow down on the SBC TSS while maintaining a slightly faster target speed for the southern lanes, this might make the transit times for the two routes equivalent, removing an incentive for vessel operators to choose the faster route.

Dynamic management could offer an additional strategy for mitigating noise pollution in this region. The Blue Whale and Humpback Whale BIAs are feeding regions that are only occupied by these species for specific months of the year. The Protecting Blue Whales and Blue Skies program incentivizes vessels to slow down during the months of peak whale feeding and migration (Morten *et al.*, 2022). Another example of a temporally dynamic management effort is the mandatory North Atlantic Right whale seasonal management areas, where vessels are required to transit at 10 knots or less during peak whale season (Laist *et al.*, 2014; Merrick *et al.*, 2001). Spatial dynamic management, such as routing efforts could be employed in the same way, by employing the SBC TSS during months out of the year when whales are not present and employing the Pt. Mugu Fairway lanes when whales are utilizing the SBC. Considering the planning unit size, which is currently under discussion for conservation efforts addressing whale entanglements, could be considered in spatial dynamic management for routing as well (Welch *et al.*, 2024).

Overall, this paper identifies an approach for modeling current anthropogenic ocean noise and simulating future scenarios. We propose actionable steps to reduce ship noise in a heavily trafficked area overlapping with critical habitats. To effectively address noise in this region, managers, industry, and government agencies may begin to implement strategies that are known to reduce anthropogenic noise and minimize potential impacts on marine species.

ACKNOWLEDGMENTS

A special thanks to members of the Scripps Whale Acoustics Lab, Scripps Machine Listening Lab, and Scripps Acoustic Ecology Lab for their support over the duration of the project. We thank Jessica Morten and Sean Hastings for information on the 2023 Port Access Route Study. We thank Dr. John Ahlquist for thoughtful conversations on applying marine science to policy topics. A special thank you Lee Kindberg, for support and inspiration for this project, and a career dedicated to investigating sustainable solutions for marine transportation. This work was funded by the Dr. Nancy Foster Scholarship (Office of National Marine Sanctuaries) and the UCSD Science Policy Fellowship.

AUTHOR DECLARATIONS

Conflict of Interest

The authors declare that they have no competing interests.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Aktas, T. U., Shi, J., Lim, G. J., Prousalidis, J., D'Agostino, F., and Liang, C. (**2023**). "Decarbonization of the Maritime Transportation Systems: Recent progress, challenges, and prospects," in *Proceedings of the 2023 IEEE Electric Ship Technologies Symposium, ESTS 2023*, August 1–4, Alexandria, VA, pp. 224–230.

Barlow, J., and Forney, K. A. (**2007**). "Abundance and population density of cetaceans in the California Current ecosystem," Fish. Bull. **105**(4), 509–526.

Calambokidis, J., Kratofil, M., Palacios, D. M., Lagerquist, B., Schorr, G., Hanson, B., Baird, R., Forney, K. A., Becker, E. A., Rockwood, C., and Hazen, E. (**2024**). "Biologically Important Areas II for cetaceans within U.S. and adjacent waters—West Coast region," Front. Mar. Sci. (published online).

Calambokidis, J., Steiger, G. H., Curtice, C., Harrison, J., Ferguson, M. C., Becker, E., DeAngelis, M., and Van Parijs, S. M. (**2015**). "Biologically important areas for cetaceans within U.S. waters–A special issue," Aquat. Mamm. **41**(1), 39–53.

Checkley, D. M., and Barth, J. A. (**2009**). "Patterns and processes in the California Current system," Prog. Oceanogr. **83**(1–4), 49–64.

Chou, E., Southall, B. L., Robards, M., and Rosenbaum, H. C. (**2021**). "International policy, recommendations, actions and mitigation efforts of anthropogenic underwater noise," Ocean Coastal Manage. **202**, 105427.

Collins, M. D. (**2001**). "User's Guide for RAM Versions 1.0 and 1.0p. 14" (Naval Research Laboratory, Washington, DC).

Crowder, L. B., Osherenko, G., Young, O. R., Airamé, S., Norse, E. A., Baron, N., Day, J. C., Douvere, F., Ehler, C. N., Halpern, B. S., and Langdon, S. J. (**2006**). "Resolving mismatches in U.S. ocean governance," Science **313**(5787), 617–618.

Findlay, C. R., Rojano-Doñate, L., Tougaard, J., Johnson, M. P., and Madsen, P. T. (**2023**). "Small reductions in cargo vessel speed substantially reduce noise impacts to marine mammals," Sci. Adv. **9**(25), p.eadf2987.

Haren, A. (**2007**). "Reducing noise pollution from commercial shipping in the Channel Islands National Marine Sanctuary: A case study in marine protected area management of underwater noise," J. Int. Wildl. Law Policy **10**, 153–173.

Hildebrand, J. A., Frasier, K. E., Baumann-Pickering, S., and Wiggins, S. M. (**2021**). "An empirical model for wind-generated ocean noise," J. Acoust. Soc. Am. **149**(6), 4516–4533.

IMO (**2014**). "Guidelines for the reduction of underwater noise from commercial shipping to address adverse impacts on marine life" (IMO, London), Vol. 44, Issue April.

IMO (**2018**). "Furthering international efforts to reduce the adverse impacts of underwater noise from commercial ships," (IMO, London), Vol. 73, Issue 18.

IMO (**2023**). "Revised guidelines for the reduction of underwater radiated noise from shipping to address adverse impacts on marine life," (IMO, London).
IWC (**2014**). Draft Joint Workshop Report: Predicting Sound Fields—Global Soundscape Modelling to Inform Management of Cetaceans and Anthropogenic Noise, 15–16 April, 2014, Leiden, Netherlands, Report SC/65b/Rep03.
Kubacka, M., Żywica, P., Vila Subirós, J., Bródka, S., and Macias, A. (**2022**). "How do the surrounding areas of national parks work in the context of landscape fragmentation? A case study of 159 protected areas selected in 11 EU countries," Land Use Policy **113**, 105910.
Laist, D. W., Knowlton, A. R., and Pendleton, D. (**2014**). "Effectiveness of mandatory vessel speed limits for protecting North Atlantic right whales," Endang. Species Res. **23**(2), 133–147.
MacGillivray, A., and De Jong, C. (**2021**). "A reference spectrum model for estimating source levels of marine shipping based on automated identification system data," J. Mech. Sci. Eng. **9**(4), 369.
MacGillivray, A. O., Li, Z., Hannay, D. E., Trounce, K. B., and Robinson, O. M. (**2019**). "Slowing deep-sea commercial vessels reduces underwater radiated noise," J. Acoust. Soc. Am. **146**(1), 340–351.
Malinka, C. E., Tollit, D. J., Trounce, K., and Wood, J. D. (**2023**). "Evaluating the benefits of noise reduction mitigation: The ECHO program," in *The Effects of Noise on Aquatic Life* (Springer, New York), pp. 1–21.
Marine Mammal Protection (**1972**). "Marine Mammal Protection Act, 1," https://www.govinfo.gov/app/details/COMPS-1679 (Last viewed August 15, 2023).
McKenna, M. F., Soldevilla, M., Oleson, E., Wiggins, S., and Hildebrand, J. A. (**2009**). "Increased underwater noise levels in the Santa Barbara Channel from commercial ship traffic and the potential impact on blue whales (*Balaenoptera musculus*)," in *Proceedings of the 7th California Islands Symposium*, February 5–8, Ventura, CA, pp. 141–149.
Merrick, R. L., Clapham, P. J., Cole, T. V. N., Gerrior, P., and Pace, R. M. I. (**2001**). "Identification of seasonal area management zones for North Atlantic right whale conservation," in *Proceedings of the Northeast Fisheries Science Center Reference Document* (NFSC, Woods Hole, MA), p. 28.
Morten, J., Freedman, R., Adams, J. D., Wilson, J., Rubinstein, A., and Hastings, S. (**2022**). "Evaluating adherence with voluntary slow speed initiatives to protect endangered whales," Front. Mar. Sci. **9**, 833206.
National Marine Sanctuaries (**2000**). "National Marine Sanctuaries Act, 2000."
Oleson, E. M., Calambokidis, J., Burgess, W. C., McDonald, M. A., LeDuc, C. A., and Hildebrand, J. A. (**2007**). "Behavioral context of call production by eastern North Pacific blue whales," Mar. Ecol. Prog. Ser. **330**, 269–284.
Palomo, I., Martín-López, B., Potschin, M., Haines-Young, R., and Montes, C. (**2013**). "National Parks, buffer zones and surrounding lands: Mapping ecosystem service flows," Ecosyst. Serv. **4**, 104–116.
Redfern, J. V., Hatch, L. T., Caldow, C., DeAngelis, M. L., Gedamke, J., Hastings, S., Henderson, L., McKenna, M. F., Moore, T. J., and Porter, M. B. (**2017**). "Assessing the risk of chronic shipping noise to baleen whales off Southern California, USA," Endang. Species Res. **32**(1), 153–167.
Ricciardulli, L. (**2022**). "The climate data guide: CCMP: Cross-calibrated multi-platform wind vector analysis," https://climatedataguide.ucar.edu/climate-data/ccmp-cross-calibrated-multi-platform-wind-vector-analysis (Last viewed August 15, 2023).
Santa Barbara Amateur Radio Club Inc. (**2024**). "Santa Barbara Wireless Foundation," https://sbwireless.org/current/ (Last viewed August 15, 2023).
Shafer, C. L. (**1999**). "US National Park buffer zones: Historical, scientific, social, and legal aspects," Environ. Manage. **23**(1), 49–73.
Smith, T. A., and Rigby, J. (**2022**). "Underwater radiated noise from marine vessels: A review of noise reduction methods and technology," Ocean Eng. **266**(P1), 112863.
UNCTAD (**2022**). Navigating Stormy Waters, UNCTAD/RMT/2022 (United Nations, Geneva, Switzerland).
United States Coast Guard (**2011**). "Port Access Route Study," in *The Approaches to Los Angeles-Long Beach and in the Santa Barbara Channel* (United States Coast Guard, Washington, DC) Vol. 76, Issue 211.
United States Coast Guard (**2023**). "Port access route study (PARS): The Pacific Coast From Washington to California" (United States Coast Guard, Washington, DC), Vol. 88, Issue 107.
Welch, H., Liu, O. R., Riekkola, L., Abrahms, B., Hazen, E. L., and Samhouri, J. F. (**2024**). "Selection of planning unit size in dynamic management strategies to reduce human–wildlife conflict," Conserv. Biol. **38**(3), e14201.
Zhang, Z. G., Yin, J. C., Wang, N. N., and Hui, Z. G. (**2019**). "Vessel traffic flow analysis and prediction by an improved PSO-BP mechanism based on AIS data," Evolving Syst. **10**(3), 397–407.
ZoBell, V. M. (**2023**). *Moving Cargo, Keeping Whales: Investigating Solutions for Ocean Noise Pollution* (University of California, San Diego, CA).
ZoBell, V. M., Frasier, K. E., and Hildebrand, J. A. (**2021a**). "Sound levels of participating vessels during the 2021 vessel speed reduction program in the Santa Barbara Channel," Marine Physical Laboratory Technical Memora 659 (Marine Physical Laboratory, San Diego, CA).
ZoBell, V. M., Frasier, K. E., Morten, J. A., Hastings, S. P., Peavey Reeves, L. E., Wiggins, S. M., and Hildebrand, J. A. (**2021b**). "Underwater noise mitigation in the Santa Barbara Channel through incentive-based vessel speed reduction," Sci. Rep. **11**(1) 18391.
ZoBell, V. M., Gassmann, M., Kindberg, L. B., Wiggins, S. M., Hildebrand, J. A., and Frasier, K. E. (**2023a**). "Retrofit-induced changes in the radiated noise and monopole source levels of container ships," PLoS One **18**(3), e0282677.
ZoBell, V. M., Hildebrand, J. A., and Frasier, K. E. (**2023b**). "Sound levels of participating vessels during the 2023 vessel speed reduction program in the Santa Barbara channel," *Marine Physical Laboratory Technical Memora* (Marine Physical Laboratory, San Diego, CA).
ZoBell, V. M., Hildebrand, J. A., and Frasier, K. E. (**2024**). "Comparing pre-industrial and modern ocean noise levels in the Santa Barbara Channel," Mar. Pollut. Bull. **202**, 116379.