Mapping underwater vessel noise propagation to assess acoustic impact of anthropogenic noise on the Florida Keys National Marine Sanctuary

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ABSTRACT
Anthropogenic noise is increasing in the oceans and can have a variety of impacts on marine organisms ranging from physiological damage to an individual, to disruption of group communication. In some coastal systems, smaller recreational vessels used for fishing and diving trips are the dominant anthropogenic sound source. While there have been many studies looking at the impact of sounds from larger vessels on marine mammals, there is limited knowledge of sound impacts from smaller vessels on mammals, as well as fish and invertebrate species that inhabit these shallow coastal areas. The goal of this study was to predict the acoustic footprint of dominant vessel tracks within and around the Florida Keys National Marine Sanctuary (FKNMS). The potential influence and intensity of anthropogenic noise within protected areas of the FKNMS was investigated using dBSea, an acoustic propagation modeling software, and AIS vessel traffic data. Predicted sound levels from larger vessels did not propagate into the sanctuaries studied, and smaller vessels, though underrepresented in the vessel traffic data, may have more of a local impact in the shallow water of the sanctuary system. These methods and predictions can be used with long-term passive acoustic monitoring and automatic identification system (AIS) vessel tracking data to establish guidelines to better protect the natural acoustic environment of the FKNMS.

INTRODUCTION

Anthropogenic noise is increasing throughout the ocean as a result of vessel (shipping and recreational), construction (pile driving), military (active sonar), and other sound-making activities (Hawkins & Popper 2017). Because sound propagates well underwater, it is an important cue and common communication tool for a wide range of marine species including mammals, fish, and invertebrates (Hawkins & Popper 2017, Whitfield & Becker 2014). There is a growing need to assess the potential impacts of anthropogenic noise on natural acoustic habitats and the behavioral and physiological effects on marine species subjected to the noise.

Integrating vessel traffic information from the Automatic Identification System (AIS) with noise propagation modeling can aid in evaluating anthropogenic noise impact in marine systems. This data can provide location information and vessel characteristics including size, tonnage, draft, speed, and on-board equipment for vessels present in the study area of interest (Neenan et al. 2017). Using the location information, and incorporating known source levels for different vessels, propagation models can be used to predict the received sound levels propagating from these tracked vessels (Neenan et al. 2017, Veirs et al. 2016, Hatch et al. 2008). Neenan et al. (2017) assessed the cumulative impact of vessel noise modeled from AIS vessel track lines and found that monthly received levels were highest during summer months when there was increased vessel activity in UK waters. Within the Stellwagen Bank National Marine Sanctuary, predicted noise levels from large commercial vessel traffic contributed substantially to sound levels within the sanctuary, particularly around high traffic locations (Hatch et al. 2008). Additional studies expand on this work by adding information from passive acoustic recordings of the study area to evaluate the impact of tracked vessels on the communication space of select marine mammals and fish (Putland et al. 2018, Stanley et al. 2017).

These studies provide evidence that integrating AIS data with noise propagation models is an effective method to assess anthropogenic noise impacts, however the study areas were further offshore where the water is deep, and larger vessels have a greater influence. With increases in coastal population, tourism, and recreation, associated anthropogenic sounds will also increase in these shallower areas, and there is a need to examine propagation into and around shallow water environments (Gonson et al. 2016, Hawkins & Popper 2017, Whitfield & Becker 2014). One such area is the Florida Keys, and the Florida Keys National Marine Sanctuary (FKNMS). As of 2017, the Florida Keys was home to 77,000 residents with 2.9 million annual visitors (Symons 2017). Diving, recreational and commercial fishing, and recreational boating are all popular activities for both residents and tourists visiting and living in the Florida Keys. Every ten years, researchers and community partners conduct a survey of use of the FKNMS by dive operators, commercial fishermen, and environmental groups. Between 1995/1996 and 2005/2006 the study found increased use of FKNMS zones by these groups, particularly by dive operators visiting sanctuary preservation areas (SPAs) (Shivlani et al. 2008). New initiatives by NOAA, the National Marine Sanctuary Program and the US Navy aim to maintain protection status of these areas by assessing the potential anthropogenic noise impacts in these designated sanctuaries (NOAA/NMS 2018). Predicting the sound footprint produced by various anthropogenic noise sources can provide a baseline characterization of received sound levels and potential acoustic impacts throughout the system (Halliday et al. 2017).

Modeling underwater sound propagation is a complex problem, particularly in shallow coastal systems like coral reefs (Costley et al. 2009, Hawkins & Popper 2017). Bathymetry, bottom type, water temperature, and salinity, among other things, all influence how far a sound can travel (Halliday et al. 2017, Hawkins & Popper 2017). In addition, variations in the source of sound, what is producing the sound, and how loud the sound is, must be considered. For example, boat noise can vary greatly depending on boat size, the load it is carrying, the engine size and location, and specific propeller characteristics (Ainslie et al. 2009, Costley et al. 2009, Holles et al. 2013, Veirs et al. 2016). Using AIS vessel traffic data and modeling noise propagation along tracks within highly trafficked areas, we hope to address the following questions: 1) For the most widely used ship tracks, what are the predicted received levels associated with vessels within the area surrounding the FKNMS? 2) What is the area of overlap of the acoustic footprint exceeding audible and behavioral sound threshold levels and the MPA boundaries?

METHODS

Study Area

The Florida Keys National Marine Sanctuary (FKNMS) is one of NOAA’s national marine protected areas, and is home to diverse, and fragile, marine habitats and species. Within the FKNMS there are 25 different sanctuaries that vary in size, water depth, level of protection, and proximity to shipping channels. For the purpose of this study, we are interested in assessing vessel traffic activity and noise propagation within and around 10 of these sanctuaries off the lower Florida Keys (Figure 1).

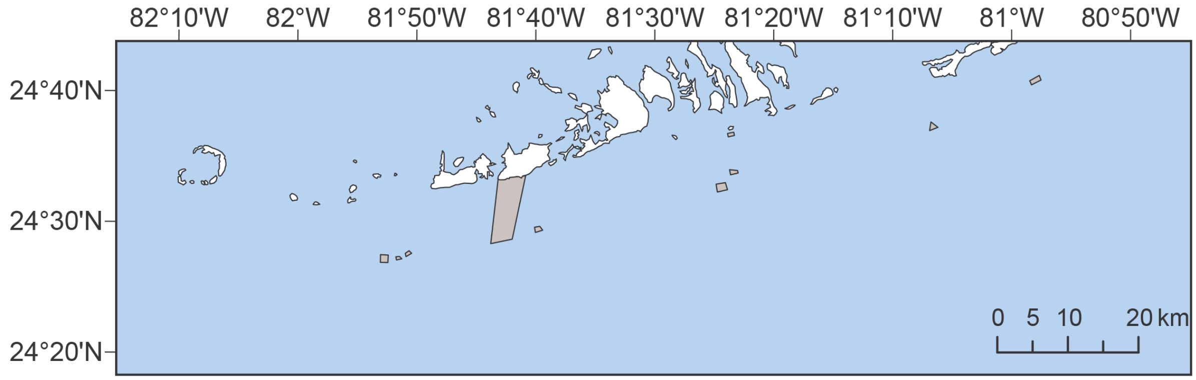


Figure 1: Site map of the lower Florida Keys and the ten sanctuaries of interest (gray polygons).

Vessel Tracking Data

Automatic Identification System (AIS) vessel tracking data was retrieved from marinecadastre.gov, a joint initiative from BOEM and NOAA to provide ocean information to scientists, managers and the public (BOEM & NOAA). AIS information was acquired for Zone 17 for all of 2017, and filtered to include the study area of interest, which includes the Florida Keys National Marine Sanctuary (xmin: 24.25°N, xmax: 24.75°N, ymin: 82.75°W, ymax: 80.75°W)

The raw AIS data contains points with attributes on location, time, speed over ground (SOG), vessel dimensions (length, width, draft), unique identifying information (MMSI), vessel name, and vessel code type (among other information). Using the Track Builder Pro 1.0 toolbox for ArcPro (Esri), the point data were converted into track lines using the recommended default settings, which breaks track lines when time delay between points exceeds 30 minutes and distance between consecutive points is greater than 1 mile. Vessel tracks were categorized by vessel type (i.e., Cargo, Tanker, Tug/Tow, Passenger, Fishing, Pleasure Craft/Sailing) using the vessel type code.

To produce models that accurately represent vessel traffic in the area, density maps for each vessel type were created using the AIS Vessel Transit Counter tool provided in the Track Builder Pro Toolbox. The transit counter provides the number of vessel tracks greater than 1km in length within each 100m x 100m grid cell. Using the density maps as a guide, individual vessel tracks from each vessel type were selected to best represent the dominant path(s) taken by that category. These track lines were then converted to point tracks with points equally spaced by 1 km for input into the noise propagation modeling software.

Noise propagation modeling

The commercial propagation modeling software dBSea (Marshall Day Acoustics, UK) was used to model vessel noise propagation throughout the lower Florida Keys. Model inputs include bathymetry, solver type, calculation frequencies, sound source (location, source level), calculation grid cell size, and water column and seafloor properties.

Bathymetry data was retrieved from GeoMapApp (Ryan et al. 2009, gmrt.org/GMRTMapTool) and saved as an ascii file with maximum grid resolution (61 m /node).

A smaller area of interest than the AIS data was used to reduce calculation time (xmin: 24.31°N, xmax: 24.73°N, ymin: 82.25°W, ymax: 80.75°W) The calculation grid was set up as follows:

	points	Size
X	305	500.7 m
Y	95	500.9 m
Z depth	75	7 m
Radial slices	100	3.6°
Range points	100	1522 m

Water column and Seafloor Properties

A sound speed profile for the area during the month of July was calculated using decadal average temperature and salinity data from the World Ocean Atlas for a point just offshore of the Florida Keys (24.5°N, 81.5°N) (Figure 2). Temperature for the model run was set to 17°C, the water column average temperature in July. Seafloor properties were set to the default of a layer of sand, as the spur and groove reef tract typical of the area is a mixture of sand and coral covered rocky bottom.

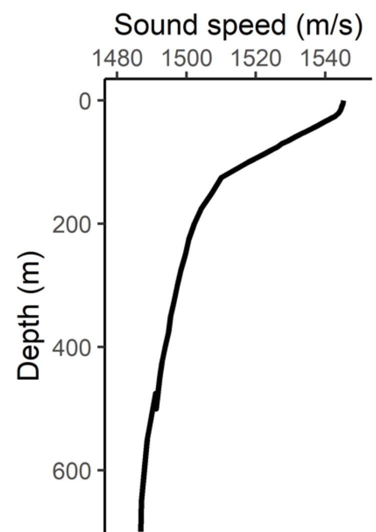


Figure 2: Sound speed profile for the waters off the Florida Keys calculated using temperature and salinity information from July.

Moving sound sources

For a moving source model, the noise propagation modeling software requires the location, time between points, depth of sound source, and sections to calculate between point sources. Time between each 1km spaced point was calculated using an average speed of the selected vessel or the vessel category average speed from the AIS data. Point tracks were edited to fit within the bounding box of the model area. Depth of the source was determined from the draft of the vessel, when available in the attribute data, or set to a reasonable depth based on vessel type. No additional computation sections were added between the input points. Source levels for each vessel type were taken from a meta-analysis of vessel noise propagation from Veirs et al. (2016) (Figure 3). Veirs et al. (2016) determined a median source level spectra for each vessel category by modeling noise propagation from vessel tracks recorded within the Salish Sea, which contains the commercial shipping ports for Seattle and Tacoma WA, USA, as well as Vancouver, BC, Canada.

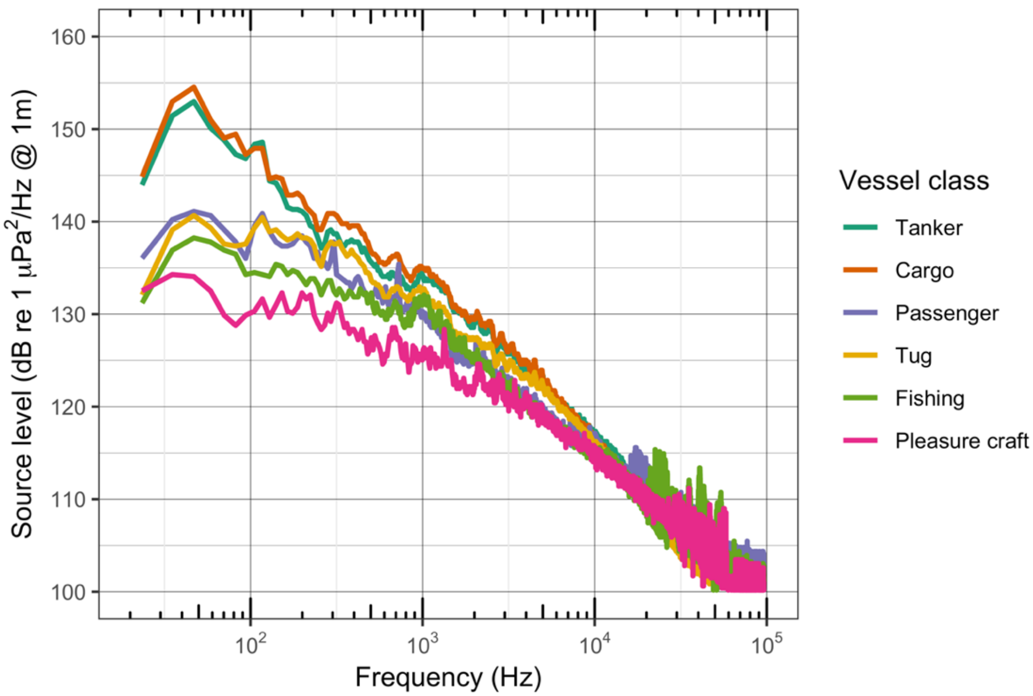


Figure 3: Acoustic spectra of noise produced by different categories of vessels. Spectra represent the median of all vessel source levels by vessel class calculated by Veirs et al. 2016. Figure adapted to include information for vessels of interest for this study from code and data provided by Veirs et al. 2016. For the purposes of this project, each model run for each vessel category used this median source level profile. A summary of selected vessel tracks, speed, and depth can be found in Table 1.

Table 1: Description of noise propagation model parameters for different vessels.

	Vessel Type	speed (m/s)	Draft (m)	SL (dB)	Calculation points	Notes
Overseas New York	Tanker	7.77	12.2	158.0	156	Offshore
Maersk Memphis	Cargo	7.27	10.9	159.2	156	Offshore
Genesis Patriot	Tug/Tow	4.32	5.1	149.1	156	Offshore
Kirstin Grace	Tug/Tow	4.6	3	149.1	145	Nearshore
Empress of the Seas	Passenger	6.36	7.1	149.0	128	Cruise ship
Yankee Freedom III	Passenger	12.65	2	149.0	50	Ferry
Grand Nellie	Passenger	2.67	1	149.0	39	Tour boat
Capt. Blinky	Passenger	5.6	1	149.0	15	Pilot boat
Stimstar	Fishing	12.86	1.5	146.1	85	nearshore
Stimstar	Fishing	12.86	1.5	146.1	29	offshore
Big Daddy	Fishing	3.85	1.5	146.1	37	Gulf-bound
Satori	Pleasure/Sail	5.35	1	142.1	30	Offshore
Pelican	Pleasure/Sail	3.02	1	142.1	39	Gulf-bound
Blue Pearl	Pleasure/Sail	5.35	1	142.1	88	Nearshore

Of the available solve equations (ray tracing, normal modes, parabolic equation), all model runs were calculated using the parabolic equation with Pade's terms set to 5, and octave assessment bandwidths between 31.5 and 500 Hz. The parabolic equation model for noise propagation calculations is commonly used because it incorporates seafloor and water column properties, and is suitable for deep and shallow water systems (Neenan et al. 2017).

Acoustic impact assessment

To assess acoustic impact on the study region, maps of received sound pressure levels (SPLs) were produced. Received levels were classed into the current audible and behavioral acoustic thresholds, 90 dB and 120 dB respectively (Halliday et al. 2017, Hawkins & Popper 2017). The number of cells from each model run that exceeded those levels were summed to show which areas were at higher risk.

RESULTS

Vessel traffic patterns

Over the one-year period (Jan 1 – Dec 31, 2017), a total of 4,205 unique vessels and 33,759 tracks greater than 1km in length were recorded in the study area surrounding the Florida Keys National Marine Sanctuary (Table 2). Recreational, Passenger, Tug/Tow and Cargo vessels were the most dominant vessel types. Vessel track patterns were consistent through space and time, however the proportion of tracks from different vessel types changed throughout the year (Figure 4). Recreational (Pleasure Craft/Sailing) vessels made up the majority of recorded tracks, however there were fewer tracks of this class recorded in the fall (Sep/Oct). The number of tracks per month was relatively consistent throughout the year ranging between 1997 and 3767 tracks within a given month. Though not directly included in the analysis or propagation models, there were numerous tracks for class Other or Not Available. Many of these tracks crossed over the marine reserves and should be considered in future analyses.

Table 2: Summary of vessel track information for the Florida Keys in 2017. Vessel tracks less than 1 km in length were excluded from analysis.

	Total Tracks	Unique vessels	Average vessel length (m)	Average speed (knots)
Tanker	2712	178	188	14.3
Cargo	4619	414	173	14.1
Tug/Tow	4420	229	36	9.1
Passenger	5223	146	113	9.8
Fishing	2626	165	23	4.2
Pleasure Craft/Sailing	8976	1129	20	10.4
Other	1474	1474	61	7.4
Not Available	3709	470	11	9.4

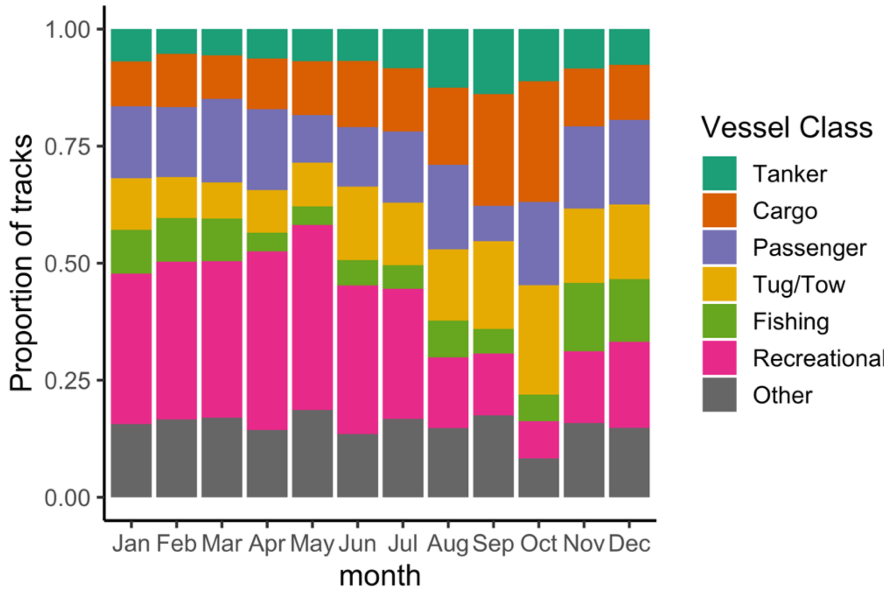


Figure 4: Proportion of total tracks greater than 1 km in length by month in 2017 for each vessel class.

Vessel traffic also varied within the boundaries of different sanctuaries (Table 3). Western Sambo Ecological Reserve had the highest counts of tracks within its boundaries, dominated by more than 1000 recreational vessels. Looe Key Research Only sanctuary had the fewest identified tracks.

Table 3: Number of tracks by vessel type that intersects with each reserve boundary plus a 500 m buffer.

	Total	Cargo	Passenger	Tug/Tow	Fishing	Recreational	Other
Western Sambo ER	1936	1	131	46	48	1192	518
Sand Key SPA	133	1	21	1	2	72	36
Looe Key SPA	96	0	6	0	2	59	29
Rock Key SPA	72	1	16	1	2	32	20
Eastern Dry Rocks SPA	66	0	14	0	3	25	24
Eastern Sambo RO	49	0	7	1	2	30	9
Coffins Patch SPA	49	0	1	0	23	15	10
Newfound Harbor SPA	38	0	0	6	1	18	13
Sombrero Key SPA	36	0	3	1	3	23	6
Looe Key RO	11	0	0	0	0	8	3

Density of vessel tracks varied by vessel type, with tracks from larger vessel classes (Tanker, Cargo, Tug/Tow) concentrated offshore, and tracks from smaller classes dominating nearshore areas (Figure 5). Fishing vessels left port around Key West and were more concentrated in the Gulf of Mexico. Passenger and recreational vessels were present closer to shore, predominately leaving Key West to go offshore, or running in two dominant paths parallel to shore on either side of the marine sanctuaries.

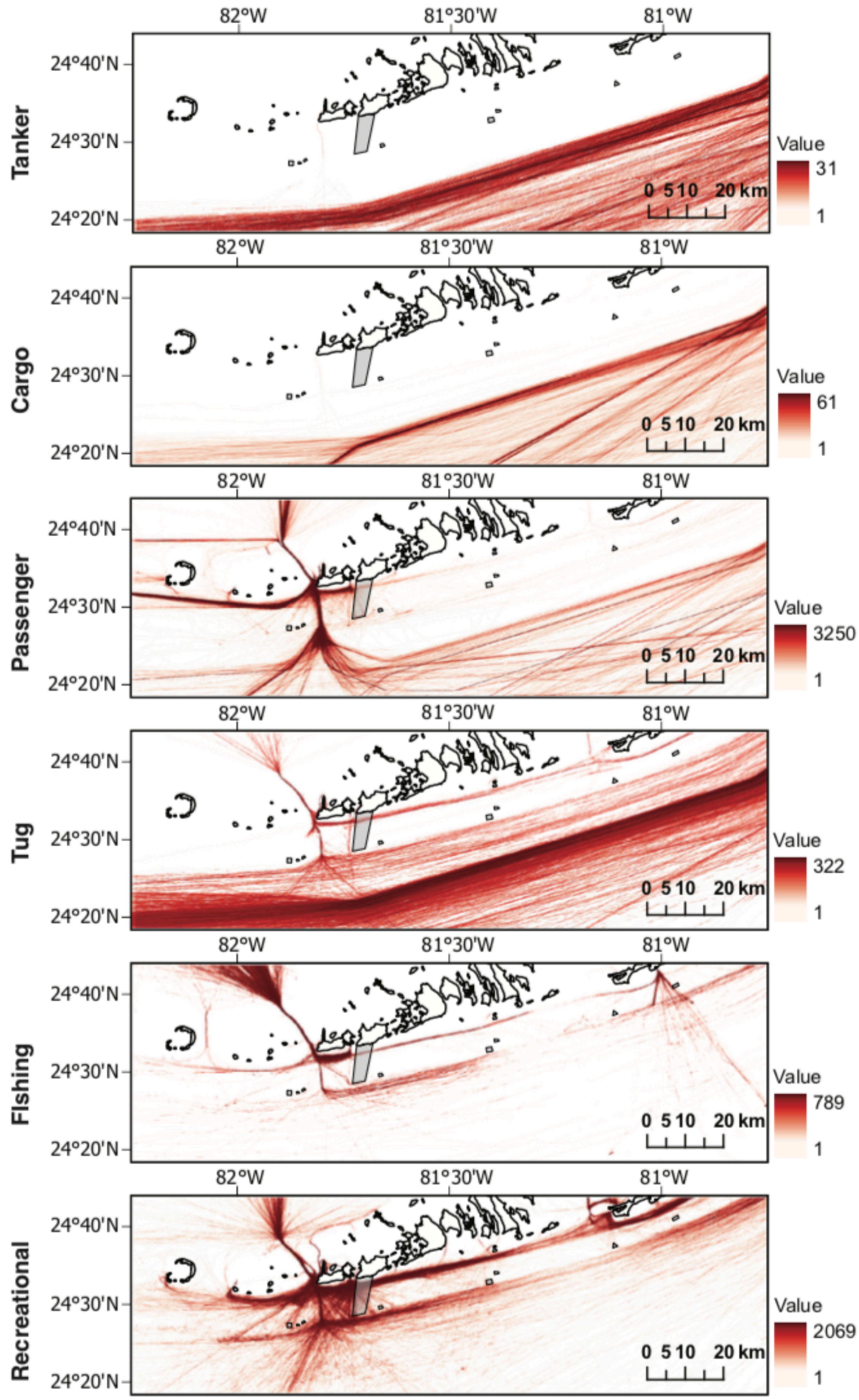


Figure 5: Vessel track density by class showing the total number of tracks that passed through each $100m^2$ grid cell. Density maps are displayed using the histogram equalize stretch function.

Tracks used for propagation modeling were extracted from the high traffic areas for each vessel class (Figure 6). Tanker and Cargo class vessels had one model track each, as the majority of tracks for these class types followed similar tracks offshore. Two tracks were modeled for the Tug/Tow class – one offshore track, and one track closer to shore that traveled back towards the Gulf of Mexico. Four tracks were modeled for the Passenger class to account for 1) ferry traffic leaving Key West towards the Dry Tortugas, 2) cruise ship traffic leaving Key West for offshore islands, 3) pilot vessels leaving Key West to bring larger ships in/out of port, and 4) tourist cruises to FKNMS sites. For fishing vessels, three tracks were modeled, including one track in the dominant traffic area in the Gulf of Mexico, and two tracks associated with the same vessel (*Stimstar*) that traveled parallel to the keys, and made multiple trips offshore. Three tracks in the Recreational vessel class were modeled to predict levels for tracks parallel to the Keys, traveling towards the Gulf, and traveling from Key West to areas offshore.

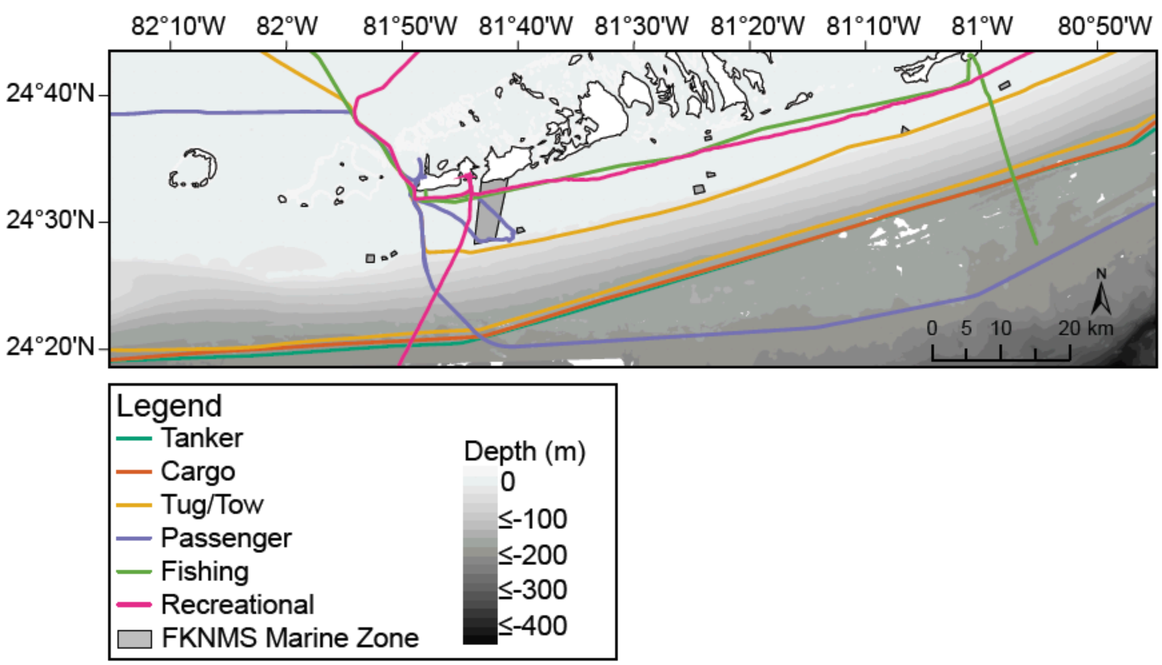


Figure 6: Study site map showing selected vessel track lines used in the propagation model, bathymetry of the study area, and the location of FKNMS marine zones.

Noise propagation modeling and acoustic impact

Noise from vessels along tracks further off shore propagated throughout the study region, but attenuated drastically along the shelf break (Figure 7). This illustrates that bathymetry highly influenced propagation of noise in the region. Received sound levels were highest for models including larger vessels (Tanker, Cargo) than those with smaller vessels (Recreational). While noise associated with vessel tracks propagated throughout the majority of the study region, particularly for larger vessel classes, the received levels exceeding the audible and behavioral thresholds were contained to the area surrounding the modeled track (Figure 8). Most of the predicted noise associated with smaller fishing and recreational vessels was below 90 dB.

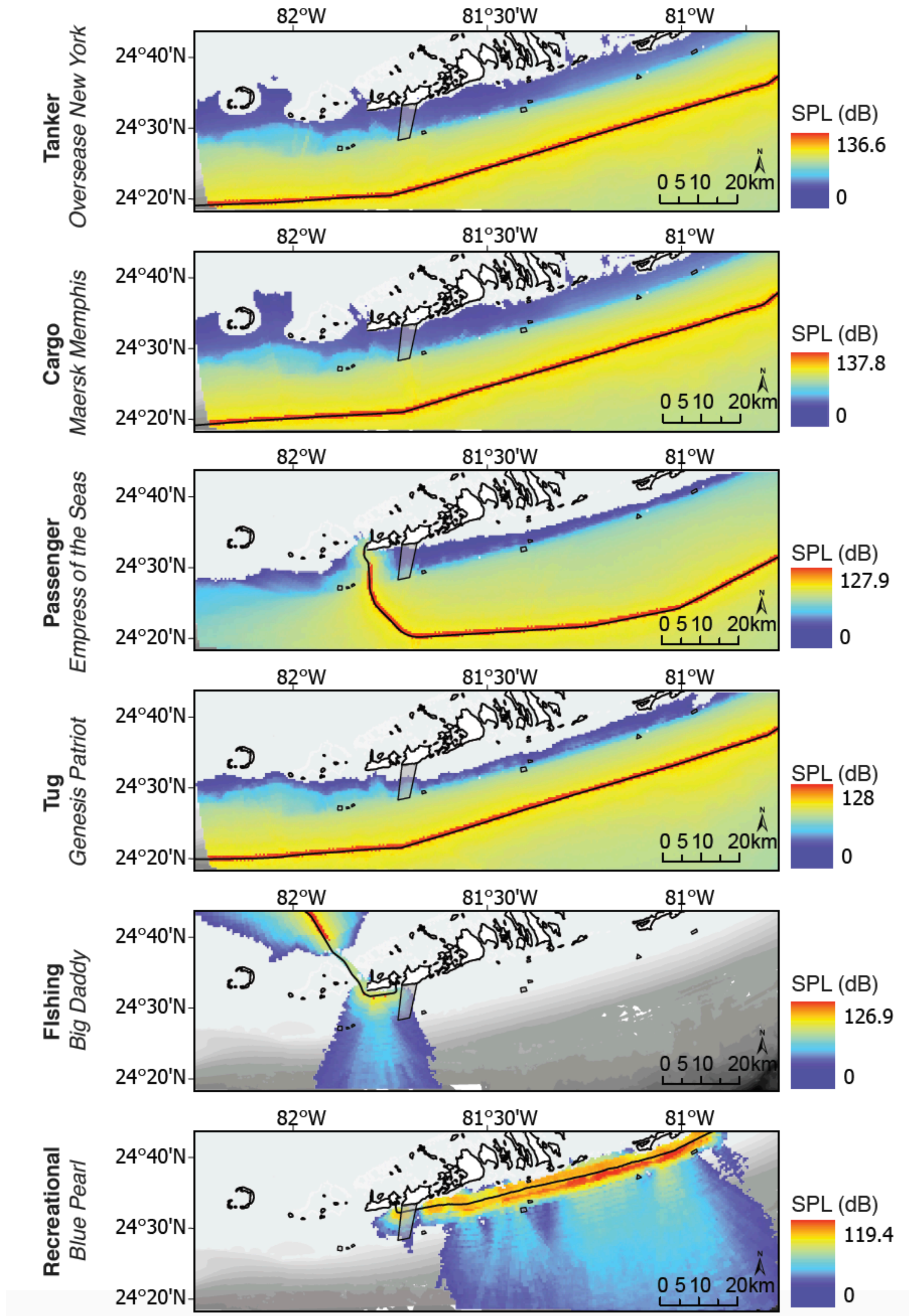


Figure 7: Vessel noise propagation model results for representative tracks from each vessel category. Track lines used in the model are shown in black, color range of the received sound levels are different for each vessel, with the maximum received level shown in red, and lower levels shown in blue.

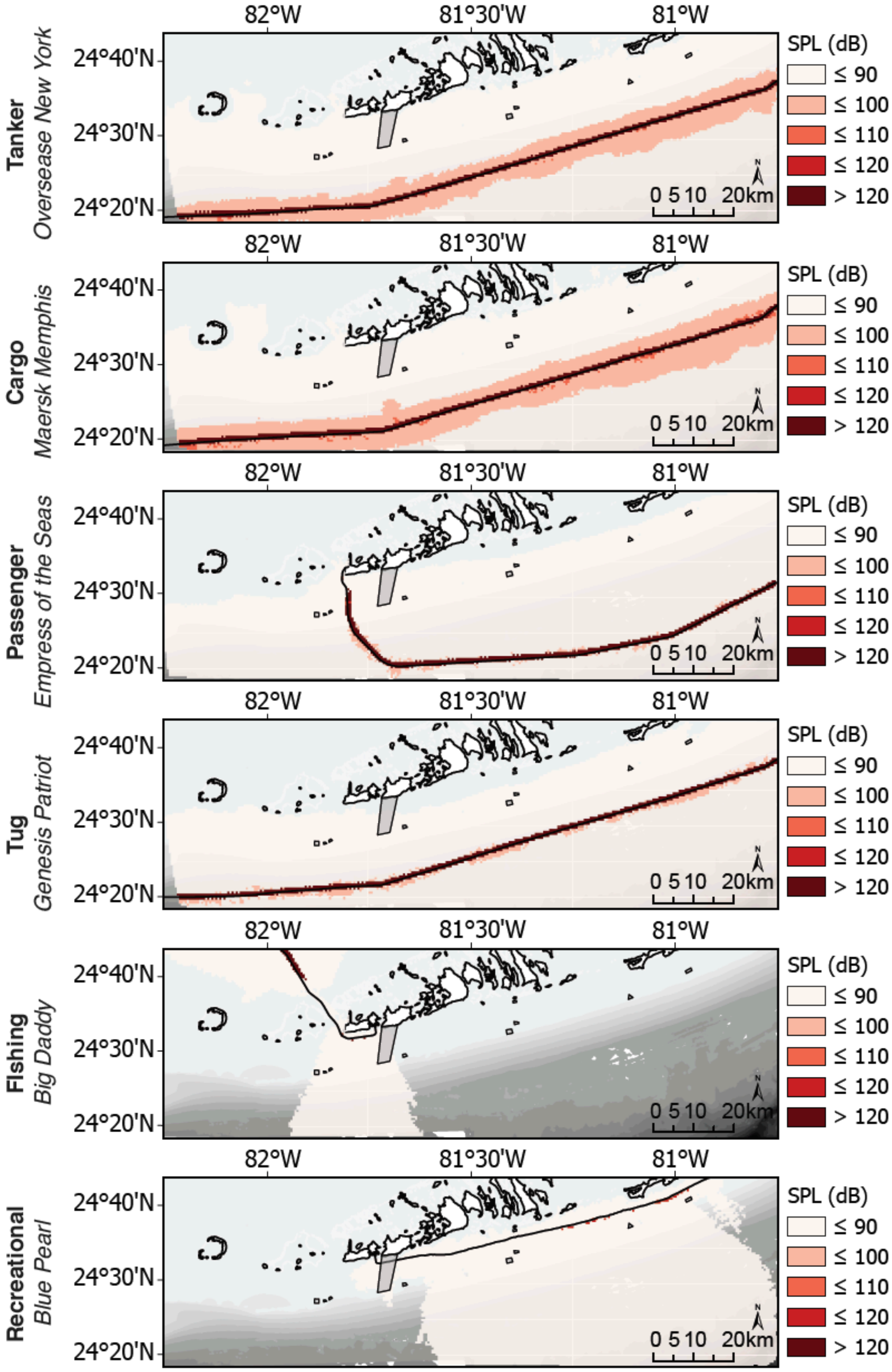
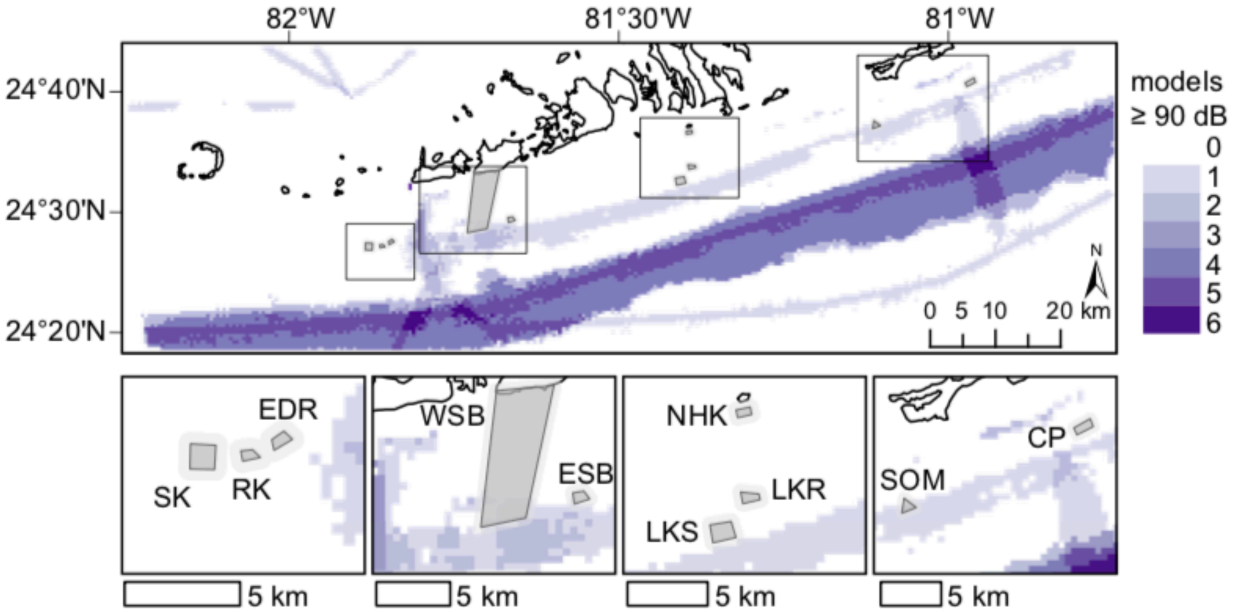


Figure 8: Vessel noise propagation maps with classed received sound levels (dB). Sound levels were classed into ranges relevant to thresholds set by NOAA. The audible threshold is set at 90dB, and the behavioral threshold is set at 120 dB. Note that only the larger shipping vessels with higher source levels have noise greater than 120 dB.

The overall impact of predicted vessel noise associated with modeled tracks on the FKNMS was minimal. Eight out of the ten sanctuaries in the study region did not have received levels that exceeded either the audible (90 dB) or behavioral (120dB) thresholds set by NOAA (Figure 9). The two sanctuaries that had some overlap with noise levels exceeding the thresholds were sites that were close to a major shipping channel (WSB), or was directly intersected by a modeled track (SOM).



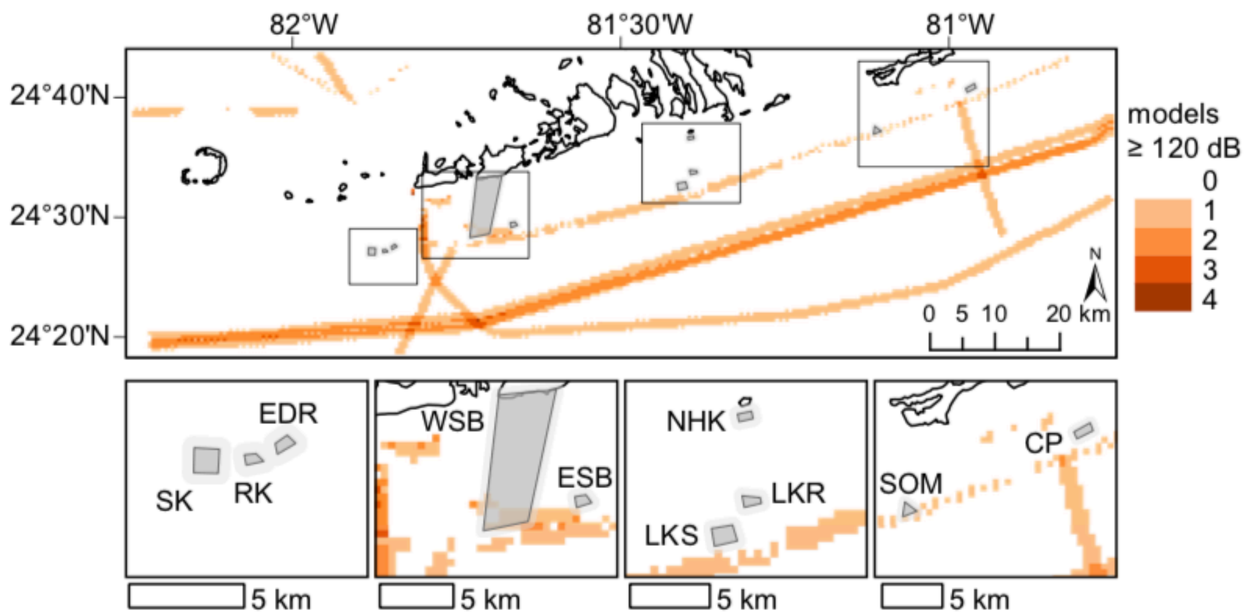


Figure 9: Map of the total number of model runs that exceeded the audible threshold (90 dB, top) or the behavioral threshold (120 dB, bottom) for each 500 m^2 grid cell in the study area. Inset maps show a close-up view of each group of sanctuary sites, with a 500 m buffer around each site (shown in light gray).

DISCUSSION

Vessel traffic information paired with noise propagation modeling has been used to passively assess use of, and the potential anthropogenic impact on, marine environments. Unlike similar studies, the acoustic impact from modeled vessels was minimal within the FKNMS boundaries, where shallow bathymetry and smaller vessels influenced the resulting sound field.

Vessel traffic

Vessel traffic information obtained for the area surrounding the FKNMS illustrates the prevalence of smaller, recreational boats for this system. While the AIS data provided some information on recreational vessels, AIS transmitters are only required for tug/tow vessels, vessels greater than 300 tons, or vessels carrying more than 165 passengers, resulting in an underrepresentation of the likely dominant vessel class within this study area (Federal Register 2003). With advancements in technology and reduced costs, we expect that AIS technology will increase in popularity and will be installed on these smaller vessels, and in the future could provide a more comprehensive view of vessel traffic in systems dominated by smaller recreational vessels. The traffic patterns found in this study provide a baseline characterization of all vessel classes and the impact of different vessel noise based on highly used areas by tracked vessels.

Impact assessment

The sanctuaries within the FKNMS are very shallow, with an average depth of 7 m for seven of the ten sanctuary sites of interest, and 22 m for the remaining three sites (Eastern Dry Rocks, Rock and Sand Key). The resulting patterns of noise propagation throughout the study region highlights the influence bathymetry has on the attenuation of vessel noise. In shallow water, the frequency below which sound does not propagate (i.e., the cutoff frequency f_c), is governed by the following equation:

$$f_c = \frac{c_w/4D}{\sqrt{1 - {c_w}^2/{c_s}^2}}$$

where c_w is the speed of sound in water, D is the water depth, and c_s is the bottom speed of sound (Au & Hastings 2008). For a sandy bottom with a water depth of 5 m, f_c= 200 Hz. Since the majority of the sanctuary has water depths less than 10 m, most of the sound associated with boat noise (frequencies below 500 Hz) will not propagate and will only be detectable at or close to the sound source (Au & Hastings 2008, Costley et al. 2009). So, while noise from larger vessels offshore propagates throughout the study area, it may be more important to consider the localized sound impact of many vessels traversing directly over the sanctuary.

In addition to the influence of bathymetry, modeling recreational vessels comes with other challenges. Recreational vessels have more variability when it comes to source levels given the wide variety of water craft (skiffs, jet-skis, inboard vs outboard motor, motor size) (Ainslie et al. 2009, Bassett et al. 2012, Costley et al. 2009, Veirs et al. 2016). This variability would make it difficult to accurately represent the total sound contribution or patterns of propagation by this important vessel class. This is in contrast to other studies that evaluated impacts on sanctuaries situated in deeper water where there was a higher contribution to the sound field from larger, more predictable (in both location and vessel characteristics) vessels (Halliday et al. 2017, Hatch et al. 2008, Neenan et al. 2017). Here, the shallow nature of the study area, combined with the conservative vessel source level estimates (Veirs et al. 2016), resulted in little to no impact of anthropogenic sound within the FKNMS.

Future assessments should consider the cumulative impact of tracks made from smaller vessels, since sound is not likely to propagate far from the source, but the sheer number of vessels passing over an area may represent a significant degree of increased anthropogenic noise. In the waters of the Intracoastal Waterway in North Carolina, the number of recreational vessels passing by a hydrophone had the greatest influence on environmental noise levels (Haviland-Howell et al. 2007). It is likely that there are many more instances of recreational vessels that are not tracked by the AIS, including the many scuba diving, fishing, and eco-tourism charter boats that operate within the Florida Keys. A search of the National Oceanic and Atmospheric Association's Marine Recreational Fisheries Statistics Survey database showed that an estimated 181,878 charter, and 4,615,304 private/rental angler boat trips were taken in the ocean fishing area throughout east Florida in 2017 (MRFSS; www.sefsc.noaa.gov/about/mrfss.htm). While these numbers include areas outside of the current study area, it represents a great deal of vessel noise from fishing operations alone that is likely unaccounted for with the AIS data. Getting an estimate on the location and amount of time these vessels are within the boundaries of the sanctuaries could provide a better understanding of the acoustic impact.

CONCLUSION

The mission of the National Marine Sanctuary program is to, "protect natural and cultural features while allowing people to use and enjoy the ocean in a sustainable way". Recent evidence of increased ocean noise related to vessel traffic and the potential ecological impacts of this added noise, has led to a need to understand how anthropogenic noise may be impacting sanctuaries and other marine protected areas. Combining AIS vessel traffic data with underwater noise propagation modeling is one way to passively assess use and impacts of vessels within sanctuaries. Future work should integrate these methods with passive acoustic monitoring of sanctuary soundscapes to validate predicted noise levels from tracked vessels and assess patterns in the anthropogenic and natural components of the soundscape.

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SUPPLEMENTAL MATERIAL

Workflow and project code can be found here: https://github.com/swricci/vessels-fknms
Animations of vessel noise: https://swricci.github.io/vessels-mapbox/

Supplemental Figures

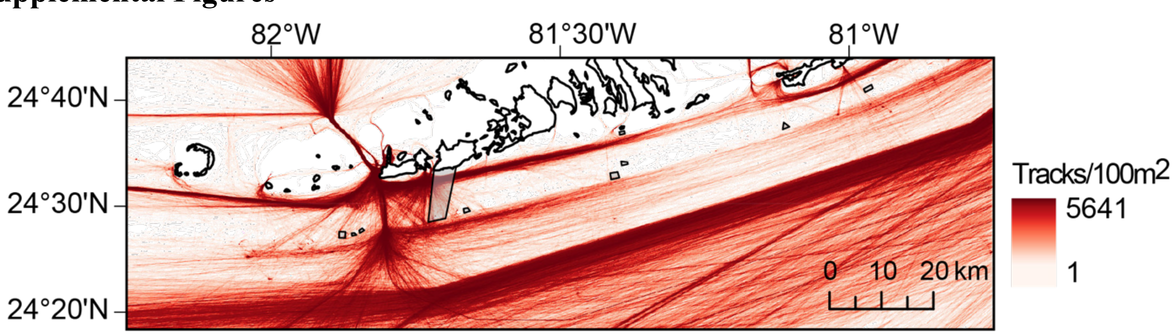

Figure S1: Density map for all vessels from 2017 in the study area surrounding the FKNMS. Density was calculated as the total number of tracks that passed through each 100 m^2 grid cell. Color is displayed using the histogram equalize function.

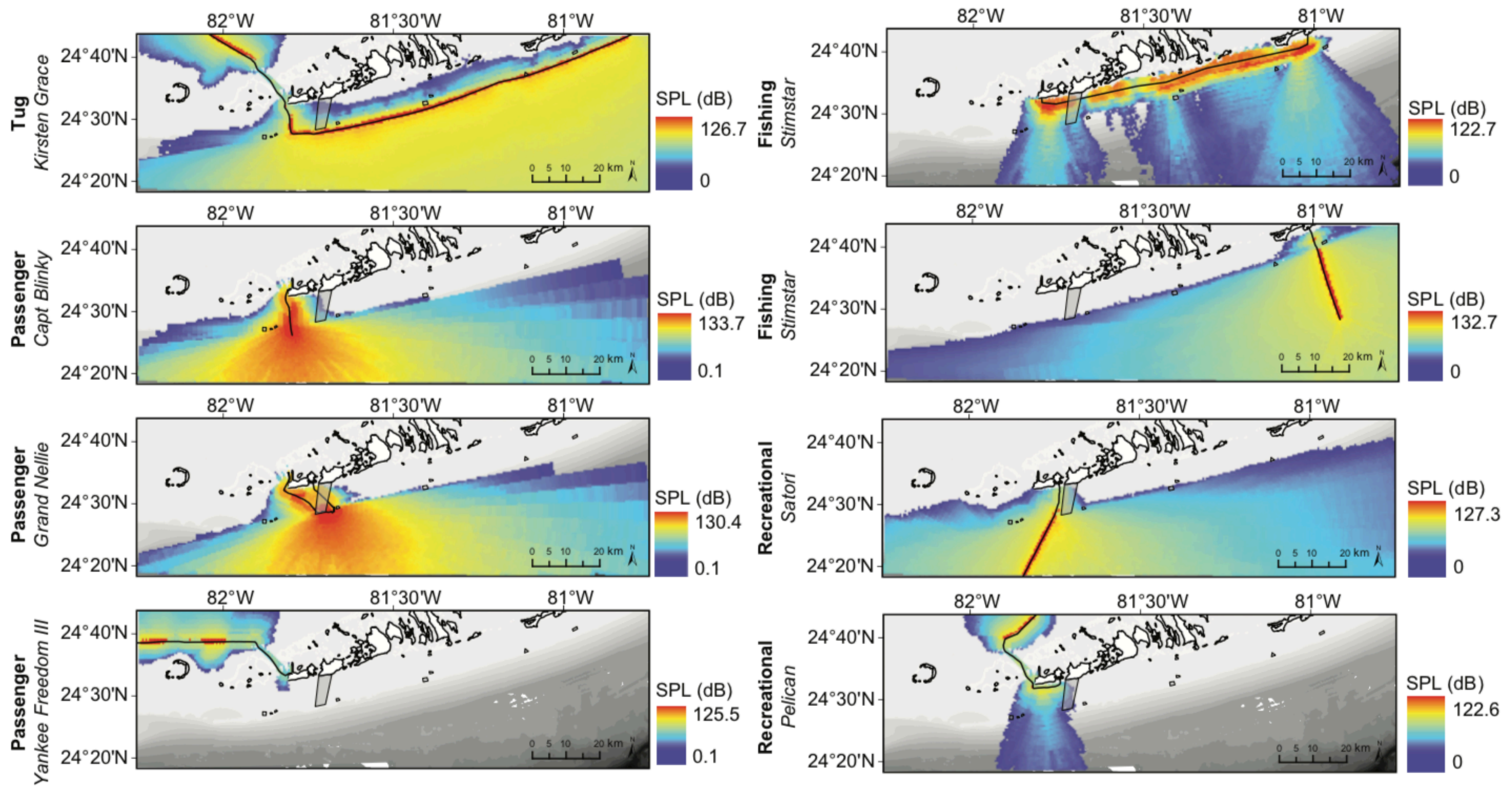

Figure S2: Model results for remaining vessel tracks. Track lines used in the model are shown in black, color range of the received sound levels are different for each vessel, with the maximum received level (SPL in dB) shown in red, and lower levels shown in blue.

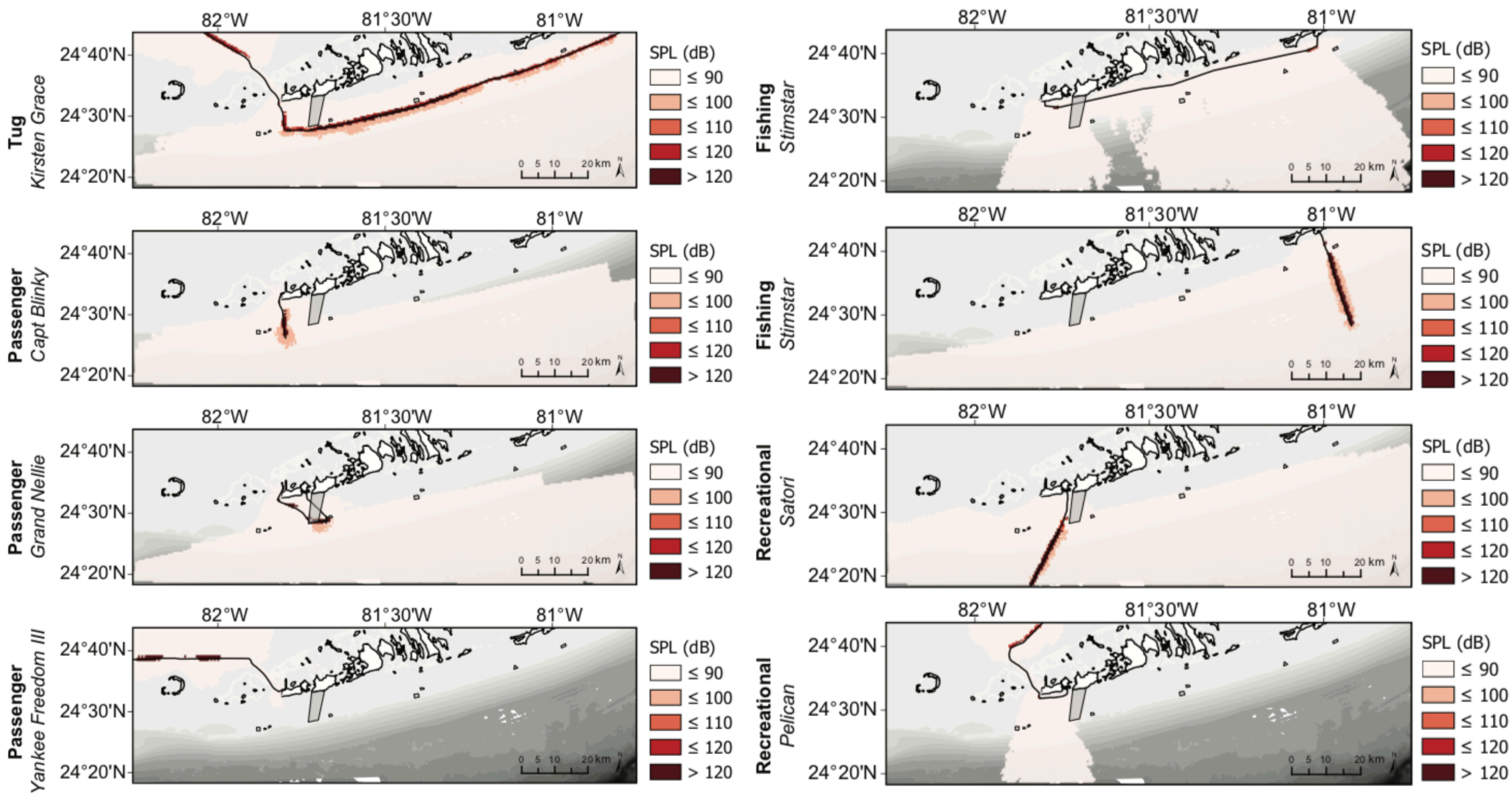

Figure S3: Vessel propagation model results for remaining model runs, with received SPLs (dB) shown in classed bins. Sound levels were classed into ranges relevant to thresholds set by NOAA. The audible threshold is set at 90dB and the behavioral threshold is set at 120 dB.