Short- and long-term monitoring of underwater sound levels in the Hudson River (New York, USA)

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There is a growing body of research on natural and man-made sounds that create aquatic soundscapes. Less is known about the soundscapes of shallow waters, such as in harbors, rivers, and lakes. Knowledge of soundscapes is needed as a baseline against which to determine the changes in noise levels resulting from human activities. To provide baseline data for the Hudson River at the site of the Tappan Zee Bridge, 12 acoustic data loggers were deployed for a 24-h period at ranges of 0–3000 m from the bridge, and four of the data loggers were re-deployed for three months of continuous recording. Results demonstrate that this region of the river is relatively quiet compared to open ocean conditions and other large river systems. Moreover, the soundscape had temporal and spatial diversity. The temporal patterns of underwater noise from the bridge change with the cadence of human activity. Bridge noise (e.g., road traffic) was only detected within 300 m; farther from the bridge, boating activity increased sound levels during the day, and especially on the weekend. Results also suggest that recording near the river bottom produced lower pseudo-noise levels than previous studies that recorded in the river water column. © *2016 Acoustical Society of America.*

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I. INTRODUCTION

There is increasing interest and concern about underwater sound levels resulting from human activities and their potential effects on aquatic life (e.g., Southall *et al.*, 2007; Popper and Hawkins, 2012; Hawkins *et al.*, 2015; Hawkins and Popper, 2014; Ketten, 2014; Popper and Hawkins, 2016). While many of the concerns deal with the potential impacts of high intensity impulsive sounds, such as those from pile driving, sonars, and seismic exploration (Popper *et al.*, 2014), there are also important issues associated with an increase in less intense, but more continuous, man-made noise from recreational and commercial boating, bridge traffic, and other human activities on or near the water (Mitson and Knudsen, 2003; Bailey *et al.*, 2010; Erbe, 2013; Pirotta *et al.*, 2015).

The long-term increases in marine sound levels may result in a variety of potential effects. In terrestrial environments, which are better studied than in-water environments, chronic exposure to noise affects foraging success, avoidance of predators, reproductive productivity, and community structures (Slabbekoorn and Halfwerk, 2009; Barber *et al.*, 2010; Kight *et al.*, 2012; Shannon *et al.*, 2014). With terrestrial animals and humans, there has also been extensive research demonstrating the effects of noise at a molecular and cellular level where impacts are detected in cardiovascular health, the immune system, cognition, sleep patterns, metabolism, and many other areas (Kight and Swaddle, 2011; Le Prell *et al.*, 2012). In marine environments, continuous noise sources potentially affect mammal foraging activity (Pirotta *et al.*, 2012; Pirotta *et al.*, 2015), stress levels (Rolland *et al.*, 2012), vocalizations (e.g., Parks *et al.*, 2007; Risch *et al.*, 2012), habitat selection (Tougaard *et al.*, 2009; Skeate *et al.*, 2012), changes in path (Williams *et al.*, 2002), and many other effects (e.g., Southall *et al.*, 2007). Continuous and impulsive noise has also been shown to potentially affect fish in several ways including hearing (Popper *et al.*, 2005; Popper *et al.*, 2014), habitat selection (Holles *et al.*, 2013; Parmentier *et al.*, 2015), and acoustic communication (Radford *et al.*, 2014; Whitfield and Becker, 2014; Dooling *et al.*, 2015).

When considering the potential effects of increased man-made marine and aquatic noise, a major concern is determining the changes in sound levels that result from human activities (such as industrialization) compared to natural sources. This is not difficult for intense impulsive sounds that are much higher than natural sound levels. Determining subtle changes resulting from long-term human activities is substantially harder and can only be done by comparing sound levels while the activities occur to baseline sound levels measured without the activities (Cato, 1976, 2012; Dahl *et al.*, 2007).

The problem arises, however, that there is a dearth of noise level data for any aquatic environment (Wenz, 1962; Urick, 1983). The earliest data are the well-known Wenz curves (Wenz, 1962), which show noise levels for an ocean basin and demonstrate the changes in levels resulting from different sea states and shipping levels. More recently,

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various investigators have built upon the Wenz curves to suggest the likely species that would potentially be affected by noise level increases (Dahl *et al.*, 2007; Southall *et al.*, 2007; Ketten, 2014).

The problem with the Wenz curves and more recent analysis of marine noise is that they are primarily for open oceans and deep water bodies (McDonald *et al.*, 2006; Hildebrand, 2009; Klinck *et al.*, 2012; Roth, 2012). There are fewer data on marine or aquatic noise levels in shallow waters such as harbors (Merchant *et al.*, 2012; Erbe, 2013; Paiva *et al.*, 2015; Pirotta *et al.*, 2015), lakes (Wysocki *et al.*, 2007; Amoser and Ladich, 2010; Cott *et al.*, 2012; Martin and Cott, 2016), and rivers (Lugli and Fine, 2007; Vračar and Mijić, 2011). There is one report of acoustic measurements in the Hudson River (Roh *et al.*, 2008); however, it examines the attenuation of high frequency sound (10–80 kHz) and does not document the soundscape. More extensive results from shallow waters are needed to understand the impacts of increased human use of these areas. Most notably, the number of ship passages and the average ship size in harbors (e.g., U.S. Department of Transportation, 2015) will impact noise levels over large areas.

The Tappan Zee Bridge is located on the Hudson River about 40 km north of New York City and is part of the federal I-87/I-287 interstate highway (Fig. 1). The bridge carries over 125 000 vehicles each day and is a major component of the northeast U.S. vehicular corridor to upper New York State. The 4900 m bridge crosses approximately 3500 m of shallow water (3–5 m depth) on the west side of the river and a deeper shipping channel (10–15 m depth) on the east side. We had the opportunity during the preparation of the environmental impact statement for the replacement of the Tappan Zee Bridge on the Hudson River to do short- and long-term pre-construction measurements of the underwater noise levels. A total of 12 sites above and below the current bridge were recorded. The goal of the current project was characterization of underwater noise levels and correlation of underwater sound levels with other measurable external factors such as wind speed, tidal stage, vehicle traffic levels on the current bridge, and train traffic levels from a commuter railway on the eastern shore of the river. The result is a description of the general riverine soundscape and the contribution of man-made sound sources to the environment.

II. METHODS

The study area extended north and south of the current bridge and included monitoring across the river to study the noise variability with water depth. The replacement bridge, currently called the "New NY Bridge," is being constructed just north of the Tappan Zee Bridge (see http://www.newnybridge.com). The noise monitoring program consisted of short-term noise monitoring at 12 locations throughout the study area from 9 to 12 August 2010, and long-term monitoring at four of the original locations from 12 August to 9 November 2010.

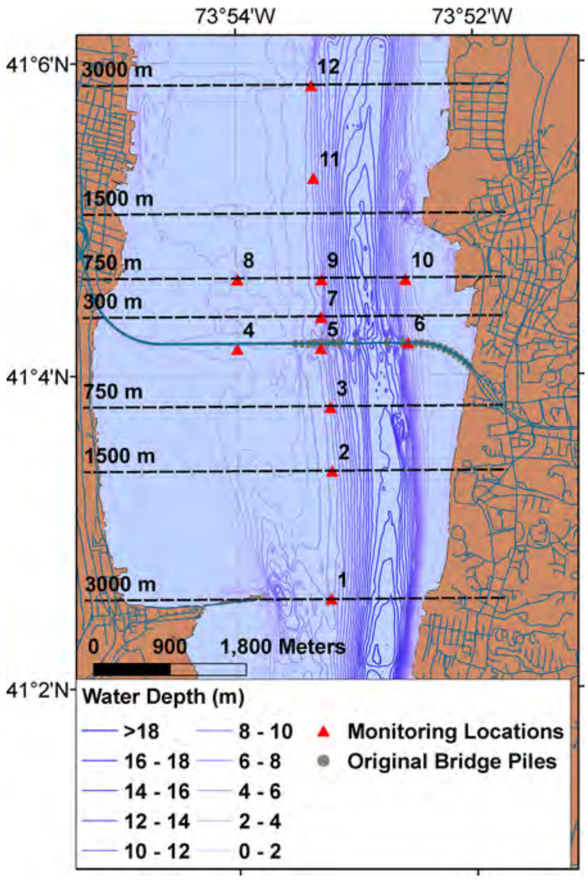

FIG. 1. (Color online) Schematic of the Hudson River about 40 km north of New York City showing the location of the Tappan Zee Bridge and the recorder stations used in this study. North is to the top. The legendary town Tarrytown, New York (made famous by the great 19th Century American author Washington Irving[1]), is on the east side of the river (right). Nyack is on the west side (left). The dashed lines show the distance from the existing bridge. The triangles indicate monitoring locations. Station numbers are above and to the right of their triangle icons.

A. Data collection

Short-term monitoring was performed with AURAL-M2 recorders (by Multi-Électronique Inc., Rimouski, QC, Canada) and Autonomous Multichannel Acoustic Recorders (AMARs; JASCO Applied Sciences, Halifax, NS, Canada) (Fig. 2). Long-term monitoring was performed with the AMARs. The AURALs were sampled continuously at 32 768 samples per second (sps). They were fit with HTI-96-MIN (High Tech Inc.) hydrophones (-160 dBV/1 μPa sensitivity) and set with a 22 dB gain. The AMARs sampled continuously at 32 000 sps. They were fit with GTI-M15B (GeoSpectrum Technologies Inc., Halifax, NS, Canada) hydrophones (-160 dB re dBV/1 μPa sensitivity) and set with an 18 dB gain. The gains of both systems were set to minimize the recorded acoustic noise floor of the complete recorder and hydrophone system. The noise floor was $\sim$45 dB re 1 μPa/$\sqrt{\text{Hz}}$ for the AURAL recorders and $\sim$37 dB re 1 μPa/$\sqrt{\text{Hz}}$ for the AMARs. All recorders were calibrated with a G.R.A.S. 42-AA (G.R.A.S., Holte, Denmark) pistonphone calibrator before deployment.

Six AMARs and six AURALs were deployed on 9 and 10 August and retrieved on 11 and 12 August 2010 for the short-term monitoring (Table I, Fig. 1). Four AMARs were

FIG. 2. AMAR recorders on steel base plates ready for deployment in the Tappan Zee River. Spandex flow shields cover the hydrophones to help reduce psuedo-noise from river currents moving water around the hydrophones.

re-deployed at Stations 1, 3, 4, and 12 on 11 and 12 August for the long-term program (Table I, Fig. 1). The long-term recorders were retrieved 16 November 2010; the units had stopped recording by this date (Table I).

The sound monitoring stations were in areas of recreational navigation and sport fishing activities, and therefore required low-profile moorings to prevent obstruction and entanglement. Each recorder was installed on a 40-kg steel mooring plate to weight it to the riverbed (Fig. 2) and to prevent it from moving in the river currents of up to 1 m/s. Spandex flow-shields were fitted over the hydrophones to minimize pseudo-noise from water flowing over the hydrophones (Fig. 2). The riverbed composition was suitable for grapple hook retrieval of the equipment. To facilitate retrieval, each recorder was attached to a 50 m sinking line and a 5 kg anchor weight. The anchor weight was deployed downstream of the mooring plate to provide a grapple snag line. Geographic locations of recorders were logged with a handheld GPS (Garmin GPSMap 76CSx, Olathe, KS, USA).

Non-acoustic data (weather, tidal stage, bridge traffic, and train traffic) were collected for correlation with the acoustic measurements. Daily rainfall, air temperature, wind speed, water temperature, and water salinity for 9 August to 16 November 2010 were obtained from the Piermont Pier station in Piermont, NY, located about 3.2 km south of the Tappan Zee Bridge (HRECOS, 2010). Tidal measurements of the Hudson River were obtained for two stations: Tarrytown station (Station ID 8518919, CO-OPS, 2010) located about 0.8 km north of the bridge and Piermont Pier station (HRECOS, 2010) located about 3.2 km south of the bridge.

The Hudson Line train movements were obtained from Metro-North Railroad. The Hudson Line is a passenger- and freight-service rail line located on, or just inland from, the east shoreline of the Hudson River within the study area. Data were provided as time-stamps, speeds, and identities of trains passing the Irvington and Tarrytown Stations, as well as the CP25 and CP26 signposts.

B. Data analysis

1. Total sound levels

Total sound levels at each monitoring station were examined to document baseline underwater sound conditions in the Hudson River. The acoustic data from each station were analyzed by Hamming windowed fast Fourier transforms (FFT) with a 1/30th-Hz resolution and 50% window overlap. Four FFT outputs were averaged to obtain 1-min spectra, and then the magnitudes of the 30 spectral bins centered at each 1 Hz band were summed to generate 1-Hz power spectral densities for each minute of data (dB re 1 μPa^2/Hz). For example, the 30 FFT bins from 0.533 to 1.467 Hz were summed to create the output at 1 Hz. By

TABLE I. Geographical locations of acoustic monitoring stations and the start/deployment and end/retrieval date and time of monitoring for short- and long-term monitoring. All times are eastern daylight time. Stations 4, 5, and 6 were closest to the current bridge.

Station	Recorder Type	Latitude (N)	Longitude (W)	Water depth (m)	Start	End
Short-term noise monitoring						
1	AMAR	41°02′34.2″	73°53′13.3″	5	10 Aug 10:14	11 Aug 17:50
2	AURAL	41°03′23.3″	73°53′12.3″	5	9 Aug 10:24	12 Aug 10:40
3	AMAR	41°03′47.7″	73°53′13.0″	5	9 Aug 17:05	11 Aug 17:20
4	AMAR	41°04′11.1″	73°54′00.3″[a]	3	9 Aug 18:22	11 Aug 11:00
5	AMAR	41°04′10.4″	73°53′17.6″[b]	7	9 Aug 16:44	11 Aug 14:47
6	AURAL	41°04′09.2″	73°52′35.9″	8	10 Aug 10:35	12 Aug 10:30
7	AURAL	41°04′22.3″	73°53′17.4″	5	10 Aug 11:35	12 Aug 09:00
8	AURAL	41°04′37.0″	73°53′59.7″	3	10 Aug 11:21	12 Aug 09:25
9	AMAR	41°04′36.8″	73°53′17.2″	5	9 Aug 13:48	11 Aug 10:00
10	AURAL	41°04′36.7″	73°52′34.7″	3	10 Aug 10:48	12 Aug 10:15
11	AURAL	41°05′15.7″	73°53′20.9″	5	10 Aug 11:38	12 Aug 09:50
12	AMAR	41°05′51.3″	73°53′21.7″	4	9 Aug 12:55	11 Aug 09:35
Long-term noise monitoring[c]						
1	AMAR	41°02′33.3"	73°53′14.0″	5	12 Aug 08:31	28 Sep 18:47
3	AMAR	41°03′47.2"	73°53′13.1″	5	12 Aug 08:41	6 Oct 09:18
4	AMAR	41°04′10.3"	73°54′00.0″[a]	3	11 Aug 18:22	9 Nov 20:34
12	AMAR	41°05′50.0"	73°53′22.2″	4	11 Aug 16:24	8 Nov 05:03

[a] Off Tappan Zee Bridge Pier 121.
[b] Off third concrete pier west of main span.
[c] Expected recording end date was 9 November 2010.

starting with a 1/30-Hz resolution, FFT spectral leakage from strong tonal sources or DC offsets were better isolated in the frequency domain than if a 1-Hz resolution FFT was employed.

Sound levels at each monitoring station were analyzed using the 1-min root-mean square (rms) sound pressure levels (SPLs) for the frequency bands 10–100, 50–1000, 100–2500, and 10–2500 Hz. The frequency bands were chosen to overlap the main frequency bands of man-made sound (10–100 Hz for large vessels and 100–2500 Hz for small vessels), fish hearing (50–1000 Hz; Fay, 1988; Popper *et al.*, 2003; Ladich and Fay, 2013), and geophonic sounds from wind and waves (100–2500 Hz). The low-frequency cutoff for a water depth of 5 m is 75 Hz (Urick, 1983), so the lowest frequency band of 10–100 Hz should only contain energy from sources close to the recorder. This band may also contain pseudo-noise from flow around the hydrophone, which is not a real sound source in the environment. The results from the short-term monitoring were computed for the 24 h period of 11:00 on 10 August to 11:00 on 11 August 2010 eastern daylight time (EDT) when all recorders were in the water. The rms SPLs are presented as time series, as statistical distributions, and an examination of the sound level cadence per day, per week, and per tidal cycle.

Correlations of sound levels with tidal water height, wind speed, air temperature, and bridge vehicle traffic counts were investigated by linear regression. Regressions were performed on noise levels in all four frequency bands.

2. Automated detection of man-made noise

Sounds from human activities can have two possible effects on the soundscape—they can either be prominent foreground sources that may be uniquely perceived from the background or they contribute to the overall background (Jennings and Cain, 2013). Foreground sources may be detected through manual and automated methods. Sources that contribute to the background can only be quantified by comparison to a similar location without the sources.

Large and small vessel noise was detected with an existing vessel detector (Martin, 2013) adapted for detecting vessels in shallow water. Inputs to the vessel noise detector were the 1 min rms SPLs, 1/3-octave-band rms SPLs, and the number of tonals present. The detector was adapted for shallow water and small vessels by changing the vessel noise energy band from 40–315 to 40–2000 Hz, and by reducing the minimum vessel passage duration from 5 to 3 min (Martin, 2013). This algorithm detects vessel passages that acoustically stand out from the background. A vessel must pass close enough to the recorder to increase the sound levels in the vessel detection band. It does not detect more distant vessels or distinguish multiple vessels passing a recorder together. The vessel detector results were used to identify time periods to manually examine for man-made events in the short-term data and for comparisons of the 1/3-octave band sound levels with and without detectable vessel traffic.

III. RESULTS

A. Short-term noise monitoring

The goal of the short-term monitoring was to document the spatial variability of sound levels along the length and width of the river near the bridge site and to associate the sounds with sources. To examine the contribution of man-made, geophonic, and pseudo-noise sound sources, we compared the relative amplitude of the 10–100, 50–1000, and 100–2500 Hz bands to the full 10–2500 Hz band. The 10–100 Hz band contains most of the energy at all stations (Fig. 3 and Table II); however, the stations show markedly different interquartile ranges in this band. The interquartile range represents the variability in the sound levels where a wider range suggests that transient sound sources contribute to the soundscape and a narrow range suggest a monotonous soundscape. The stations farther from the bridge and along the west side of the channel have greater interquartile ranges than those near the bridge (Figs. 3 and 4). The stations at the bridge have high median rms SPLs in all bands, especially the 10–100 Hz band, and small interquartile ranges in all bands. The 50–1000 Hz band closely tracks the 100–2500 Hz band median and interquartiles ranges at all stations except Station 5, which is closest to the bridge.

When combined, these results suggest that (1) the bridge is generating nearly constant sounds below 50 Hz with some energy above 50 Hz; (2) far from the bridge there is a second sound source below 50 Hz, which is highly variable; (3) along the river channel there are variable sound sources above 50 Hz. The sound source far from the bridge below 50 Hz is pseudo-noise from flow around the hydrophone. It follows a ~12-h pattern from the marine tide at the bridge location (e.g., Station 1 in Fig. 5). The variable sound sources above 50 Hz along the river channel are most likely marine traffic, from small pleasure craft and larger commercial vessels. These sound sources can be distinguished based on their duration and temporal occurrence. For example, at Station 1 (Fig. 5) there are far fewer transient events at night (00:00–06:00) than during the day. The extended duration vessel passage at 05:45 is an example of a slower, louder commercial vessel compared to faster pleasure crafts (personal water craft and motor boats).

The rms SPLs at slack tide at night represent the natural state of the river's soundscape with minimal man-made sound or pseudo-noise (Table III). The median rms SPL in the 10–100 Hz band is 85.4 dB re 1 μPa (range 81.2–95.3 Hz). The median rms SPL in the 100–2500 Hz band is 80.9 (range 79.2–82.4), which is near the noise floor of the recorders.

B. Long-term noise monitoring

The median rms SPL and interquartile range characteristics of the soundscape during the long-term monitoring match the short-term results (Figs. 6, 7, and 8). Close to the bridge (Station 4, Fig. 6), the sound levels in all bands are 7–10 dB higher during the day than night and are ~4 dB louder on weekdays than weekends. Farther from the bridge, the sound levels in all bands increase 4–8 dB during the day

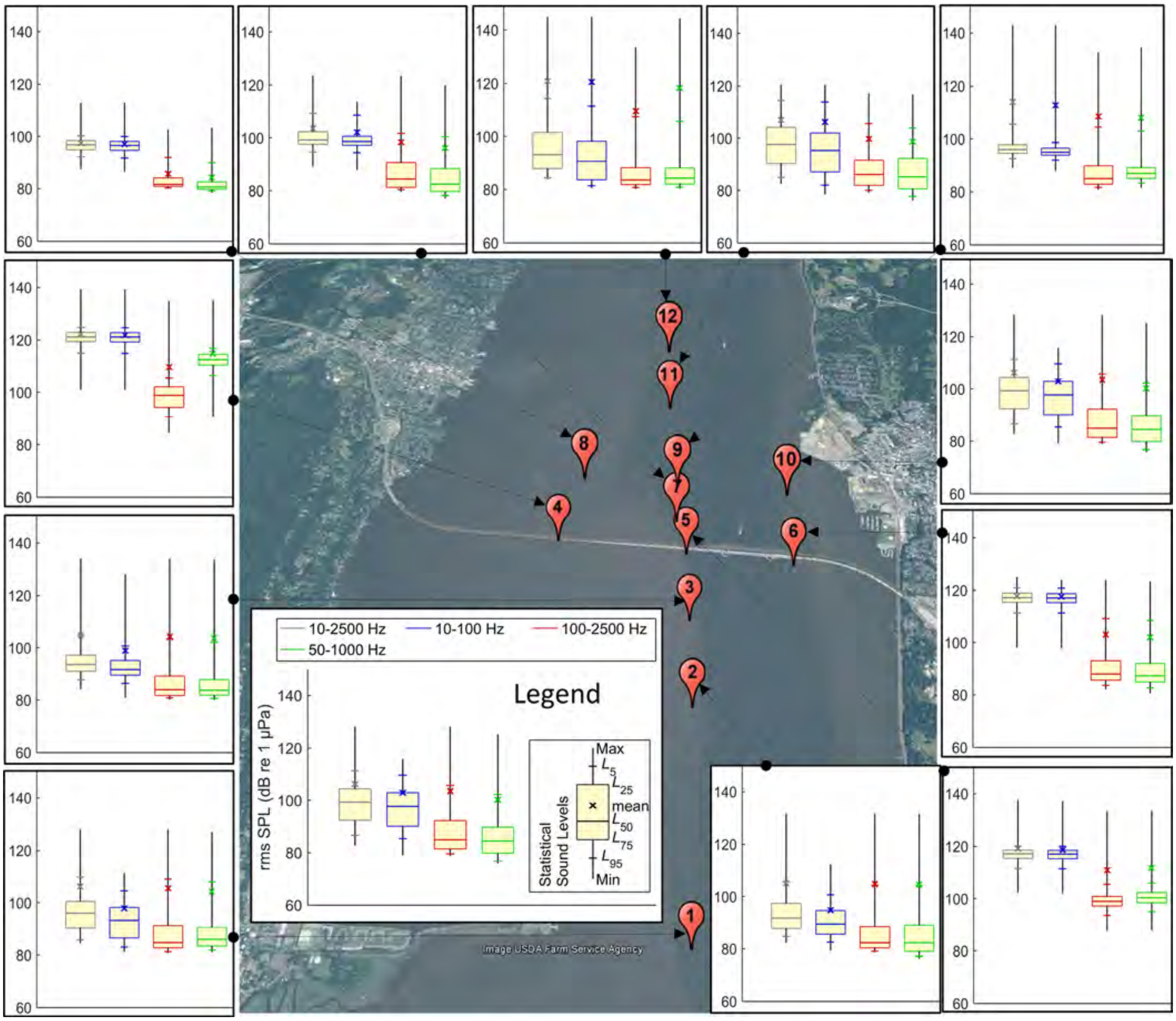

FIG. 3. (Color online) Sound levels measured at each short-term monitoring location from 11:00 on 10 August to 11:00 on 11 August 2010 (EDT). Data for each site gives the range and mean for different bands of sound. Note that the image has the same orientation as Fig. 1. The Tappan Zee Bridge is shown as the line closest to Stations 4, 5, and 6. See legend for further details.

TABLE II. Median 1-min rms SPL (dB re 1 μPa rms (interquartile range) at the 12 short-term recording stations (Fig. 3) for 11:00 on 10 August to 11:00 on 11 August 2010. Data are the four analysis bands of 10–2500, 10–100, 100–2500, and 50–1000 Hz. Stations 4, 5, and 6 were closest to the current bridge.

Station	Recorder Type	Depth (m)	Distance to bridge (m)	10–2500 Hz	10–100 Hz	100–2500 Hz	50–1000 Hz
1	AMAR	5	3000	96.1 (10.2)	93.3 (10.9)	85.1 (9.2)	86.4 (7.5)
2	AURAL	5	1500	91.7 (9.5)	89.8 (8.9)	82.0 (7.7)	81.1 (9.0)
3	AMAR	5	750	93.5 (5.8)	91.6 (5.4)	84.0 (7.6)	84.0 (6.4)
4	AMAR	3	0	121.1 (3.9)	121.0 (3.8)	99.1 (7.7)	112.5 (4.4)
5	AMAR	7	0	116.8 (3.4)	116.7 (3.4)	98.5 (4.0)	99.6 (3.7)
6	AURAL	8	0	117.4 (3.9)	117.3 (3.8)	88.9 (7.3)	88 (6.5)
7	AURAL	5	300	99.4 (4.8)	98.9 (3.9)	84.1 (8.7)	81.9 (7.6)
8	AURAL	3	750	96.7(3.6)	96.5 (3.6)	81.9 (3.2)	80.7 (2.9)
9	AMAR	5	750	95.5 (3.1)	94.7 (2.5)	84.7 (7.3)	86.8 (4.7)
10	AURAL	3	750	99.6 (12.3)	97.8 (13.0)	84.4 (11.1)	82.9 (9.9)
11	AURAL	5	1500	97.7 (14.5)	95.5 (16)	85.9 (9.9)	84.4 (11.4)
12	AMAR	4	3000	93.4 (11.9)	90.7 (13.8)	84.6 (7.7)	85.3 (6.8)

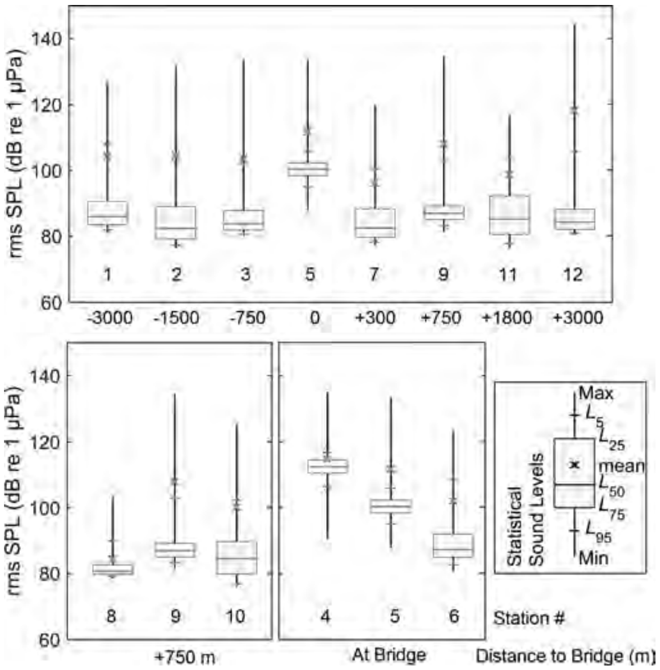

FIG. 4. Measured sound levels for the 50–1000 Hz band showing comparative sound levels along the river (top) and across the river (bottom; left are stations 750 m north of the bridge, right are the stations at the bridge). Data from Fig. 3.

compared to the night, with the highest differences on the weekends (Figs. 7 and 8) with some increases on Thursdays and Fridays. The sound levels at the bridge are not masked by pseudo-noise from tidal currents (Fig. 6); however, the 10–100 Hz band does increase 4–8 dB during tidal flow at the stations farther from the bridge (Figs. 7 and 8). Far from the bridge the sound levels above 50 Hz show no correlation with the tidal flow (Figs. 7 and 8). The 1-min rms SPLs in the 100–2500 Hz band had a positive Pearson correlation with wind speed of 0.30 (Fig. 9), indicating a partial dependence of sound levels on wind speed.

C. Sound sources

The Hudson River data contains man-made and biological sounds. Pleasure crafts are the primary man-made sound source present within the monitoring area (with the exception of the bridge noise). They produce significant broadband noise that temporarily increased the sound levels in the range of 100 Hz and above (e.g., the peaks in Fig. 5). When detectable, the pleasure crafts often increase the 1/3-octave bands noise by about 5–10 dB for bands above 200 Hz (Figs. 7 and 8). Shipping vessels up to 180 m length with 8 m draught are also present, but not common, in the shipping channel. Turbo-prop and regional jet aircraft were also detected along the line of stations at the south end of the project area (Stations 1, 2, and 3). The aircraft noise was typically in the frequency range of 100–700 Hz and showed rapid Doppler shifts for the turbo-prop aircraft [Fig. 10(A)]. Jet aircraft caused rapid Lloyd's mirror broadband interference patterns without tonals (not shown).

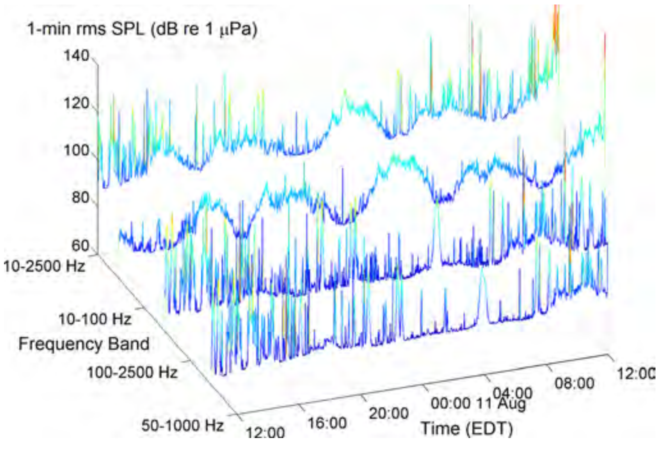

FIG. 5. (Color online) The 1-min in-band rms SPLs measured at Station 1 at 10:24 on 10 August to 17:50 on 11 August 2010 (EDT).

Several fish sounds (e.g., honks, groans, grunts, and drumming) were recorded at all stations in the Hudson River. Broadband fish honks were record at all stations and at all times of day [e.g., Fig. 10(B)]. Fish grunts were recorded at many stations at all times of day. Drumming sounds, likely from cusk eel, were recorded near the deep water channel.

IV. DISCUSSION

These results represent the first comprehensive and *continuous* long-term analysis of the aquatic soundscape in a shallow water environment. The results also represent the first analysis of a soundscape that includes sounds from a busy highway bridge.

The short- and long-term monitoring findings show that potential impact on the soundscape from the Tappan Zee Bridge traffic only occurs at locations very close to the bridge (Figs. 3 and 4 and Table II). If the bridge traffic sounds are entering the water through the bridge piers, then it is likely that the low frequencies produced by the traffic are not propagating to the farther stations due to the shallow water cutoff (Urick, 1983; Rogers and Cox, 1988). It is also interesting to consider whether the sounds recorded near the bridge traveled through air. The in-air sound levels near the bridge range from 60 to 70 dBA re 20 μPa (http://goo.gl/ZMi5bp). Since sound traveling vertically increases in amplitude on entering water (Zhang, 2002), the amplitude near the bridge, accounting for changes in reference pressure and density (but ignoring the effect of A-weighting), would be on the order of 130 dB re 1 μPa and would decrease rapidly with incident angle (Zhang, 2002). Thus it is possible that the bridge sounds are traveling through an air–water path rather than emitting from the bridge piles.

The partial dependence of sound levels in the 100–2500 Hz band on wind speed agrees with studies of the dependence in the open ocean (e.g., Wenz, 1962; Vagle *et al.*, 1990; Ma *et al.*, 2005; Reeder *et al.*, 2011). The underwater sound generated by wind depends on the formation of waves, which in turn depends water depth, how long the wind has blown, and fetch over which the waves can build (see Reeder *et al.*, 2011). Therefore it is not unexpected that some very low sound levels were measured during periods of higher winds (Fig. 6). These sound levels likely

TABLE III. Median rms SPLs (dB re 1 μPa rms) from 15-min windows at the 12 short-term recording stations (Fig. 3) during different tidal conditions between 11:00 on 10 August and 11:00 on 11 August 2010. Data are presented for the 10–100 and 100–2500 Hz bandwidths. Stations 4, 5, and 6 were closest to the current bridge. All times are eastern daylight time. Note that since these results are only for a single 15-min window, a transient sound source may affect individual recorders but should not affect the overall trend in the results.

	Day, slack tide 10 August 2010 12:45–13:00		Day, fast tide 10 August 2010 16:00–16:15		Night, slack tide 11 August 2010 01:00–01:15		Night, fast tide 11 August 2010 04:30–04:45	
Station	10–100 Hz	100–2500 Hz	10–100 Hz	100–2500 Hz	10–100 Hz	100–2500 Hz	10–100 Hz	100–2500 Hz
1	87.8	105.3	101.7	99.2	82.4	82.1	105.2	84.7
2	86.2	90.8	91.4	86.4	82.5	79.2	101.5	90.7
3	90.2	87.5	97.7	84.5	86.8	81.4	101.1	104.3
4	122.2	102.8	121.0	98.9	119.3	100.0	121.7	92.9
5	118.6	100.2	118.3	99.5	114.3	96.3	115.3	100.1
6	118.2	86.9	118.4	89.7	114.5	85.2	117.8	102.6
7	99.4	85.7	98.4	83.3	95.3	80.9	101.0	85.5
8	98.2	81.6	98.8	83.9	94.4	80.9	100.1	81.2
9	94.2	89.0	97.7	89.3	93.0	82.4	98.3	85.9
10	89.6	85.1	101.1	84.5	85.4	79.6	108.3	86.1
11	84.6	89.2	114.0	95.0	81.2	80.6	112.7	91.6
12	82.0	80.7	103.4	83.6	81.6	81.3	114.8	85.7
Median (excluding 4, 5, 6)	97.5	87.6	96.5	87.8	83.3	80.8	97.4	85.3

correspond to winds from directions with less fetch or times when the winds were not sustained.

A. Levels compared to other shallow areas

Since most interest in marine sound levels has focused on deep water, there are few data in the literature with which to compare the current results. Perhaps the most comprehensive study to date was an analysis of sounds from locations in and around Austria (Wysocki *et al.*, 2007; Amoser and Ladich, 2010). Wysocki *et al.* (2007) examined sound levels at several times over one year at 12 sites that ranged from stagnant water masses to fast moving streams, including in the Danube River near Vienna. In most cases, the instantaneous sound levels were between 80 and 110 dB re 1 μPa rms and the two sites with high flow rates had higher sound levels. However, despite these levels being, on first look, comparable to those reported here, actual comparisons cannot be made. The water depths at most sites in the Austrian study were less than 3 m (and some less than 1 m), and the hydrophones were located very close to the surface; therefore, the Austrian results have even lower contributions from propagating low frequency energy than those in the current study.

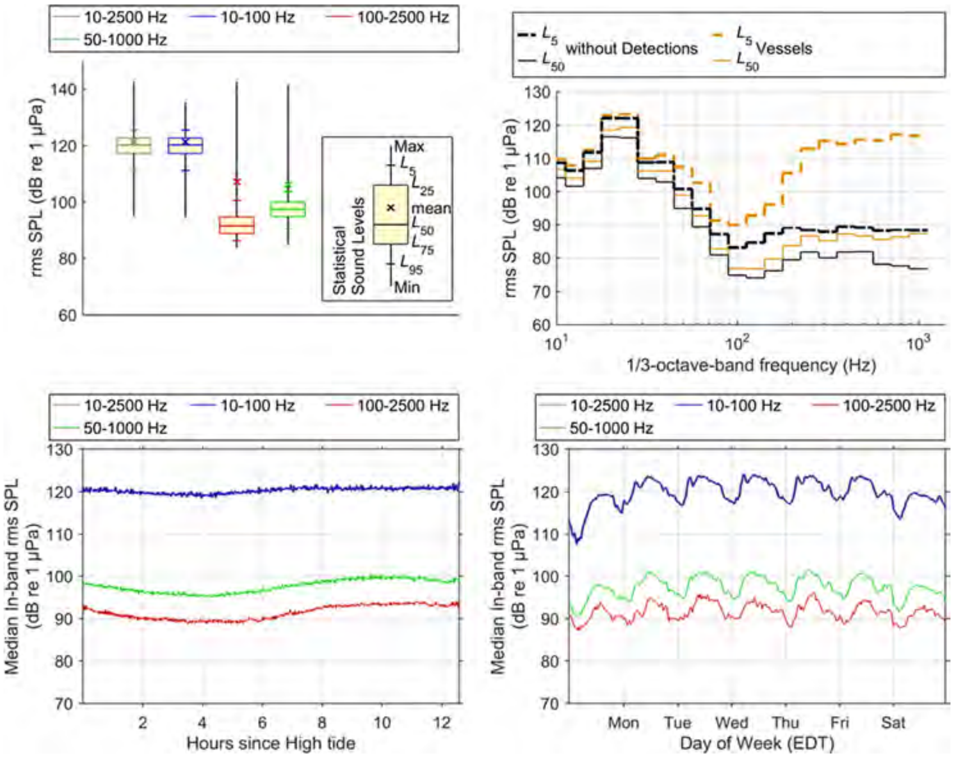

FIG. 6. (Color online) Summary of the long-term soundscape at Station 4. (Top left) The distribution of sound levels in each frequency band. (Top right) The 1/3-octave-band rms SPL for minutes without unique vessel detection and with vessel detections. The median (L_{50}) and extreme (L_5) levels are shown. (Bottom left) Median sound levels for each minute after the high tide. (Bottom right) Weekly cadence in the median 1-min rms SPLs in each band. All data from 11 August to 9 November 2010 are included in these results. The 10–100 Hz and 10–2500 Hz curves are coincident.

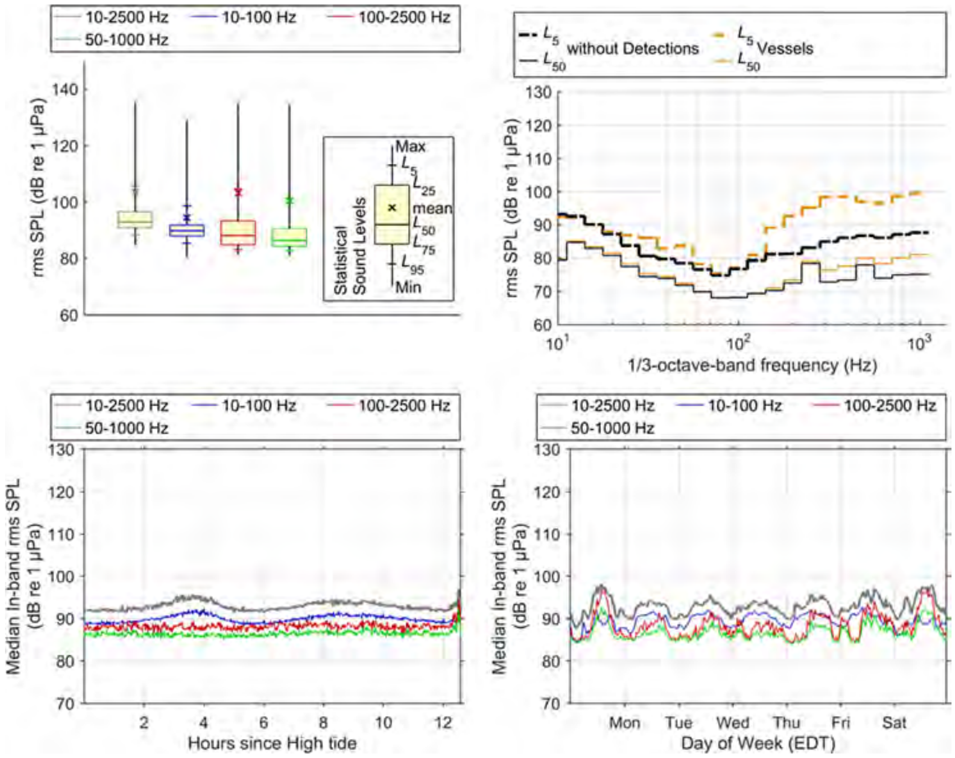

FIG. 7. (Color online) Summary of the long-term soundscape at Station 3. (Top left) The distribution of sound levels in each frequency band. (Top right) The 1/3-octave-band rms SPL for minutes without unique vessel detection and with vessel detections. The median (L_{50}) and extreme (L_5) levels are shown. (Bottom left) Median sound levels for each minute after the high tide. (Bottom right) Weekly cadence in the median 1-min rms SPLs in each band. All data from 12 August to 27 October 2010 are included in these results.

In a follow-up to the Austrian study, Amoser and Ladich (2010) measured sound levels at seven of the sites used in the earlier study. Data were recorded at each site for 1−3 min every 2 months for one yr. The methodology was the same as in the earlier study. The authors found a 4−15 dB variation in sound levels over the year depending on location. However, since there was only a single short recording each day, it is impossible to know if the variation was a sampling error (e.g., if multiple recordings had been made, what would the variation have been within each day) or real. Indeed, as shown in the Hudson River, there is substantial variation in sound levels over the course of a day (e.g., Fig. 5).

A sound level study in the Sava, Tisa, and Danube Rivers near Belgrade, Serbia, do provide potentially comparable measurements to the current study (Vračar and Mijić,

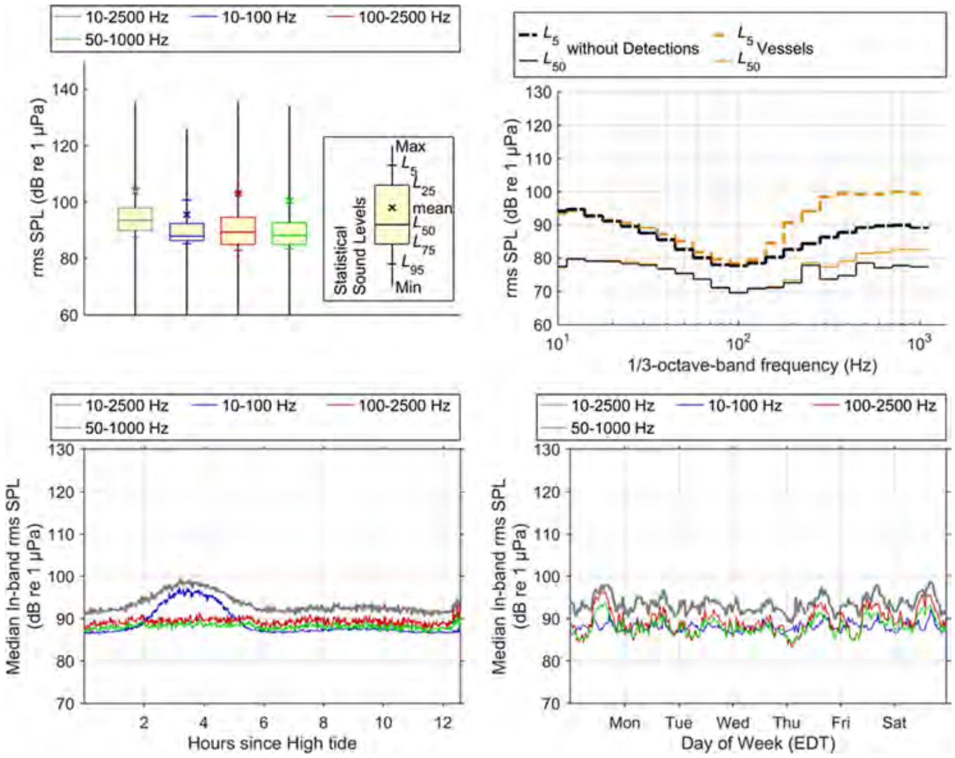

FIG. 8. (Color online) Summary of the long-term soundscape at Station 12. (Top left) The distribution of sound levels in each frequency band. (Top right) The 1/3-octave-band rms SPL for minutes without unique vessel detection and with vessel detections. The median (L_{50}) and extreme (L_5) levels are shown. (Bottom left) Median sound levels for each minute after the high tide. (Bottom right) Weekly cadence in the median 1-min rms SPLs in each band. All data from 11 August to 8 November 2010 are included in these results.

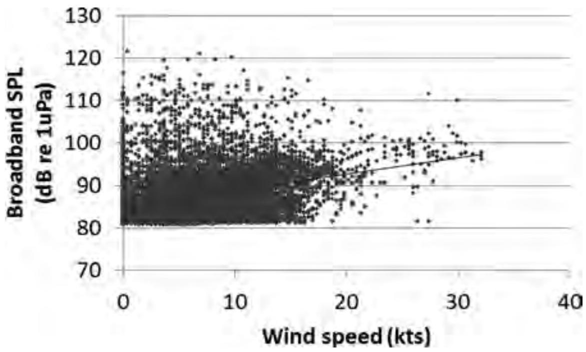

FIG. 9. Scatter plot of wind speed versus broadband SPL in the 100–2500 Hz band. The equation of the regression line is SPL = 84.85 + 0.38*WindSpeed.

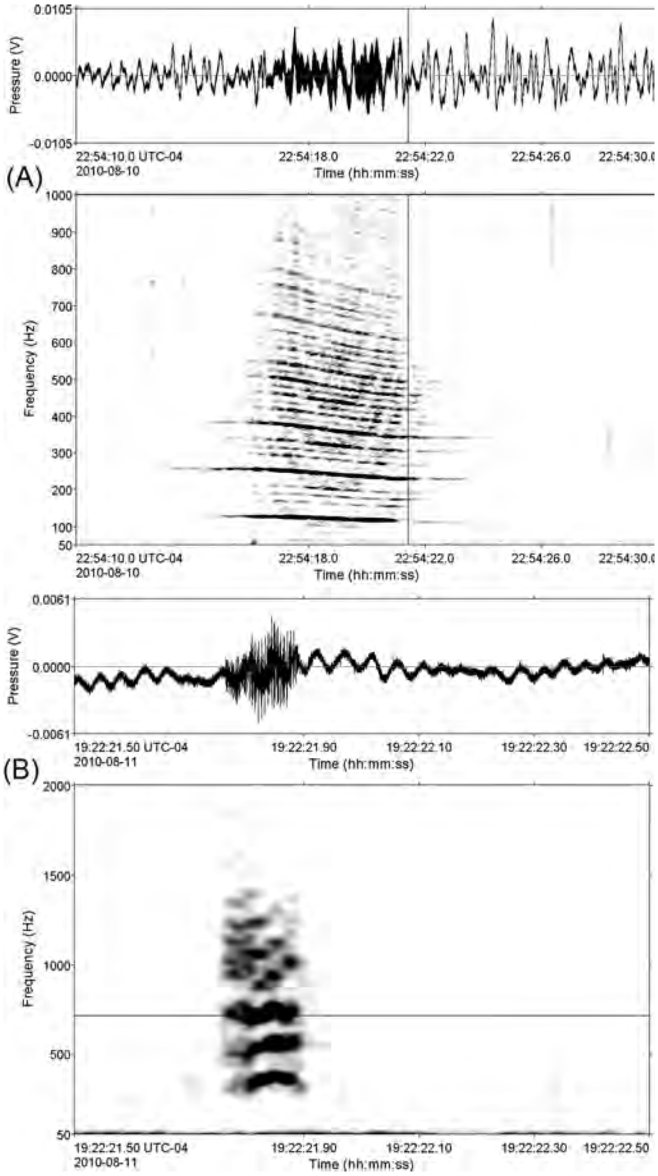

FIG. 10. (A) A 20-s spectrogram of a turbo-prop aircraft passing over Station 2 on 10 August 2010. The downshift in frequency is the Doppler shift as the plane passed overhead (32 768 pt FFT, 16 000 data points, 800 pt advance, Hamming window). (B) One second spectrogram of a fish honk from Station 8 on 11 August 2010 (8192 point FFT, 1024 data points, 256 point advance, Hamming window).

2011). These measurements were made in water depths similar to the Hudson sites, and with similar current velocities (currents at the Tappan Zee Bridge peak at 1 m/s during spring tides and $\sim$0.6 m/s at neap tides—see http://goo.gl/BGDTu8). The measurements were made over periods of days from hydrophones suspended 2 m below the surface and held somewhat stationary by a 12 kg weight (Vračar and Mijić, 2011). The results were reported as power spectral densities. The authors used data from time periods without any visible vessel traffic near the recorders, so that they felt the results represented the natural state of the river. The maximum level of the power spectral densities from the Tisa River is $\sim$10 dB above those from the Hudson River at stations far from the bridge (80$-$90 dB re 1 μPa^2/Hz; Fig. 11), while the maximum power spectral density from the Danube and Sava Rivers are more comparable to the stations near the Tappan Zee Bridge (110 dB re 1 μPa^2/Hz). The peak frequencies for the Serbian study are in the range of 30 Hz, which is below the low frequency cutoff for propagating sound energy in 9 m of water ($\sim$40 Hz; Urick, 1983; Rogers and Cox, 1988). In the present study, the stations farther away from the bridge showed a constant decline below 10 Hz (Fig. 11). The median power spectral densities at 100 Hz in the present study were 50$-$60 dB re 1 μPa^2/Hz, much lower than the Serbian levels of 95$-$105 dB re 1 μPa^2/Hz. The decrease in sound levels as a function of frequency from the Serbian study was between 10 and 12 dB per decade (100–1000 Hz), much less than typically reported in the open ocean ($\sim$16 dB per decade, e.g., Ma *et al.*, 2005). The stations closest to the Tappan Zee Bridge had decays of 17$-$23 dB per decade (200$-$2000 Hz, Stations 4 and 5, Fig. 11).

The Hudson results may also be compared with reports of shallow water marine sound levels. The power spectral densities of stations far from the bridge in the current study had decays of $\sim$20 dB from 10 to 100 Hz and variable densities from 100 to 1000 Hz (Fig. 11). This pattern is similar to the spectral characteristics reported by Erbe (2013) in waters

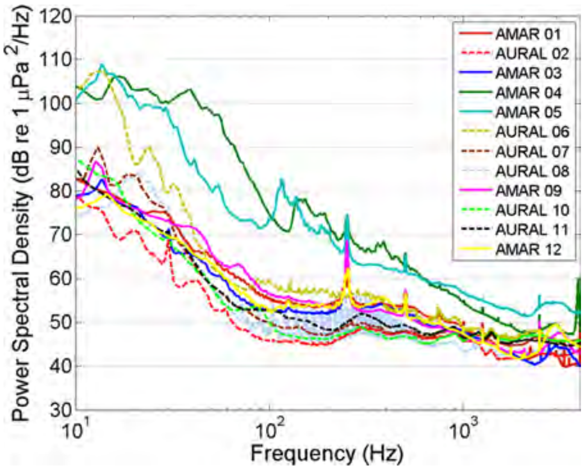

FIG. 11. (Color online) Median (50th percentile) 1-min average power spectral densities for all short-term noise monitoring stations. The AMARs used in this study had an artifact at 250 Hz. The AURALs had an artifact at 16 Hz, and its harmonics can be seen in these curves. The artifact energy was not included in any of the sound level metrics reported in this paper.

2.5 m deep at Bramble Bay, Australia. The current sound levels, however, are ∼20 dB re 1 μPa^2/Hz lower than those in Bramble Bay at all frequencies. Merchant *et al.* (2012) collected nine days of continuous data in 30 m of water at Falmouth Harbour (UK) and reported the 1/3-octave-band 24-h sound exposure level (SEL) with and without shipping present. The 24-h SEL is equivalent to the 24-h rms SPL plus 10*log10(number of seconds per day), which is 49.4 dB. Therefore the median SEL results from Merchant *et al.* (2012) can be compared with the median 1/3-octave-band rms SPL + 49.4 dB (top right panels of Figs. 7 and 8). The levels recorded in the Hudson are 3–5 dB above the Falmouth Harbour levels below 50 Hz, within 3 dB from 50 to 125 Hz, and are 3–7 dB below the Falmouth Harbour levels above 125 Hz. The larger fetch for wind-driven noise is likely responsible for the increased sound levels in Falmouth above 125 Hz. The intermittent SELs reported by Merchant *et al.* (2012) were 10 dB higher than the L_5 vessel 1/3-octave-band levels measured in the Hudson (Figs. 7 and 8).

These differences suggest that the measurements from the current study made close to the river bottom provided better isolation from flow noise effects than the water-column measurements made in the Serbian study. Further, the environment in the Hudson appears to be relatively quiet. It is acknowledged that positioning the hydrophone so close to the bottom and using a steel plate will lead to reflections that will modulate the measured sound levels at frequencies above 1 kHz. This effect is present in the median percentiles (Fig. 11), although difficult to detect compared to other effects. For the current study where frequencies below 1 kHz were considered most important, the hydrophone location produced accurate measurements. For future measurements, it is recommended that the hydrophone be placed at ∼0.5 m above the river bottom to improve the measurements above 1 kHz while still greatly reducing pseudo-noise compared to a hydrophone in the water column.

B. Levels compared to hearing in Hudson River fishes

There are a large number of fish species in the Hudson River, with 16 considered to be the most important by federal agencies. These include two endangered sturgeon species, the Atlantic sturgeon (*Acipenser oxyrhynchus*) and shortnose sturgeon (*Acipenser brevirostrum*). Neither species is thought to hear above about 800 Hz (Lovell *et al.*, 2005; Meyer *et al.*, 2010). Most other species in the Hudson, including striped bass (*Morone saxatilis*) and weakfish (*Cynoscion regalis*), are unlikely to hear sounds above 1 kHz (Ramcharitar and Popper, 2004; Ramcharitar *et al.*, 2006). However, there are species of catfish and clupeid (herring-like fishes) in the river that hear sounds up to several kilohertz (Poggendorf, 1952; Enger, 1967; Mann *et al.*, 2001). While there are no data for hearing sensitivity for most Hudson River fishes, and no data available for particle motion data in the Hudson River or particle motion sensitivity of the Hudson River fishes, one can tentatively "extrapolate" from what is known about hearing in related species. All related species are likely to have very poor sensitivity to sound pressure at frequencies below 75 Hz, and most are likely to primarily detect particle motion (Ladich and Fay, 2013). Data for the species that only detect sounds below about 1 kHz suggest that their threshold of hearing is above the sound pressure levels in the river (e.g., Lovell *et al.*, 2005; Ramcharitar *et al.*, 2006), and even the pressure detecting species that hear up to several kilohertz are unlikely to perceive the measured noise in the environment. Indeed, it is reasonable to speculate that even when a fish come close to the current bridge (e.g., Station 4), it is unlikely to hear the vehicle sounds on the bridge.

V. SUMMARY AND CONCLUSIONS

This study represents, to the authors' knowledge, the first reported long-term and continuous monitoring of underwater noise in any shallow-water environment, and particularly in a frequency range that overlaps that of commercial activities and the hearing range of marine life. The results not only provide total underwater sound levels, they demonstrate the wide variation in sound levels resulting from environmental conditions, as well as variation in sound levels over days, weeks, and months. The variability measured in the current study was not only temporal, but spatial. Twelve measurements of the sound levels made over the same 24-h period made within 3000 m of the bridge showed three distinct patterns of median sound levels, interquartile ranges, and frequency dependence.

The spatial and temporal variability demonstrate the need for continuous monitoring in all areas of interest as opposed to sampling for a few minutes or even a few hours at a small number of sites. The absolute sound levels were very low, but that is perhaps less significant in comparison with other sites since the sound levels (and sound spectrum) are site-specific and dependent on water depth, bottom type, and many other factors. The results strongly suggest that performing measurements near the river bottom better isolates the hydrophone from flow noise and is preferred to suspending a hydrophone in a river current.

A significant outcome of this study is that the sounds from the current Tappan Zee Bridge, while present in the water, were only recorded at hydrophones very close to the bridge. Indeed, the daily cycle of vehicular traffic could be seen in the recordings, as could the difference between weekdays, when the bridge carries very heavy commuter traffic, to weekends when much of the traffic is associated with travelers, and not commuters. At the same time, the sound from the bridge was not recorded on any of the stations at distances greater than 300 m from the bridge, suggesting that traffic sounds, at least in shallow waters with sandy bottoms, do not propagate well. This is not surprising since most of the Hudson River is shallow, and this would filter out lower frequency traffic sounds.

It is also of some interest that the sounds from the train traffic on the east bank of the Hudson River were not seen in any of the recordings. In designing the study, it was anticipated that the trains would be noted in at least some recordings, but any such sound would have to have been transmitted through the substrate. This suggests that the tracks are not tightly coupled to the substrate, the relatively soft substrate did not propagate the sounds well, and/or that the frequencies generated by the trains were too low to be detected in the water column.

Finally, the authors caution that the sound levels recorded for the current bridge may not match levels from the bridge now under construction. The New NY Bridge consists of two spans with hollow steel piles for support compared to the wooden piles of the Tappan Zee Bridge. That, and differences in construction techniques since the original bridge was built in the early 1950s, may result in different amounts of sound in the water, whether the transmission path is through the bridge piles or through the air. However, now that there is a baseline for the Hudson River and the current bridge, it will be relatively easy, and very interesting, to do a comparable study when the new bridge is in use.

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[1] See: http://americanliterature.com/author/washington-irving/short-story/rip-van-winkle

Amoser, S., and Ladich, F. (**2010**). "Year-round variability of ambient noise in temperate freshwater habitats and its implications for fishes," Aquat. Sci. **72**, 371–378.

Bailey, H., Senior, B., Simmons, D., Rusin, J., Picken, G., and Thompson, P. M. (**2010**). "Assessing underwater noise levels during pile-driving at an offshore windfarm and its potential effects on marine mammals," Mar. Pollut. Bull. **60**, 888–897.

Barber, J. R., Crooks, K. R., and Fristrup, K. M. (**2010**). "The costs of chronic noise exposure for terrestrial organisms," Trends Ecol. Evol. **25**, 180–189.

Cato, D. (**1976**). "Ambient sea noise in waters near Australia," J. Acoust. Soc. Am. **60**, 320–328.

Cato, D. H. (**2012**). "Physical biologists and biological physicists: Combining biology and physics in research on the effects of noise on aquatic life," in *Effects of Noise on Aquatic Life*, edited by A. N. Popper and A. D. Hawkins (Springer, New York), pp. 509–513.

CO-OPS (**2010**). "NOAA Tide Predictions" (Center for Operational Oceanographic Products and Services, National Oceanic and Atmospheric Administration, U.S. Department of Commerce. http://tidesandcurrents.noaa.gov/tide_predictions.shtml (Last viewed 1/4/15).

Cott, P. A., Mann, D. A., Higgs, D. M., Johnston, T. A., and Gunn, J. M. (**2012**). "Assessing disturbance from under-ice noise on fishes in boreal lakes," in *Effects of Noise on Aquatic Life*, edited by A. N. Popper and A. D. Hawkins (Springer-Verlag, New York), pp. 363–366.

Dahl, P. H., Miller, J. H., Cato, D. H., and Andrew, R. K. (**2007**). "Underwater ambient noise," Acoust. Today **3**, 23–33.

Dooling, R. J., Leek, M. R., and Popper, A. N. (**2015**). "Effects of noise on fishes: What we can learn from humans and birds," Integr. Zool. **10**, 29–37.

Enger, P. S. (**1967**). "Hearing in herring," Comp. Biochem. Physiol. **22**, 527–538.

Erbe, C. (**2013**). "Underwater noise of small personal watercraft (jet skis)," J. Acoust. Soc. Am. **133**, EL326–EL330.

Fay, R. R. (**1988**). *Hearing in Vertebrates: A Psychophysics Databook* (Hill-Fay Associates, Winnetka, IL).

Hawkins, A. D., Pembroke, A. E., and Popper, A. N. (**2015**). "Information gaps in understanding the effects of noise on fishes and invertebrates," Rev. Fish Biol. Fish. **25**, 39–64.

Hawkins, A. D., and Popper, A. (**2014**). "Assessing the impacts of underwater sounds on fishes and other forms of marine life," Acoust. Today **10**, 30–41.

Hildebrand, J. A. (**2009**). "Anthropogenic and natural sources of ambient noise in the ocean," Mar. Ecol. Prog. Ser. **395**, 5–20.

Holles, S., Simpson, S. D., Radford, A. N., Berten, L., and Lecchini, D. (**2013**). "Boat noise disrupts orientation behaviour in a coral reef fish," Mar. Ecol. Prog. Ser. **485**, 295–300.

HRECOS (**2010**). "Hudson River environmental conditions observing system" (USEPA, NOAA, Hudson River Foundation, and the Hudson River Estuary Program of the New York State Dept of Environmental Conservation). http://hudson.dl.stevens-tech.edu/hrecos/d/index.shtml (Last viewed 1/4/15).

Jennings, P., and Cain, R. (**2013**). "A framework for improving urban soundscapes," Appl. Acoust. **74**, 293–299.

Ketten, D. R. (**2014**). "Sonars and strandings: Are beaked whales the aquatic acoustic canary?," Acoust. Today **10**, 46–56.

Kight, C. R., Saha, M. S., and Swaddle, J. P. (**2012**). "Anthropogenic noise is associated with reductions in the productivity of breeding Eastern Bluebirds (*Sialia sialis*)," Ecol. Appl. **22**, 1989–1996.

Kight, C. R., and Swaddle, J. P. (**2011**). "How and why environmental noise impacts animals: An integrative, mechanistic review," Ecol. Lett. **14**, 1052–1061.

Klinck, H., Nieukirk, S. L., Mellinger, D. K., Klinck, K., Matsumoto, H., and Dziak, R. P. (**2012**). "Seasonal presence of cetaceans and ambient noise levels in polar waters of the North Atlantic," J. Acoust. Soc. Am. **132**, EL176–EL181.

Ladich, F., and Fay, R. R. (**2013**). "Auditory evoked potential audiometry in fish," Rev. Fish Biol. Fish. **23**, 317–364.

Le Prell, C. G., Henderson, D., Fay, R. R., and Popper, A. (**2012**). *Noise-Induced Hearing Loss: Scientific Advances* (Springer Science & Business Media, New York).

Lovell, J., Findlay, M., Moate, R., Nedwell, J., and Pegg, M. (**2005**). "The inner ear morphology and hearing abilities of the Paddlefish (*Polyodon spathula*) and the Lake Sturgeon (*Acipenser fulvescens*)," Comp. Biochem. Physiol. A **142**, 286–296.

Lugli, M., and Fine, M. L. (**2007**). "Stream ambient noise, spectrum and propagation of sounds in the goby *Padogobius martensii*: Sound pressure and particle velocity," J. Acoust. Soc. Am. **122**, 2881–2892.

Ma, B. B., Nystuen, J. A., and Lien, R.-C. (**2005**). "Prediction of underwater sound levels from rain and wind," J. Acoust. Soc. Am. **117**, 3555–3565.

Mann, D. A., Higgs, D. M., Tavolga, W. N., Souza, M. J., and Popper, A. N. (**2001**). "Ultrasound detection by clupeiform fishes," J. Acoust. Soc. Am. **109**, 3048–3054.

Martin, B. (**2013**). "Computing cumulative sound exposure levels from anthropogenic sources in large data sets," Proc. Mtgs. Acoust. **19**, 010048.

Martin, S. B., and Cott, P. A. (**2016**). "The under-ice soundscape in Great Slave Lake near the city of Yellowknife, Northwest Territories, Canada," J. Great Lakes Res. **42**, 248–255.

McDonald, M. A., Hildebrand, J. A., and Wiggins, S. M. (**2006**). "Increases in deep ocean ambient noise in the Northeast Pacific west of San Nicolas Island, California," J. Acoust. Soc. Am. **120**, 711–718.

Merchant, N. D., Witt, M. J., Blondel, P., Godley, B. J., and Smith, G. H. (**2012**). "Assessing sound exposure from shipping in coastal waters using a single hydrophone and Automatic Identification System (AIS) data," Mar. Pollut. Bull. **64**, 1320–1329.

Meyer, M., Fay, R. R., and Popper, A. N. (**2010**). "Frequency tuning and intensity coding of sound in the auditory periphery of the lake sturgeon, *Acipenser fulvescens*," J. Exp. Biol. **213**, 1567–1578.

Mitson, R. B., and Knudsen, H. P. (**2003**). "Causes and effects of underwater noise on fish abundance estimation," Aquat. Living Resour. **16**, 255–263.

Paiva, E. G., Kent, C. P. S., Gagnon, M. M., McCauley, R., and Finn, H. (**2015**). "Reduced detection of Indo-Pacific bottlenose dolphins (*Tursiops aduncus*) in an inner harbour channel during pile driving activities," Aquat. Mamm. **41**, 455–468.

Parks, S. E., Clark, C. W., and Tyack, P. L. (**2007**). "Short- and long-term changes in right whale calling behavior: The potential effects of noise on acoustic communication," J. Acoust. Soc. Am. **122**, 3725–3731.

Parmentier, E., Berten, L., Rigo, P., Aubrun, F., Nedelec, S., Simpson, S., and Lecchini, D. (**2015**). "The influence of various reef sounds on coral-fish larvae behaviour," J. Fish Biol. **86**, 1507–1518.

Pirotta, E., Merchant, N. D., Thompson, P. M., Barton, T. R., and Lusseau, D. (**2015**). "Quantifying the effect of boat disturbance on bottlenose dolphin foraging activity," Biol. Conserv. **181**, 82–89.

Pirotta, E., Milor, R., Quick, N., Moretti, D., Di Marzio, N., Tyack, P., Boyd, I., and Hastie, G. (**2012**). "Vessel noise affects beaked whale behavior: Results of a dedicated acoustic response study," PLoS One **7**, e42535.

Poggendorf, D. (**1952**). "The absolute threshold of hearing of the bullhead (*Amiurus nebulosus*) and contributions to the physics of the Weberian apparatus of the Ostariophysi" (translated by H. E. Adler and B. Cappelli), Z. Vergleigh Physiol. **34**, 222–257.

Popper, A. N., Fay, R. R., Platt, C., and Sand, O. (**2003**). "Sound detection mechanisms and capabilities of teleost fishes," in *Sensory Processing in Aquatic Environments*, edited by S. P. Collin and N. J. Marshall (Springer-Verlag, New York), pp. 3–38.

Popper, A. N., and Hawkins, A. D. (**2012**). *The Effects of Noise on Aquatic Life* (Springer Science+Business Media, New York).

Popper, A. N., and Hawkins, A. D. (**2016**). *The Effects of Noise on Aquatic Life II* (Springer Science+Business Media, New York).

Popper, A. N., Hawkins, A. D., Fay, R. R., Mann, D. A., Bartol, S., Carlson, T. J., Coombs, S., Ellison, W. T., Gentry, R. L., and Halvorsen, M. B. (**2014**). "Sound exposure guidelines," in *ASA S3/SC1. 4 TR-2014 Sound Exposure Guidelines for Fishes and Sea Turtles: A Technical Report prepared by ANSI-Accredited Standards Committee S3/SC1 and registered with ANSI* (Springer, New York), pp. 33–51.

Popper, A. N., Smith, M. E., Cott, P. A., Hanna, B. W., MacGillivray, A. O., Austin, M. E., and Mann, D. A. (**2005**). "Effects of exposure to seismic airgun use on hearing of three fish species," J. Acoust. Soc. Am. **117**, 3958–3971.

Radford, A. N., Kerridge, E., and Simpson, S. D. (**2014**). "Acoustic communication in a noisy world: Can fish compete with anthropogenic noise?," Behav. Ecol. **25**(5), 1022–1030.

Ramcharitar, J., Gannon, D. P., and Popper, A. N. (**2006**). "Bioacoustics of fishes of the family Sciaenidae (croakers and drums)," Trans. Am. Fish. Soc. **135**, 1409–1431.

Ramcharitar, J., and Popper, A. N. (**2004**). "Masked auditory thresholds in sciaenid fishes: A comparative study," J. Acoust. Soc. Am. **116**, 1687–1691.

Reeder, D. B., Sheffield, E. S., and Mach, S. M. (**2011**). "Wind-generated ambient noise in a topographically isolated basin: A pre-industrial era proxya)," J. Acoust. Soc. Am. **129**, 64–73.

Risch, D., Corkeron, P. J., Ellison, W. T., and Van Parijs, S. M. (**2012**). "Changes in humpback whale song occurrence in response to an acoustic source 200 km away," PLoS One **7**, e29741.

Rogers, P. H., and Cox, M. (**1988**). "Underwater Sound as a Biological Stimulus," in *Sensory Biology of Aquatic Animals*, edited by J. Atema, R. R. Fay, A. N. Popper, and W. N. Tavolga (Springer-Verlag, New York), pp. 131–149.

Roh, H.-S., Sutin, A., and Bunin, B. (**2008**). "Determination of acoustic attenuation in the Hudson River Estuary by means of ship noise observations," J. Acoust. Soc. Am. **123**, EL139–EL143.

Rolland, R. M., Parks, S. E., Hunt, K. E., Castellote, M., Corkeron, P. J., Nowacek, D. P., Wasser, S. K., and Kraus, S. D. (**2012**). "Evidence that ship noise increases stress in right whales," Proc. R. Soc. B **279**, 2363–2368.

Roth, E. H. (**2012**). "Underwater ambient noise on the Chukchi Sea continental slope from 2006–2009," J. Acoust. Soc. Am. **131**, 104–110.

Shannon, G., Angeloni, L. M., Wittemyer, G., Fristrup, K. M., and Crooks, K. R. (**2014**). "Road traffic noise modifies behaviour of a keystone species," Anim. Behav. **94**, 135–141.

Skeate, E. R., Perrow, M. R., and Gilroy, J. J. (**2012**). "Likely effects of construction of Scroby Sands offshore wind farm on a mixed population of harbour *Phoca vitulina* and grey *Halichoerus grypus* seals," Mar. Pollut. Bull. **64**, 872–881.

Slabbekoorn, H., and Halfwerk, W. (**2009**). "Behavioural ecology: Noise annoys at community level," Curr. Biol. **19**, R693–R695.

Southall, B. L., Bowles, A. E., Ellison, W. T., Finneran, J. J., Gentry, R. L., Greene, C. R., Jr., Kastak, D., Ketten, D. R., Miller, J. H., Nachtigall, P. E., Richardson, W. J., Thomas, J. A., and Tyack, P. L. (**2007**). "Marine mammal noise exposure criteria: Initial scientific recommendations," Aquat. Mamm. **33**, 411–521.

Tougaard, J., Carstensen, J., Teilmann, J., Skov, H., and Rasmussen, P. (**2009**). "Pile driving zone of responsiveness extends beyond 20 km for harbor porpoises (*Phocoena phocoena* (L.))," J. Acoust. Soc. Am. **126**, 11–14.

Urick, R. J. (**1983**). *Principles of Underwater Sound* (McGraw-Hill, New York).

U.S. Department of Transportation (**2015**). "Beyond traffic 2045: Trends and choices" (U.S. Department of Transportation, Washington, D.C.).

Vagle, S., Large, W. G., and Farmer, D. M. (**1990**). "An evaluation of the WOTAN technique of inferring oceanic winds from underwater ambient sound," J. Atmos. Ocean Technol. **7**, 576–595.

Vračar, M. S., and Mijić, M. (**2011**). "Ambient noise in large rivers (L)," J. Acoust. Soc. Am. **130**, 1787–1791.

Wenz, G. M. (**1962**). "Acoustic ambient noise in the ocean: Spectra and sources," J. Acoust. Soc. Am. **34**, 1936–1956.

Whitfield, A., and Becker, A. (**2014**). "Impacts of recreational motorboats on fishes: A review," Mar. Pollut. Bull. **83**, 24–31.

Williams, R., Bain, D. E., Ford, J. K. B., and Trites, A. W. (**2002**). "Behavioral responses of male killer whales to a 'leapfrogging' vessel," J. Cetacean Res. Manage. **4**, 305–310.

Wysocki, L. E., Amoser, S., and Ladich, F. (**2007**). "Diversity in ambient noise in European freshwater habitats: Noise levels, spectral profiles, and impact on fishes," J. Acoust. Soc. Am. **121**, 2559–2566.

Zhang, Z. Y. (**2002**). "Modelling of sound transmission from air into shallow and deep waters," in *Proceedings of Australian Acoustical Society Conference*, Adelaide, Australia, pp. 13–15.