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Techniques for distinguishing between impulsive and non-impulsive sound in the context of regulating sound exposure for marine mammals[a)]

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ABSTRACT:

Regulations designed to mitigate the effects of man-made sounds on marine mammal hearing specify maximum daily sound exposure levels. The limits are lower for impulsive than non-impulsive sounds. The regulations do not indicate how to quantify impulsiveness; instead sounds are grouped by properties at the source. To address this gap, three metrics of impulsiveness (kurtosis, crest factor, and the Harris impulse factor) were compared using values from random noise and real-world ocean sounds. Kurtosis is recommended for quantifying impulsiveness. Kurtosis greater than 40 indicates a sound is fully impulsive. Only sounds above the effective quiet threshold (EQT) are considered intense enough to accumulate over time and cause hearing injury. A functional definition for EQT is proposed: the auditory frequency-weighted sound pressure level (SPL) that could accumulate to cause temporary threshold shift from non-impulsive sound as described in Southall, Finneran, Reichmuth, Nachtigall, Ketten, Bowles, Ellison, Nowacek, and Tyack [(2019). Aquat. Mamm. **45**, 125–232]. It is known that impulsive sounds change to non-impulsive as these sounds propagate. This paper shows that this is not relevant for assessing hearing injury because sounds retain impulsive character when SPLs are above EQT. Sounds from vessels are normally considered non-impulsive; however, 66% of vessels analyzed were impulsive when weighted for very-high frequency mammal hearing. https://doi.org/10.1121/10.0000971

(Received 19 March 2019; revised 11 March 2020; accepted 11 March 2020; published online 3 April 2020)

[Editor: Arthur N. Popper] Pages: 2159–2176

I. INTRODUCTION

It has been known for centuries that humans suffer noise-induced hearing loss when exposed to intense sound (Akay, 1978). The hearing loss may be a temporary threshold shift (TTS) or permanent threshold shift (PTS) in hearing sensitivity, respectively. The equal energy hypothesis (EEH) (Eldred *et al.*, 1955) proposes that equivalent hearing injury will occur for intense sound sources over a short duration as for lower level sources over a long duration if the sound exposure levels (SELs) are the same; i.e., noise-induced hearing loss depends on intensity and duration. A listener's perception of a sound's intensity depends on the frequency response of their hearing system. Weighting functions emphasize frequencies where the listener's hearing sensitivity to sound is high and to de-emphasize frequencies where sensitivity is low. Marine mammal functional hearing groups have been defined based on similarities in their hearing capabilities and sound production. Cetaceans can be divided into low-frequency (LF), high-frequency (HF), and very high-frequency (VHF) groups (Southall *et al.*, 2019).

The EEH is the foundation of regulations to protect human hearing (NIOSH, 1998) and is an integral part of regulations to limit the impact of human activities on marine mammals (Southall *et al.*, 2007; NMFS, 2018; Southall *et al.*, 2019). Since Eldred *et al.* (1955), numerous measurements have shown that mammals, including marine mammals, are affected differently by non-impulsive and impulsive sounds and therefore the EEH by itself does not adequately predict the effects of sound on hearing threshold shifts (Ward, 1962; Roberto *et al.*, 1985; Finneran, 2015a; Kastelein *et al.*, 2015). The temporal pattern of impulsive sounds, as well as their frequency content, rise-time, duration, and amplitude affect the onset and magnitude of TTS (Buck *et al.*, 1984; Danielson *et al.*, 1991; Finneran *et al.*, 2002; Kastelein *et al.*, 2014a). For non-impulsive sounds, exposure to longer durations of lower sound pressure levels (SPLs) can result in larger TTS effects than exposure to the same SEL from shorter but higher amplitude sounds (Mooney *et al.*, 2009; Kastelein *et al.*, 2012a). Finneran *et al.* (2010b) demonstrated that exposing bottlenose dolphins to a 64-s tone had a greater effect than an equivalent SEL from four 16-s tones separated by 224 s, presumably because their hearing recovered between tones in the second

[a)]This paper is part of a special issue on The Effects of Noise on Aquatic Life.

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case. Regulations designed to mitigate the effects of sound on marine mammals have distilled the complexity of temporal and amplitude effects into separate equal energy threshold levels for non-impulsive and impulsive sounds, where the impulsive TTS thresholds are 8–13 dB below the non-impulsive thresholds (depending on hearing group, Southall *et al.*, 2019). Initial guidelines for other marine taxa are discussed in Popper *et al.* (2014).

Qualitatively, impulses are characterized as acoustic events that are broadband, short duration (<1 s) with high peak sound pressures and short rise times (NIOSH, 1998; NMFS, 2018). While quantitative definitions for the difference between impulsive and non-impulsive sounds are missing from the regulations, several impulsive metrics have been suggested for aerial and underwater sounds. Southall *et al.* (2007) proposed that regulations should use the Harris (1998) definition that says an impulse is present if there is more than a 3 dB difference between the impulse time weighted SPL and the slow-time weighted SPL (referred to here as the Harris impulse factor; time weightings are discussed in Sec. II E). Pekkarinen and Starck (1983) proposed that an A-weighted crest factor greater than 15 dB predicts impulse hazards for human workers (see Sec. II E). Kurtosis was proposed by Erdreich (1986) as an indicator of impulsiveness for assessing effects of noise on factory workers (see Sec. II E). Kurtosis has also been used in studies of the effects of noise on terrestrial mammals (Hamernik *et al.*, 2003; Qiu *et al.*, 2013) and as a characteristic to describe seismic impulses during an exposure study of harbor porpoise (Kastelein *et al.*, 2017). It has been proposed as a metric to distinguish impulsive sounds in the studies of fish and invertebrates; however, no studies have applied it to date (Popper and Hawkins, 2019). Hamernik *et al.* (2007) showed that PTS increases with kurtosis for the same SEL up to a kurtosis of 40.

Due to refraction, absorption, and scattering, long-distance underwater sound propagation attenuates high frequencies more than low frequencies. Multi-path reflections influence the temporal pattern of a sound by adding extra arrivals at longer distances (e.g., Martin *et al.*, 2017). Because these effects change the structure of an impulse over distance, it has been proposed that impulsive sounds transform to non-impulsive as they propagate. Because non-impulsive and impulsive sounds have different thresholds within the regulations to protect hearing of marine mammals, it is important to have an objective metric that measures the impulsiveness of sounds. As there are no agreed metrics for a quantitative delineation of impulsive from non-impulsive sound, sounds are currently grouped by their source. Impact pile driving and seismic airgun surveys are considered impulsive sources, while vessels and vibratory pile driving are considered non-impulsive sources. Sonar pulses, both HF pulses from multibeam sonars and echosounders as well as lower frequency pulses from naval sonar, are grouped by the American regulator (NMFS, 2018) with the non-impulsive sources due to their narrowband nature, but sonar pulses are considered impulsive by the European Union Expert Group on Noise (Dekeling *et al.*, 2014).

There is a minimum level of sound required to start accumulating energy for estimating hearing injury because mammals do not suffer threshold shift in normal acoustic environments even when integrating over very long durations. This safe level is known as "effective quiet" (Ward *et al.*, 1976), and it is poorly understood or quantified for any species, including humans. Below the level of effective quiet, the impulsive or non-impulsive nature of a sound is irrelevant for assessing auditory impairment and injury, although it may be a consideration for studying disturbance or masking of biologically important sounds. It is desirable to develop a general rule for assessing effective quiet because simple measures that are straightforward to use in practice improve compliance and understanding of regulatory policy.

A limit for effective quiet can be derived from the Southall *et al.* (2019) daily TTS threshold for non-impulsive sources. Sounds with a per-minute SEL that are 31.6 dB [$10\log_{10}$ (1440 min/1 day) dB] below the threshold can never accumulate and lead to a 24-h SEL exceedance. The proposed effective quiet threshold (EQT) is the 1-min auditory frequency weighted SPL that accumulates to this 1-min SEL, which numerically is 18 dB below the 1-min SEL [because $10\cdot\log_{10}(1\text{ min}/1\text{ s})$ dB = 17.7 dB]. Thus, the proposed level for effective quiet is equivalently a 1-min SPL that is 50 dB below the numeric value of the auditory frequency-weighted Southall *et al.* (2019) daily SEL TTS threshold for non-impulsive sources. One-minute analysis windows are recommended to average over multiple impulsive events from typical human sound sources and to make the time-unit of analysis manageable. The proposed 1-min auditory frequency weighted SPL EQTs are of 129, 128, and 103 dB re 1 $\mu\text{Pa}^2\cdot\text{s}$ for LF, HF, and VHF cetaceans, respectively. The equivalent 1-min auditory frequency weighted SEL EQTs are 147, 146, and 121 dB re 1 $\mu\text{Pa}^2\cdot\text{s}$. The EQT for humans ranges between 55 and 70 dBA, where the "A" designation indicates that the "A" auditory frequency weighting has been applied (Flamme *et al.*, 2012; to find the roughly comparable underwater SPLs add 62 dB).

The proposed limits for effective quiet may be compared to the limited experimental results available to assess their validity (Fig. 1). Mooney *et al.* (2009) found that effective quiet for bottlenose dolphins exposed to octave band noise centered at 5.6 kHz was 150–160 dB re 1 μPa^2. Using the level of 150 dB re 1 μPa^2, the HF cetacean auditory frequency weighted SPL for the sound used is approximately 145 dB re 1 μPa^2, 17 dB above the proposed threshold. Similarly, the sounds used in Kastelein *et al.* (2012b) that did not cause significant TTS in harbor porpoise had an auditory frequency weighted SPL of 108 dB re 1 μPa^2, which is 5 dB above the proposed limit. The lowest SEL at 16 kHz that caused TTS in harbor porpoise after 1 h was 159 dB re 1 $\mu\text{Pa}^2\cdot\text{s}$, which is equivalent to a 1 min very-high frequency weighted SPL of 120 dB re 1 μPa^2 (Kastelein *et al.*, 2019). Observations of sound levels that did not cause TTS in odontocetes from impulsive sounds are at least 2 dB above the proposed limits (Finneran *et al.*, 2000; Lucke *et al.*, 2009; Kastelein *et al.*, 2016; Kastelein *et al.*, 2017). There is

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https://doi.org/10.1121/10.0000971

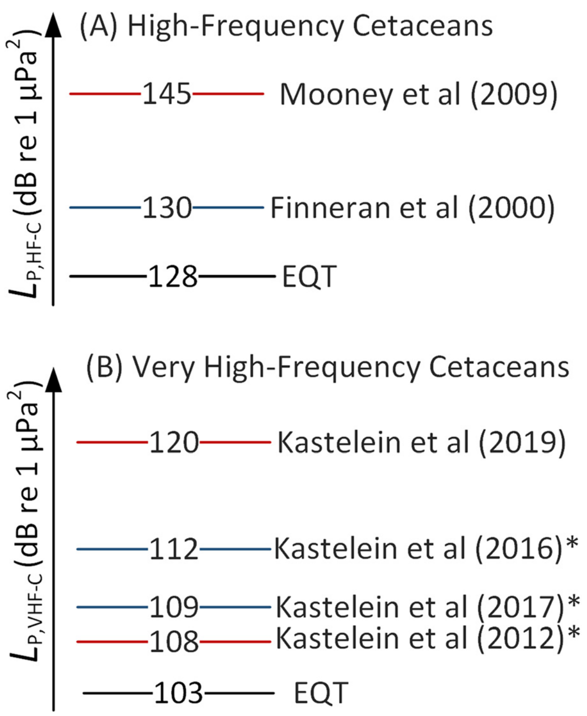

FIG. 1. (Color online) Existing results used to validate the proposed EQTs for (A) HF-Cs and (B) VHF-Cs (Southall *et al.*, 2019). The results were recomputed as the 1-min auditory frequency weighted SPLs, based on descriptions from the literature references. The results with red lines used continuous sounds, those with blue used impulsive sounds. The VHF results with an asterisk are the per-minute auditory frequency weighted SPL that caused 1–4 dB of TTS four minutes after end of exposure.

evidence that long exposures (multiple hours) to low intensity sound lead to higher hearing impairment than an equivalent SEL from a higher sound level for shorter durations (e.g., Kastelein *et al.*, 2012b). The proposed thresholds for effective quiet may need to be carefully considered if there is a realistic expectation that an animal will be exposed to sounds above the threshold for many consecutive hours.

The questions addressed here are: (a) what metric should be used to identify the presence of impulses, (b) can a threshold for impulsiveness be recommended, and (c) do the sounds from impulsive sources become non-impulsive before the sound levels drop below the proposed EQTs? The results are expected to inform the development of regulatory thresholds for marine mammals.

II. METHODS

To achieve the goals of this work, four types of data were analyzed: randomly distributed noise data, short-term real-world data with known high-level human sounds, long-term monitoring data, and data that replicate the sounds employed during TTS experiments on marine mammals. This section describes each of the data sets, as well as the metrics used in the analysis.

A. Random data

To demonstrate the range of values generated by different impulsive metrics, the metrics were applied to Gaussian random data as well as two Gamma and two Rayleigh distributed random noise data sets. The first Gamma distribution with Shape 1 and Scale 2 had a relatively long high amplitude tails, while the distribution with Shape 6 and Scale 1 did not. For the Rayleigh distribution, scale parameters of 2 and 10 were chosen for comparing examples with and without high amplitude tails, respectively.

B. Short-term real-world data sets

Six short-term data sets containing high amplitude human-generated sounds were analyzed to provide an indication of their auditory frequency weighted sound levels and impulsiveness. All recordings were made with Autonomous Multi-Channel Acoustic Recorders (AMARs; JASCO Applied Sciences). These data sets have no substantial contributions from flow-induced noise or other acoustic artifacts.

The short-term data include a seismic survey, vibratory and impact pile driving, oil and gas drilling, vessel passages, and naval sonar (Fig. 2). An additional data set recorded in the Chukchi Sea in 2014 was analyzed as a reference, as it contained no detectable human or biologic sound sources. The sounds from shallow-water oil and gas drilling program (Fig. 2, Panel A) in the Chukchi Sea are an example of sound from dynamic positioning operations, in this case from a semi-submersible drillship. An example of fisheries echosounder sounds (Fig. 2, Panel B) is provided from the passage of a 58 m fishing vessel by the Georgia Strait Observatory (ONC, 2019). The vibratory pile driving data (Fig. 2, Panel C) were collected 10 m from the insertion of a 3 m diameter pile in water 7 m deep using a Super Kong 600 vibratory hammer. Recordings at a distance of 541, 1900, 4912, and 9067 m from the Block Island Wind Farm (Fig. 2, Panel D) provide examples of sounds from impact pile driving (for more on this data set, see Martin and Barclay, 2019). The seismic survey data (Fig. 2, Panel E) were collected in Baffin Bay, west of Greenland (for more information, see Frouin-Mouy *et al.*, 2017; Martin *et al.*, 2017). In the Baffin Bay data, a 62.3 L (3480 in^3) airgun array was towed from 36 km south (starting at 03:00, 4 Sep 2012) to 2 km north of the recorder in water 600 m deep. A 12 kHz multibeam sonar on the seismic vessel was present throughout the 5 min of data shown. Several naval sonars (Fig. 2, Panel F) with center frequencies from 1200 to 5500 Hz were recorded by chance with a recorder in 1600 m deep water during the "ObSERVE" baseline monitoring program off Ireland (Kowarski *et al.*, 2018).[1] Other recordings of multiple naval sonars from the east coast of Canada were also analyzed. Table I contains further information on each data set.

C. Long-term real-world data sets

Five long-term data sets were analyzed to provide results from typical passive acoustic monitoring projects. All recordings were made with autonomous multi-channel acoustic recorders (AMARs, JASCO Applied Sciences). The selected data sets have no substantial contributions from flow induced noise or other acoustic artifacts.

https://doi.org/10.1121/10.0000971

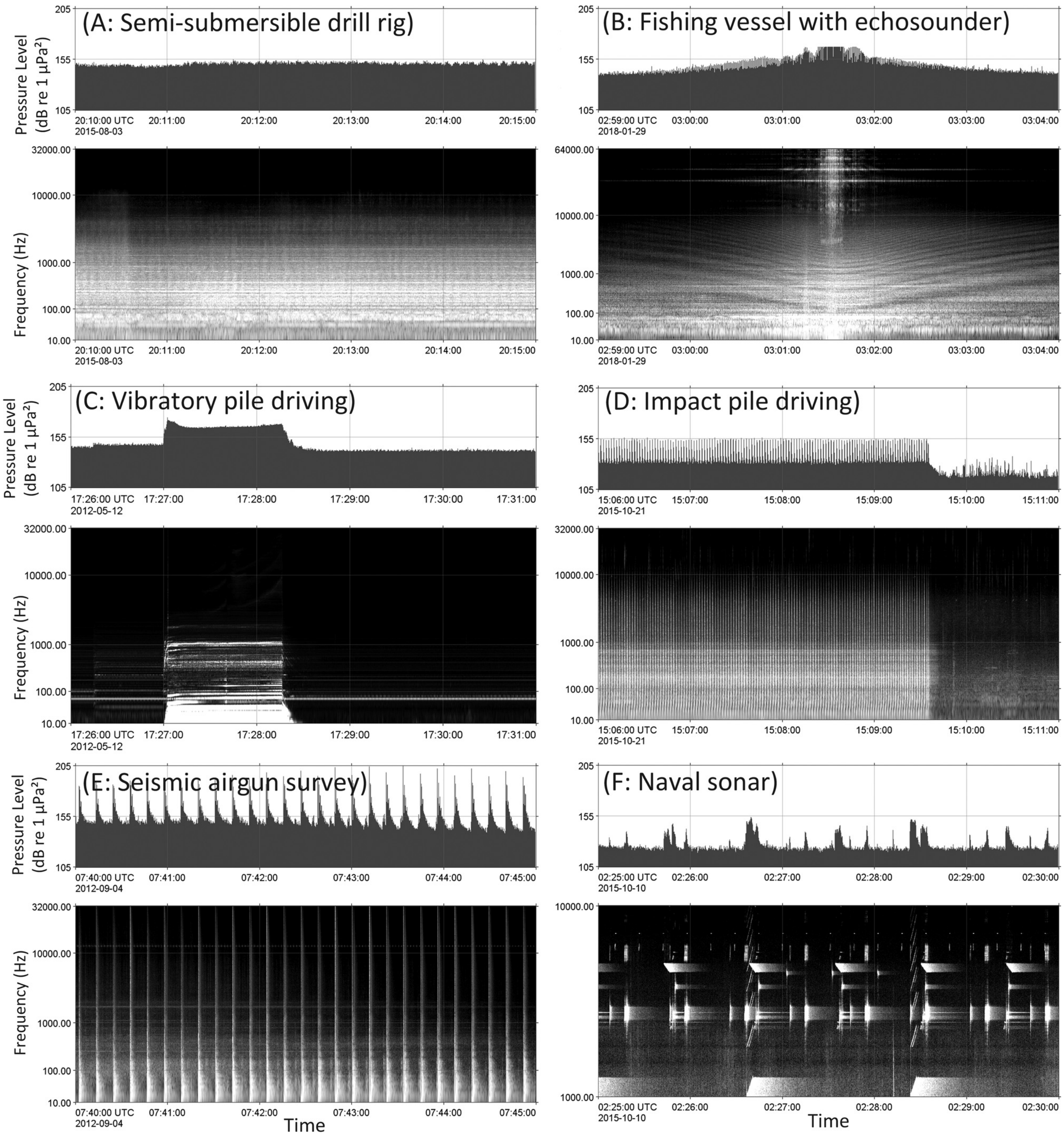

FIG. 2. Five-minute snapshots of the short-term real-world data analyzed. Recorded sound types were: (A) dynamic positioning vessel, (B) vessel passage with echosounders, (C) vibratory pile driving, (D) impact pile driving, (E) seismic airgun survey, and (F) naval sonar. For each example, the top panel is the SPL and the bottom panel is the spectrogram [FFT parameters: 0.2 s of data, 0.1 s overlap, 2 Hz resolution (0.3 s zero padding), Hann window; spectrograms are normalized to optimize the visual representation of the data]. The vertical axes in the spectrograms are log-frequency. Data set (F) is restricted to 1000–10 000 Hz to better visualize the sonar pulses.

The long-term data sets (Table II) were each 6–10 weeks long and were selected because they were known to contain human sound sources of interest and they were sampled at 128, 250, or 375 kHz so that the very-high frequency cetacean auditory-weighting function could be applied to the data. The data had duty cycles between 1 min out of 15 to 1 min out of 30. A total of 26 978 min of data were analyzed and are presented as a single group in the results. The first data set was collected in 160 m of water at the northeastern edge of the Grand Banks. This location was at least 30 km from three-dimensional (3 D) seismic surveys for approximately half of the recording. The second data set was collected in water 870 m deep on the Blake Escarpment as part of the Atlantic Deep-water Eco-system Observatory Network project.[2] The third data set was collected in water 1280 m deep in the Orphan Basin off Newfoundland, Canada. The

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https://doi.org/10.1121/10.0000971

TABLE I. Short-term real-world acoustic recordings used in this study.

Data represented	Location	Latitude (° north)	Longitude (° east)	Depth (m)	Sample rate (kHz)
Ambient sound	Chukchi Sea, 2014	71.19	–163.5	50	375
Semi-submersible drill rig	Chukchi Sea, 2015	71.19	–163.5	50	64
Heavy port traffic and fisheries echosounder	Port of Vancouver	49.05	–123.3	170	128
Vibratory pile driving	Hudson River	43.04	73.53	7	64
Seismic survey	Baffin Bay	74.16	61.98	603	64
Impact pile driving at 1900 m	Block Island Wind Farm	41.06	–71.45	42	64
Naval sonar	GMIT ObSERVE Mooring	55.63	–9.73	1620	32[a]
	Scotian Shelf	42.55	62.18	1831	250

[a]The ObSERVE data are the only recording sampled at less than 64 kHz, which is the minimum sample rate recommended for measuring the HF- and VHF weighted sound levels from man-made sources (Martin *et al.*, 2019). Because the sonar's energy did not exceed 10 kHz, the 32 kHz sample rate was acceptable for this source.

selected data included seismic surveys that passed within several kilometers. The fourth data were collected in water 1830 m deep off Nova Scotia, Canada. The selected data period included 5 days with Naval sonar exercises in the area. The final data were from the same Port of Vancouver observatory as short-term data set (Fig. 2, Panel E), which were included to assess the SEL and kurtosis from a variety of vessels. Only 2546 min of the Port of Vancouver data were used to avoid biasing the results with too many detections from one data set.

D. Simulations of sound exposure data that elicited TTS in marine mammals

Numerous studies of marine mammal TTS have been conducted in controlled settings (Finneran, 2015b). These studies informed the development of the auditory frequency weighting functions and TTS thresholds in NMFS (2018) and Southall *et al.* (2019). Various types of fatiguing signals were employed (Table III). Finneran *et al.* (2000) exposed bottlenose dolphins and a beluga whale to sounds resembling distant explosions without causing TTS; here, the most intense signal used was simulated. Finneran *et al.* (2010a) exposed bottlenose dolphins to 16 and 64 s long tones at 3 kHz. Popov *et al.* (2013), Kastelein *et al.* (2012b), and Kastelein *et al.* (2014b) evaluated TTS in porpoise and beluga whales using band-limited Gaussian random noise that was easily simulated to estimate its impulsive properties. Kastelein *et al.* (2015) generated frequency-modulated up-sweeps centered at 6.5 kHz to evaluate the effect of active naval sonars on porpoise. Here, simulations of the 6.5 kHz frequency modulation (FM) signals were used to evaluate the impulsiveness that the animals were exposed to during Kastelein's experiments but also to examine how different duty cycles, amplitudes, bandwidths, and pulse durations affect the measured impulsiveness. All simulations were performed at a sample rate of 512 kHz. The simulated signals, at the SPLs shown in the Table III, were added to 100 dB re 1 μPa^2 Gaussian noise as the ambient background. Transient signals were tapered with a 5% Tukey window to remove start-up effects.

E. Metrics computed

This analysis used the SPL, SEL, and three possible measures of impulsiveness: kurtosis, crest factor, and the Harris impulse factor. Biologically relevant values of these metrics were obtained by using filtered pressure time-series, p_w, where the filters were finite-impulse-response (FIR) implementations of the auditory frequency weighting functions defined in Southall *et al.* (2019) (see Appendix). The metrics were also computed on a broadband time series that was FIR filtered to remove energy below 10 Hz. All computations were performed using custom MATLAB software (MathWorks Inc; Natwick, Massachusetts, R2018b).

Impulsive metrics were computed using a 1-min time window, which is a standard soundscape analysis duration (Ainslie *et al.*, 2018) and has the advantage of providing metric values without concern for whether data are non-impulsive or impulsive as it integrates over multiple

TABLE II. Long-term real-world acoustic recordings used in this study.

Data represented	Latitude (° north)	Longitude (° east)	Recorder depth (m)	Sample rate (kHz)	Duty cycle (min)	Data duration (min)
3D seismic, minimum distance 30 km	46.36	47.74	160	375	1 / 15	9098
Open ocean with some shipping	29.25	78.35	870	250	1 / 20	5271
Open ocean (1 April to 24 May); seismic air-gun survey (25 May to 30 Jun) at distances of 5 km+	48.73	49.38	1280	250	1 / 20	4493
Deep water open ocean with distant shipping and close-by naval sonar	42.55	62.18	1831	250	1 / 20	5570
Heavy vessel traffic	49.05	123.3	170	128	1 / 30	2546

TABLE III. Overview of the fatiguing sounds from marine mammal TTS studies. The test subjects were TT, bottlenose dolphins (*Tursiops truncatus*); DL, beluga whales (*Delphinapterus leucas*); PP, harbor porpoises (*Phocoena phocoena*).

Study	Subject species	Fatiguing sound
Popov *et al*. (2013)	DL	Half-octave noise at 11.2, 22.5, 45, and 90 kHz at 165 dB re 1 μPa^2 for 1, 3, 10, or 30 min
Kastelein *et al*. (2012b)	PP	Octave band noise centered at 4 kHz with SPLs of 124, 136, or 148 dB re 1 μPa^2 for 7.5, 15, 30, 60, 120, or 240 min
Kastelein *et al*. (2014b)	PP	6.5 kHz continuous tone at 118, 124, 130, 136, 142, 148 or 154 dB re 1 μPa^2 for 60 min
Finneran *et al*. (2000)	TT and DL	Signal resembling explosions with sharp compression to rarefaction transition; maximum SEL 179 dB re 1 μPa^2·s and peak-to-peak SPL of 221 dB re 1 μPa^2 (estimated mid-frequency weighted SEL of 172 dB re 1 μPa^2·s); this was a simulation of 500 kg HBX-1 explosive at 1.7 km
Finneran *et al*. (2010a)	TT	3 kHz tones at 192 dB re 1 μPa^2, 16-s or 64-s long
(Kastelein *et al*., 2015)	PP	1 second long 6–7 kHz FM upsweeps at 166 dB re 1 μPa^2 at either at duty cycle of 1 sweep every 10 seconds or continuous repetition

transients (e.g., Fig. 2). It also meets the criterion from Hamernik *et al*. (2003) that kurtosis be computed on at least a 30-s window. The effect of window length on kurtosis is discussed in Sec. IV A.

SPL in decibels (dB) is ten times the logarithm (base 10) of the sound pressure, which is the integral of the squared sound pressure over some period of time, T, normalized by a reference squared pressure $P_o{}^2$ and integration time T [Eq. (1), see also ISO, 2017]

$$L_{P,\mathrm{W,T}} = 10\log_{10}\left(\frac{1}{TP_o^2}\int_0^T p_w^2(t)dt\right)\mathrm{dB}, \tag{1}$$

where P_o is 1 μPa, so that $L_{\mathrm{P,W,T}}$ is in dB with a reference of 1 μPa^2. For this analysis, the auditory frequency weighted SPL were computed from the filtered time-series.

SEL in decibels (dB) is ten times the logarithm (base 10) of the sound exposure, which is the integral of the squared sound pressure over some period of time, T, normalized by a reference squared pressure $P_o{}^2$ and reference time T_o [Eq. (2), see also ISO, 2017]

$$L_{\mathrm{E,W,T}} = 10\log_{10}\left(\frac{1}{T_0P_o^2}\int_0^T p_w^2(t)dt\right)\mathrm{dB}, \tag{2}$$

where T_o is normally 1 s and P_o is 1 μPa, so that $L_{\mathrm{E,W,T}}$ is in dB with a reference of 1 μPa^2·s. For this analysis, the auditory frequency weighted SEL were computed from the filtered time-series.

Kurtosis is a measure of the asymmetry of a probability distribution of a real-valued variable. Kurtosis, β, is the fourth moment of the time series divided by the square of the second moment [Eq. (3)],

$$\beta = \frac{\mu_4}{\mu_2^2}.;$$
$$\mu_2 = \frac{1}{t_2 - t_1}\int_{t_1}^{t_2}[p_w(t) - \overline{p_w}]^2\mathrm{d}t$$
$$\mu_4 = \frac{1}{t_2 - t_1}\int_{t_1}^{t_2}[p_w(t) - \overline{p_w}]^4\mathrm{d}t\ , \tag{3}$$

where $\bar{p}_\mathrm{w}$ is the mean. Kurtosis is a dimensionless quantity. The kurtosis of Gaussian distributed random data is 3. Data with continuous sinusoidal signals have a kurtosis in the range of 0–3, and data with transients have a kurtosis above 3.

The crest factor (CF),

$$CF = L_{\mathrm{p,W,pk}} - L_{\mathrm{p,W,rms}}$$
$$= 10\log_{10}\left(\frac{1}{p_o^2}\max\left(p_w^2(t)\right)\right)$$
$$- 10\log_{10}\left(\frac{1}{p_o^2}\int_0^T\frac{\left(p_w^2(t)\right)}{T}dt\right), \tag{4}$$

is the peak auditory frequency weighted SPL level ($L_{\mathrm{p,W,pk}}$) minus the root mean square (rms) auditory frequency weighted SPL ($L_{\mathrm{p,W,rms}}$). The weighted SPL is computed from the weighted pressure time-series p_w using an analysis duration, T, of 1 min. The crest factor is in decibels. An auditory frequency weighted crest factor greater than 15 dB was proposed by Starck and Pekkarinen (1987) as an indicator that impulsive sounds are present using a 10-min analysis window. The 10-min analysis window is likely too long. Consider a sinusoidal signal in Gaussian noise that lasts 1 min and has a rms amplitude 12 dB above the noise. The crest factor with a 10-min analysis window for this signal is 15 dB, but it is clearly not an impulse. Using a 1-min analysis window reduces the duration the background is integrated over, which should make the crest factor more effective for detecting impulses.

The Harris (1998) impulse factor is the maximum value for each minute of the impulse time-weighted SPL minus the slow time-weighted SPL. The time-weighted SPL is related to the sound level meter time-response settings (ANSI, 2006). The time weightings apply exponential averaging windows to a time series, where the time constant for the slow-time weighting is 1.5 s, and the impulse-time weighting has a rise time of 35 ms and a decay time of 1.5 s. The impulse factor is measured in decibels, with a maximum value of 23 dB that is related to the difference in the window durations. Southall *et al*. (2007), based on Harris (1998), recommended a 3 dB threshold for the impulse factor as an interim threshold for distinguishing impulsive and non-impulsive sounds.

Man-made sound sources are most likely to exceed regulatory thresholds for the LF and VHF cetacean functional hearing groups, rather than those for HF cetaceans (Martin *et al.*, 2019). Therefore, the sound levels and impulsive metrics for these groups are discussed in more detail in this analysis. The HF cetaceans (i.e., delphinids) are also discussed because of the extensive hearing threshold experiments that have been conducted with this group. Pinnipeds and sirenians are not discussed; however, the results are expected to be applicable to these groups as well. Similarly, all other marine taxa are not discussed because we do not have auditory frequency weighting functions or TTS thresholds for any other group (except those proposed for sea turtles, Finneran *et al*, 2017). The methods and results obtained are expected to be directly applicable once the required functions and thresholds are determined.

III. RESULTS

A. Random data

The random noise results provide a baseline for comparison to the real-world data and controlled sound exposure data. All five random noise distributions evaluated have similar kurtosis, crest factors, and Harris impulse factors (Table IV). The Harris impulse factor was below the proposed threshold of 3 dB for all distributions and auditory frequency weighting functions. The weighted crest factor threshold of 15 dB proposed by Pekkarinen and Starck (1983) is the crest factor for a Gaussian distribution. Note that changing the duration of the analysis window would not change the crest factor for random noise data. The maximum kurtosis measured for any of the distributions was 4, well below the threshold for fully impulsive sound in terrestrial mammals of 40. The Gamma distributed random data with shape parameter 1 and scale 2 had the highest kurtosis, crest factor, and Harris impulse factor. The random data were sampled at 512 kHz; applying the LF cetacean auditory frequency weighting function removed ∼90% of the signal bandwidth, which lowered the kurtosis and crest factor but increased the Harris impulse factor.

B. Short-term real-world data

The short-term real-world data's impulsive metrics covered a wide range of values (Fig. 3) and deviated substantially from the random data's values (Table IV). Unlike the randomly distributed data, applying the Southall *et al.* (2019) auditory frequency weighting functions changed the impulsive metric values for the short-term data. The kurtosis, crest factor, and Harris impulse factor all increased for the VHF weighted time-series compared to the unweighted and LF weighted time-series (Fig. 3). The kurtosis, crest factor, and Harris impulse factor are well correlated and respond similarly to changes in the data (e.g., Fig. 4). The crest factor and $10\log_{10}$(kurtosis) are particularly well correlated (Fig. 5). The linear equation crest_factor = 0.998*[10*$\log_{10}$(kurtosis)] + 11.9 dB has an R^2 value of 0.80, indicating that the two are strongly related. Kurtosis is used as the indicator of impulsiveness for this section; the choice of the impulsive metric is discussed further in Sec. IV.

Figure 6 presents time-series of the short term data's 1-min auditory frequency weighted kurtosis and sound levels to help understand the temporal relationships between exceeding the effective quiet and impulsiveness thresholds. The EQTs are presented in terms of the SEL as it is more intuitive for impulsive signals. The ambient sound data from the Chukchi Sea in 2014 with no sources present were processed as a baseline and had un-weighted as well as low frequency cetacean (LF-C) and very high frequency cetacean (VHF-C) auditory frequency weighted kurtosis near 3 throughout the recording. These data confirm that open ocean sound with no detectable sources present has a similar kurtosis to random distributed noise.

The sound from the dynamic positioning system of the semi-submersible drill rig [Fig. 6(A)] had a kurtosis near 3 for the 30 min shown (and generally throughout the full two months of data recorded) regardless of the weighting function applied. The sounds exceeded the LF-C EQT but not the VHF-C threshold.

The kurtosis and sound levels during the overpass of a fishing vessel with echosounders enabled increased as the vessel approached the recorder [Fig. 6(B)]. The kurtosis of the LF weighted time-series was near 3 except at the closest point of approach (CPA). In contrast, the VHF weighted kurtosis at this location (Strait of Georgia) was elevated throughout the 60 min and reached 537 during the CPA. The per-minute VHF-C auditory frequency weighted SEL during the overpass exceeded 156 dB re 1 μPa^2·s. This 1-min SEL

TABLE IV. One-minute impulse metrics for random distributed data with typical noise amplitude distributions weighted by the LF and VHF cetacean Southall *et al.* (2019) auditory frequency weighting functions. Values that exceed the thresholds are bold. Un-weighted data were high pass filtered at 10 Hz.

Metric	Threshold indicating impulsiveness (dB)	Weighting	Gaussian Mean 0 Var 1	Gamma Shape 1 Scale 2	Gamma Shape 6 Scale 1	Rayleigh Scale 2	Rayleigh Scale 10
Kurtosis	40	Un-weighted	3	4	2.6	2.7	2.7
		LF	3	3.2	2.9	2.9	2.9
		VHF	2.7	4	2.6	2.7	2.7
Crest factor	15	Un-weighted	**15**	**19.2**	13.6	13.8	14
		LF	**15**	**15.7**	14	14	14
		VHF	**15**	**20**	13.3	13.8	13.5
Harris (1998) impulse factor	3	Un-weighted	1.0	1.3	0.84	0.9	0.9
		LF	2.4	2.5	2.5	2.3	2.2
		VHF	1.3	1.5	1.4	1.2	1.2

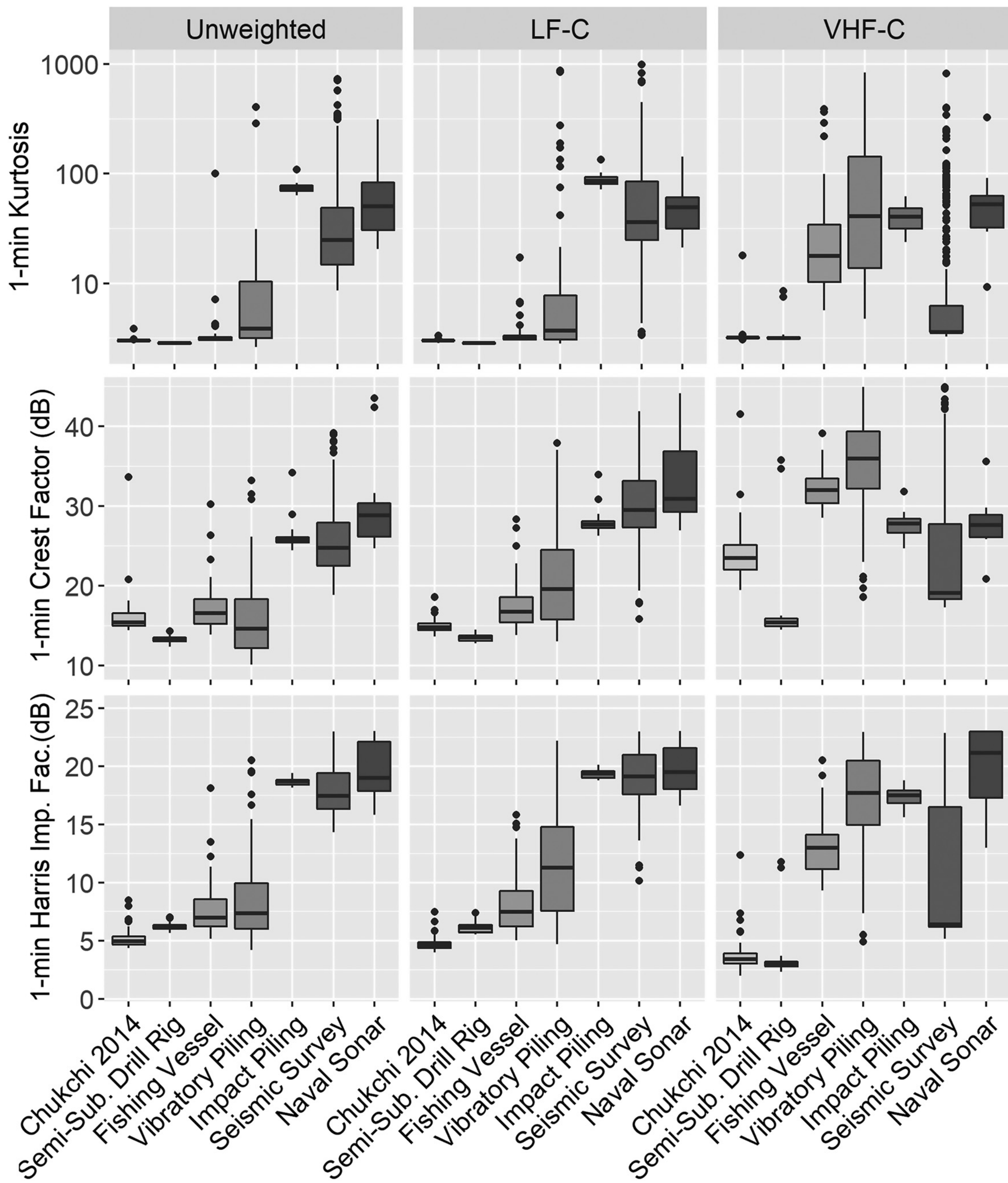

FIG. 3. The distributions of the 1-min impulse metrics for the short-term real-world data sets for un-weighted data and the data weighted by the LF-C and VHF-C Southall *et al*. (2019) auditory frequency weighting functions. Unweighted data are 10 Hz and above high pass filtered. For each data type and auditory frequency weighting function, the boxes shown the interquartile range (i.e., the middle half of the distribution). The horizontal line in the box is the median value. The vertical lines show the range of values for the 25% of the data above or below the middle half. The dots above or below the line indicate outlier values.

is above the daily SEL limit for PTS from impulsive sound (155 dB re 1 $\mu Pa^2 \cdot s$) but below the threshold for non-impulsive sound (173 dB re 1 $\mu Pa^2 \cdot s$) for VHF-Cs (Southall *et al*., 2019).

The sounds emitted during vibratory pile driving had a low kurtosis for all weighting functions [Fig. 6(C)]. However, the complete soundscape from tugs, barges, cranes, and compressors had 1-min sound levels that often exceeded the proposed EQTs. When the vibro-piling was inactive, the 1-min auditory frequency weighted kurtosis for LF-Cs reached 1684 and 6838 for the VHF-Cs [Fig. 6(C)].

The 1-min auditory frequency weighted sound levels from impact pile driving were above the proposed EQTs for LF-Cs and VHF-Cs at 1900 m [Fig. 6(D)]. Data from the Block Island Wind Farm were available from four recorders at nominal distances of 500, 2000, 5000, and 9000 m from the pile driving, depending on which pile was driven (Martin and Barclay, 2019). Similar to the seismic survey,

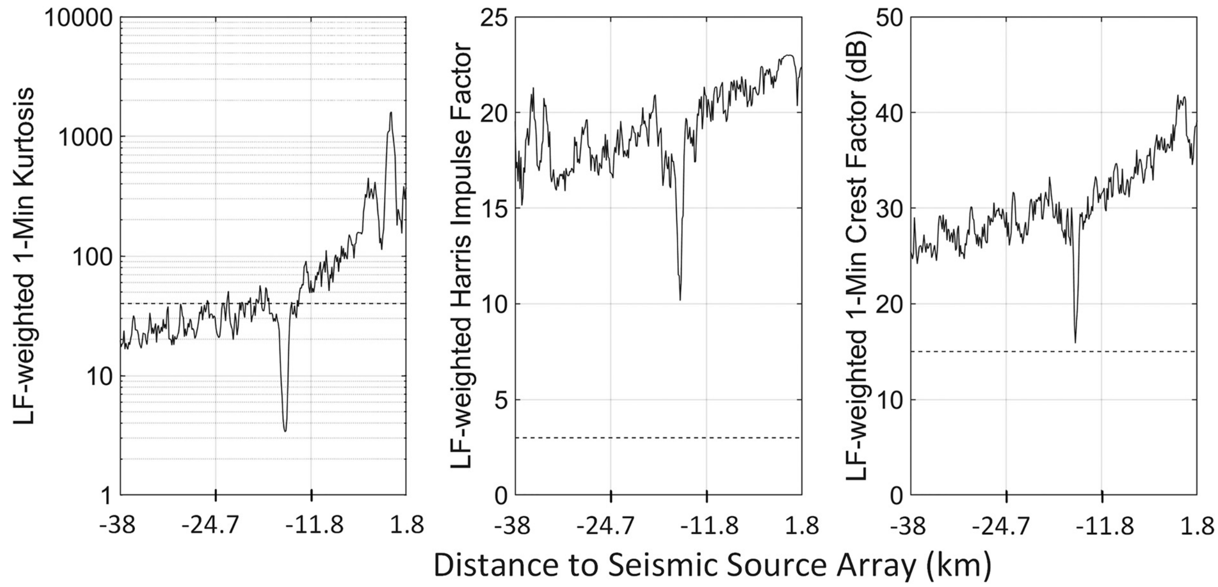

FIG. 4. LF auditory frequency weighted 1-min impulse metrics for the Baffin Bay seismic data (Fig. 2, panel E) plotted against distance to the seismic source array (negative distances are approaching the receiver). The dashed lines are the thresholds for impulsiveness proposed in the literature. The decrease in the metrics at ~06:00 was caused when another vessel passing directly over the recorder. This vessel's sound levels exceeded the seismic sound levels for a short period and made the LF-C auditory frequency weighted metrics more like non-impulsive sound.

the 1-min auditory frequency weighted sound levels and kurtosis were higher for locations closer to the sound source (Fig. 7). The auditory frequency weighted kurtosis had values of 16–126 across all distances and weightings (Fig. 7).

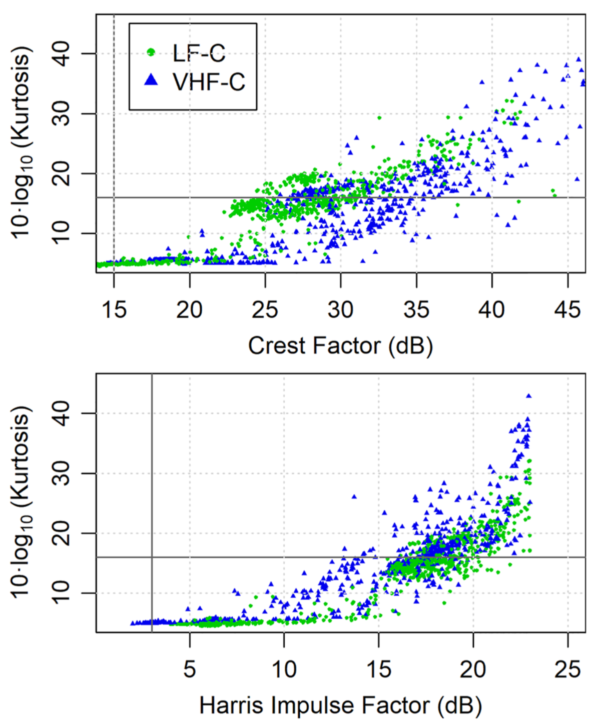

FIG. 5. (Color online) Scatterplots of (top) $10\log_{10}$(kurtosis) versus crest factor and (bottom) $10\log_{10}$(kurtosis) versus Harris impulse factor for all short-term real-world data. Symbol colors indicate the auditory frequency weighting function applied. The horizontal dark gray lines indicate a kurtosis of 40. The vertical dark gray lines indicate a crest factor of 15 and a Harris impulse factor of 3.

The auditory frequency weighted sound levels were above the EQTs for all distances measured (Fig. 7).

The seismic data [Fig. 6(E)] has a kurtosis that generally increased with sound level. The VHF-C weighted kurtosis was 3 when the pulses did not contribute to the per-minute SEL. The LF weighted kurtosis was 13–30 at a distance of 38 km from the seismic source with a weighted 1-min SEL of ~140 dB re 1 $\mu Pa^2 \cdot s$ (also see Fig. 4). Just before 06:00 (at approximately 15 km), another vessel without a seismic array passed over the recorder. The received sound energy from this vessel was higher than that from the seismic survey, and the LF-C auditory frequency weighted kurtosis dropped to nearly 3, but the VHF weighted SEL rose quickly to almost 400. The VHF weighted kurtosis from the vessel was caused by cavitation noise as well as thumps and squeals from the ship's operation.

The kurtosis associated with the naval sonar in the ObSERVE data set [Fig. 6(F)] was between 20–58 for the LF- and VHF weighted time-series. The per-minute sound levels were near the EQT for LF-Cs and well below EQT for VHF-Cs; the range to the source is unknown.

C. Long-term real-world data

The long-term data were analyzed to provide insight into how often the EQT thresholds are exceeded "in the real-world." The data also provide insight into the distribution of impulsiveness when the sound levels are above EQT. All six data sets (Sec. II C) were merged for this analysis—a total of 26 978 min of data (Table II). Only outlier minutes exceeded the proposed EQTs—0.2% for LF-C, 0.01% for HF-C and 1.25% for VHF-C weighted SPL (Fig. 8). The percent of the kurtosis values that exceeded 40 were 10.2, 26.4, and 28.1%, respectively (Fig. 8). Only 0.06, 0.01, and

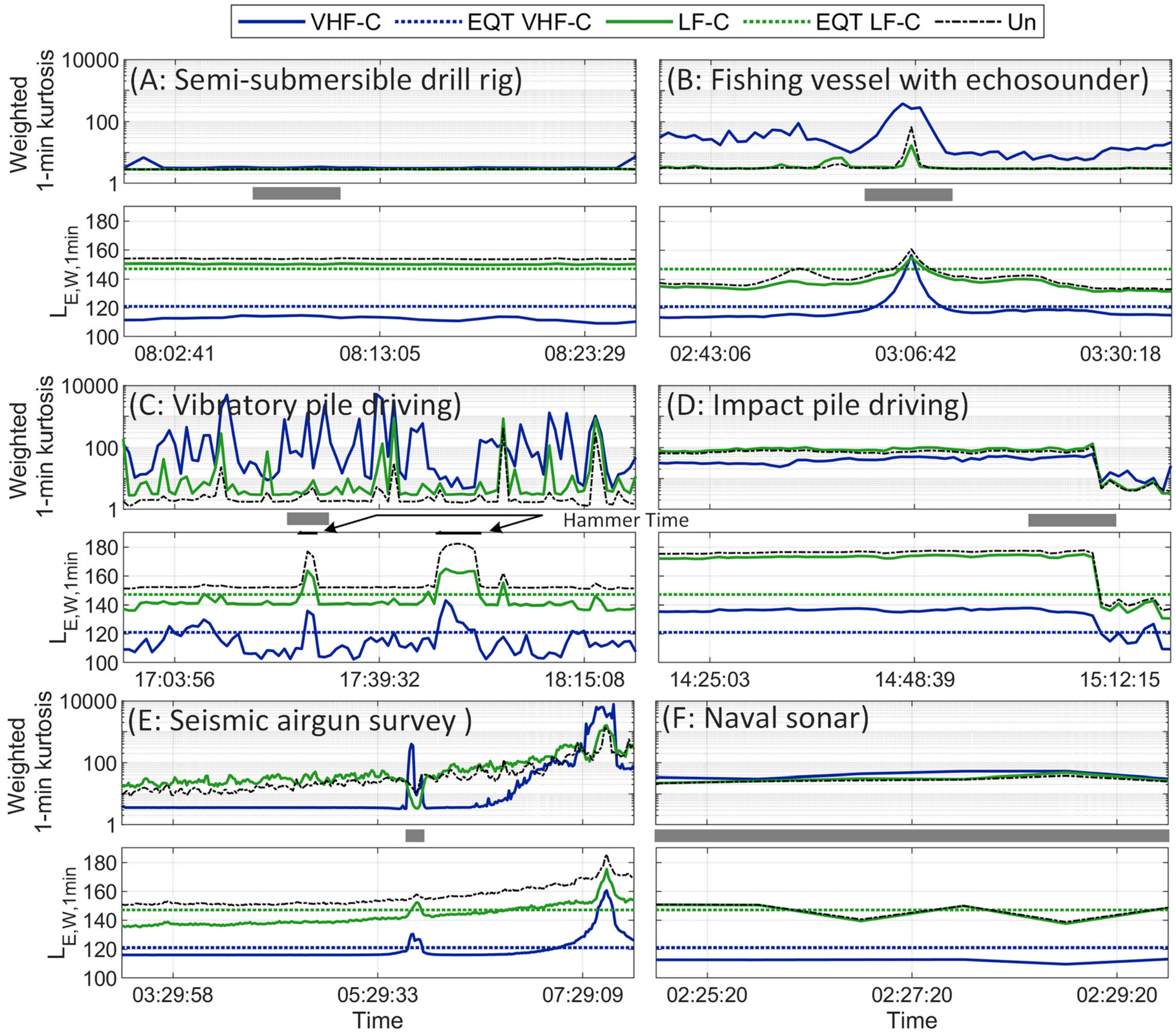

FIG. 6. (Color online) One-minute Southall *et al.* (2019) auditory frequency weighted (top panels) kurtosis and (bottom panels) SEL for the six short-term real-world data sets (Table I, Fig. 2). Weighting functions applied: VHF-Cs (blue), LF-Cs (green), and Un, unweighted data (10 Hz and above; black dashed lines). The auditory frequency weighted EQTs, adjusted for the SEL metric, are shown as the green and blue dashed lines. The grey highlights between the panels show the time windows presented in Fig. 2. The VHF-C sound levels were self-noise limited at ∼117 dB re 1 μPa^2·s for the seismic data (panel E).

1% of the data had a kurtosis greater than 40 and exceeded the EQTs, respectively. For the VHF-Cs, 55% of the minutes that had a kurtosis greater than 40 and exceeded the EQT were due to clicks and whistles from other marine mammals (delphinids and sperm whales). Anthropogenic sources accounted for the remaining exceedances: 29% by vessels, 10% by naval sonar or echosounders, and 6% by seismic airgun surveys. The LF-C exceedances were all caused by anthropogenic sources: primarily seismic airgun surveys by also sonar and in one case a vessel passage. A related result was that rain occasionally exceeded the VHF-C auditory frequency weighted EQT at but always had a kurtosis near 3.

The relationship between kurtosis and crest factor in the long-term data was linear, like the short-term data (Fig. 9). Unlike the short-term data, the LF and VHF data did not have the same linear relationship. Two sound sources with different linear intercept terms are present in this result—an intercept of ∼10 for the LF-C data versus ∼28 for the VHF-C data. This means that the second class of sounds had a higher base crest factor and a greater increase in crest-factor per "unit" kurtosis than the first class. A manual review of the data indicated that the higher intercept data were generally associated with mammal clicks and whistles, a sound type not present in the short-term data sets.

D. Simulations of sound exposure data that elicited TTS in marine mammals

Table V contains the kurtosis values for LF-C, HF-C, and VHF-C auditory frequency weightings of the controlled sound exposure experimental data. The band-limited Gaussian noise data of Popov *et al.* (2013) and Kastelein *et al.* (2012b) had a kurtosis of 3, as expected for randomly distributed noise for all marine mammal auditory frequency weightings. The constant frequency sounds emulating the

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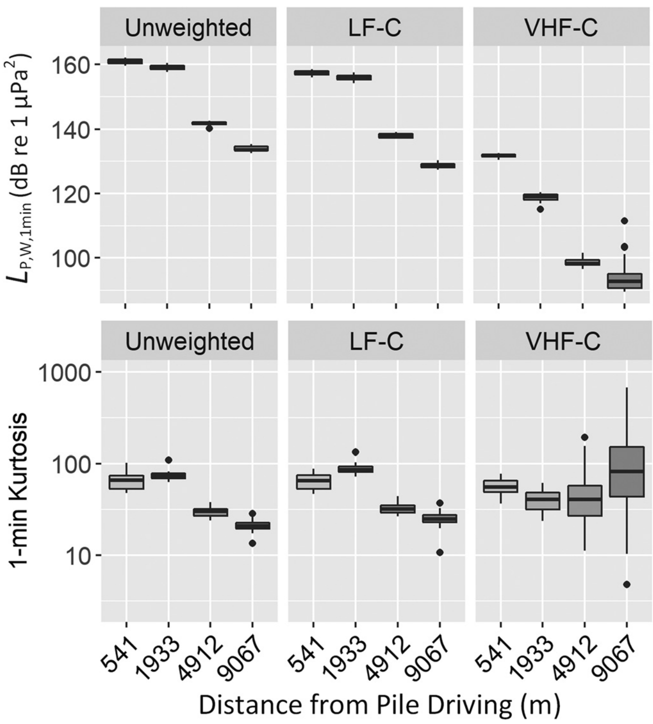

FIG. 7. The range of 1-min SPL and kurtosis weighted by LF-C and VHF-C Southall *et al.* (2019) auditory frequency weighting functions for 30 min of impact pile driving data measured in 25 m of water at the Block Island Wind Farm. Un-weighted data are 10 Hz and above high pass filtered. The proposed EQT is 129 dB re 1 μPa^2 for LF-Cs and 103 dB re 1 μPa^2 for VHF-Cs. Ambient sounds and pile driving both contributed to the 1-min VHF-C auditory frequency weighted sound levels at 9067 m. Note that the SPL depended on the angle of the pile, strike energy, and pile penetration (see Martin and Barclay, 2019). For each range and auditory frequency weighting function, the boxes shown the interquartile range (i.e., the middle half of the distribution). The horizontal line in the box is the median value. The vertical lines show the range of values for the 25% of the data above or below the middle half. The dots above or below the line indicate outlier values.

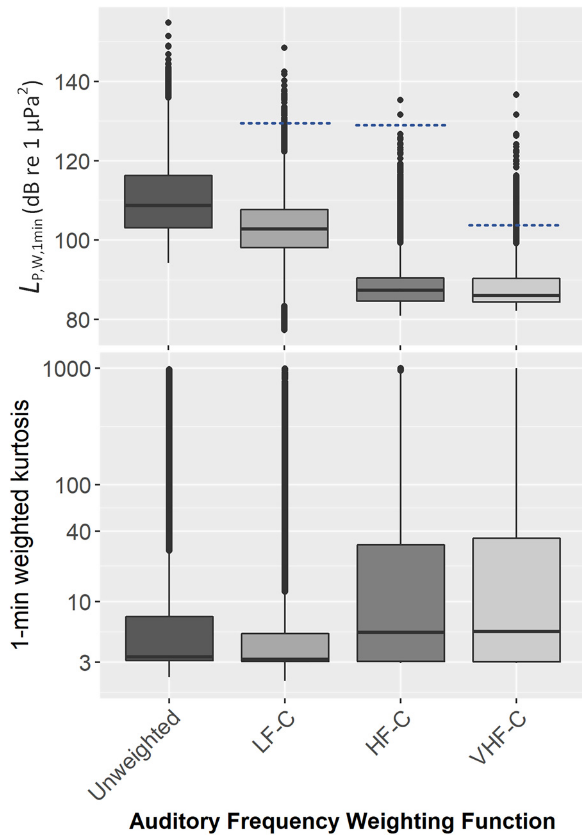

FIG. 8. (Color online) Distributions of the auditory frequency weighted SPL and kurtosis for the 1-min samples of the long-term real-world data. For each auditory frequency weighting function, the boxes shown the interquartile range (i.e., the middle half of the distribution). The horizontal line in the box is the median value. The vertical lines show the range of values for the 25% of the data above or below the middle half. The dots above or below the line indicate outlier values. The dashed blue lines show the proposed EQTs.

signals employed by Finneran *et al.* (2010a) and Kastelein *et al.* (2014b) as well as the frequency-modulated sweeps used by Kastelein *et al.* (2015) reduced the kurtosis to levels below the randomly distributed value of ∼3 for all weightings when the signal was present for the entire minute; the kurtosis increased above 3 when the sound was intermittent. The change in kurtosis showed a frequency-weighting dependence, i.e., 6–7 kHz frequency modulated sweeps investigated by Kastelein *et al.* (2015) had a higher kurtosis when VHF than when LF weighted.

Clearly impulsive sounds, such as simulated explosive sounds (Finneran *et al.*, 2000), generated extremely high kurtosis values that increased by factors of 3–4 for the HF- and VHF weightings compared to the LF weighting. The single airgun pulses studied in Lucke *et al.* (2009) had similarly high kurtosis values, especially when HF- and VHF-weighted (not shown). The replay pile driving signals that induced between 2 and 5 dB of TTS in porpoise after 3 h (Kastelein *et al.*, 2016) had an unweighted per-strike SEL of 145 dB re 1 μPa^2·s, which was equivalent to a per minute SPL of 145 dB re 1 dB re 1 μPa^2. Compared to the Block Island Wind Farm results (Fig. 7), these signals would have a VHF-C auditory frequency weighted SPL of ∼112 dB re 1 μPa^2 and a kurtosis of ∼47. To confirm the per-mintue sound levels, the spectrum used in Kastelein *et al.* (2016) was VHF-C auditory frequency weighted and the per-minute SPL estimated to be 112 dB re 1 μPa^2.

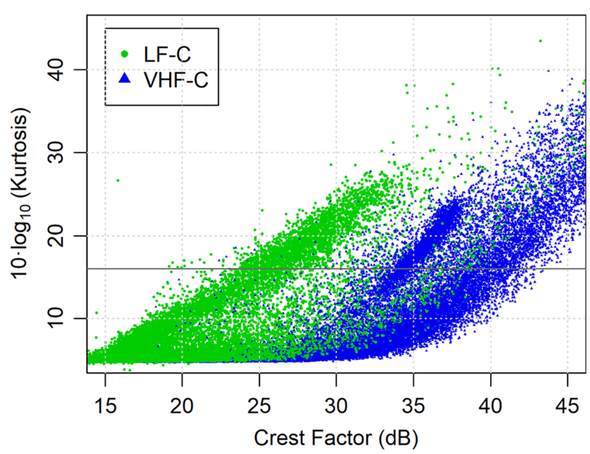

FIG. 9. (Color online) Scatterplot of 10log$_{10}$(kurtosis) versus crest factor for the long-term real-world data. The colors symbol indicate the auditory frequency weighting function applied (LF-C and VHF-C). The dark gray dashed line indicates a kurtosis of 40.

TABLE V. Impulse metrics of fatiguing sounds from controlled threshold shift experiments weighted by the LF-C, HF-C, and VHF-C Southall *et al.* (2019) auditory frequency weighting functions. The test subjects exposed were TT, bottlenose dolphins (*Tursiops truncatus*); DL, beluga whales (*Delphinapterus leucas*); PP, harbor porpoises (*Phocoena phocoena*). Un-weighted data are 10 Hz and above high pass filtered.

				1-minute weighted kurtosis			
Study	Subject species	Fatiguing sound	Measurement Condition	Un- weighted	LF weighted	HF weighted	VHF weighted
Popov *et al.* (2013)	DL	Half-octave noise at 11.2, 22.5, 45 and 90 kHz at 165 dB re 1 μPa^2 for 1, 3, 10 or 30 min	11.2 kHz	3	3	3	3
			22.5 kHz	3	3	3	3
			45 kHz	3	3	3	3
			90 kHz	3	3	3	3
Kastelein *et al.* (2012b)	PP	Octave band noise centered at 4 kHz at 124, 136 or 148 dB re 1 μPa^2 for 7.5, 15, 30, 60, 120 or 240 min		3	3	3	3
Kastelein *et al.* (2014b)	PP	6.5 kHz CW tone at 118, 124, 130, 136, 142, 148 or 154 dB re 1 μPa^2 for 60 min		1.5	1.5	1.5	1.5
Finneran *et al.* (2000)	TT & DL	Signal resembling explosions with sharp compression to rarefaction transition; maximum SEL 179 dB re 1 μPa^2·s and peak-to-peak SPL of 221 dB re 1 μPa^2 (estimated mid-frequency weighted SEL of 172 dB re 1 μPa^2·s)	500 kg HBX-1 at 1.7 km	4.2×10^5	3.6×10^5	9×10^5	1.2×10^6
Finneran *et al.* (2010a)	TT	3 kHz tones at 192 dB re 1 μPa^2, 16-s long or 64-s long.	16 s	7.6	7.6	7.6	8.8
			64 s	1.5	1.5	1.5	1.5
(Kastelein *et al.*, 2015)	PP	1 second long 6–7 kHz FM upsweeps at 166 dB re 1 μPa^2 at either at duty cycle (DC) of 1 sweep every 10 s or continuous repetition	10% DC	15.4	15.4	15.9	16.3
			100% DC	1.5	1.5	1.6	1.6

IV. DISCUSSION

This section discusses the three questions addressed by this work: (a) what metric should be used to identify the presence of impulses, (b) can a threshold for impulsiveness be recommended, and (c) do the sounds from impulsive sources become non-impulsive before the sound levels drop below the proposed EQTs? Section IV A includes a discussion of how kurtosis changes as a function of the number, duration, amplitude, and bandwidth of impulses in a pulse train. The relevance of kurtosis as a metric of impulsiveness is discussed for the cases of vessel and sonar sound. We conclude by introducing the possibility of developing a single number, the impulsiveness adjusted SEL, to predict the effects of human sounds on marine life.

A. What metric should be used to identify the presence of impulses?

Figures 4, 5, and 9 demonstrate that at a high-level, all three of the proposed impulsive metrics are approximately equivalent indicators of impulsiveness. The Harris impulse factor is restricted to a maximum value of 23 dB, which is related to the ratio of the areas under the impulse and slow time-weighting functions. Similarly, the crest factor is constrained to be between ∼15 dB (the value for Gaussian random data) and an absolute maximum value equal to the broadband dynamic range of the analog-to-digital data collection system, which is between 90 and 110 dB for most acoustic recorders, but has a practical limit of ∼60 dB (see Figs. 5 and 9). When the kurtosis reaches the value indicative of fully impulsive from the chinchilla studies (40), the crest factor is between 22 and 43 dB (Figs. 5 and 9), while the Harris impulse factor is between 10 and 20 dB (Fig. 5).

The choice of metric to employ as the indicator of impulsiveness can be informed by considering what factors in the data affect the metric's value. From its definition, the Harris impulse factor only depends on the values in the time series over ∼1.5–2 s, and therefore is not sensitive to the repetition rate of impulses like pile driving, echosounders, and seismic airgun surveys. We know from the work of Danielson *et al.* (1991) that the repetition rate is important. The analysis window for crest factor and kurtosis may be chosen by the analyst, which allows for the repetition to be included in the metric's value. The crest factor responds to longer time windows by increasing the duration used for the rms SPL, which generally lowers the rms SPL and increases the crest factor.

Kurtosis is more sensitive to the temporal features of the signal than the crest factor. It depends on the number, duration, and repetition rate of impulses, as well as the analysis window chosen (Table VI). The rows of Table VI are grouped to examine how changing one parameter affects the kurtosis. The first five columns contain the parameter values while the last three columns are the 1, 10, and 60 s kurtosis. The 1- and 10-s columns contain multiple values which indicate the minimum and maximum kurtosis for that duration over a 5-min period. The first two groups of rows demonstrate that kurtosis is higher when the impulses are shorter and spaced farther apart in time. By comparing the range of values in the 1, 10, and 60-s columns we see that kurtosis reaches a stable repeatable value when there are at least 4–5 evenly spaced impulses in the analysis window. The third group of rows shows that higher amplitude impulses increase kurtosis, but not as much as changes in the pulse duration or spacing. The fourth group of rows indicates that the kurtosis does not depend on the bandwidth of the sweep (for the 10 Hz and above unweighted data).

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TABLE VI. Comparison of the 1-, 10-, and 60-second kurtosis for different configurations of frequency modulated sweeps similar to those employed in Kastelein *et al.* (2015). The center frequency for all sweeps was 6500 Hz. The values shown are unweighted.

	Bandwidth (Hz)	Pulses per minute	Pulse duration (s)	Pulse amplitude (dB)	Kurtosis (1 s) Min/Max	Kurtosis (10 s) Min/Max	Kurtosis (60 s)
Changing pulses per minute	1000	100	0.1	20	6.7 / 11	7.6 / 8.0	8
	1000	10	0.1	20	3 / 11	19 / 21	21
	1000	1	0.1	20	3 / 11	3 / 19	8.3
Changing pulse duration	1000	10	0.001	40	3 / 1042	1670 / 1880	1860
	1000	10	0.01	40	3 / 144	620 / 1043	718
	1000	10	0.1	40	3 / 14	74 / 144	88
Changing amplitude	1000	10	0.1	20	3 / 11	19 / 21	21
	1000	10	0.1	40	3 / 14	74 / 144	88
	1000	10	0.1	60	3 / 15	75 / 145	90
Changing bandwidth	100	10	0.1	40	3 / 14	74 / 144	88
	1000	10	0.1	40	3 / 14	74 / 144	88
	10 000	10	0.1	40	3 / 14	74 / 144	88
Simulated pile driving	12 000	30	0.01	70	3 / 149	300	300

The kurtosis of odonotocete click trains is very high, as demonstrated by the simulated sperm whale clicks in the last row of Table VI. This result replicates the long-term real-world data where the 1-min HF weighted kurtosis from dolphin click trains often exceeded 100 000. The choice of a one-minute window to measure the kurtosis perceived by odonotocetes may be questioned since their echolocation system clearly operates on much shorter time scales. Further, the explosive results show that single events will increase kurtosis as the analysis window duration increases (see the Finneran *et al.*, 2000, results in Table V). Evidence for longer windows is contained in Table VI that shows the kurtosis stabilizes once the analysis window has a representative number of impulses within the time analyzed, and thus there is a clear minimum window duration for kurtosis for repeated signals. Odontocetes have the ability to reduce their hearing sensitivity for periods of at least 30 s following the arrival of an earlier impulse (Nachtigall and Supin, 2013; Nachtigall *et al.*, 2018), which suggests that 30 or 60 s are not unreasonable kurtosis analysis window for this species group.

A final factor in the choice of which metric to use is the complexity of implementation and acceptance within the research community. The crest factor is simplest to implement, followed by the kurtosis, and then the Harris impulse factor. Kurtosis has proven useful for studying impulses with humans as well as terrestrial mammals (Hamernik *et al.*, 2010; Qiu *et al.*, 2013).

Based on existing work employing kurtosis, relative ease of implementation, better sensitivity to pulse repetition rates than crest factor or Harris impulse factor, and acceptance within the in-air community, kurtosis is the recommended metric to use as an indicator of impulsiveness. A one-minute analysis window is recommended for all species groups. Research into the relevance of kurtosis for marine mammals is required.

B. Determining a threshold for impulsiveness

The kurtosis values computed from the short- and long-term real-world data regularly exceeded the in-air threshold of 40 that indicates fully-impulsive sounds (Hamernik *et al.*, 2007). In particular, the VHF-C weighted kurtosis is on the order of 1000–10 000 when odontocetes clicks and whistles are present. At the other extreme, the proposed thresholds for impulsiveness when using the crest factor and the Harris impulse factor metrics are very close to the values for Gaussian random noise (Table IV). Thus, regardless of which impulsive metric is employed as the indicator of impulsiveness for underwater sounds, appropriate thresholds must be derived.

Guidance on an appropriate threshold may be obtained from the experiments of Kastelein *et al.* (2016). The researchers exposed harbor porpoise to playbacks of pile driving sounds with a weighted per-minute SPL of 112 dB re 1 μPa^2 and an estimated kurtosis of 47 (see Sec. III D). The test subjects had a 0–2 dB TTS at 8 kHz 12–16 min after exposure to 15 min of the sound, which increased to 2–5 dB of TTS after 3 h. The total exposure after 15 min was 142 dB re 1 μPa^2·s, very close to the Southall *et al.* (2019). TTS threshold for VHF-Cs to impulsive sounds of 140 dB re 1 μPa^2·s. Based on this result, it appears that a kurtosis of 40 that was demonstrated as the fully impulsive threshold for chinchillas is also appropriate as an initial threshold for marine mammals. From Fig. 5, a crest factor of 30 or a Harris impulse factor of 20 are equivalent thresholds to ensure that the kurtosis is generally greater than 40.

C. The transition of impact pile-driving and seismic survey sounds from impulsive to non-impulsive

The final question addressed here is: do the sounds from impulsive sources change to become non-impulsive before the sound levels drop below the proposed EQTs? This question is most relevant to the two loudest and most encountered human impulsive sound sources: impact pile driving and seismic surveys. In Sec. IV B, it was argued that a kurtosis of 40 indicates that a sound is fully impulsive. At the other end of the impulsiveness scale are sounds with a kurtosis of 3. Between these bounds, sounds transition from non-impulsive to impulsive. For the minutes of real-world data that exceeded the proposed 1-min EQTs, it is relevant to determine the nature of the sounds—are they impulsive or non-impulsive? The known non-impulsive sounds (background sound, rain, dynamic positioning, and some vessel sounds) had 1-min weighted kurtosis near the Gaussian random noise value of 3. The auditory frequency weighted 1-min kurtosis values from impact pile driving were between 25 and 60 when the sound levels were above the EQT (Fig. 7). Similarly, the weighted 1-min kurtosis was above 40 when the weighted sound levels were greater than the EQTs for the seismic airgun data [Fig. 6(E)]. Thus, the transition from impulsive to non-impulsive sounds is not a factor that needs to be considered when accumulating sound to assess possible hearing threshold shifts in marine mammals due to pile driving and seismic surveys.

D. The impulsiveness of vessels and sonars

Managing vessel signatures to minimize their auditory frequency weighted kurtosis may be important for reducing the effects of vessel sound on marine mammals. The VHF-C weighted kurtosis of sound from vessels was between 3 and >200 but was much lower for the LF-C weighting (Figs. 3 and 6). This result demonstrates that kurtosis generally increases when low frequencies are removed from the time series, which often removes the highest energy component of anthropogenic sounds, increasing the signal-to-noise ratio at higher frequencies which then increases the kurtosis. The vessel sounds that generate high kurtosis when VHF-C auditory frequency weighted is a mix of rubbing and rasping sounds, cavitation sounds, and mechanical knocking (e.g., Fig. 10). Of the 104 examples of vessels exceeding the VHF-C EQT in the long-term data set, 69, or 66%, also had a weighted kurtosis greater than 40. We recommend that an experiment be conducted to compare the TTS onset of porpoise using sounds such as Fig. 10 and a sound with an equal SEL but a kurtosis of 3 to help determine if some vessels should be classified as impulsive sources.

Naval sonar and echosounders considered in this analysis have kurtosis that suggests they are impulsive, yet they have very different waveforms from each other and from broadband impulses like impact pile driving or from the vessels shown in Fig. 10. Echosounders are characterized by short pulse lengths that yield a high kurtosis compared to the longer pulse lengths of naval sonars (Fig. 6, Table VI). However, echosounders have a higher pulse rate than naval sonars, which reduces the kurtosis (Table VI). The 10% duty cycle sonar pulses simulated in Kastelein *et al*. (2015) that had a 1-min kurtosis of 15 (Table V). The short-term real-world naval sonar data had a kurtosis between 20 and 200 for both the LF-C and VHF-C auditory frequency weighted time-series (Fig. 3). The naval sonar detected in the long-term real-world data had kurtosis values between 30 and 300 for both cetacean groups. The echosounders that exceeded the proposed EQT for VHF-Cs in the long-term data also had weighted 1-min kurtosis between 30 and 300. Echosounders in the Port of Vancouver data (Fig. 6, Panel B)

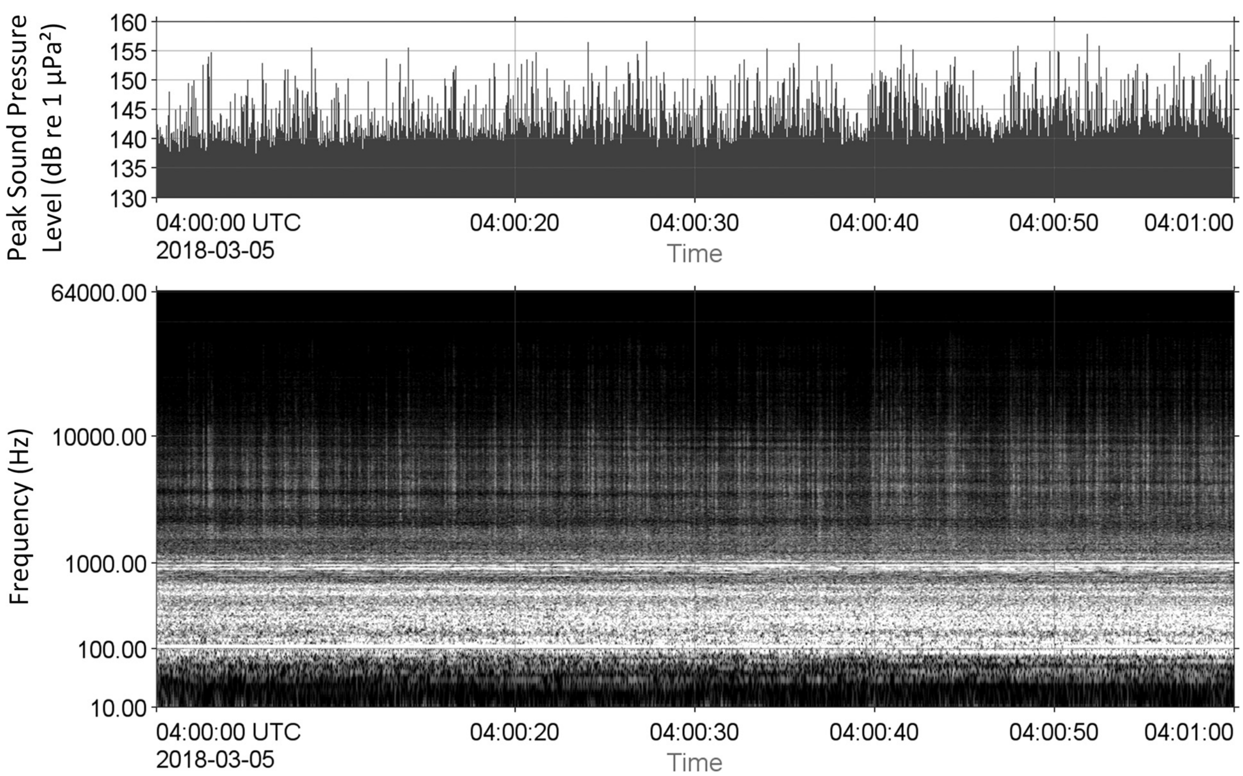

FIG. 10. Example of a 1-min of vessel sound recorded at the Port of Vancouver that had LF auditory frequency weighted kurtosis of 5.6 and VHF weighted kurtosis of 122.

had an LF-C weighted kurtosis of 17 and a VHF-C weighted kurtosis of 358.

Naval sonar and echosounders share the property that they are relatively narrowband in frequency. Therefore, if sonars induce a threshold shift, it affects the frequency of the sonar and half an octave above the sonar's band (see, for example, Popov *et al.*, 2011; Finneran and Schlundt, 2013; Popov *et al.*, 2013). Animals are able to compensate for a narrowband threshold shift through a process similar to comodulation masking relief (Branstetter *et al.*, 2016). Thus communication after TTS from sonars is more likely to be maintained than after exposure to a broadband impulse such as impact pile driving and seismic surveys. The distribution of sound levels across bands needs to be considered for sonar versus pile driving or seismic airguns. Sonar is concentrated at the source frequencies whereas pile driving is broadband and centered in the 100–300 Hz range (Bailey *et al.*, 2010; Martin and Barclay, 2019) and seismic airguns are broadband with most energy below 50 Hz (Gisiner, 2016; Martin *et al.*, 2017).

Applying the kurtosis metric to delineate impulsive sound types requires careful consideration. We propose that kurtosis is suitable for determining that pile driving and seismic surveys are always impulsive when their sound levels are higher than the EQTs, but it may not be an absolute indicator of impulsiveness for the purposes of regulatory separation of sources as impulsive or non-impulsive. Experiments showing avoidance of naval sonars and echosounders suggest that behavioral responses of marine species to these sources likely occur at longer distance to the source and have greater fitness implications than could be expected from narrowband TTS (D'Amico *et al.*, 2009; Miller *et al.*, 2014; Curé *et al.*, 2016; Sivle *et al.*, 2016; Cholewiak *et al.*, 2017; Wensveen *et al.*, 2019).

E. Towards an impulsiveness-corrected SEL as the predictor of hearing injury

Current recommendations for managing the effects of human sounds on marine life treat impulsive and non-impulsive sounds separately (Popper *et al.*, 2014; NMFS, 2018; Southall *et al.*, 2019). This division was created to help manage the complexity of the effects of sound on animals; however, its simplicity creates other issues such as accounting for impulsive sounds transitioning to non-impulsive as they propagate. Based on studies of humans, Zhao *et al.* (2010) proposed a kurtosis-corrected SEL as a single threshold for predicting the onset of hearing injuries. Their relationship was recast by Goley *et al.* (2011) and demonstrated with data from both humans and chinchillas,

$$L_{E,W,adj} = L_{E,W} + \lambda \log_{10} \frac{\beta}{\beta_G}, \tag{5}$$

where β_G is a kurtosis of a Gaussian distribution [Eq. (3)] and λ is determined by a fit to the measured data of threshold shift versus exposure level at different levels of kurtosis. Note that Goley *et al.* (2011) did not use an auditory weighting function for the chinchillas. Instead, they summed the SPL in the octave bands of 0.5, 1, 2, and 4 kHz, which are the bands most affected during the TTS experiments.

Validating an impulsiveness-corrected SEL for marine mammals requires dedicated experiments that establish the biologic thresholds and relevance of kurtosis for assessing effects of sound on hearing. Experiments similar to those of Hamernik *et al.* (2003, 2007, 2010) and Qiu *et al.* (2013) that tested the degree of TTS in chinchillas exposed to sounds with different kurtosis at the same SEL, as well as the same kurtosis at different SEL, should be conducted. Broadening the experiments to include a wider range of marine taxa is also recommended. The goal of these experiments would be to replicate in-air research that suggests there is a maximum kurtosis above which threshold shifts only increase with increasing sound exposure. The work should also look at TTS and periodicity of impulsive sounds. Sonars, pile driving, and seismic surveys have a stable pulse rate, which potentially allows odontocetes, including the VHF-Cs such as harbor porpoises, to predict the pulse arrival and adapt their hearing sensitivity (Nachtigall *et al.*, 2018).

V. CONCLUSIONS

In this work, we introduced a general definition for the EQT in marine mammals and investigated the impulsiveness of human and natural sounds whose per-minute sound levels exceeded the proposed EQT. The properties of three impulsive metrics described in the literature were compared using randomly distributed noise data and real-world data from multiple types of sources. The 1-min auditory frequency weighted kurtosis was recommended as the best metric for quantifying impulsiveness. An auditory-frequency weighted kurtosis threshold of 40 appears to be appropriate as an initial limit for a sound being "fully" impulsive when considering the effects of sound on marine mammal hearing. The kurtosis of impact pile driving and seismic survey sounds are always impulsive when their sound levels are above EQT, and therefore the transition from impulsive to non-impulsive pulse characteristics does not need to be factored into regulations for protecting marine mammals from impulsive sound sources. Approximately 66% of the vessel data that exceeded the EQT also exceeded the impulsiveness threshold. This suggests that managing the kurtosis of a vessel's sound signature may be as important as managing its amplitude when assessing the effects of noise on some marine mammals.

ACKNOWLEDGMENTS

The authors thank the anonymous reviewers whose comments helped refine the manuscript and improve its readability. Thanks to Karen Scanlon for her assistance editing this manuscript. The authors thank the following organizations for including their data sets in this analysis: Shell Global Solutions for the Chukchi Sea 2014 and 2015 as well as the Baffin Bay seismic data; Deepwater Wind / Block Island Wind Farm for the Block Island datal; the Irish

Department of Communications, Climate Action and Environment for the naval sonar data collected by the ObSERVE Project; the Environmental Studies Research Fund, which provided support for JASCO Applied Sciences to collect the deep-water data off Nova Scotia, and the Department of Fisheries and Oceans Canada, North-west Atlantic Fisheries Center to collect the 2018 DFO-CT data from the north-eastern edge of the Grand Banks. Lucke et al. (2009) TTS data were collected as part of the research project MINOS+ funded by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, Grant No. Fkz 0329946B; data were used with permission of Professor Ursula Siebert, Institute for Terrestrial and Aquatic Wildlife Research (ITAW), Germany. Thanks to Andrew Martin for assisting with the manual analysis of the sound sources. Thanks to Michael Ainslie for pointing out that the filter method employed here to generate biologically relevant time-series metrics has wide application. Thanks to all the JASCO Applied Sciences teams and vessel crews who participated in the data collection programs whose data were used in this manuscript.

APPENDIX—COMPUTATION OF WEIGHTED IMPULSIVE METRICS

The filters were designed in MATLAB using the following code:

```
NfilterPoints = samplingFrequency;
freqs = linspace(0, samplingFrequency/2, 25 000);
response = zeros(size(freqs));
for p = 1:length(response)
        response(p) = getWeighting
        (auditoryFilterName, freqs(p));
end
response = sqrt(response); % because filtering is done
on voltage data not power
freqs = freqs / (samplingFrequency/2);
d = fdesign.arbmag('N,F,A',NfilterPoints, freqs,response);
Hd = design(d,'freqsamp');
```

where *getWeighting* is a user provided function that generates the amplitude response of the auditory frequency weighting function. Tougaard and Beedholm (2019) provide examples and software for computing the weighting functions. The responses for the 10 Hz and above filter were [0, 0.01, 0.8, 1, 1, 1] at frequencies of [0, 7, 10, 14, 100, 0.5*fs] Hz. The filters were applied to the time series in MATLAB using the command:

filtered = fftfilt(Hd.numerator, rawTimeSeries).

Note that by using the sampling frequency as the number of points in the filter definitions, all sample rates will have the same frequency roll-offs.

[1]For more information, see www.dccae.gov.ie/ObSERVE.
[2]For more information, see www.adeon.unh.edu.

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