Sound exposure level as a metric for analyzing and managing underwater soundscapes

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The auditory frequency weighted daily sound exposure level (SEL) is used in many jurisdictions to assess possible injury to the hearing of marine life. Therefore, using daily SEL to describe soundscapes would provide baseline information about the environment using the same tools used to measure injury. Here, the daily SEL from 12 recordings with durations of 18–97 days are analyzed to: (1) identify natural soundscapes versus environments affected by human activity, (2) demonstrate how SEL accumulates from different types of sources, (3) show the effects of recorder duty cycling on daily SEL, (4) make recommendations on collecting data for daily SEL analysis, and (5) discuss the use of the daily SEL as an indicator of cumulative effects. The autocorrelation of the one-minute sound exposure is used to help identify soundscapes not affected by human activity. Human sound sources reduce the autocorrelation and add low-frequency energy to the soundscapes. To measure the daily SEL for all marine mammal auditory frequency weighting groups, data should be sampled at 64 kHz or higher, for at least 1 min out of every 30 min. The daily autocorrelation of the one-minute SEL provides a confidence interval for the daily SEL computed with duty-cycled data. © *2019 Acoustical Society of America*. https://doi.org/10.1121/1.5113578

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I. INTRODUCTION

Mankind's increasing use of the ocean for transportation, food, and energy extraction has led to an increase in marine pollutants, including sound. Studies of these activities demonstrate potentially negative impacts of our activities on marine life (Southall *et al.*, 2019). The effects of sounds on humans and animals can be visualized as a series of four zones or concentric rings of diminishing impact around the sound source (e.g., Fig. 1 in Dooling *et al.*, 2015). In this model, the highest level of impact occurs in zone 1 from exposures that cause physical barotrauma or permanent hearing loss (e.g., Halvorsen *et al.*, 2012a; Casper *et al.*, 2017), followed by temporary hearing loss in zone 2 (see review in Finneran, 2015), then masking of important biological sounds used by animals in zone 3 (Shannon *et al.*, 2016), and finally in zone 4 the sound levels elicit subtle behavioral or physiological stress responses (Rolland *et al.*, 2012).

The zone-view of the effects of noise does not accurately reflect the complexity of auditory injury or impairment and the choices animals make to accept sound exposure for other advantages such as feeding or mating (Ellison *et al.*, 2012). When animals make the choice not to respond to noise, they can stay in an area where very long sound exposures result in auditory injury and impairment, and thus zone 2 may be larger than zone 4 (Hawkins and Popper, 2017). Similarly, behavioral reactions to sound can cause animals to rapidly leave an area, which could result in dangerously rapid depth changes (Jepson *et al.*, 2003; Blix *et al.*, 2013) or entering an area that results in stranding (Cox *et al.*, 2006); in this manner zone 4 becomes zone 1.

As a general rule regulations impose a requirement on human ocean activities to predict the size of zone 1, then ensure that no endangered or threatened animals are within that area (Erbe, 2013). Regulations to reduce masking, disturbance, and behavioral responses are less common but may be applied, for instance, to whale watching boats (e.g., see the Canadian whale watching regulations[1]). As more studies of the effects of sound become available, it will be possible to manage the effects of a wider range of man-made sound to prevent behavioral changes that could affect feeding, navigating, mating, rearing of young, or the harvesting of commercial fish stocks. *The Population Consequences of Acoustic Disturbance* (NRC, 2005) and "Population Consequences of Disturbance" (King *et al.*, 2015) models provide frameworks for understanding the sub-lethal effects of sound on marine populations (Costa *et al.*, 2016).

Managing sound levels requires indicators that relate sound characteristics, including amplitude to effects on marine life. Sound exposure level (SEL), peak sound pressure level,

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and the sound pressure level are three amplitude metrics typically used to quantify sound in the environment. Early marine sound mitigation regulations were based on keeping sound pressure levels below the level associated with measured injuries to the hearing of marine mammals (NMFS and NOAA, 1995; NOAA, 1998). Evidence has since demonstrated that peak sound pressure level and SEL are better predictors of injury for most groups of marine life (Southall *et al.*, 2007; Popper *et al.*, 2014; Southall *et al.*, 2019). Peak sound pressure level is associated with immediate physiological injury to tissues (Halvorsen *et al.*, 2012b). The sound pressure level varies with the averaging time, which makes it difficult to obtain repeatable values between research teams or methods, especially when analyzing the effects of impulsive sound sources (Madsen, 2005; Hawkins *et al.*, 2014). SEL is associated with fatigue injury through the equal energy hypothesis that states the effects on hearing are the same for the same total energy (Eldredge and Covell, 1958). For example, a sound pressure level of 190 dB re 1 μPa^2 for 1 s or 160 dB re 1 μPa^2 for 1000 s both have a SEL of 190 dB re 1 μPa^2 s and are expected to have the same effect on hearing. The daily SEL metric has an additional advantage over the sound pressure level of an acoustic event in that its duration is precisely defined. It is also simple to compute since it does not depend on detecting when a signal is present.

There are many research results that show the equal energy hypothesis does not represent the complexity of the effects of sound on hearing. It is well established that impulsive sounds affect hearing at lower SELs than continuous sounds (Ward, 1962; Akay, 1978; Finneran, 2015). The temporal pattern of impulses also changes the effects of sound on hearing for the same total SEL. In terrestrial mammals, including humans, 1 pulse per second has significantly greater impact than 10 pulses per second or 1 pulse every 10 s (Danielson *et al.*, 1991; Qiu *et al.*, 2013). Within the American regulations to protect marine life from human sounds, the dependence of hearing effects on sound's temporal patterns are reflected in different equal energy thresholds for continuous and impulsive sounds (Popper *et al.*, 2014; NMFS, 2018). Significant research is still required to understand how sound's characteristics, besides the pressure amplitude and energy, affect marine life. Particularly important are particle motion effects on fish and invertebrates and the temporal patterns of the sound on all marine taxa (Finneran, 2015; Hawkins and Popper, 2017; Houser *et al.*, 2017; Popper and Hawkins, 2018).

The publication of the *Technical Guidance on Assessing the Effects of Anthropogenic Sound on Marine Mammal Hearing* (NMFS, 2016) and a minor revision (NMFS, 2018) have made the auditory frequency weighted SEL, integrated over 24 h, the primary metric for predicting and measuring the effects of human industrial sound on marine life. However, this metric is not well understood—there are few examples of typical SELs or how the SEL depends on movement of sources and receivers, limited information on how to collect data for assessment of daily SEL, or results showing what additional information about the environment can be obtained by analyzing the daily SEL. This study addresses these data gaps through the analysis of 12 long-term data sets that provide examples of natural soundscapes and those affected by human activities. The temporal characteristics of human sound sources and natural environments are addressed in a separate study.

This manuscript is supported by extensive supplemental material[2] that includes: why SEL is a measure of the received energy, how to compute SEL across multiple events, further information on auditory weighting functions, hydrophone and recorder self-noise data, gamma random noise distributions that are similar to typical ocean noise distributions, statistical measures (mean, variance, skewness, kurtosis, gamma fit, and autocorrelation durations) for each data set, and confidence intervals for duty-cycled daily SELs.

II. METHODS

A. Data sets

Twelve data sets from ten recording locations (Fig. 1) were analyzed to provide an indication of the range of daily SEL, show how SEL accumulates from different sources, and provide examples of how different data collection techniques affect daily SEL. All recordings were performed using an AMAR G3 recorder (JASCO Applied Sciences, Dartmouth, NS, Canada) and either M8 or M36 hydrophones (GeoSpectrum Technologies Inc, Dartmouth, NS, Canada) or HTI-99-HF hydrophones (High Tech Inc, Long Beach, MS) (Table I). The data sets were selected to ensure that flow noise and other artefacts did not contribute to the daily SEL.

B. SEL

The acoustic metrics and terminology employed in this analysis follow ISO Standard 18405 (ISO, 2017). The SEL is a representation of sound energy that is defined as 10 dB 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_0^2 and reference time T_0,

$$L_{E,T} = 10\log_{10}\left(\frac{1}{T_0 p_0^2}\int_0^T p^2(t)\,dt\right) \text{ dB re } 1\ \mu\text{Pa}^2\text{ s}. \quad (1)$$

T_0 is normally 1 s and p_0 is 1 μPa, so that the unit of $L_{E,T}$ are dB re 1 μPa^2 s. The daily SEL is 49.4 dB higher than the arithmetic mean of the daily sound pressure level.

There are two pathways by which sound can affect hearing—intense, high amplitude sounds that damage hearing organs, or long-term exposure that causes temporary or permanent threshold shifts. The long-term exposures only affect hearing if the sounds are within an animal's hearing frequency range. Therefore, during SEL analysis recorded sounds are typically filtered by the animal's auditory frequency weighting function before integrating to obtain SEL. Weighted sound exposure and SEL are defined as

$$E_{p,W,T} = \sum_{n=0}^{N}\int_0^{f_s/2} W(f)S_t(f)df \text{ Pa}^2\text{ s}, \quad (2)$$

$$L_{E,W,T} = 10\log_{10}\left(\frac{E_{p,W,T}}{T_0 p_0^2}\right) \text{ dB re } 1\ \mu\text{Pa}^2\text{ s}, \quad (3)$$

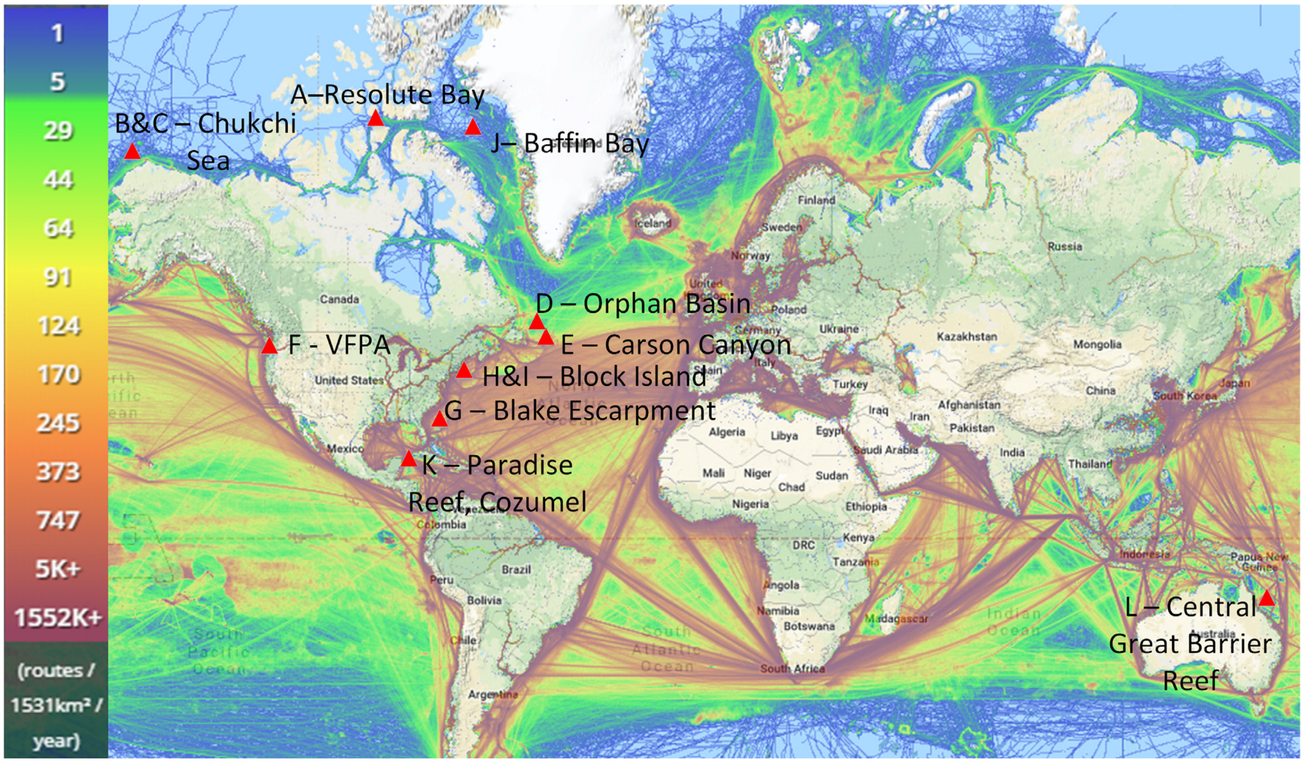

FIG. 1. (Color online) Recording locations whose data were used in this analysis. The underlay of the map is the 2017 marine traffic density (see footnote 3).

where $W(f)$ is the auditory frequency weighting function and $S_t(f)$ is the power spectrum of the pressure time series over a period of t seconds. The total signal duration T is normally divided into N equal sized blocks of duration t whose sound exposures are summed before taking $10\log_{10}$ to convert to the decibel representation.

Auditory frequency weighting functions and auditory injury thresholds have been defined for six groups of marine mammals: low-, high-, and very high-frequency cetaceans, sirenians, as well as otariid and phocid seals in water (Southall *et al.*, 2019; sirenians are not considered here). As a first approximation, the low-frequency auditory weighting function may be thought of as a 100 Hz high pass filter. Similarly, the phocid and otariid functions are ∼4 kHz high pass filters, the high-frequency function is ∼10 kHz high pass filter, and the very high-frequency function is ∼20 kHz high pass filter. For this analysis, the full bandwidth SEL for the recordings is computed starting at the 10 Hz decidecade and is referred to as the "10+ Hz SEL" or the "10 Hz and above SEL." The SEL that is applied under American regulations for marine life other than mammals is the 10+ Hz SEL [Eq. (1)]. Research on the hearing of other marine animal groups is needed to define their auditory frequency weighting functions and exposure thresholds. Equation (3) may be applied to the power spectrum as shown, or it may be applied to the decidecade SEL for an event using the center frequencies of the decidecades to compute the weighting (see the supplemental material[2] or Tougaard and Beedholm, 2019).

C. Determining the effects of duty cycling on SEL

Seven of the data sets used in this analysis were duty-cycled between high and low sample rates (Table I). The high sample rate data were essential for detecting the calls of high- and very high-frequency marine mammals, as well as for computing the weighted SEL for these groups. To estimate the weighted SEL from the duty-cycled data, we first computed the per-minute sound pressure level ($L_{p,1\,\mathrm{min}}$) and per-minute dedidecade sound pressure levels ($L_{p,\mathrm{ddec,1min}}$) for the data from both sample rates. A one-minute duration was chosen since it is the shortest continuous duration used in this analysis (Table I) and a common duration for estimating the sound pressure level (Ainslie *et al.*, 2018). The measured data had missing sound pressure and decidecade sound pressure values due to the duty cycling. These were estimated by linear interpolation of the linear data (i.e., $10^{Lp/(10\,\mathrm{dB})}$) on either side of the missing values. The linear decidecade sound pressures were weighted by the marine mammal auditory frequency weighting functions, then summed to obtain the weighted per-minute sound pressures, and those were summed to obtain the daily sound exposure at each sampling rate,

$$L_{E,W,24h} = 10\log_{10}\left(\sum_{t=0}^{t=1440\,\mathrm{min}} 10^{L_{P,W,t}/10}\right) + 10\log_{10}(60\,\mathrm{s/min}). \qquad (4)$$

For each auditory frequency weighting function, the daily SEL was computed from all available data with enough bandwidth. The minimum sample rates were 8000 Hz for 10+ Hz and low-frequency cetacean weightings, 16 000 Hz for otariid and phocid weightings, and 48 000 Hz for high- and very high-frequency cetacean weightings. When data from more than one sample rate were available the data sets were merged in time before interpolating.

TABLE I. Acoustic recordings used in this study. System spectral noise floor values with a superscript "R" indicate that the noise floor limit was from the recorder, and the remainder of the limits are due to the hydrophones.

Location ID	Location name	Primary Sound Sources	Water depth (m)	Latitude (degrees N)	Longitude (degrees E)	Recording dates	Hydrophone type	Hydrophone sensitivity level (dB re 1 V/μPa)	System spectral noise floor (dB re 1 μPa^2/Hz)	Sample rate and duty cycle	10 Hz + daily SEL noise floor (dB re 1 μPa^2)[a]
A	Resolute Bay	Open ocean and small boats (16 Aug–2 Oct); Ice + open water noise (3 Oct–2 Nov)	60	74.65	−94.84	16 Aug–2 Nov 2014	M8E-V35dB	−165	32	2 min at 96 kHz; 2 min sleep	128.2
B	Chukchi Sea, 2014	Open ocean	47	71.34	−163.1	6 Aug–14 Oct 2014	M8E-V35dB	−165	34$^{\mathrm{R}}$	13 min at 16 kHz; 2 min at 375 kHz	135$^{\mathrm{R}}$
C	Chukchi Sea, 2015	Dynamic positioning from semi-submersible drill rig; location is 1 km from Chukchi 2014 site	51	71.19	−163.5	25 Jul–2 Oct 2015	M8E-V35dB	−165	32	64 kHz continuous	126.5
D	Orphan Basin	Open ocean (1 Apr–24 May); seismic airgun survey (25 May–30 Jun)	1282	48.73	−49.38	1 Apr—30 Jun 2016	HTI-99-HF	−163	42	11 min at 8 kHz; 1 min at 250 kHz; 8 min sleep	142
E	Carson Canyon	Open ocean, fishing, seismic air-gun survey	120	45.46	−48.79	4 Sept–17 Oct 2016	M36-V35-100	−165	34$^{\mathrm{R}}$	7 min at 16 kHz; 1 min at 375 kHz	135$^{\mathrm{R}}$
F	Vancouver-Fraser Port Authority	Recorded under the port of Vancouver's inbound shipping lane	170	49.05	−123.3	1 Jan–7 Apr 2018	M36-V35-100	−165	32	128 kHz continuous	129.5
G	Blake Escarpment	Open ocean with some shipping	872	29.25	−78.35	15 Mar–9 Jun 2018	M36-V35-100	−165	34$^{\mathrm{R}}$	16 min at 8 kHz; 1 min at 250 kHz; 4 min sleep	134$^{\mathrm{R}}$
H	Block Island, 850 m from piling	Impact pile driving	26	41.11	−71.52	14 Oct–3 Nov 2015	M8E-V0dB	−200	53$^{\mathrm{R}}$	64 kHz continuous	147$^{\mathrm{R}}$
I	Block Island, 9100 m from piling	Impact pile driving	42	41.06	−71.45	14 Oct–3 Nov 2015	M8E-V35dB	−165	32	64 kHz continuous	126.5
J	Baffin Bay	Seismic airgun survey except first two days	603	74.16	61.98	30 Jul–30 Sept 2012	M8E-V0dB	−200	56$^{\mathrm{R}}$	64 kHz continuous	150$^{\mathrm{R}}$
K	Paradise Reef	Coral Reef, 500 m from cruise ship pier; frequented by small tourist dive boats	11	20.47	−86.98	15 Jul–2 Sept 2017	M36-V35-100	−165	34$^{\mathrm{R}}$	14 min at 32 kHz; 1 min at 375 kHz	135$^{\mathrm{R}}$
L	Central Great Barrier Reef	Coral reef without human sources	18	−18.8	147.5	27 Apr–15 Jul 2013	M8E-V35dB	−164	34$^{\mathrm{R}}$	7 min at 64 kHz; 2 min at 375 kHz; 6 min sleep	135$^{\mathrm{R}}$

[a] Daily 10 Hz and above SEL noise floor is the spectral noise floor + 10 log$_{10}$(86 400 sec/day) + 10 log$_{10}$(recorder bandwidth); see the supplementary material.

The low duty cycle for higher sample rates (Table I) means that the daily SEL for the seals, as well as the high- and veryhigh-frequency cetaceans, were extrapolated from only 4%–10% of a day's data. To estimate the error from this extrapolation, the daily SEL were computed from the continuously sampled data sets (data sets C, F, H, I, and J) with duty cycles simulated by decimating the data to 1 min every 2, 3, 4, 5, 6, 8, 10, 12, 15, or 20 min. The errors were the full bandwidth continuous daily SEL subtracted from the SEL calculated after decimating in time so that a negative value means the subsampled SEL was less than the actual SEL. For each decimation rate, the decimated daily SEL was computed for all starting points of the subsampling, which increased the sample size for estimating the effects of subsampling. For example, the Chukchi Sea 2015 data (data set C) had 67 full daily SEL, 134 daily SEL estimates at the 1:2 decimation rate, and 1340 at 1:20.

When using daily SEL computed from duty-cycled data it is useful to know the range of errors that could result from the duty cycling. Since the duty-cycled SEL were computed by interpolating the available measurements, the accuracy of the daily SEL depends on how well the measurement made at some time T can be predicted from the previous measurement, for example $T - 20$ min for the Orphan Basin data. It was expected that the error would be related to the decimated data's autocorrelation. The error in daily SEL obtained by subsampling each of the continuous data sets was plotted against the first autocorrelation time lag of the subsampled one-minute sound exposures [Eq. (2)] for that day. This corresponds to a lag of 2, 3, 4, 5, 6, 8, 10, 12, 15, or 20 min depending on the subsampling. The resulting distributions were characterized by their mean values and the 95% confidence intervals. We also tested how well the subsampled autocorrelation matched the autocorrelation of the original data. To assess the generality of these results, the same analysis was performed using gamma-distributed random data rather than continuous data sets. The characteristics of the gamma-random data are discussed in the supplemental material.[2] Comparisons were made for the marine mammal auditory frequency weighting function weighted and 10+ Hz daily SEL.

III. RESULTS

A. Daily SEL levels in the data sets

Figure 2 shows the daily SEL for data sets A–L (Fig. 1, Table I). Table II lists the mean daily SEL and standard deviations. The mean high- and very high-frequency auditory frequency weighted SEL were often self-noise limited for the data from Orphan Basin (D) and Baffin Bay (J). Figure 3 provides autocorrelations of the one-minute SEL from the full duration of each recording.

The data sets include natural soundscapes as well as soundscapes with different types of human activity. The Resolute Bay (A) and Chukchi Sea 2014 data (B) are both Arctic recordings in water depths of 50–60 m. In Resolute Bay (A) during open water the daily SEL depends on the passage of small boats. After ice arrives the sound levels drop due to both the ice cover and less wind driven noise. In the Chukchi Sea 2014 during periods of low background sound levels (presumably periods of low winds) the 10+ Hz daily SEL dropped to 140–145 dB re 1 μPa^2 s and increased to 160 dB dB re 1 μPa^2 s during periods of high winds. Since the mean low-frequency cetacean auditory frequency weighted daily SEL were within 2.5 dB below the 10+ Hz SEL, at least half of the sound energy was above 100 Hz in this soundscape. The 10+ Hz, low-frequency, otariid, and phocid weighted SEL were highly auto-correlated for the 26 h shown in Fig. 3, which indicates that a slowly varying process was affecting the sound levels—i.e., wind and wave driven sound. In contrast, ice formation and movement in Resolute Bay data (A) increased the variability in the daily SEL and decorrelated the data within 30 min.

Blake Escarpment (data set I) and Orphan Basin (data set D; Figs. 2 and 3, Table II) had similar mean low-frequency cetacean auditory frequency weighted SEL that were also close to the low-frequency cetacean auditory frequency weighted levels in the Chukchi Sea in 2014. Both had maximum daily 10+ Hz SEL of 160 dB re 1 μPa^2 s, except for three days at Blake Escarpment. At Blake Escarpment, the 10+ Hz SEL were 8.4 dB above the low-frequency cetacean auditory frequency weighted SEL, while in Orphan Basin, prior to the start of seismic surveys on 25 May 2016, the 10+ Hz SEL was only 2.9 dB above the low-frequency cetacean auditory frequency weighted SEL, like the Chukchi Sea in 2014. The autocorrelations of the Orphan Basin data remained high after 26 h, like the results in the Chukchi, whereas the Blake Escarpment autocorrelation dropped below 0.1 within 30 min. The autocorrelation difference indicates that the primary source of sound changes on the scale of 30 min at Blake Escarpment. The differences between the 10+ Hz SEL and low-frequency cetacean auditory frequency weighted SEL were due to energy in the 10–100 Hz frequency band. This is the band with highest energies from heavy shipping (e.g., Wenz, 1962; McDonald *et al.*, 2006; Chapman and Price, 2011), but it may also contain energy from animals (e.g., fishes and large whales), seismic surveys, or flow-induced noise around hydrophones. Manually reviewing the Blake Escarpment data showed that vessels frequently passed the recorder, but there were no other distinct sound sources when no vessels were present.

The Chukchi Sea 2015 exploratory drilling program (data set C) and Vancouver-Fraser Port Authority (data set F) data contain high levels of sound from vessels. The Chukchi Sea 2015 data were 1 km from exploratory oil and gas drilling, and had a 10+ Hz and low-frequency cetacean auditory frequency weighted daily SEL 26 dB higher than the same site in 2014. At 16 km from the drilling activities, the average 10+ Hz daily SEL was 16 dB higher than in 2014 (not shown). Most of the sound was produced by dynamic positioning systems whose energy is above 100 Hz, which can be seen by the small difference between the 10+ Hz and the low-frequency cetacean auditory frequency weighting function SEL. This difference was higher at the 16 km measurement site due to more sound from support vessels instead of the drilling platform. At the Vancouver-Fraser Port Authority the mean 10+ Hz daily SEL was 14 dB above the Chukchi in 2014. The differences decreased with increasing frequency but were still ~7 dB for the high-

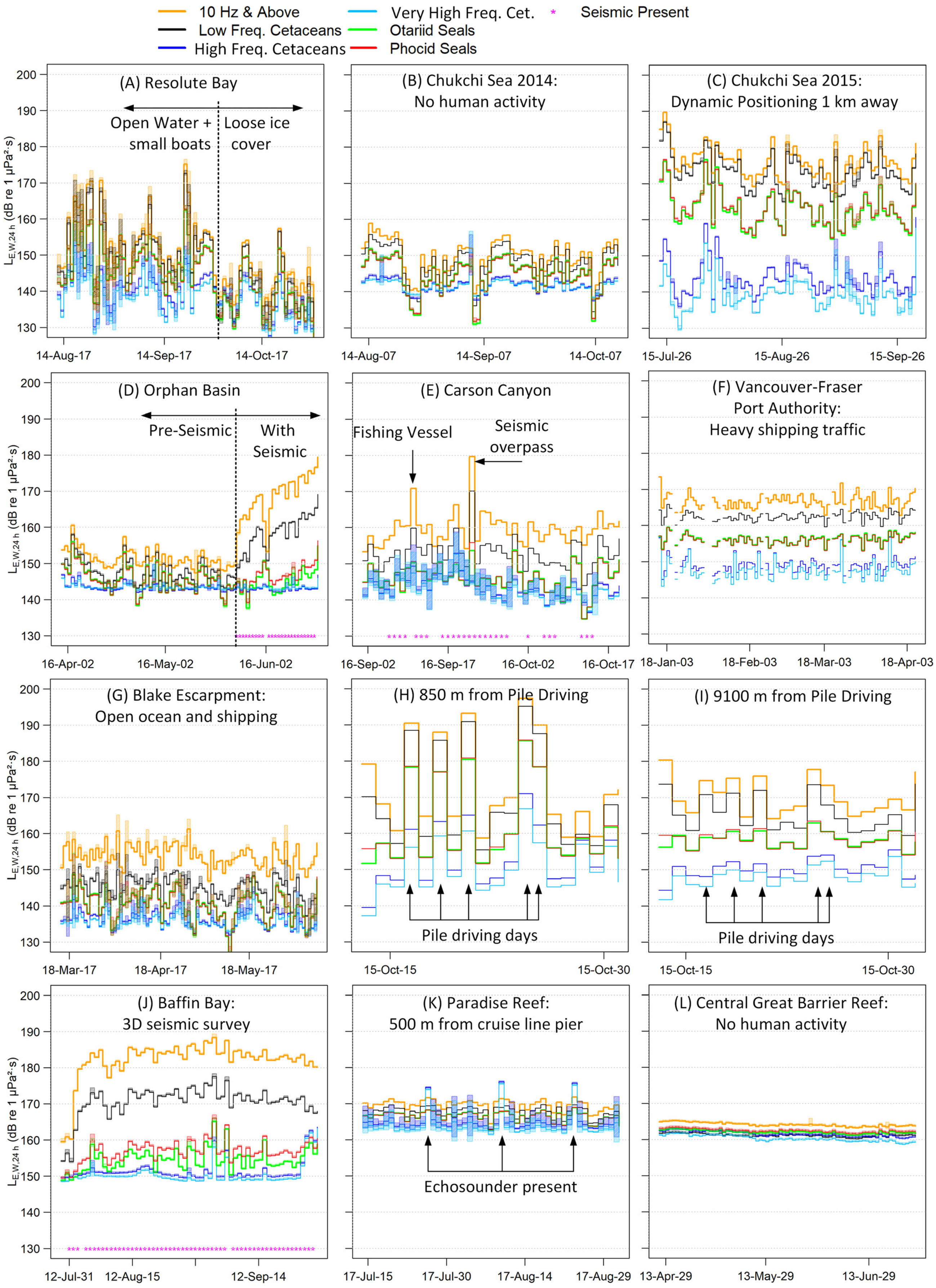

FIG. 2. (Color online) Daily weighted SEL for sites A–L (Table I, Fig. 1) with sound levels shown in Table II. For each figure the 10+ Hz SEL is shown along with the five NMFS (2018) marine mammal auditory frequency weighting functions. For the duty-cycled recordings (data sets A, B, D, E, G, K, and L), the SEL was computed as described in Sec. II C. The 95% confidence interval is shown by the shaded boxes around each days' weighted SELs.

TABLE II. Arithmetic mean daily SEL (dB re 1 μPa^2 s) and standard deviations (gray bracketed text) for data sets A–L (Figs. 1 and 2). The Resolute Bay data (A) has been divided into open-water and small boats (16 Aug–2 Oct) and with ice-cover (3 Oct–2 Nov) periods. The Orphan Basin (D) data have been divided into pre-seismic (1 Apr–24 May) and with-seismic (25 May to 30 Jun) periods.

Location ID	Location name	Data description	10 Hz and above	Low-frequency Cetacean	High-frequency Cetacean	Very high-frequency Cetacean	Phocid seals	Otariid seals
A	Resolute Bay Aug–Sept	Open ocean	162.9 (8.2)	160.5 (8.0)	143.8 (4.9)	141.9 (4.8)	152.6 (6.3)	152.5 (6.3)
A	Resolute Bay Ice Covered (Oct–Nov)	Ice + open water noise	147.2 (5.7)	145.7 (6.7)	138.3 (5.1)	137.2 (4.9)	142.0 (6.1)	142.1 (6.3)
B	Chukchi Sea, 2014	Open ocean	151.8 (4.7)	150.0 (4.9)	142.3 (2.2)	142.1 (1.8)	146.4 (4.8)	146.6 (5.0)
C	Chukchi Sea, 2015	Dynamic positioning from semi-submersible drill rig	178.7 (4.4)	176.2 (4.6)	148.1 (4.4)	143.6 (4.1)	166.5 (4.9)	166.4 (5.1)
D	Orphan Basin—pre-seismic	Open ocean	152.5 (2.6)	149.4 (3.3)	143.5 (1.1)	143.5 (0.6)	147.0 (3.4)	147.3 (3.6)
D	Orphan Basin—with seismic	Seismic survey getting closer to recorder with time	172.2 (6.0)	161.2 (5.0)	142.7 (1.0)	142.8 (0.6)	148.2 (3.3)	146.6 (3.5)
E	Carson Canyon	Open ocean, fishing, seismic airgun survey	159.7 (4.8)	152.4 (4.4)	143.0 (3.0)	142.5 (2.9)	145.9 (3.9)	145.8 (3.8)
F	Vancouver-Fraser Port Authority	Port of Vancouver's inbound shipping lane	167.2 (2.0)	162.6 (1.3)	149.9 (2.3)	148.7 (2.7)	156.3 (1.3)	156.4 (1.3)
G	Blake Escarpment	Open ocean with some shipping	154.8 (3.1)	146.2 (3.1)	137.6 (2.8)	136.5 (2.2)	141.8 (4.1)	141.9 (4.2)
H	Block Island, 850 m from piling	Impact pile driving	187.6 (13.1)	185.4 (13.6)	161.1 (8.4)	157.1 (7.6)	176.0 (11.6)	175.7 (11.7)
I	Block Island, 9100 m from piling	Impact pile driving	172.9 (4.9)	168.0 (4.8)	151.0 (2.6)	148.8 (2.8)	159.1 (2.4)	158.8 (2.7)
J	Baffin Bay	Seismic airgun survey except first two days	183.5 (5.6)	171.8 (4.4)	153.0 (2.8)	152.0 (2.8)	158.0 (3.0)	156.0 (3.2)
K	Paradise Reef	Coral Reef, 500 m from cruise terminal; frequented by small tourist dive boats	169.8 (1.5)	168.0 (1.5)	166.8 (2.8)	165.9 (2.9)	166.7 (1.3)	166.7 (1.3)
L	Central Great Barrier Reef	Coral reef without human sources	164.2 (0.5)	161.2 (0.5)	161.6 (0.7)	160.4 (0.8)	162.5 (0.5)	162.1 (0.5)

and very high-frequency auditory frequency weighted SEL. The Carson Canyon data (data set E) also show the effects of vessel range on SEL. The project's fishing vessel operated for several days within 1–4 km of the recorder, but there was no obvious signal of its presence in the daily SEL results. A different fishing vessel passed directly over the recorder on 11 Sept and generated a daily SEL comparable to the drilling program in the 2015 Chukchi data (data set C) or near the Vancouver transit lanes (data set F).

Seismic surveys (Baffin Bay, Orphan Basin after 25 May, Carson Canyon on 22 Sept; data sets J, D, E, respectively) increased the daily 10+ Hz SEL by 10–40 dB and the low-frequency cetacean auditory frequency weighted SEL increased by 0–30 dB depending on the closest daily range to the vessel. The shortest range recorded to a seismic array was 100 m which occurred in Baffin Bay on 4 Sept 2012 and generated a 10 Hz + daily SEL of 189 dB re 1 μPa^2 s. In Baffin Bay (data set J), the airgun arrays were on average 40 km from the recorder (Martin *et al.*, 2017). At Orphan Basin (data set D; after 25 May), the ranges to the recorder were unknown, but presumed to be longer than 200 km when the survey began, decreasing to ∼20 km at the end of recording. In this recording, the 10+ Hz daily SEL values increased 10–30 dB from pre-seismic, and the low-frequency cetacean auditory frequency weighted SEL increased 0–20 dB. The otariid and phocid auditory frequency weighted SEL did not increase due to the seismic pulse energy until several weeks into the survey when the range to the vessel decreased and the high-frequency signal strength increased, similar to the Baffin Bay results (Fig. 2). The change in autocorrelation as a result of the seismic surveys can be seen in monthly plots (Fig. 4).

The daily SEL at Block Island (H and I) were among the highest compared here, likely due to the large amounts of activity associated with the pile driving program (Table II). The average daily SEL at the 9100 m location on days without piling were generally higher than at 850 m. At 9100 m vessels passing the recorder contributed a similar amount to the daily SEL as the pile driving (see also Fig. 6). The impact pile driving increased the daily SEL by 10–25 dB at 850 m from the pile driving compared to the levels at 9100 m. The high- and very high-frequency marine mammal auditory frequency weighted SEL did not increase during pile driving at 9100 m due to the relatively high SEL that had already accumulated from the vessels. The 9100 m location was in 42 m of water and was farther from Block Island, so we presume it received more energy from shipping than the 850 m location.

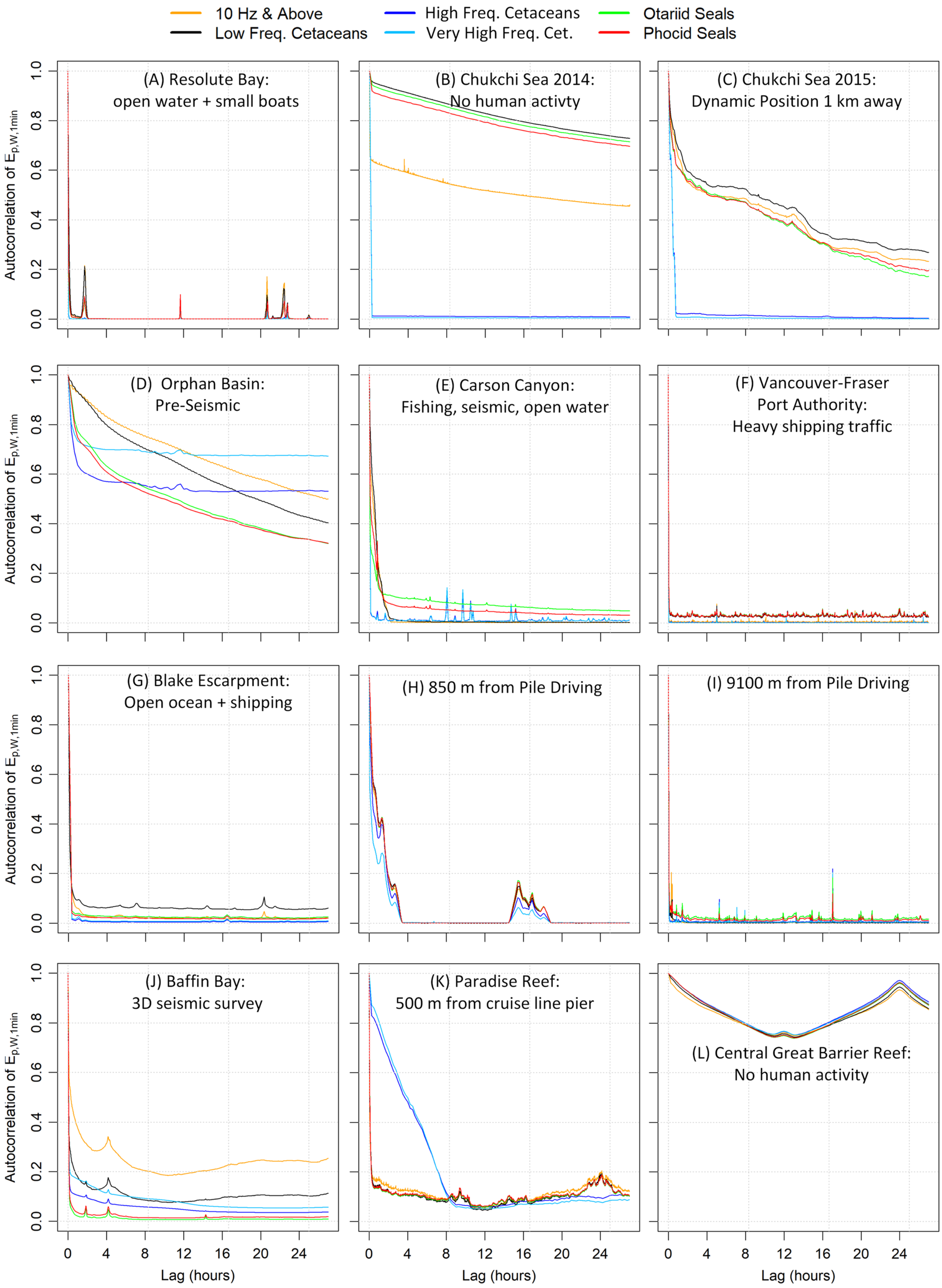

FIG. 3. (Color online) Autocorrelations of the one-minute sound exposure at sites A–L (Table I, Fig. 1). For each plot, the 10+ Hz data are shown along with the five NMFS (2018) marine mammal auditory frequency weighting functions. For data sets that were divided into subsets in Table II, only one subset is included in this figure.

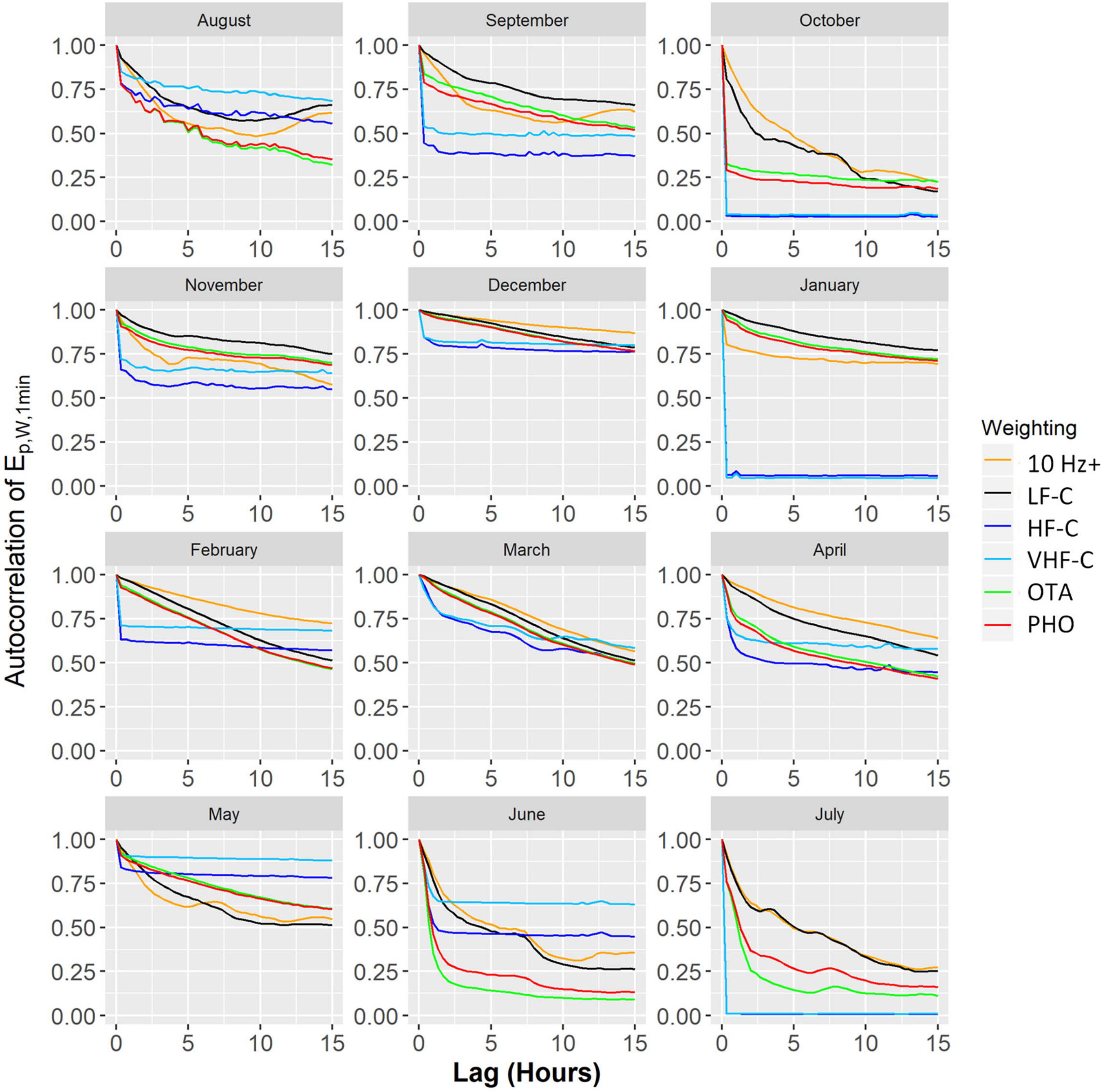

FIG. 4. (Color online) Example of the autocorrelation of each month's one-minute auditory frequency weighted SEL for the Orphan Basin data. (Top left) August 2015, (bottom right) July 2016. August, September, and part of October 2015, as well as part of May, and all of June and July, 2016, had seismic survey activity in the area. The auditory frequency weighting functions shown are 10 Hz+ (10 Hz and above); LF-C, low-frequency cetacean; HF-C, high-frequency cetaceans; VHF-C, very high-frequency cetaceans; PHO, Phocid seals; and OTA, otariid seals.

Coral reef (K and L) soundscapes are substantially different from the other environments measured (Figs. 2 and 3). The daily SEL in these locations was constant with standard deviations less than 1 dB at the Great Barrier Reef and 1–3 dB at Paradise Reef. At both sites there is a peak in the autocorrelation of the one-minute sound exposures at 24 h due to the sonorous activity of many reef animals that are synchronized with the solar cycle. Few anthropogenic sounds were present in the Great Barrier Reef recording (L), which resulted in an autocorrelation of almost 1 after 24 h. The Great Barrier Reef site is the only one where the low-frequency cetacean auditory function weighted SEL was not the highest weighted daily SEL. The Paradise Reef location was ∼500 m from a cruise ship pier and frequented by many tourist dive boats. A total of 76 cruise ships visited the port during the recording period with visits typically lasting 10 h from ∼08:30–18:30. This human activity elevated the daily SELs by 5–10 dB compared to the Great Barrier Reef, changed the autocorrelation structure, and resulted in the low-frequency cetacean auditory function weighted SEL being the highest weighted SEL on most days. The peak in the autocorrelation structure at 10 h is a result of the vessels entering and leaving port. The peak at 24 h is due to daily patterns in the vessel activity as well as from the soniferous animals on the reef. There is a notable peak in the high- and very high-frequency auditory frequency weighted SEL on 27 July, 10 August, and 24 August, which was caused by a 27 kHz echosounder. The very high-frequency cetacean SEL exceeded the (Southall *et al.*, 2019) permanent threshold shift regulatory limit for continuous noise on those days. The echosounder has been linked to one of the cruise ships that was the only vessel in port on the 27th of July, and her only other port visits were 10 and 24 August. None of the other 16 unique cruise ships that visited the port appeared to have left their echosounders running.

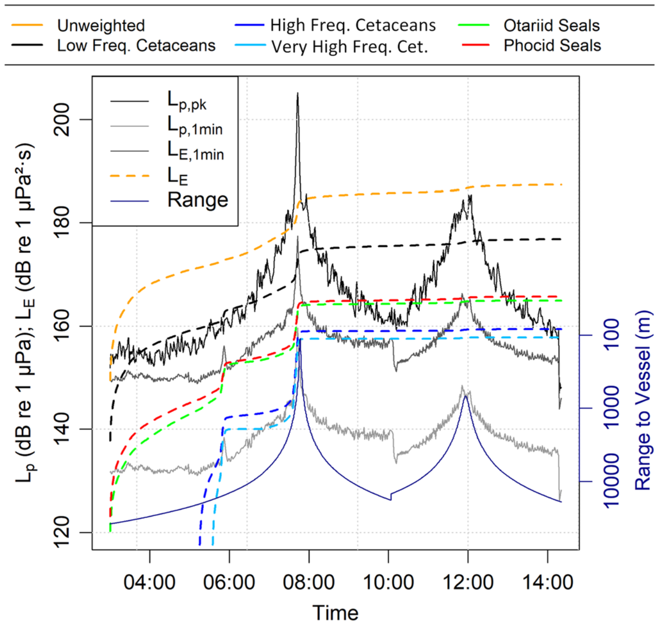

FIG. 5. (Color online) Accumulation of SEL over a 12-h period on 4 Sept 2012 during the overpass of two seismic source vessels in Baffin Bay (M). The 10+ Hz SEL increased from 184.5 dB re 1 μPa^2 s after the first vessel passed at 07:50 to 186.7 dB re 1 μPa^2 s at 12:00 when the second passed. For more on this data set, see Martin *et al.* (2017).

B. Accumulation of SEL

1. Case 1: Vessels and seismic surveys in Baffin Bay

Figure 5 shows 12 h of data from the Baffin Bay data set (J) during which two seismic vessels passed by the recorder. SEL accumulated slowly while the first seismic vessel approached the recorder. At ∼05:45, the seismic support vessel passed near the recorder; its propulsion sounds were the first sounds above the recorder noise floor for the high- and very high-frequency weighted daily SEL. The total SEL increased rapidly in the last kilometer as the per-pulse SEL increased by 20 dB. The remainder of the passage of the first vessel plus the entire passage of the second vessel only increased the 10+ Hz SEL by 2 dB. The weighted SEL increased by smaller amounts. The daily SEL did not increase for the remainder of the 24-h period (not shown).

2. Case 2: Accumulation of SEL near a pile-driving construction site

The daily SEL is the sum of the ambient sound from wind and waves, human activity, and biologic sounds. The daily SEL at a receiver depends on the source level of each source and the attenuation of sounds with distance (Fig. 6). Figure 6 shows the accumulation of SEL on 25 Oct 2015 during pile driving at Block Island (H and I). At a range of 850 m from the piling [Fig. 6(a)], a vessel passed the recorder at ∼04:00, which increased SEL by 5–10 dB. Three bouts of impact piling began at 18:15. The first bout increased the daily SEL by 10–25 dB, depending on the auditory frequency weighting. Between the vessel passage and the start of piling the daily SEL increased slowly, likely due to ambient background sound. The ambient sound did not increase the daily SEL after pile driving. At 9100 m from the pile driving location [Fig. 6(b)], vessel passages at midnight and ∼07:00 were the primary source of daily SEL. The first bout of pile driving did not add enough sound energy to the daily SEL to be discernible. The second and third bouts of pile driving only made a slight increase in the low-frequency cetacean auditory frequency weighted SEL.

C. Effects of duty cycles on SEL

Duty-cycling introduces an error in the daily SEL estimate whose mean value ranges from −1.7 to +1.1 dB. The

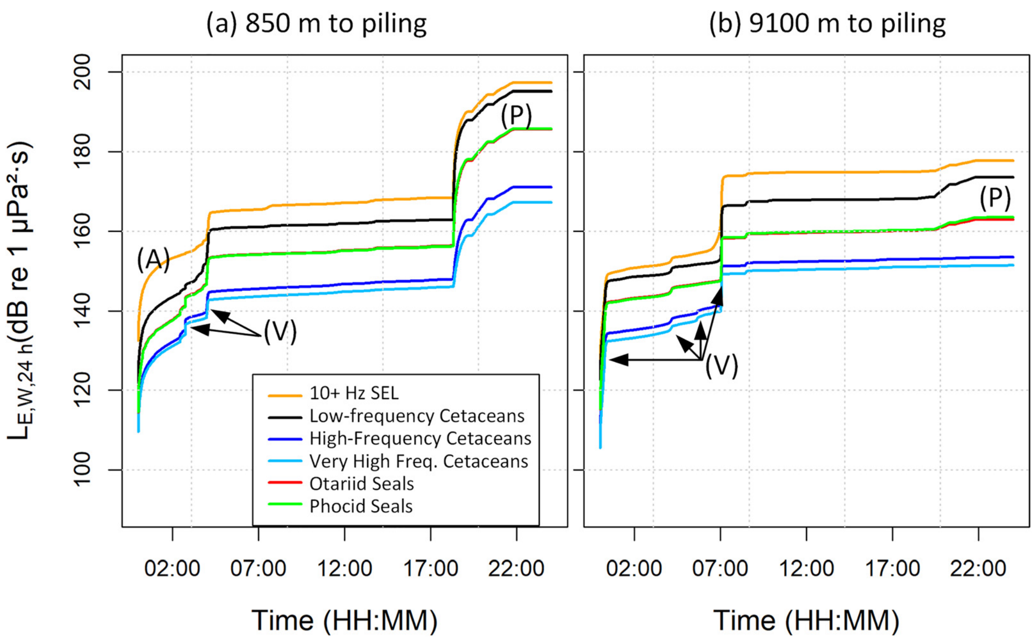

FIG. 6. (Color online) Comparison of the accumulation of SEL over a 24-h period at two ranges from pile driving on 25 Oct 2015 during construction of the Block Island Wind Farm, USA. The primary source of sound during large changes in SEL are annotated: (A), Ambient; (V), Vessel Passages; (P), impact pile driving. (a) 850 m from the piling location. (b) 9100 m from the piling location.

error in estimated SEL increases with decreasing autocorrelation; the errors are more often underestimates of SEL rather than overestimates. The relationship between autocorrelation (at the first available time lag—i.e., 2, 3, 4, etc., minutes, as described in Sec. II C) and SEL error was not linear and had a large range of error values for any one correlation value. Therefore the 95% confidence intervals were determined empirically from the measured data. To confirm that the behavior of the real data sets was predictable, the results were compared with gamma-distributed random noise. The worst case 95% confidence interval for the error is ± 6 dB, both for the real data and simulations with gamma-distributed random noise (see the supplemental material[2]). As an example of the use of the confidence interval results, the range of SEL error for each day and auditory frequency weighting function were added to Fig. 2 as shaded areas around the expected value.

IV. DISCUSSION

A. Accumulation of SEL from stationary and moving sources and implications for the distance from a source where auditory injury may occur

An important property of SEL from human sound sources is that the relative movement of the source and receiver determines how SEL accumulates, which is clearly shown in Figs. 5 and 6 as well as by the echosounder at Paradise Reef [Fig. 2(K)]. The highest 10 Hz and above daily SEL of 193 dB re μPa^2 s was recorded on 21 Oct 2015 at 850 m from the pile driving. This was 4 dB higher than the maximum seismic daily SEL, even though the seismic vessel passed only 100 m from the recorder (Baffin Bay, 4 Sept 2012). This result underscores how moving sources like seismic and vessels mitigate accumulation of SEL compared to a stationary source like pile driving. A moving biologic receptor would similarly mitigate the accumulation of SEL from stationary sources as well as mobile ones. If we assume that most sensitive biologic receptors will move, even if just over distances of several hundred meters, then the closest point of approach (CPA) to the source will dominate the received SEL (as shown in Figs. 5 and 6 and by Monte Carlo simulations; Gedamke *et al.*, 2011). The duration of CPAs is typically on the order of minutes, and thus integration over a period of an hour will accumulate all of the energy from a moving human source that a biologic receptor would encounter. As noted in Southall *et al.* (2019), further investigation of appropriate SEL integration and rest times is required.

It is known that hearing begins to recover quickly after exposure to loud sounds (Hirsh and Ward, 1952). For example, porpoise recovered from 10 dB of temporary threshold shift (TTS) within an hour (Kastelein *et al.*, 2012). It is therefore reasonable to consider resetting SEL exposure an hour after CPA for moving human sources and/or moving biologic receivers. For continuous sources of sound, such as dynamically positioned oil rigs or sea-floor production facilities, a different approach is required, which is acknowledged in NMFS (2018), although no specific advice is given. For this type of source the distance around the activity where one would expect animals to be affected, and likely excluded, is equal to the area where the average sound level is above the threshold of effective quiet (Ward *et al.*, 1976; Mooney *et al.*, 2009; Kastelein *et al.*, 2017). There is some evidence for this effect in the detections of odontocetes 2 km compared to 20 km from a mobile offshore drilling unit working in 2400 m of water off Nova Scotia (Martin *et al.*, 2019). Further work in understanding effective quiet, hearing recovery, and appropriate accumulation times is required for all marine taxa.

B. Identifying soundscapes dominated by wind and wave sounds

The data sets analyzed here demonstrate a range of effects that our use of the oceans has in changing soundscape experienced by marine life. Recordings such as Chukchi Sea 2014 (B) and Orphan Basin pre-seismic (D) provide a baseline soundscape for the open ocean that is measurably different from the other environments. Similarly, the Great Barrier Reef is a baseline coral reef environment that contrasts with the measurements at Paradise Reef.

From the results we propose the following indicators to identify soundscapes that are unaffected by anthropogenic activity or intense biologic sound production: (1) the daily 10+ Hz SEL is below 160 dB re 1 μPa^2 s, even in high winds; (2) the low-frequency cetacean auditory frequency weighted SEL is within 3 dB of the 10+ Hz SEL (i.e., at least half of the daily SEL is from frequencies above 100 Hz); and (3) the low-frequency cetacean auditory frequency weighted SEL has a correlation coefficient above 0.6 for time lags of at least 3 h when computed with one-minute SEL over periods of at least 1 month. For coral reefs, the proposed indicators are slightly different: (1) the daily 10+ Hz SEL is below 170 dB re 1 μPa^2 s, even in high winds; and (2) the autocorrelations of all auditory frequency weighted one-minute SEL are above 0.75 at 24 h lag when computed using at least 1 month of data. The duration over which the autocorrelations remain high indicates how isolated the soundscape is from variable sound sources, usually of human origin. The details of the low-frequency cetacean auditory frequency weighting are not important for these results—rather the results depend on excluding energy between 10 and 100 Hz—which is the effect of the low-frequency cetacean weighting. We replicated these results by computing SEL using only 100–20 000 Hz decidecades [Eq. (4)].

It is important to understand the properties of the long-term autocorrelation of the one-minute sound exposure as a soundscape indicator. The autocorrelation of the sound exposure is defined as the sum of the sound exposure (E_p) times the delayed version of itself, divided by the summed square,

$$R_{EE}(\tau) = \frac{\sum_{t=0}^{T-1} E_p(t)E_p(t-\tau)}{\sum_{t=0}^{T-1} E_p(t)E_p(t)}. \quad (5)$$

This operation will always have a value of one when τ is zero. When τ is not zero, the autocorrelation measures the change in sound exposure for each value of τ. This operation is susceptible to being dominated by large amplitude values that overwhelm other patterns that may be in the data. For example, the echosounder at Paradise Reef (K) was only present 1 day in 14, yet the high- and very high-frequency weighted sound exposures are above 0.1 for 10 h, the duration that the vessel was in port. This is also a property of the autocorrelation that also makes it useful as a soundscape descriptor—loud sources at random times reduce the autocorrelation and indicates human effects on the acoustic environment. At the same time, it is important to separate the data into periods that are dominated by identifiable sources before assessing the soundscapes during those periods individually. For this reason, we have divided the Orphan Basin data into pre-seismic and with seismic periods, and the Resolute Bay data into open water and ice-covered periods (Table II). In general, consider determining the autocorrelation on a month-by-month basis to look for long-term variability in a soundscape (e.g., Fig. 4).

A few notes on how autocorrelation was used in this analysis are warranted. First, autocorrelation was performed on the sound exposure, rather than the SEL [see Eqs. (2) and (3)]. The choice is essential so that the large range of exposure values can decorrelate the soundscape when sources like ships are present. When SEL is used the correlation coefficient remains near one for all data sets for lags of days. Second, the absolute values of the sound exposure are important, and therefore the data should not be demeaned before performing the autocorrelation. For many other applications of autocorrelation this is not the case. As a result of this choice, autocorrelation coefficient values below zero will not occur. Finally, the data used for autocorrelation must be evenly spaced. For example, the Chukchi Sea 2014 data (B) have 2 min of data at the high sample rate, and 13 min at the low sample rate. All this data, when sorted in time, may be autocorrelated to determine the properties of the 10 Hz and above SEL or the low-frequency cetacean auditory frequency weighted SEL. For the remaining weighted SEL only 1 min of the 2 min of high sample rate data should be used.

C. Selecting hardware and duty cycles for SEL analysis

The data sets analyzed illustrate two considerations when selecting recording equipment and determining the recording configuration: it is possible for the recording system noise floor to be higher than the TTS thresholds for very high-frequency cetaceans, and the recording configuration may not support accurate assessment of the auditory frequency weighted SEL.

The recording system noise floor and sampling rate set the minimum daily SEL that can be measured, which may be higher than the Southall *et al.* (2019) TTS thresholds from non-impulsive sound sources for very high-frequency cetaceans of 153 dB re 1 μPa^2 s and the impulsive threshold of 140 dB re 1 μPa^2 s (see Tables 6 and 7 of Southall *et al.*, 2019). For hydrophone data acquisition systems, the spectral noise floor is the sum of noise from the analog-to-digital converter, hydrophone pre-amplifier, and hydrophone ceramic. Different hydrophone noise floors had a notable effect in the data sets analyzed. The Orphan Basin data (D) were computed from data sampled at 250 000 Hz using HTI-99-HF hydrophones, which resulted in a SEL noise floor of ~142 dB re 1 μPa^2 s (Table I, Fig. 2). The Blake Escarpment data (G) were also recorded at 250 kHz, but with the lower noise GeoSpectrum M36 hydrophone, so that the minimum high-frequency marine mammal daily SEL was ~134 dB re 1 μPa^2 s—which is visible as a lower noise floor in Fig. 2. The Baffin Bay (L) and Block Island 850 m (H) configurations are typical of recordings made near high-intensity human activities such as pile driving and seismic surveys where low sensitivity hydrophones are needed to avoid saturation from the sound source. The low-sensitivity resulted in spectral density noise floor of 53 dB re 1 μPa^2/Hz, which with 64 kHz sampling rate, the noise integrated to a daily minimum SEL of 150 dB re 1 μPa^2 s.

Solutions for the noise floor limit are to reduce the bandwidth analyzed and/or only integrating for the period when the source is present. As discussed above 24 h is the currently recommended duration but should be reconsidered as more data becomes available. With respect to the recording bandwidth, the main sounds of interest for the effects of man-made noise on marine life (pile driving, seismic arrays, vessels, and naval sonar) are all dominated by frequencies below 10 kHz, with some energy reaching 30 kHz and higher at short ranges (Simard *et al.*, 2016; Martin *et al.*, 2017; MacGillivray, 2018). Based on these frequencies and our understanding of the hearing bands of marine mammals, as well as most fishes and invertebrates, recording programs concerned with quantifying SEL should analyze data sampled at ~64 000 Hz. This sampling rate results in a usable frequency band of ~30 kHz, which captures the energy of most sound sources of interest, reaches the 0-dB attenuation range of the very high-frequency cetacean auditory frequency weighting function, and the bandwidth is narrow enough that most recorders and hydrophones will not be self-noise limited. With respect to the daily SEL from human sources, a higher sample rate is only required to study the effects of sources such as echosounders and multibeam sonars. Recording programs whose objectives include detections of odontocete clicks also need to sample faster than 64 000 Hz.

The recording duty cycle is a system configuration parameter that affects the confidence interval of the daily SEL estimates. As the duty cycle decreases the autocorrelation coefficient decreases and the daily SEL error increases—i.e., higher errors at 1 min in 20 min than 1 min in 2 min (see supplemental material[2]). When the duty cycle is less than 1 min in 30 min the decimated autocorrelation does not track the true autocorrelation reliably and SEL should not be computed from such data. When selecting a duty cycle, we recommend recording more often rather for longer periods if daily SEL is a desired output of the project. For example, recording for 1 min every 6 min is much more useful than recording for ten consecutive minutes per hour. This result is also true when determining the presence of mysticete whales using duty-cycled data (Thomisch *et al.*, 2015). The minimum recording duration we recommend is 1 min, however, 30 s would likely provide good data as well. We have also found that when cycling between multiple sample rates, selecting a total duty cycle that is an even number of minutes is preferred as it allows more options when downsampling before autocorrelation (e.g., the Chukchi Sea 2014 data discussed in Sec. IV B). When recording data to measure SEL for regulatory compliance, continuous recording is strongly recommended.

D. Using the daily SEL in soundscape management—Cumulative effects assessment

A goal of many environmental assessments is to understand how a proposed project will add to existing human activity and affect the animals in the area. When estimating the effects of underwater sound from multiple human activities, Ellison *et al.* (2016) provide a method based on summing the SEL from each activity for simulated animals moving through the project area. This operation is difficult for locations with many existing sound sources whose movements and source factors are uncertain. Instead, long-term baseline measurements may be used to determine the existing daily SEL, to which SEL from the proposed activity may be added. It is also possible to use the difference between the daily SEL and accepted sound tolerance levels (e.g., the Southall *et al.*, 2019, TTS thresholds) is such an indicator of how much additional sound may be added to the environment without risk of inducing TTS. This comparison has limitations since it accumulates sound that is likely below the threshold for effective quiet and could, for some recorder configurations, include system noise. It is also limited since it does not account for healing of the hearing system between intermittent exposures and the temporal effects of sound patterns are not accounted for in this approach (or the equal-energy hypothesis in general; Hamernik *et al.*, 2003). Regardless, it is still a useful “first-look” at the capacity of animals in the environment to be exposed to additional sound without hearing injury or impairment. Locations where the sound levels are elevated by continuous sources (e.g., Chukchi Sea 2015, Vancouver-Fraser Port Authority) require special consideration if new impulsive sound sources may be added to the environment. At these locations the continuous sound levels are high enough that low- and high-frequency cetaceans are already past TTS for impulsive sounds before an impulsive source starts. Studies have shown that animals and humans become more susceptible to impulsive sounds when high levels of continuous sound are already present (Henderson and Hamernik, 1986; Ahroon *et al.*, 1993; Kastelein *et al.*, 2015). Examples of these situations include pile driving in a busy harbor, vertical seismic profiling to image newly drilled oil and gas wells, or the narrow beam of an echosounder below a passing ship.

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[1] https://bit.ly/2zx03ye (Last viewed 17 June 2019).

[2] See supplementary material at https://doi.org/10.1121/1.5113578 for material that includes: why SEL is a measure of the received energy, how to compute SEL across multiple events, further information on auditory weighting functions, hydrophone and recorder self-noise data, gamma random noise distributions that are similar to typical of ocean noise distributions, statistical measures (mean, variance, skewness, kurtosis, gamma fit, and autocorrelation durations) for each data set, and confidence intervals for duty-cycled daily SELs.

[3] 2017 marine traffic density provided by www.marinetraffic.com (Last viewed 26 April 2019).

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