Detection and characterization of whale signals using seafloor cabled seismic networks offshore Japan

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***Abstract*—Ocean ambient noises against seismic signals are well studied using archived waveforms recorded on three-component seismometers and hydrophones connected to a seafloor cabled seismic network off Kushiro, Hokkaido, Japan basically facing the Pacific Ocean. The system was deployed to install in late July 1999 by Japan Agency for Marine-Earth Science and Technology (JAMSTEC). Outstanding "noises" at frequency bands of 15-30 Hz are recorded on all components of both seismometers and hydrophones, which are directly recognized as fin whale calls in comparison with in-situ visual surveys carried in September to October 2009. It is extremely conspicuous that a seasonal variation of the fin whale calls has been revealed in ambient noise spectrograms of continuous long-term waveform records from 2009 to 2013. High-intensity signals associated with the fin whale calls appear commonly in the periods from September to February over cold winter at high latitudes. The remarkable seasonal pattern should be corresponded to their annual living behavior and might be related to climate changes in the Pacific Ocean.**

Keywords—whale calls; baleen whale; fin whale; acoustic waves; ocean bottom seismology; ambient noise

I. INTRODUCTION

Long-range migratory behavior has been found in a number of animal species. Though many ecological and biogeographic factors are conceivable to affect migratory behavior, seasonality in resources is a major basic driving force for long-distance migrations balancing between benefits of increased source availability and costs associated with the migratory process in terms of time, energy and mortality [1]. That holds true in most baleen whale species to undertake long migrations between high-latitude productive for feeding during summer and low-latitude warmer for mating and breeding during winter [2, 3]. Discovery tag returns from commercial whaling suggest that blue whales (*Balaenoptera musculus*) and fin whales (*Balaenoptera physalus*) of the two largest baleen whales [4] undertake long-distance migrations between high and low latitudes [2, 3, 5, 6]. That notion is supported by acoustic data recording "20-Hz" voices for fin whales from the regions of the North Pacific [7] and western Antarctic [8, 9].

The low-frequency vocalizations at around 20 Hz of the baleen whales are the most powerful and ubiquitous biological sounds in the world's oceans [10, 11]. Most characteristics of vocalizations are roughly common in rhythmical patterns to individual species of baleen whales. Sequentially repeated 20-Hz signals of fin whales are composed of "short" 1-s pulses, compared with "long" 20-s pulses identified with blue whales [12]. The short pulse is combined with regular intervals ranging 7-26 s basically to make rhythmical songs. The dominating low frequency part of the song consists stereotyped 1-s long down-sweeps centered at 20 Hz that appear in bouts of either single calls or doublets, repeated for up to many hours at a time with a regular inter-pulse-interval that varies among fin whale stocks [12, 13, 14]. Their powerful vocalizations at lower frequencies can propagate over long distances in the SOFAR (Sound Fixing And Ranging) channel of the low velocity zone with little loss in the signal energy. These characteristics allow tracking of individual fin whales to know their ecological behavior in detail.

Passive acoustic observations has been increasingly used as a tool to study the presence, relative abundance, migratory movements and behavior of large baleen whales using the underwater observations by using the autonomous hydrophone arrays deployed virtually in the world's oceans [15, 16, 17] including in the North Atlantic [12], in the eastern North Pacific [13, 18, 19, 20], in the North Pacific [21, 22], and in the Arctic [23]. On the other hands, several permanent seafloor cabled seismic networks have been operated offshore Japanese islands to monitor earthquakes and tsunamis since late 1970's, which basically consist several sensor units of three-component seismometers and hydrophones for investigation of seismicity and pressure gauges for tsunami monitoring. Huge data has been continuously recording in real time since their deployments. Some conspicuous signals associated not only with geophysical events from earthquakes [24], submarine volcanic eruptions [25, 26, 27], or tsunamis [28] are detected on the hydrophones and the seismometers but also with some biophysical sounds of the baleen whales. As for the biophysical sounds detection, advances in these continuous seismic networks for a long-time could enable us first to reveal the seasonality during passing and staying near the stations offshore Japanese islands in the western North Pacific where there have been still few evidences for acoustic observations of baleen whales.

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II. DATA

A. Permanent seafloor seismic data

Japan Agency for Marine-Earth Science and Technology (JAMSTEC) developed a permanent geophysical observatory on deep ocean bottom, composed from three seismic stations with 40-60 km of horizontal intervals of each station (KOB1, KOB2, and KOB3, which are located at depths of 2329, 2428, and 2124 m, respectively), two tsunami stations, and cable-end environmental station connected along about 240 km length optical fiber cable, and installed at the southern end of the Kurile seismogenic zone caused by subduction of the Pacific Plate, approximately 100-150 km offshore Kushiro, Hokkaido, Japan in late July 1999 as shown in Figure 1 [29]. The system has continuously provided us with data in real time with few missing since August 1999.

The seismic station of this system is equipped with a three-component servo accelerometer with a flat frequency response between 0.05 and 200 Hz (JA-5III-A, Japan Aviation Electronics Industry Ltd., Tokyo, Japan), and a hydrophone with a flat frequency response between 4 and 4000 Hz and with a sensitivity of -190 dB re V/μPa (ITC-1010A, International Transducer Corp., CA, USA) before a digital filter processing. They are continuously recorded with a sampling rate of 100 Hz at resolution of 3.35E-9 V/LSB by a 24-bit A/D converter. After digital processing, the transit frequency band areas are between 0.5 and 40 Hz and between 1 to 40 Hz for accelerometer and hydrophone, respectively, which means that both sensor could be sensitive to the low-frequency signals of baleen whales around at 20 Hz.

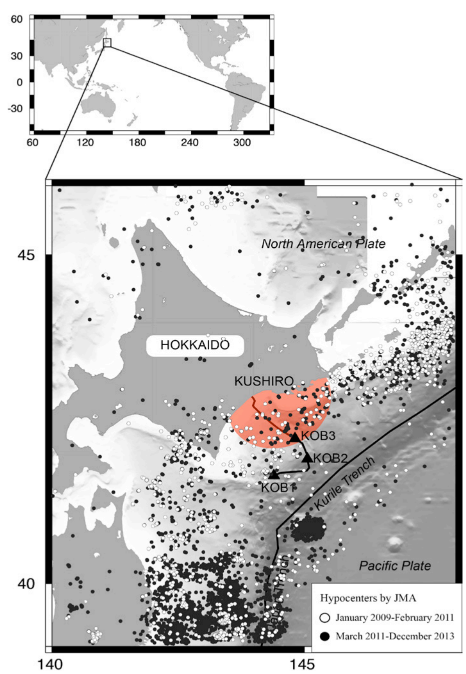

Fig. 1. Locations of KOB1, KOB2, and KOB3 of the seafloor cabled seismic networks are shown by black triangles. Red region shows in-situ cetacean sighting survey area within 50 nautical miles radius from the Kushiro port. Earthquake hypocenters from 2009 through 2013 with magnitude greater than 3.0 and at depths shallower than 70 km are shown by white and black dots occurred before and after the 2011 Tohoku earthquake, respectively. This figure was created by the Generic Mapping Tools (GMT) [42].

B. Comparison with in-situ visual surveys

We compared the seismic analysis with the actual cetacean occurrences that had been made by shipboard cetacean sighting survey under the coastal component of JAPAN-II research program in 2009, which covered water within 50 nautical miles radius from the Kushiro port in 5 September to 17 October 2009, whose area is reproduced in Figure 1 [30]. During those surveys, several species of the baleen whale included a total 51 individuals (21 schools) of fin whales were sighted [30].

The details of those 51 individuals of fin whales sighted by in-situ visual survey are reproduced (Table I) together with the locations and the dates. Based on those fact-finding of fin whales, we analyzed the acoustic data recorded on the hydrophones and the seismometers at the off Kushiro seafloor cabled seismic stations at those sighted dates. Comparison with those inspections and confirmations of the scene as the first step could move into further analysis for long-term continuous data sequentially to examine presences and absences of fin whales through whole year besides the sighted dates.

TABLE I. DATAILS OF 51 INDIVIDUALS OF FIN WHALES SIGHTED BY IN-SITU VISUAL SURVEYS OFF KUSHIRO

Date	North Latitude	East Longitude	Number
18 Sept. 2009	42°32’44”	144°24’56”	5
26 Sept. 2009	42°41’25”	144°44’57”	1
26 Sept. 2009	42°41’08”	144°34’33”	2
26 Sept. 2009	42°37’20”	144°37’12”	3
26 Sept. 2009	42°35’04”	144°33’11”	2
26 Sept. 2009	42°41’09”	144°41’15”	1
27 Sept. 2009	42°36’00”	144°23’03”	2
27 Sept. 2009	42°34’51”	144°24’03”	2
27 Sept. 2009	42°38’49”	144°29’24”	1
30 Sept. 2009	42°44’56”	144°18’25”	1
30 Sept. 2009	42°30’36”	144°17’26”	1
1 Oct. 2009	42°39’34”	144°25’33”	1
12 Oct. 2009	42°30’40”	144°33’07”	3
12 Oct. 2009	42°30’55”	144°35’01”	7
12 Oct. 2009	42°27’40”	144°31’10”	11
15 Oct. 2009	42°43’51”	144°27’57”	2
16 Oct. 2009	42°39’56”	144°18’33”	2
16 Oct. 2009	42°29’48”	144°09’26”	1
16 Oct. 2009	42°26’43”	144°05’08”	1
17 Oct. 2009	42°37’51”	144°15’15”	2

III. RESULTS

A. Fin whale calls in ambient spectrograms

Acoustic data recorded on both seismometers and hydrophones were analyzed with a custom software program, TRITON [31] developed in MATLAB (The MathWorks, Inc., MA, USA). As TRITON can work with WAV formatted data, which is typically acoustic time series, original data were converted to WAV format. We created hourly spectrograms from Fast Fourier Transform (FFT) convolved at 1000-point size, 0%-overlapped, Hanning-windowed data to extract spectral features. The resulting spectrograms (Figure 2) had resolution of 0.1 Hz and 1 s in frequency and time, respectively.

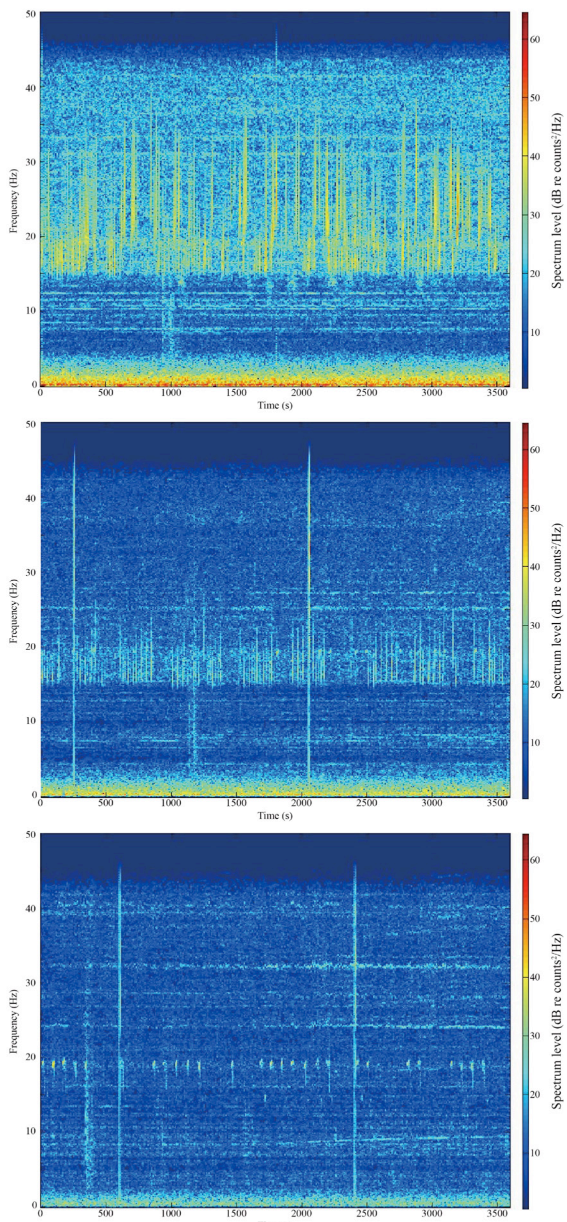

Fig. 2. Hourly spectrogram of fin whale vocalization for the single type from 11:30 on 24 September (Top), for the doublet type from18:26 on 30 September (Middle), and for undefined type from 14:20 on 1 October (Bottom) in 2009 in JST, recorded at KOB2. Note that these signals were confirmed to recognize fin whale vocalizations by our visual surveys.

B. Classification of fin whale vocalizations

Fin whale vocalizations are characterized as repeated 20-Hz pulse series with a unique rhythm [12]. We analyzed 5-year continuous acoustic data from 2009 through 2013 to detect repeated pulse series in frequency bands of around 20 Hz identified as fin whale calls in ambient noise spectrograms derived from all components of seismometer and hydrophone data at all of three stations of the off Kushiro cabled network. Intense pulses in amplitudes are found in the season from autumn into winter with a seasonal variation as discussed later for detail. Figure 2 shows typical examples of hourly spectrogram including outstanding fin whale vocalizations derived from the hydrophone at KOB2 in September to October 2009. These fin whale vocalizations could be classified into three kinds of single, doublet types based on Watkins et al. (1987) [12] and "undefined" calls that have not been reported in previous studies on fin whale vocalization detected in the Pacific Ocean. The "undefined" types should be recognized as different calls in that both the duration and the interval length are distinctively longer than the other two types.

TABLE II. CLASSIFICATIONS OF OBSERVED FIN WHALE CALLS

	January	February	September	October
Single*	1080 (59%)	416 (26%)	652 (45%)	2034 (52%)
Doublet*	628 (35%)	1182 (74%)	100 (7%)	1639 (41%)
Undefined	112 (6%)	0 (0%)	712 (48%)	264 (7%)
Total	1820 (21%)	1598 (18%)	1464 (17%)	3937 (44%)

* After Watkins et al. (1987).

In order to quantitatively clarify these features of the undefined fin whale vocalization types, we analyzed the acoustic data by using a sound analysis and synthetic software of Avisoft-SASLab Pro Version 5.2.09 (Avisoft Bioacoustics, Berlin, Germany). The Avisoft can automatically resolve each unit composing pulse series to measure the parameters of duration, peak frequency, and interval length of each unit. Here we set -4 dB as the threshold amplitude and 20.0 ms as the holding time in the automatic measurements. These measurements were explored in the frequency domain. In this case the spectrogram parameters were given as follows: 512-point FFT size, 87.5% overlap, and Hamming window.

We examined characteristics of repeated 20-Hz pulse series of fin whale calls detected by hydrophone at KOB2 in January, February, September, and October 2009. Each unit was automatically extracted with constant threshold in amplitude from successively pulse bouts and was measured the duration, interval, peak frequency and bandwidth. Totally, 8819 acoustic units were resolved and classified into each types of single, doublet and undefined types as indicated in Table II. Most appearance was in October, which counted up to 3397, though other months were comparable. Measurements were successfully carried out for all of the resolved acoustic units.

As a result, these estimated parameters for both single and doublet types well consistent with previous studies for fin whale vocalization, which the 20-Hz signals composed 1-s pulses at 7-26 s intervals produces signal bouts lasting for a long time [12], as shown in Table III. For the "undefined" type, on the other hands, the parameters of duration, interval length and bandwidth are significantly different from the other two types, especially in that the duration is much longer than one of others although the duration longer than 1 s has never been reported in past studies, suggesting that it might be valid to categorize it as a new one.

TABLE III. CHARACTERIZATIONS OF CLASSIFIED FIN WHALE CALLS

	Single** (N=4182)	**Doublet**** (N=3549)		**Undefined** (N=1088)
Duration [s]*	0.6 ± 0.2	0.6 ± 0.3		2.0 ± 1.7
Interval length [s]*	18.5 ± 13.9	Primary (N=1412)	Secondary (N=1562)	38.5 ± 44.0
		19.3 ± 2.4	27.4 ± 2.6	
Peak frequency [Hz]*	18.4 ± 2.9	16.5 ± 0.6		18.9 ± 0.6
Bandwidth [Hz]*	5.3 ± 0.5	3.7 ± 0.9		1.3 ± 0.5

* Mean value and standard deviation are listed.

** After Watkins et al. (1987).

In addition, a time or seasonal variation was discovered in the pulse interval length of doublet types. The doublet type is composed with a pair of two pulsed with nominal rest (primary) and alternating pulse intervals (secondary). Figure 3 shows the pulse interval length for the doublet type as a function of time for comparison with two seasons between autumn and winter. The interval lengths of both the primary and the secondary pulses detected from September to October of autumn were significantly longer than the ones detected from January to February of winter.

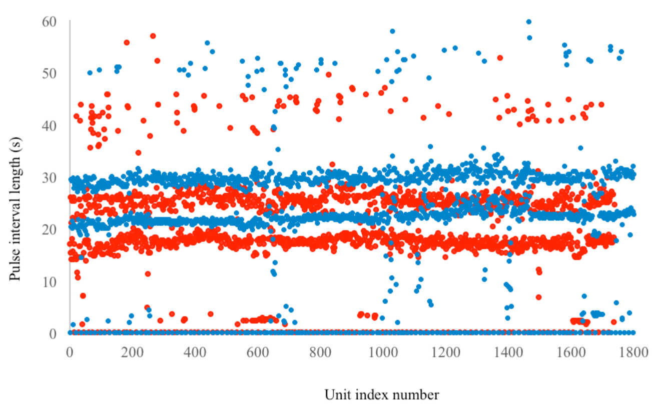

Fig. 3. Measured pulse interval lengths in second of fin whale doublet pulses with primary and secondary pulses detected at KOB2 during two periods from September to October (autumn) and from January to February (winter) in 2009 shown by red and blue dots, respectively. Unit index number on the horizontal axis is allocated in time order.

C. *Seasonal variation of fin whale vocalization*

The TRITON software can also compress the WAV files for sequentially visual overview by creating Long-Term Spectral Averages (LTSAs) [31]. LTSAs are effectively compressed spectrograms created using the Welch algorithm [32]. In order to examine annual variations, LTSAs are created by coherently averaging 24 spectra created from FFT convolved at 500-point size, 0%-overlapped, Hanning-windowed data for a whole year. The resulting annual LTSAs have resolutions of 0.2 Hz and 120 s in frequency and time, respectively.

We created annual LTSAs sequentially from 2009 to 2013 for all the data of both seismometers and hydrophones at all the stations. Figure 4 shows the created annual LTSAs for each year of 2009 to 2013 from continuous data recorded on the hydrophone at KOB2 as an example. Extremely conspicuous seasonality of fin whale calls was revealed in the ambient noise spectrogram. It is a surprise that outstanding signal bands at frequencies of around 15-20 Hz were continuously detected at variable source levels, but at considerably higher levels, in a long period from September to February even through cold winter at considerably higher latitudes. These bands were composed with signal bouts lasting at least approximately as long as three days with a high source level.

IV. DISCUSSION

A. *Seasonality in fin whale presences in the western North Pacific Ocean*

As a most noticeable result in the present study, seasonal variations of fin whale calls off Kushiro located in the western North Pacific Ocean were revealed, which is the first evidence for seasonality in this region although there have been several reports on observed fin whale vocalizations [33-35]. It, however, has been still unknown why such a remarkable seasonality in fin whale presences from September to February through winter at considerably higher latitudes were caused, although it is unquestionable that strong vocalization should be generated by biologically strong motivations such as, mating, breeding, and feeding. Based on previous studies reported on feeding of the baleen whales, the peak of sounds should appear as a diurnal modulation, because most fin whale perform daily vertical migrations up and down the water column controlled by the light intensity appearing in dense prey for their most efficient strategy [19, 36-38].

Fin whale vocalizations are usually recorded year round in different areas of the world's ocean with a clear seasonal peak: from January to April in the North Atlantic [3]; from July to December in the eastern North Pacific [13, 18, 19, 20]; from August to February in the North Pacific [21, 22]; from November to December in the Arctic [23]. The annual peak in fin whale singing coincides with the conception time, suggesting that the strong sound is part of a mating display [21, 39, 40]. This is supported by genetic evidence that all singing fin whales in loud voices were males [39]. The peak singing period in the western North Pacific was in September to February, which similarly coincides with the conception time, inferring that at least partial populations of fin whales in the western North Pacific might likely mate even at considerably higher latitudes [41]. It has been assumed that most baleen whales undertake migrations between low-latitude mating and breeding fields in winter and high-latitude feeding fields in summer [2, 3]. The observed seasonality on the world's ocean including the present study suggest that this simplified bimodal pattern of feeding at high-latitude in winter and mating at low-latitude in summer is not entirely to clear the fin whale migration pattern related to the ecology.

B. *Detectability of fin whale in seismogenic zone*

We confirmed that it is useful to detect fin whale sounds at low frequencies around 20 Hz by using the acoustic data from deep seafloor seismic stations, even though in a high-seismicity period. After the 2011 Tohoku earthquake with magnitude 9.0 on 11 March 2011 which occurred at 142.86° E, 38.10° N, 23.7-km-deep, the seismic activity beneath the Japanese islands is higher than before the giant earthquake occurred. The seismicity both before and after the Tohoku earthquake during the periods from 2009 to 2013 is shown in Figure 1, which was determined by Japan Meteorological Agency (JMA), showing that the seismicity was actually higher than before the earthquake around the cabled stations. The dominant frequencies of seismic waves generated by earthquakes and regarding events are below 10 Hz, which are lower than fin whale's 20-Hz sounds, meaning that they can be completely separated to identify each other in the frequency domain.

There are also several seafloor seismic cabled networks offshore Japan islands for monitoring of earthquakes, tsunami and volcanic activities to mitigate disasters: off Sanriku array of 3 seismometers since 1997 by Earthquake Research Institute, University of Tokyo; off Boso array of 4 seismometers since 1986 by JMA, off Tokai array of 3 seismometers since 1979 by JMA, off Tonankai array of 5 seismometers since 2008 by JMA; off Muroto array of 2 seismometers since 1997 by JAMSTEC. Recently, JAMSTEC developed a dense seafloor network system covering a wide area, named DONET, the first project of whose has been already completed to deploy in the Kumano Basin in 2011 (DONET-1) and the second one of whose is just currently deploying off Kii (DONET-2). In near future, a large network fully covered with the area along the Japan Trench named S-NET will be deployed by National research Institute for Earth science and Disaster prevention, which has 150 seismic stations connected to cables with 5700-km-long. These large, dense and permanent seismic networks would be very powerful tools for detection of migration as well as seasonality of the baleen whales, which should be corresponded to their annual living behavior and might be related to climate changes in the global ocean.

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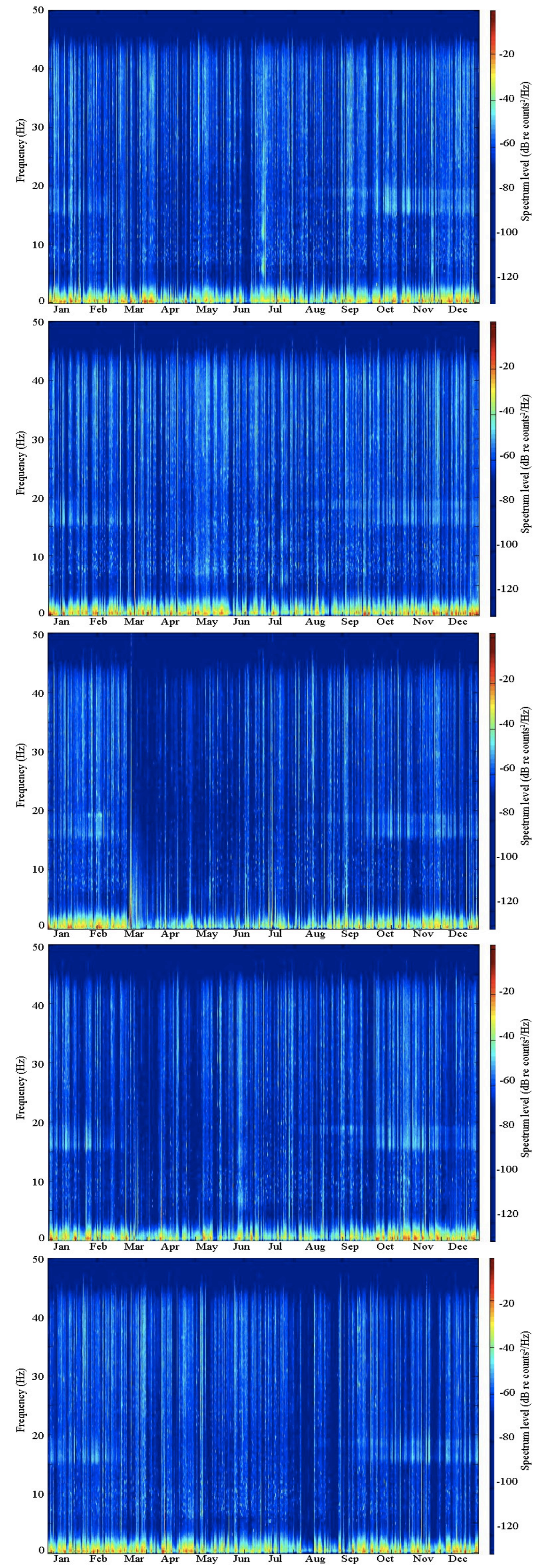

Fig. 4. Annual spectrograms for the year of 2009 (Top) to 2013 (Bottom) of ocean bottom hydrophone data recorded at KOB2.

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