LIMNOLOGY
and
OCEANOGRAPHY

ASLO

Limnol. Oceanogr. 66, 2021, 3714–3727

doi: 10.1002/lno.11911

Baseline soundscapes of deep-sea habitats reveal heterogeneity among ecosystems and sensitivity to anthropogenic impacts

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Abstract

Underwater soundscapes, though invisible, are crucial in shaping the biodiversity of marine ecosystems by acting as habitat-specific settlement cues for larvae. The deep sea has received little attention in soundscape research, but it is being targeted for mineral extraction to feed the ever-growing needs of our society. Anthropogenic impacts on soundscapes influence the resilience of key shallow-water habitats, and the same likely applies to the deep. Japan is a forerunner in deep-sea mining, but virtually no deep soundscape baselines exist for Japanese waters. Here, we report baseline soundscapes from four deep-sea locations in Japan, including the Suiyo Seamount hydrothermal vent, the abyssal plain around the Minamitorishima Island home to manganese nodule fields and muds rich in rare-earth elements, twilight depths off Sanriku, as well as a typical bathyal system in Suruga Bay. Long-duration audio recordings were visualized and factorized by an unsupervised machine learning model, revealing differing characteristics among the habitats. Two locations near the coast are highly influenced by shipping noise. The Suiyo vent is characterized by low-frequency sounds from venting, and the abyssal Minamitorishima is quiet with a flat spectral shape. Noise from observation platforms is likely sufficient to alter soundscape characteristics, especially in offshore locations, suggesting offshore mining-targeted areas are susceptible to impacts from anthropogenic noise. We argue that the monitoring of soundscapes is an indispensable component for assessing potential mining impacts on deep-sea ecosystems. Our results establish reference points for future soundscape monitoring and assessment in Japanese waters as well as similar ecosystems globally.

Despite comprising over 75% of the world's biosphere (Angel 1997), the deep sea remains the last frontier on Earth—but it is far from untouched by humankind. From plastic debris to shipping noise, our activities have cast vivid shadows to the deep, evident even at the bottom of the Mariana Trench (Dziak et al. 2017; Chiba et al. 2018). Recently, surging interests in mining the deep for minerals to feed the ever-growing global needs have stepped our potential influence up to a new level (Van Dover et al. 2018; Smith et al. 2020). However, these resources also coincide with biodiversity hotspots hosting species that cannot live anywhere else. For example, hydrothermal activities produce seafloor massive sulfides and fuel lush chemosynthesis-based communities, cobalt-rich ferromanganese crusts occur on seamounts with cold-water corals, and manganese nodule fields are rare hard settlement substrates in the vast abyssal plain (Glover et al. 2018; Van Dover et al. 2018). Building effective environmental impact assessments in order to balance exploitation with conservation is critical (Clark et al. 2020), but we know too little about deep-sea ecosystems and mining is approaching too fast (Glover et al. 2018). There is a desperate need for observation methods that

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Additional Supporting Information may be found in the online version of this article.

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Author Contribution statement: All authors conceptualized the present study collaboratively. C.C., T.-H.L., H.K.W., and S.K. contributed to soundscape data acquisition. T.-H.L. and T.A. carried out data analysis. T.-H.L. and C.C. interpreted the results and drafted the manuscript. All authors contributed to the draft and approved the final submitted manuscript.

monitor the overall ecosystem health, widely applicable to different habitats and relatively cost-effective to implement (Levin et al. 2019).

Ocean sound is one such monitoring method, recently recognized as one of the Essential Ocean Variables by the Global Ocean Observing System (Miksis-Olds et al. 2018; Howe et al. 2019; Levin et al. 2019). Defined as the total sound of an area comprising those originating from biological (biophony), geological (geophony), and human activities (anthropophony), underwater soundscapes are an effective indicator and proxy of habitat quality (Piercy et al. 2014; Erbe et al. 2015; Guan et al. 2015), as well as the level of anthropogenic interference (Mooney et al. 2020; Duarte et al. 2021). As low-frequency sounds propagate for long distances (Munk et al. 1994), one or a few hydrophones are sufficient to cover the habitat noninvasively, and commercially available deep-sea hydrophones already exist at much lower costs than visual-based survey systems involving towed cameras or submersibles (Aguzzi et al. 2019). Monitoring underwater soundscapes has proven useful for ecosystem dynamics, including the spatiotemporal changes of geophysical events, soniferous communities, and anthropogenic activities (McWilliam and Hawkins 2013; Haver et al. 2020; Lin et al. 2021*a*). Soundscapes are further advantageous in generating time-series data, crucial for evaluating ecosystem resilience (Lin et al. 2015; Coquereau et al. 2017).

There is emerging evidence of extensive interaction between habitat-specific soundscape and biodiversity, especially as invisible signposts for larvae of marine animals to settle in their preferred environments (Stanley et al. 2010; Lillis et al. 2013; Eggleston et al. 2016). Marine benthic animals typically have two phases in their life—a bottom-dwelling adult stage and a pelagic, dispersing larval stage. For a species to thrive its larvae must be able to detect and settle in an appropriate habitat, a process we still know very little about, especially for deep-sea species (Sen et al. 2014; Mitarai et al. 2016; Yahagi et al. 2017). Different shallow-water ecosystems have distinct soundscapes due to environmental characteristics and communities of soniferous animals, which larvae are known to use as settlement cues (Lillis et al. 2013, 2018; Archer et al. 2018). The same mechanism has been hypothesized to be true for deep-sea animals (Crone et al. 2006; Lin et al. 2019).

Anthropogenic noise interferes with the health of marine organisms and therefore the ecosystem (Simpson et al. 2016; Wei et al. 2018; Popper et al. 2020). Loud anthropophony masks acoustic signals that marine larvae use for phonotaxis (Lecchini et al. 2018). To monitor changes in soundscapes, it is important to establish baselines of environmental sounds before the impacts occur. To date, relatively few soundscape baseline characterizations have been carried out at the deep seafloor (Dziak et al. 2017), but the fact that mining activities can severely

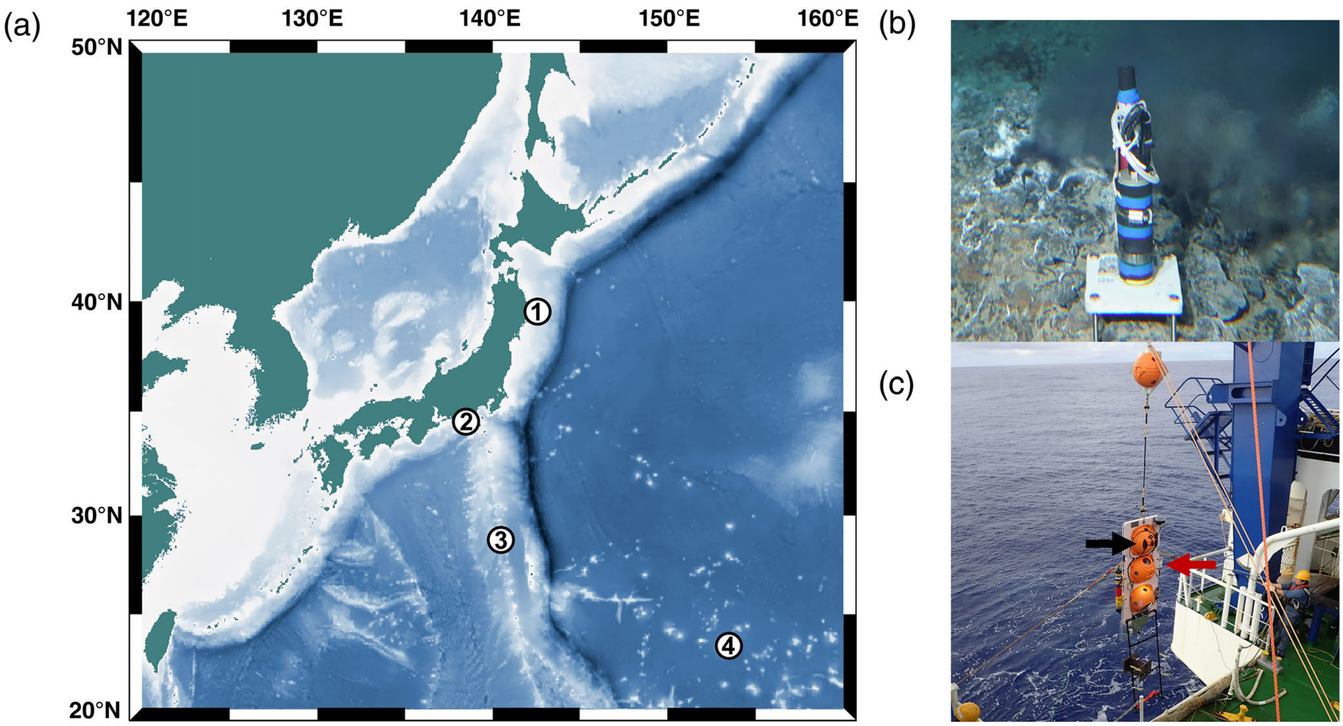

Fig. 1. Map showing the four deep-sea ecosystems surveyed and photos of deep-sea sound recording systems. (**a**) The four study sites are (1) off Sanriku, (2) Suruga Bay, (3) Suiyo Seamount, and (4) Minamitorishima Island. (**b**) Field deployment of the 2000 m rated recorder at the Suiyo vent field next to a vent orifice. (**c**) A 6000 m rated recorder fixed on the exterior of Edokko Mark 1 being deployed off Minamitorishima Island. Black and red arrows indicate the hydrophone and the recorder, respectively.

impact the local soundscape has been evident in oil and gas extraction—through both exploratory air guns and actual drilling (Hildebrand 2009; Kyhn et al. 2014; Wiggins et al. 2016).

Japan has become the world's first country to successfully undertake lifting of massive sulfides from active hot vents as well as ferromanganese crusts from seamounts (Okamoto et al. 2019), and has been eyeing the extraction of manganese nodules and rare-earth elements from the abyssal plain (Machida et al. 2016; Takaya et al. 2018). As such, characterizing deep-sea soundscapes in Japan is a matter of urgency, but no such baseline exists as of yet. In this study, we aimed to characterize the soundscapes of four deep-sea ecosystems around Japan (Fig. 1). This includes the Suiyo Seamount, an active hydrothermal vent on the Izu-Bonin Arc (Kasuga and Kato 1992), and abyssal plains off Minamitorishima Island with manganese nodule fields on muds highly enriched in rare-earth elements (Machida et al. 2016; Takaya et al. 2018). In order to test whether different deep-sea environments have distinct soundscape characteristics, we included two nearshore systems, one off Sanriku area, northern Honshu, in the twilight zone and one in the Suruga Bay, central Honshu, at a bathyal depth. We also aimed to evaluate the impact of anthropophony on the soundscapes, including operational noise of deep-sea exploration platforms.

Materials and methods

Deep-sea sound recording systems

Two types of underwater sound recording systems were used in this study. One type was designed to resist a pressure of 20 MPa, corresponding to a depth rating of 2000 m. This shallower type was composed of a DS-850 digital recorder (Olympus, Japan) sealed in a typical tube-like aluminum pressure-resistant container and the commercially available 2000 m rated deep-sea hydrophone AQH-020D (AquaSound, Japan). The DS-850 digital recorder has a depth of 16 bit and can record sounds with sampling frequencies up to 48 kHz. The AQH-020D hydrophone has a sensitivity of −195 dB re 1 V μPa^{-1} and a flat frequency response between 20 Hz and 20 kHz. A second, deeper, type was designed to withstand the pressure of 60 MPa, corresponding to 6000 m depth rating. This deeper system was based on an LS-P4 digital recorder (Olympus, Japan) sealed in a cylindrical, pressure-resistant titanium housing coupled with a commercially available 6096 m (20,000 ft) rated HTI-94-SSQ hydrophone (High Tech, U.S.A.). The LS-P4 digital recorder has a depth of 24 bit and can record sounds using sampling frequencies up to 96 kHz. The HTI-94-SSQ hydrophone has a sensitivity of −198 dB re 1 V μPa^{-1} and a flat frequency response between 2 Hz and 30 kHz. Both systems were tested for their designed pressure tolerance levels in a pressure chamber at the Japan Agency for Marine-Earth Science and Technology (JAMSTEC). Underwater sounds were recorded in uncompressed Waveform Audio File Format with sampling frequencies of either 44.1 kHz (DS-850 digital recorders) or 88.2 kHz (LS-P4 digital recorders). To better characterize the spectral characteristics of soundscapes in deep-sea benthic environments, we used the high-gain setting (equivalent to a power gain of 56 dB) and deactivated automatic gain control throughout all recordings.

Study areas and the collection of soundscape data

Field deployments of the abovementioned two types of underwater sound recorders were made by multiple deep-sea observation platforms between July 2019 and March 2020 (Table 1). After retrieving the recorders in each survey, we extracted the underwater sounds recorded at the seafloor for acoustical analyses.

In the active hot vent field inside a caldera on the summit of Suiyo Seamount, Izu-Bonin Arc, 2000 m rated recorders were placed on the seafloor using manipulators of the manned deep submergence vehicle (DSV) *Shinkai 6500* during the R/V *YOKOSUKA* cruise YK19-10. Being an active vent field, Suiyo Seamount is characterized by a lush chemosynthesis-based community dominated by invertebrate animals especially the vent mussel *Bathymodiolus septemdierum* (Kasuga and Kato 1992). Being approximately 700 km southeast of Tokyo, this is a relatively remote location. Three recording surveys were undertaken between four DSV *Shinkai 6500* dives. Between the first (#1549, 21 August 2019) and the second dives (#1550, 22 August 2019), the recorder was placed on an

Table 1. Summary of soundscape recordings. Total duration shows the length of underwater recordings when the recorders are deployed at the seafloor. Effective duration shows the length of underwater recordings without evident noise influence associated with the operation of deep-sea observation platforms.

Study area	Research vessel	Platform	Dates	Recording depth (m)	Total duration (h)	Effective duration (h)
Off Sanriku*	R/V *KAIMEI*	Free fall camera system	25 Jul 2019–05 Aug 2019	250–1011	64.5	29.3
Suruga Bay	Chartered boat	Edokko Mark 1	04–05 Nov 2019	1686	21.3	18.9
Suiyo Seamount*	R/V *YOKOSUKA*	Stand-alone, deployed by DSV *Shinkai 6500*	21–25 Aug 2019	994–1384	96.6	36.4
Minamitorishima Island	R/V *KAIREI*	Edokko Mark 1	14 Mar 2020	5500	15.2	13.8

*Multiple recording locations within the study area.

active diffuse flow location where venting with visible bubbling did not occur (28°34.2715′N, 140°38.6216′E, depth 1384 m). The next deployment between the second and the third dives (#1551, 23 August 2019) was placed outside the active vent, on the caldera rim (28°34.1438′N, 140°38.9641′E, depth 994 m). Finally, between the third and the last (#1552, 25 August 2019) dives, the recorder was placed right next to visibly bubbling venting orifice (Fig. 1b, 28°34.3288′N, 140°38.5758′E, depth 1381 m).

Minamitorishima Island marks the easternmost point of Japan, and at about 1800 km away from Tokyo, it is by far the most remote location of the four. As it is virtually uninhabited, there is limited shipping and traffic around the island. The Pacific abyssal plain around the island is covered in vast fields of manganese nodules (Machida et al. 2016). Below the seafloor, a rich reservoir of rare-earth elements enriched mud is present (Takaya et al. 2018); the nearby Takuyo-Daigo Seamount is known for high-quality cobalt-rich ferromanganese crusts (Nozaki et al. 2016). The abyssal biodiversity in the area remains under sampled and uncharacterized but is possibly similar to other Pacific manganese nodules fields such as those in the Clarion-Clipperton Zone (Wiklund et al. 2017). For recordings around the Minamitorishima Island, a 6000 m rated recording system was attached to Edokko Mark 1 (Type HSG), an all-in-one deep-sea monitoring lander system (Kawagucci et al. 2020) constructed by Okamoto Glass (Fig. 1c). Edokko Mark 1 was deployed on an abyssal nodule-covered area just east of Takuyo-Daigo Seamount (23°05′N, 153°50′E, depth 5500 m). This was done on-board the R/V *KAIREI* cruise KR20-01E, and the Edokko Mark 1 was deployed for 1 d on 14 March 2020. We attempted to record the full dive, from the moment of deployment to the retrieval on-board, but this was slightly cut short due to the limited storage volume (32 GB) becoming full after 15.4 h.

Recordings of the benthic habitats on the shelf and slope off Sanriku area in Tohoku region, northern Honshu was carried out in nine surveys on-board R/V *KAIMEI* cruise KM19-05C, between 21 July 2019 and 05 August 2019. The area surveyed was within an area enclosed by 39°02.3486′N, 39°24.1055′N, 142°08.2092′E, and 142°27.0315′E; the depth range was between 250 and 1011 m, primarily within the twilight zone (Supporting Information Table S1). Biodiversity off Sanriku area has been characterized as dominated by brittle stars covering muddy bottoms with sporadic appearances of various other animals (Yamakita et al. 2018). This area is close to land and populated areas, with considerable shipping activity. During each survey, one 2000 m rated recorder was fixed on a free fall camera system with fish bait. The free fall camera systems were deployed in the morning and retrieved in the afternoon due to system maintenance requirements.

Suruga Bay, located in central Honshu, is a classic "typical" locality for marine biology surveys in Japan (Fujikura et al. 2010). Being just next to highly populated cities in the Kanto area, it is an area where constant shipping occurs. Here, a 2000 m rated recorder was attached to Edokko Mark 1 and deployed on mud bottom at a bathyal depth of 1686 m in the central region of the bay (34°58.3952′N, 138°43.2089′E). Only one survey was conducted from 04–05 November 2019, and the dive was recorded in full, including the periods when Edokko Mark 1 was being deployed and recovered on-board.

Characterization of underwater soundscapes

Underwater sounds were visualized using long-term spectrograms (LTS). The LTS is a widely used plot that allows efficient visualization of the spectral and temporal variations in the audio data, especially long-duration recordings (Merchant et al. 2015). We only analyzed the frequency range between 20 Hz and 20 kHz herein, in order to provide comparable results between the two types of recording systems used. Initially, audio recordings were segmented into 1-min fragments. Then, each 1-min fragment was analyzed using discrete Fourier transformation (window length: 4410 for 44.1 kHz sampling rate, and 8820 for 88.2 kHz sampling rate, nonoverlapping Hamming window) to generate a magnitude spectrogram with a frequency resolution of 10 Hz and a time resolution of 0.1 s. Next, we measured statistical features in each frequency bin over the entire spectrogram to obtain power spectra that retain the spectral characteristics of each 1-min fragment. Last, the power spectra were transformed into log scale and consecutively combined to generate an LTS. Here, a median power spectrum was measured to represent each 1-min fragment. The use of median value will prevent the influence of high-intensity transient sounds, such as the noise produced when fishes interacted with baited cameras, and ensure the observed spectral shapes are associated with ambient sounds of the recording sites. Underwater sounds with occurring durations exceeding 1 min, such as shipping noise and the chorus of marine soniferous animals, were also visualized (Lin et al. 2021*a*).

Based on the median-based LTS, we manually annotated the audio segments containing evident noise generated from deep-sea observation platforms used. This included noise produced from research vessels, acoustic communication between the research vessels and the platforms, as well as the operational noise of DSV *Shinkai 6500*. The noise-associated data were separated to investigate the change of soundscape characteristics due to the operation of deep-sea observation platforms. The rest of acoustic data were used to analyze the spectral variation of baseline soundscapes by calculating the 1st to the 99th percentiles for each 10-Hz frequency bin.

Understanding the variations of acoustic components is crucial for evaluating how soundscapes vary among habitats (Kuehne et al. 2013; Lin et al. 2021*a*). To ensure the analysis of habitat-specific soundscapes reflects the spectral shape observed at each study area, we subtracted each power spectrum to the value recorded at 20 kHz, where a frequency has the lowest energy variation (Supporting Information Fig. S1). Despite that, multiple sound sources may be recorded simultaneously and increase the difficulty of acoustical analysis (Lin and Tsao 2020). In order to investigate the soundscape structure, we applied non-negative matrix factorization (NMF) in the analysis of median-based LTS. NMF is an algorithm for data decomposition alternative to principal component analysis (Lee and Seung 1999). It learns a set of latent factors (*W*) and their coefficients (*H*) that approximately reconstruct the input data (*V*):

$$V_{ij} \approx \sum_{r=1}^{n} W_{ir} H_{rj} \quad (1)$$

where i and j represent the frequency bins and time fragments on the median-based LTS, respectively, and n represents the number of factors desired in the decomposition of the median-based LTS.

A non-negative constraint was applied in the learning procedure so that the latent factors and coefficients are purely additive. The advantage is that the factorization result reflects the additive nature of sounds. As a result, sound sources hidden in a mixture spectrogram and their spectral features can be uncovered using the latent factors (Smaragdis et al. 2014). In addition, the coefficients of each latent factor reveal the source-specific changes in relative amplitudes. The capability of unsupervised feature learning without prior information specific to individual sources has made NMF a popular tool in tasks such as separating human speakers and musical instruments from a mixture of sounds (Lin and Tsao 2020). It has also been effectively used to separate biological chorus and nonbiological sounds from the spectral-temporal representations of long-duration audio (Lin et al. 2017, 2021a, 2021b).

The performance of NMF depends on the choice of rank (number of latent factors). This may be determined by prior expectations on the number of sound sources in the soundscapes. Due to the lack of such information, we used a computational approach to determine the optimal rank for the data set. Initially, we ran a series of NMF modeling by changing the rank from 1 to 10 and measured the root mean squared error (RMSE) of the reconstruction result. Then, we observed the evolution of RMSE to determine the rank. Based on the rank chosen, a set of latent factors and their temporal coefficients were obtained. The temporal coefficients were subsequently transformed into ratios to quantify the relative contribution of latent factors for each fragment of the median-based LTS:

$$H_{rj} = \frac{H_{rj}}{\sum_{r=1}^{n} H_j}. \quad (2)$$

Assessment of impacts from deep-sea observation platforms

In order to evaluate whether the noise generated from deep-sea observation platforms altered the soundscape characteristics, we used the learned latent factors as the prior knowledge of the soundscapes. At the beginning of the NMF modeling, temporal coefficients were initiated by random values. In the modeling procedure, latent factors were fixed, and only temporal coefficients were allowed to update for 200 iterations (Lin and Tsao 2020). Visualizations of underwater sounds and NMF modeling were performed using the MATLAB-based Soundscape Viewer toolbox (https://codeocean.com/capsule/7292152).

We combined the temporal coefficients associated with the operation of deep-sea observation platforms and those associated with deep-sea benthic environments. The entire set of temporal coefficients were analyzed by applying uniform manifold approximation and projection (UMAP). UMAP is a dimension reduction technique based on manifold learning (McInnes et al. 2018). It has been widely used to project high-dimensional data sets to low-dimensional spaces while preserving local and global structures of data representations, providing an informative visualization of data heterogeneity (Sethi et al. 2020; Thielk and Gentner 2020). If the pattern of temporal coefficients were significantly changed due to operational noises, then UMAP will project the data onto a different location. UMAP was performed using the Python package *umap*, using the default parameters.

Results

We collected a total of 197.6 h of underwater sounds from 14 surveys covering a depth range between 250 and 5500 m. After removing periods with evident interference due to platform operations, there were a total of 98.4 h of underwater recordings available for characterizing soundscapes of the deep-sea benthic environments. Details on the audio recordings collected at each of the four study areas were summarized in Table 1.

Spectral variations of median-based LTS showed that the soundscapes recorded off Sanriku and in Suruga Bay displayed a low-frequency spectral hump centered at 100 Hz, where sound pressure spectrum levels recorded were between 69.4 and 93.0 dB re 1 $\mu Pa^2 Hz^{-1}$. The spectrum levels displayed a downward shape in frequencies lower than 50 Hz and frequencies higher than 200 Hz (Fig. 2a,b). There were at least 30–60 dB increments at the frequencies of spectral hump compared to the spectral levels of 20 kHz. The spectral hump was mainly contributed by sounds from shipping activities, including a low-frequency tonal component and a U-shaped interference patterns at frequencies > 100 Hz (Fig. 3a,b).

The spectral variation of soundscape associate with the Suiyo Seamount vent site also showed a downward shape, but the spectral hump was not prominent (Fig. 2c). Instead, the Suiyo soundscape was dominated by sounds below 100 Hz, where spectrum levels recorded were between 66.3 and 93.7 dB re 1 $\mu Pa^2 Hz^{-1}$. Compared to the pattern observed off Sanriku and in Suruga Bay, the spectrum levels dropped in a much faster speed in the frequencies past

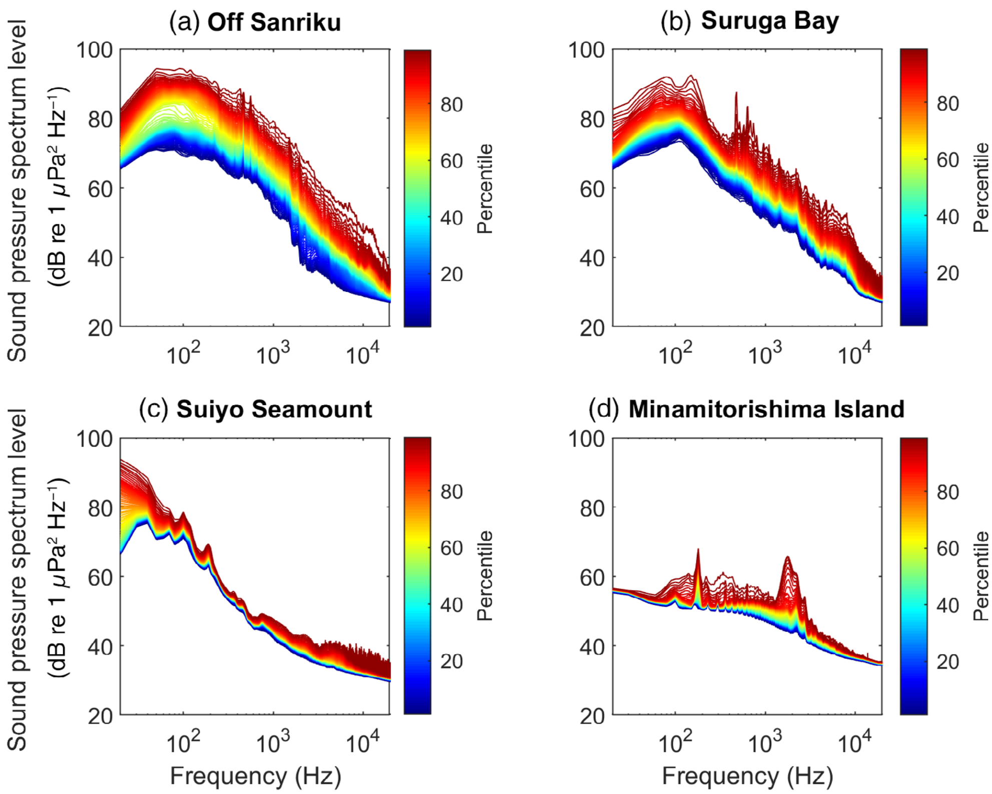

Fig. 2. Spectral variations of deep-sea soundscapes. Recordings from (**a**) off Sanriku, (**b**) Suruga Bay, (**c**) Suiyo Seamount, and (**d**) Minamitorishima Island. Only data without recordings of the operational noise generated by deep-sea observation platforms were analyzed.

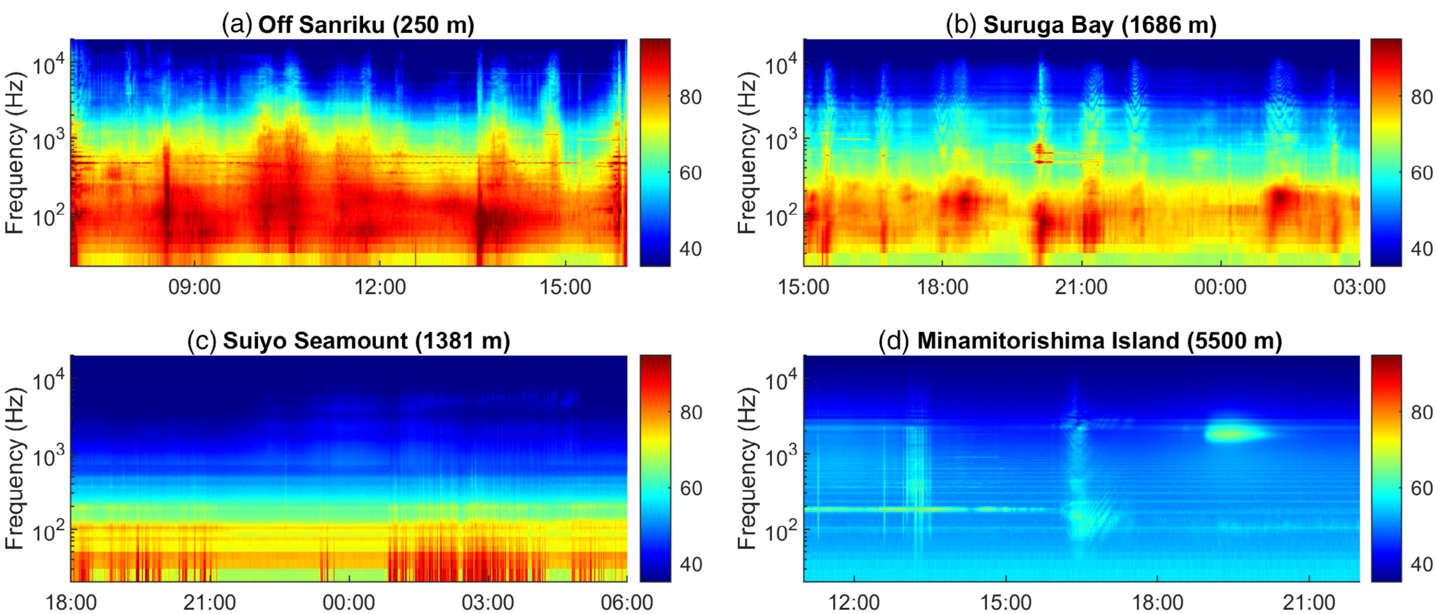

Fig. 3. Visualization of deep-sea soundscapes using the median-based LTS. Data show the recordings from (**a**) off Sanriku on 28 July 2019, (**b**) Suruga Bay on 04–05 November 2019, (**c**) Suiyo Seamount on 23–24 August 2019, and (**d**) Minamitorishima Island on 14 March 2020. Color bars indicate the sound pressure spectrum levels (dB re 1 μPa^2 Hz^{-1}).

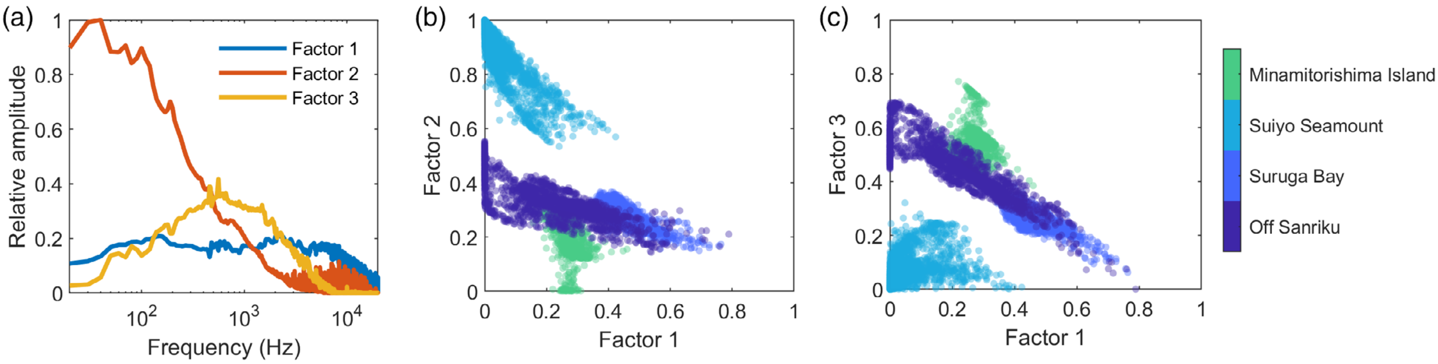

Fig. 4. Divergence of deep-sea soundscapes. (**a**) Spectral characteristics of the three latent factors learned from NMF. Distribution of coefficients associated with (**b**) the first and the second factors, and (**c**) the first and the third factors.

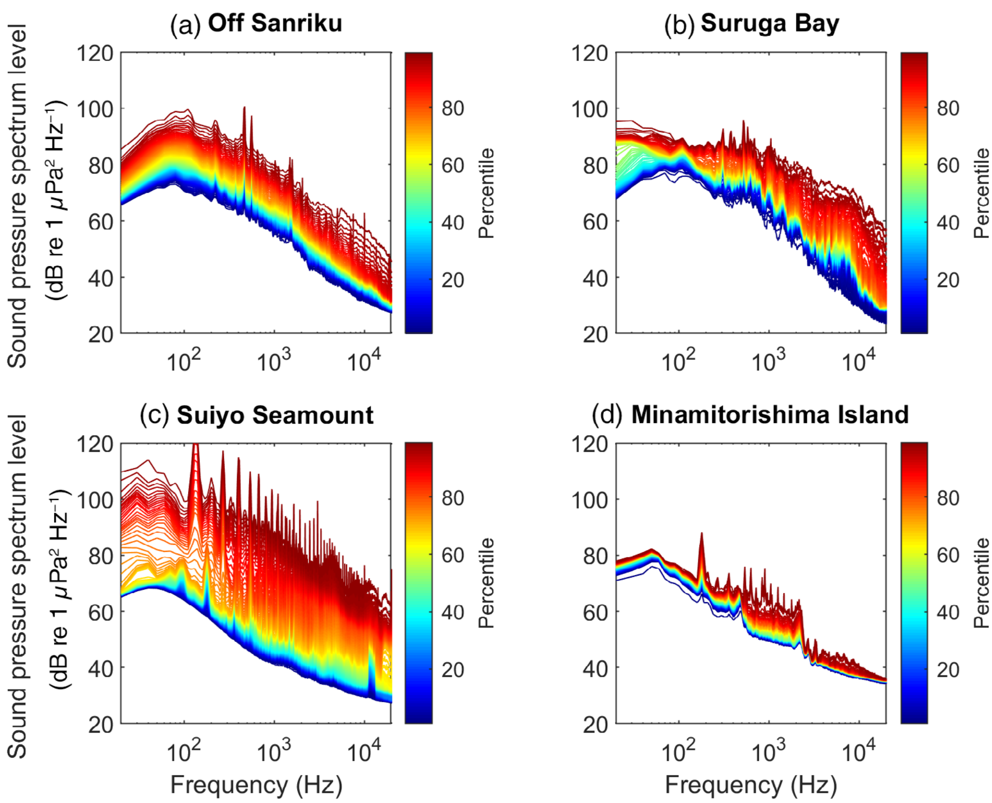

Fig. 5. Spectral variations of noise-impacted soundscapes. Recordings from (**a**) off Sanriku, (**b**) Suruga Bay, (**c**) Suiyo Seamount, and (**d**) Minamitorishima Island. Only the recordings presenting operational noise generated by deep-sea observation platforms were analyzed.

100 Hz. The LTS (Fig. 3c) indicated that low-frequency sounds comprised of narrowband tones (30–50, 70–80, and 100–110 Hz), with power levels 6–10 dB higher than the ambient level recorded within the caldera rim, and high-intensity broadband pulses (< 120 Hz), with highest power levels ~ 30 dB higher than the ambient level. Although these signals consistently occurred at the location next to the volatile venting orifice, they were not evident at the location without volatile venting and the caldera rim (Supporting Information Fig. S2). Therefore, these signals are interpreted as geophony associated with nearby venting activity.

The soundscape off Minamitorishima Island was distinctly different from the previous three sites. The spectral

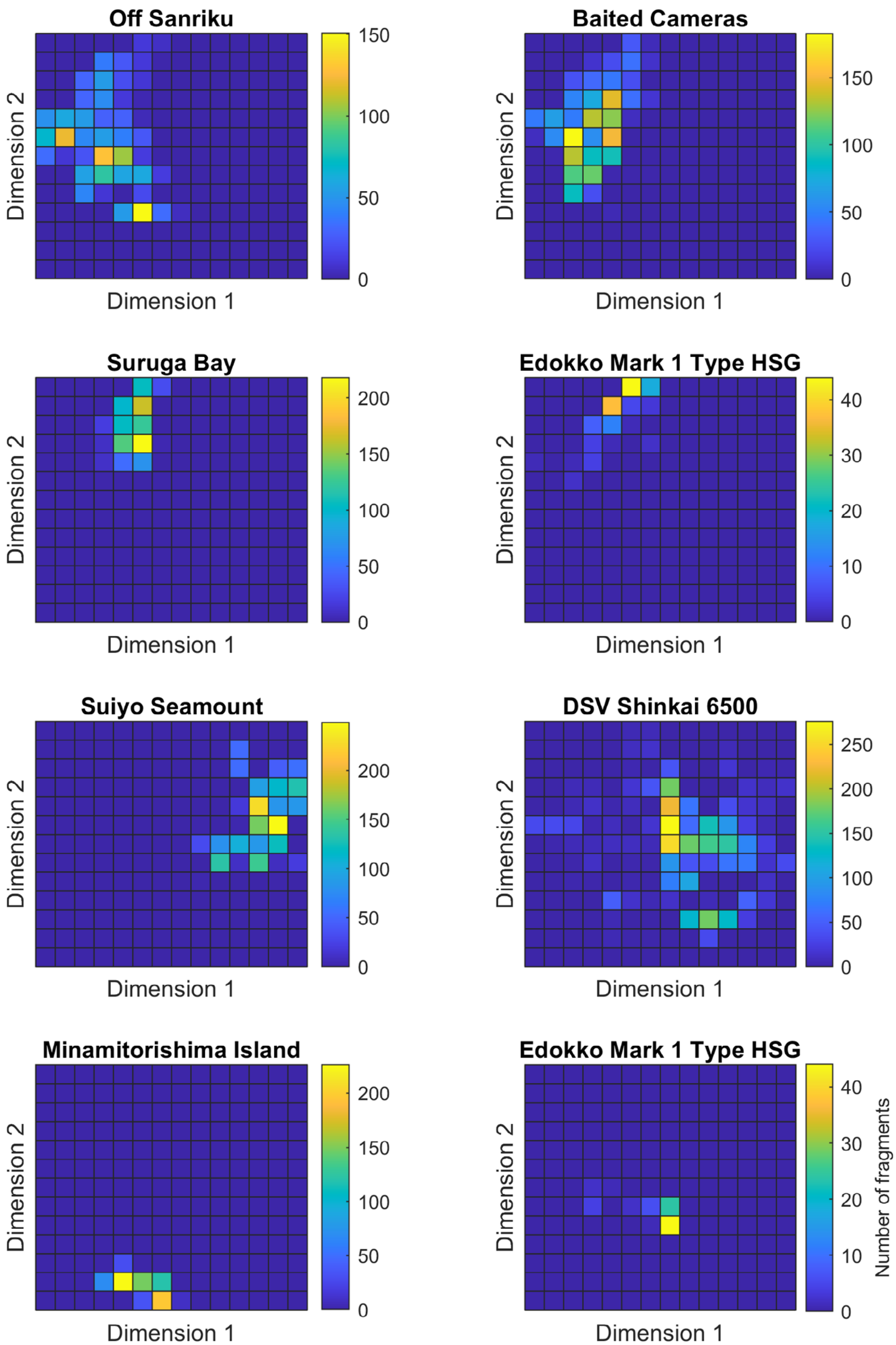

Fig. 6. Soundscape changes due to operational noise of deep-sea observation platforms. Coefficients of the three latent factors learned from NMF were projected onto a two-dimensional map using UMAP and subsequently transformed the map as a histogram. The histograms show the variation of baseline soundscapes of the four study areas (left panels) and the corresponding shift when the soundscapes were impacted by operational noise (right panels).

shape was relatively flat in frequencies below 1 kHz, and the spectral levels below 500 Hz were recorded between 49.7 and 61.1 dB re 1 μPa^2 Hz^{-1}, much lower than that observed at the other sites (Fig. 2d). Interestingly, we observed a chorus of soniferous marine animals with a spectral peak of 1.8 kHz and a bandwidth of 1 kHz on the median-based LTS. This signal was only detected from 19:00 h to 20:30 h (Fig. 3d).

Based on the analysis of reconstruction errors, we chose to use three latent factors in the factorization of median-based LTS, as the reduction of RMSE became less significant as the rank increased (Supporting Information Fig. S3). The three latent factors learned by NMF were characterized by a low-frequency component, a medium-frequency component, and a broadband component (Fig. 4a). According to the distribution plot of coefficients associated with the first and second factors, the low-frequency component represents a reliable acoustic indicator of Suiyo Seamount (Fig. 4b). The other two components contributed much less to the soundscapes recorded at Suiyo Seamount, compared to the other three study areas.

The distribution plot based on the first and third factors showed that the soundscape divergence at the three non-vent habitats was mainly due to the mixture of the medium and broadband components (Fig. 4c). In both off Sanriku and Suruga Bay, there was a negative relationship between the two components. While the medium component primarily contributed a major part of the soundscapes recorded off Sanriku, the soundscapes of Suruga Bay were mainly contributed by the broadband component. This pattern corresponded to the wider spectral hump of the soundscapes off Sanriku. For the soundscapes recorded near Minamitorishima Island, there was a small cluster with a high contribution from the medium component. Our manual investigation showed that this cluster was associated with biological chorus.

The soundscapes recorded during the operation of deep-sea observation platforms still maintained similar spectral shapes off Sanriku and in Suruga Bay. However, the noise produced from platform operations significantly changed the spectral shapes observed at Suiyo Seamount and on the abyssal plain near Minamitorishima Island (Fig. 5). By applying UMAP in the visualization of distributional changes in temporal coefficients learned using our NMF model, the variation was much wider, and the high-density region shifted when DSV *Shinkai 6500* was operating nearby. In addition, UMAP projected the audio data to an entirely different region when operating Edokko Mark 1 off Minamitorishima Island (Fig. 6).

Discussion

Disparity of deep-sea soundscapes among sites

Our results clearly show that different deep-sea benthic ecosystems possess distinct soundscape characteristics. The Suiyo hydrothermal vent is characterized by low-frequency geophony, and the abyssal manganese nodule field in Minamitorishima Island is relatively quiet with a flatter spectral shape. Since a large proportion of sounds originates from the sea surface and deteriorate toward deeper waters, it is not unexpected that the abyssal Minamitorishima Island is the quietest. Furthermore, we noticed the low-frequency soundscape off Minamitorishima Island was quieter than that at Challenger Deep, Mariana Trench. The acoustic data reported by Dziak et al. (2017) demonstrated a hadal environment influenced by numerous seismic activities, persistent shipping traffic, and the passing of a Category 4 typhoon, a pattern not found in the recordings collected off Minamitorishima Island. Due to the remote location of Minamitorishima Island and lower shipping activities around it, the discrepancy between the two acoustic data sets could imply the influence of anthropogenic and geophysical activities on deep-sea soundscapes.

The two near-coast sites we investigated, off Sanriku and Suruga Bay, were most similar to each other. In addition, difference in spectral shapes was not evident among the various recording locations off Sanriku (Supporting Information Fig. S4). As expected from their close distance to shore and primary shipping routes, both sites were heavily impacted by noise generated from shipping activities. Nevertheless, they were still discernible from the proportions of medium and broadband components. One factor that may explain this is the depth, as the acoustic energies attenuate before reaching the deep seafloor (Short 2005; Hildebrand 2009). As a result, soundscape of the deeper Suruga Bay displayed a lower contribution from the medium component. Other factors such as the geographical settings (insular slope vs. bay) and seasonal weathers (summer vs. fall) could also have altered the soundscape characteristics.

Soundscapes reveal potential vent-specific habitat cues

Among our recording sites, the Suiyo Seamount exhibited a unique acoustic source of hot vents. Sound of vents have previously been recorded on the Juan de Fuca Ridge (Crone et al. 2006) and an eruptive venting event on the NW Rota-1 volcano on the Mariana Arc (Chadwick et al. 2008). The dominance by low-frequency sounds in Suiyo is consistent with both previous recordings, reliably classifying the low-frequency sounds as geophony emitted from hydrothermal activities. Like the Juan de Fuca Ridge, the Suiyo hydrothermal vent generates narrowband tones and broadband pulses in the frequency range < 120 Hz, the former are likely influenced by the cavity size of vents. Broadband pulses are indicative of the scales of explosive eruptions, with potential mechanisms involving fluid heterogeneity and the volume changes associated with the cooling of hydrothermal fluid (Crone et al. 2006). Although the amplitudes of broadband pulses recorded at Suiyo are similar to Juan de Fuca Ridge ($\sim$ 30 dB above ambient level), they are not comparable to the explosive venting at the NW Rota-1 volcano ($\sim$ 50 dB above ambient level).

Japanese waters contain hydrothermal vents in two main regions, the Izu-Bonin volcanic arc where Suiyo is located, and the Okinawa Trough in a Back-Arc Basin setting (Fujikura et al. 2010; Mitarai et al. 2016). The biodiversity between vents of the two regions are distinctive (Watanabe and Kojima 2015; Watanabe et al. 2019) and even the few shared species exhibit drastically different abundances (Watanabe et al. 2020). Their larvae could potentially recognize the specific sounds associated with vents in specific regions. Many vents in the Okinawa Trough, for example, are characterized by boiling of the vent fluid (Ishibashi et al. 2015), expected to generate a unique acoustic signal (Crone et al. 2006). It remains unclear how much biophony vent animals produce but lately even soft-bodied invertebrate animals have been found to make loud sounds (Goto et al. 2019) and biophony generated by the different underlying biodiversity may contribute to region-specific sounds. The potential for such region-specific soundscapes within the same habitat type to drive biogeography is an exciting possibility that has not been considered in the deep sea.

The disparity between Izu-Bonin and Okinawa vent environments makes Japan an excellent candidate for future research toward understanding the relationships between soundscapes and larval settlement in the natural deep ocean. One avenue would be to compare biological communities (Nakajima et al. 2014) and soundscape signatures among vents in the two regions to test if soundscapes can explain the disparity in community composition. Another would be to deploy larval traps (Mullineaux et al. 2010) at locations with different sound levels, to test if the amount of settling larvae follows an acoustic gradient. With signatures and absolute sound levels in Suiyo presented herein, similar future data for an Okinawa vent would be most useful.

An indispensable component for deep-sea conservation

We argue that the monitoring of deep-sea soundscapes will significantly improve our knowledge on ecosystem recovery and the associated impacts due to mining activities. Each habitat having distinctive soundscape baseline is congruent with the hypothesis that habitat-specific soundscapes potentially serve as "signposts" for larvae of deep-sea animals to settle (Lin et al. 2019), as is known for key shallow-water habitats like coral reefs and estuaries (Vermeij et al. 2010; Lillis et al. 2013). Mechanosensory receptors for hearing appeared early in the evolution of animals, and many aquatic fauna such as cephalopod mollusks and fishes including elasmobranch and teleosts are sensitive to sounds below 1 kHz, which is the dominant component of anthropogenic sources (Duarte et al. 2021). Since very little is known about settlement cues of deep-sea larvae, future efforts are urgently required to culture and carry out settlement experiments with larvae of deep-sea species. The soundscape data presented herein will be useful for future settlement experiments of keystone species, such as the substrate-forming *Bathymodiolus* mussels or siboglinid tubeworms in vents, as has been done with coral species (Lillis et al. 2018).

Two of the localities we investigated, namely the Suiyo Seamount vent and near Minamitorishima Island, are potential targets of deep-sea mining; baseline soundscapes before such exploitations will be critical in assessing the environmental impacts. Crucially, our results show that compared to the two coastal sites, soundscape characteristics of both Suiyo and Minamitorishima Island were significantly altered by the presence of research vessels and deep-sea research platforms such as DSV *Shinkai 6500* (Fig. 6). Although such research platforms are only present on a scale of hours to days and are unlikely to present immediate threats to the ecosystems, drilling and mining activities are expected to occur across months to years. If deep-sea larvae indeed use soundscape for settlement, deep-sea mining activities will likely generate anthropophony at a level that prevents them from perceiving such cues. As low-frequency sounds propagate over long distances (Munk et al. 1994), such impacts may extend to nearby areas, impacting either multiple island-like sites nearby (e.g., hydrothermal vents, seamounts) or a much wider area than that being physically mined (e.g., manganese nodule fields, rare-earth elements enriched mud).

Limitation: Recording duration

The main limitation of the present study is that due to the short deployments of the surveys in the present study, we were unable to characterize the long-term variability in the soundscape of each habitat. Deep-sea soundscapes exhibit temporal variabilities, as changes in wind speed and rainfall have been known to contribute the frequencies higher than 200 Hz (Erbe et al. 2015; Haver et al. 2020). Although the underwater recordings analyzed here were not collected in stormy weather, some discrepancies observed may be associated with seasonal conditions. Soundscapes may also be affected by diurnal and seasonal changes in anthropogenic and biological activities, which can only be revealed by long-term soundscape monitoring (Haver et al. 2017; Lin et al. 2021*b*). The short deployments could also be the reason that we did not detect many animal vocalizations. Although we detected one biological chorus off Minamitorishima Island, pinpointing the species responsible remains difficult. Moreover, this chorus could have also originated from pelagic organisms instead of benthos. As a next step, we will look to carry out long-term monitoring of key deep-sea habitats in order to explore these variabilities in different ecosystems around Japan, particularly those threatened by mining activities. Cabled deep-sea observatories have been providing important long-term monitoring data for decades (Aguzzi et al. 2019) and have high potential to be the basis for long-term soundscape recordings (Levin et al. 2019). Australia's Integrated Marine Observing System, for example, has provided soundscape data for twilight depths (Erbe et al. 2015). Although Japan used to maintain a deep-sea observatory in Sagami Bay, it has largely been retired (Nakajima et al. 2019). Using observatories to collect deep soundscapes around Japan will require new stations.

A more cost-effective alternative is the deployment of stand-alone landers capable of environmental monitoring over months or years. The Edokko Mark 1 system used herein (Kawagucci et al. 2020), for example, has a model for observations up to 1 yr (Edokko Mark 1 365). Carrying out soundscape recordings as part of routine monitoring on such platforms is more flexible, as they are not restricted by underwater power cables. Furthermore, the International Seabed Authority and countries worldwide are currently working toward a "Mining Code", a standard set of regulations for deep-sea mining that contains standards for environmental assessment and monitoring (Van Dover et al. 2018; Smith et al. 2020). If hydrophones and underwater recorders of sufficient specifications can be included as standard monitoring parameters, this would rapidly increase the baseline data available for deep-sea habitats over the coming years. Deep-sea ecosystems may be out of sight, but they can definitely hear us—let's not leave them out of our minds.

Data availability statement

The soundscape recordings used in the present study is available at Depositar, under the project entitled "Ocean Biodiversity Listening Project" (https://data.depositar.io/en/dataset/deep-sea-soundscapes-of-japan).

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Acknowledgments

We thank the captains and crews of R/Vs *KAIMEI* (cruise KM19-05C), *KAIREI* (cruise KR20-01E), and *YOKOSUKA* (cruise YK19-10) as well as pilots and technical teams of DSV *Shinkai 6500* and Edokko Mark 1 during the research cruises for their tireless efforts of data collection. We are grateful to Ken Takai, Tetsuya Miwa, Shinji Tsuchida, and Yoshihiro Fujiwara (JAMSTEC) for leading the relevant research cruises and for accommodating soundscape recordings in their cruise planning and execution. We thank the Research and Development Partnership for Next Generation Technology of Marine Resources Survey (J-MARES) and Okamoto Glass Co., Ltd. for operation of Edokko Mark 1 on-board the research cruise KR20-01E. Hiroyuki Yamamoto (JAMSTEC) is gratefully acknowledged for bringing together collaborative efforts among the authors. The cruise KM19-05C was supported by the research program on Tohoku Ecosystem-Associated Marine Sciences (TEAMS) of the Ministry of Education, Culture, Sports, Science and Technology (MEXT), Japan. The cruise KR20-01E and this work was supported by the Japanese Council for Science, Technology, and Innovation (CSTI), Cross-ministerial Strategic

Innovation Promotion Program (SIP) "Innovative Technology for Exploration of Deep-Sea Resources" (Lead agency: JAMSTEC). CC and HKW were supported by a Japan Society for the Promotion of Science (JSPS) Grant-in-Aid for Scientific Research under the grant code 18K06401. T-HL was supported by JSPS Grant-in-Aid for Scientific Research under the grant code 18H06491 and Academia Sinica. This is a *GACHIKO* Cruise Episode #1 (YK19-10) output. The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript. We are grateful to the reviewers for providing constructive comments, which improved an earlier version of this manuscript.

Conflict of Interest

None declared.

Submitted 22 February 2021
Revised 05 June 2021
Accepted 01 August 2021

Associate editor: James Leichter