SUPPLEMENTARY MATERIALS FOR

PMEL PASSIVE ACOUSTICS RESEARCH

QUANTIFYING THE OCEAN SOUNDSCAPE FROM WHALES TO WAVE ENERGY

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INTRODUCTION: ADDITIONAL ACOUSTICS PROGRAM BACKGROUND

Program History

NOAA began early investments in underwater acoustic research following the discovery of seafloor hydrothermal vent systems along the Galápagos spreading center in the late 1970s, when PMEL began a program using NOAA ships for multibeam surveys of Northeast Pacific mid-ocean ridges (Malahoff et al., 1982). In 1984, PMEL formed the Vents Program (Hammond et al., 2015) to quantify hydrothermal systems and their distribution along the Juan de Fuca Ridge (JdFR) system, a ~1,000 km-long spreading center off the Pacific Northwest coast. A key goal of this program was to develop hydroacoustic-based methods to detect, both remotely and in real time, seafloor volcanism and associated hydrothermal activity along the entire JdFR (Fox et al., 1995). The use of hydroacoustic methods was began with 1960s research at the University of Hawai'i designed to detect seafloor earthquakes using a Pacific Ocean-wide military hydrophone array then used to locate missile impacts on the ocean surface (Johnson et al., 1963).

In the early 1990s, at the end of the Cold War, PMEL began a collaboration with the US Navy to access real-time underwater acoustic data from the cabled hydrophone arrays deployed across the North Pacific (Dziak et al., 2011). PMEL's goal was to use this unique deep-ocean listening array to detect otherwise unobserved submarine volcanic activity along the JdFR system. This "swords to plowshares" project resulted in several scientific breakthroughs, including the first real-time detection of a crustal magmatic intrusion and subsequent seafloor volcanic eruption at a mid-ocean ridge (Dziak et al., 1995; Fox et al., 1995). This was accomplished through the remote tracking of seismo-acoustic earthquake signals using this wide aperture (hundreds of kilometers) sound-channel hydrophone array. The intrusion of magma at a mid-ocean ridge is the fundamental process for ocean crust creation and the driving mechanism of global plate tectonics. However, these mid-ocean ridge eruptions typically produce intense, low-magnitude earthquake activity that is very difficult to detect using land-based seismological stations.

UNDERWATER ACOUSTIC TECHNOLOGY DEVELOPMENT: ADDITIONAL INFORMATION

Autonomous Hydrophones—Shallow and Mid-Water

The single, ceramic hydrophone model used is an ITC-1032, which is omnidirectional with a nominal sensitivity of −192 dB re 1 V- µPa^{-1}. An internal battery pack powers the filter/amplifier, the clock, and the processor, called a CF2 (Persistor Instruments). The instrument continuously records at a sampling rate of 1 kHz with 16-bit resolution. The pre-amplifier has an eight-pole anti-aliasing filter at 400 Hz and has a filter curve to equalize the spectrum against typical ocean noise over the pass band (e.g., Dziak et al., 2019). Typically, we use either a microprocessor-controlled, temperature-correcting crystal oscillator with an average time drift of 1.95 s yr^{-1} (for multi-year deployments) or a low-power cesium atomic clock with an average time drift of ~0.1 s yr^{-1} (when the hydrophone will be recovered and data analyzed within a year or less). The hydrophone electronics can be housed in either titanium or fiberglass-composite pressure cases depending on whether they are intended for deep, sound channel deployments (400–900 m) in temperate to polar regions or for relatively shallow (<100 m) coastal research. Arrays of these moorings can also be efficiently deployed from a regional class oceanographic vessel.

Full-Ocean Depth Hydrophone

The Full-Ocean Depth Hydrophone (FODH) has a flat response under 1 kHz and internal high-pass filters with roll-off frequencies of 7 Hz. It also has a built-in signal-conditioning amplifier with a gain of 7 dB, which makes the hydrophone sensitivity −175 dB re 1V/µPa. With the hydrophone filters and variable frequency pre-amp gain, the system's noise floor is below the Wenz (1962) sea state 0 sound levels up to 10 kHz. Lastly, all pressure-sensitive components, including the hydrophone, were successfully tested at the equivalent of 11 km hydrostatic pressure prior to deployments at the Deep Sea Power and Light (San Diego, California) facility in below-ground battleship gun barrels.

LARA, RAOS, and CRAB Buoys

During test deployments of the Long-term Acoustic Real-time sensor for Polar areas (LARA) system, the passive acoustic module (125 kHz sample rate, 16-bit resolution) recorded wind speed, related ambient sound, and various biological signals that included fin, humpback, and sperm whales sounds and the calls of Pacific white-sided dolphins. The system is capable of one profile per day for one year, making it suitable for collecting high-resolution water-column data in the extreme weather and water conditions of the Arctic.

Following LARA, the next step in our development of near-real-time systems is the RAOS, or Real-time Acoustic Observing System (Matsumoto et al., 2016). The system consists of two modules: (1) a seafloor mounted, passive-acoustic module (62 kHz sample rate), and (2) a surface buoy that receives information on acoustic detections via an underwater acoustic modem link, then relays this information to shore via Iridium satellite. The RAOS system was designed to detect the calls of killer whales (*Orcinas orca*) but was used in an ambient soundscape study at a wave-energy device test facility off Newport, Oregon (Haxel et al., 2016). The RAOS was deployed at 60 m water depth, where it recorded high sea-state conditions as well as snapping shrimp sounds and dolphin clicks.

PASSIVE ACOUSTICS SCIENTIFIC RESEARCH: ANTHROPOGENIC SOUND

Additional Information on Ambient Sound During the COVID-19 Pandemic

The impact of the COVID-19 pandemic on global commerce resulted in an observed reduction of ocean sound levels by ~1–2 dB due to decreased container ship traffic (Thompson and Barclay 2020; Dahl et al., 2021). To investigate potential changes in ocean ambient sound in the Northeast Pacific, we analyzed acoustic data from four PMEL moored autonomous underwater hydrophones (AUHs), including Ocean Noise Reference Station Network sites at Ocean Station Papa and the Olympic Coast National Marine Sanctuary and in the Beaufort Sea as well as at Axial Seamount. Using data sampled between summer 2018 and fall 2020, we quantified weekly median sound levels in the 63 Hz and 125 Hz one-third octave bands, the main frequency bands of commercial ship noise. The results indicate these sites also exhibit a 1–2 dB (~10%–30%) decrease in sound levels during spring-summer 2020 as compared to 2018–2019, consistent with the previous studies (Dziak et al., 2022). However, the reduction in ocean sound levels during the COVID-19 pandemic are not as low (by 2–4 dB) as observed at shallow water sites during the 2007–2010 economic recession (McKenna et al., 2012) and following September 11, 2001 (Rolland et al., 2012).

Shallow Water and Glider Measurement of Ambient Sound Levels

Shallow water sound sources and levels are important to quantify because of the strong influence of human activities and their potential to impact sensitive coastal ecosystems. Haxel et al. (2013) used PMEL AUHs to measure year-long ambient sound levels (<100 Hz) in 50 m of water off the Oregon coast. Dominant sound sources include locally generated ship noise (seen in 66% of the hours in the record), breaking surf, wind-induced wave breaking, and baleen whale vocalizations. Additionally, noise radiated from distant commercial ship traffic increased spectral levels in the 35–100 Hz band.

Ocean gliders also offer a quiet and efficient platform for making ambient sound measurements in remote areas (e.g., Gulf of Mexico; Mellinger and Fregosi, 2019). Haxel et al. (2019) used a Slocum glider with an embedded passive acoustic data logger to record ambient sound along the outer continental shelf break off the Oregon and Washington coasts. Wind-induced surface wave breaking is a dominant contributor to sound levels <100 Hz in the region, as is near- (<50 km) and far-field radiated vessel noise. Thus, mobile gliders can be an effective means for characterizing surface wind conditions and spatiotemporal variation in ocean sound over a broad region. However, comparison of glider and fixed recorder measurements indicates that flow noise contamination does contribute to differences in spectral levels for frequencies <50 Hz (Fregosi et al., 2020).

Full-Ocean Depth Sound Levels

In 2015, we took on the technical challenge of making a recording of the ambient sound levels in the deepest spot of the global ocean, Challenger Deep in the Mariana Trench. We used a PMEL-built deep-ocean instrument package, including a FODH and an RBR pressure-temperature sensor on a 45 m-long mooring. The mooring was specifically ballasted to descend at a slow 0.5 m s^{-1} rate to avoid rapid pressure changes that might damage the hydrophone element (Dziak et al., 2015). The hydrophone recorded continuously for 24 days at a 32 kHz sample rate, with the pressure logger registering a mooring depth of 10,854.7 m.

The successful deployment and recovery of this full-ocean depth hydrophone was, to our knowledge, the first multi-day, broadband record of ambient sound made at Challenger Deep and the deepest sound recording ever made (Dziak et al., 2017a). Also at the time, the pressure records provided only the fifth direct depth measurement made at Challenger Deep. Observed sound sources included earthquake acoustic signals (T phases), baleen and odontocete cetacean vocalizations, ship propeller sounds, airguns, active sonar, and a Category 4 typhoon. Overall, Challenger Deep exhibited 70–80 dB re 1u Pa^2 Hz^{-1} dB sound levels in the ship traffic band (20–100 Hz), reflecting moderate shipping due to nearby, persistent commercial and military ship traffic. The Challenger Deep sound levels of 40–60 dB re 1u Pa^2/Hz dB in the 500 Hz to 1 kHz band were due to sea surface wind and wave action related to sea states of 0–2.

The success of this deep ocean mooring system demonstrates the value of employing relatively low-cost ocean sampling methods (as compared to robotic or manned submersibles) to recover data from otherwise inaccessible deep-sea areas. Although this was a relatively short 24-day record, earthquakes, ship noise, and baleen whale calls seem to be a common component of the Challenger Deep soundscape. Additionally, it is clear that sea surface wind and wave noise caused by large storms can penetrate to the deepest parts of the ocean and dominate the ambient sound field. Our study indicates that Challenger Deep, the ultimate hadal (>6,000 m) environment, can be relatively quiet but is not as acoustically isolated as previously thought, and weather-related surface processes can influence the soundscape in the deepest parts of the ocean.

In 2020, we partnered with the private company Caladan Oceanic to once again deploy the FODH at Challenger Deep, but this time the hydrophone was mounted on a seafloor lander system deployed from R/V *Pressure Drop* (Ying-Tsong Lin, Woods Hole Oceanographic Institution and Victor Vescovo and Tim McDonald, Caladan Oceanic, LLC, *pers. comms*., 2020). The lander with hydrophone was deployed for three hours per day over a four-day period from June 21 to June 25. Objectives of the experiment were to characterize seabed geoacoustic properties at these extreme depths and to measure ocean sound levels during the pandemic when sound from nearby container ships was at a minimum. The acoustic records show that in the absence of shipping, ambient sound levels are dominated by sea state and wind speed, where stronger winds generate larger sea surface waves (Lin et al., 2021). As observed during 2015, Challenger Deep can be a very quiet spot, where average ambient sound levels were as low as 50 dB re 1μPa Hz^{-1} in the 0.1–1.0 kHz band during low sea states.

UN Decade of the Ocean – Ocean Shot

Underwater passive-acoustic researchers across NOAA are also part of a broad interagency working group, called the Ocean Sound and Marine Life Task Force, whose goal is to further passive acoustic research applications, facilitate intergroup communication, and work toward mitigating human-made noise impacts on marine animals and ecosystems. This effort was recognized as a United Nations-endorsed program under the UN Decade of Ocean Science for Sustainable Development (2021–2030; https://oceandecade.org/). Under these auspices, we have proposed an ambitious "Ocean Shot" (Dziak et al., 2020) that proposes to simultaneously deploy full-ocean depth hydrophones at the five deepest locations in the global ocean to measure the baseline "natural quiet" in what should be the quietest locations on Earth. This massive undertaking will require integrating expertise from industry, national and international governments, and non-governmental organizations as well as philanthropic organizations, and will likely take until the end of the 2020 decade to come to fruition.

GEOPHYSICAL SOUND

Additional Discussion on Hotspot and Arc-Volcano Research

It has been 83 years since the first seismo-acoustic detection of a submarine volcanic eruption—Kick'em Jenny in the Caribbean Sea. Since then, a total of more than 119 submarine volcanic eruptions have been detected using hydroacoustic methods (Tepp and Dziak, 2021), with roughly half of the observations detected at distances >500 km. The reported seismo-acoustic signals cover a wide variety of processes, including earthquakes, explosions, various types of tremor, signals related to lava extrusion, and landslides. Given the hazards submarine eruptions pose to society and the growing interest in mining near submarine volcanoes, an improved understanding of submarine eruption dynamics and continued technological development to improve our ability to detect submarine volcanic activity will be critical in the coming decades.

Shallow-Water Volcanic Eruptions

Other significant, shallow-water arc-volcanic eruptions have been recorded using AUHs in the previous two decades. Before its 2022 catastrophic explosion and resulting global tsunami (Poli and Shapiro, 2022), there was a major eruption at Hunga Ha'apai-Hunga Tonga volcano in the Kingdom of Tonga in 2009. Although the 2009 volcanic event was an order of magnitude smaller than the one in 2022, the hydroacoustic record shows clear seismic precursors, which allowed quantification of the total energy release during the two-day eruption (Bohnenstiehl et al., 2013). Beginning in December 2016, there was an 8.5-month long series of explosive eruptions at Bogoslof Volcano, a seamount whose summit forms a small island in the Aleutian chain. These eruptions produced multiple ash plumes reaching 2–12 km into the atmosphere, disrupting commercial air traffic (Tepp et al., 2020). Each eruption also produced explosion tremor signals whose acoustic magnitudes were linearly related to explosion plume height. This suggests that underwater acoustic records of explosions may be used to forecast the height of ash plumes during future eruptions.

Mid-Ocean Ridges

We also continued our hydroacoustic studies of mid-ocean ridge tectonic and volcanic activity, deploying hydrophones along ridges that exhibit a wide range of spreading rates, including the slow-spreading Bransfield back-arc basin (Antarctic Peninsula) and the equatorial Mid-Atlantic Ridge (Parnell-Turner et al., 2022), as well as the faster-spreading equatorial East Pacific Rise (Dziak et al., 2009) and the Central, Southeast, and Southwest Indian Ridges (Royer et al., 2015). Overall, the nature and rates of hydroacoustically detected seismicity rates vary wide widely across these ridge and transform systems, with high/low rates correlated with spreading rate, ridge-crest magma supply, and hydrothermal venting, as well as ridge segment symmetry and asymmetry. Significant magmatically driven accretionary events were detected at the East Pacific Rise (9°N; Tolstoy et al., 2008; Dziak et al., 2009), and there was an apparent rift-wide extension event at the Bransfield Strait in 2006 (Dziak, et al., 2010).

Estimating Seafloor Gas Flux

As climate change is the most pressing environmental issue of our time, we have also developed passive acoustic techniques to assess carbon and methane gas fluxes from a seafloor volcanic source in the Mariana Islands and a cold methane seep off the Oregon coast. Dziak et al. (2012) used PMEL AUHs to record degassing explosion sounds from a ~500 m deep erupting volcano and to measure explosive gas flux (primarily H_2O, SO_2, and CO_2). The annual CO_2 eruption flux was estimated at 0.4 ± 0.1 Tg a^{-1}, which represents ~0.2%–0.6% of the annual estimated output of CO_2 from all subaerial arc volcanoes. This study suggests submarine volcanoes can be a significant and sustained source of CO_2 to the shallow ocean.

Dziak et al. (2018) used a remotely operated vehicle to deploy a portable Acousonde 3B (232 kHz sample rate) within a 1,225 m seafloor methane bubble stream on the Oregon continental shelf. The acoustic signature of the overall bubble seep site, some of the first records obtained at a deep-water site, can be seen as broadband (1.0–45 kHz) series of short-duration (~10–20 ms) oscillatory signals that occur in clusters lasting 2–3 s. Acoustic estimates of bubble radii (consistent with video records of the bubble streams) allowed for volume estimates of ~21.4 ± 1.2 liters of methane gas released over a 3.75 min time period. These volume estimates are an order of magnitude larger than measurements made at shallow water (<150 m) sites (Salmi et al., 2011), which may be due to differences in environmental conditions or empirical techniques used.

Future Geophysical Acoustics Research

As our Pacific-wide moored hydrophone systems are recovered in 2023, we plan to further investigate the acoustic signatures of the massive 2022 Hunga Ha'apai-Hunga Tonga eruption and tsunami on recently recovered PMEL Pacific-wide hydrophones. Moreover, other submarine volcanoes in US territorial waters are also recently active (e.g., Ahyi in the Mariana Islands and Vailulu'u near American Samoa) and present hazards to nearby coastal communities. A potential means to mitigate these hazards is to deploy a hydrophone tethered to a surface buoy with a satellite antenna (e.g., the Coastal Real-time Acoustic Buoy, or CRAB) to enable near-real-time detection of resurgent volcanic activity.

BIOGENIC SOUND

Additional Background on PMEL Bio-Acoustic Research

Our analysis of North Pacific military hydrophone data in the 1990s demonstrated that, in addition to detecting seafloor volcanic activity, the hydrophone arrays also recorded bio-acoustic signals generated by the vocalizations of blue and fin whales (e.g., Stafford et al., 1999a). The spatiotemporal patterns of these signals (calls) provided a wealth of information on the seasonal population distribution of these endangered cetaceans. Thus, the military array data were the impetus for PMEL to develop in-house hydrophone technologies to further expand our marine mammal bio-acoustic research.

Over the last decade, we have used our moored hydrophones, profile floats, and gliders to study blue, fin, and other vocal baleen and odontocete cetacean species (e.g., right, Bryde's, sperm) in regions across the globe. This includes study of fin, blue, right, humpback, and sperm whales in the Gulf of Alaska (Mellinger et al., 2004; Stafford et al., 2007); blue, fin, Bryde's, and humpback whales in the eastern north and tropical Pacific (Stafford et al.,1999b, 2004; Heimlich et al., 2005; Fournet et al., 2018a,b; Fregosi et al., 2020); fin and beaked whales in the North Atlantic (Nieukirk et al., 2004, 2012; Matsumoto et al., 2013); fin and blue whales in the Atlantic basin (Haver et al., 2017); fin and sei whales in the European Arctic (Klinck et al., 2012; Nieukirk et al., 2020); Bryde's whales in the Mariana Islands detected using Seagliders and moored hydrophones (Nieukirk et al., 2016; Dziak et al., 2017a; Tepp et al, 2022); as well as blue whales in the Southwest Pacific and Indian Oceans (Balcazar et al., 2015, 2017; Samaran et al., 2013; Royer, 2015). We have also documented the acoustic seasonal presence of blue, fin, and minke whales, as well as leopard seals, in the waters off the Antarctic Peninsula (Mellinger et al., 2007; Dziak et al., 2010, 2015), in the Ross Sea and around the Balleny Islands (Yun et al., 2022; Dziak et al., 2017b), and we have made a comprehensive analysis of blue whale calls circum-Antarctica (Miller et al., 2021).

A curious bio-acoustic phenomenon has also been observed in recent decades in the Northeast Pacific (as well as globally), where the frequency of blue (A-B calls) and fin (20 Hz pulse) whale calls have been shown to be decreasing between ~0.17 Hz yr^{-1} and 0.32 Hz yr^{-1} (Weirathmueller et al., 2017; Malige et al., 2022; Rice et al., 2022). While many hypotheses have been suggested to explain this frequency shift, for example, increase in body size, global ambient noise due to shipping, climate change, or increases in abundance post-whaling (McDonald et al., 2009), no current theory accounts for all aspects of this phenomenon (Rice et al., 2022). Dziak et al. (2017c) presented a recent model of blue whale sound production that suggests calls are produced via passive, pulsed airflow in upper respiratory spaces rather than resonance of internal organs. This implies call frequencies could be actively modulated by baleen whales to center fundamental tones at different frequency bands during vocalizations.

CRYOGENIC SOUND

Additional Background on PMEL Cryo-Acoustic Research

Icequakes in the Bransfield Strait, Scotia Sea, and Balleny Islands regions show strong seasonal variability, reflecting the annual freeze-thaw cycle with most icequakes being detected during the austral summer months, likely due to increased thermal stress. This results in overall ambient sound levels being highest during austral spring and summer, as surface noise, ice cracking, and biological (whale call) activity intensifies. Moreover, Dziak et al. (2015) showed that peak mean sound levels (<100 Hz) directly correlate with wind speed, suggesting noise effects from wind are immediate and last only as long as wind is sustained.

In contrast to the West Antarctic Peninsula, seasonal sea ice sound patterns are not clearly observed in the Ross Sea, where frequent katabatic winds drive sea ice from the area, and icequakes from nearby ice shelves generate strong noise levels even in austral winters (Yun et al., 2022). Additionally, ambient sound levels can be as much as ~10–20 dB higher in the open, deep ocean of the Scotia Sea as compared to the relatively shallow Bransfield Strait (Dziak et al., 2015). This is likely due to the Scotia Sea being a deep-ocean site and exposed to sound sources throughout the Southern Ocean, whereas the Bransfield Strait is a shallow ocean basin enclosed by the Antarctic Peninsula and offshore islands.

To study the iceberg sound generation process in detail, we acoustically tracked the massive iceberg A53a (~55 × 25 km) as it sailed from the Weddell Sea and through the Scotia Seas (Dziak et al., 2013). As it first ran aground and pinwheeled in the shallows (~124 m deep) of Bransfield Strait, abrasion of the iceberg keel with the seafloor generated continuous harmonic tremor signals and icequakes with periods (~20 min) of total energy flux densities of ~252 dB μPa^2-sec, equivalent to the sound energy of ~214 supertankers operating over this same time period (Dziak et al., 2013). Lastly, once the iceberg was freed from the shallows, we detected and located a clear clustering of icequakes along the path of A53a as it sailed through the Scotia Sea. These icequakes were likely caused by the disintegration of the berg as it propagated northeastward through the ocean before impacting the South Georgia Island continental shelf.

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TABLE S1. NOAA PMEL Autonomous Hydrophone Deployments

GEOGRAPHIC LOCATION	YEARS DEPLOYED	SAMPLE RATE (Hz)	REFERENCE
Equatorial East Pacific	1996–2006; 2006–2008	100	Fox et al., 2001
Gulf of Alaska, East Pacific	1999–2001	500	Mellinger et al., 2004
North mid-Atlantic, South Azores	1999–2003; 2004–2005	100	Smith et al., 2002
North mid–Atlantic, Azores to Reykjanes	2002–2003; 2005–2007	100	Goslin et al., 2012
Mariana Islands	2003–2004	110	Dziak et al., 2005
Scotia Shelf – western North Atlantic	2004–2005	2,000	Mellinger et al., 2007
North New Zealand – Brothers volcano	2005–2005	250	Dziak et al., 2008
Antarctic Peninsula– Scotia Sea	2005–2009; 2019–2020	250; 1,000	Dziak et al., 2010
Central Indian Ocean	2006–2008	250	Royer et al., 2015
Southeast Greenland – Iceland	2007–2008	2,000	Mellinger et al., 2011b
Fram Strait – Atlantic Arctic	2009–2014	2,000	Klinck et al., 2012
Southwest Pacific – Lau Basin	2009–2010	250	Bohnenstiehl et al., 2013b
Equatorial Atlantic	2011–2015	250	Parnell-Turner et al., 2022
US Coastal Array – Ocean Noise Reference Network	2014–present	5,000	Haver et al., 2018
Mariana Islands – Challenger Deep	July–August 2015	32,000	Dziak et al., 2017a
Antarctica – Balleny Islands	2015–2016	1,000	Dziak et al., 2017b
Antarctica – Ross Sea	2015–2017; 2018–2019; 2020–present	1,000; 1,000; 2,000	Yun et al., 2021
Aleutian Islands – Bogoslof Volcano	2017	2,000	Tepp et al., 2020
Mariana Islands	2017–2018	1,000	Tepp et al., 2022
Antarctica – Amundsen Sea	2020–present	5,000	Currently deployed
Aleutian Islands – North of Adak	2022–present	5,000	Currently deployed