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Ambient Sound at Challenger Deep, Mariana Trench

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ABSTRACT. We present a record of ambient sound obtained using a unique deep-ocean instrument package and mooring that was successfully deployed in 2015 at Challenger Deep in the Mariana Trench. The 45 m long mooring contained a hydrophone and an RBR™ pressure-temperature sensor. The hydrophone recorded continuously for 24 days at a 32 kHz sample rate. The pressure logger recorded a maximum pressure of 11,161.4 decibars, corresponding to a depth of 10,829.7 m, where actual anchor depth was 10,854.7 m. Observed sound sources included earthquake acoustic signals (T phases), baleen and odontocete cetacean vocalizations, ship propeller sounds, airguns, active sonar, and the passing of a Category 4 typhoon. Overall, Challenger Deep sound levels in the ship traffic band (20–100 Hz) can be as high as noise levels caused by moderate shipping, which is likely due to persistent commercial and military ship traffic in the region. Challenger Deep sound levels due to sea surface wind/waves (500 Hz to 1 kHz band) are as high as sea state 2, but can also be very low, equivalent to sea state 0. To our knowledge, this is the first long-term (multiday to week) broadband sound record, and only the fifth in situ measurement of depth, ever made at Challenger Deep. 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.

INTRODUCTION

Challenger Deep is an 11 km long, 2.25 km wide, east-west trending basin located in the Mariana Trench, ~300 km southwest of the island of Guam within the territorial waters of the Federated States of Micronesia (Figure 1). Because Challenger Deep is the deepest point in the world ocean (10,984 m; Gardner et al., 2014), the extreme hydrostatic pressures there make obtaining even synoptic physical and biological measurements of the deep-sea environment difficult. Challenger Deep has, however, been the focus of renewed in situ exploration as exemplified by recent dives by both the Woods Hole Oceanographic Institution (WHOI) autonomous underwater vehicle *Nereus* in 2009 (Lippsett and Nevala, 2009) and James Cameron's solo dive in a manned submersible on March 26, 2012 (Than, 2012). Although many important scientific observations were made during these expeditions, rigorous ambient sound level measurements at these extreme ocean depths were not collected. Ambient sound measurements can provide insights into the health of a marine ecosystem by offering a picture of the diversity of vocalizing marine animals and a sense of what natural sources of sound contribute to the ocean soundscape, and they can help us gauge the impact of man-made noise in the deep ocean.

There have been other recent efforts to deploy deep-ocean moorings with sensor packages to probe the world's ocean trenches. In 2009, a team from Scripps Institution of Oceanography (SIO) deployed an untethered instrument platform equipped with a 30 kHz hydrophone (depth rated to 11 km), designed to record during controlled descent from the surface (Barclay et al., 2009). A series of descents were made with this instrument in the Mariana Trench (maximum depth of 9,000 m) and in the Philippine Sea (6,000 m), providing, at that time, the deepest ambient sound level measurements collected (Barclay et al., 2009; Barclay and Buckingham, 2010). Also, in 2010, researchers at the Lamont-Doherty Earth Observatory (LDEO) designed a deep-ocean seafloor seismometer and pressure case capable of surviving to extreme depths. The LDEO platform was deployed near Challenger Deep; however, seismo-acoustic sensors were not included in the test deployment (Maya Tolstoy, LDEO, *pers. comm.*, 2013). Thus, recordings of ambient sound levels at Challenger Deep remained elusive.

From July to November 2015, a team of National Ocean and Atmospheric Administration (NOAA), University of Washington, and Oregon State University scientists and engineers designed, built, deployed, and recovered a deep-ocean hydrophone and pressure sensor mooring at Challenger Deep. The goal of this project was to record ambient sound levels in this ultimate hadal zone environment in order to establish baseline sound levels in what was expected to be one of the most acoustically isolated ocean ecosystems.

This paper presents the 24-day-long hydrophone record of ambient sound successfully recorded at Challenger Deep, discusses the temporal character of the various natural and man-made sound sources, and compares the overall sound levels at Challenger Deep to global sound averages. We also present a direct pressure-based measurement of ocean depth made during the mooring deployment, one of only five direct depth measurements ever made at Challenger Deep.

EXPLORATION AND SOUNDSCAPE SIGNIFICANCE

Hadal zones at deep-ocean trenches are among the least explored environments on Earth. Research in these extreme environments is challenging, and scientific discoveries are limited by access to the few exploration vehicles that are capable of working at depths >7,000 m. Given the recent loss of the deep submergence vehicle *Nereus* (WHOI, 2014), exploration of these unique environments has turned to free-falling landers (SOI, 2014) and specialized deep-ocean moorings that remain stationary once they reach the seafloor (Dziak et al., 2015). Although this approach is constrained to discrete spatial sampling (point sampling) during each deployment, the ability to collect long-term information on time-varying physical and biological processes enables baseline characterization of the environmental conditions and marine ecosystems at hadal zones (Taira et al., 2004).

The ocean is nearly transparent to low-frequency sound, and even weak sound signals can propagate over long distances with little loss in signal strength (Munk, 1994). The term "soundscape" is used here to describe the acoustic sources and signals that are present at a particular location and time; these sounds are typically broken into three broad source categories: biological, geophysical, and anthropogenic (Pijanowski, 2011). Moreover, man-made noise in the ocean is thought to have increased by a factor of three to four (or 9–12 dB) in areas near major shipping lanes since the 1960s, largely due to increases in vessel traffic transiting the world ocean and an increase in the gross tonnage of ships used in the modern shipping fleet (Frisk et al., 2003; Hildebrand, 2009). Sounds generated by anthropogenic activities such as shipping, oil and gas exploration, and military sonar can be harmful to marine mammals that rely on low-frequency sound to send and receive acoustic-based information. For example, studies show that increased sound levels from anthropogenic activities can hinder marine mammal communication (Hatch et al., 2012), alter communication behavior (Parks et al., 2012), change locomotive behavior (Goldbogen et al., 2013), and induce stress (Rolland et al., 2012). To what extent anthropogenic sounds might impact marine animals at hadal zone depths is largely unknown.

HISTORICAL BACKGROUND

In 1875, HMS *Challenger* became the first ship to fully explore the Mariana Trench, sounding the abyss with explosives that provided a depth estimate of 8,184 m (Gardner et al., 2014). In 1952, the HMS *Challenger II* crew used explosives, a hand-held stopwatch, and a wireline sounding machine to estimate the depth at 10,862 m (Carruthers and Lawford, 1952). Other noteworthy echosounder-based measurements ensued over the decades, including estimates of (1) 11,034 m from the research ship *Vityaz* (USSR) in 1957, (2) 10,933 m from R/V *Thomas Washington* (USA) in 1976, (3) 10,920 ± 10 m by R/V *Kairei* (Japan) in 1984, (4) and 10,903 m by R/V *Kilo Moana* (USA) in 2008 (Gardner et al., 2014). After comprehensive modeling, the latest, most thorough effort using echosounders occurred in 2011 from USNS *Sumner;* it yielded an estimate of the deepest point at 10,984 m ± 25 m (Gardner et al., 2014).

In contrast, there are, understandably, relatively few direct measurements of depth at Challenger Deep using in situ pressure sensors. The first direct measurement of depth occurred during the historic dive of the manned bathyscaphe *Trieste* in 1960. The *Trieste* crew, the first humans to visit Challenger Deep, used an onboard pressure sensor to measure a calibrated depth of 10,911 m (Piccard and Dietz, 1961). The next in situ measurement did not occur until 2002, when the Japan Agency for Marine-Earth Science and Technology (JAMSTEC) deployed the remotely operated vehicle (ROV) *Kaiko* (Therberge, 2008). The ROV recorded a depth of 10,896 m, again using an onboard pressure sensor; however, no claim was made that this was the maximum depth at Challenger Deep. The last direct depth measurement, prior to this report, was performed by James Cameron using his specially designed submersible *Deepsea Challenger*. The National Geographic Society (2012) reported that Cameron made a pressure-gauge-based estimate of 10,908 m. Again, no claim was made that this was the deepest point at Challenger Deep.

What is clear from these previous efforts is that it is very difficult to first find the exact spatial coordinates of the deepest location and then to make an accurate and precise measurement of the full ocean depth. Echosounder and multibeam sonar can provide only an averaged model of seafloor depth because the measurements are (1) made from a rolling and pitching surface ship, and (2) reliant on the accuracy of water-column sound speed models. However, in situ pressure measurements collected by a free-falling instrument package can also be driven away from the correct depth location by prevailing currents, and robotic and/or manned submersibles can drift from the intended location despite efforts to maintain position relative to the sea surface.

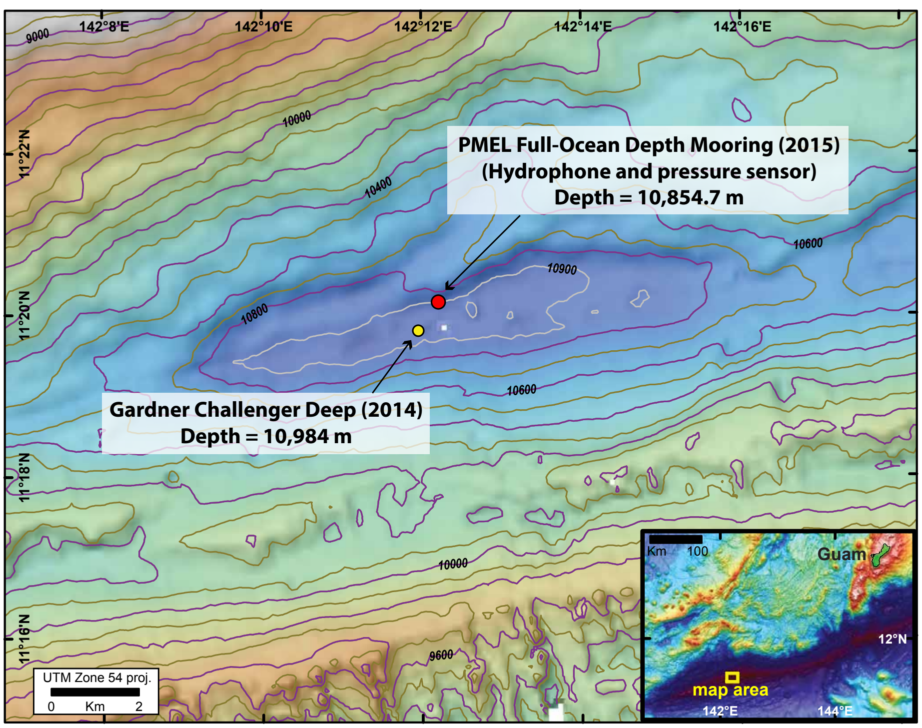

FIGURE 1. Bathymetric map of Challenger Deep, Mariana Trench (after Gardner et al., 2014). The inset shows map location relative to Guam (~370 km from Challenger Deep). The yellow dot shows the location of the deepest point estimated from bathymetry (Gardner et al., 2014). The red dot shows the surveyed location of the full-ocean depth hydrophone and pressure sensor mooring. *Map courtesy of S. Merle, NOAA/PMEL/EOI*

MOORING AND SENSOR DESCRIPTION

The Challenger Deep mooring (see online supplemental Figure S1) is 45 m in length and consists of a hydrophone instrument package, an RBR™ depth and temperature logger, and nine Vitrovex® glass spheres encased in plastic "hardhats." The glass floats are specially designed for 12,000 m depth operations. The hydrophone and pressure sensors are attached in a double-yoke frame to a 1 m long stainless steel rod shackled within the mooring for extra support. The top mooring assembly has an aluminum mast with a Xeos satellite beacon (GPS/Iridium transmitter) and a flag for visibility in surface recovery operations. Housed inside one of the two top floats is a redundant Xeos satellite beacon. This in-line system is attached to an anchor using a specially modified dual acoustic release package employed to increase the probability of recovery. The mooring is deployed from top to bottom using the anchor as weight to expedite its free-fall descent to the seafloor. For recovery, an acoustic release is triggered from the surface ship to detach the anchor and allow the platform to rise to the surface.

The NOAA/Pacific Marine Environmental Laboratory (PMEL) designed a hydrophone pressure housing capable of operational recording at full ocean depths (Figure 2a,b). The pressure case is made of 0.7 inch (1.8 cm) thick 6AL-4V titanium, allowing it to withstand the hydrostatic pressure at 15,000 m depth, providing a factor of 1.5 safety margin. The low-power-consumption hydrophone electronics are capable of continuous recording at a 32 kHz sample rate with 16-bit resolution, resulting in a three-week-long record of ambient sound. The data are stored on a 128 GB Compact Flash card, enabling rapid data transfer and backup upon recovery.

The hydrophone used for this study is a low-power version of the HTI92WB/PC, with a built-in differential output manufactured by High Tech Inc., Mississippi. It is an oil-filled pressure-compensated hydrophone with a nominal element sensitivity of −182 dB re 1V/μPa, which can withstand extreme high pressure up to 20,000 psi. It has a relatively flat response below 1 kHz with two internal high-pass filters: one is mechanical and the other is electrical. The oil is exchanged between the inside and outside of the ceramic element through an orifice that serves as a first-order mechanical high-pass filter with a roll-off frequency of 7 Hz. The second internal high pass is a resistor-capacitor (RC) filter formed by the capacitance of the element and the input impedance of the first stage amplifier with a roll-off frequency at 50 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. The sensitivity is omnidirectional at 13 kHz in an x-y plane. With the combined filters of the hydrophone and variable frequency gain of the pre-amp, the analog system's noise floor stays below the Wenz sea state 0 noise curve up to 10 kHz.

One caveat is that the hydrophone is sensitive to rapid changes in pressure, and its rate of descent/ascent should not exceed 5 m s^{-1} or there is a risk of damaging the ceramic element. To account for this, the mooring shown in Figure 2 was tested to ensure proper buoyancy versus weight compensation to achieve the optimum ascent/descent rates targeted between 0.5–1.0 m s^{-1}. The mooring system was tested in Puget Sound, Washington, in 200 m of water to confirm the vertical velocity specification. All pressure-sensitive components, including the hydrophone and the GPS beacon, were successfully tested at 11,000 m hydrostatic pressure at Deep Sea Power and Light (San Diego, California) prior to shipment to Guam.

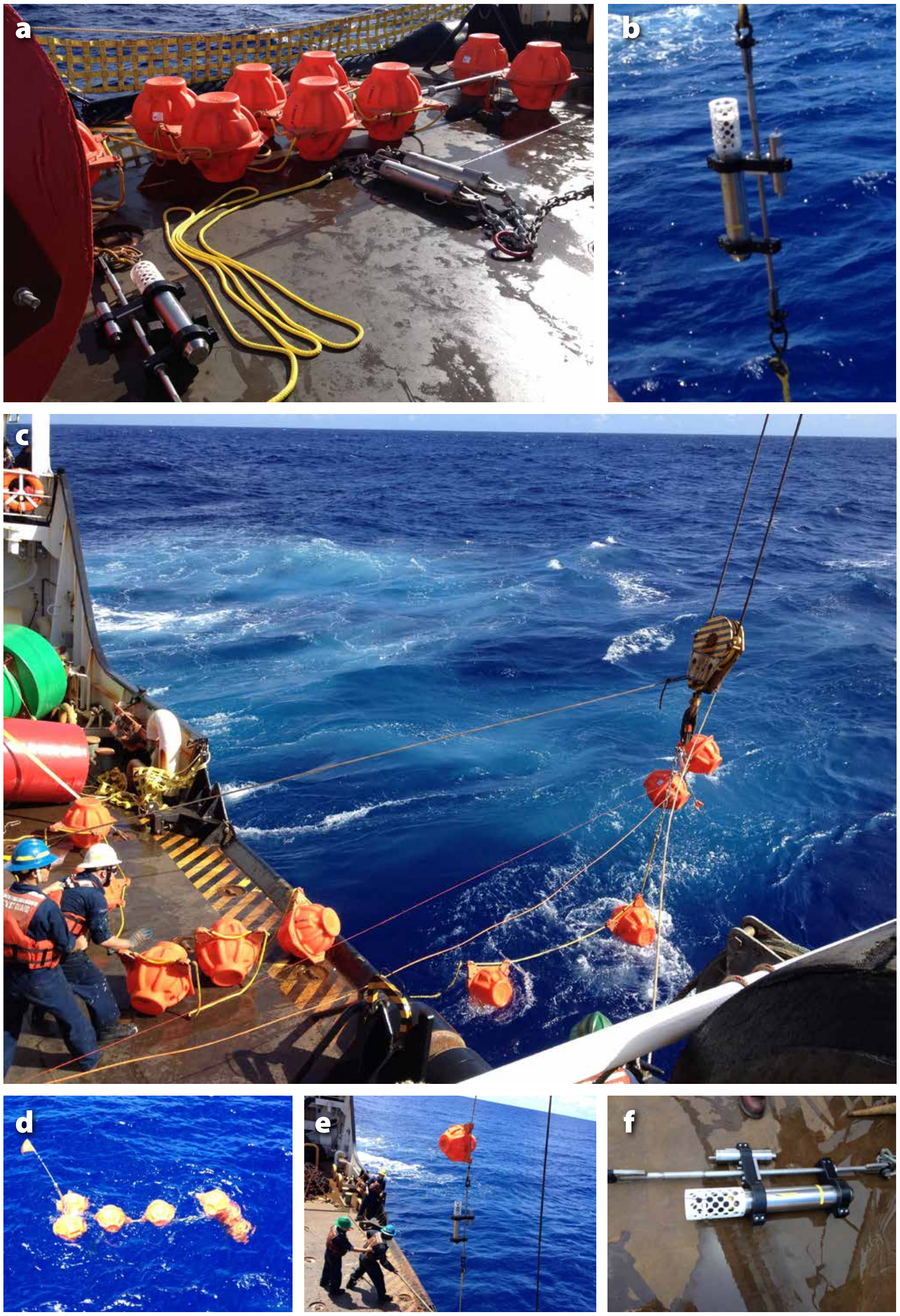

FIGURE 2. (a) Hydrophone and pressure mooring on deck of US Coast Guard Cutter *Sequoia*. Glass floats in orange plastic hardhats and the RF beacon mast are at the top of the picture, dual releases are located at middle right, and the hydrophone pressure case and pressure sensor, which are yoked to a 1 m long stainless steel rod shackled within the mooring, are at left. (b) and (c) Hydrophone and mooring being deployed using the ship's crane. The crane block is at the top of the image with floats below it. (d) Top of mooring (flag, mast, and floats) floating at the sea surface after release from the seafloor. (e) Recovery of sensors and float onto ship using crane. (f) Hydrophone and pressure sensor on deck immediately after recovery.

Mooring Deployment and Recovery

During July 20–23, 2015, the mooring was deployed from US Coast Guard Cutter *Sequoia*, which is based in Apra Harbor, Guam. The target deployment site, the deepest point identified by Gardner et al. (2014), is located in a relatively small basin within the main east-west-trending trough of Challenger Deep (Figure 1). A first attempt to deploy the hydrophone mooring there was made during January to March 2015. Despite difficulties caused by the presence of Typhoon *Mekkhala*, the mooring was successfully deployed and recovered. However, the hydrophone stopped recording once a depth of 1,700 m was reached, likely due to a faulty power unit (Dziak et al., 2015). The hydrophone problem was corrected, and a second deployment from *Sequoia* followed in summer 2015.

Once on site, ocean surface current speed and direction were estimated at 1 knot, moving from east to west. The ship was then positioned 1 km to east of the target deployment site for the anchor drop. The anchor and mooring were in the water at 10:00 Guam time (Figure 2c). Using an Edgetech 8011M deck unit and transducer, we were able to range to the specially modified Benthos 865A dual acoustic releases on the mooring as it descended through the water column at the designed rate of 0.6 m s^{-1}. With a water depth in excess of 10 km, it took ~6 hours for the mooring to reach the seafloor. As it descended, the acoustic slant range from transducer to release approached true water depth. The mooring stopped descending once a depth (slant range) of 10,752.61 m was reached; however, this estimate was based on assuming a sound speed of 1,500 m s^{-1} over the entire water column, which is somewhat slower than the expected sound speed at depth. The ship next circled the anchor drop location while several slant ranges to the mooring were collected. These ranges and GPS ship locations were then used to derive mooring location and depth using a simple nonlinear regression algorithm and an 11 km deep sound speed profile available on the MB-System seafloor mapping software website (Caress et al., 2015). Our calculations showed the mooring was located at 11°20.127'N, 142°12.0233'E. This location is roughly 1 km northeast of the target location of the deepest depth identified by Gardner et al. (2014; Figure 1). The bathymetric depth here is also consistent with the initial mooring survey depth of ~10,750 m.

The mooring recovery cruise, once again onboard *Sequoia*, took place during November 2–4, 2015, which was delayed from the original planned date because of another typhoon, *Champi*, that passed near the deployment site. On-site acoustic communication between the mooring and the transducer was excellent, even with the exceptional water depth. The mooring released immediately and began to rise to the surface at roughly twice its descent rate (~1.2 m s^{-1}), reaching the surface in ~2.5 hours. The satellite beacons transmitted as planned, and messages subsequently received provided the precise location of the mooring at the surface. The mooring was spotted at a distance of 1.5 km, with seven floats bobbing horizontally at the sea surface and the mast and flag extended vertically in the air (Figure 2d). The mooring was hoisted on board using the crane, and both instruments were found to be intact and undamaged (Figure 2e,f).

> "...the success of this deep-ocean mooring system demonstrates the value of employing the relatively low-cost ocean sampling methodology used here (as compared to robotic or manned submersibles) to recover data from otherwise inaccessible deep-sea areas."

SENSOR PERFORMANCE

Pressure and Temperature Data Loggers

In addition to the robust mooring and release performance, the RBR™ pressure and temperature sensors also performed as designed. The pressure data log shows the sensor was subjected to a maximum pressure of 11,161.4 decibars (see Figure S2). The sensor depth was then estimated from pressure using the Thermodynamic Equation of Seawater-10 (TEOS-10) relationships that can be derived from software routines available online to perform the calculations (IOC, SCOR, IAPSO, 2010). We simply input the Challenger Deep measurements of pressure in decibars, the measured temperature (2.45°C), and the practical salinity (34.6 ppt) at Challenger Deep available from the US Navy's Generalized Digital Environmental Model (Allen, 2012). The latitude and longitude location of the sensor are also required; we used the acoustically ranged location of the mooring while on the seafloor (11°20.127'N; 142°12.0233'E). However, the dynamic height anomaly and sea surface geopotential are typically ignored in the TEOS-10 model when converting between pressure and depth. These calculations resulted in a maximum depth estimate of 10,829.7 m. Because the sensor is 25 m above the anchor on the mooring, the actual anchor depth of the mooring is 10,854.7 m. To our knowledge, this is only the fifth in situ measurement of depth ever made at Challenger Deep.

There is, however, the question of what uncertainty should be assigned to this maximum depth estimate. McDougall et al. (2003) evaluated the TEOS-10 relationship's fit to the equation of state (e.g., Feistel and Hagen, 1995) over a range of pressures, temperatures, and salinity in the ocean water column. This region forms a polygonal shape of seawater referred to as an "oceanographic funnel," which represents a section of ocean with realistic parameters of environmental relevance from the sea surface down to the depth equivalent to a pressure of 8,000 decibars. The TEOS-10 funnel-test algorithm for the Challenger Deep depth measurement of 11,161.4 decibars well exceeds the maximum decibar funnel limit, which casts doubt on the absolute accuracy of our depth estimate as presented here. However, the TEOS-10 model does state that the uncertainty in depth estimates is up to 4 m at 5,000 decibars. This implies that the uncertainty in our depth estimate should be roughly twice this value, or ±8.9 m. The only other method to infer uncertainty is to use the manufacturer's estimate of sensor accuracy: ±0.05% for the full-scale depth at 11 km (https://rbr-global.com/products/sensors). This suggests an uncertainty of ±5.4 m at the sensor depth, which is less than the uncertainty from the model calculation.

Further analysis of the pressure record shows that there is a two- to three-week period during which the RBR™ gauge acclimates to the ambient pressure conditions. This acclimation period is seen in Figure S2 as the gradual, asymptotic decline in recorded pressure during the first 40 days of the total deployment, which, with the mean removed, levels off at a Δ depth of –0.5 m. Additionally, the spring-neap and semidiurnal tidal cycles at Challenger Deep are well resolved in power spectral density estimates of the pressure time series (see Figure S2, bottom), indicating that even at these extreme ocean depths, tidal processes dominate fluctuations in ambient pressure.

The temperature gauge on the RBR™ also showed that a maximum temperature of 28.4°C was recorded in the surface waters prior to deploying the anchor over the side of the ship, and a minimum 1.5°C was recorded for a short time as the mooring reached the seafloor. However, the seafloor temperatures then stabilized at 2.45°C for the remainder of the deployment.

Full-Ocean Depth Hydrophone

During the four-month deployment, the hydrophone operated successfully at full bandwidth (32 kHz) for 24 days (July 13 to August 6, as planned), including recording the full descent from the surface to 10,852 m while passing through a 25.9°C temperature range. Analysis of the hydrophone acoustic recordings reveals a number of interesting sound sources that contribute to ambient levels at Challenger Deep. A spectrogram of the entire 24-day recording period (Figure 3) is dominated by broadband seismo-acoustic energy from earthquake activity. The earthquake acoustic energy is focused under 4 kHz, but registers as high as 10–12 kHz. Additionally, anthropogenic sounds from surface vessels, baleen whale vocalizations, sperm whale clicks, and several odontocete whistles have been identified within the record. Detection of the whistles and clicks is somewhat surprising given the generally low source level of odontocete whistles (e.g., Au, 1993; Soldevilla et al., 2008); the expected high attenuation rates of these high-frequency signals, for example, roughly 0.5 dB km^{-1} at 10 kHz (Ainslie and McColm, 1998); and the fact that click sounds are unlikely to be directed at a sensor on the seafloor, as these clicks are more commonly emitted at small angles to the horizontal. Lastly, there is a clear increase in broadband sound levels beginning on August 1, 2015, that is sea surface wind and wave noise caused by the Category 4 Typhoon *Soudelor* as it moved from east to west through the region north of Saipan. This part of the record shows that weather-related surface processes can affect ambient sound levels and clearly influence the soundscape in the deepest parts of the ocean.

MARIANA TRENCH SOUND PROPAGATION, SOURCES, AND LEVELS

To aid in our analysis of the individual sound sources identified in the Challenger Deep record, we constructed acoustic ray trace propagation models of signal loss using the software Bellhop (Porter et al., 2011). Figure 4 shows three of these simulations for sea surface sound sources, directly overhead and to the north and south of the Challenger Deep location in the Mariana Trench. The propagation models indicate that in the deepest sections of the Mariana Trench there is likely a 10–15 dB

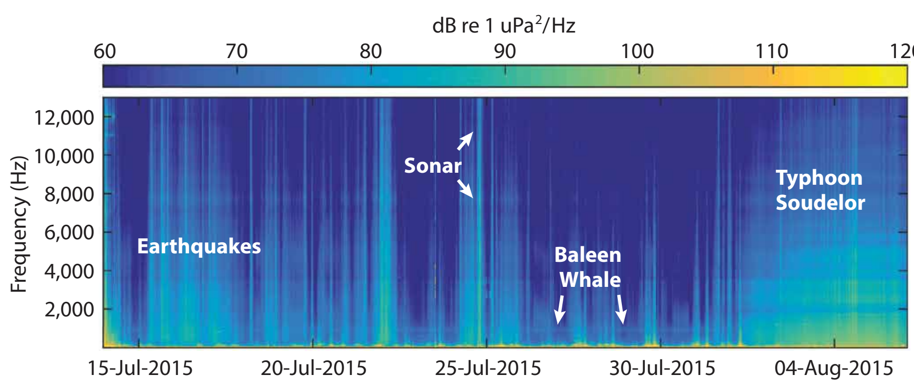

FIGURE 3. Frequency spectra of the entire 24-day recording period (1 Hz to 12.5 kHz bandwidth). Short-duration (several minute) bursts of broadband energy are from ocean crust earthquakes along the Mariana arc and trench. Relatively high-frequency energy on July 25 is from active sonar, which is short duration and in the 1 Hz to 10 kHz band. Broadband energy from August 2 to August 6 is wind and surface wave noise from Typhoon Soudelor (Category 4) near Saipan. Continuous, narrow-band frequency signals are ongoing vocalizations of baleen whales.

reduction in received level signal strength from sound sources generated north and south of the trench axis, where acoustic rays outside of the trench attenuate rapidly due to multiple seafloor-sea surface reflections. This observation is supported by previous acoustic studies at the Tonga Trench that showed the bottom of the trench is shadowed from surface noise by the trench walls (Barlcay and Buckingham, 2014). This implies that the sound sources comprising the baseline sound levels at Challenger Deep mostly derive from sources at the surface and/or in the water column directly above the basin. However, it also seems likely that seismo-acoustic energy from earthquakes occurring deep within the oceanic crust of the Mariana region will introduce acoustic energy into the basin via propagation paths through the trench floor or walls. The following sections describe in more detail the variety of acoustic sources recorded at Challenger Deep.

Geophysical Sources

The Mariana Trench is an active accretionary boundary where the Pacific Plate is being subducted beneath the Philippine Plate at the rate of 1.0–4.6 cm yr^{-1} (Smoczyk et al., 2013). Consequently, the Mariana Trench and the Challenger Deep are very seismically active regions and produce moderate-sized earthquakes ($m_b \geq 4$) that are detected by global seismic networks every few days. Thus, we expected the hydrophone would detect a significant number of earthquakes, especially given that the hydrophone was deployed in situ and therefore would detect much smaller magnitude events.

Figure 5a shows an example of the acoustic arrival (T-phase) packet from a body wave magnitude (m_b) 5.0 earthquake occurring 50 km northeast of Challenger Deep on July 16, 2015, 23:28 GMT. The main shock is followed by dozens of aftershocks that are readily observed within the record. This record is typical of T-phase signals from earthquakes recorded in the deep ocean, characterized by broadband energy (mainly focused <100 Hz), with signal durations of 60–120 s. The onset of a T-phase packet from a large earthquake will also usually exhibit a fast-propagating seismic phase (P wave) that has traveled entirely through oceanic crust. The P-wave signal is the low-frequency, impulsive signal that arrives ~10 s before the T-phase packet (Figure 5a). As noted earlier, the earthquake T-phase signal packets on the long-term spectrogram are very high frequency (≥10–12 kHz). Previous observations of seismo-acoustic energy are not nearly as broadband, being typically under 100 Hz (e.g., Wilcock et al., 2011). The high frequency of the seismo-acoustic energy observed here may be caused by the very close proximity of the hydrophone to these large earthquake sources and/or the high sample rate of the full ocean-depth hydrophone, which employs a sample rate not typically used for seismic studies.

Figure 5b shows a histogram count of earthquakes per day recorded on the Challenger Deep hydrophone. A total of 3,814 T-phase signals were detected during the 24-day recording period, with an average of 159 T-phase events detected per day. A total of 996 T-phase events had P-wave seismic arrivals associated with them, at an average of 41.5 P-wave detections per day. Typically, both P waves

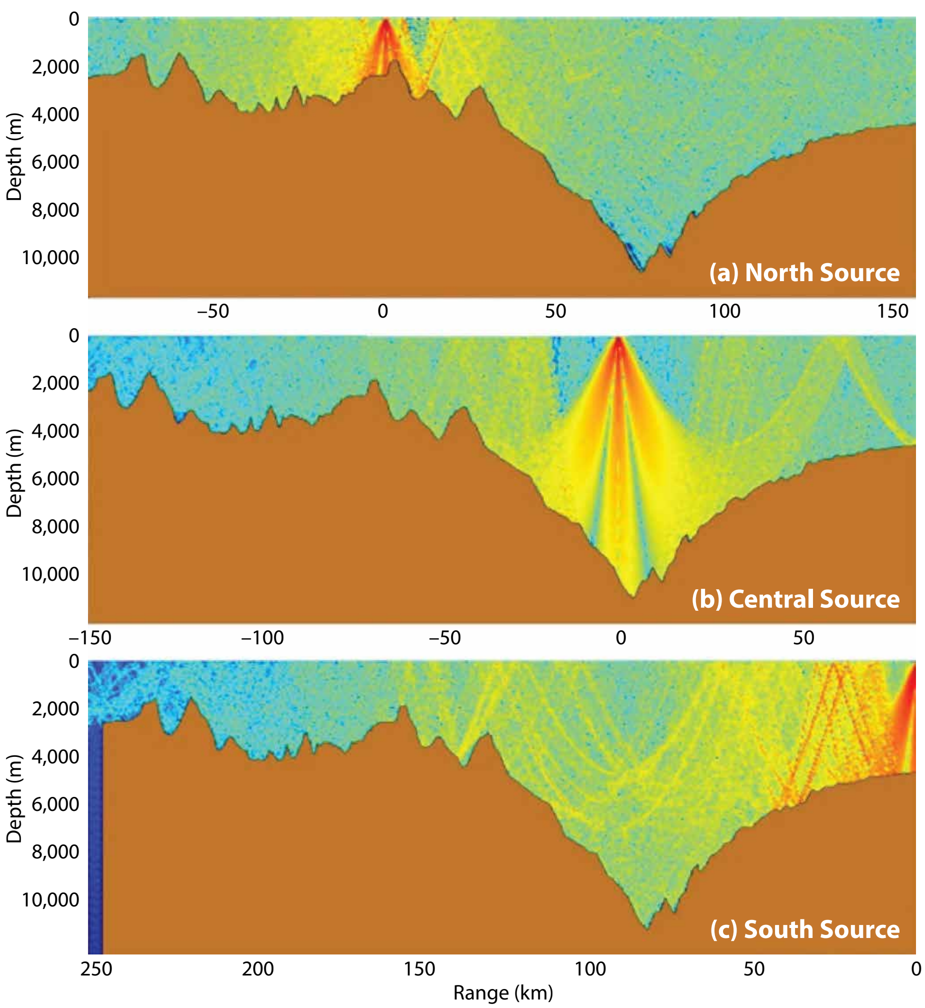

FIGURE 4. Ray tracing model simulations using the software Bellhop (Porter, 2011) with a 100 Hz source at 30 m depth (present near surface, water column source) from (a) north, (b) central, and (c) south of the Challenger Deep basin. Red is high energy, blue is lowest energy, representing a 60 dB relative transmission loss. Most of the energy from sound sources at the sea surface north and south of Challenger Deep is scattered prior to reaching the bottom of the trench, while acoustic energy from a source directly above the trench axis propagates to full basin depth. *Image courtesy of J. Caplan-Auerbach, Western Washington University*

and T phases are recorded from local and regional earthquakes. Large (m_b >7) global earthquakes will produce detectable P waves only (Dziak et al., 2004). At Challenger Deep, the majority of earthquakes detected during the recording period were local and/or regional events, while during the same time only a total of six large m_b 6.0–7.0 earthquakes occurred worldwide. Therefore, almost all earthquakes detected generated P waves and T phases, and the P-wave and T-phase counts are well correlated. Moreover, a search of the US national earthquake online database (https://earthquake.usgs.gov) shows that a total of 84 earthquakes of $3.9 \leq m_b \leq 5.3$ occurred within 1,000 km of Challenger Deep along the Mariana, Ryuku, and Philippine Trenches during the hydrophone deployment period. This implies the full-ocean depth hydrophone likely detected several hundred more earthquakes below the m_b 3.9 detection threshold of land-based seismic networks in the region.

Figure 5c shows received levels of T-phase signal packets. Because there are several earthquake-generated T-phase signals each day on the hydrophone record, we use the daily median of the received T-phase energy levels (peak to peak) to represent the overall earthquake-produced sound levels in the 1–100 Hz frequency band. The daily median levels range from 79.9 dB to 102.9 dB re 1 μPa^2/Hz during the 24-day recording period, with an overall median of 83.9 dB re 1 μPa^2/Hz. Also, there are several times during the 24 days when there are clear increases in the number of earthquakes and received energy levels: July 15, July 21, July 24, and August 1. All of these increased acoustic energy levels correspond to clusters of three to five m_b 4–5 earthquakes near the islands of Guam, Agrihan, and Farallon de Pajaros. We estimate the total acoustic received level of all T-phase signals recorded over the 24-day period to be 167.12 dB re 1 μPa^2/Hz. Thus, natural seismic energy is a significant contributor to ambient sound levels at Challenger Deep.

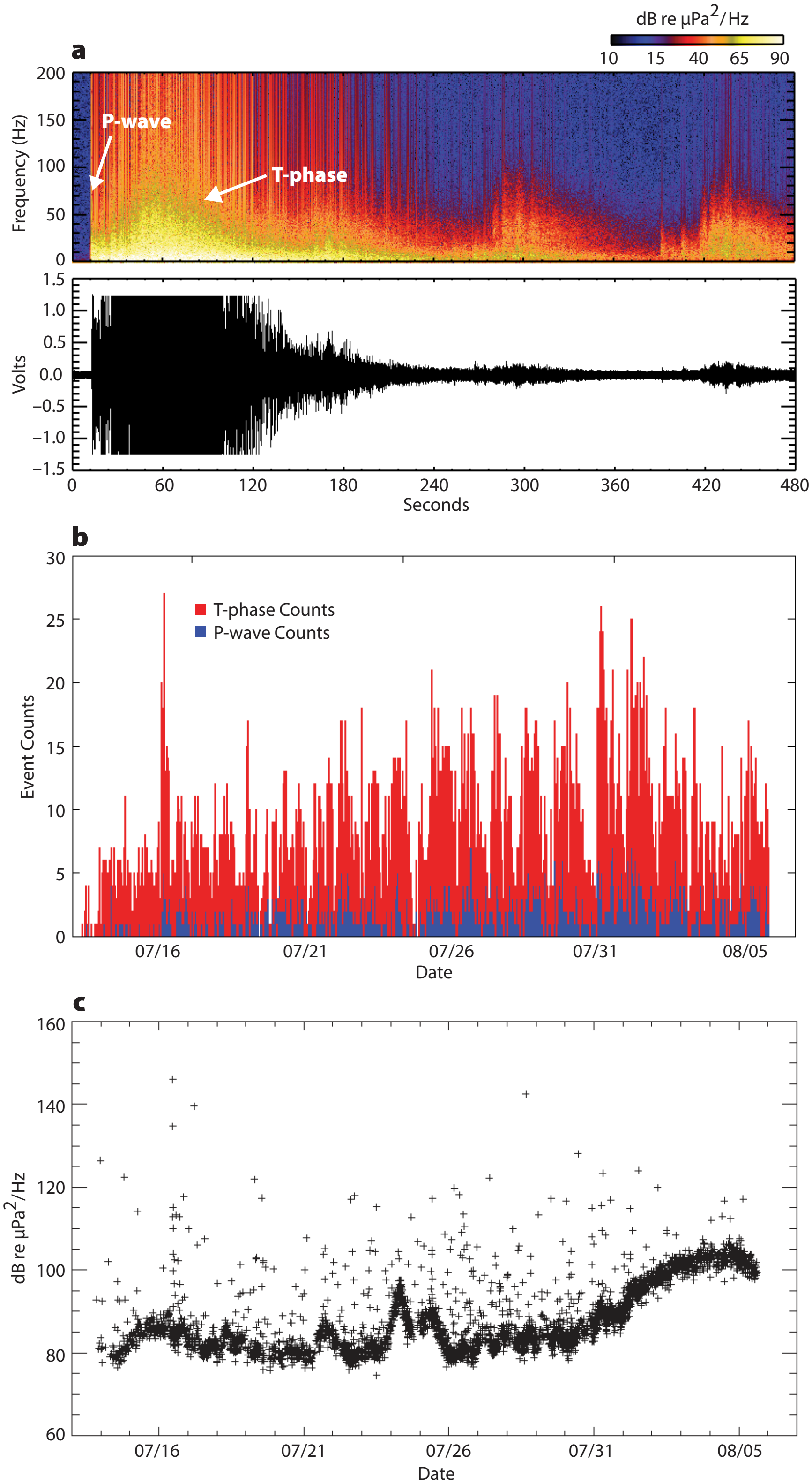

FIGURE 5. (a) Time-series and spectrogram of the July 15, 2015, 5.0 m_b earthquake located ~50 km northeast of Challenger Deep at 10 km depth. The impulsive, broadband first arrival is the direct seismic P wave; a long-duration emergent T phase can be seen arriving one to two minutes later. Four aftershocks associated with this mainshock were also recorded. (b) Histogram of T-phase signal packets per hour recorded from local and regional earthquakes (<500 km distance). Also shown are counts of P-wave earthquake arrivals. Because the majority of earthquakes detected were local to regional events and generated detectable P waves and T phases, the P-wave and T-phase counts are well correlated. All P- and T-phases signals were manually identified by an analyst. (c) Received levels of T-phase signal packets from a 10-second window of maximum peak-to-peak amplitude over the 1 Hz to 100 Hz band. Highest levels correspond to large, local events.

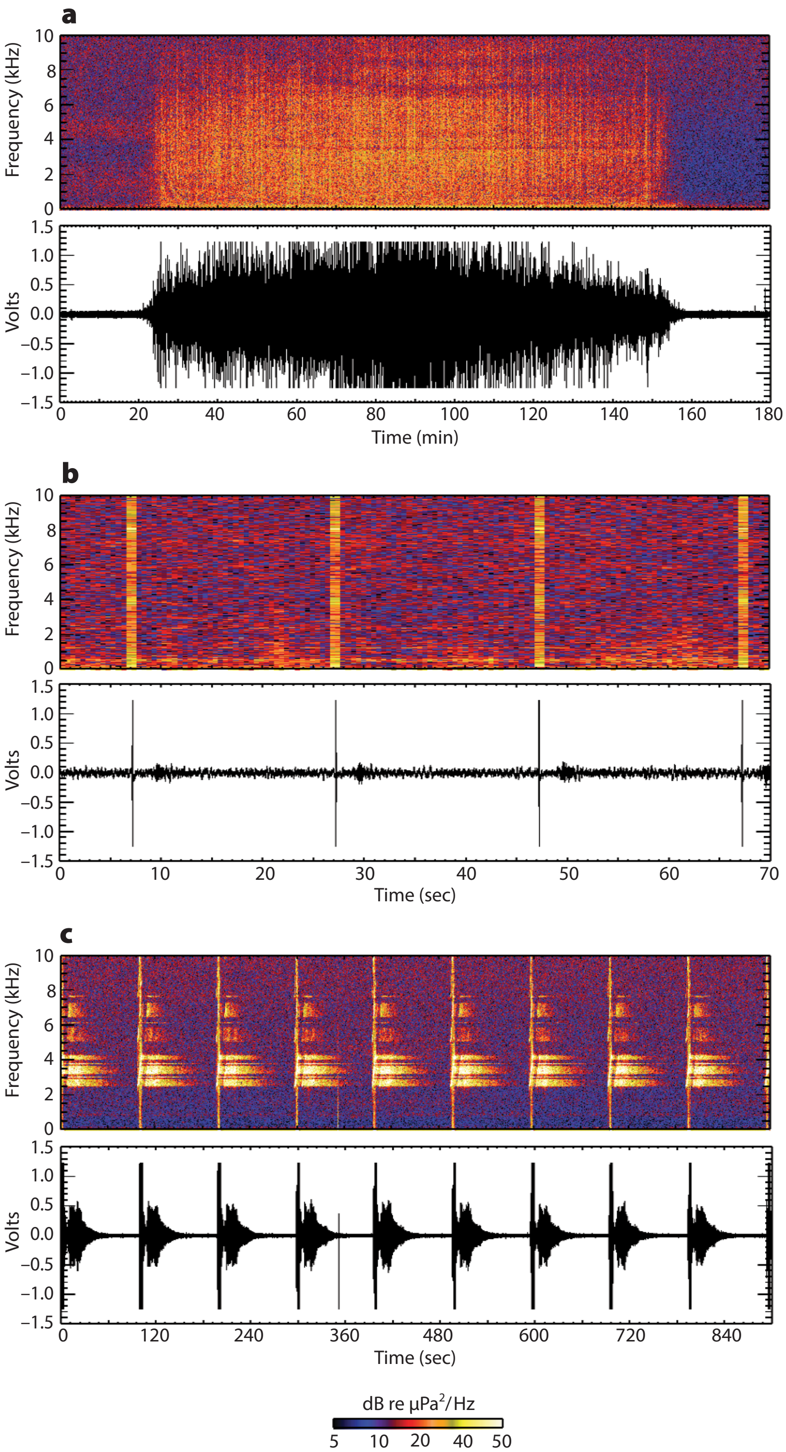

FIGURE 6. Examples of time series and spectrogram of sound sources recorded at Challenger Deep. (a) An example of ship propeller sound (recorded on July 29, 2015) seen in the spectra as a series of relatively narrow bands of energy that change frequency due to changing interference patterns as a ship passes over the hydrophone. The time series shows ship sounds loud enough to clip the hydrophone record (that is, the amplitudes of the signals are truncated, or clipped, meaning the signals exceeded the dynamic range of the recording system). (b) Four airgun bursts, each exhibiting short-duration (~1 s) energy over the 1 Hz to 8 kHz band. Airgun records are clipped as well. (c) Example of intense, active sonar pings recorded on July 25, 2015. Pings are each ~80 s in duration, occur at ~1.5 minute spacing, and are characterized by a broadband, short-duration ping followed by three narrow-band pulses centered at ~2.85, 3.5, and 4.25 kHz.

Biological Sources

The Mariana Island region is host to a wide variety of mysticetes (seven species) and odontocetes (22 species; Fulling et al., 2011). Figure S3a,b shows example spectrograms of odontocete and mysticete vocalizations recorded on the Challenger Deep hydrophone. The most common type of baleen whale call observed resembles a call recently recorded and characterized during acoustic glider surveys over the Mariana Trench (southeast of Guam and east of the Challenger Deep) in late 2014 and early 2015 (Hill et al., 2016; Nieukirk et al., 2016). These calls are characterized by a ~38 Hz harmonic tone followed by a broad-frequency metallic sweep up to 7.5 kHz, and are considered most likely to be from a minke whale (Nieukirk et al., 2016). Figure S3c shows a histogram of the percent of the day these vocalizations were observed on the Challenger Deep hydrophone. Generally, the call was seen on the hydrophone >5 times per day, the exception being July 24–25 and August 1–2 when calls decreased to <5 per day.

While many odontocete whistles are identified within the record, we were not able to use the clicks to identify the variety of possible source species. However, given that both mysticete and odontocete whales are not known to dive deeper than 3,000 m (Baird et al., 2006), obtaining a record of their calls on the seafloor at Challenger Deep demonstrates the favorable propagation conditions for acoustic rays traveling vertically from the sea surface.

Anthropogenic Sources

Over one-third of global shipping activity is made up of large (>10,000 gross tons) commercial ships (container ships and product tankers) that produce tonal noise at ~40 Hz and bulk carriers that produce noise at ~100 Hz (McKenna et al., 2012). The commercial port of Guam is a major shipping hub for the northwestern Pacific and Micronesia. Guam is also the location of US Naval Base Guam, a key military hub that is home to dozens of US Pacific Fleet units. Typically, ship propeller sounds are seen as continuous, discrete-frequency bands of energy in the spectrogram at 2, 4, 6, and 10 kHz (and can be much less than 40 Hz), although these bands can exhibit constructive and destructive interference patterns of several kilohertz over relatively short (2–3 minute) periods (Figure 6, top). Figure 7a shows the histogram of the number of hours per day that ship propeller sounds were observed on the Challenger Deep hydrophone. With the exception of the time when Typhoon *Soudelor* was in the region (August 3–5), ship propeller sounds were observed 10–24 hours per day. Thus, the sounds of ship traffic are a significant contribution to the ocean soundscape around Guam and at the southern Mariana Trench. Unfortunately, many of the records of the ship propeller sounds are clipped, which can affect the spectral character of the received sound levels.

Seismic airguns, commonly used for oil and natural gas exploration beneath the seafloor, are one of the main sources of anthropogenic sound below 100 Hz (Tolstoy et al., 2004). Organized in multi-unit arrays, each airgun generates a bubble that expands and then contracts, releasing pressurized air underwater and creating a loud transient signal (<0.1 s, 235–240 dB *re* 1 Pa at 1 m in the 2–188 Hz frequency band) that can penetrate the seafloor (Hatch and Wright, 2007). Figure 6b shows the hydrophone records of airgun bursts recorded at Challenger Deep, and Figure 7b shows the hours per day when airgun pulses were observed. Airgun activity was relatively intermittent during this 24-day recording period, occurring on seven different days between 1 and 10 hours on each of these days. We estimated the median received level of the airgun pulses (1 Hz–14 kHz frequency range) to be 99.4 dB *re* 1Pa.

In addition to ship propeller and airgun noise, the Challenger Deep hydrophone also recorded persistent signals from active sonar, which we assumed to be military in origin (Southall et al., 2012). Each of these sonar signal packets are ~80 s in duration (and occur at ~1.5 minute spacing), and are characterized by an initial broadband, short-duration (~5–10 sec) burst followed by three narrow band pulses centered at ~2.85, 3.5, and 4.25 kHz. These following pulses may also possibly be reflections/reverberations. The pings were observed 4–12 hours per day for four days from July 22–25 (Figure 7c). We estimate the received levels of the broadband ping and narrow-band pulses range from 58.1–68.0 dB *re* 1Pa.

Overall Sound Levels

To place the sound levels observed at Challenger Deep in context with global averages, Figure 8 compares the ambient sound levels observed at Challenger Deep with the global sound levels estimated in the 1960s. These curves (Wenz, 1962) show the average sound spectral energy levels for different measures of ship traffic (heavy to moderate) and sea state due to variation in wind speeds (Figure 8a). Anthropogenically induced noise from heavy shipping creates the highest sound level values of ~90 dB re 1µ Pa^2/Hz in the 20–100 Hz band, whereas wind has highest noise levels of 70–75 dB re 1µ Pa^2/Hz at sea states 3 to 6 in the 500 Hz–1 kHz band.

In comparison, Figure 8b shows the Challenger Deep sound level distributions at the 10^{th}, 50^{th}, and 90^{th} percentiles. Challenger Deep exhibits sound levels of 70–80 dB re 1µ Pa^2/Hz in the 20–100 Hz ship traffic band. Thus, noise levels from ship traffic at Challenger Deep appear equivalent to noise levels caused by moderate shipping in other parts of the world. This is consistent with the persistent military and commercial ship traffic in and out of the Port of Guam. In the 500 Hz–1 kHz wind-driven sea state band, Challenger Deep ambient sound levels are ~40 dB to 60 dB re 1µPa^2/Hz. Thus, noise levels at Challenger Deep due to wind/waves are relatively low at sea states of 0 to 2, and therefore it seems that Typhoon *Soudelor* did not have a substantial impact on overall noise levels during the recording period. Indeed, as can be seen in Figure 8b, ambient sound levels are so low that the hydrophone is recording mainly hydrophone system noise starting at 5 kHz on the 10^{th} percentile curve, and at 10 kHz on the 50^{th} and 90^{th} percentile curves. These very low sound levels at Challenger Deep are not too surprising given the high attenuation of acoustic energy from regional sound sources that are not directly above the Mariana Trench, as well as the low sea states that can persist in the region between passing high-wind events.

Lastly, in Figure 8b, an interesting

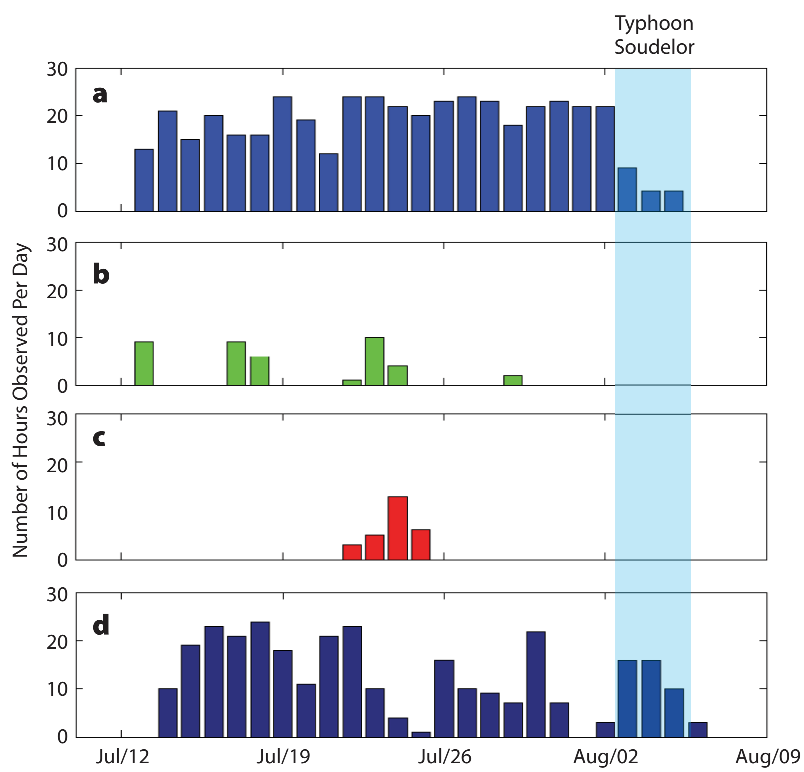

FIGURE 7. (a) Histogram showing the number of hours per day that ship propeller noise was observed on hydrophone record. (b) Number of hours per day airgun sounds were observed. (c) Number of hours active sonar was observed. (d) Number of hours per day baleen whale calls were observed. This histogram is the same as Figure S3c, and is shown here to highlight how it compares with anthropogenic source counts.

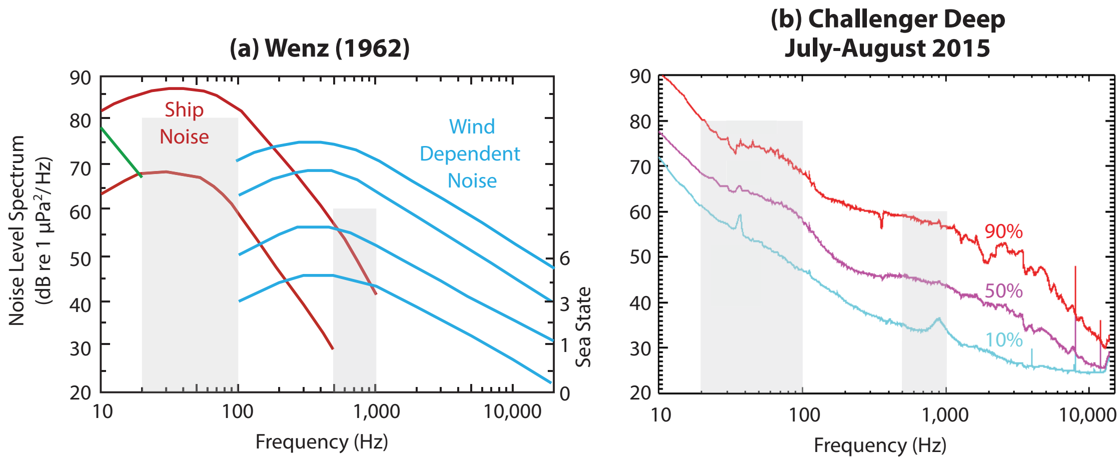

FIGURE 8. (a) Diagram showing global estimates of sound levels due to ship traffic noise and wind-driven sea state (Wenz, 1962; adapted from NRC, 2003). Shaded areas highlight the 20–100 Hz "ship traffic" noise band (red lines), and the maximum sound levels due to surface winds and various sea states (blue lines; 500 Hz–1 kHz band). The green line shows the ambient sound level due to microseism background energy. (b) Challenger Deep sound level distributions at the 10th, 50th, and 90th percentiles. Shaded areas highlight the same frequency bands as Wenz curves to compare sound levels. Challenger Deep ship noise (90th percentile) can be as high as moderate ship-traffic noise in Wenz curves (~70–80 dB re 1µPa²/Hz). Maximum noise levels due to wind/waves in Challenger Deep are equivalent to sea states 0 to 2 (~60 dB re 1µPa²/Hz at the 90th percentile). Spectral spikes at ~8 kHz and 12 kHz are due to instrument noise. Hydrophone system noise starts at 5 kHz in 10th percentile, and becomes 50th to 90th percentile above 10 kHz. Spectral peak at 40 Hz in 10th percentile band are part of a complex baleen whale call recently identified in the Mariana Trench by Nieukirk et al. (2016; Figure S3). The peak at 900 Hz is also likely a baleen whale call, but its origin is currently not known.

spectral peak can be seen at ~900 Hz in the 10th percentile curve. We speculate that this sustained signal is biological in origin, as it is unknown what else would produce a somewhat narrow-band peak over almost the entire duration of the Challenger Deep recording. In detailed review of the spectral data, no single call can be clearly identified, the frequency does not match that of any known whale call in the area, and the spectral peak appears merely as a rise in energy around 900 Hz. The origin of this signal thus remains a subject of conjecture. However, another spectral peak that can be seen at 40 Hz in the 10th percentile band is part of the complex baleen whale call recently identified in the Mariana Trench (see Figure S3).

SUMMARY

The successful deployment and recovery of a hydrophone and pressure sensor mooring provided, to our knowledge, the first multiday, broadband record of ambient sound made at Challenger Deep, as well as only the fifth direct depth measurement. Moreover, the success of this deep-ocean mooring system demonstrates the value of employing the relatively low-cost ocean sampling methodology used here (as compared to robotic or manned submersibles) to recover data from otherwise inaccessible deep-sea areas.

Although based on a relatively short 24-day sample size, the overall hourly counts of anthropogenic and natural sound sources indicate earthquakes, ship noise, and baleen whale calls are 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. Given the relatively common occurrence of typhoons in the western Pacific Ocean (http://www.ssd.noaa.gov/PS/TROP/Basin_WestPac.html), storm noise is likely a significant part of the long-term soundscape in the region.

ONLINE SUPPLEMENTAL MATERIAL

Supplemental Figures S1–S3 are available online at https://doi.org/10.5670/oceanog.2017.240.

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