Ocean noise in the tropical and subtropical Pacific Ocean

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Ocean ambient noise is well studied in the North Pacific and North Atlantic but is poorly described for most of the worlds' oceans. Calibrated passive acoustic recordings were collected during 2009–2010 at seven locations in the central and western tropical and subtropical Pacific. Monthly and hourly mean power spectra (15–1000 Hz) were calculated in addition to their skewness, kurtosis, and percentile distributions. Overall, ambient noise at these seven sites was 10–20 dB lower than reported recently for most other locations in the North Pacific. At frequencies <100 Hz, spectrum levels were equivalent to those predicted for remote or light shipping. Noise levels in the 40 Hz band were compared to the presence of nearby and distant ships as reported to the World Meteorological Organization Voluntary Observing Ship Scheme (VOS) project. There was a positive, but nonsignificant correlation between distant shipping and low frequency noise (at 40 Hz). There was a seasonal variation in ambient noise at frequencies >200 Hz with higher levels recorded in the winter than in the summer. Several species of baleen whales, humpback (*Megaptera novaeangliae*), blue (*Balaenoptera musculus*), and fin (*B. physalus*) whales, also contributed seasonally to ambient noise in characteristic frequency bands. © *2013 Acoustical Society of America*. [http://dx.doi.org/10.1121/1.4820884]

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I. INTRODUCTION

Ocean noise is important to marine life including marine mammals, fishes, and other soniferous organisms that use sound to locate prey, communicate, and mate with conspecifics and to sense and navigate their environment. Sources of ambient noise in the ocean can be broadly divided into sounds resulting from natural physical processes (e.g., wind-driven waves, rainfall, seismicity), sounds from biologics, and anthropogenic sounds such as commercial shipping, sonar, and oil and gas exploration (Hildebrand, 2009).

These noise sources vary in frequency and temporal character. Noise in the ocean at very low frequencies (<10 Hz) is produced by seismicity and surface wave interactions. In the deep ocean, distant commercial shipping is the dominant noise source in the 10–200 Hz band with levels that are relatively flat below 50 Hz (Wenz, 1962) and energy that extends to higher frequencies when ships are nearby (McKenna *et al.*, 2012b). Wind-driven surface waves produce sound from below 100 Hz to above 20 kHz, but often shipping sounds prevent wind from being a dominant contributor to ambient ocean noise below 200 Hz with a decrease in levels above 500 Hz of about 6 dB/octave (Knudsen *et al.*, 1948; Wenz, 1962; Urick, 1983).

Ocean noise levels have been studied at numerous locations. However, most studies have been focused on the temperate North Atlantic and North Pacific as much of the world's navies have been concentrated in those regions (Urick, 1983; Ross, 2005; McDonald *et al.*, 2006a). Deep-ocean background noise levels in the eastern North Pacific have been increasing since the 1960s mainly due to shipping (Andrew *et al.*, 2002). Simple linear trends in contemporary (6–12+ yr) traffic noise indicate that recent levels are slightly increasing, holding steady or decreasing (Andrew *et al.*, 2011). The average rate of increase at 30–50 Hz in temperate oceans has been 2.5–3 dB per decade (McDonald *et al.*, 2006a; Chapman and Price, 2011), and since the industrial revolution, the overall increase in ocean ambient noise below 500 Hz has been estimated to be at least 20 dB (Hildebrand, 2009).

Ambient noise levels in the tropics and subtropics, on the other hand, have received less attention. In the 1970s, noise recordings were collected around Australia, mostly in tropical waters (Cato, 1976). Earlier, during the 1940s, the U.S. Navy made recordings at multiple locations in the central and southwest Pacific at depths greater than 200 fathoms and frequencies above 100 Hz (Johnson and Johnston, 1944). More recently, ambient noise was recorded at the deep (approximately 4800 m) cabled station ALOHA located 100 km north of Oahu (Duennebier *et al.*, 2012).

In this paper, we present monthly and daily patterns in ocean ambient sound at multiple locations across the central and western tropical and subtropical Pacific for which little historic data exist. The goals of this study were to establish the current baseline of noise at those locations and to evaluate the relationship between shipping and ambient sound levels across sites.

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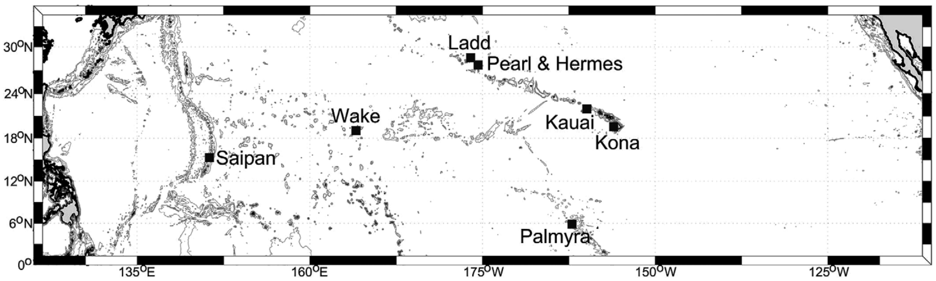

FIG. 1. Locations of the seven HARP deployment sites across the central and western tropical and subtropical Pacific Ocean. Gray lines are 500, 1000, 2000, and 3000 m depth contours. See Table I for site latitude, longitude, depth, and recording periods.

II. METHODS

A. Acoustic recordings and analysis

Autonomous, bottom-mounted high-frequency acoustic recording packages, HARPs (Wiggins and Hildebrand, 2007), were deployed at seven sites across the central and western tropical and subtropical Pacific Ocean (Fig. 1) with the hydrophones generally placed in the sound channel at depths between 600 and 1100 m (Table I). The deployment locations were off Kona on the west shore of Hawai'i Island (referred to as Kona in the remainder of the paper), off the southwestern coast of Kaua'i in the channel between Kaua'i and Ni'ihau (Kauai), off the southeast side of Pearl and Hermes reef (Pearl and Hermes) and on the north slope of the Ladd Seamount (Ladd) in the Northwestern Hawaiian Islands, to the northeast off Palmyra atoll (Palmyra), southeast of Wake Island (Wake), and off the west coast of Saipan (Saipan). HARPs were deployed for various periods, but we analyzed as close to one full year of data as was available during 2009 and 2010 (Table I). Most data were recorded on a duty cycle with a 5 min recording interval over variable cycle durations. HARPs sampled initially at 200 kHz, but to allow for more efficient data analysis, the recordings were low-pass filtered and downsampled to 2 kHz for an effective bandwidth between 15 and 1000 Hz. Hydrophones were calibrated at the U.S. Navy's Transducer Evaluation Center (TRANSDEC) in San Diego, CA.

Spectrum levels were calculated first by calculating 5 s spectral averages with 1 Hz frequency resolution from average energy in five 1 s blocks of data (calculated using Hanning window and with no overlap). Subsequently, these spectral averages were additionally averaged over 200 s from each 5 min period for consistency with other measurements of ocean noise (*sensu* McDonald *et al.*, 2006a). Monthly average power spectral densities were computed in logarithmic (dB) realm over the 15–1000 Hz band. Also variation in noise over the course of a day was investigated by comparing hourly average power spectral densities in the same frequency band during each month of deployment. Periods with consistent low frequency flow noise and instrument self-noise were removed, but transient signals (e.g., whale calls, ship passage) were included as, at times, they were major contributors of ocean ambient sound. A fraction of the original data that remained for analysis after this step is given as "clean data" in Table I. All spectrum levels are reported as dB re: 1μPa^2/Hz.

We calculated basic statistics of noise levels at each location for two frequencies chosen as representative, 50 Hz for ship-dominated noise and 500 Hz for weather dependent noise, based on the cumulative probability distributions of 200 s samples. Median (50th percentile), first, tenth, 90th, and 99th percentiles and unbiased skewness and kurtosis were calculated from the probability distributions. Skewness (third standardized moment, $\gamma_1 = \mu_3/\sigma^3$ where μ_3 is the third moment about the mean and σ is the standard deviation) is a measure of asymmetry of the probability distribution. Kurtosis (fourth standardized moment, $\gamma_2 = \mu_4/\sigma^4$) is a measure of "peakedness" in the probability distribution. All averaging statistics were calculated on a logarithmic scale.

B. Ship location data

As a proxy for the number of commercial ships within the detection range of each HARP, we used data collected as

TABLE I. HARP deployment locations with latitude, longitude, and depth of each of the seven sites, as well as recording period of data used for the analysis, percent of data during that recording period that could be used (percentage clean data), and the total hours of data analyzed (number of hours analyzed).

Site name	Latitude	Longitude	Depth (m)	Recording period	Percentage clean data	No. h analyzed
Kona	19°34.9′N	156°0.9′W	620	25 Oct to 15 Dec 2009 30 Sept 2010 to 12 Mar 2011	99.9	2206.4
Kauai	21°57.2′N	159°53.4′W	720	6 Oct 2009 to 13 May 2010 4 Jun to 31 Jul 2010	56.9	1938.4
Palmyra	5°53.7′N	162°2.2′W	700	5 Oct to 12 Nov 2009 12 Jun to 25 Aug 2010 9 Sep to 16 Oct 2010	99.5	2841.4
Pearl and Hermes	27°43.6′N	175°38.1′W	750	3 Oct 2009 to 24 May 2010 1 Jun to 13 Aug 2010	20.5	605.0
Ladd	28°37.6′N	176°43.7′W	1090	18 May to 15 Aug 2009	99.9	1076.7
Wake	19°3.0′N	166°41.0′E	800	31 Jan to 25 Apr 2010	91.2	929.0
Saipan	15°19.0′N	145°27.4′E	690	6 Mar to 25 Aug 2010	90.3	466.8

part of the World Meteorological Organization Voluntary Observing Ship Scheme (VOS) climate project. Ships of many countries voluntarily transmit their location updates, along with the weather information, multiple times a day under this program. For this analysis, we downloaded data collected between May 2009 and March 2011 from http://www1.ncdc.noaa.gov/pub/data/vosclim/. The data contained locations of ships and stationary buoys and oil platforms, but only data producing tracklines (i.e., non-stationary and those with more than one location datum) in the Pacific Ocean were used for the analysis. Ship tracklines were created with the assumption that ships traveled in shortest (great circle) lines between successive data submissions, which would minimize travel and fuel costs.

The number of nearby and distant ships was estimated for each month and each location to evaluate their relationship to average noise levels at 40 Hz for that month. The number of nearby ships was estimated as the number of tracklines that passed within a 100 km "non-shadowed radius" of each recorder during that month. The non-shadowed radius is defined as the area around the recorder that does not have any land obstructions to sound propagation. To estimate a reasonable radius for the "nearby ship" monitoring, we assumed average ship noise of 160 dB re: 1 μPa@1 m at 40 Hz (McKenna *et al.*, 2012b), with the average background noise around 70 dB re: 1 μPa^2/Hz at frequencies below 100 Hz. We also assumed $\text{TL} = 20\log_{10}(r_0) + 13\log_{10}(r/r_0)$, with $r_0 = 4$ km. From those assumptions, it follows that ship noise levels are reduced to background noise at a distance of approximately 100 km, which was taken as a maximum range over which nearby ships would be heard.

Under the right conditions, low frequency sound can propagate over long distances, so in addition to nearby ships, we also wanted to account for "distant" ships. The most likely contribution from distant sources would result from down-slope propagation effects (Ross, 1993), so tracklines of all ships crossing a continental slope or island ridges located in the direction without underwater obstructions (e.g., land or sea mounts in water shallower than the HARP depth) between the instrument and the slope were added as each month's distant ship contribution. For Saipan, for example, that meant including passage of ships over any of the shelf breaks around the western edge of the Philippine Sea between the south end of Japan and the south end of the Philippines. In the case of Wake and Palmyra, ships coming across the shelf break from the Solomon and Bismarck Sea or between Solomon Islands and American Samoa, respectively, were counted. Because the HARP at Ladd seamount was facing to the north, we added ships passing across the shelf break by the western Aleutian Islands as distant shipping contributions for this site. The Pearl and Hermes HARP, which was facing to the south, on the other hand, had no contribution from distant shipping because there were no continental shelves to which it was exposed, but only south Pacific islands such as Fiji or Samoa, where there was no ship traffic during monitored time based on the VOS data. In the case of Kona and Kauai HARPs, ships crossing the Hawaiian Island chain ridges more than 100 km away were counted. Each track was counted only once, even if it crossed a shelf at two different locations, as it still represented passage from a single ship.

To look at relationships between passing ships and noise levels, we calculated monthly mean noise level at 40 Hz, a frequency where commercial ship noise is a dominant contributor, for each site. We used a *t*-test to test whether there is a difference in the monthly mean noise level at 40 Hz between months with and months without nearby and distant ships. Next, we calculated Pearson's correlation coefficients to test if there is a positive relationship between the number of passing ships based on the VOS program and the noise recorded at 40 Hz across sites. We performed this test for each shipping condition, as well as for the composite shipping (nearby + distant ship). The tests were conducted using Bonferroni corrected α-levels of 0.017 for each test. All statistical analyses were performed using the statistics toolbox in MATLAB (The MathWorks Inc., Natick, MA).

III. RESULTS

Average monthly pressure spectrum levels varied over time and across sites (Fig. 2). The highest levels at frequencies dominated by shipping (<100 Hz) were consistently recorded at Kona and Saipan with levels generally ranging between 72–78 and 71–73 dB re: 1 μPa^2/Hz at 50 Hz, respectively, while levels were the lowest at Palmyra and Wake (67–69 and 68–70 dB re: 1 μPa^2/Hz at 50 Hz, respectively). The monthly variation at Kona, Kauai, and Pearl and Hermes was relatively large (approximately 5 dB re: 1 μPa^2/Hz at 50 Hz), while it was relatively low at Saipan (2 dB re: 1 μPa^2/Hz at 50 Hz). Spectrum levels at frequencies typically dominated by wind and waves (>200 Hz) were the lowest (<60 dB re: 1 μPa^2/Hz above 200 Hz) and had the least variation at Palmyra, although there were no winter and spring recordings from Palmyra. At these frequencies, spectrum levels also were low at Ladd Seamount during summer months, but elevated in May (56 and 67 dB re: 1 μPa^2/Hz at 500 Hz). Other sites all exhibited 5–10 dB of variation in pressure spectrum levels at frequencies >200 Hz with most variation at Kauai and Pearl and Hermes (approximately 8 dB difference at 500 Hz). Winter and spring months generally had higher levels and summer and fall had lower pressure spectrum levels at frequencies above 200 Hz.

Cumulative sound levels were generally long-tailed toward the high pressure spectrum levels, especially at lower frequencies (Fig. 3). This positive skewness (larger spread to the right of the mean) at low frequencies was mostly due to the infrequent passage of ships that contributed to only occasional increases in pressure spectrum levels over shipping frequencies (20–100 Hz) at most locations (Fig. 4). Somewhat unique, the site at Ladd had a more distinct spectral distribution with less variability at lower frequencies, indicating few close ship passages [Fig. 4(C)]. High kurtosis values for distributions at 50 Hz at Wake and Kauai, on the other hand, likely indicate more frequent close ship passages as kurtosis values >3 indicate a distribution with more outliers. While there seemed to be little variation in the ambient noise statistics at low frequencies (<100 Hz), there was a seasonal change in skewness at high frequencies (>200 Hz)

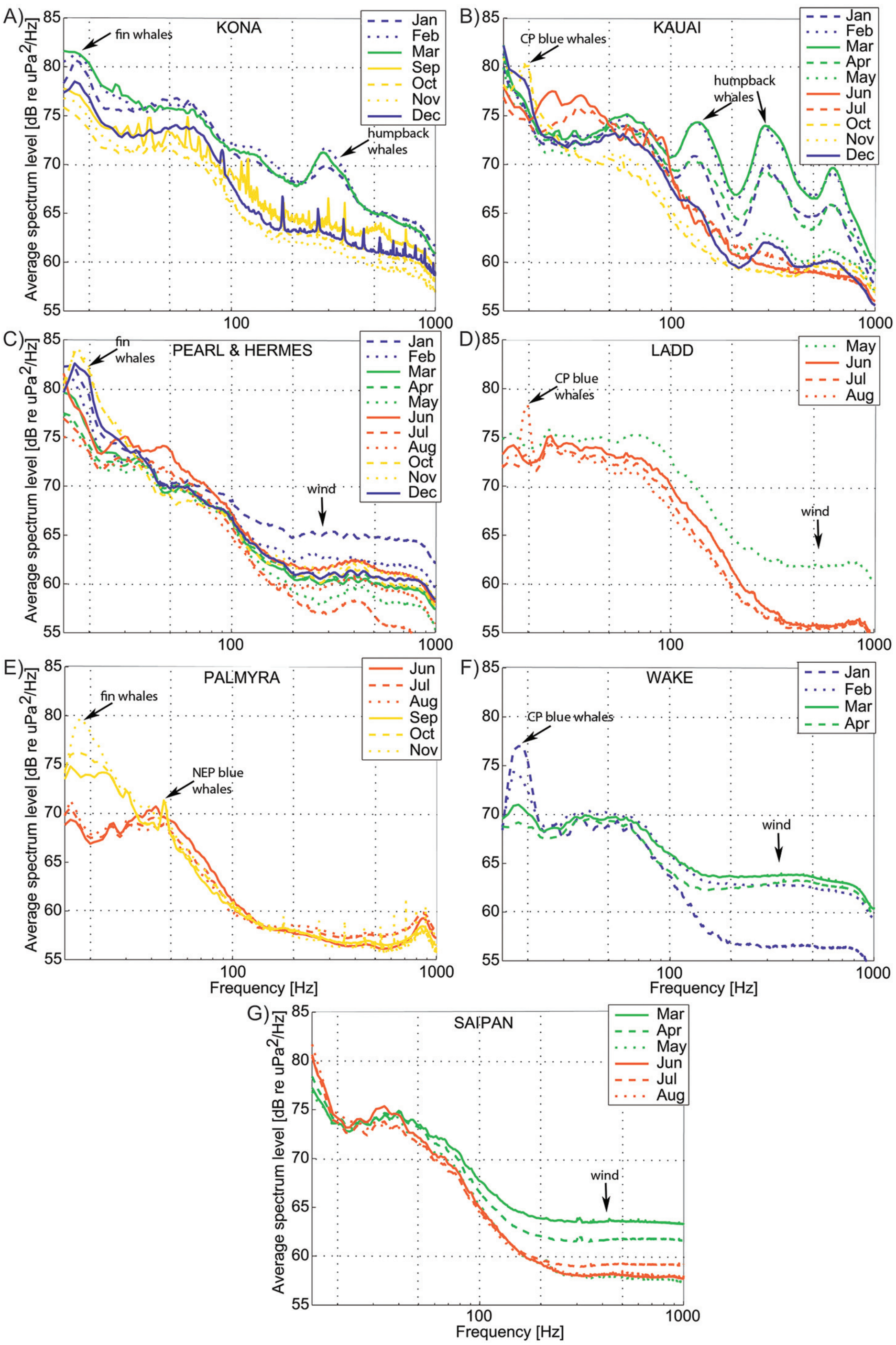

FIG. 2. Average monthly sound pressure spectrum levels from 15 to 1000 Hz at seven sites across the Pacific Ocean: (A) Kona, (B) Kauai, (C) Pearl and Hermes, (D) Ladd, (E) Palmyra, (F) Wake, and (G) Saipan. Color and line types used for each month are consistent across sites with green color denoting spring (March, April, and May), red summer (June, July, August), yellow fall (September, October, November), and blue winter months (December, January, February). In each color set, the first month is always shown as a solid line, the second month is a broken line, and the third month is a dotted line. Arrows are pointing to frequency bands representative of fin whale calls, central Pacific (CP) and northeast Pacific (NEP) blue whale calls, humpback whale calls, and wind band.

indicative of changes in wind activity at this site [Fig. 2(D)]. In March, negative skewness likely indicative of higher wind conditions was common, particularly at Wake [Figs. 3(C) and 4(B)], but by October, all sites except Kauai had positive skewness [Fig. 3(D)].

In general, even though the seasonal change in spectrum levels was evident across the spectrum, there was little consistency in diel patterns of sound levels at these sites, as exemplified by recordings from Saipan (Fig. 5). One notable exception was a strong peak in pressure spectrum levels at 500 Hz, likely from fish sounds, at 20:00 (local time) as shown in the example from Kona and also visible in Saipan [Fig. 5(C)]. Similar peaks were present also during most months in Palmyra, with Ladd and Kauai also showing an increase in noise at night, but less of a clear peak at 20:00 h. This peak extended to lower frequencies at Palmyra, as low as 100 Hz, and to higher frequencies (up to 900 Hz) at Ladd and Kona. The site at Kona was also unique with a clear daytime (between 08:00 and 17:00 local) increase in ambient noise of approximately 4 dB at 500 Hz [Fig. 5(C)], likely due to its proximity to a port with heavy boating activity and a popular fish aggregating device (FAD). Saipan and Wake, on the other hand, showed some indication of seasonally increasing ambient noise at frequencies over 100 Hz after 10 am, possibly an indication of increasing wind.

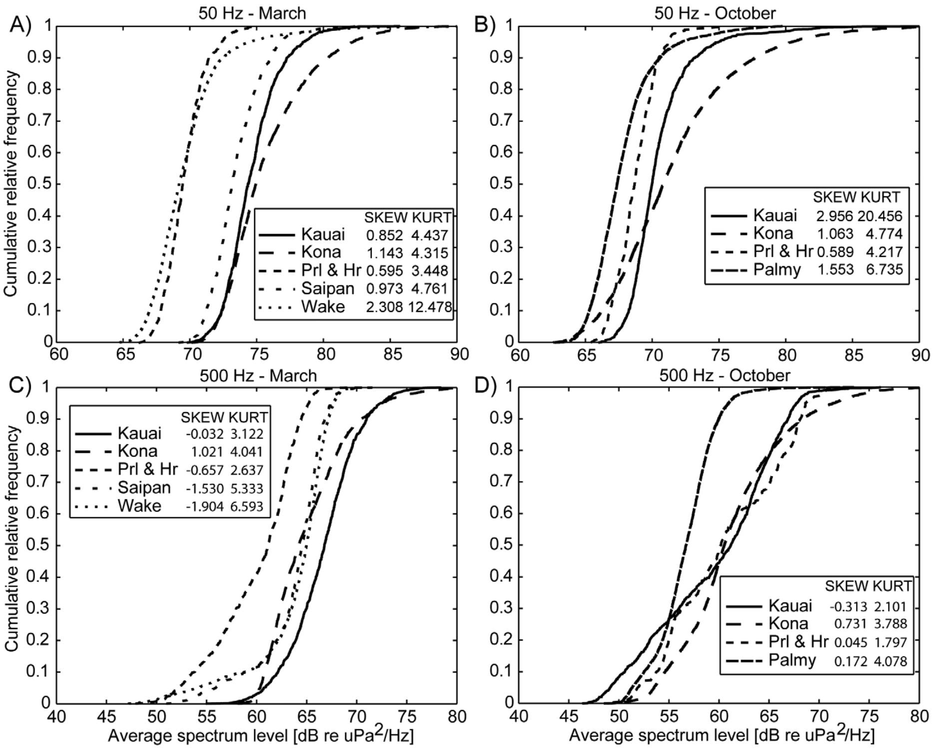

FIG. 3. Cumulative density functions of average sound pressure spectrum levels at 50 and 500 Hz in March and October at all sites with recordings during those months. The skewness and kurtosis for each month are in the inset. Prl & Hr, Pearl and Hermes; Palmy, Palmyra.

A. Biological sounds

Baleen whale signals were an important sound source seasonally at a range of frequencies. The large level of monthly variation in the ambient noise levels at frequencies >200 Hz in Kauai, for example, was due to the occurrence of humpback whale (*Megaptera novaeangliae*) songs [Fig. 2(B)]. Those songs were the major component of ambient noise at that site between January and April, increasing the spectrum levels by up to 6 dB, assuming overall elevated winter levels are due to wind. Similar variation in sound pressure spectra, although of lower levels (up to 3 dB) was recorded during the January–March period in Kona, also as a result of humpback whale song [Fig. 2(A)].

Two different blue whale (*Balaenoptera musculus*) call types, the northeast Pacific and central north Pacific (McDonald *et al.*, 2006b), were recorded at four sites. The northeast Pacific blue whale B calls were visible as a 2 dB increase in the pressure spectrum level at 48 Hz in September at Palmyra [Fig. 2(E)]. Central north Pacific blue whale calls were responsible for increased spectrum levels at 19 Hz at Wake in January and February and Ladd in August

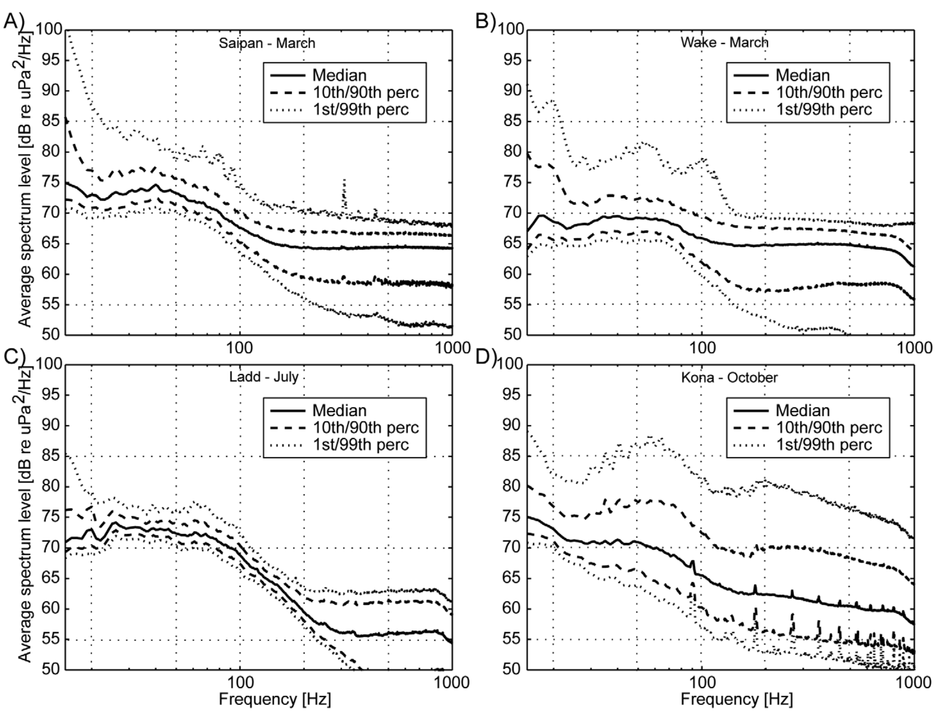

FIG. 4. Examples of representative monthly sound pressure spectrum levels. Solid line is the median, broken lines are tenth and 90th percentiles, and dotted lines are first and 99th percentiles. (A) In Saipan in March, a small contribution of LFA is noticeable in the 99th percentile as peaks at 300 and 400 Hz. (B) Wake in March had the typical negative skewness at high frequencies, indicative of predominately stormy conditions with passing quiet periods. (C) Ladd in July shows the typical plot with relatively constant level of distant shipping and large level of variation in wind-driven noise. (D) Kona in October had positive skewness across all frequencies, the result of occasional ship passage and passage of storms.

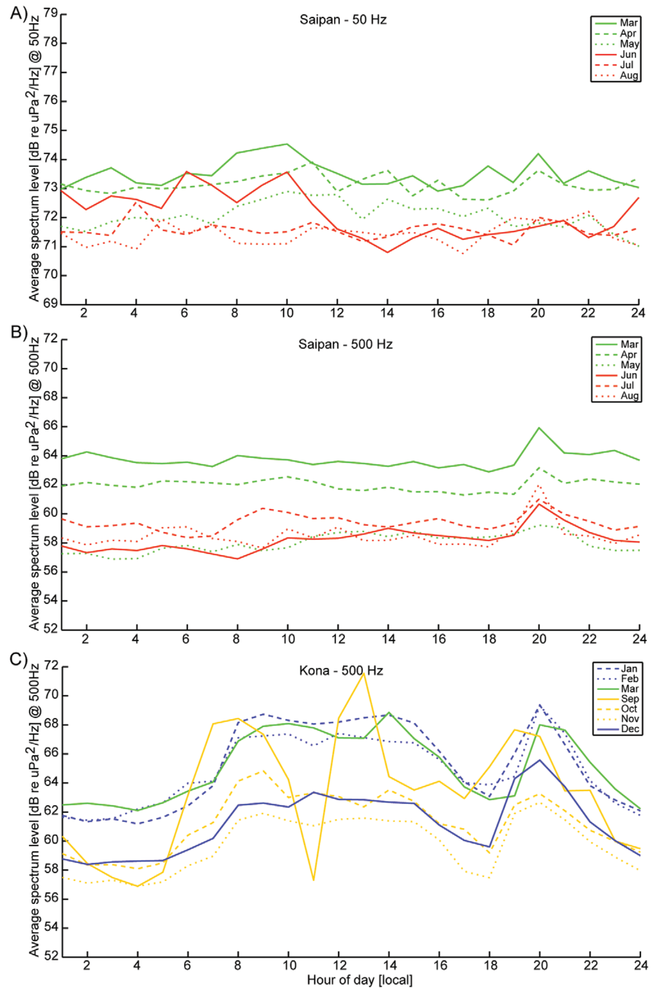

FIG. 5. Examples of hourly average sound spectrum levels at 50 and 500 Hz. (A) There is no diel pattern at 50 Hz at Saipan, even though seasonal variation is noticeable. (B) In Saipan at 500 Hz there is a consistent peak in spectrum levels around 20:00 local. (C) At Kona at 500 Hz, there is an increase in levels during daytime, as well as a peak at 20:00. All color and line types are the same as in Fig. 2.

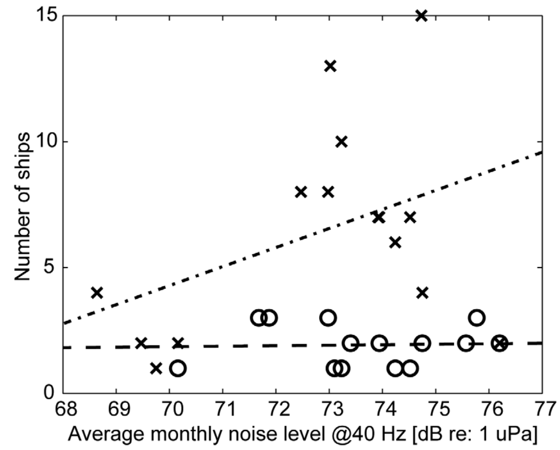

FIG. 6. Average monthly noise levels at 40 Hz relative to the number of ships recorded in that month. Data for nearby ships are given with ○ and distant ships are represented with ×. Linear least-squares fits for each set of data are represented with dashed (nearby) and dash-dotted lines (distant ships).

[Figs. 2(F) and 2(D), respectively]. Faint (distant) central north Pacific-type calls were also responsible for the increase in sound pressure level at 19 Hz in October at Kauai [Fig. 2(B)].

Energy from fin whale (*B. physalus*) 20 Hz pulses was visible in the averaged pressure spectrum in Kona during most months with data (September–March), but it was particularly noticeable between December and March [Fig. 2(A)], although during that time some of that energy was also contributed by central Pacific blue whale calls. At Pearl and Hermes, fin whale 20 Hz pulses were the dominant source of ambient noise <25 Hz during the fall and winter months [Fig. 2(C)]. Faint 20 Hz fin whale pulses also were contributing to higher average pressure spectrum levels at frequencies <30 Hz in October and November at Palmyra [Fig. 2(E)] and at Wake from January through March [Fig. 2(F)].

B. Anthropogenic sounds

Average monthly ambient noise spectrum level at 40 Hz across sites when ships were present was 73.0 dB re: 1 μPa^2/Hz, which was significantly higher [$t(45) = 2.57$, $p = 0.01$] than during months with no reported VOS ships, when the average noise level was 71.6 dB re: 1 μPa^2/Hz. While shipping was the dominant anthropogenic source of ambient noise at these remote locations, it was not as prevalent a contributor as it is in other parts of the North Pacific Ocean, and based on our data, the relationship between the noise spectrum level at 40 Hz and the number of passing ships was not significant (Fig. 6). Nevertheless, the positive correlation between the monthly noise levels at 40 Hz was the strongest with the number of distant ships ($r = 0.42$, $p = 0.12$), followed by combined shipping ($r = 0.30$, $p = 0.19$). There was no relationship between the monthly noise at 40 Hz and nearby shipping ($r = 0.04$, $p = 0.89$).

Shipping was not the only anthropogenic source of ambient sound at these sites. In March and April, multiple events of low-frequency active (LFA) sonar activity were recorded off Saipan. This activity was confined to a short time period and thus it contributed to the sound spectrum by raising narrow band levels between 300 and 400 Hz in the 99th percentile by no more than 5 dB [Fig. 4(A)].

IV. DISCUSSION

Overall ambient noise recorded at seven sites across the central and western Pacific Ocean was lower than noise recently reported at other, more northerly Pacific locations (Andrew *et al.*, 2002; McDonald *et al.*, 2006a). For example, levels across our sites ranged generally between 67 and 76 dB re: 1 μPa^2/Hz at 50 Hz, while they have been reported recently to be 85–90 dB re: 1 μPa^2/Hz at 50 Hz off the U.S. West Coast. Similarly, our range of 55–67 dB re: 1 μPa^2/Hz at 500 Hz is generally lower than the values (66 and 68 dB re: 1 μPa^2/Hz at 500 Hz) reported by Andrew *et al.* (2002) and McDonald *et al.* (2006a). Ambient noise levels recorded at 50 Hz at some sites were as low as the lowest spectrum levels recorded in 1950s in the West Atlantic and the East Pacific (Ross, 2005) but not as low as those recorded in isolated basins of Southern California Bight by McDonald *et al.* (2008). Generally the levels we report here correspond to ambient noise levels that are predicted when only remote or light levels of shipping are present (Ross, 1976). At frequencies above 200 Hz, recorded average ambient noise levels corresponded to average wind speeds of 4–16 kn or sea states 1–3 (Knudsen *et al.*, 1948).

In general, there was little temporal variation in the monthly spectrum levels at frequencies below 100 Hz. Exceptions to that were the Kona and Kauai sites, where local shipping and boating is likely to contribute to noise substantially more than at other more remote and less populous locations. Consistent with this, Palmyra and Wake, sites with low population and less local boating, exhibited less monthly variation in low frequency noise. Increased low frequency noise variability is consistent with ambient noise trends observed when boats are near the recording location (Bannister *et al.*, 1979; McDonald *et al.*, 2008). In addition at Kona, the diel pattern of increasing ambient noise levels at 500 Hz in the morning and consistent positive and relatively high negative skewness also point to nearby sources of passing boat noise.

The ambient noise at 40 Hz was not significantly correlated to shipping based on the VOS data, but the broader noise statistics point to a possible link between the two factors. Because the VOS program is voluntary, not all shipping traffic is included in these data. Also because the rate of the location reports varies for ships, it should be noted that ship tracks used were often only estimates of the actual shipping route taken. Finally, we cannot evaluate the bias in the location or types of ships covered by the program, thus we cannot estimate if our proxy for overall shipping in the area has a consistent systemic bias.

Automatic Information System (AIS) is a ship tracking method that can provide more comprehensive and less biased information on ship locations (Bassett *et al.*, 2012; McKenna *et al.*, 2012a) than the VOS data, but standard AIS uses radio frequencies to transmit data from ships; this limits its range and therefore usefulness for this study because of the remoteness of most locations. Satellite-AIS has become more widely implemented since 2008 but still faces issues with reliable reception. Thus we were limited to the data available from the VOS program, which in 2010 included participation of ships from 28 countries mostly from Europe and North America as well as some ships from other Pacific Rim countries like Australia, New Zealand, Japan, South Korea, and Hong Kong. In the absence of AIS data, it should be possible to count the passage of nearby ships directly from the acoustic records and thus obtain a better correlation between the low frequency ambient noise levels and nearby shipping activity, but such analysis was outside the scope of this study.

Most of the monitoring locations were located well outside the major shipping lanes and were found mostly in basins that were exposed to little or no shipping, and thus ambient noise at most sites was in the range that would be expected for areas with light to moderate shipping activity (Urick, 1983). Saipan, the site closest to the shipping lanes coming out of Asia, also had among the highest ambient noise levels at 40 Hz. The HARP at Ladd was the only one facing the shipping lanes in the North Pacific that connect Asia with North America. In general, the ambient noise at frequencies below 100 Hz was 4–5 dB higher at Ladd than at a site like Wake, which was facing toward the less trafficked, southern shipping routes. Low variability of noise at low frequencies at Ladd also suggests a distant source of shipping, unlike Kauai and Pearl and Hermes sites, which were likely exposed to some closer shipping traffic on route from Hawaii to Asia and Australia.

The dependence of ocean ambient noise on wind-driven waves has been well documented (Knudsen *et al.*, 1948), and its contribution was noticeable at most sites with average spectrum levels corresponding to sea states from 1 to 3. In general, there was a seasonal change in wind speed, seen as an overall decrease in ambient noise levels at frequencies >200 Hz during the boreal summer when winds are low and increased levels in the boreal winter with higher wind speeds. This change in wind levels was also reflected by the change in skewness at 500 Hz at most sites from negative to positive between March and October, respectively. This seasonal change corresponds to the wind stress changes across the Pacific (Hellerman and Rosenstein, 1983).

The large amount of inherent local variability in ambient noise over time (Wenz, 1962; McKenna, 2011) complicates our ability to compare our recordings to the recordings made in the 1940s and the 1970s and evaluate trends in ambient noise in this region of the Pacific Ocean. Changes in wind speed can contribute up to 15–20 dB and, in isolated basins, passage of ships can contribute as much as 6–9 dB to noise levels locally (McDonald *et al.*, 2008). Ambient noise also varies with depth (Urick, 1983), although the effect is not large at low frequencies and depths below the thermocline (Lomask and Frassetto, 1960; Hodges, 2010). Furthermore, as shown in this study, there is a large amount of variability in ambient noise based on location (e.g., Ladd and Pearl and Hermes) and timing of the recordings (winter versus summer). Recordings from Hawaii from the 1940s were collected during daytime and in average sea states 1–2, but the exact location and depth of those recordings is not known (Johnson and Johnston, 1944). Likewise, the recordings from Cato (1976) were collected at variable depths and during an unknown time of the year. The ambient noise levels recorded during those studies fall within the ranges recorded in our study (61–72 dB re: 1 μPa^2/Hz at 100 Hz), but the variables that cannot be accounted for (e.g., different location, variation in depth or time of year of recording) currently make it impossible to accurately estimate long-term trends in the ambient noise in the central or western Pacific through the comparison of previously made recordings with the recordings described here. For a meaningful comparison of ambient noise over time, it would be crucial to exactly replicate temporal and spatial sampling of the original recording locations (McDonald *et al.*, 2006a).

A. Biological sounds

Cetacean and potential fish sounds were important components of ambient noise at different temporal scales. Baleen whale sounds were seasonally important contributors at a variety of frequencies. Humpback whales are seasonally present off Hawaii where they come to mate during the winter

(Au *et al.*, 2000), and our recordings reflect that same seasonal trend. The humpback whale contribution to the ambient noise was higher in Kauai than Kona, indicating that possibly more animals were located near Kauai. Neither of these locations is prime humpback habitat in Hawai'i, as the highest abundances are usually observed in the vicinity of Maui, Moloka'i, and Lana'i (Mobley *et al.*, 1999).

Northeast Pacific blue whales are found along the west coast of North and Central America (Mate *et al.*, 1999; Calambokidis *et al.*, 2009). Their sounds have been recorded off southern California and in the Eastern Tropical Pacific (ETP) starting in late summer and peaking during early winter (Stafford *et al.*, 1999; Oleson *et al.*, 2007). The timing of the occurrence of the calls in Palmyra matches the start of the calls in southern California and the ETP. The other blue whale call type, central north Pacific, has been recorded across the central Pacific from Hawaii to Wake and north to the Gulf of Alaska (McDonald *et al.*, 2006b). It is interesting that while these calls were recorded at Ladd, at a site nearby, Pearl and Hermes, where we had a more complete year of data, these calls were not present. This difference is likely the result of the exposure of these two instruments to different regions: Ladd HARP was facing open waters to the north and Pearl and Hermes HARP was facing southeast.

Fin whales were the cause of the largest increase in levels at a specific frequency band due the biological noise with up to 11 dB seasonal increase at Palmyra, while blue whales at Wake and humpback whales at Kauai caused increases up to 8 dB, albeit at very different frequencies. Distant shipping caused an increase of 7–13 dB at lower frequencies at most of these remote sites; this is comparable to the increase due to shipping in the eastern Pacific Ocean in the 1960s (McDonald *et al.*, 2006a). Given the subsequent increase in shipping noise in the eastern Pacific and the ability of baleen whales to maintain their sound levels above ambient noise in that environment (McDonald *et al.*, 2006a), it seems possible that shipping noise would not cause a major masking problem for baleen whale sounds in these regions.

In addition to identifiable cetacean sounds, one other biological, likely fish sound at variable frequencies between 100 and 900 Hz, was detected at five of the sites (Kona, Kauai, Ladd, Palmyra, and Saipan). At three sites the levels in frequency band associated with this signal (100–500 Hz) peaked just after sunset, while at the other two sites the peak was less strong, but it also occurred during the night. Diel patterns in low frequency ambient noise (around 100 Hz) have been reported previously, but in those recordings the maximum levels occurred around midnight (Wenz, 1961). The frequency range and diel pattern in the occurrence of this sound suggest a fish sound source (Širović *et al.*, 2009). Further investigation, however, is needed to confirm the source of the diel increase in ambient noise levels in the 100–500 Hz band across these sites.

V. CONCLUSION

Overall, ambient noise at these seven sites was lower than reported for most other locations in the North Pacific. Some of the areas where these recordings were collected, such as Wake, Ladd, or Palmyra, are among the least noisy parts of the Pacific Ocean measured so far. Spectrum levels at frequencies below 100 Hz were equivalent to those predicted for remote or light shipping, indicative of the locations of most of these sites well outside of the major shipping lanes in the northern Pacific Ocean. At frequencies where most of the energy comes from wind (>200 Hz), higher levels recorded in the winter than in the summer were consistent with the seasonal variation in wind patterns in the northern hemisphere.

There have been rising concerns about the impacts of increasing noise in the ocean on marine mammals (Southall *et al.*, 2007; Hildebrand, 2009; Moore *et al.*, 2012), and these quiet locations could serve as potential refuges from the noise. While many factors drive the distribution of cetaceans (e.g., prey availability, temperature, etc.), we do not understand how noise may impact their distribution. A detailed analysis of the presence of baleen whales in these areas in relation to ambient noise, given the high variability in ambient noise across sites, could offer useful insights into the implications increasing ambient noise may have on these species.

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