# Increases in deep ocean ambient noise in the Northeast Pacific west of San Nicolas Island, California

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Recent measurement at a previously studied location illustrates the magnitude of increases in ocean ambient noise in the Northeast Pacific over the past four decades. Continuous measurements west of San Nicolas Island, California, over 138 days, spanning 2003–2004 are compared to measurements made during the 1960s at the same site. Ambient noise levels at 30–50 Hz were 10–12 dB higher (95% CI=2.6 dB) in 2003–2004 than in 1964–1966, suggesting an average noise increase rate of 2.5–3 dB per decade. Above 50 Hz the noise level differences between recording periods gradually diminished to only 1–3 dB at 100–300 Hz. Above 300 Hz the 1964–1966 ambient noise levels were higher than in 2003–2004, owing to a diel component which was absent in the more recent data. Low frequency (10–50 Hz) ocean ambient noise levels are closely related to shipping vessel traffic. The number of commercial vessels plying the world's oceans approximately doubled between 1965 and 2003 and the gross tonnage quadrupled, with a corresponding increase in horsepower. Increases in commercial shipping are believed to account for the observed low-frequency ambient noise increase. 
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## I. INTRODUCTION

Deep ocean ambient noise has been predicted to be increasing over the past few decades due to anthropogenic sources (National Research Council, 2003). Increases in the number, size, speed, and horsepower of commercial ships led Ross (1976, 1993, and 1974) to predict that ocean ambient noise levels at low frequencies (10–150 Hz) had increased 15 dB between 1950 and 1975. At frequencies above about 150 Hz, ocean ambient noise levels are dominated by wind driven surface waves (National Research Council, 2003). At frequencies below 5 Hz, the dominant noise source is microseisms (Webb, 1998).

In the 1960s, the US Navy conducted ambient noise measurements using cabled hydrophones at a series of deep ocean sites off the west coast of North America (Wenz, 1969). These sites were situated at water depths of about 1000 m and were coupled to the deep sound channel. Measurements of ocean ambient noise in the deep sound channel are a summation of sound sources across the ocean basin plus local noise. Andrew *et al.* (2002) re-examined one of those sites off Point Sur, on the coast of central California, providing an ocean ambient noise level comparison spanning nearly four decades. They found about a 10 dB increase in ambient noise level in the 20–80 Hz range which they attribute primarily to increases in commercial shipping. This study reports on changes in ambient noise from measurements made west of San Nicolas Island, off the coast of southern California, a site previously characterized by Wenz (1968a).

## II. MEASUREMENTS, 1960s AND NOW

### A. Cabled hydrophone recordings, 1964–1966

A cabled seafloor hydrophone array is located on the continental slope approximately 80 km southwest of San Nicolas Island, California (Fig. 1). This hydrophone array was part of the US Navy's sound surveillance system, and is referred to as San Nicolas South. An ocean ambient noise study was conducted using this array from January 1964 through June 1966 by making magnetic tape recordings from a single hydrophone channel. A detailed analysis of these ambient noise data was reported by Wenz (1968a) in which analog filters were used to analyze 200 s segments of data three times each hour over the entire 30 months of data. Analyses included distributions, means, standard deviations, and variability by time of day, by month, and by year. Wenz (1969) also discusses transient events and compares this site with four other sites labeled Point Sur, Coos Bay, Pacific Beach North, and Pacific Beach South. Wind speed, shipping departure time data, and biological sources were considered in an attempt to explain the significant diel (day/night) and other temporal variations in these data.

Transient signals, including ships passing nearby, greater than 3 dB above ambient noise were examined by Wenz (1968a) for the San Nicolas South data. About 10% of the data contained transients more than 3 dB above the back-

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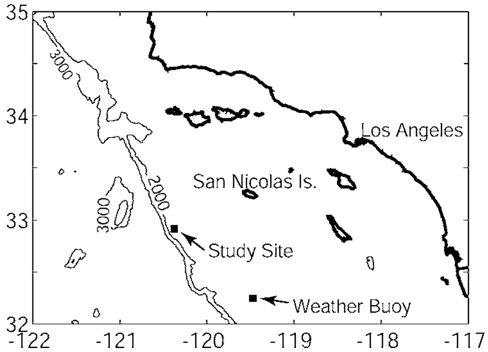


FIG. 1. Location of the ambient noise study site off southern California, west of San Nicolas Island. Bathymetric contours (2000 and 3000 m) delineate the continental shelf. A nearby weather buoy gives detailed information on wind and wave conditions.

ground average and were removed from the analysis, yet the overall average was changed by less than 1 dB by doing so.

### B. Autonomous hydrophone recordings, 2003–2004

A seafloor autonomous acoustic recording package (ARP), similar to that described by Wiggins (2003), was used to collect ambient noise data during 2003–2004 at the same site as Wenz's 1964–1966 cabled hydrophone measurements. The recorder was deployed at location 32° 54.932′ N, 120° 22.580′ W, at a depth of 1090 m, with the hydrophone suspended 10 m above the seafloor. The San Nicolas South location used for Wenz's study is reported as 32° 54.913′ N, 120° 22.548′ W at a depth of 1106 m (Curtis *et al.*, 1999). To within the potential inaccuracies in both measurements, the ARP was at the same location as studied by Wenz (1968a). The hydrophone used by Wenz is thought to have been on or very near the seafloor, but not buried within the seafloor sediments.

Continuous recordings were made at a sampling rate of 1000 Hz from November 3, 2003 to March 19, 2004. Initial quality control and inspection of the data was conducted by producing spectrograms as 5 min average spectra in 1 Hz bins. Review of the data in this form revealed no evidence of instrumental problems throughout the recording period. In high current areas (>2 kts) mechanical noise is induced by flow and strum on the hydrophone, but at this site, as is typical of most deep water sites, there is no evidence of flow noise. As with all near seafloor acoustic recorders, there are occasional "fish bumps" or brief impulsive sounds of unknown, possibly biological origin (Buskirk, 1981). Other common transient sounds can be readily classified as blue whales, fin whales, humpback whales, ships, and low frequency active sonar. There is no distinct evidence of fish sounds.

Transients due to nearby ships were not removed in the 2003–2004 data analysis as these are uncommon events. Also, based on Wenz's evaluation of transient impact (1968a), we do not believe shipping transient removal would significantly change the average ambient noise levels at this site, especially since this site is in relatively deep water and outside major shipping lanes.

### C. Calibration

ARP calibration was conducted using a reference hydrophone at the U. S. Navy's Transducer Evaluation Center facility in San Diego (TRANSDEC), to verify the theoretical calibration which was based on nominal component specifications. Calibration was conducted from 10 to 250 Hz. These calibrations were extrapolated (from 230 to 470 Hz) to account for the sampling limit of the recorder used in this study. Differences between the actual instrument used for measurements at the San Nicolas South site and the one tested at TRANSDEC are expected to be less than 1 dB, due to slight differences in hydrophone sensitivity and circuitry. The ARP hydrophone consisted of six Benthos AQ-1 elements electrically joined and effectively colocated to make one effective hydrophone. Corrections for hydrophone pressure and temperature at the seafloor site were not included. Manufacturer's specifications for these corrections and with independent testing (Lastinger, 1982) suggest these corrections are less than 0.5 dB for the data presented in this study.

The calibration testing showed the theoretical response of the instrument to be within 1 dB of the measured response. The seafloor recorder is not expected to have a meaningful response below 2 Hz. The high frequency rolloff of the recorder used at San Nicolas South begins at 470 Hz, and provides 30 dB/octave of protection from aliasing. The noise floor of the instrument is approximately 53 dB re 1 $\mu\mathrm{Pa}^2/\mathrm{Hz}$.

### D. Spectral averaging

To be consistent with the analysis of Wenz (1968a), 200 s of data were used for each spectral average. Wenz used only three averages per hour, presumably because of data processing limitations, while this study used continuous data with no overlap between spectral averages, processed with a Hanning window. All of the spectra were calculated in 1 Hz bins, however, when a direct comparison to Wenz's data was desired, 1/3 octave band levels were computed from the 1 Hz bin data. The 1 Hz bin data provide more detailed information to help identify sound sources and presumably would have been used by Wenz, if the computational technology had been readily available at the time.

## III. RESULTS

Average pressure spectrum levels for the 4.5 months recorded in 2003–2004, were elevated at low frequencies, when compared to averages for the 30 month period recorded in 1964–1966 (Fig. 2). Ambient pressure spectrum levels at low frequencies (30–50 Hz) were 10–12 dB higher in 2003–2004. Level comparisons in the 10–30 Hz band are complicated by whale calling. Above 50 Hz the differences between recording epochs decrease, and were only 1–3 dB at 80–200 Hz. Above 200 Hz the 1964–1966 average ambient spectrum levels were higher than those in 2003–2004, owing partially to a diel component in the 1964–1966 data (discussed later), which was absent in the recent data.

One approach to estimating uncertainty in the average spectrum levels for 2003–2004 is by combining an estimated 95% confidence interval for the calibration errors of 1 dB

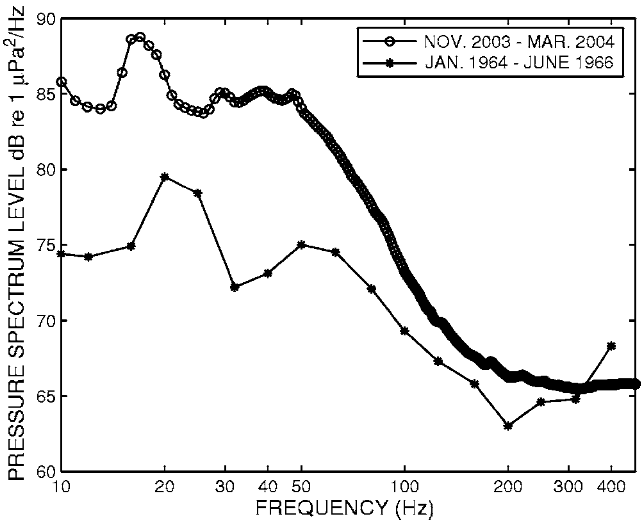


FIG. 2. Mean pressure spectrum levels (1 Hz bins) at the San Nicolas South site for November 2003 to March 2004, compared to January 1964 to June 1966. Band level averages were reported by Wenz (1968a, 1968b) as corrected to units of pressure spectrum level.

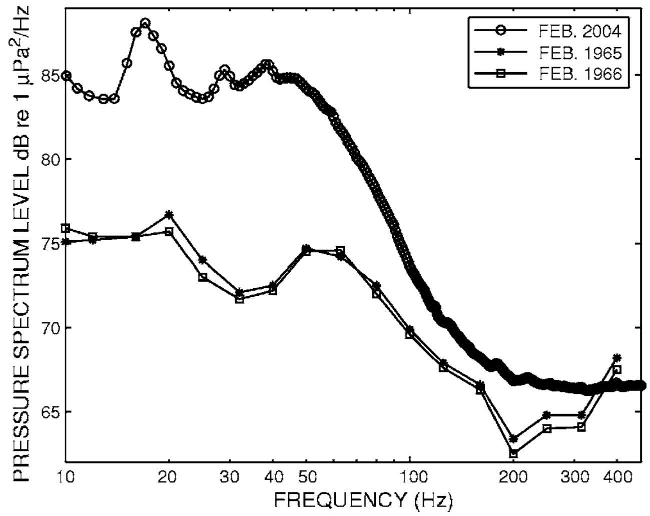


FIG. 3. Sound pressure spectrum levels (1 Hz bins) for the month of February 2004 compared to February 1965 and 1966. During February blue whales are absent from this site and the peak near 17 Hz in 2004 is from fin whale calls.

with the year to year variability of each months average level for the 30 months of data collected by Wenz. At 40 Hz, the standard deviation of the year to year comparison for each monthly average level in the Wenz data is 1.2 dB. Combining these two independent uncertainties as $\sqrt{(1.96^{*}1.2)^2+1^2}=2.6$ dB as a 95% confidence interval on a one month average spectrum level. This approach is considered to provide a high estimate of actual uncertainty because it assumes a one month duration sample is required to provide an independent estimate of ambient noise. If only one week were required to produce an independent estimate of ambient noise, then the 1.2 dB would be divided by $\sqrt{4}$, four being the number of independent measurements in one month. Changes in weather may be the longest duration factor in determining what defines an independent measurement.

Seasonal differences in ocean ambient levels occur due to seasonal changes in wind driven waves, biological sound production, and shipping route changes. The strongest seasonal signal at the San Nicolas South site is due to blue whale singing (Burtenshaw *et al.*, 2004), which appears primarily as a broad peak near 20 Hz in the spectral data. Blue whales are known to be present at this site only from June through January, while fin whales are present year-round (Oleson, 2005). February through May there are no blue whales calls present, although fin whales calls are still evident (Fig. 3) in the 2003–2004 data. Fin whale calls produce a 3 dB peak of spectral energy near 16–18 Hz in the February 2004 data, but their calls are not obviously present in the February 1965 and 1966 data. Excluding the band of fin whale calling, the average February 2004 ambient pressure spectrum level is 10–14 dB higher than the February 1965 and 1966 levels over the 10–50 Hz band (Fig. 3). Above 100 Hz, there is only a 1–2 dB difference between the two sets of February noise data.

A comparison of recordings between November 2003 and November 1964 and 1965 reveals a strong blue whale presence (Fig. 4). Wenz (1969) reports as much as 18 dB of signal-to-noise for these whale calls in the spectral averages at the San Nicolas South site during 1964–1966. The blue whale call levels in peak season cannot be compared because 2003 data are not available during that time period, which occurs earlier in the fall (Burtenshaw *et al.*, 2004). Year to year variability is discussed in Burtenshaw *et al.* (2004), and it is obvious that blue whale call spectrum levels have increased substantially since 1964.

A long-term shift in the frequency of the blue whale calling is seen in the plot comparing November 2003 and 1964–1965 (Fig. 4). In 2003 the spectral energy peak due to blue whale calling is near 16 Hz, whereas in 1964–1965 the energy peak is near 22.5 Hz, corresponding to the dominant blue whale call frequency at that time (Thompson, 1965).

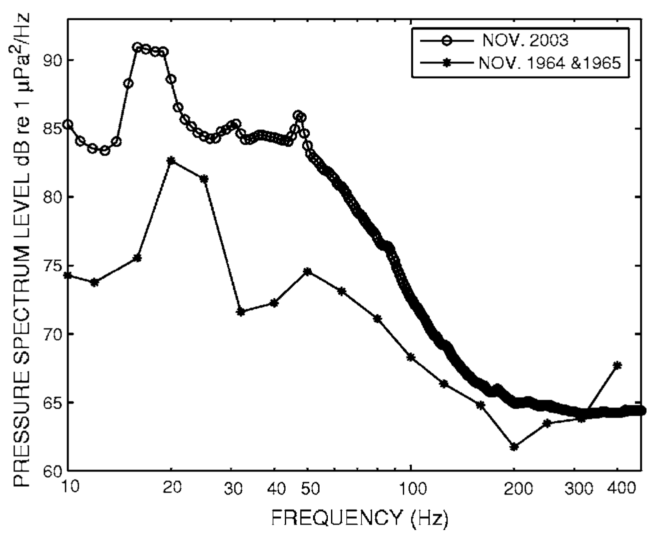


FIG. 4. Pressure spectrum level for November 2003 compared to November 1964–1965 in which blue whale calls are prominent near 16 Hz in 2003 and near 22.5 Hz in 1964–1965, illustrating a more than 30% the shift in call frequency over four decades.

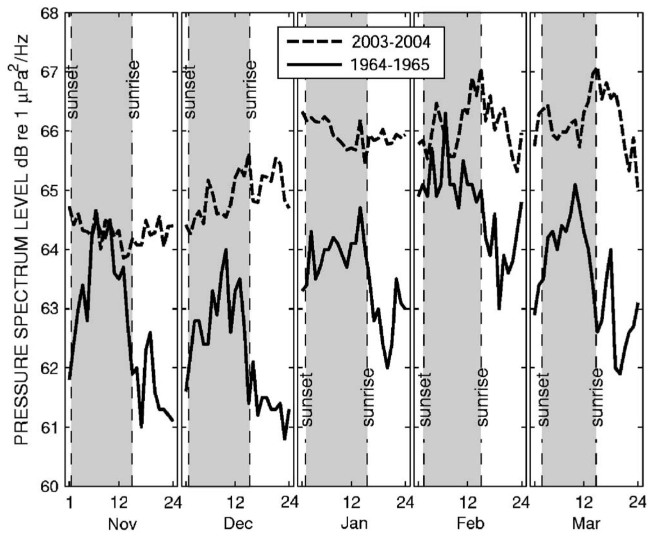


FIG. 5. Monthly averaged pressure spectrum levels at 315 Hz, plotted vs time of day (in GMT). The average band levels from 1964–1965 (solid line) are compared to 2003–2004 (dashed line) with band levels scaled as equivalent pressure spectrum levels. The hours from sunset to sunrise are shaded. Nightly chorusing, presumably from fish, is observed in 1964–1965 and is absent in 2003–2004.

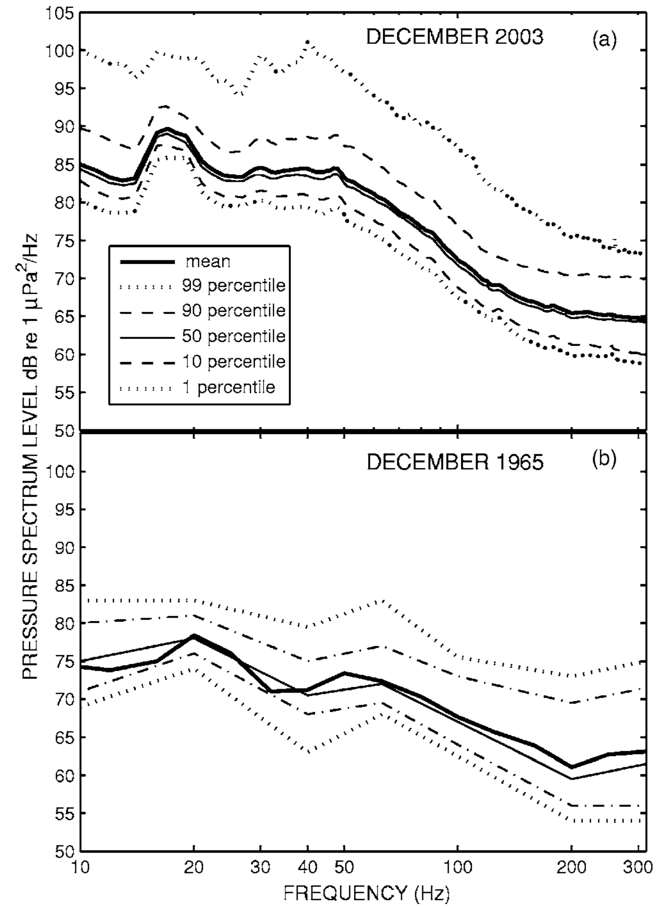


FIG. 6. (a) December 2003 cumulative distribution function for pressure spectrum levels at the San Nicolas South site. (b) December 1965 at the San Nicolas South site, after Wenz (1968a). Note the 50th percentile line does not closely track the mean because the mean was computed at 1/3 as many frequencies as the 50th percentile, each over a wider bandwidth.

Additional peaks at 32 and 48 Hz in the 2003 spectra are harmonics of the blue whale song fundamental and the 88 Hz peak is from an overtone within the blue whale song. Fin whale calls are not apparent in the average spectra when blue whale calling is as strong as occurs here in November even though from examination of the 2003–2004 data it is known that fin whale calls are present.

The 200–500 Hz frequency band displays a 2–4 dB diel variation in ambient noise for data from 1964–1966, which is absent in the 2003–2004 data (Fig. 5). In 1964–1966, higher sound pressure levels occur at night, typically with peak energy around midnight. There is no apparent seasonal change in the amount of diel variation in 1964–1966. No diel signal is observed in the 2003–2004 data. The ambient pressure spectrum level data above 200 Hz also have a seasonal increase of about 3 dB in overall level from November to January–February, both for the 1964–1966 and the 2003–2004 data sets (Fig. 5). These trends are likely related to changes in the average wind speeds with season.

Pressure spectrum levels for the San Nicolas South site in December 2003 are compared (Fig. 6) as cumulative distribution functions to the December 1965 data (Wenz, 1968a). These data for 2003 show a mean pressure spectrum level at 10–50 Hz of about 85 dB re 1 $\mu$Pa$^2$/Hz, decreasing to about 65 dB re 1 $\mu$Pa$^2$/Hz between 50–200 Hz, and remaining constant for 200–500 Hz. The spectrum level cumulative distributions are typically long tailed for higher values (Fig. 6). The ambient spectrum level 99th percentile is about 15 dB above the mean, whereas the first percentile is about 5 dB below the mean. Wenz (1968a)plotted cumulative distributions only for selected months and selected frequencies for the 1964–1966 ambient noise data, thus the distributions over the entire recording periods cannot be compared.

## IV. ANALYSIS

### A. Shipping, 10–150 Hz

The 10–12 dB increase in ocean ambient pressure spectrum level in the 30–50 Hz band at this site may be representative of the entire Northeast Pacific, and is likely related to changes in commercial shipping. Vessel operation statistics indicate a steady growth in shipping traffic over the past few decades (Mazzuca, 2001). In addition to increases in the number of commercial vessels, the average gross tonnage and horsepower per vessel has increased. Lloyd's Register (1965, 2003) indicates that the world's commercial fleet approximately doubled during the past 38 years, from 41 865 vessels in 1965 to 89 899 vessels in 2003. Moreover, during the same period the gross tonnage (GT) of commercial vessels nearly quadrupled from 160 million GT in 1965 to 605 million GT in 2003 with a similar increase in propulsion power (Ross, 1993). Also, port turn-around time is faster today resulting in more days per year spent at sea by each ship.

A doubling of the number of ships alone would explain only 3 dB of the observed noise increase, since the noise from individual ships will combine incoherently [follow a 10*log(N) increase]. Higher sound levels from at least some of the vessels are needed to explain the additional 7–9 dB increase in the 30–50 Hz band. Commercial vessel gross tonnage has been suggested as a proxy for shipping produced noise (National Research Council, 2003), but gross tonnage predicts noise increases from 1965 to 2003 of only 6 dB. Factors that can contribute to higher ship noise levels include greater average ship speeds, propulsion power, and propeller tip speeds (Ross, 1976).

### B. Whales, 15–20 Hz

The long-term noise data presented here, together with other raw recordings of blue whales (Thompson, 1965; McDonald *et al.*, in press), show that the peak energy for blue whale call frequencies have shifted downward from about 22.5 Hz in 1964–1966 to near 16 Hz in 2003 (Fig. 4). In Wenz's data the blue whale dominant frequency occurs near the boundary between the third octave bins, thus both the 20 and 25 Hz bins show the signal. The monthly or yearly averaged noise data presented here sum large numbers of whale calls (~10 000–100 000), so that the observed frequency shift is an aggregate of calling for a large segment of these whale populations. It is tempting to see the blue whale call frequency shift as a response to increased shipping noise, for instance, as a means to decrease signal loss during propagation. However, there is little change in signal attenuation between 22 and 16 Hz, even for long-range (>10 km) propagation On the contrary, a lowered fundamental call frequency would result in lowered blue whale call source levels (Aroyan *et al.*, 2000), assuming a fixed air volume during call production. Decreased call source level is counter to the expectation that call source levels would increase to compensate for increased noise (the Lombard effect). Likewise, by shifting the fundamental call frequency from above 22 to 16 Hz, the change in background noise due to shipping is negligible so it seems unlikely that increased shipping noise is the dominant cause for blue whale call frequency shifts.

The blue whale population off California, however, has been increasing (Calambokidis and Barlow, 2004). An increased population density could lead to higher whale call peak energy levels in the long-term spectral averages. Increasing call source levels in the presence of increased noise (the Lombard effect) may be another factor explaining the higher (~10 dB) whale call peak energy in 2003 compared to 1964–1966 (Fig. 4). Note that these arguments apply to fin whales as well as blue whales, since blue whales are absent from the San Nicolas South site in the spring, and the energy peak observed near 17 Hz during 2004 (Fig. 3) is due to fin whale calls, although there is no obvious fin whale peak in the Wenz data.

### C. Marine life, 40–500 Hz

Many biological sounds have diel variation, but the species responsible for each diel pattern is not always known. The character and seasonality of the sounds indicate whether the source is most likely made by crustacean, fish or whale (Fish, 1964; Edds-Walton, 1997). A 10–20 dB diel pattern, with higher intensities during the night at frequencies of 80–300 Hz, was reported west of San Clemente Island in 1963 (Wenz, 1942; 1964; Wenz *et al.*, 1965) in a water depth of 110 m (60 fathoms) in May through August. The diel pattern diminished during the fall and was absent in November and December. Observations at the same site in 1958–1959 reported biological sounds, but lacked a diel pattern. This change was attributed to changes in the abundance of sound producing fish. Fish chorusing is known to produce as much as 40 dB of seasonal change in background ambient noise at 325 Hz (Fish, 1964).

The 3 dB nightly chorus reported for the 1964–1966 San Nicolas South data is different from that reported for a similar setting along the continental shelf located farther north (Pacific Beach, Washington) in 1964–1966 (Wenz, 1968b). The Pacific Beach site has diel variation in the 40–100 Hz band with a peak level around 0800 local time (after sunrise) and a low around 2200 local time (just before midnight). The range of seasonal and geographic variations for diel patterns exhibited at the five stations off the west coast of the United States (Wenz, 1969) are not yet fully understood, but are likely related to the presence and relative abundance of different species of sound producing fishes and crustaceans.

Humpback whale calls and song are present at frequencies greater than 200 Hz in the 2003–2004 San Nicolas South recordings, but do not contribute significantly to the ambient pressure spectrum level when averaged over monthly or seasonal time periods as these calls are too sparse to have significant impact on such a long term average. Therefore, although humpback whales are known to produce diel chorusing (Au *et al.*, 2000), they are not a probable cause of diel variations in the 1964–1966 San Nicolas South data.

Snapping shrimp noise occurs predominantly at frequencies above 1 kHz (Albers, 1965; Au and Banks, 1998), above the frequencies analyzed in this study, but may have an impact on noise levels at the San Nicolas South site when wind speeds are low. Shrimp noise increases by as much as 9 dB during the night, showing a minimum at noon and peaks just before sunrise and just after sunset (Everest *et al.*, 1948). Snapping shrimp are believed to occupy waters depths less than 55 m (Everest *et al.*, 1948), thus their noise contribution to the San Nicolas South site would be the result of sound propagation from tens of kilometers distance, from sites farther up the continental shelf. Snapping shrimp presence in 1964–1965, therefore, seems unlikely to explain the 2–4 dB of diel variation observed.

Fish choruses have been recorded in deep water hundreds of kilometers from shallow water with diel variability of 10 dB at 480 Hz (Kelly *et al.*, 1985) and probable fish sounds have been recorded at 600 m depths where the water depth was 1600 m (Mann and Jarvis, 2004). Most studies of fish sound production have, not surprisingly, focused on shallow water species, but it may be that deep water fish species are responsible for the observed diel variation and increased average ambient levels observed by Wenz in 1964–1965, which were absent in 2003–2004 recordings.

### D. Wind driven surface wave noise, 200–500 Hz

Wind driven wave noise is an important contributor to ocean ambient noise in the 200–500 Hz band (Ross, 1976).

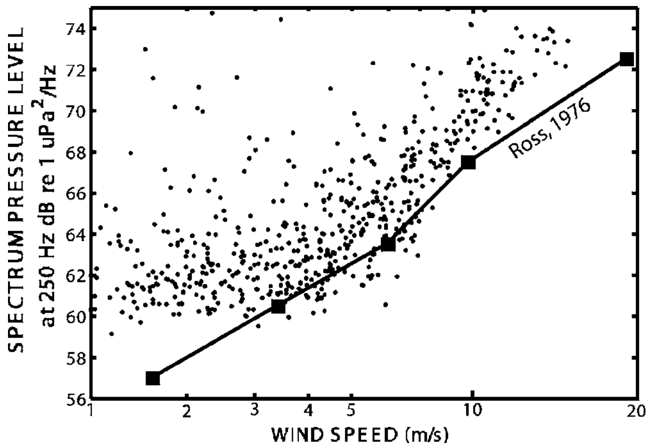


FIG. 7. Sound pressure level at 250 Hz for the San Nicolas South site vs hourly mean wind speed during November, 2003 at Tanner Bank (NDBC buoy 46047). The influence of wind driven wave noise is apparent above 6 m/s (11.7 kts). The Ross (1976) predicted mean ambient spectrum level at 250 Hz for sea surface agitation corresponding to wind speed is shown.

Wenz (1969) compared wind data for five northeast Pacific sites and suggested wind was the primary cause for differences in average ambient noise levels above 200 Hz. Assuming the observed increases in ambient noise are representative, the breakpoint between shipping and wind dominated noise has probably now moved well above 200 Hz. Wind data relevant to the San Nicolas South site are available from a National Data Buoy Center (NDBC) weather buoy on Tanner Bank (Fig. 1), approximately 110 km to the southeast (NDBC buoy 46047, 32.43 N 119.53 W). To test for dependence of ambient noise on wind, sound pressure levels at 250 Hz were plotted as a function of wind speed for the 2003–2004 San Nicolas South data (Fig. 7). The 110 km separation between the wind and the ambient noise recording sites may result in some error, but a correlation between wind speed and ambient noise is apparent above 6 m/s (11.7 kts). The wind related ambient noise levels from Ross (1976) are plotted in Fig. 7. A correlation between satellite derived wind speeds and ambient noise levels was previously reported for the San Nicolas South site (identified as site *f*) by Curtis *et al.* (1999).

In an attempt to understand the contribution of wind to the differences in ambient noise levels between 1964–1966 and 2003–2004, shown in Figs. 2–4, wind data from the two recording periods were compared. The mean wind speed reported from the Historical Wind Speed data base of the National Climatic Data Center from ship observations for the one degree grid block containing the San Nicolas South site was 7.0 m/s (13.7 kts) during November through March of 1963–1966. Wind data for 2003–2004 (from NDBC buoy 46047) show average wind speeds during the recording period of 5.7 m/s (11.0 kts). Wind speed during the recording period was lower than the 1991–2001 average wind speed of 6.4 m/s (12.5 kts) for November through March at NDBC buoy 46047. Although the 1964–1966 wind data come from different measurement methods and different locations, it appears the 2003–2004 recordings were made during a period of relatively low average winds. As an approximate correction Fig. 7 was examined, where a shift in wind speed from 5.7 to 7.0 m/s along a linear regression yields about 2.6 dB of increased ambient noise. This suggests that the observed increase in ambient noise at 250 Hz (1–3 dB) between 1964–1966 and 2003–2004 might have been significantly (~2.6 dB) greater if wind speeds had not been below average during the 2003–2004 recording period. A wind speed distribution analysis would be needed to more accurately predict the correction.

## V. DISCUSSION

The noise level experienced at a particular site depends on the presence of noise sources such as whales, ships, and wind driven waves combined with the losses for sound propagation between the source locations and the site location. Owing to propagation complexities, shipping noise does not directly correspond to the distribution of ships. Ship or wave generated noise from the sea surface will contribute to ambient noise levels across the entire ocean basin if it is introduced into the deep sound channel. One pathway for shipping noise to enter the deep sound channel is at locations where the sound channel intersects bathymetric features such as the continental slope (Wagstaff, 1981; Dashen and Munk, 1984; Hodgkiss and Fisher, 1990). By a process commonly referred to as down-slope conversion, noise propagating down the continental slope can readily enter the deep sound channel. Therefore, shipping lanes that traverse the continental slope will be sites for efficient conversion of noise into the deep sound channel.

Another route for noise to enter the deep sound channel occurs at high latitudes, where the sound channel shoals to intersect the sea surface (Bannister, 1986). In this setting noise produced at the sea surface by shipping or waves will enter the deep sound channel and propagate efficiently to distant sites. Great circle vessel routes (the shortest distance) put most of the shipping traffic at high latitudes in the North Pacific, passing near the Aleutian Islands. The high latitude North Pacific is a major shipping route carrying the substantial vessel traffic between ports along the west coast of North America and Asia. Shipping noise that enters the deep sound channel at high latitude will then propagate to lower latitude sites, and become a component of the ambient noise.

The San Nicolas South site is relatively quiet when compared to other North Pacific sites with noise measurements made near the axis of the deep sound channel (Wenz, 1969). The major shipping lanes pass well north of the San Nicolas South site with vessels remaining over relatively shallow water until being far from this site. Downslope conversion of ship noise from these shipping lanes would take place off central California or points farther north. The relative proximity to major shipping lanes may explain why the noise levels at Point Sur were consistently 4–8 dB higher than those at San Nicolas South (Wenz, 1969). Noise measurements at San Nicolas South may be more broadly affected by shipping at high latitudes and by downslope conversion in the Western Pacific.

If it is assumed the San Nicolas South measurements are broadly representative of changes in the Northeast Pacific deep sound channel, ambient noise has been increasing at a

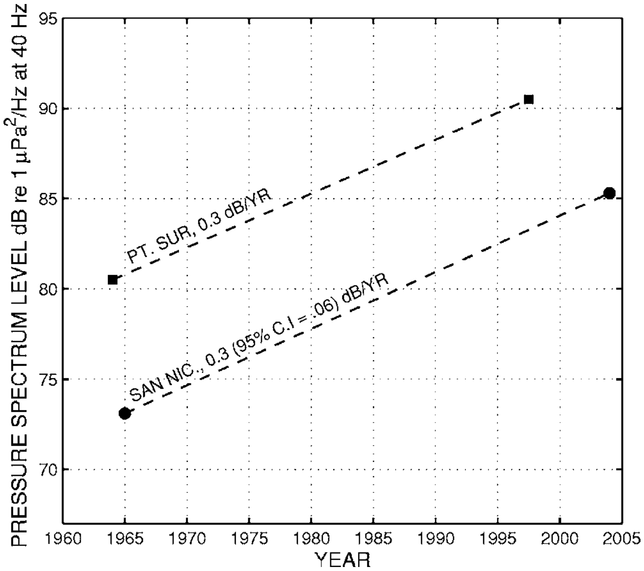


FIG. 8. North Pacific ambient noise measurements at low frequency (40 Hz) show an overall increase of about 3 dB per decade, based on repeat measurements at (●) San Nicolas South (this study) and (■) Point Sur (after Andrew *et al.*, 2002).

rate of 2.5–3 dB per decade over the past four decades in the 30–50 Hz band (Fig. 8). The repeated measurements at Point Sur, California from Andrew *et al.* (2002), and this study at the San Nicolas South site, although different in overall noise levels, have approximately the same trend for increasing ambient noise over the past few decades.

Ross (1976) argues that horsepower to the 4/3 power should be used as a rule of thumb for conversion to noise power. Ross (1976) further suggests that relatively few of the largest, and the fastest, vessels may be producing most of the noise. For instance, oil tankers and bulk dry transport vessels represent nearly 50% of the total gross tonnage, but less than 19% of the total number of vessels in the world's commercial fleet (data from Lloyd's register for 2001). Ross (1976) predicted 0.4 dB/yr noise increases (near 50 Hz) during the years 1950–1975 by adding the decibel increase due to the number of ships to 4/3 of the decibel increase in average horsepower per ship. Using these rules and further analyzing shipping data, it may be possible to match the observed increase in noise levels of about 12 dB near 40 Hz from 1964 to 2004.

Concerns have developed regarding the impacts of ocean ambient noise levels on marine mammals and other marine life (National Research Council, 2003, 2005). Characterization of the long-term changes in ocean ambient noise will require repeated measurements at multiple sites as present ship noise models may have large errors (Heitmeyer *et al.*, 2004), and will need to incorporate empirical measurements for validation (Etter, 2003). These measurements of ambient noise at a site west of San Nicolas Island, California, combined with studies by Andrew *et al.* (2002) and Ross (1976) suggest that low frequency ambient noise within the North Pacific deep sound channel has increased by at least 15 dB since 1950.


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