PAPER

Broadband Acoustic Environment at a Tidal Energy Site in Puget Sound

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ABSTRACT

Admiralty Inlet, Puget Sound, Washington, has been selected as a potential tidal energy site. It is located near shipping lanes, is possibly a highly variable acoustic environment, and is frequented by the endangered Southern Resident killer whale (SRKW). Resolving environmental impacts is the first step to receiving approval to deploy tidal turbines. Several monitoring technologies are being considered to determine the presence of SRKW near the turbines. Broadband noise level measurements are critical for determining design and operational specifications of these technologies. Acoustic environment data at the proposed site were acquired at different depths using a cabled vertical line array from two cruises during flood and ebb tidal periods in May and June 2011. The ambient noise level decreases approximately 5 dB re 1 μPa per octave for frequency ranges of 1-70 kHz and increases approximately 5 dB re 1 μPa per octave for the frequency from 70 to 100 kHz. The difference between noise pressure levels in different months varies from 10 to 30 dB re 1 μPa for the frequency range below 70 kHz. Commercial shipping and ferry vessel traffic were found to be the most significant contributors to sound pressure levels for the frequency range of 1-50 kHz, and the variation could be as high as 30 dB re 1 μPa. These noise level measurements provide the basic information for designing and evaluating both active and passive monitoring systems proposed for deployment and operation of a tidal power generation alert system.

Keywords: underwater acoustics, noise measurement, sound propagation, tidal power

Introduction

Underwater ambient noise research has a long history and began during World War II, as a result of the availability of calibrated instruments and a critical need to understand the performance of active and passive sonar systems. Knudsen et al. (1948) and Urick and Pryce (1954) summarized most of the wartime research. The classic paper by Wenz (1962) was notable, as it supplied a graphical spectrum of omnidirectional noise levels versus frequency from sources including wind, rainfall, shipping, and biota. The growth of the offshore (wind, wave, tidal) renewable energy industry in recent years has focused concern on the potential impact of a variety of machine factors, including noise, on marine biota. Public concern about the potential impact of human activity on marine life has stimulated a renaissance of ambient noise studies as one of the most important areas of study in underwater acoustics and acoustical oceanography (Halpern et al., 2008; Richardson et al., 1995; Dahl et al., 2007; Hildebrand, 2009; Tougaard et al., 2009; Martinez et al., 2011).

Admiralty Inlet in northern Puget Sound has been selected by Snohomish County Public Utility District as a pilot site for the deployment of two OpenHydro hydrokinetic turbines because of its strong tidal current. Puget Sound is a large, fjordal system occupied by a variety of commercial and recreationally important species and is home to an endangered population of *Orcinus orca*—the Southern Resident killer whale (SRKW) (Krahn et al., 2002). Quantifying and resolving potential environmental impacts is a first step to receiving approval to deploy these turbines in Admiralty Inlet.

Of particular concern is the potential for blade strike or other negative interactions between the SRKW and tidal energy devices. A variety of technologies including passive and active monitoring systems, are being considered as potential tools to determine the presence of SRKW in the vicinity of the proposed test sites. Our work to develop a passive monitoring system involves modification to an energy-based juvenile salmon acoustic telemetry system (McMichael et al., 2010; Weiland et al., 2011; Deng et al., 2011). Broadband ambient and turbine system noise level measurements are therefore critical for determining design and operation specifications for the monitoring systems (Urick, 1983; Burdic, 1990).

Ocean noise modeling is a complicated subject. Evaluation and estimation of the acoustic environment at certain locations has been relying heavily on continuous surveys and measurements, by using data from Wenz (1962) as reference values to understand the deviation from the general ocean environment for better prediction (Andrews et al., 2002; McDonald et al., 2006, 2008).

A team from the Northwest National Marine Renewable Energy Center has been using a variety of instruments to collect ambient acoustic data in Admiralty Inlet during the past 2 years (Bassett et al., 2010). However, these data covered frequencies up to only 40 kHz. For our proposed passive and active monitoring systems, the possible frequency range extends up to 75 kHz for the passive system and 200 kHz for the active system, resulting in the requirement of measurements at higher frequencies.

Acoustic environment data at the proposed site were acquired at different depths using a cabled vertical line array (VLA) from three different cruises during flood and ebb tidal period in February, May, and June 2011. The preliminary results from the February cruise have been reported in Xu et al. (2011). In this paper, we describe the broadband sound pressure level (SPL) measurements at the Admiralty Inlet site at different depths with frequencies ranging from 1 to 100 kHz in combination with other information during high tidal periods from the other two research cruises carried out in May and June 2011.

Experimental Methods

A cable-hydrophone system was employed for both cruises because of its simplicity for assembling and flexibility to be used with available data acquisition systems. In this section, we first introduce the hydrophones, ocean environmental sensors, and data acquisition systems and then give a brief description of the measurements made during each cruise.

Hydrophones

Reson TC4014-5 and TC4032-5 hydrophones were deployed during both cruises, and additional Reson TC4032-1 hydrophones were deployed during the June cruise. The TC4032 has a sensitivity of −170 dB re 1 V/μPa and frequency range of 5 Hz to 120 kHz (TC4032-1) or 100 Hz to 120 kHz (TC4032-5). The TC4014-5 has a sensitivity of −186 dB re 1 V/μPa and usable frequency range of 15 Hz to 480 kHz. Each hydrophone was individually calibrated by the manufacturers for the frequency range of 250 Hz to their usable frequency ranges. They were also recalibrated in-house in a water test tank lined with anechoic material for frequencies above 10 kHz (Deng et al., 2010).

For each cruise, the hydrophones were combined to form a VLA. For the May cruise, the VLA was deployed directly off the aft end of the vessel using a braided nylon rope as a tension member. A buoy was used to secure the VLA to the vessel. This configuration allowed the decoupling of the VLA from the motion of the vessel to remove a potential source of noise. For the June cruise, the braided nylon rope was replaced by a haired fairing with 3.8-cm to 5.1-cm polyester fibers on four sides of an aramid rope to reduce any potential noise associated with cable strumming, although based on the currents and the cable diameter we would expect the strumming noise to be below 500 Hz.

Ocean Environmental Sensors

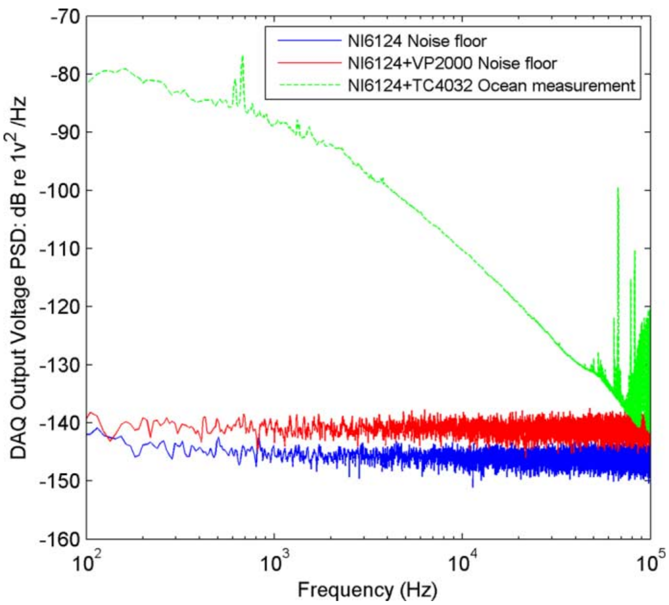
To monitor the depth of the VLA and the temperature and salinity of the ocean environment, a Seabird MicroCat SB37 and multiple Onset temperature and depth sensors were attached to the cabled array. All of these instruments were self-contained. The sampling rates of the OnSet sensors and SB 37 were set up at their maximum values during the deployments at 1 and 0.16 Hz, respectively.

Data Acquisition Systems and Sampling Strategy

The sound pressure data from each hydrophone were collected using a National Instruments (NI) PXIe-6124 data acquisition system (DAQ) with 16-bit analog-to-digital converters, acquiring data at a sampling rate of 2.5 MHz with an input voltage range of ±1 V. Reson VP2000 (EC6081) 1 MHz bandwidth voltage preamplifiers with bandpass filters were used in conjunction with the data acquisition systems, which were designed for use with piezoelectric hydrophones. The low pass filter with cutoff frequency of 1 MHz was applied. The PXIe-6124 has a noise floor of −147 dB re 1 V^2/Hz at the 2.5-MHz sampling rate with an input voltage range of ±1 V. The self-noise floors of the data acquisition systems determine the lowest SPL each specific hydrophone could measure. Figure 1 shows the noise floor of the DAQ and a sample ocean measurement at 2.5 MHz sampling rate. The noise floor of the PXIe-6124 connected to the VP2000 preamplifiers with the input grounded was approximately −140 dB. The sample ocean measurement from the quietest period was

FIGURE 1

The data acquisition system's noise floor and a sample ocean measurement from a quiet period at 2.5 MHz sampling rate.



above the system noise floor in the frequency range of 100 Hz to 100 kHz so the measurements were not limited by the DAQ system noise floor in this frequency range.

For the May cruise, a data acquisition code was implemented to collect four channels simultaneously on a single NI PXIe-6124 for 20 continuous seconds and a duty cycle up to 91%. During the June cruise, the sampling duration was improved to 30 continuous seconds with the duty cycle up to 95%.

General Description of Two Cruises

Both cruise times were chosen during either high ebb or flood tide periods in Admiralty Inlet for this investigation. During each cruise, the VLA, assembled with hydrophones and other environmental sensors, was deployed from a ship platform (the *R/V Robertson*, operated by Applied Physics Laboratory, University of Washington) at a site where the water depth was around 55 m, approximately 1 km offshore from Fort Casey in Admiralty Inlet. To avoid contamination from any sound sources other than the ocean environment, the boat engine was shut off, and the boat was allowed to drift freely until it drifted too far away from the target site. Depending on the strength of the tides and current, each drift lasted from around 20 to 40 min. The acoustic measurements were carried out during each drift. The details of each drift track and shipping traffic information obtained from Automatic Identification System (AIS) data (May only) were superimposed onto the bathymetry map of north Admiralty Inlet (Figure 2). The AIS data were not available for the June cruise due to a system failure of the AIS receiver installed at Fort Casey State Park.

During the May cruise, conducted during a high ebb tide to determine how the tidal currents possibly cause increases in noise levels, an acoustic Doppler current profiler (ADCP)was turned on and off throughout most of the cruise. Only the last drift, drift 6, was clean without ADCP. Three pressure sensors with temperature (OnSet) and conductivity (Seabird 37) were attached to the VLA to record the conditions at the hydrophone deployment depth to measure the background sound speed profile.

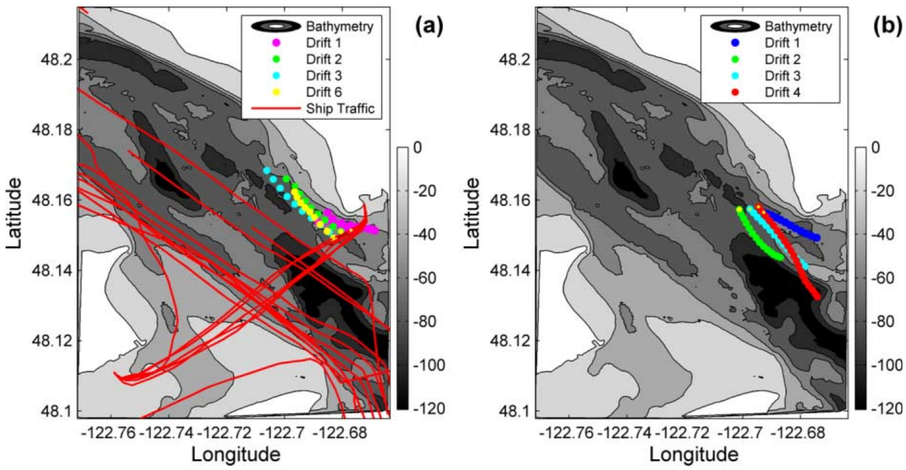
The June cruise was conducted during a flood tide, and an additional deployment was conducted to have a TC4014-5 hydrophone continuously deployed up and down throughout the cruise to measure the SPL through the entire water column. Pressure sensors with temperature (OnSet) and conductivity (Seabird 37) were attached directly below the TC4014-5 hydrophone to obtain more complete sound speed profile measurements.

Data Analysis

Welch's method (Welch, 1967) was used to process all the data with a fast Fourier transform (FFT) length of 262,144, Hanning window, and 50% overlap for the averaging, which corresponds to an approximate 0.104-s time window of data. The frequency bin size was approximately 9.54 Hz. Each dataset was analyzed for 1-s period and averaged over its sampling length, which was 20 s for the May cruise and 30 s for the June cruise. Therefore, the power spectrum density (PSD) of SPL presented in the following section corresponds to the power spectrum of a 1-Hz frequency band. The averaged PSD for each drift is the arithmetic average of the PSDs from the 20-s estimation of the May cruise and the 30-s estimation of the June cruise in the spectral space.

FIGURE 2

Bathymetry map of the north Admiralty Inlet overlapped with acoustic survey site locations and ship traffic (ship traffic not available on June 9, 2011). The colored dots indicate the acoustic sampling location points. The different colors indicate the different drifts. (a) May 10, 2011. (b) June 9, 2011. (Color versions of figures available online at: http://www.ingentaconnect.com/content/mts/mtsj/2012/00000046/00000002.)



Commercial shipping and ferry vessel traffic were found to be the most significant contributors to ambient noise levels at this site. Post-processed data from the AIS, which tracks ship movement, was used to determine the location of ships during each recording. However, AIS data were not available during the third cruise in June.

Results and Discussion

The depths of the hydrophones on the VLA varied during each of the individual drifts for each cruise (Figure 3) due to the strong current and drifting of the research vessel. This was especially evident for the hydrophones at the deeper depths. During the May cruise, for drifts 1-3 and 6, three depth sensors were deployed with the VLA (Figure 3a, black, red, and blue curve) and two depth sensors were deployed for drifts 3 and 4. During the June cruise, three depth sensors were attached to the static VLA (Figure 3b).

May Cruise

The PSD of SPL data from the May cruise data are shown (Figure 4) for four drifts using the TC4032. Two sets of SPL data from the hydrophones are displayed in the following way: the averaged PSD of SPL data for the entire drift (dark blue curves) are overlaid with all the data on PSD of SPL averaged for every 20 s during that drift with clouds of dots. Thus, Figure 4 shows both the averaged measurement result and the spread of the measurements during that drift.

During all of the drifts, the shipping traffic contributed to the narrowband signal in the frequency range of 100 Hz to 10 kHz, consistent with the AIS recording of the relatively busy traffic during the survey period. Drifts 2 (Figure 4b) and 3 (Figure 4c) were conducted during the strongest

FIGURE 3

Depth measurements from different sensors during each cruise. (a) 10 May 2011. (b) 9 June 2011. The different colors indicate the depth measurement from different sensors assembled on the VLA.

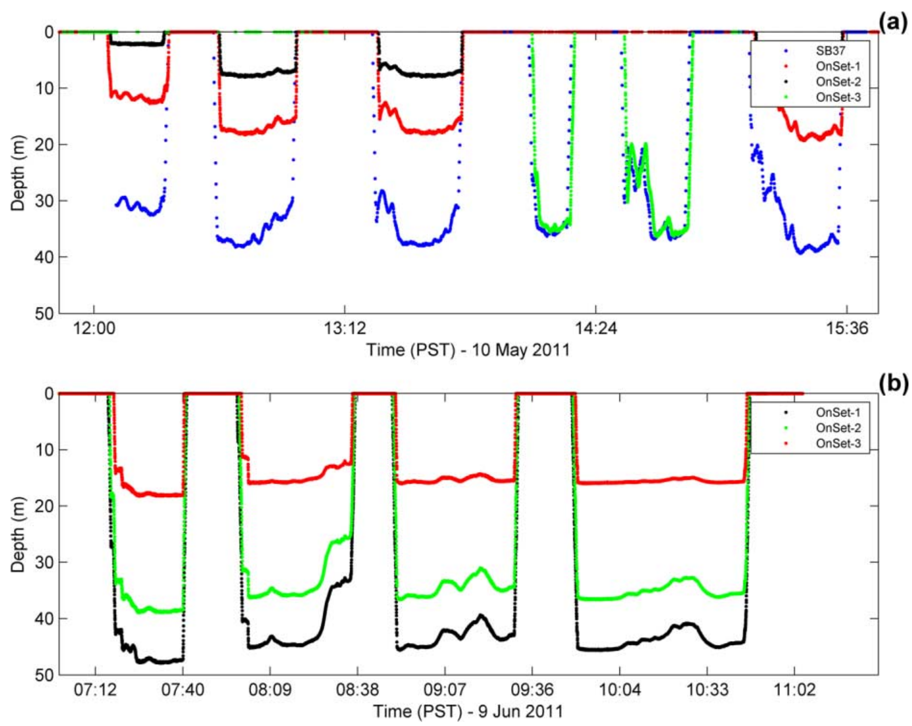
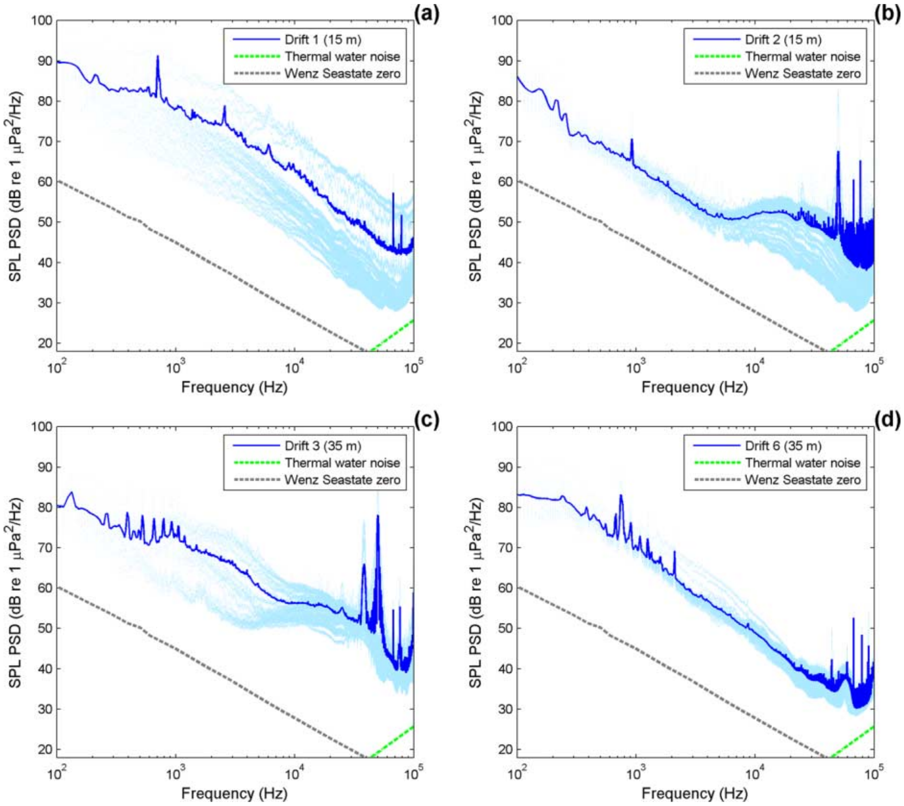


FIGURE 4

PSD of SPL measured during the May 10 cruise: (a) Drift 1, (b) Drift 2, (c) Drift 3, and (d) Drift 6. The blue solid lines in each panel correspond to the average result of each drift from the TC4032, respectively; the cloud of dots indicates the average result from each 20-s section data during each drift.



tide period with an ADCP being operated on and off during the drift. There were two tonal signals at 35 and 50 kHz when the ADCP was on even though its operating frequency was 307 kHz. The measurements of both drifts show the similar broadband signal structure at the frequency range of 7-50 kHz. Especially for drift 2, the SPL variations range about 30 dB in the dot-cloud plots. Drift 2 corresponded to the time frame from 12:30 PM to 1:00 PM, which was the beginning of strongest ebb tide for that day. The broadband signal variations from drift 2 were stronger than those from drift 3 and could possibly be caused by the strong tide moving around the cobbles or other seabed load in the beginning of the ebb tide and settling down after that (Mason et al., 2007). Finally, the measurements from all four drifts show that the averaged PSD of SPL decreases 5 dB per octave in the frequency band between 1 and 70 kHz.

June Cruise

Figure 5 shows the PSDs of SPLs from four drifts from the June cruise. The measurements of the hydrophones from two depths with vertical separation of about 30 m in water depth from surface are shown in a manner similar to that of the May cruise data (Figure 4), with both the averaged result for the entire drift (in curves) and all the single measurements for the 30-s time durations (dot-cloud). The PSD of SPL shows consistently higher SPLs from the deep hydrophone than those from the shallow hydrophone. The difference is about 5-10 dB in the frequency band up to 70 kHz.

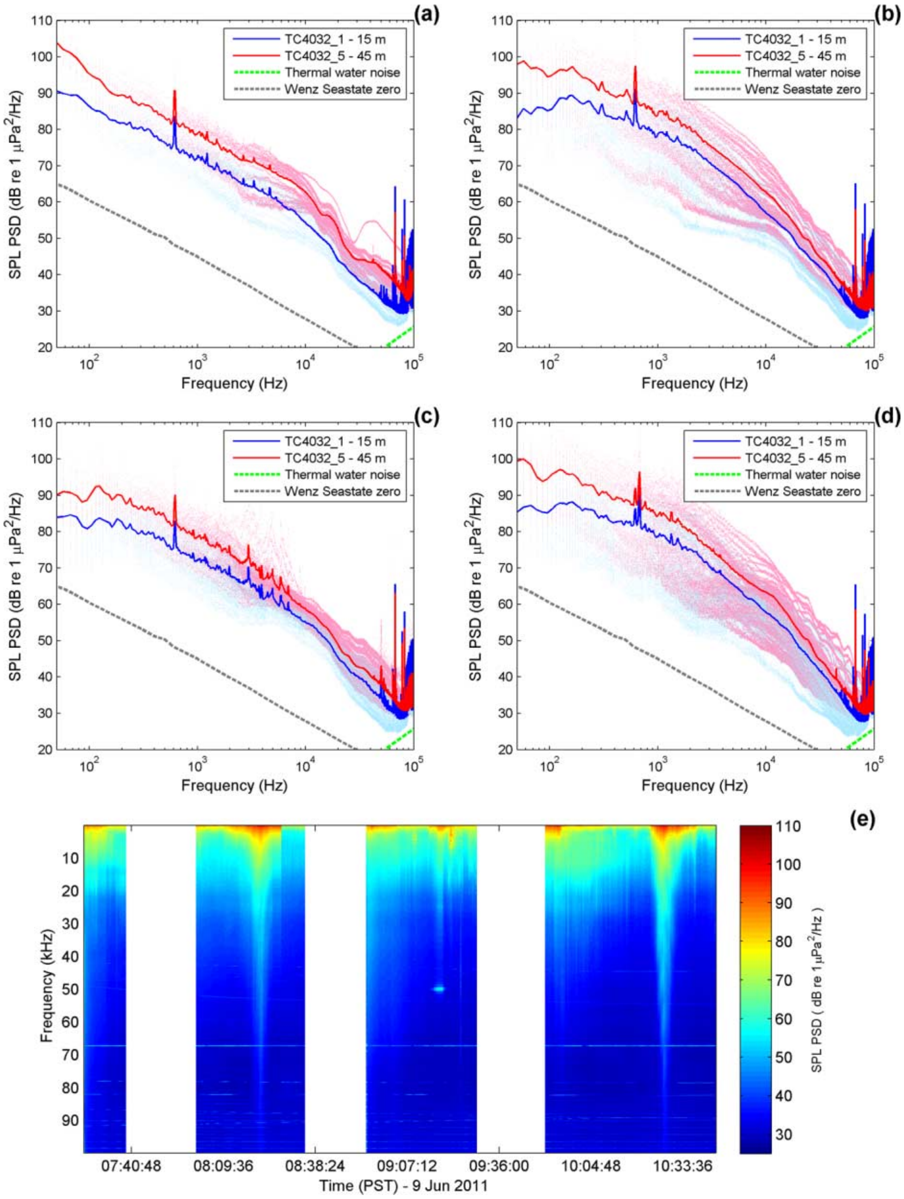
The averaged PSD from all drifts shows a similar 5 dB decrease per octave for the frequency band below 70 kHz to that of other measurements during the May cruise. The overall variation of the PSD in drifts 2 and 4 (the dots cloud plots of Figures 5b and 5d) are higher (40-50 dB) than those of the other two drifts (20 dB). These large SPL variations are due to the near-distance shipping traffic (ferry, high-speed ferry) especially during these two drifts.

The spectrogram of the entire June 9 cruise (Figure 5e) displays the PSD as a function of time and frequency collected from the deeper hydrophone at depth of 45 m. It shows the SPL signature caused by the nearby shipping traffic and high-speed ferry during drifts 2 and 4, which caused the SPL to increase in the frequency band up to 50 kHz.

A yoyo type of measurement of the TC4014-5 hydrophone was carried out during the June cruise, in which a TC4014-5 was continuously deployed up and down throughout the cruise to measure the SPL through the entire water column. The deployment was carried out carefully; the hydrophone with depth sensor was deployed from the surface to a depth of 38 m up and down continuously with an average speed at 0.4-0.5 m/s. This slow motion was intended to reduce the flow noise due to the movement of the hydrophone. The depth sensor measurement of the hydrophone during drift 3 shows the hydrophone movement as a function of depth and time (Figure 6, inset panel). The

FIGURE 5

PSD of SPL measured from four drifts during the June cruise: (a) Drift 1, (b) Drift 2, (c) Drift 3, and (d) Drift 4. The blue and red solid lines in each panel correspond to the average results of each drift from TC4032-1 and TC4032-5, respectively; the cloud of dots indicates all the measurement results from each 20-s section data during each drift. (e) Spectrogram of all four drifts collected from hydrophone TC4032-5 (45-m depth).



hydrophone was deployed from the surface to 38 m. Each deployment of this hydrophone from surface to the deep depth and back to surface took about 180 s. Drift 4 was separated into four sections according the surrounding observations of shipping traffic during the deployment. The PSD was estimated for every second and averaged for a few deployments in four continuous periods. Therefore, the PSD from this measurement (Figure 6) was the results averaged over time and depth. The blue curve for the second ferry SPL was primarily the result of the high-speed ferry.

SPL Measurement Comparison

Background Sound Speed Profiles From Different Cruises

In general, the ocean water column consists of stratified water layers because of the inhomogeneous nature of temperature, salinity, and pressure from different water depths. The noise distribution is closely related to background sound speed profiles. For this shallow coastal ocean survey site, the entire water column is, in general, very well mixed (Polagye & Thomson, 2010). The sound speed profiles measured through both cruises (Figure 7) show that the sound speed variation through the water column was relatively small, with variations of less than 3 m/s during the May and June measurements. This information is useful for modeling the noise in this region.

Comparison of SPL Measurements From Two Different Cruises

The maximum and minimum SPL measurements in the frequency range of 1-100 kHz from both cruises were plotted together for comparison (Figure 8). These measurements are not comprehensive because they are the measurements taken in a specific time frame and only last a couple of hours in total. Figure 8 basically shows the maximum and minimum pressure levels one could encounter in that region from the broadband frequency range. Note that the minimum SPLs at the frequency band below 20 kHz from both May (blue solid curve) and June (green solid curve) measurements were approximately 15-20 dB above the Wenz sea state zero pressure level. The higher SPL measured was from the May cruise. It is about 10-30 dB higher than the

FIGURE 6

Drift 4 data from yoyo type of measurement of TC4014 on June 9 cruise: (a) PSD of SPL for four different time sections during drift 4 and (b) (inset panel) movement of the hydrophone as a function of depth and time during drift 4.

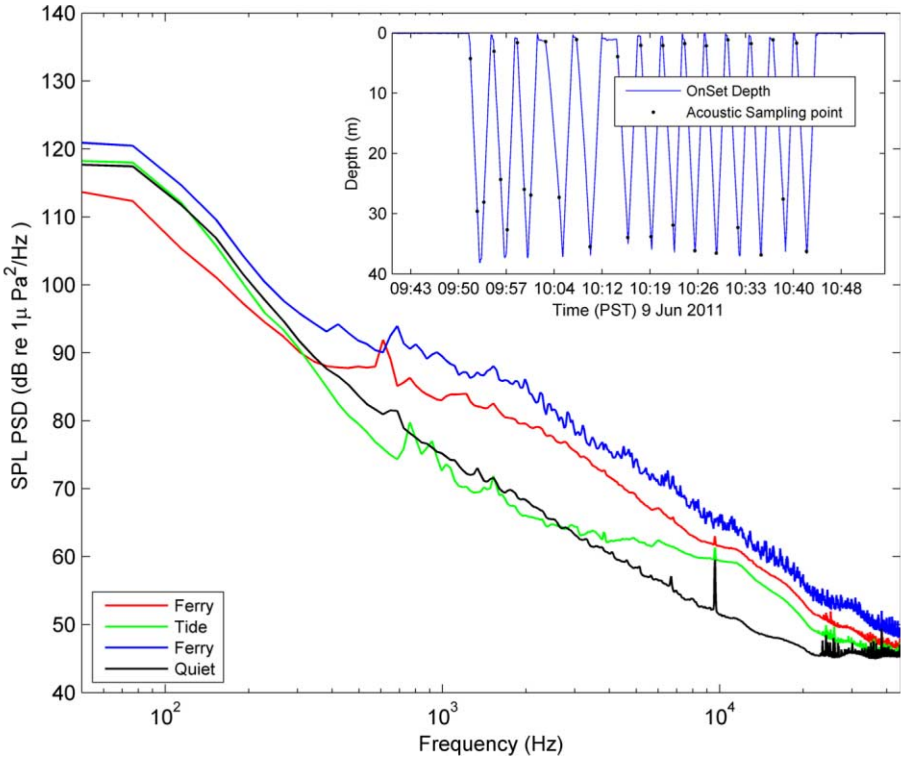
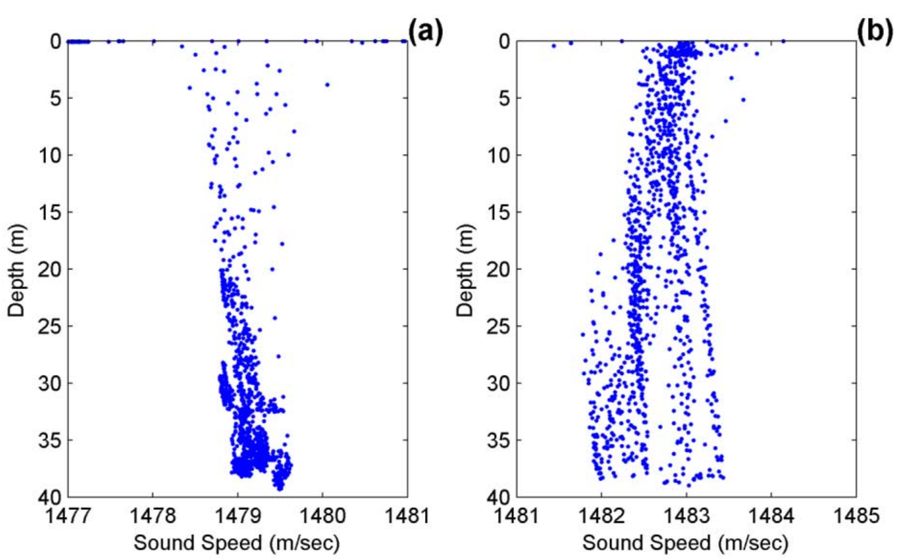


FIGURE 7

Sound speed profiles from two different cruises. (a) May 10 cruise and (b) June 9 cruise.



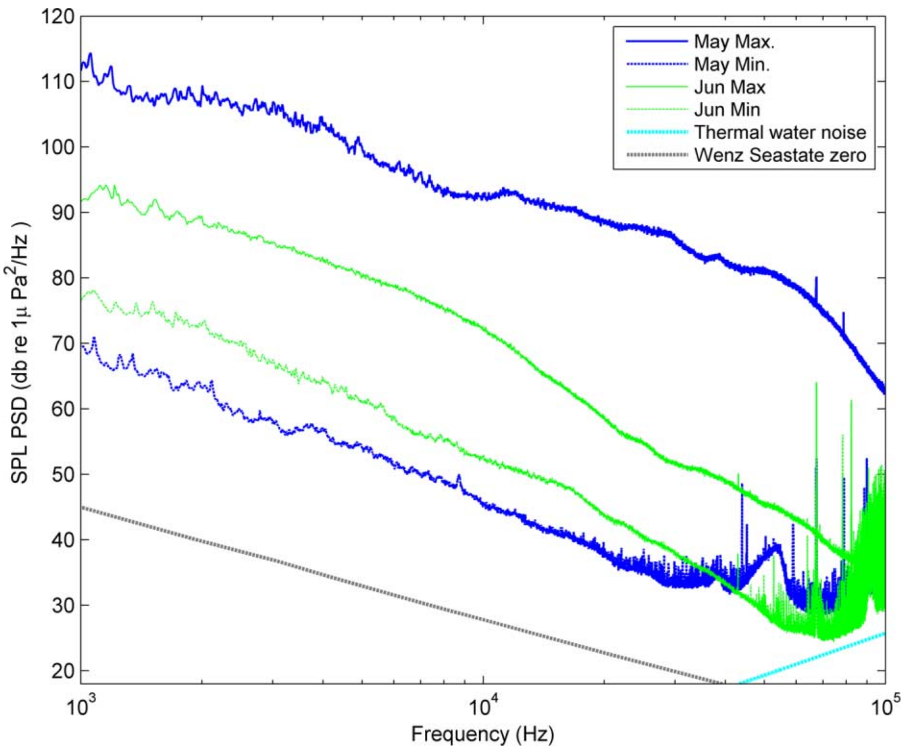
measurements from the June cruise in the 1-70 kHz frequency band. The AIS data provided information on the shipping tracks for the local region. Although AIS data from the June cruise were not available, and ferry, high-speed ferry, and other boats were observed during the cruise, the shipping traffic alone could not explain the abnormally high maximum SPL from the May cruise.

Conclusion and Summary

Broadband measurements of SPL were carried out using a VLA of hydrophones during May and June 2011 at different depths with frequencies ranging from 1 to 100 kHz at Admiralty Inlet in northern Puget Sound, a potential test site for the deployment of hydrokinetic turbines. Different pressure sensors with temperature and conductivity were also attached to the VLAs to measure the conditions at the hydrophone deployment depth to attempt to characterize the SPL caused by bedload transportation as well as to measure the sound speed profiles throughout the water column. The measurement results showed the ambient noise level generally decreases about 5 dB for the frequency range of 1-70 kHz per octave and increases about 5 dB per octave for the frequency range of 70-100 kHz. The differences in noise pressure level from measurements of different months ranged from 10 to 30 dB for the frequency band below 70 kHz. Even though the variation of noise pressure level for the frequency range above 70 kHz was dominated by thermal noise and was relatively small (<10 dB) (Mellen, 1952), the measurements from the different months show a higher SPL than thermal noise. This indicates there are other acoustic

FIGURE 8

The maximum and minimum SPLs measured from two cruises.



sources that contribute to the frequency band from 70 to 100 kHz besides thermal noise (Zedel, 2001).

The underwater noise level was affected by natural and anthropogenic sources. Commercial shipping and ferry vessel traffic were found to be the most significant contributors to SPL variations for the frequency range of 1-50 kHz at this site, and fluctuation could be as high as 30 dB. In addition, the bedload transport may have increased the broadband SPL for frequencies from 3 to 50 kHz.

The acoustic environment in the Admiralty Inlet is very complex. SPLs vary with different geographic locations and time and are also strongly affected by the commercial shipping traffic. Even though the measurement results above 70 kHz were possibly affected by electrical noise, these ambient noise level measurements during the high tidal period from two different months provide basic information for designing and evaluating both active and passive sonar detection systems proposed for deploying and operating of a tidal power generation alert system. The deployment of long-term autonomous self-contained instruments should be considered as future work direction.

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