Variation in Southern Resident Killer Whale (*Orcinus orca*) Acoustic Signals in Relation to Environmental Factors

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INTRODUCTION

An animal's ability to communicate is greatly dependent on its environment. They must overcome various hurdles dealing with sound loss and attenuation of sound in the medium that they are attempting to communicate in (Marler 1961). Many species have been shown to modify sound depending on different habitats and environmental constraints. The Southern Resident killer whales (SRKWs) inhabit the Salish Sea off the coast of Washington and British Columbia, which is a complex shallow-water environment (Jones and Wolfson 2006). The varied bathymetry of the area leads to variations in sound propagation throughout the habitat (Jones and Wolfson 2006). It is possible that the SRKWs will alter their acoustic signals based on the sound propagation of the area they are in. In areas where sound is attenuated more readily, phonation repetition rates may increase in an effort to be sure that information gets across.

Animals have been shown to cope with the differences in sound transmission in different habitats in many different ways. It has long been known that birds have different dialects and display geographic variation (Morton 1975; Hunter and Kreb 1979; Lemon 1997). For example, Hunter and Kreb (1979) showed that great tit (*Parus major*) songs vary significantly between habitats, adjusting frequency range, average frequency and variety of notes dependent on woodland versus forest. Studies have also shown that species of frogs increase their call rates if there is increased ambient noise in their environment (Sun and Narins 2005).

Many species of bats are also known to alter their echolocation click rates depending on their environment. Free-tailed bats (*Tadarida*) display different echolocation signals in different situations (Simmons et al. 1978). Indeed, these bats utilize every kind of echolocation signal currently known to bats (Simmons et al. 1978). When foraging above the treeline, they use narrowband or constant frequency (CF) clicks (Simmons et al. 1978). These clicks generally have only one harmonic, and focus the energy of the click at the optimum frequency within the hearing range of the bats (Simmons et al. 1978). They are typically used at a rather low repetition rate (Simmons et al. 1978) In contrast, when the bats are placed in a cluttered room or other areas where they need to constantly be aware of their surroundings, the bats use a brief, broadband frequency signal with a high repetition rate (Simmons et al. 1978). These signals have multiple harmonics, and are used to obtain quick, detailed information about their environment (Simmons et al. 1978). These same trends have been noted in many other species of bats, including *Myotis emarginatus*, *Pipistrellus pipistrellus*, *Nyctalus noctula,* and *Eptesicus fuscus* (Schumm et al. 1991; Pye 1967; Obrist 1995; Simmons et al. 1978).

Marine mammal environments can also limit the animals' sound production. Because sound attenuates much less in water than light, many marine animals use sound to communicate information (Richardson et al. 1995). The physics behind sound propagation is even more complex than in a terrestrial ecosystem. Bathymetry, slope, depth, currents, salinity, bottom type, bottom and surface interactions and the sound speed profile all play a role in how sound travels in the marine environment (Knobles et al. 2003).

The way sound moves through water is highly dependent on location and thus difficult to predict without understanding the environment. One characteristic of the marine environment that has a major effect on sound propagation is depth. Sound in the marine environment is subject to two kinds of spreading: spherical and cylindrical, and these are altered by depth. Spherical spreading is the decrease in sound level when the sound propagates away from the source uniformly in all directions. This can only occur in deepwater. When the water becomes shallower and the sound waves interact with the bottom and surface, cylindrical spreading occurs. Cylindrical spreading occurs when sound hits the bottom or surface and traps the sound from radiating out equally in all directions. In ideal situations, sound levels actually decrease more slowly when cylindrical spreading takes place, although surface and bottom interactions often make the propagation more complicated.

Many studies have looked at how sound propagates in areas of different depths; however, they have found few rules that hold true globally. One that has been demonstrated is that, in deep water, low frequencies experience little attenuation and are capable of traveling long distances (Kibblewhite and Denham 1971). Jensen and Kuperman (1983) provided evidence for this phenomenon, and additionally looked more closely at complex shallow water environments. In these environments, sound propagation gets more complex as sound waves come into contact with the surface and bottom much more frequently. Sound becomes prone to cylindrical spreading, and bottom interactions become increasingly important (Jensen and Kuperman 1983). It was found that higher frequencies lose more energy to bottom interactions than low frequencies do (Jensen and Kuperman 1983; Knobles et al. 2003; Richardson et al 2005). Although this has been found to be true in several different studies, at least one study conducted in shallow water environments in Hawaii found that *higher* frequencies traveled better (Mercado and Frazer 1999). This illustrates the complexity behind sound propagation in shallow water and how each case should be treated independently.

Although it is known that features such as depth potentially affect the propagation of sound produced by marine mammals, little is known about how marine mammals communicating with sound cope with differences in sound propagation in different environments. Several studies have been done on cetaceans that highlight ways that marine mammals cope with increased ambient noise, which decreases the active space, or distance over which the signals travel (Richardson et al. 1995; Holt 2008). Humpback whales have been shown to increase their song durations when there was sonar in the area (Miller et al. 2000). A captive beluga whale (*Delphinapterus leucas*) as well as captive bottlenose dolphins that were moved from a quiet environment to an area with increased ambient noise shifted the peak frequencies and sound pressure levels of their clicks and also increased the repetition rate (Au et al. 1974; Au et al. 1985). Similar behavior has also been shown in killer whales (Holt et al. 2009). It has been shown that killer whales increase the amplitude of their calls in the presence of increased ambient noise due to vessel traffic (Holt et al. 2009). It has also been shown that killer whales have increased the duration of their calls over time, presumably because of increased ambient noise (Wieland 2007; Wieland et al. 2010). These are all ways to cope with the potential loss of information that may occur in areas with high levels of ambient noise. It is feasible to assume that they may also adjust their call rates in response to differences in sound propagation between areas of different bathymetry, where there is similar risk that information loss may occur.

The SRKWs are an ideal population to study how vocalizations of marine mammals are affected by bathymetry. They are known for being very vocal (Veirs and Veirs 2005). There are three main sounds that are used by killer whales: clicks, whistles and pulsed calls (Ford 1987; Ford 1989). Clicks are used primarily for echolocation, and tend to be brief and varied (Ford 1989). The frequencies can either be narrow or broadband (Ford 1989). Killer whales also often use click trains made up of a series of clicks that can occur as fast as 300 clicks a second (Ford 1989). Killer whales also use whistles (Ford 1989; Thomsen et al. 2000). The function of whistles is largely unknown. What is known is that they are often a tone with few or no harmonics, although they do often have changes in frequency within the duration of the call (Ford 1989; Thomsen et al. 2000). Whistles can have a wide range of durations; Ford (1991) measured durations of 50 ms to 10-12 s and also found that they range in frequency from 1.5-18 kHz.

The final and most common type of vocalization produced by killer whales is pulsed calls (Ford 1989). These vocalizations are distinguished by high pulse-repetition rates. The pulses can vary in frequency and repetition rates (Ford 1989). Pulsed calls can also have two fundamental frequencies, and some also have a whistle component (Ford 1989; Ford 1991). Ford (1989) found that most of the energy in pulsed calls was concentrated between 1 and 6 kHz, but the high-frequency components extend to over 30 kHz. Killer whales produce three different types of pulsed calls (Ford 1989; Ford 1991). These calls are discrete, variable and aberrant calls (Ford 1989; Ford 1991). Discrete calls are repetitive, pulsed calls that have a distinctive structure that allows them to be recognized and categorized (Ford 1989; Ford 1991). Variable calls are non-repetitive calls that could not be categorized readily by structural cues (Ford 1989; Ford 1991). Ford (1989) described aberrant calls as calls that were similar to discrete calls, but were distorted or modified to the point that they couldn't be categorized into discrete categories.

Another factor that makes the SRKWs an ideal study population is the fact that their summer range lies in the area surrounding the San Juan Islands (National Marine Fisheries Service 2008). This area is complex and varied. Jones and Wolfson (2006) studied sound propagation of vessel noise in Haro Strait. They found that bathymetry played a significant role in how the sound propagates through the environment (Jones and Wolfson 2006). The glacier-carved Haro Strait is characterized by steep slopes and a relatively deep depth of up to 320 meters, while parts of Salmon Bank on the south side of San Juan Island are less than 10 meters deep (McLellan 1927; Green 2010). Sound most likely propagates quite differently in each of these environments, which are both frequented by SRKWs. Because the SRKWs are exceptionally vocal, it will be possible to make adequate comparisons of call rates between areas of different bathymetry.

METHODS

Data Collection:

Data was collected from a 42' catamaran, the *Gato Verde,* for a five week study period from late April to late May. Data was collected to assess sound propagation in areas of different bathymetry and SRKW acoustic signals in relation to their environment.

<u>Sound propagation in areas of different bathymetries</u>: The area surrounding the San Juan Islands was divided into zones based on depth. Four representative sites that included areas where the SRKWs were frequently seen were selected (Figure 1). These included the deepwater President's Channel, off of Lime Kiln, a site off the south side of San Juan Island, and a shallow water site directly over Salmon Bank. In order to try to minimize confounding variables, all measurements were taken at slack tide. Tidal state was determined using tide charts and the software OpenCPN. At each site, GPS coordinates were taken from the *Gato Verde* and recorded. Other metadata such as wind speed in knots and sea state were also recorded.

A single LabCore hydrophone with a peak sensitivity of 5 kHz and a sampling rate of 48000 was lowered from the *Gato Verde*. An underwater speaker was taken out on *Gatito*, the dingy. Three people were present on the dingy at all times: one person to lower and raise the speaker, one person who used a laser rangefinder to measure the distance from *Gatito* to the

Gato Verde. An Apple IPod was hooked up to the underwater speaker and used to broadcast tones from the speaker. Tones were recorded by a single hydrophone attached to a Sound Devices recorder aboard the stationary Gato Verde. For two of the sites, President's Channel and over Salmon Bank, only one tone was played. This tone was an upsweep created using Audacity 1.3 Beta (Unicode) software (http://audacity.sourceforge.net/about/credits). The upsweep ranged in frequency from 400 hz to 6000 hz. For the other two sites (Lime Kiln and over the slope by Salmon Bank), three tones were used. These tones included the upsweep, as well as a flat 1000 hz tone and a flat 4000 hz tone.

At each site, *Gatito* was driven a certain distance away from the boat. This distance varied between sites, as currents and weather made for difficulties in holding position at certain sites, such as Lime Kiln and over Salmon Bank. However, at each of these areas, at least 7 points along a transect moving away from *Gato Verde* were sampled. At each of these points, distance was measured using the laser rangefinder and the underwater speaker was lowered to a depth of three meters. GPS waypoints were taken, and the tones were broadcast over the speaker. The sound was recorded for thirty seconds on the Sound Device set up on the *Gato Verde.* After this, *Gatito* moved to another point between 50 and 100 m away from the last point, until a point around 700 m was reached. The procedure was repeated for each site.

The only site that was sampled differently was Lime Kiln. In order to increase sample size and take advantage of resources, Lime Kiln samples were taken from both a single hydrophone lowered to three meters and a stationary hydrophone at a depth of 26 feet. The stationary hydrophone is one of the hydrophones in the Salish Sea Hydrophone Network, and is used to record whale calls at Lime Kiln. It recorded continuously until the end of the experiment, and the data was stored on an external hard drive in Lime Kiln Lighthouse. The other hydrophone was hooked up to the Sound Device and taken out on *Gatito*, while the underwater speaker was left on *Gato Verde,* where it was lowered again to a depth of three meters each time tones were broadcasted. *Gatito* maneuvered directly over the stationary hydrophone for each point, while *Gato Verde* moved along a transect away from *Gatito*. Distances between the two vessels were recorded using the laser rangefinder from *Gatito.* Because strong winds and waves made it difficult to hold position, times when the dingy was directly over the stationary hydrophone were recorded, and these files were the ones used in analysis.

<u>SRKW acoustic signals</u>: When killer whales were present, a towed array of hydrophones was used to record calls and clicks of the whales. The array consisted of four LabCore hydrophones on one line. Each hydrophone had a peak sensitivity of 5 kHz and a sampling rate of 48000. These hydrophones were located on a single line and spaced ten meters apart. The hydrophone closest to the boat was ten meters from the point of attachment. A lead weight was attached to the array and lowered to keep the array underwater at a constant depth. The hydrophones were all hooked up to two two-channel Sound Device 702 recording units. The array was lowered when the *Gato Verde* was appropriately ahead of a group of whales, and *Gato Verde* tried to parallel the whales at all times, in accordance with Be Whale Wise regulations. Speed of the boat was kept below a maximum of three knots, and all turns when it was possible that the array was not in a straight line were recorded. As soon as the array was lowered, GPS coordinates were measured and recorded.

While the array was deployed, an operator stationed at the Sound Device recorders listened to the underwater noise in real time with headphones attached to the recorders. When vocalizations or clicks were detected by the operated, they began recording. Recording continued either until no acoustic signals were heard or the decision was made to leave the whales for the day. A selected number of calls that are most frequently used by J-Pod were chosen as a focus of this study. S1, S4, S10, S16, and S42 are some of the calls heard most frequently in the Salish Sea this time of year (Wieland 2007). These calls also represent a broad frequency range. If any of these calls were heard in real time, the time in the recording was noted and the call marked on the phonation data sheet. If clicks were heard, the time was also recorded, and "clicks" was marked on the data sheet. Each day, the recorded files were downloaded onto an external hard-drive as back-up.

Data Analysis:

Sound propagation: Sound propagation was measured by estimating spreading. Wav sound files were imported into the computer program Audacity 1.3 Beta (Unicode) for analysis. The first complete sound was picked for analysis as it was most likely the sound that was closest to the distance measured with the rangefinder. For analysis of the upsweep, the Plot Spectrum feature in Audacity was used to determine the received levels of the frequencies measured in this study: 900 hz, 1000 hz, 1100 hz, 4000 hz, 7000 and 10000 hz. The 7000 and 10000 hz frequencies were measured from the harmonics of the upsweep. These frequencies were chosen because they all lie within the range of the calls analyzed. Background noise was accounted for by selecting a section of the recording immediately before the upsweep started was selected and the Plot Spectrum feature was used to measure the received levels of the background noise at the same four frequencies. This same method was used for each of the tones, however, only the received level at 1000 hz was analyzed for the 1000 hz tone, and only the received level of 4000 hz was measured for the 4000 hz tone.

In order to see if there were differences in sound propagation between sites, the dB levels measured in Audacity were exported for analysis. The dB levels that were measured from the chirp represented the combined signal/background noise levels. Only the signal level was used for this study, so the background levels had to be subtracted to isolate the signal. In order to do this, the combined signal/background level was converted to watts. The background level was also converted from dB to watts, and then subtracted from the combined signal/background power. The absolute value was taken, and the resulting difference was converted back to decibels. This gave the received level of the signal. This was done for all four frequencies at each site. The resulting levels were graphed, and a linear regression line was calculated. Spreading was determined from the equation of the linear regression line. R 2.12.22 for Windows was used to determine statistical significance between sites and frequencies.

SRKW acoustic signals: In order to address the possibility that the whales increase the call rates of calls of a certain frequency range based on sound propagation in the different environments, the frequency ranges of the five focus calls addressed in this study (S1, S4, S10, S16 and S42) was measured. This was accomplished by analyzing five clear examples of each call selected from the folders Sea Sounds and Sea Sound 2004s, which was provided to Beam Reach by Val Veirs. Raven Pro 1.3 (http://www.birds.cornell.edu/brp/raven/RavenAcknowledgements.html) was used to determine the start frequency, end frequency, peak frequency, change in frequency from the start to the peak frequency, change in frequency from the peak to end frequency and the duration of the examples with the exception of S10. Because S10 is a highly variable call that has a very broad frequency range, only the start frequency and maximum and minimum frequency were measured.

Call rate of all five of these calls was also determined from recordings taken from the Spring 2011 whale encounters. All sound files from 5/10/2011 and 5/11/2011 were analyzed. An additional two files were analyzed from 5/15/2008 to increase sample size. All of the files were listened to, and the number of each call made per minute was recorded. It was assumed that all 25 whales of J-Pod plus L-87 were present at the time and call rate of the entire pod per minute was determined. For the 2008 data, it was assumed that all 24 whales of the pod at that time were present during recording as well.

In order to record the geographic region of recorded call and whether they were in "shallow" or "deep" environments, GPX tracks were downloaded from the computer onboard the *Gato Verde.* Generic Mapping Tools (Wessel 2011), an open source program developed by the University of Hawai'i was used to determine depth at each GPS location. The command grdtrack was used. This command reads the latitude and longitude columns in the GPX table and adds the additional data, in this case depth, to the table. The real time of each minute of the recordings was then matched up to the minutes when GPS coordinates were taken, and the coordinates and corresponding depths were then manually combined with the call rates per minute. Using the depth data, each minute of the recordings was designated as being "shallow water" or "deep water." In order to make the results comparable to the spreading results while keeping the sample size of each category fairly equal, shallow water was sites were 100 m or less, while deepwater sites were over 150 m in depth. Statistical analysis was conducted in R 2.12.22.

RESULTS

Experimental Data:

Spreading was done at a total of four different sites in the waters of the San Juan Islands (Figure 1). T-tests were run on the different frequencies measured that compared them to each other. It was found that there was no significant difference between 900hz, 1000 hz, and 1100 hz, and there was no difference between 4000 hz, 7000 hz and 10000 hz. Therefore, these frequencies were binned into high and low frequency categories in order to address whether high or low frequencies propagated better in the environments measured.

In an effort to allow comparison of spreading results to where whales were sighted, the sites were also binned into two categories based on depth. The "shallow" sites included both sites along the south side of San Juan Island, which were all less than 80 m deep. The "deep" sites included Lime Kiln and Presidents Channel, which were greater than 150 m in depth (Figure 1). For each category, the slopes of the regression lines of the low frequencies were compared to the high frequencies using a t-test. No significant difference between high and low frequency propagation in either deep or shallow water was found ($t = -0.7547$, p-value = 0.4625 for deep water; $t = -1.449$, p-value = 0.1743 in shallow water) (Figure 2). The sites were then compared to each other. A t-test comparing the sound loss of high frequencies in shallow water to the sound loss of high frequencies in deep water was run. This found that high frequencies experience significantly more attenuation in shallow water than in deep water ($t = 4.5422$, p-value = 0.001575) (Figure 3). A t-test was then run comparing the sound loss of low frequencies between shallow and deep water. It was found that lower frequencies also experienced less attenuation in deepwater than in shallow water when _ = 0.05 was used ($t = 2.1903$, p-value = 0.04842) (Figure 3).

To determine basic call characteristics, 5 examples of each call type (S1, S4, S10, S16, S42) were analyzed, and average start, end and peak frequencies, as well as duration were calculated for all but S10, when only the minimum and maximum frequency was looked at. S1, S4, and S16 all had a relatively narrow frequency range, and had average start frequencies between 986.18 hz and 1136.96 hz (Table 1). S42 was a two-component call. It had a lower range component that was similar to S1, S4, and S16, but it also had a high frequency component that extended from an average of 4188.175 hz to 9119.1 hz (Table 1). S10 was a highly variable call that ranged in frequency from 731.1 hz to 5555.6 hz, with an average maximum frequency of 4470.3 hz and an average minimum frequency of 1782.94 hz (Table 1).

Observational Data:

345 minutes of recordings were analyzed. These included recordings from over Haro Strait and Salmon Bank, on the south side of San Juan Island (Figure 4). These recordings included 170 minutes of deepwater data (greater than 150 meters in depth) and 135 minutes of shallow water data (less than 100 meters in depth). S1 calls were found in the most minutes, and also had the highest rate of use (Table 2, Figure 5). None of the data were distributed significantly, so a log transformation was done. After the log transformation, the data comparing the call rate of the pod per minute for the S1 call was the only data set that was distributed normally. A t-test was run on the transformed data comparing the average call rate per pod per minute in shallow water to the average call rate in deep water. A t-test was selected because there were two variables that were being looked at, the call rate in shallow and in deep water. The t-test found that there was a significant difference in the call rate between the two environments (t=4.090, p-value =

6.051×10^{-5}). There was a higher call rate of S1 calls per minute in shallow water than in deeper water (Table 2, Figure 5).

The call rates for all of the other calls (S4, S10, S16 and S42) were not distributed normally even after a log transformation. The high number of zeroes present resulted in right skewed data. For these calls, the probability of not hearing the call at a given minute was calculated for both shallow and deep water areas. Although the data could not be tested for statistical significance, there was a higher probability of hearing a call at a given minute for all of the calls tested in shallow water than in deep water (Table 2). In an effort to get statistical measurements on the call rates, the minutes that had no calls heard were taken out. This allowed for an assessment of whether the whales altered the call rates when the calls were used in both shallow and deep environments. Because the data was still not normally distributed, a Wilcoxon Signed Rank test was conducted on each call. This test was chosen because it is nonparametric, meaning that it can be used even with a non-normal dataset, and compares two variables. This test found no significant difference in any of the calls. The call rates (with minutes where there were none of the calls heard removed) for all of the calls did not vary significantly between shallow and deep environments.

DISCUSSION

The Southern Resident killer whales were listed under the Endangered Species Act in 2005 (NOAA 2008), and the recovery plan developed by NOAA outlined three major threats to the whales. One of them was the acoustic threat posed by vessel noise and the possibility that increased noise could mask killer whale acoustic signals (NOAA 2008). While several studies have started to look at the effect of boat noise on killer whales, few have actually looked at how the sound propagates through the environment, which is a critical piece of knowledge. This study began to try to understand how sound propagates throughout the summer range of the SRKWs.

The fact that a significant difference in sound propagation was found between shallow and deepwater environments (Figure 3) illustrates that there are variations in the sound propagation in the waters surrounding the San Juan Islands. Sound loss occurs at a slower rate in deeper waters than in shallower waters. This can be explained by the decreased bottom interactions that occur there. Because the speaker was only lowered to a depth of three meters at both the shallow and deep sites, both areas would be prone to surface interactions. However, the deep sites would have fewer bottom interactions, as it takes longer for the sound waves to reach the bottom. The bottom can affect sound loss, as some sound is absorbed by the sediment. This is especially true for soft sediment bottoms (Richardson et al. 1995). Soft substrates absorb more sound, increasing attenuation of sound waves (Richardson et al. 1995). In the area of Salmon Bank where the spreading experiments took place, the bottom consisted of a sandy substrate (Greene 2010). In contrast, most of the area in Haro Strait is hard rock or gravel substrate, which would not absorb as much sound (Greene 2010, Richardson et al. 1995). This could help explain why the attenuation was less in deeper water.

The fact that attenuation of high and low frequencies was not significantly different within deep and shallow water was not predicted by the hypothesis. Several studies have found that high frequencies are more prone to attenuation due to the complex bottom and surface interactions that occur in shallow water areas (Jensen and Kuperman 1982). However, this study looked at lower frequencies (such as 200 hz) than those that were measured in the present study (Jensen and Kuperman 1982). The frequencies that I measured were chosen because they represented frequencies on the low end of the killer whale calls that were studied, but perhaps were not low enough or different enough from the high frequencies measured to experience significantly different rates of attenuation. However, these results could be beneficial when considering how the sound loss of killer whale calls is affected by the environment. Of course, it is important to note that only four sites were sampled. Each of these sites was sampled only once, so it would be interesting to look at more shallow and deepwater sites for more comparisons.

While this study focused primarily on propagation of sound in areas of different depths in order to allow for more direct comparison between spreading experiments and killer whale recordings without severely limiting the sample size, there are other variables that further complicate sound transmission that would also be interesting to look at in the future. For one, sound travels differently over slopes in the ocean floor (Dosso and Chapman 1986; Richardson et al. 1995). Sound waves propagating down-slope attenuate less (Dosso and Chapman 1986; Richardson et al. 1995). This is true particularly for higher frequency sounds (Dosso and Chapman 1986; Richardson et al. 1995). However, the opposite is true when sound waves travel up-slope (Richardson et al. 1995). There are increased bottom reactions, leading to increase attenuation of the sound waves, especially at higher frequencies (Richardson et al. 1995). Sound waves that come at an angle to the slope tend to glance off of the bottom, while those that contact the bottom at a nearly perpendicular angle are usually absorbed by the bottom, making the angle of the slope important (Richardson et al. 1995, Val Veirs pers. comm.). It would be interesting to continue research and investigate whether the frequencies looked at in this study are significantly affected by slopes of areas surrounding the San Juan Islands.

The original hypothesis of the study was that killer whales would increase their call rate in areas where sound experienced greater rates of attenuation to make up for the possible loss of information. Based on the results of the spreading experiment, one would therefore expect that the call rates would increase in shallow water, where sound attenuates at a faster rate. This was found to be true for the S1 call (Figure 5). While the rates of the other calls in the study were not statistically significant, they all had a higher rate in shallow environments (Figure 5). The other calls were used much less frequently than S1, which is the call most commonly used by J-Pod. This resulted in data sets that were severely right-skewed, and made it hard to perform statistics to test for significant differences in rates. Perhaps future studies with larger sample sizes of times when the whales were very vocal would be able to find significant differences.

S1 has been identified as a potential contact call for J-Pod, and it is believed that it is important to maintain group cohesion (Ford and Fisher 1983; Wieland 2007). If this is true, it can be assumed that the information conveyed in the call is vital. This would make it important to ensure that the information gets transferred from sender to receiver. This could also help explain why the rate increased a significant amount. The whales need to overcome the increased attenuation rate of sound in the shallow water environment, and so increased the repetition rate of the call. Studies have shown similar behavior in other species as well; some species of frogs have been shown to increase their call rates in response to an increase in anthropogenic noise (Sun and Narins 2005). These calls are used to attract mates (Sun and Narins 2005), and so it can be argued that they may be similarly important to the S1 contact call of J-Pod. Right whales (*Eubalaena australis*) have also been shown to increase the repetition rates of their calls in response to increased noise (Parks et al. 2007), as have beluga whales (Lesage et al. 1999).

While these studies looked at increased call rates in response to higher background noise levels rather than increased attenuation based on environmental factors, both of these scenarios are dealing with the increased probability that information in the call will be lost. However, these studies also highlight a limitation of the present study. It was hard to control for confounding variables such as the number of boats in the area. While background noise measurements were measured during spreading experiments, none were taken when recording the whales. While the number of boats was periodically counted during the recording session, this study did not get a measure of how much noise boats were producing. The possibility that there was increased anthropogenic noise in shallow areas such as Salmon Bank, perhaps because it is a prime fishing location or because of its relative proximity to Friday Harbor, must be taken into consideration. The whales could have been increasing the rate of their calls in response to increased anthropogenic noise rather than increased attenuation in the area.

One thing that would be interesting to study in the future is whether the composition of the calls shifts between areas of different sound propagation. This study looked only at the call rates of five calls made by J-Pod. However, perhaps not only the rate of the call changes, but the actual composition of calls changes as well. S1 could represent a larger proportion of the total calls made. One study done on great tits (*Parus major*) found that songs of birds living in forested areas had a narrower frequency range than the songs (Hunter and Krebs 1979). The average change in frequency of the fundamental harmonic of S1 calls was around 500 hz (Table 1), which is relatively narrow considering the variation that occurs in calls such as S10, where the fundamental frequency ranged from just over 700 hz to over 5000 hz in the examples looked at (Table 1). The possibility that whales in the pod shift to produce more narrowband calls like S1 in shallow water is a question that should be addressed in the future.

Another potential future project could be to add a behavior aspect to a study like this. The present study did not control for behavior. While it appeared that the whales were socializing and traveling the two days that they were recorded, it is difficult to understand the true behavior of the whales, as most of their time is spent below the surface. However, there is a possibility that the whales could prefer areas of a certain bathymetry for each behavior. For example, perhaps they primarily forage when in shallow water. Alterations in behavior could be the driving force for the changes in call rate. This information could also be used for management of the population, as it could help protect areas that may be important for different behaviors.

CONCLUSION

With a vocal species such as the Southern resident killer whales of the Salish Sea, it is important to understand the limitations to sound transmission in the environment that they live in. SRKWs inhabit an area that has a complex and unique bathymetry, which raises the possibility that some areas transmit sound better than others. This study found that the sound level decreased at a faster rate in shallow water than in deep water. In addition, the call rate of the S1 call increased significantly when the whales were in shallow water, perhaps to overcome the increased rate of sound loss. This information should be taken into consideration when developing management proposals. For example, perhaps it would be beneficial to try to limit the number of boats surrounding the whales in shallow water. Because they already have to compensate for increased rates of attenuation in these environments, having to also overcome boat noise in these areas could further stress the population.

Further research addressing the behavior of the whales in relation to bathymetry would also be beneficial when developing management plans. Also, further research doing more spreading experiments that perhaps cover a larger range of frequencies would be beneficial to further investigate how noise propagates in the SRKW habitat. Research such as this could help further understand the effects of anthropogenic noise on SRKWs, and whether we could potentially be having more of an impact on them in different environments because of the sound transmission.

FIGURES AND TABLES

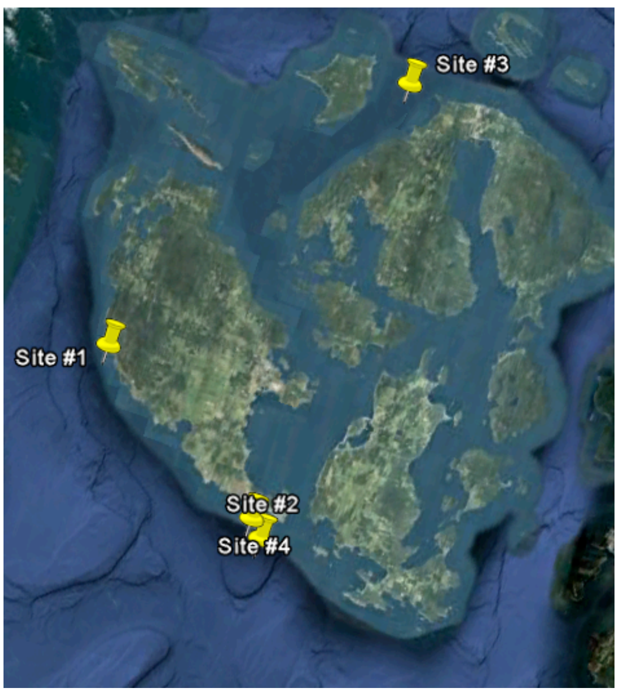

Figure 1. Study sites where sound propagation was measured. Sites #1 and #3 were deepwater (>150m deep) sites, and sites #2 and #4 are shallow water (>80 m deep) sites.

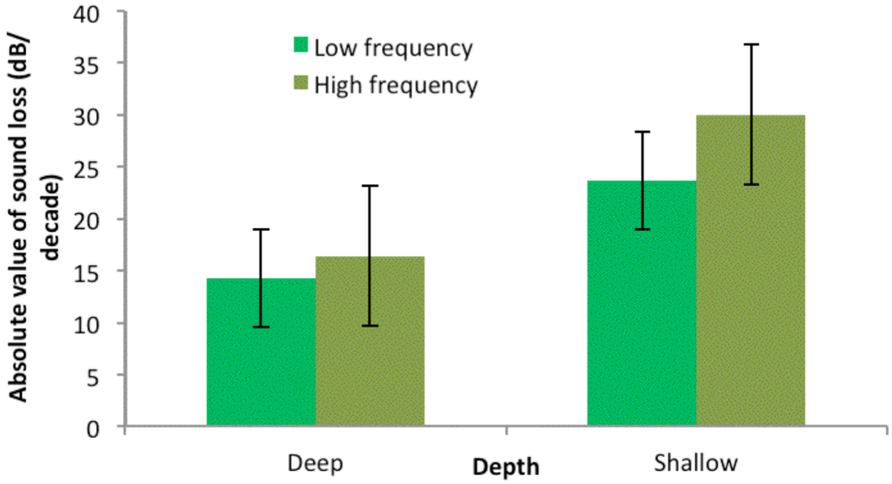

Figure 2. Sound loss of high and low frequencies at deep water (>150 m deep) sites and shallow water (<80 m deep) sites. Low frequencies measured were 900hz, 1000hz, and 1100hz. High frequencies measured were 4000hz, 7000hz, and 10000hz.

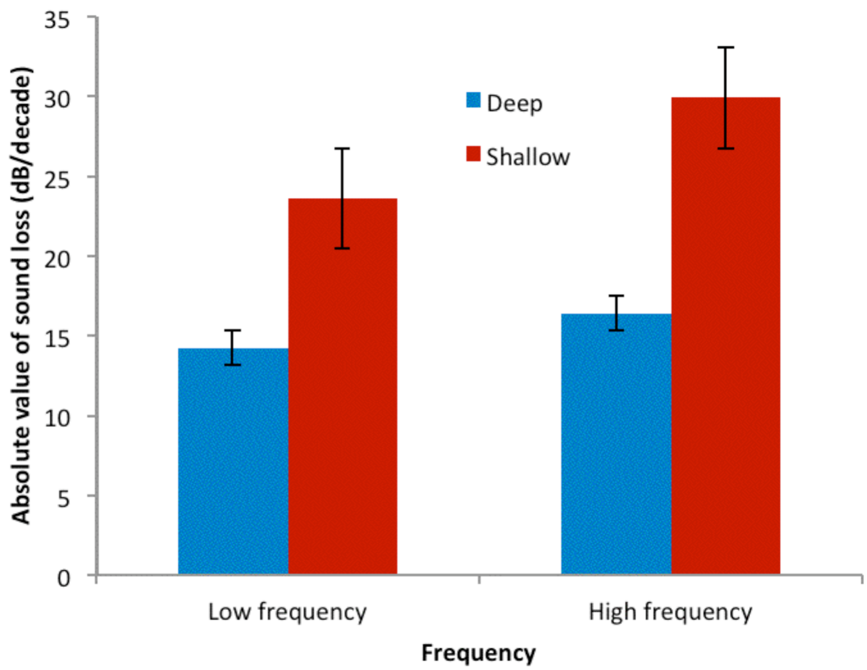

Figure 3. Sound loss of different frequency ranges in areas of different depths.

Table 1. Basic call characteristics of the five call types measured in this study. Contains start frequency, end frequency, and peak frequency in hertz. Delta frequency is the difference from the highest to lowest of these measurements. S42 is a two component call with a high frequency component. For S10, the start and end frequency were actually the minimum and maximum frequency of the call, respectively.

Call Type	Component	Start frequency (hz)	End frequency (hz)	Peak frequency (hz)	Delta frequency (hz)	Duration (s)
S1	1	986.18	717.42	1224.24	238.06	1.2
S4	1	1001.28	938.125	1001.28	63.155	0.416
S16	1	1136.96	1076.68	1180	103.32	0.7
S42	1	1001.28	1087.15	1001.53	85.87	0.31825
	2	4188.175	7396.68	9119.1	4930.925	
S10	1	731.1	5555.6		4824.5	

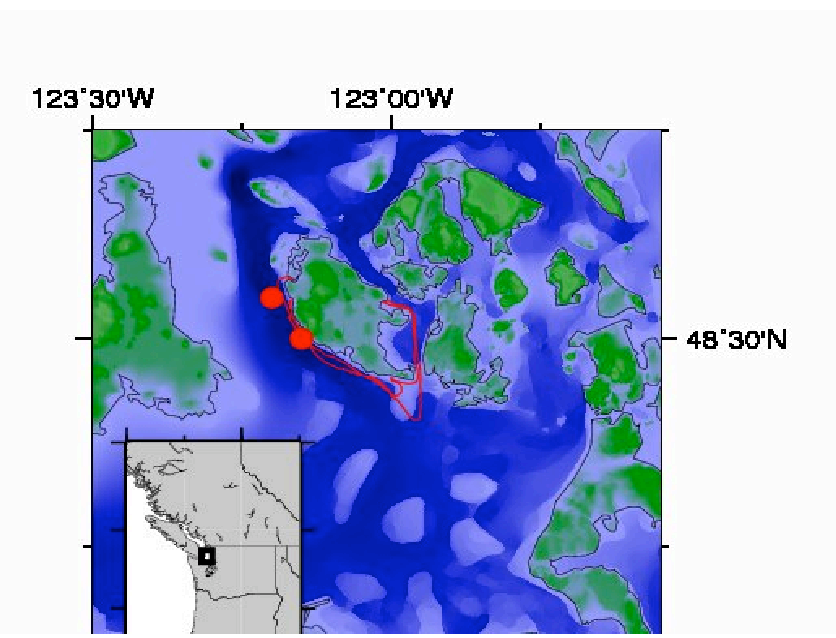

Figure 4. The tracks of the boat on the two days (5/10/2011 and 5/15/2011) when calls were analyzed. The red tracks indicate the track followed by the *Gato Verde*.

Table 2. Breakdown of calls heard in recordings taken on 5/10/2011 and 5/15/2011. Includes the total minutes that the call was heard in, the average call rate per pod per minute in shallow water and in deep water, and the probability that no call would be heard in a given minute.

Call Type	Minutes heard	Rate Shallow	Rate Deep	P no call/min	
				Deep	Shallow
S1	205	4.507	2.348	0.506	0.393
S4	95	0.860	0.360	0.809	0.654
S10	66	0.426	0.247	0.910	0.735
S16	50	0.449	0.056	0.966	0.765
S42	43	0.250	0.135	0.933	0.846

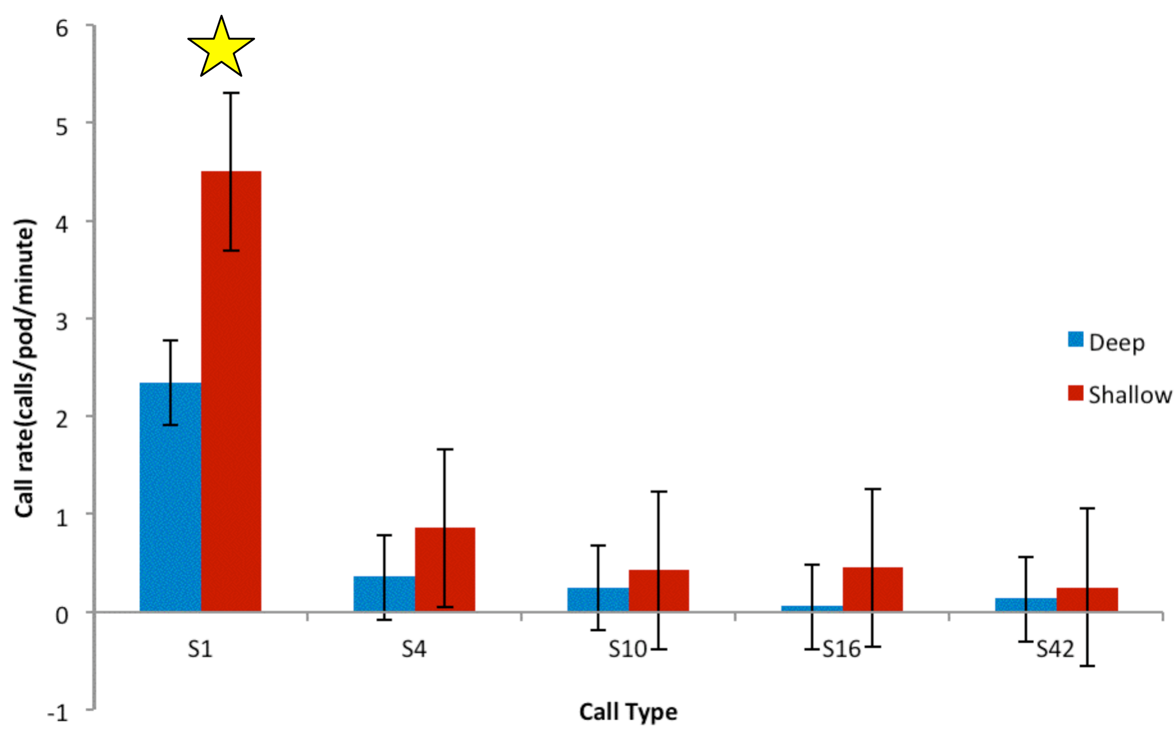

Figure 5. Variation in average call rate/pod/minute of the five different calls looked at per minute. The star represents statistical significance.

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