VARIATIONS OF FIN WHALE VOCALIZATIONS IN THE NORTHEAST PACIFIC AND THE EFFECTS OF ENVIRONMENTAL PARAMETERS ON ACOUSTIC SENSITIVITY

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Abstract

Declines in fin whale populations have instigated significant interest regarding their life history, feeding patterns, mating habits, and migration. Our current lack of understanding could be remediated by the use of passive acoustic methods to examine vocalization patterns. Data from seismometers and hydrophones exclusively associated with cabled observatories have been analyzed to monitor vocalization changes with distance from shore and between normal (2014-5) and El Niño Southern Oscillation (ENSO; 2015-6) years. Tens of thousands of calls were resolved, with a total of $3.6*10^5$. During ENSO relative to the normal season, there was a decrease in overall vocalizations along with a regional shift both onshore and southward. Additionally, as exhibited in both seasons, vocalization patterns occurred later in time at offshore instruments relative to those onshore. This time lag was more pronounced at higher latitudes. Different instruments and environments allowed for a quantified analysis of sensitivity as both instrument specifications and environmental parameters fluctuated. Sensitivity was found to linearly increase with depth by ~0.03% m^{-1}. Seismometers atop basalt were 2x as sensitive as those on sediment. Seismometers on basalt exhibited ~78% the sensitivity of hydrophones; those on sediment exhibited ~38% sensitivity. According to these changes in sensitivity, the use of weighted data was proposed based on ecological and instrumental characteristics.

Introduction

Overview of fin whales

The awe of the fin whale (*Balaenoptera physalus*) is due in part to its massive size as the second largest animal on Earth (fig. 1), only slightly smaller than the blue whale (*Balaenoptera*

Figure 1: Morphology of a fin whale with a human included for size comparison. Source: http://dinoanimals.com/animals/fin-whale-one-of-the-largest-whales/

musculus). Females generally grow larger than males, but the average specimen is ~18.3 m in length, longer than an average articulated city bus (Mizroch and Rice, 2006). Vocalizing with one of the loudest biological sounds, a fin whale's acoustic habitat can range for hundreds of kilometers. As a member of the mysticetes, baleen plates are used in place of teeth to filter seawater for food, mainly krill but also other zooplankton and small schooling fishes (Flinn et al. 2002). Females usually calve in a two year breeding cycle, comprised of a one year gestation period followed by ~6 months to 1 year before weaning (Mizroch. et al 2009).

Declines in population began during the first half of the 20th century cause by relentless whaling techniques (Mizroch et al. 2009). In a period of 200 years, it is estimated that more than two million whales were killed, including fin, blue, right, sperm, humpback, and Byrde's whales (Clapham et al. 1999). Since their inclusion in the Endangered Species Act of 1973, and the subsequent outlaw of their capture in 1976 by the International Whaling Commission (IWC), significant interest has grown regarding the fin whale's distribution, migratory habits, mating routines, and feeding behaviors (Stafford et al. 2009). While global estimates remain elusive, the population of fin whales in the North Pacific is estimated to be around 1652 (1142 – 2389; Zerbini et al. 2006).

As human-ocean interaction increases, understanding the anthropogenic influence on cetaceans becomes essential for determining our effect on these creatures. Although whaling is likely not a significant issue at the present (Clapham et al. 1999), shipping vessels are a major concern. For whales, auditory communication is required for long distance interactions in an ocean with limited sight. Shipping vessels have been restricting this acoustic habitat for decades, especially within the lower frequencies in which fin whales vocalize. Over the past half century, low frequency ambient noise, defined as 10 – 50 Hz, has increased approximately 2.5 – 3.0 dB (decibels) per decade due to an increase in shipping vessels (McDonald et al. 2006). A 3.0 dB increase is equivalent to a doubling of the acoustic energy.

Fin whale vocalizations range in frequency from 18-300 Hz, with the most common call being a down swept 20 Hz pulse lasting ~1 second (McDonald and Fox 1999). This is the call examined in this study (fig. 2). Songs can be composed of repetitive single notes at a fixed inter-pulse interval (IPI; defined as the time between calls) or complex combinations of doublets or triplets with differing IPIs (Oleson 2005, Watkins et al. 1987). Fin whales vocalize with source levels at one meter around 189 dB re 1μPa (Širović et al. 2007; Weirathmueller et al. 2013). For reference, this is about 8 times the intensity of a large tanker (181 dB). These low frequency, high intensity sounds can travel in the ocean for hundreds of kilometers, and are therefore essential in communication over extremely long distances (Payne and Webb 1971). This species is so noisy that even when no individual calls can be resolved, a seasonal band of elevated intensity around 20 Hz is attributed to constantly calling distant fin whales (Mellinger 2014).

In the Northeast Pacific, although fin whales are known to vocalize all year long, calls vary seasonally with a bell curve pattern of increased vocalization occurring between August and April (Moore et al. 1998; Širović et al. 2007). There is some indication that a diurnal cycle exists as well, with higher calling during the night (Oleson 2005; Watkins et al. 1987). Although vocalization can be used a proxy for abundance, catch statistics and visual surveys have verified

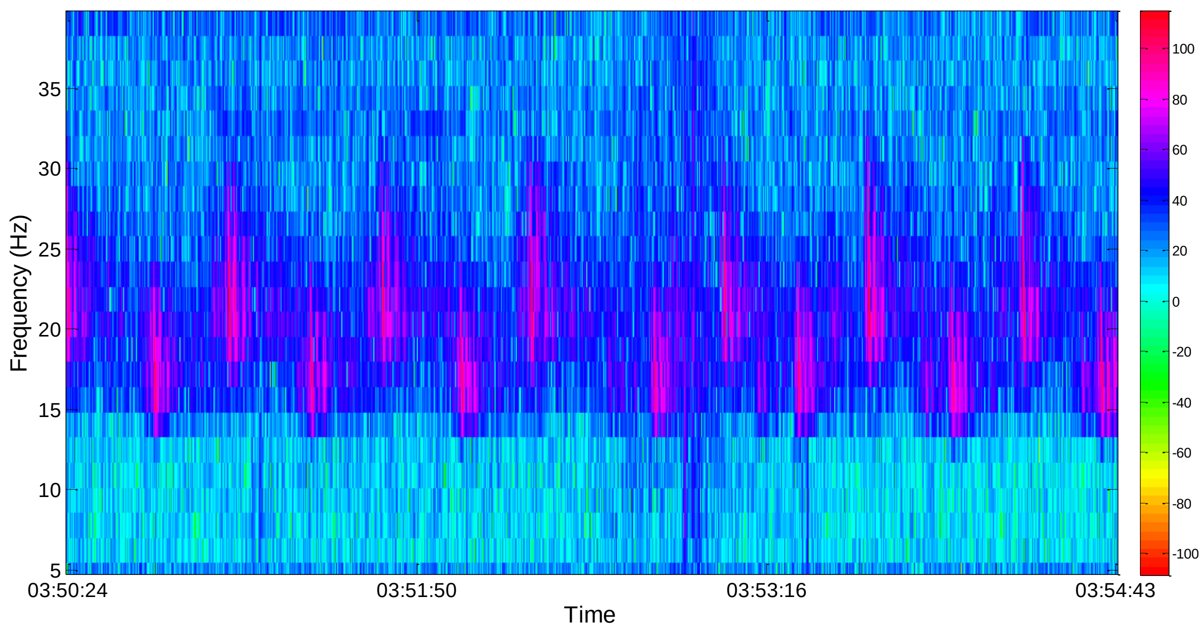


Figure 2: A spectrogram of fin whale vocalizations. Time represented by [hours]:[minutes]:[seconds] since the time 00:00:00 15 January 2015. Color bar indicates amplitude at the receiver.

fin whale presence during times of reduced or no calling (Mizroch et al. 2009). The songs are produced exclusively by males and are thought to be a mating display related to food availability. Vocalizing males may be proving their fitness by showing females locations of elevated productivity (Croll et al 2002). In humpback whales, increased levels of testosterone in the fall and winter months bolster the hypothesis that their songs are mating displays (Vu et al. 2015). Although no studies have examined seasonality of hormones in fin whales, similar phenomena occur in many marine mammals.

Little is known about the migratory patterns of fin whales, although at least a portion of the population may follow most baleen whales in migrating from high latitude feedings grounds in summer months to low latitude mating grounds in winter months. Northward migration is prompted by food availability. In the North Pacific, eastern boundary currents in the summer months create elevated krill populations, a staple zooplankton in their diet (Mizroch et al. 2009).

A strong positive correlation exists between fin whale arrival in feeding grounds and an increase in krill (Nemoto 1955). Perhaps more convincing is the lack of fin whales found in a known feeding ground during a year with relatively low krill abundance (Nemoto and Kasuya 1965). In the Mediterranean, fin whale movements have been shown to strongly correlate with changes in environmental parameters, namely patches of zooplankton (Littaye et al. 2004). This same study found that during years of decreased productivity, the whales followed short term environmental changes resulting in temporary populations of krill.

It is not known with certainty the reason for a southward migration to mate, although it has been equivocally hypothesized that elevated water temperatures associated with low latitudes may be energetically advantageous for calving (Kawaruma 1975). In all whales, survival is dependent on continuous swimming, so a migration even of such magnitude is not notably energetically intensive (Mizroch et al. 2009). There is evidence to suggest that a portion of the population does not participate in this migration (Soule and Wilcock 2013). Catch statistics show that fin whales en route to feeding grounds have a diminished blubber content, possibly making it advantageous for the sexually immature population to remain in productive northern latitudes (Stafford et al. 2007, Kawamura 1975). The assumption that calving grounds remain exclusively in lower latitudes is not certain, although there have been no direct sightings of calves in northern areas (Mizroch et al. 2009). It is worth noting that few calving grounds have been verified in lower latitudes either (Mizroch et al. 2009).

Effects of different analytical techniques

Various tools have been utilized to study whales such as visual surveys, tagging, and historical whaling records. More recently, passive acoustic methods have been widely used due to their non-intrusive nature and ability to increase sample size (Hatch and Clark, 2004; Watkins et al., 1987). Due to notably high vocalization, fin whales have the capacity to become a model cetacean species for research through the use of passive acoustics. However, when calling decreases significantly in the spring and summer, non-acoustic methods can be vital. Despite these techniques, very little is known about fin whales in the North Pacific. A lack of information restrains accurate hypotheses on population structure (Carretta et al. 2005), although for conservation purposes the IWC describes three subpopulations in the North Pacific: Northeast-Pacific (Gulf of Alaska), California-Oregon-Washington, and Hawaii.

Data from acoustic studies are affected by a multitude of environmental parameters such as depth dependent acoustic properties and variable seafloor reflection coefficients. This study explores how detection sensitivity to fin whale calls changes with depth and substrate type to investigate the use of weighted data based on these discrepancies. Note this needs significant attention when making *quantitative* comparisons; *qualitative* spatiotemporal patterns can still be resolved through unweighted assessments. In addition, many other factors besides depth and substrate affect an instrument's sensitivity such as bathymetric features or the whale's direction of motion but were not the focus of this study, and therefore will not be discussed further.

Many studies including this one have compiled data from differing acoustic instruments based on availability in order to increase temporal or spatial resolution. In these cases, relative sensitivity can be a function of instrument specifications. Hydrophones are generally used as the most effective way of collecting acoustic data, as pressure differences are measured within the water column itself. Seismometers differ in that they measure movements in the underlying seafloor. However, seismometers can still be an effective tool in the study of fin whales as their vocalizations are powerful enough to create detectable vibrations in the seafloor (McDonald

1995, Dunn and Hernandez 2009, Weirathmueller 2013). Additionally, the extensive global seismic network provides an opportunity for supplementary research questions to be explored in addition to the primary function of earthquake detection. By using seismometers to listen to whales, the purpose of this seismic network can be expanded to include cetacean research.

Supplementary Information

This study was partly motivated by the recent installation of the Cabled Array off the coast of Oregon, funded and managed by the Ocean Observatories Initiative (OOI; Kelley et al. 2014). This cabled observatory, one of the largest in the world, will allow for whale analyses on an unprecedented temporal scale due the constant flow of data available to anyone with an internet connection. Additionally, the broad longitudinal extent of hydrophones and seismometers associated with the Cabled Array can be used for exploring vocalization with respect to distance from shore both seasonally and annually. This study uses the Cabled Array in conjunction with Ocean Network Canada's cabled observatory NEPTUNE to examine a large portion of the Northeast Pacific (fig. 3). The use of cabled observatories will revolutionize cetacean science with its ease of access and capacity to exponentially increase both temporal and spatial scales otherwise impossible with more traditional techniques, acoustic or otherwise.

Understanding vocalizations produced by this species adds to the growing body of knowledge regarding their population structure. With this awareness comes a greater appreciation for their intelligence and, in turn, conservation efforts. Additionally, this information informs policy towards less invasive shipping routes by determining established whale grounds around which shipping vessels could be limited or banned.

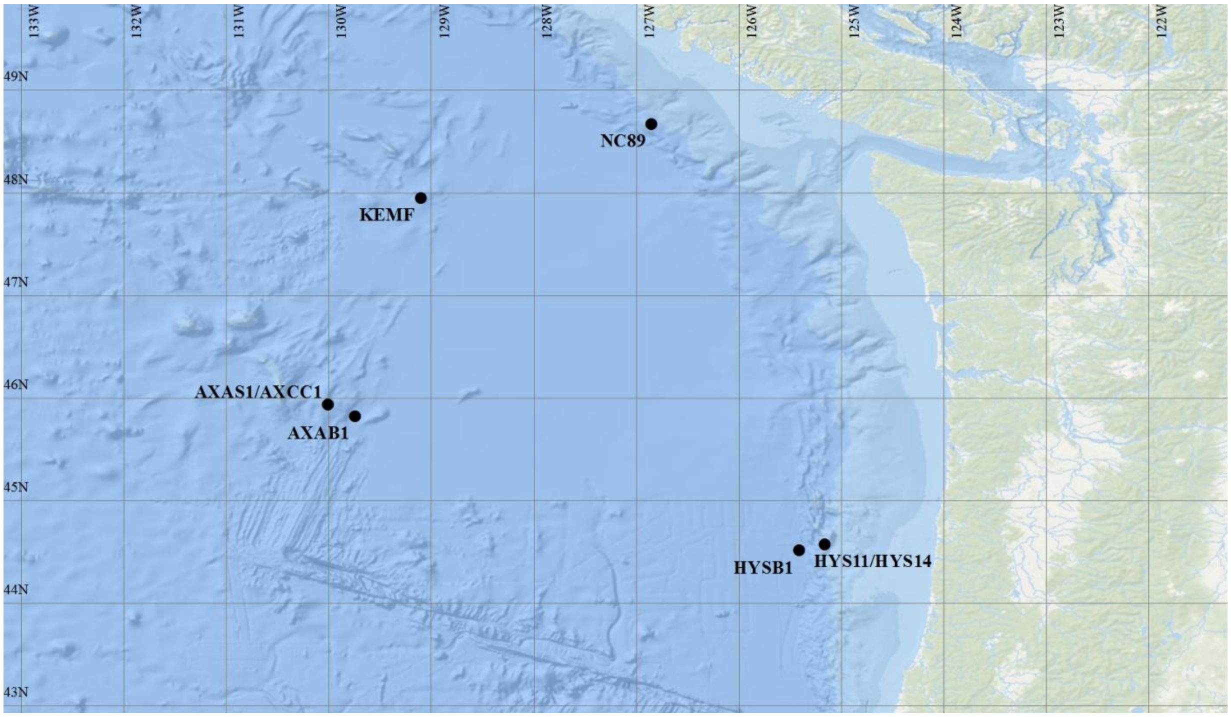


Figure 3: Map of the station locations. The two northern instruments (KEMF and NC89) are a part of Canada's NEPTUNE cable whereas the other six instruments are associated with the newly installed Cabled Array.

In addition to the scientific benefits of studying fin whales, this research has societal implications. Recent history has demonstrated the general public's captivation with whales. Whale beachings are followed by half a dozen articles grasping for an explanation. The rise of the Greenpeace foundation was facilitated with the slogan 'Save The Whales,' which they developed after listening to some of the first recordings of humpback whales obtained by Roger Payne (May 2014). Society's fascination stemmed partly from these recordings, which uncovered the complexity of whale songs and pointed towards an unprecedented intelligence in cetaceans, and in the oceans in general. Studying these creatures thus provides a means of connecting the public with science, allowing them to be ambassadors for marine preservation.

Methodology

Study Sites and Instrument Specifics

Two cabled observatories were used. One of them, the OOI Cabled Array, was completed in 2014 and funded by the OOI. The cable extends ~470 km from Pacific City, Oregon, to its final destination at an underwater volcano, Axial Seamount, atop the Juan de Fuca plate boundary. Another portion of cable associated with the same observatory curves towards the south along the continental shelf and slope, passing over a methane seep site. The other observatory, called NEPTUNE, is maintained by Ocean Networks Canada and has been gathering data since 2009. This cable originates in Barkley Sound off Vancouver Island and creates a loop extending ~250 km offshore the entrance to the Straits of Juan de Fuca. Eight instruments associated with these cabled observatories were selected for detection of calls, six of which were associated with the OOI Cabled Array and two with NEPTUNE (fig. 3).

The following six instrument are connected to the OOI Cabled Array (table 1). On the summit of Axial Seamount, an underwater volcano, lies both a short period seismometer (AXAS1) and a hydrophone (AXCC1) separated by ~2 km. ~20 km to the southeast, at the base of Axial, is a hydrophone (AXBA1). Notable is the acoustic 'shadow' created from the volcano to the northwest. Closer to shore, at the base of the continental slope, is a hydrophone (HYSB1). ~20 km to the northeast is a methane seep site called Hydrate Ridge where both a hydrophone (HYS14) and a short period seismometer (HYS11) were used, separated by ~0.5 km. Although seemingly redundant, data were gathered from both a hydrophone and a seismometer in close proximity at two locations in order to compare their relative sensitivities to fin whale vocalizations.

Location	**Instrument**	**Abbreviation**	**Depth (m)**	**Substrate**	**Distance to**	**Coordinates**

					Shore (km)	
Axial Summit	Seismometer	AXAS1	1529 (shallow)	Basalt	466 (offshore)	45.9 ºN 130.0 ºW (south)
Axial Summit	Hydrophone	AXCC1	1529 (shallow)	Basalt	466 (offshore)	46.0 ºN 130.0 ºW (south)
Axial Base	Hydrophone	AXBA1	2609 (deep)	Sediment	446 (offshore)	45.8 ºN 129.7 ºW (south)
Slope Base	Hydrophone	HYSB1	2920 (deep)	Sediment	106 (onshore)	44.5 ºN 125.4 ºW (south)
Hydrate Ridge	Seismometer	HYS11	785 (shallow)	Sediment	85 (onshore)	44.6 ºN 125.2 ºW (south)
Hydrate Ridge	Hydrophone	HYS14	785 (shallow)	Sediment	85 (onshore)	44.6 ºN 125.1 ºW (south)
Endeavor Vent Field	Seismometer	KEMF	2205 (deep)	Basalt	247 (offshore)	47.9 ºN 129.1 ºW (north)
Clayoquot Slope	Seismometer	NC89	1258 (shallow)	Sediment	85 (onshore)	48.7 ºN 126.8 ºW (north)

Table 1: Information on each instrument's environmental characteristics. For the depth, distance to shore, and latitude columns, the word in parentheses represents the qualitative identifier for each parameter. The cutoff value between 'deep' and 'shallow' instruments is 2000 m. 'Onshore' and 'offshore' are divided at 200 km from the coastline, approximately the extent of the continental slope. For latitude, stations south of 47 ºN are denoted 'south' while those north are 'north.'

The following two instruments are connected with NEPTUNE and are farther north than the previously described locations (fig. 3, table 1). Seismometers were used at both stations. A short period seismometer (KEMF) is located in the Endeavor hydrothermal vent field, on the spreading ridge between the Pacific plate and the Juan de Fuca plate. A broadband seismometer (NC89) is located to the northeast at the base of the continental slope. Note that only NC89 is a broadband seismometer, while all others are short period. However, over the frequency range of this study (~15-25 Hz), both should have equal sensitivities. The vertical components of the seismic data were used due to better seafloor coupling relative to other channels. More information on any of these instruments can be found at the Incorporated Research Institutes for Seismology (IRIS) Data Management Center (DMC).

This study took place over the duration of two vocalization seasons: 2014-5 and 2015-6. A vocalization season is defined here as August through March, inclusive. Temporal boundaries were chosen based on the onset and end of seasonal fin whale calling described in the literature, although missing data delayed the start date for all OOI stations (table 2). For all stations, the end date was 31 March 2016.

Instrument	Start Date	Missing Times
AXAS1	04 November 2014	05 Nov 2014 08 – 10 Dec 2014 06 – 07 Mar 2015 10 – 15 Jun 2015
AXCC1	15 January 2015	06 – 07 Mar 2015 10 – 15 Jun 2015
AXBA1	15 January 2015	06 – 07 Mar 2015 10 – 15 Jun 2015
HYSB1	15 January 2015	06 – 07 Mar 2015 10 – 15 Jun 2015 20 Nov – 05 Dec 2015
HYS11	04 November 2014	05 Nov 2014 08 – 10 Dec 2014 06 – 07 Mar 2015 10 – 15 Jun 2015
HYS14	15 January 2015	06 – 07 Mar 2015 10 – 15 Jun 2015
KEMF	01 August 2014	16 – 17 Mar 2016
NC89	01 August 2014	22 – 23 Aug 2014 18 – 24 Sep 2014 12 Nov 2014 – 13 Jan 2015

TABLE 2: Data gaps and beginning of data acquisition for each instrument. Note that these are only gaps spanning one day or longer. Data gaps also shown graphically in figure 5.

Comparisons were made based on the parameters of depth, latitude, and distance to shore. Stations were categorized as ‘deep’ or ‘shallow’ based on a cutoff depth of 2000 m (table 1). ‘North’ stations were defined as those at latitudes above 47ºN while all others were ‘south.’ Lastly, a distance to shore analysis was accomplished by segregating ‘onshore’ and ‘offshore’ instruments where ‘onshore’ stations were less than 200 km from the coastline.

Data Analysis

MATLAB was used for data acquisition (see Appendix). 'Picks,' defined as computer selected fin whale calls, were determined through comparison of a mathematically derived simulated call to the raw data. Signal-to-noise ratios (SNR) were calculated as quantifications of the correspondence between the fabricated call and the data (fig. 4).

Variability in peak SNR values was unavoidable due to changing vocalization distances, azimuths, and other characteristics. To account for this, adjustable parameters were set to increase precision and accuracy. A legitimacy threshold of 9.5 was determined for SNR values through manual examination of spectrograms, with the goal of reducing false picks without nullifying actual calls (fig. 4). Picks below this value were discarded. This final threshold value was chosen based on the spread of SNR values for stations with elevated background noise, namely AXAS1 due to its proximity to an active volcano. Though noise levels varied between stations, a single value (9.5) was used universally to ensure data comparability. Additionally, a filter based on the Inter-Pulse Interval (IPI) was created based on call characteristics found in the literature. Any pick with an IPI of less than 15 or greater than 35 seconds was discarded.

Results

Parameter Definitions and Data Gaps

The 2014-5 and 2015-6 seasons will be referred to as S1 and S2, respectively. The Calling Midpoint (CM) refers to the middle of the vocalization season, as determined by calculating the mean time for all picks in a season. Note that this is *not* the peak in vocalization or the median. Onset of calling is defined as the first day of the season on which there were over 100 calls per day. This definition is applicable for all stations except NC89. During S2, the lack of calling at this instrument made the onset appear *after* the CM, as daily call counts did

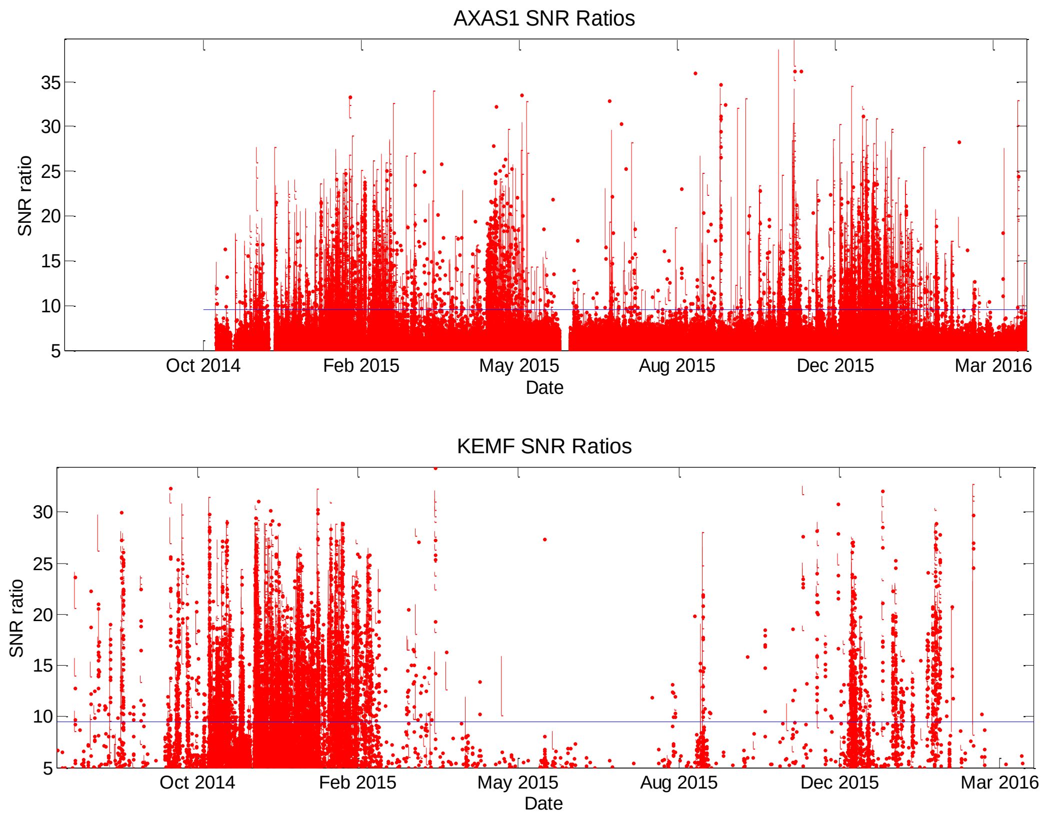


Figure 4 (previous page): Values of the signal to noise ratio (SNR) for all picks at AXAS1 and KEMF plotted with a blue line indicating the SNR threshold of 9.5, determined based on elevated background noise at AXAS1 due to proximity to an active volcano. KEMF is referenced as an instrument with lower background noise for comparison. Note that these plots are prior to both SNR and Inter-Pulse Interval (IPI) filters. Data acquisition did not begin for AXAS1 until 04 November 2014.

not hit 100 until later in the season. Therefore, solely for NC89, the onset threshold was 50 calls per day for both S1 and S2.

All OOI instruments had a delayed start date due to lack of data availability (table 2, fig. 5). Save for one at HYSB1, all data gaps of one day or longer were shared among OOI instruments, leading to the conclusion that most missing times post start date were cable-wide.

Station Results

A total of $3.6*10^5$ calls were analyzed. Total annual calls, onset of calling, and CM were calculated for each instrument (table 3, fig. 5).The CM and onset of calling for S1 is unreliable and therefore not calculated for stations AXCC1, AXBA1, HYS14, and HYSB1, as data acquisition did not begin until mid-season (15 January 2015).

Discussion and Conclusions

Hydrophones vs. Seismometers

One motivation for this study was to determine the legitimacy of using seismometers for fin whale detection. In order to address this issue, two comparisons were made between the hydrophone/seismometer pairs for Axial Seamount (AXCC1/AXAS1) and Hydrate Ridge (HYS11/HYS14). Due to missing data, only S2 was used for comparison. Note that there is a small distance between each pair that could influence data comparability. There is is ~2 km between the AXAS1/AXCC1 pair and ~0.5 km between the HYS11/HYS14 pair. These were the minimum distances between seismometers and hydrophones found at each site.

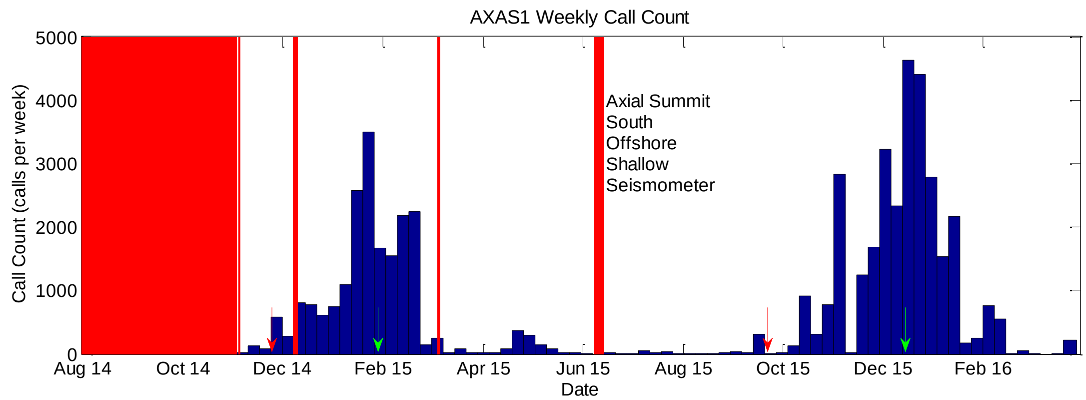
This comparison has both discrepancies and correspondences. For one, the small sample size reduces the certainty of these results. Future examination should include more hydrophone/seismometer coupled instruments for reliability. However, the compared instruments are in the same general location, at the same depth, on the same substrate, and appear to share the same data gaps. Additionally, the hydrophones and seismometers were installed simultaneously.

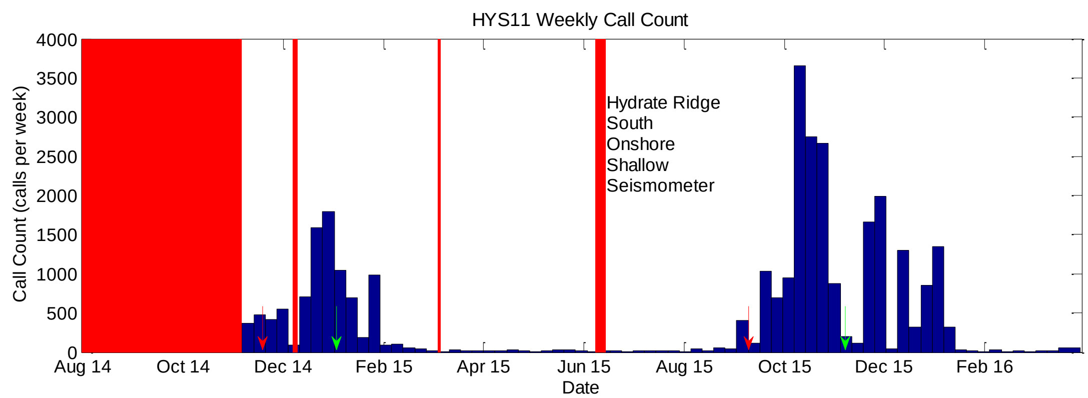
The relative sensitivities have been calculated for seismometers and are defined as the percent of picks received relative to the associated hydrophone (table 3). This calculation was done using the entirety of S2 as well as the months of February and March during S1. Prior S1

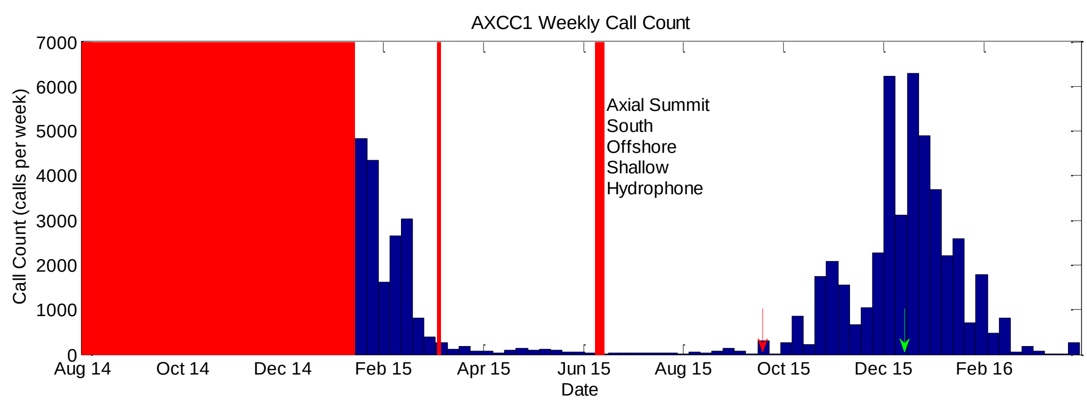
Instrument	Calling Onset (S1; S2)	Calling Midpoint (S1; S2)	Total Calls (S1; S2) (x10^4 calls)	Percent Change S2/S1 (%)
AXAS1	17 November 2014; 20 September 2015	22 January 2015; 15 December 2015	1.94; 3.14	23
AXCC1	N/A; 01 September 2015	N/A; 16 December 2015	1.83; 4.48	37
AXBA1	N/A; 02 September 2015	N/A; 17 December 2015	2.77; 5.67	35
HYSB1	N/A; 11 August 2015	N/A; 12 November 2015	0.871; 11.3	53
HYS11	11 November 2014; 08 September 2015	27 December 2014; 07 November 2015	0.926; 2.16	40
HYS14	N/A; 10 August 2015	N/A; 14 November 2015	0.517; 6.39	37
KEMF	11 September 2014; 09 December 2015	20 December 2014; 22 December 2015	1.68; 0.153	9
NC89	11 August 2014; 26 September 2015	10 October 2014; 30 October 2015	0.148; 0.0303	20

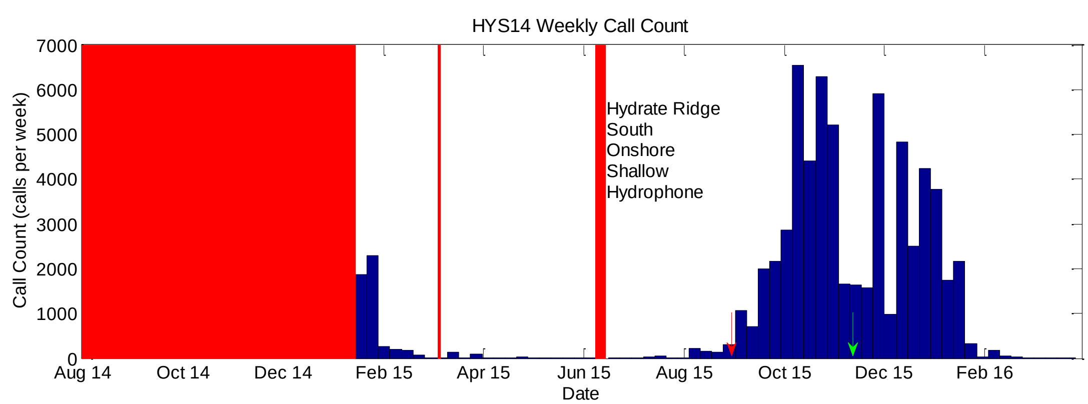
Table 3: Results for each instrument, including onset, midpoint, and total calls. Note that for instruments AXCC1, AXBA1, HYSB1, and HYS14, the S1 onset and midpoint are not assessed due to the mid-season S1 data acquisition start date (15 January 2015). This also reduced the value of the total calls.

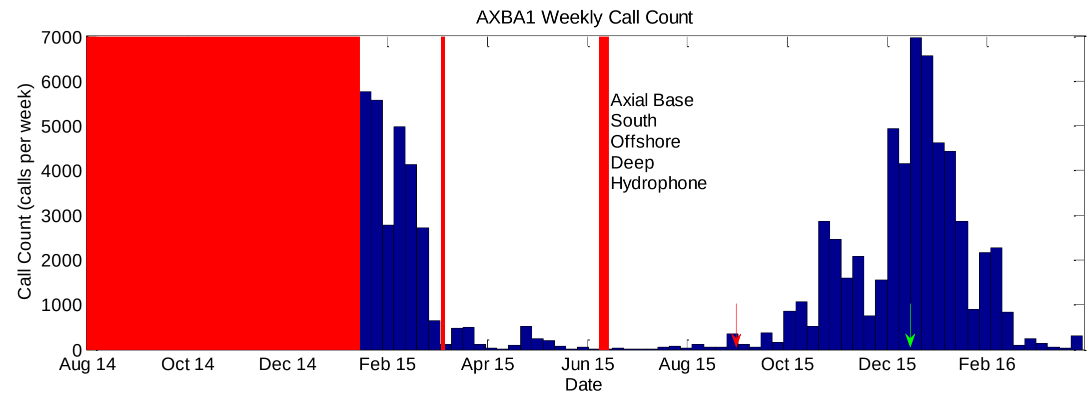
data was neglected due to missing data. Seismometer sensitivities were 78% and 38% for axial and hydrate ridge, respectively. These data provide useful insights into the legitimacy of using seismometers for acoustic cetacean research. As expected, seismometers were less sensitive than hydrophones. But perhaps more valuable is the difference between the sensitivities. The seismometer at Axial was 2.05x more sensitive than the one at Hydrate Ridge. It is possible that this is due to substrate type, as harder substrates are more effective acoustic reflectors than softer ones. Therefore, this study used weighted data depending on substrate type while using *seismometers*, where data from sediment was weighted 2 times heavier than from basalt. Note that this technique is only necessary when using seismic data; hydrophone data will be unaffected, as it detects pressure differences in the water column, not the underlying substrate.

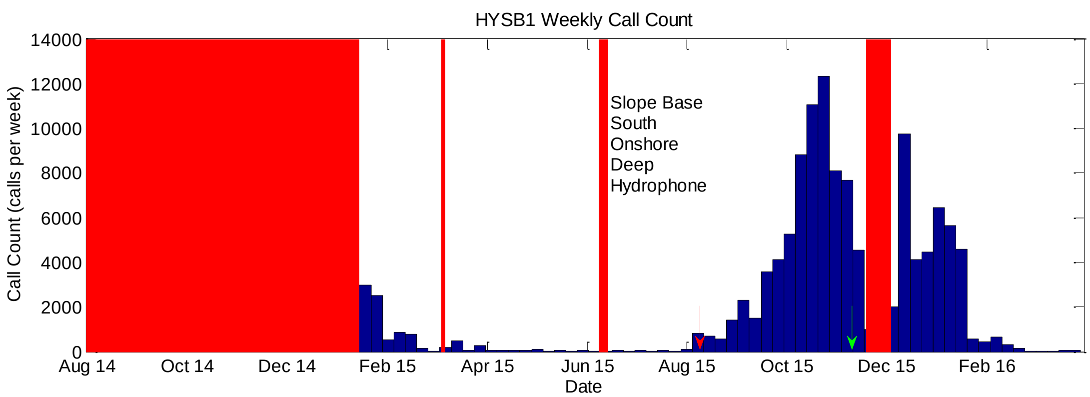

AXAS1 Weekly Call Count
Call Count (calls per week)
Date
Axial Summit
South
Offshore
Shallow
Seismometer
Aug 14
Oct 14
Dec 14
Feb 15
Apr 15
Jun 15
Aug 15
Oct 15
Dec 15
Feb 16


HYS11 Weekly Call Count
Call Count (calls per week)
Date
Hydrate Ridge
South
Onshore
Shallow
Seismometer


AXCC1 Weekly Call Count
Call Count (calls per week)
Date
Axial Summit
South
Offshore
Shallow
Hydrophone


HYS14 Weekly Call Count
Call Count (calls per week)
Date
Hydrate Ridge
South
Onshore
Shallow
Hydrophone


AXBA1 Weekly Call Count
Axial Base
South
Offshore
Deep
Hydrophone
Call Count (calls per week)
Date
7000
6000
5000
4000
3000
2000
1000
0
Aug 14
Oct 14
Dec 14
Feb 15
Apr 15
Jun 15
Aug 15
Oct 15
Dec 15
Feb 16


HYSB1 Weekly Call Count
Slope Base
South
Onshore
Deep
Hydrophone
Call Count (calls per week)
Date
14000
12000
10000
8000
6000
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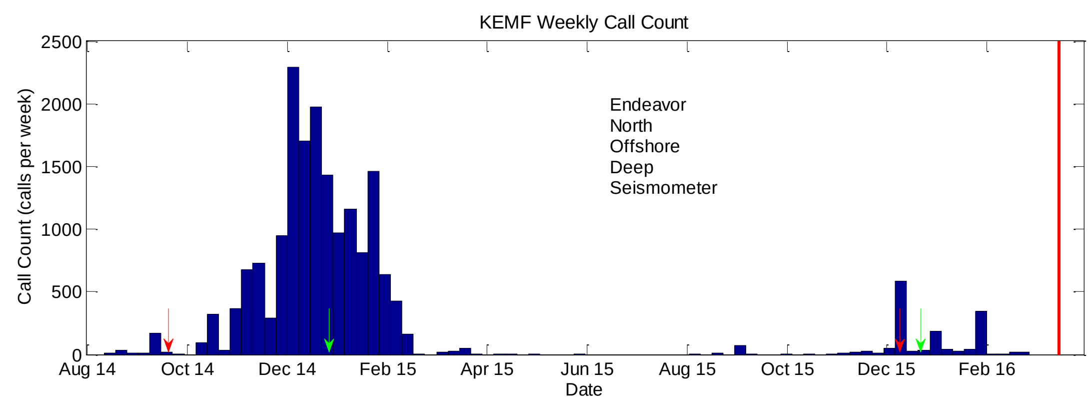
Aug 15
Oct 15
Dec 15
Feb 16


KEMF Weekly Call Count
Endeavor
North
Offshore
Deep
Seismometer
Call Count (calls per week)
Date
2500
2000
1500
1000
500
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Aug 15
Oct 15
Dec 15
Feb 16

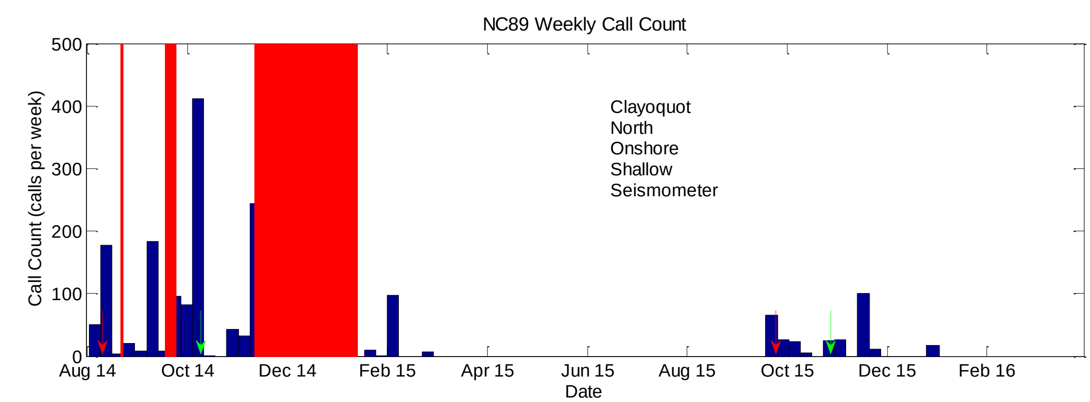

NC89 Weekly Call Count
Clayoquot
North
Onshore
Shallow
Seismometer
Call Count (calls per week)
Date
500
400
300
200
100
0
Aug 14
Oct 14
Dec 14
Feb 15
Apr 15
Jun 15
Aug 15
Oct 15
Dec 15
Feb 16

Figure 5 (previous 2 pages): Histograms of weekly call counts at each station. Red sections indicate missing data segments of one day or longer. Red arrows indicate onset date while green arrows indicate Calling Midpoint (CM) date. Note that the scale for the y-axes are variable from between plots.

Additionally, comparisons of seismic and hydrophone data should factor in that seismic data will have a ~78% relative sensitivity, and ~38% in sediment.

Effect of Depth

By comparing the hydrophones deployed around Axial Seamount (AXBA1 and AXCC1) and those near Hydrate Ridge (HYSB1 and HYS14), the effect that depth has on instrument sensitivity was quantified. The depth differences are 1079 m between AXBA1 (2607 m) and AXCC1, and 2136 m between HYSB1 (2921 m) and HYS14 (785 m). No substrate corrections need to be made as all instruments are hydrophones and therefore remain unaffected by the acoustic consequences of substrate differences. This will not be an ideal comparison, as depth is not the only changing variable. The horizontal distances between the Axial pair (AXBA1/AXCC1) and the Hydrate Ridge pair (HYSB1/HYS14) are 23.9 km and 21.2 km, respectively. In addition, differing bathymetric features will undoubtedly change the sensitivity of each location relative to its partner. For example, in the case of Axial, the instrument is in the acoustic shadow of the volcano (located to the west) and thus could have reduced sensitivity to vocalizations occurring on the opposite side of Axial.

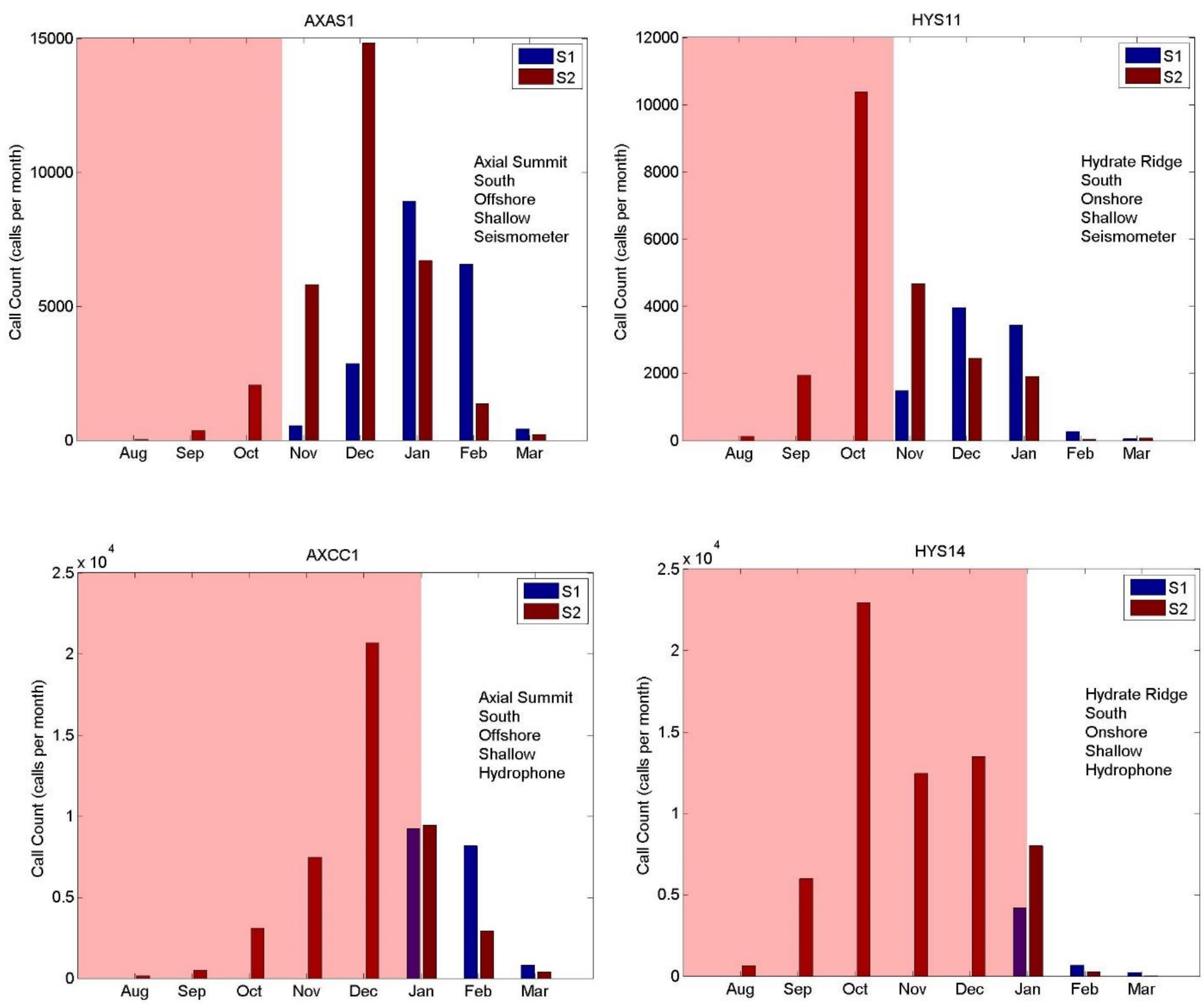
Nonetheless, the comparison between the locations provided useful information for determining the effect of depth on sensitivity to calling. The instruments at all four stations are identical to one another and were installed simultaneously, minimizing the possibility for instrumentation bias. Also, all instruments shared most data gaps spanning one day or longer.

Furthermore, the following percentages were calculated using the combined total call counts of S1 and S2 in order to confirm the consequence of depth. AXBA1 (8.44e4 calls) received 134% of calls relative to AXCC1 (6.31e4 calls), while HYSB1 (12.2e4 calls) received 177% of calls relative to HYS14 (6.91e4 calls). The agreement between these datasets show that call sensitivity increased with depth within the bounds of these stations (785-2921 m), and that the Hydrate Ridge pair exhibited a greater difference in received picks than the Axial pair, corresponding to a greater difference in depth between instruments.

When the differences were examined in greater detail, a notable pattern presented itself. There turned out to be a linear relationship between these percent differences when normalized to depth. The percent of calls that the deep instruments received in excess of the shallow instruments were 33.9% and 76.5% for the Axial and Hydrate Ridge pairs, respectively. For the axial pair, the normalized value was (34% / 1079 m) = 0.032 % m^{-1} while for the hydrate pair it was (77% / 2136 m) = 0.036 % m^{-1}. The similarity of these two values suggested that the effect of depth over this range was relatively linear. Note that no seismometers were used in this depth analysis. Since hydrophones detect pressure differences in the water, while seismometers detect movements in the seafloor, there could be some discrepancies regarding this linear relationship in its application to seismic data. However, although linear sensitivity may deviate, the increase in sensitivity with depth should still hold true, since seafloor motion is induced by pressure differences in the water column. For the purposes of this study, the assumption was made that when using seismometers sensitivity increased linearly with depth, following the linear pattern of ~0.034% m^{-1} exhibited by hydrophones.

S1 and S2 Differences

Calling decreased significantly from the normal year to the ENSO event (table 3, fig. 6, fig. 7). This was especially pronounced in the northern stations. During S2, KEMF and NC89 received only 9% and 20%, respectively, of the calls received in S1 of these stations were not influenced by the extensive early S1 season data gaps that affected OOI stations. Histograms for stations farther south appear to indicate the opposite inter-seasonal pattern at first glance (fig. 6), although this artificial phenomenon is a result of the missing data associated with early season S1, making overall S1 vocalizations seem significantly diminished.



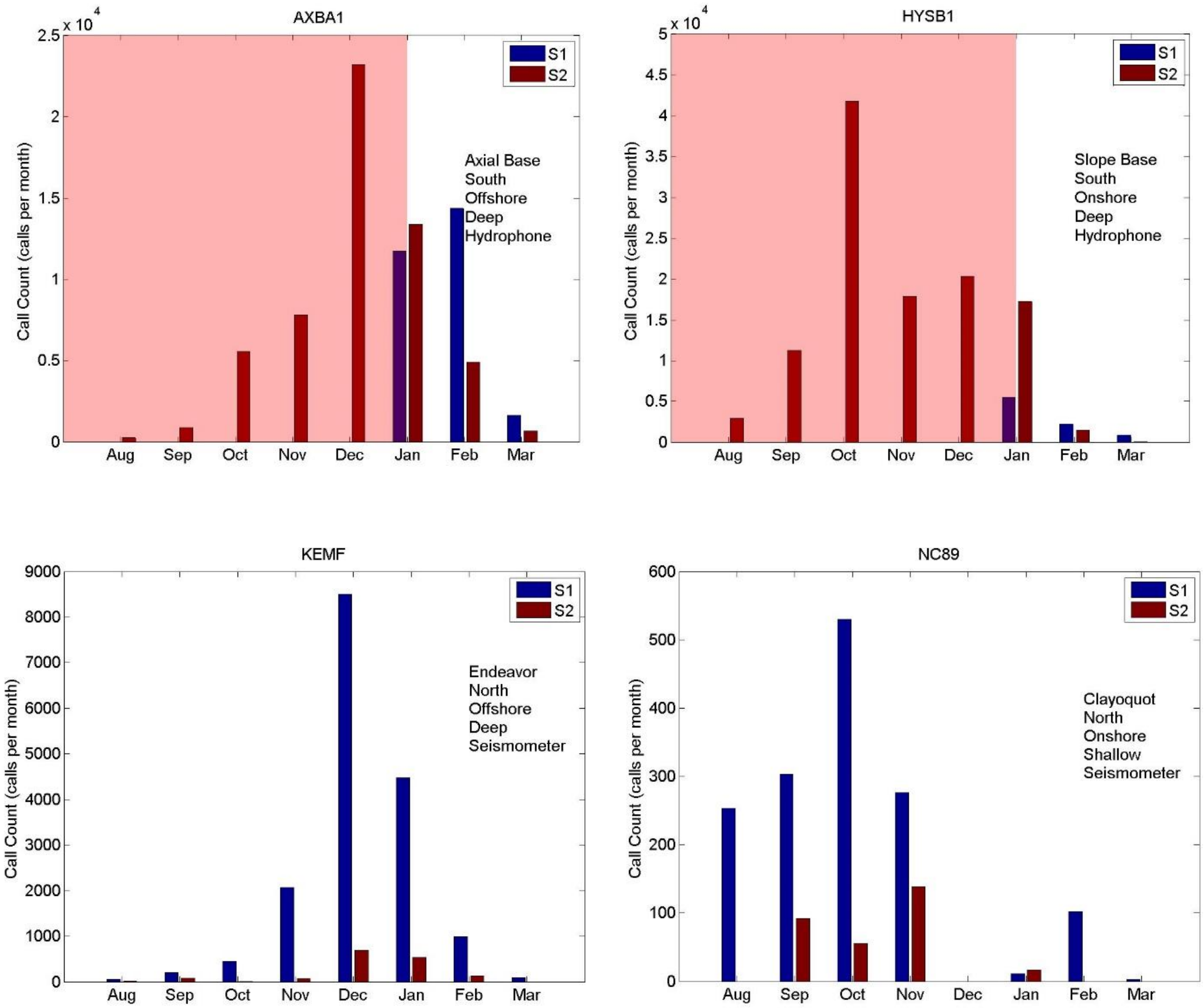


Figure 6 (continued from previous page): Monthly comparisons between S1 (2014-5; normal year) and S2 (2015-6: ENSO year) for all stations, with station characteristics labelled on figure. Red sections indicate time prior to start date for S1, and therefore designate a lack of data as opposed to a lack of calls. For AXAS1 and HYS11, data acquisition began on 04 November 2014. For AXCC1, AXBA1, HYSB1, and HYS14, data began 15 January 2015. For KEMF and NC89, data began 01 August 2014. Note that for all months without extensive data gaps, there were more calls in S1 than S2. This pattern is especially pronounced in the northern stations.

Accordingly, only February and March data were compared between S1 and S2 in the southern instruments, as the extensive data gaps ended after 15 January 2015. S2 final counts at every station were less than half of S1, except for HYSB1 which was only slighter greater than half (table 1, fig. 7).

Distance to Shore: Timing

Distance from shore was found to strongly influence timing of vocalizations, with stations closer to shore exhibiting both an earlier onset and CM (fig. 8). The S1 onset for KEMF, which is 247 km from shore, was exactly one month later than that of NC89, which is 85 km from shore. S2 onset was even more exaggerated, with the occurrence at NC89 happening over two months earlier than at KEMF. The conclusions drawn from these differences may initially seem biased due to different onset definitions; the onset threshold for KEMF was 100 calls per day while for NC89 it was 50 calls per day, due to extremely low S2 vocalizations at NC89 (more explanation in methods section). However, even when threshold for NC89 was raised to 100 calls per day, S1 onset for NC89 remained one month prior to KEMF. Similar phenomena occurred with their CMs (fig. 8). For S1, the CM for NC89 was greater than two months earlier than that of KEMF, while for S2 they were separated by nearly two months as well. Therefore, both the onset and CM for the northerly stations during both seasons were consistently significantly earlier for NC89 relative to KEMF. It should be noted that a large chunk of data was missing for NC89 during the middle of S1 (12 November 2014 to 13 January 2015). This likely affected S1 CM, but was irrelevant in the determination of onset.

For southerly OOI stations, only AXAS1 and HYS11 seismometers will be examined in the distance to shore interpretation for S1, as they are the only OOI instruments with data prior to 15 January 2015. Also notable are the significant amount of uncorrected data gaps associated with these stations in all late 2014 and early 2015 (04 November 2014 through 15 January

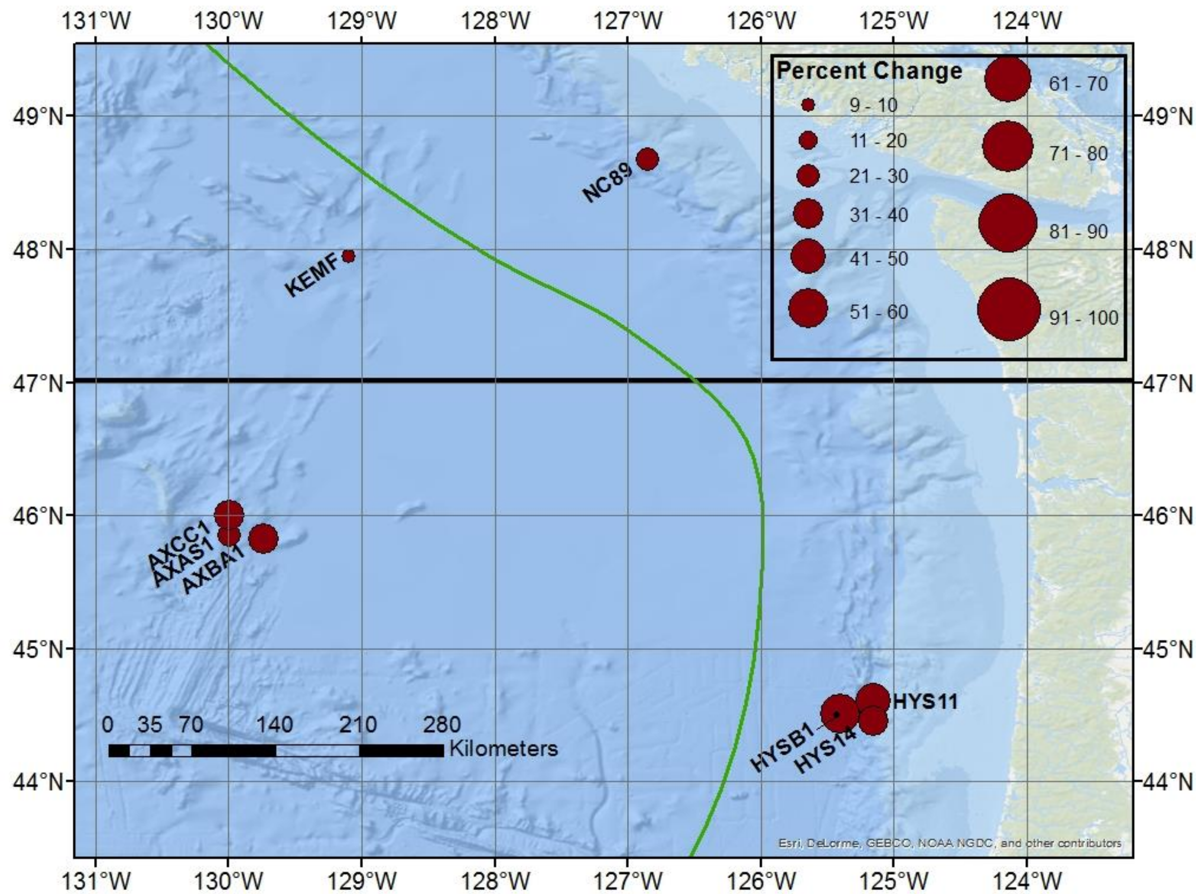


Figure 7: Instrument locations weighted with the percent change from S1 (normal year) to S2 (ENSO year), with 100% representing no change and values less than 100% indicating a decrease from S1 to S2. Values range from 9% at KEMF to 53% at HYSB1, therefore indicating a universal decrease from S1 to S2. The pairs (AXCC1/AXAS1) and (HYS11/HYS14) share respective coordinates, but are offset for visualization. Black line at 47°N separates 'north' instruments from 'south' instruments. Green line distinguishes 'onshore' from 'offshore' at 200 km from the coastline. Note that for southern instruments, only February and March values are compared due to data gaps in early S1 for all OOI instruments. The north and offshore categories both exhibited greater inter-seasonal decrease relative to south and onshore, respectively, as indicated by the smaller symbol sizes.

2015). These missing data restrain the ability to draw conclusions as they decrease early S1 picks. However, these two instruments appear to share the same data gaps (table 2, fig. 5), so any differences between the two should be valid. For all OOI stations, S2 analysis is applicable.

During S1 for AXAS1, which is 466 km from shore, calling began ~1 week later than at HYS11, for which the distance to shore is 106 km. During S2, HYS11 calling began ~2 weeks

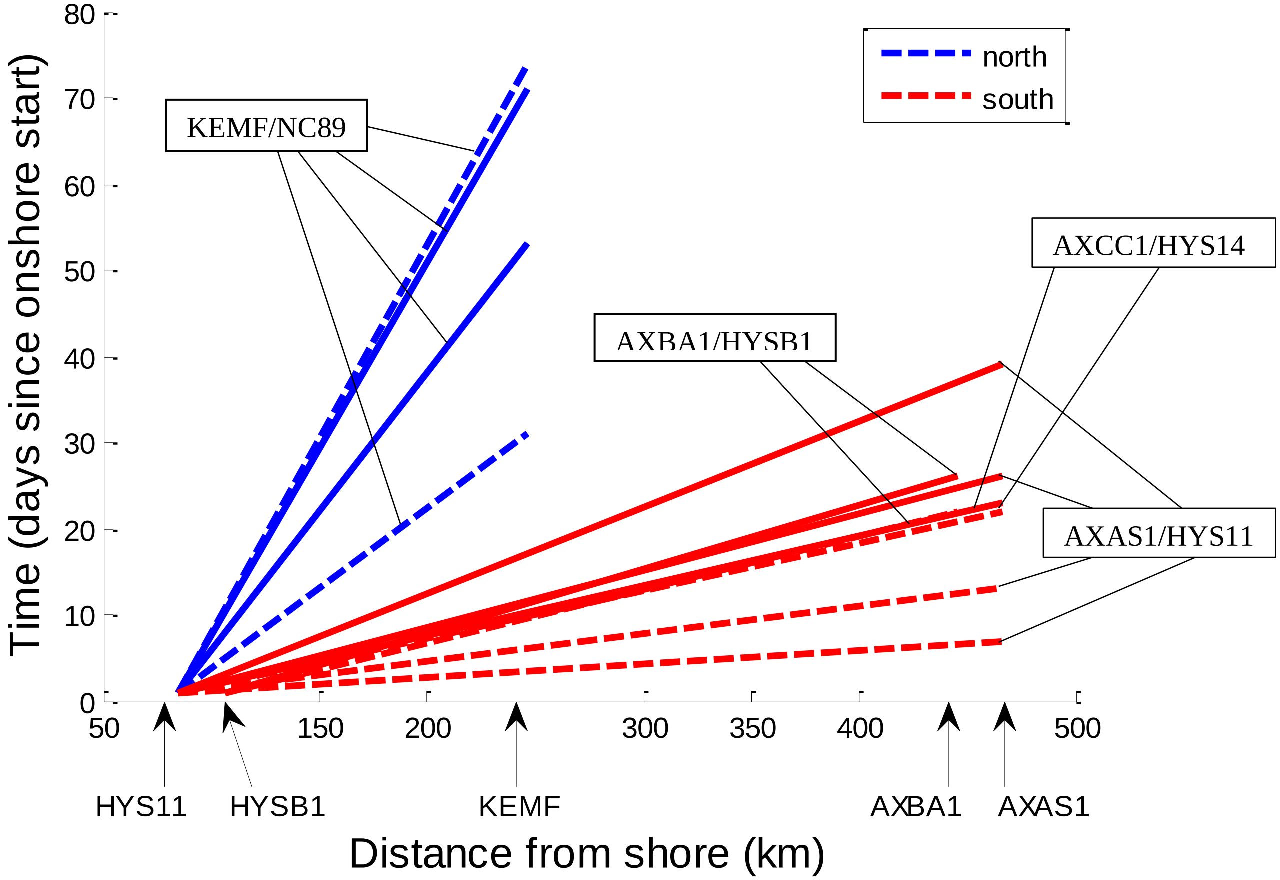


Figure 8: The effect of distance to shore on timing of vocalization patterns. Instruments are labelled on the x axis at their respective distances from shore. Note that location of HYS11 is the same as HYS14 and NC89, while the location of AXAS1 is the same as AXCC1. Solid lines represent Calling Midpoint (CM) while dashed lines represent onset of calling. Time is normalized to every onshore instrument, defining (t = 1) to the times of all events (either onset or CM, including S1 and S2) at the *onshore* instrument. This means that (t = 1) represents multiple absolute times. Each line is a connection between the timing of an event at the onshore instrument to the timing of the correlate event at the offshore instrument. A positive slope therefore represents an onshore event preceding the correlate offshore event, with higher slopes indicating a longer time lag with respect to distance between the offshore and onshore pairs. For the northern dataset, the instrument pair was NC89/KEMF (north seismometers), while for the southern dataset the following instrument pairs were used: AXAS1/HYS11 (south shallow seismometers), AXCC1/HYS14 (south shallow hydrophones), and AXBA1/HYSB1 (south deep hydrophones). It is clear that (1) all timing phenomena (both onset and CM during S1 and S2) occur later at the offshore instrument and (2) there is a longer time lag with respect to distance at the northern stations compared to the southern stations.

earlier than AXAS1. The same pattern was evident upon examination of their CMs. For both S1 and S2, CM occurred ~1 month earlier at HYS11. For other OOI stations, only S2 will be examined. Additionally, comparisons will only be drawn between stations with similar depths – between HYS14 and AXCC1 (shallow hydrophones), as well as between HYSB1 and AXBA1 (deep hydrophones). Onset for HYS14, which is 106 km from shore, was 3 weeks earlier than for AXCC1, which is 466 km from shore, and HYS14 CM was 1 month earlier. HYSB1 (85 km from shore) exhibited an onset and CM that were ~3 weeks and ~1 month earlier, respectively, than those of AXAB1 (446 km from shore). This temporal pattern was dependent on latitude, with instruments farther north exhibiting a greater lag compared to southern instruments (fig. 8).

Differences between timing of these phenomena could be a result of timing differences between subpopulations, or could indicate an offshore migration as the season progresses. Either of these could be attributed to a shift in the regional food supply with time, in association with the Transition Zone Chlorophyll Front (TZCF). The TZCF is a rapid decrease in chlorophyll concentration with latitude, from the elevated northern concentrations to the diminished concentrations in the subtropics. As the winter progresses, the TZCF moves farther south, from ~42° N in August to ~31º N in February (Bogard et al. 2004; fig. 9). Around 130º W, which is the western boundary for stations examined in this study, the TZCF dips sharply towards the southeast, following coastal upwelling patterns (fig. 9). Thus at a given latitude this feature will be farther south as proximity to shore decreases. Fin whales may therefore be located nearshore during early season before the southward movement of the TZCF allows for offshore migration without sacrificing food availability.

However, there have been inconsistent findings regarding the migration of fin whales relative to proximity to shore. This study's results are contrary to previous findings indicating

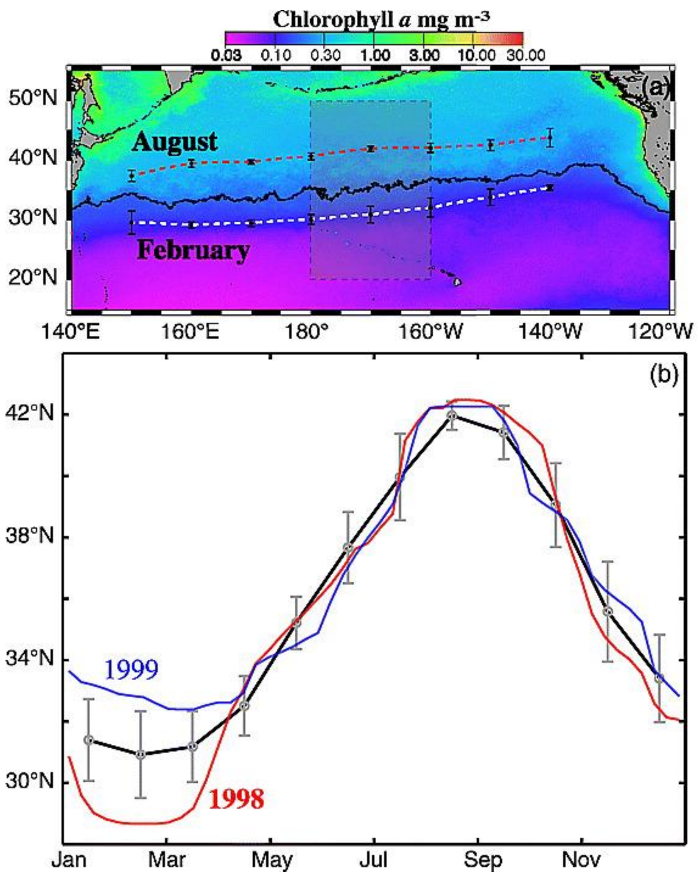


Figure 9 (from Bograd et al. 2004): (a) Climatological mean surface chlorophyll-a in the North Pacific Ocean from SeaWiFS ocean color over the period September 1997 to October 2003. The 0.2 mg m−3 surface chlorophyll-a isopleth (black contour), which defines the TZCF, is overlaid. The mean positions of the TZCF and standard deviations in 10°-longitude zones between 140°W–150°E are shown for February (white dashed) and August (red dashed). The region explored in this study, bounded by 160°W–180°, is shown in the translucent box. (b) Monthly mean and standard deviation of the latitude of the 0.2 mg m−3 chlorophyll-a isopleth over the region bounded by 160°W–180° in the North Pacific Ocean. Data from 1998 (El Niño; red) and 1999 (La Niña; blue) are overlaid. Tic marks are at the beginning of the month.

that fin whales in southern California migrate from offshore grounds in the summer/fall to onshore grounds in the winter/spring (Douglas et al. 2014). An acoustic study in the same area, though, did not resolve this pattern in their data, as fin whales were located nearshore during the fall (Širović et al. 2015).

This discrepancy could highlight a bias in methods of data acquisition. Douglas et al. (2014) determined this offshore/onshore migration from sighting data whereas both this study and Širović et al. (2015) did not find that pattern and both used acoustic data. Therefore, this study proposes that *vocalization* shifts from onshore in the early season towards offshore as the season progresses, though the entire non-vocalizing population may not exhibit this pattern. As males are the only ones producing these calls, it is possible that this indicates different regional preferences between the two sexes.

Distance to Shore: Total Counts

Distance to shore also affected the total amount of calls received, with total counts increasing with distance from shore in the northern stations. Before comparison, corrections need to be made according to the previous *Hydrophones versus Seismometers* and *Effect of Depth* sections. For the NEPTUNE instruments, NC89 should be weighted for differences in depth and substrate, both making NC89 less sensitive relative to KEMF. The depth difference between NC89 and KEMF is 947 m, meaning that NC89 should be weighted with the addition of (0.03% m^{-1})*(947 m) = 28.4% of total vocalizations. Additionally, NC89 should be weighted by a factor of two to correct for substrate type. Therefore, the S1 count for NC89 of 0.148e4 after weighting becomes 0.380e4, and the S2 value goes from 0.0303e4 to 0.0778e4. Percent differences will be calculated relative to the offshore station. Using these newly corrected values, NC89 had 22% of calls relative to KEMF during S1 and 51% during S2.

However, the low percentage of calls received at NC89 during S1 is not an accurate representation due to the large data gap in the middle of the vocalization season. This gap occurred later than the S2 CM for NC89, and after S1 calling appeared to peak, but still significantly decreased overall picks (fig. 6). Comparing times of non-missing S1 data (August, September, October, February, and March) was considered. However, two factors constrained the feasibility of this approach. For one, a significant temporal lag in calling was exhibited by KEMF relative to NC89, meaning that for a given time, each station was *not* at the same stage in their respective vocalization seasons. Also, the S1 CM for KEMF (20 December 2015) occurred directly in the middle of the extended data gap for NC89, meaning that taking out this segment of time would inadvertently maximize the reduction of overall S1 calling for KEMF. In fact, the months of November, December, and January during S1, which would be taken out of analysis, were the 3 months with the highest calls in the season (fig. 6), cumulatively representing ~85% of S1 calling. Thus, the post-reduction comparison between these two datasets seems too biased and will not be further considered.

For the OOI stations, the distance to shore pattern was mixed. Comparisons will only be drawn between identical instruments at similar depths with similar missing data profiles, and will always be relative to the offshore station: HYSB1/AXBA1 (deep hydrophones), HYS11/AXAS1 (shallow seismometers), and HYS14/AXCC1 (shallow hydrophones). However, environmental corrections need to be made for these pairs as well. AXBA1 will need to be weighted heavier than HYSB1 with respect to depth. As they are hydrophones, it is unnecessary to make a substrate type correction. AXBA1 is 311 m shallower than HYSB1, meaning an addition of $(0.03\%\ m^{-1})*(311\ m) = 9.33\%$ should be made to AXBA1. New counts for AXBA1 become 3.03e4 and 6.20e4 for S1 and S2 respectively. With the comparisons between AXAS1/HYS11, both a correction for substrate and depth need to be made, as these instruments are seismometers with different depths. For the AXCC1/HYS14 pair, only a depth correction needs to be since they are hydrophones. For both, the depth difference is 744 m, so there needs to be an addition of $(0.03\%\ m^{-1})*(744\ m) = 22.32\%$ to the Hydrate Ridge stations. Also, HYS11 needs to be weighted 2 times heavier than AXAS1 due to substrate differences. Therefore, the new values for HYS11 become 2.27e4 and 5.28e4 for S1 and S2, respectively. For HYS14, the new values for S1 and S2 become 0.632e4 and 7.82e4, respectively. Using these new values, HYSB1 had 29% of calls during S1 relative to AXBA1 and 182% during S2. HYS11 detected 117% of calls relative to AXAS1 during S1 and 168% in S2. HYS14 received 35% and 122% of vocalizations relative to AXCC1 in S1 and S2, respectively.

For all S1 comparisons, there is a slight bias towards receiving more calls during S1 for the offshore station due to the differences in temporal calling patterns with distance from shore in concert with a mid-season start date. Because stations closer to shore are likely to exhibit an earlier pattern than those farther offshore, for any given date in the vocalization season more of the calling has already passed for stations closer to shore, so more calls should be missed. Therefore, the percent differences in S1 calling between all OOI stations calculated previously are likely greater in magnitude than described, because a greater portion of total vocalizations for the near shore stations occurred before the start date than those over the same time period for the offshore stations.

The northern stations exhibited more calling offshore, while the OOI stations exhibited mixed results, with some onshore stations. Upon closer examination of these percentage differences, a striking pattern becomes apparent among all instruments. The fraction of offshore calls relative to onshore calls *all* increased from S1 to S2 (fig. 8). For the KEMF/NC89 pair, the ratio between offshore and onshore calling rose 29% between S1 and S2. For the AXBA1/HYSB1 pair, the value rose by 153% from S1 to S2. Similarly, for the AXAS1/HYS11 and AXCC1/HYS14 pairs, the values rose by 51% and 87%, respectively. The magnitudes for AXBA1/HYSB1 and AXCC1/HYS14 pairs may be less than those calculated due to the aforementioned bias towards offshore sensitivity in S1. Still, it appears that a portion of the vocalizing population exhibited a move offshore, indicating a possible regional shift in the fin whale population associated with ENSO events (fig. 8).

El Nino Southern Oscillation (ENSO)

A possible explanation for the differences between S1 and S2 could have to do with the 2015-6 ENSO event, which is at least as strong as the 1997-8 event (Levine and McPhaden 2016). It is important to note the variation in the TZCF associated with ENSO events. Modelling and data both place the TZCF in the North Pacific farther south during ENSO winters relative to normal and La Niña years (fig. 9; Bograd et al. 2004). At ~42° N, the location of the summertime TZCF was consistently just south of the stations examined in this study (44º N to 49º N), while the TZCF was farther south during winter and varied by ~4°, from 28°N to 32°N, being at lower latitudes during the ENSO event. This southward migration of the TZCF associated with ENSO events could therefore shift the regional structure of the vocalizing fin whale population, allowing them to migrate farther south without a significant reduction in food supply.

A southward shift in the fin whale population is also bolstered by the differences between S1 and S2 at the northern stations compared to those at the southern stations. Although all stations exhibited reduced calling from S1 to S2, the reduction was significantly stronger in the northern stations (fig. 8). This latitudinal pattern could indicate that a larger fraction of the vocalizing population was farther south during this ENSO event relative to normal years.

Changes in the TZCF could also be responsible for the aforementioned increased fraction of offshore calling during ENSO (fig. 8). The southeast jog of the TZCF at ~130ºW (fig. 9) could restrain fin whales from going offshore during normal years. However, this feature is shifted south during ENSO, theoretically allowing a larger portion of the population to migrate offshore.

However, ENSO events have also been shown to be associated with a *decrease* in both zooplankton and cetaceans in Monterey Bay, which is just off the coast of California at a latitude of about 36.8°N. The abundance of krill has been documented to correlate with Sea Surface

Temperature (SST), such that warmer temperatures correlate with decreased populations (Benson et al. 2002). Additionally, as previously mentioned, fin whale abundance has been shown to correlate with food availability. Benson et al. (2002) showed that in Monterey Bay during the ENSO event of 1997-98, cetacean populations decreased relative to other years, following a decrease in krill.

Moreover, there have been links to decreased calling in blue whales during ENSO years in the past (Benson et al. 2002). One study linked decreased water temperatures to reduced calling, although this same study did not find any significant vocalization differences during ENSO events (Stafford et al. 2009). Although it is difficult to determine whether this change in vocalization can be extrapolated to deduce a decrease in overall abundance, there are still profound implications for this finding. As these vocalizations are involved in mating, diminished calling could result in decreased mating, affecting population structure among other factors.

Conclusions

- Fin whale vocalization patterns occurred earlier at near shore stations relative to those offshore, possibly instigated by food availability (fig. 8).
- Vocalizations decreased from S1 (normal year) to S2 (ENSO year), indicating a potential decrease in overall calling during ENSO events (fig. 6, fig. 7).
- There was a regional shift in vocalization from the normal year to the ENSO event (fig. 7). An increase occurred in the fraction of both onshore calls and southern calls relative to those offshore to the north. These differences could be attributed to the southward movement of the wintertime Transition Zone Chlorophyll Maximum in ENSO years (fig.

9), allowing fin whales to migrate both farther south and farther offshore without sacrificing food availability.

- Seismometers can be useful in the analysis of fin whale vocalization patterns. Although they can record the overall pattern of calling, they are not as sensitive as hydrophones and thus attempts to use seismic data for quantifying fin whales should be heavily evaluated. Additionally, substrate composition should be factored into any seismic examination as basalt environments will be ~2x as sensitive to fin whale vocalizations as sediments. Seismometers were found to be less sensitive than hydrophones, with ~78% and ~38% relative sensitivities on basalt and sediments, respectively.
- Deeper stations are likely to pick up more calls than shallow counterparts. In the range 785-2921 m, with the use of unweighted data, this value can be quantified after depth normalization to a value of about 0.03% m^{-1} increase with depth. Note that this value was not obtained via the use of any seismometers; only hydrophones were compared in the depth analysis.
- Further exploration into each pattern described in this paper should verify results, as this study was restricted by missing data and small sample sizes. Future research should focus on examining a larger dataset with more seasons to help bolster hypotheses. Regardless, this study introduces many patterns associated with a strong ENSO event and provides a baseline for which future years and ENSO events can be compared.

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APPENDIX

*MATLAB script**

*Note that the following script only compiled, filtered, and graphically represented the picks. The more extensive data acquisition and picking processes used code written by Michelle Weirathmueller and therefore is not shown here.

```
%%
close all
clear variables

%USER AREA

%Set up station info
fileprefix = 'AXAS1';
network = 'OO';
infofolderspecific = [fileprefix '_EHZ'];
infofolder = ['../Info_5.0/' infofolderspecific];

%Set up parameters
OnsetThresh = 100; %Threshold for number of calls per day to indicate onset
SNR_red = 9.5; %set SNR threshold
IPI0 = 35; %set upper limit for IPI in seconds
IPI1 = 15; %set lower limit for IPI in seconds
IPI_high = IPI0/86400; %convert IPI values to days
IPI_low = IPI1/86400;

%these dates will constrain the x axes
startdate = '01-Aug-2014';
enddate = '01-Apr-2016';

%these dates will constrain picks included into finaltimes
S1s = datenum('01-Aug-2014');
S1e = datenum('01-Apr-2015');
S2s = datenum('01-Aug-2015');
S2e = datenum('01-Apr-2016');

%%

addpath(['F:/My things!/_Senior Thesis/Detections_5.0/Detections_5.0/'
network '_' fileprefix])
fileStruct = dir(['F:/My things!/_Senior
Thesis/Detections_5.0/Detections_5.0/' network '_' fileprefix '/' network
'*.mat']);

for n = 1:size(fileStruct,1)
    fileMaster(n) = load(fileStruct(n).name);
end
```

```
missingdataS = [];
missingdataE = [];

stns = {'AXAS1','AXCC1','AXBA1','HYSB1','HYS11','HYS14','KEMF','NC89'};
stns2 = {[fileprefix]};
stnscmp = strcmp(stns,stns2);
stninfo = [];

%accumulate missing data segments for each station
%NOTE: In the future, try to write piece of code to evaluate ALL missing
    %data, as these are only segments of one day or longer
    %To do ^^ use mseed format
if stnscmp(1,1) == 1;
    stninfo = {'Axial Summit'; 'South'; 'Offshore'; 'Shallow';
'Seismometer'};
    isequal(stninfo{1} , 'Axial Summit'); % true
    missingdataS = [datenum('05-Nov-2014') datenum('08-Dec-2014')
datenum('06-Mar-2015') datenum('10-Jun-2015')];
    missingdataE = [datenum('06-Nov-2014') datenum('11-Dec-2014')
datenum('08-Mar-2015') datenum('16-Jun-2015')];
end

if stnscmp(1,2) == 1;
    stninfo = {'Axial Summit'; 'South'; 'Offshore'; 'Shallow'; 'Hydrophone'};
    isequal(stninfo{1} , 'Axial Summit'); % true
    missingdataS = [datenum('06-Mar-2015') datenum('10-Jun-2015')];
    missingdataE = [datenum('08-Mar-2015') datenum('16-Jun-2015')];
end

if stnscmp(1,3) == 1;
    stninfo = {'Axial Base'; 'South'; 'Offshore'; 'Deep'; 'Hydrophone'};
    isequal(stninfo{1} , 'Axial Base'); % true
    missingdataS = [datenum('06-Mar-2015') datenum('10-Jun-2015')];
    missingdataE = [datenum('08-Mar-2015') datenum('16-Jun-2015')];
end

if stnscmp(1,4) == 1;
    stninfo = {'Slope Base'; 'South'; 'Onshore'; 'Deep'; 'Hydrophone'};
    isequal(stninfo{1} , 'Slope Base'); % true
    missingdataS = [datenum('06-Mar-2015') datenum('10-Jun-2015')
datenum('20-Nov-2015')];
    missingdataE = [datenum('08-Mar-2015') datenum('16-Jun-2015')
datenum('05-Dec-2015')];
end

if stnscmp(1,5) == 1;
    stninfo = {'Hydrate Ridge'; 'South'; 'Onshore'; 'Shallow';
'Seismometer'};
    isequal(stninfo{1} , 'Hydrate Ridge'); % true
    missingdataS = [datenum('05-Nov-2014') datenum('08-Dec-2014')
datenum('06-Mar-2015') datenum('10-Jun-2015')];
    missingdataE = [datenum('06-Nov-2014') datenum('11-Dec-2014')
datenum('08-Mar-2015') datenum('16-Jun-2015')];
end
```

```
if stnscmp(1,6) == 1;
    stninfo = {'Hydrate Ridge'; 'South'; 'Onshore'; 'Shallow'; 'Hydrophone'};
    isequal(stninfo{1} , 'Hydrate Ridge'); % true
    missingdataS = [datenum('06-Mar-2015') datenum('10-Jun-2015')];
    missingdataE = [datenum('08-Mar-2015') datenum('16-Jun-2015')];
end

if stnscmp(1,7) == 1;
    stninfo = {'Endeavor'; 'North'; 'Offshore'; 'Deep'; 'Seismometer'};
    isequal(stninfo{1} , 'Endeavor'); % true
    missingdataS = [datenum('16-Mar-2016')];
    missingdataE = [datenum('18-Mar-2016')];
end

if stnscmp(1,8) == 1;
    stninfo = {'Clayoquot'; 'North'; 'Onshore'; 'Shallow'; 'Seismometer'};
    isequal(stninfo{1} , 'Clayoquot Slope'); % true
    missingdataS = [datenum('22-Aug-2014') datenum('18-Sep-2014')
datenum('12-Nov-2014')];
    missingdataE = [datenum('24-Aug-2014') datenum('25-Sep-2014')
datenum('14-Jan-2015')];
end


%%
%compile and segregate relevant information

%preallocate arrays
time_all = [];
f_all = [];
snr_all = [];
amp_all = [];

if exist(infofolder) ~= 7 % if this results directory does not exist yet
    mkdir(infofolder) % make the directory
end

%compile pick files for times, frequencies, snr, and amplitudes
for n = 1:length(fileMaster)
    time_all = [time_all fileMaster(n).pickvec.TBig];
    f_all = [f_all fileMaster(n).pickvec.fmean];
    snr_all = [snr_all fileMaster(n).pickvec.SNR];
    amp_all = [amp_all fileMaster(n).pickvec.detBig];
end

%%
%IPI filter: reduce picks based on IPI

ipi0 = diff(time_all);
ipi = [0 ipi0];
for n = 1:size(time_all,2);
    if n == 1;
    else
        if ipi(n)>IPI_high;
            time_all(n) = nan;
```

```
            snr_all(n) = nan;
            f_all(n) = nan;
            amp_all(n) = nan;
        end
        if ipi(n)<IPI_low;
            time_all(n) = nan;
            snr_all(n) = nan;
            f_all(n) = nan;
            amp_all(n) = nan;
        end
    end
end

%%
%plot all SNR values greater than 5.0 and indicate threshold

figure();
plot(time_all,snr_all,'r','LineWidth',1.0);
datetick('x','mmm yyyy','keepticks');
refline(0,SNR_red);
ylim([5 max(snr_all,[],2)]);
t = title([fileprefix ' SNR Ratios']);
set(t, 'FontSize', 15);
xlim([datenum(startdate) datenum(enddate)]);
ylabel('SNR ratio');
saveas(gcf,[fileprefix 'SNR_all.jpeg']);

%%
%reduce picks based on SNR

for n = 1:size(time_all,2)
   if snr_all(n) < SNR_red;
       time_all(n) = nan;
       snr_all(n) = nan;
       f_all(n) = nan;
       amp_all(n) = nan;
   end;
end

%save final picks
finaltimes = time_all(~isnan(time_all));
finalsnr = snr_all(~isnan(snr_all));
finalfreq = f_all(~isnan(f_all));
finalamp = amp_all(~isnan(amp_all));

save([infofolder fileprefix '_snr'], 'finalsnr');
save([infofolder fileprefix '_freq'], 'finalfreq');
save([infofolder fileprefix '_times'], 'finaltimes');
save([infofolder fileprefix '_amp'], 'finalamp');

%%
%compare and plot monthly counts for S1 vs S2 and determine onset/CM

%create duplicate time vector without nans
time_all2 = time_all;
```

```
time_all2(isnan(time_all2)) = [];

times = datevec(time_all2);
yearoffset = min(times(:,1)) - 1;
time_all3 = ones(1,length(time_all2));
monthlycounts = accumarray([times(:,1)-yearoffset, times(:,2)],time_all3);

S1M = [];
S2M = [];

%monthstart indicates the time between startdate and start of data
    %acquisition due to OOI missing data and will be used to show
    %graphically this time period
monthstart = 0.42 + ((min(time_all2) - datenum(startdate))/30);

%compile monthlycounts and make all same size
if size(monthlycounts,1) == 3;
    if size(monthlycounts,2) == 11;
        monthlycounts(:,12) = 0;
    end
    B = zeros(2,8);
    B(1,1:8) = cat(2,monthlycounts(1,8:12),monthlycounts(2,1:3));
    B(2,1:8) = cat(2,monthlycounts(2,8:12),monthlycounts(3,1:3));
else
    B = zeros(2,8);
    B(1,6:8) = monthlycounts(1,1:3);
    B(2,1:8) = cat(2,monthlycounts(1,8:12),monthlycounts(2,1:3));
end

%plot S1 vs S2
y1=transpose(B);
y2 = bar(y1);
ylab = 'Call Count (calls per month)';
ylabel (ylab, 'FontSize', 14);
Labels = {'Aug','Sep','Oct','Nov','Dec','Jan','Feb','Mar'};
set(gca, 'XTick', 1:8, 'XTickLabel', Labels, 'FontSize', 14);
title(fileprefix, 'FontSize', 14);
l = cell(1,2);
l{1}='S1'; l{2}='S2';
legend(y2,l);
S1_total = sum(B(1,1:8));
S2_total = sum(B(2,1:8));
a = finaltimes < S1e & finaltimes > S1s;
S1M = [S1M floor(mean(finaltimes(a)))];
S1_mid = datestr(S1M);
b = finaltimes < S2e & finaltimes > S2s;
S2M = [S2M floor(mean(finaltimes(b)))];
S2_mid = datestr(S2M);
x1 = 7;
y1 = (3*max(get(gca,'ylim')))/5;
txt1 = stninfo;
text(x1,y1,txt1,'fontsize',14)

%graphically show time before S1 data acquisition
%NOTE: only relevant for OOI stations
if stnscmp(1,7)==1 || stnscmp(1,8)==1;
```

```
else
    x1 = [min(get(gca,'xlim')) min(get(gca,'xlim')) monthstart monthstart];
    y1 = [0 max(get(gca,'ylim')) max(get(gca,'ylim')) 0];
    p1=patch(x1,y1,'r','EdgeColor','none');
    set(p1,'FaceAlpha',0.3);
end
saveas(gcf,[fileprefix 'CompMonths.jpeg']);

%find onset of calling for S1
y = floor(time_all2);
[a,b]=hist(y,unique(y));
i = find(a>OnsetThresh,1);
S1O = b(i);
S1_onset = datestr(S1O);

%find onset for S2
z = y > datenum('01-Aug-2015');
v = y(z);
[c,d]=hist(v,unique(v));
n = find(c>OnsetThresh,1);
S2O = d(n);
S2_onset = datestr(S2O);

%%
%NOTE: This graph unused in paper
    %As such, parameters and annotations differ

%plot DAILY times of whale calls
f=figure();
hist(y,(max(y)-min(y)))
datetick('x','mmm yyyy');
t = title([fileprefix ' Daily Call Count']);
set(t, 'FontSize', 15);
xlim([datenum(startdate) datenum(enddate)]);
ylabel('Call Count (calls per day)');

%ADD ANNOTATIONS
%...for S1 Onset
axPos = get(gca,'Position');
xMinMax = xlim;
yMinMax = ylim;
x1Annotation = axPos(1) + (S1O - xMinMax(1))/(xMinMax(2)-xMinMax(1)) *
axPos(3);
y1Annotation = axPos(2) + ((a(find(b==S1O)) - yMinMax(1))/(yMinMax(2)-
yMinMax(1))) * axPos(4);
x1 = [x1Annotation, x1Annotation];
y1 = [y1Annotation+0.08, y1Annotation+0.01];
annotation('textarrow',x1,y1,'String','S1 Onset','Color','r')

%...for S1 CM
x2Annotation = axPos(1) + (S1M - xMinMax(1))/(xMinMax(2)-xMinMax(1)) *
axPos(3);
[c1 index1] = min(abs(b-S2M));
closestValue2 = b(index1);
y2Annotation = axPos(2) + ((a(find(b==closestValue2)) -
yMinMax(1))/(yMinMax(2)-yMinMax(1))) * axPos(4);
```

```
x2 = [x2Annotation, x2Annotation];
y2 = [y2Annotation+0.08, y2Annotation+0.01];
annotation('textarrow',x2,y2,'String','S1 CM','Color','r')

%...for S2 Onset
x3Annotation = axPos(1) + (S2O - xMinMax(1))/(xMinMax(2)-xMinMax(1)) *
axPos(3);
y3Annotation = axPos(2) + ((a(find(b==S2O)) - yMinMax(1))/(yMinMax(2)-
yMinMax(1))) * axPos(4);
x3 = [x3Annotation, x3Annotation];
y3 = [y3Annotation+0.08, y3Annotation+0.01];
annotation('textarrow',x3,y3,'String','S2 Onset','Color','r')

%...for S2 CM
x4Annotation = axPos(1) + (S2M - xMinMax(1))/(xMinMax(2)-xMinMax(1)) *
axPos(3);
[c2 index2] = min(abs(b-S2M));
closestValue2 = b(index2);
y4Annotation = axPos(2) + ((a(find(b==closestValue2)) -
yMinMax(1))/(yMinMax(2)-yMinMax(1))) * axPos(4);
x4 = [x4Annotation, x4Annotation];
y4 = [y4Annotation+0.08, y4Annotation+0.01];
annotation('textarrow',x4,y4,'String','S2 CM','Color','r')

saveas(gcf,[fileprefix '_DailyHist.jpeg']);

%%
%NOTE: commented out annotations create similar results as in the DAILY
    %histogram, with words indicating onsets/CMs instead of only arrows

%plot WEEKLY calling times
g=figure();
hist(y, ((max(y)-min(y))/7));
t = title([fileprefix ' Weekly Call Count']);
set(t, 'FontSize', 15);
set(gca, 'XTick',(datenum(startdate)+1):61:datenum(enddate));
datetick('x','mmm yy','keepticks');
xlim([datenum(startdate) datenum(enddate)]);

%graphically show missing data between startdate and data acquisition
%only needed for OOI stations
if stnscmp(1,7)==1 || stnscmp(1,8)==1;
else
    x1 = [min(get(gca,'xlim')) min(get(gca,'xlim')) min(y) min(y)];
    y1 = [0 max(get(gca,'ylim')) max(get(gca,'ylim')) 0];
    p1=patch(x1,y1,'r','EdgeColor','none');
    set(p1,'FaceAlpha',0.3);
end

ylabel('Call Count (calls per week)','fontsize',14);
xlabel('Date','fontsize',14);
set(gca,'FontSize', 14);

x1 =datenum('17-Jun-2015');
y1 = (2*max(get(gca,'ylim')))/3;
```

```
txt1 = stninfo;
text(x1,y1,txt1,'fontsize',14)

%ADD ANNOTATIONS

%...for S1 Onset
%NOTE that S1 onset and CM are n/a for AXCC1, AXBA1, HYSB1, and HYS14
tf1 = {'AXCC1','AXBA1','HYSB1','HYS14'};
tf = strcmp(fileprefix,tf1);
if any(tf) == 1
else
    axPos = get(gca,'Position');
    xMinMax = xlim;
    yMinMax = ylim;
    x1Annotation = axPos(1) + (S1O - xMinMax(1))/(xMinMax(2)-xMinMax(1)) *
axPos(3);
    %y1Annotation = axPos(2) + ((counts(ceil((diff([min(y),S1O])/7))) -
yMinMax(1))/(yMinMax(2)-yMinMax(1))) * axPos(4);
    x1 = [x1Annotation, x1Annotation];
    %y1 = [y1Annotation+0.08, y1Annotation+0.01];
    y1 = [0.25, 0.14];
    annotation('textarrow',x1,y1,'Color','r')

    %...for S1 CM
    x2Annotation = axPos(1) + (S1M - xMinMax(1))/(xMinMax(2)-xMinMax(1)) *
axPos(3);
    %[c1, index1] = min(abs(b-S2M));
    %closestValue2 = b(index1);
    %y2Annotation = axPos(2) + ((a(find(b==closestValue2)) -
yMinMax(1))/(yMinMax(2)-yMinMax(1))) * axPos(4);
    x2 = [x2Annotation, x2Annotation];
    y2 = [0.25, 0.14];
    %y2 = [y2Annotation+0.08, y2Annotation+0.01];
    annotation('textarrow',x2,y2,'Color','g')
end

%...for S2 Onset
x3Annotation = axPos(1) + (S2O - xMinMax(1))/(xMinMax(2)-xMinMax(1)) *
axPos(3);
%y3Annotation = axPos(2) + ((counts(ceil((diff([min(y),S2O])/7))) -
yMinMax(1))/(yMinMax(2)-yMinMax(1))) * axPos(4);
x3 = [x3Annotation, x3Annotation];
y3 = [0.25, 0.14];
%y3 = [y3Annotation+0.08, y3Annotation+0.01];
annotation('textarrow',x3,y3,'Color','r')

%...for S2 CM
x4Annotation = axPos(1) + (S2M - xMinMax(1))/(xMinMax(2)-xMinMax(1)) *
axPos(3);
%[c2 index2] = min(abs(b-S2M));
%closestValue2 = b(index2);
%y4Annotation = axPos(2) + ((a(find(b==closestValue2)) -
yMinMax(1))/(yMinMax(2)-yMinMax(1))) * axPos(4);
x4 = [x4Annotation, x4Annotation];
y4 = [0.25, 0.14];
%y4 = [y4Annotation+0.08, y4Annotation+0.01];
```

```
annotation('textarrow',x4,y4,'Color','g')

%show patches of missing data
for n = 1:size(missingdataS,2);
    x01 = [missingdataS(n) missingdataS(n) missingdataE(n) missingdataE(n)];
    y01 = [0 max(get(gca,'ylim')) max(get(gca,'ylim')) 0];
    p2=patch(x01,y01,'r','EdgeColor','none');
    set(p2,'FaceAlpha',0.3);
end

saveas(gcf,[fileprefix '_WeeklyHist.jpeg']);
```