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Patterns of Fin whale (*Balaenoptera physalus*) Seasonality and Relative Distribution in Canadian Pacific Waters Inferred from Passive Acoustic Monitoring

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Foreword

This series documents the scientific basis for the evaluation of aquatic resources and ecosystems in Canada. As such, it addresses the issues of the day in the time frames required and the documents it contains are not intended as definitive statements on the subjects addressed but rather as progress reports on ongoing investigations.

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ABSTRACT

We used acoustic data from eight different locations distributed throughout British Columbia marine waters to examine geographic and seasonal trends in Fin whale calling. Data were analysed using an acoustic power method resulting in a call index related to the intensity of calling activity in frequency bands relevant to Fin whale song. Detection results were corrected for site-specific differences in propagation and ambient noise in order to compare call indices between locations and seasons. We also investigated diel-calling trends to infer habitat use patterns across sites. Of the sites analysed, song was present throughout all fall and winter months; notably, sites in the Hecate Strait region had the highest and most sustained activity. Peak periods of song in Hecate Strait were offset seasonally from peak periods at all other sites analysed, indicating the possibility of a seasonal movement into the Hecate Strait region during the highpoint of the breeding season. Peaks in singing aligned with estimated breeding and calving periods for Fin whales in the North Pacific and British Columbia, supporting previous acoustic studies indicating that breeding activity likely occurs in these waters. Diel patterns in calling were found in one offshore site as well as a site on the west coast of Vancouver Island, but no diel patterns were found in Hecate Strait. Our results will be useful in efforts to identify habitats of importance to Fin whales in British Columbia, but also highlight the need for further studies to fill geographic data gaps as well as seasonal gaps in wintertime ship-based effort.

1 INTRODUCTION

In Canadian Pacific waters, Fin whales are listed as 'Threatened' under the Species at Risk Act (SARA) as a result of severe depletion from intense whaling efforts off the coast of British Columbia in the early to mid 1900's (Gregr et al. 2006, COSEWIC 2005). Over the past decade, research efforts have been ongoing to identify areas of Critical Habitat to assist recovery for this species off the Pacific coast of Canada. As part of these efforts and concurrent research on other SARA-listed cetacean species in Pacific waters, the Cetacean Research Program (CRP) at the Pacific Biological Station has been collecting long-term passive acoustic monitoring (PAM) data using several types of underwater autonomous acoustic recording devices to assess the distribution and seasonality of Fin whale occurrence in British Columbia.

The songs and calls of Fin whales are some of the best-studied large whale vocalizations in the world, making the species a good candidate for PAM studies. This species is known to make several types of calls (e.g. Watkins 1981, Thompson et al. 1992, Širović et al. 2013, Oleson et al. 2014, Koot 2015), with the best-studied call used in PAM studies being the '20-Hz pulse' (Watkins et al. 1987), which is a short duration (<1s) down-sweep centered around 20Hz. Song produced by male Fin whales on a seasonal basis is primarily made of structured sequences of 20-Hz calls (Watkins et al. 1987, Thompson et al. 1992, Croll et al. 2002). As only male Fin whales sing and song is mostly produced during the species' suspected breeding season, singing behaviour in the species (as in other baleen whale species) may serve a reproductive purpose (Payne & McVay 1971, Watkins et al. 1987). A few studies have examined the presence and seasonality of Fin whale song in BC waters (e.g., Watkins et al. 2000, Stafford et al. 2005, Ford et al. 2010, Koot 2015), documenting the persistence of songs through the winter (a period with minimal ship survey effort), suggesting Fin whales may be using BC waters for reproductive purposes. However, the geographic scope of these studies was limited and they did not compare relative calling activity among locations throughout BC waters to identify areas of potential importance.

The success of using PAM to examine Fin whale calling seasonality and distribution in other locations around the world (e.g., Curtis et al. 1999; Watkins et al. 2000; Simon et al. 2010; Nieukirk et al. 2012; Širović et al. 2004, 2009, 2015; Oleson et al. 2014; Sciacca et al. 2015) indicates that conducting similar studies in Pacific Canada could provide insight into large-scale habitat use by Fin whales here. When coupled with data from other platforms (e.g. Nichol et al. 2017), PAM studies can aid in identifying regions of importance for Critical Habitat identification.

In this study, we aimed to examine the relative levels and seasonality of Fin whale song among several sites in British Columbia waters in order to aid in current efforts to identify high use areas that may represent Critical Habitat for Fin whales in Pacific Canada. We also examine the geographic trends in the seasonality of calling for Fin whales in British Columbia.

2 METHODS

2.1 DATA COLLECTION AND PROCESSING

Data for this study were collected using AURAL-M2 (Multi-Electronique), SM2M (Wildlife Acoustics), and AMAR G3 (JASCO Applied Sciences) autonomous recorders deployed at eight different locations off the BC coast (Figure 1) over various periods between 2009 and 2015 (see Table 1 for deployment details). Locations were not chosen explicitly to record Fin whales, they were often placed in locations that balanced many factors such as geographical constraints of mooring cruises, local intensity of fishing effort, investigations of other species of interest, and overlap with ship-based observer effort. Recorders were set to record on 30% duty cycles (typically 4.5 minutes of recording, and 10.5 minutes paused, cycled infinitely until batteries were depleted, see Table 1 for specific duty cycles for each deployment), except for one deployment in Eastern Hecate Strait, which recorded on a 6% duty cycle (2 minutes recording, 28 minutes paused). AURALs were configured to merge recordings from several recording cycles into a single WAV file. Prior to analysis, these merged AURAL WAV files were split and renamed with time-stamp information using custom Java-based scripts supplied by JASCO Applied Sciences. The recordings were then down-sampled to 1024Hz using the 'rate' function in the open source software SoX - *Sound eXchange* v14.4.2.

2.2 ACOUSTIC POWER AND FIN WHALE CALL INDEX (FWCI) CALCULATIONS

During periods at some CRP deployment locations off the British Columbia coast, the acoustic data exhibit a 'continuous calling band' as described in Watkins et al. (2000), Širović et al. (2004), and Simon et al. (2010), where the number and range of Fin whales calling simultaneously causes individual vocalizations to become indiscernible. In such cases, the calling is only evident as a continuous band around 20Hz in a spectrogram. Analyzing the data using automated detectors based on individual call detection has been shown to underrepresent the actual amount of calling activity during these peak periods (Širović et al. 2004). Considering this, we chose to use a published technique based on measuring the acoustic power within frequency bands representative of Fin whale calling as a proxy for calling intensity as in Širović et al. (2004, 2009, 2015), Simon et al. (2010), and Nieukirk et al. (2012).

In order to calculate the Fin Whale Call Index (FWCI), we needed to be able to compare acoustic energy within very narrow bandwidths (1-2Hz). Power spectral density provides an accurate account of sound energy within very narrow bandwidths. As in Širović et al. (2004, 2009, 2015), we used PSD as the sound metric to compute the FWCI. We used *PAMGuide* (Merchant et al. 2015) in R 3.0.0 (R Core Team 2013) to compute the calibrated PSD for each location's time series in 1Hz bins (1-sec window, 50% overlap) with 5-second time averaging (Welch 1967) using each recorder and hydrophone's technical specifications and user defined gain settings. For the AMAR G3, end-to-end system sensitivity was available and was used instead of recorder and hydrophone technical specifications.

Using the PSD, the FWCI was calculated as the instantaneous difference between the Fin whale calling band (F_{fin}) and the noise band (F_{noise}) (Figure 2a,b). The energy at 22Hz was used as F_{fin} because this frequency overlaps with the two alternating notes that comprise the 'doublet' Fin whale song found in British Columbia (Classic note and the Backbeat; Koot 2015). Adapting methods from Širović et al. (2015), Simon et al. (2010), and Nieukirk et al. (2012) the F_{noise} was calculated as the linear average of noise at 13-14Hz and 37-38Hz to exclude typical Fin whale 20-Hz calling in our study area. We assumed noise between 13Hz and 38Hz was linear and representative of the noise at 22Hz in the absence of Fin whale calling, as in Širović et al. (2015) and Simon et al. (2010). Effectively, the FWCI is a measure of the amount of energy contributed by singing Fin whales to ambient noise levels in the 22Hz band. Fin whales in the Northeast Pacific are known to use other calls in addition to the '20-Hz' pulses (e.g. the '40-hz call' - Širović et al. 2013). However, we chose to use an F_{fin} that overlapped the '20-Hz pulse' in particular because this call is the least variable of the vocalizations during the breeding season, has a frequency that has minimal overlap with calls of other species in our study area, and because it is predominantly produced in song (Watkins 1981; Koot 2015), which can be used as an indication of reproductive behaviour even though its exact role in reproduction is still not well understood (Watkins et al. 1987; Croll et al. 2002).

We applied month/site-specific correction factors (see Section 2.3, for details on creation) to the instantaneous FWCI values for each month at each deployment site to account for differences in transmission loss and detection area. The correction factor was applied by dividing each instantaneous FWCI value by the appropriate month and site's correction factor in linear space and converting back to units of dB. After correction, instantaneous FWCI values were averaged by day and by month (in linear space with conversion back to dB).

To ensure the FWCI summaries were representative of actual Fin whale calling, we conducted a manual qualitative verification of a random selection of recordings from each month from each site. In addition to manual inspection of recordings, the FWCI time series was inspected for any anomalies. After inspection, if anomalous trends were observed, the specific recordings were manually inspected for any anomalous noise sources (e.g. strum noise and other non-Fin whale sources). If such a noise source was found, the section of the time-series was removed from the data set.

All FWCI calculations and figures were made in R v3.0.0 (R Core Team, 2013). Maps were made using the 'PBSmapping' R package (Schnute et al. 2013).

2.3 AREA-TRANSMISSION-LOSS CORRECTION

Our goal was to compare results amongst the different hydrophone locations to determine if any given location or region exhibited more Fin whale calling activity than the others. Helble et al. (2013a,b) highlighted the need to correct detections for site-specific differences in propagation and ambient noise levels. Using the FWCI, which is a method based on signal-to-noise ratio, we not only needed to take into account detection area (the total area from which received calls at the hydrophone could be coming from), but also the transmission loss characteristics within a detection area. This is important because received levels will vary depending on where Fin whales are calling relative to the hydrophone; the number of calling whales may vary depending on the total size of the detection area around each hydrophone site; and detection areas vary for each hydrophone site due to differences in overall ambient noise levels and propagation characteristics, which affect signal-to-noise ratio.

As a first step in calculating a correction factor for each site, we modeled the propagation loss of a simplified (no downsweep) Fin whale '20-Hz pulse' for each location for the month of October. As in Širovic et al. (2015), we used the open-source software Effects of Sound on the Marine Environment (ESME) 2012 Workbench framework (D. Mountain, Boston University) to model transmission loss using the Range-dependent Acoustic Model (RAM) based on the Parabolic Equation, a model well suited for range-dependent environments and low frequency sounds at water depths found in our study area (Collins 1993; Farcas et al. 2015). Specifically, we used RAMGeo, which allows for range-dependent sediment layers. The simulation was conducted along 32 radials centered on the hydrophone location out to a maximum extent of 150 km. ESME used built-in environmental databases from the Oceanographic and Atmospheric Master Library (OAML) to acquire location specific bathymetry (from Digital Bathymetry Database v5.4 at 0.5-min resolution), sound speed profiles (calculated at 15-min resolution from water temperature and salinity data in the Generalized Digital Environment Model v3.0.), bottom sediment composition (from Bottom Sediment Type v2.0 at 5-min resolution), and sea surface reflectivity (from Surface Marine Gridded Climatology v2.0 wind speed at 60-min resolution) for each of the hydrophone sites used in our study. These models did not take into account fluctuations in water depth caused by tide, the effects of which may be important in shallower areas such as Hecate Strait (Farcas et al. 2015).

To determine whether differences in seasonal environmental conditions needed to be taken into account, we first ran the model for each month of the year at the Dellwood Knolls hydrophone site. Transmission loss to 150 km differed by less than 5 dB across months, so we chose to use only October environment data at all sites, assuming the differences among months at sites would be negligible, as it was in the Dellwood test. October had the least variation in transmission loss compared to other months in the Dellwood test.

We defined the frequency of the source call to be 22Hz as that was the frequency we used for F_{fin} for the FWCI (Watkins et al. 1987, Koot 2015, Širović et al. 2015). We used a Fin whale call source level of 189dB re 1μPa @ 1m (Wierathmueller et al., 2013), and a duration of 0.8 s (Watkins et al. 1987). The location-specific hydrophone depth was used as the source depth for each site. Transmission loss of the signal in dB was then calculated for every 100-m range step and 10-m depth bin along each of the 32 radials out to the maximum distance of 150 km. The data outputs were then saved in separate .csv files for each of the radials.

Assuming a singing depth for Fin whales of 20m (Stimpert et al. 2015), we then calculated each location-specific correction factor according to Širović et al. (2015), which takes into account transmission loss and detection area, as follows:

$$ATL = \sum_{j=1}^{32} \sum_{i=1}^{N} \frac{A_{ij}}{TL_{ij}} \quad (1)$$

where *N* is the total number of 100-m range steps at 20 m depth for which transmission loss was calculated for each radial; A_i, is the area (calculated in 1000 km^2) between each range step of the radial; and TL_i is the transmission loss at each range step. The resulting value for each range step was then summed over all pieces of the radial with transmission loss that did not exceed the month-specific Maximum Allowable Transmission Loss (MaxTL, see below) out to the 150 km length of the radial. These summed values were then summed over all radials. This resulted in a single 'Area-Transmission-Loss' (ATL) correction factor for each month with data available for each hydrophone site.

As in Širović et al. (2015), the monthly MaxTL that a Fin whale call could sustain before it could no longer be detected above background noise at the hydrophone was calculated for each month at each site as follows:

$$MaxTL = SL - NL - D$$

where, SL is the call source level (189 dB re 1μPa @ 1m, Wierathmueller et al. 2013), NL is the monthly ambient noise level in F_{noise} (as calculated below), and, D is the detectability of the signal. In this case, because the FWCI is measuring any change in sound level, detectability was set to 0 dB. We assumed that a Fin whale call could be detected at the hydrophone if it was produced in a range-step with transmission loss at a depth of 20-m that did not exceed the specific month's MaxTL for that hydrophone site.

NL, in dB re 1 μPa^2, was computed for each month at each site using site-specific PSD data (1 Hz-bins) for all data available for each month at the site. Noise levels were calculated by integrating the spectral density (in units of dB re 1μPa^2/Hz) over the 13, 14, 37, and 38 Hz bands in order to exclude energy contributed from singing Fin whales, and to remain consistent with F_{noise}. These levels were then averaged for each respective month for each site. Noise levels in this band were well above the reported noise floors of the recorders used in our study.

To visualize each hydrophone's detection area spatially for an example month, heat maps of the transmission loss scaled to site/month-specific MaxTL were made for each location for the month of October by interpolating each radial's modeled transmission loss values on a raster using custom routines in R (R Core Team, 2013); gaps between adjacent radials were filled by taking the median of surrounding transmission loss measurements (Figure 7).

Our focus in modeling transmission loss for Fin whale calls was not to determine the absolute detection range for the species at each site, but to describe the pattern of transmission loss of Fin whale calls within a fixed area around each site so that we could compare results among locations. The key to being able to compare among sites is that the methods were kept consistent among sites and that the chosen radial length would take into account most signal transmission loss. Our chosen radial length of 150km is consistent with other published studies that have attempted to model the detection ranges of Fin whale calls (e.g., Payne and Webb 1971, Moore et al. 1999, Watkins et al. 2000, Stafford et al. 2007, Širović et al. 2007, Simon et al. 2010, Širović et al. 2015, and Koot 2015), however, this distance likely does not encompass the entire range of actual variability.

2.4 DIEL COMPARISON

In order to visualize F_{fin} and F_{noise} by time of day, we plotted the F_{fin} and F_{noise} power summed in half hour bins for every day between October and the end of January, similar to Simon et al. (2010). To test whether there was a significant difference between day and night calling power, we selected PSD data from two periods from Southwest Hecate, Dellwood Knolls, and Brooks Peninsula (the areas with highest levels of calling). The first was a two-month period overlapping the period of peak calling at each location for all years available (Southwest Hecate = Nov 1-Dec 31; Dellwood Knolls = Oct 1 – Nov 30; Brooks Peninsula = Oct 1- Nov 31). We also chose a period prior to peak calling at each station for comparison (Southwest Hecate = Sep 1 – Oct 31; Dellwood Knolls = Aug 1 – September 30; Brooks Peninsula = August 1 – September 30, 2013).

For each location, PSD data in 5-s averages were divided into night periods and day periods based on location and date-specific sunrise and sunset times from the US Naval Observatory website. Nighttime was defined as all data between sunset and sunrise; daytime was defined as all data between sunrise and sunset. We calculated the mean F_{fin} power and the mean of the summed F_{noise} power for each continuous nighttime and daytime block. For all sites and periods, at least one dataset violated assumptions of normality and/or equal variance (based on Shapiro-Wilks and *F*-test), so we tested for diel differences using the non-parametric Mann-Whitney *U*-test.

3 RESULTS

3.1 DATA AND EFFORT

Overall, approximately 30,320 hours of duty-cycled recordings were collected over 4605 deployment days between 2009 and 2015. Coverage between sites was not consistent over this entire time period, and no sites were monitored for the entire 7-yr period. Sites were typically monitored for two consecutive years before the recorders were moved to different recording locations (see Table 1 for details).

The manual verification process resulted in the removal of 50.9 recording hours amongst all sites due to anomalous noise that influenced the call index. In most cases, the noise was attributed to intense tonal bands around 20Hz from ‘strum’ noise, which is caused by currents flowing past the mooring equipment resulting in vibrations at low frequencies. The recordings from the Eastern Hecate Strait SM2Ms were plagued by strum noise because the recorders were installed on a large oceanographic mooring with several other oceanographic instruments in a high current area. Although manual verification confirmed that fin whale calling was prolific at this site, the strum periods affected the FWCI and were so extensive that removing strum periods was impractical, so we decided to remove the dataset from the study.

3.2 TRANSMISSION LOSS AREAS

Transmission loss modelling revealed that, under site-specific average noise conditions around a hydrophone site, propagation was relatively poor for those sites located at the shelf break (e.g. Brooks Peninsula, Triangle Island, and Anthony Island). The modelling suggested that these hydrophones could not detect (or detected at very low levels) calls from Fin whales originating beyond the shelf slope. This insight highlights a future need for locating recorders more appropriately for off-shelf detection. Sound propagation was more ideal at sites located offshore, as well as sites located on expansive continental shelf areas, particularly in Hecate Strait. Propagation areas for sites in Hecate Strait were partially restricted by geographic barriers such as landmasses (mainland shoreline and the shoreline of Haida Gwaii) and bathymetry (e.g., banks such as Dogfish Bank). The Caamaño Sound detection area was entirely isolated from Hecate Strait by nearby landmasses. Figure 7 presents transmission loss areas for each site showing the detection area as transmission loss scaled to site-specific MaxTL for the example month of October.

3.3 FIN WHALE ACTIVITY

Fin whale song was found at all sites examined, though the measured levels varied between sites and over months. Also, for some months at a few sites, calling levels were consistently low relative to F_{noise}, which occasionally produced monthly FWCI averages that were negative. This does not indicate an absence of calling during that month, but that very low levels of calling were observed, and, on average, F_{fin} levels were lower than F_{noise}.

After applying site-specific correction factors, the most intense and sustained calling was present on the stations in the Hecate Strait area surrounding Moresby Trough, including the Southwest Hecate AURAL and the Caamaño Sound SM2M (Figure 4). High levels of singing were also detected at Brooks Peninsula and Dellwood Knolls (Figure 5). Singing was notably intense and sustained at the Southwest Hecate station. Relative to its transmission loss area, the call index for October and November at Caamaño Sound was the highest of all sites examined. However, it is important to note that the Caamaño Sound detection area was extremely small relative to other sites in this study, and the correction factor resulted in a large adjustment in FWCI relative to other sites. Although the Caamaño Sound analysis was based on a relatively small dataset (4 months), visual observations since 2006 (Nichol et al. 2017) have shown that Fin whales are consistently present in this small inshore area each season, and the singing levels observed are likely representative.

At any given time, typical calling detected on the Hecate Strait recorders consisted of multiple whales vocalizing over one another, especially throughout the early winter. In contrast, F_{fin} on recorders outside of Hecate Strait was typically composed of a faint continuous calling band from consistent faint song activity, overlapped occasionally by recognizable song from one or more closer individuals.

Seasonally, highest call index values were observed between September and March. Peak singing intensities in Hecate Strait occurred November-January, in Caamaño Sound in October-November, around Bowie Seamount between October-December, around Dellwood Knolls between October-November, around Triangle Island between November-December, and around Brooks Peninsula between October-November (Figure 3). A less intense secondary plateau was also observed at the Brooks Peninsula site around February. Notably, peak calling intensities on stations outside of Hecate Strait, including Caamaño Sound, occurred one or two months earlier than the peak at the Southwest Hecate stations. Also, the calling levels at the Caamaño Sound station dropped sharply after November.

3.4 DIEL COMPARISON

No statistical difference in calling power between the day and night was found at Southwest Hecate (Sep 1st – Oct 31st: p=0.1029; Nov 1st – Dec 31st: p=0.4441) or Dellwood Knolls (Aug 31st –Sept 30th: p=0.3884; Oct 1st – Nov 30th: p=1) for either of the periods tested. Nighttime calling power at Brooks Peninsula was statistically stronger (p=0.047), albeit minimally, than daytime calling levels for the period of August 1st to September 30th, and not significant for the October 1st to November 30th period (p=0.2872). Even though no statistical difference was found in the levels at Dellwood Knolls, the graphics visualizing diel energy showed slightly higher nighttime than daytime F_{fin} levels prior to November (Figure 9). The visualizations showed no observable differences in F_{fin} power for any period at the Southwest Hecate recording site (Figure 15).

If energy in the F_{noise} band influenced these results, we would expect similar patterns in the F_{noise} results, however, this did not occur. Nighttime F_{noise} levels at Dellwood (Oct 1st – Nov 30th) were significantly stronger ($p < 2e-7$). This was also observed at Southwest Hecate for the Nov 1 – Dec 31st period, likely caused by flow noise from tidal currents, as indicated by the diagonal streaks of intense energy with semi-diurnal pattern in F_{noise} in Figure 10.

4 DISCUSSION

This study represents the largest acoustic study undertaken to examine trends in the occurrence and seasonality of Fin whale calling in British Columbia to date. Our results provide interesting insights into the geographic variation in singing intensities, as well as the seasonality of singing behaviour over a large spatial scale, which will hopefully prove useful for future studies assessing population structure, reproduction, seasonal movement, and habitat use for Fin whales in Pacific Canada.

4.1 LOCATIONS OF CALLING WHALES

The great distances to which Fin whale vocalizations can propagate (Payne & Webb 1971, Širović et al. 2007, Simon et al. 2010) create uncertainty when interpreting where received calls may have originated. Our modeled detection areas for several sites overlapped one another (Figure 6 and 7), which allowed us to make general assumptions about the locations of calling whales under the assumptions and uncertainty in the transmission loss predictions (see Section 4.4, below). First, the Dellwood Knolls transmission loss area overlapped the Southwest Hecate Strait recorder's. After correcting for transmission loss-area, call indices were lower on the Dellwood Knolls recorder than at the SW Hecate Strait recorder, leading to the conclusion that the Fin whales detected on the Hecate Strait device were likely located closer to the SW Hecate Strait region than to Dellwood Knolls. Likewise, the Triangle Island transmission loss area extended into Hecate Strait and overlapped the SW Hecate device, but very low levels of calling were detected in the Triangle Island data. This again suggests that the locations of the calling whales on the Hecate Strait recorder was in the vicinity of Southern Hecate Strait. The overlapping transmission loss areas of Dellwood and SW Hecate Strait also suggest that some of the faint continuous band that characterized F_{fin} at Dellwood Knolls for most of the calling season could have been partially formed by faint and numerous calls coming from Hecate Strait, but we were not able to confirm this. On the west coast of Vancouver Island, the Triangle Island and Brooks Peninsula transmission loss areas overlapped, but Brooks Peninsula showed much stronger call index values, which suggests that whales were likely within a section of the Brooks Peninsula's detection range with good detectability.

The positioning of the Caamaño Sound recorder shielded it from Hecate Strait and restricted its detection area solely to the inside waters of the Sound, which allowed us to attribute recorded calling activity with certainty to this area. The level of singing observed in Caamaño Sound is quite notable for such a relatively small area in inside waters.

4.2 SEASONAL AND GEOGRAPHIC TRENDS IN FIN WHALE SONG IN BRITISH COLUMBIA

Passive acoustic monitoring infers the presence of a species from the presence of its vocalizations, but conclusions about absence cannot be made if there are no calls or only few calls present. This makes it challenging to determine from passive acoustics alone whether seasonal trends in Fin whale calling are caused by a change in animal presence or by changes in calling behaviour that occur throughout the year (e.g. song).

At most sites, the prevalence of song increased drastically from late summer to early winter. Fin whale song is a seasonal behaviour, and the increase in the FWCI over this period (as well as the subsequent decrease after early winter), is not necessarily a proxy for the number of animals increasing or decreasing in a region. For instance, very large aggregations of Fin whales were observed from ship-based surveys within the detection range of the Southwest Hecate recorder in August 2013, yet the FWCI during this period on the recorder was low relative to mid-winter levels. This suggests that at least some of the increase in FWCI into the fall and winter is caused by a shift in calling behaviour.

Similarly, other changes in calling behaviour also affect interpretation of seasonality. For example, a within-season change in the length of the Inter-pulse Interval (or Inter-note interval - the length of time between successive pulses) in song has the potential to affect the call index (Nieukirk et al. 2012). Oleson et al. (2014) documented that the inter-pulse interval of Fin whale song in the North Pacific increases as the singing season progresses. This could cause a decline in the call index (because there would be fewer calls per unit of time) (Širović et al. 2015). Similar to results from Oleson et al. (2014) for the North Pacific, Koot (2015) found that the inter-note interval for Fin whale song in British Columbia lengthens throughout the singing season until it is at its longest interval coincident with peak measured calling intensities in our study between November and February for Hecate Strait. The fact that, in our study, call index levels for Hecate Strait were most intense during the period with the longest inter-note interval is most likely due to an increase in the actual number of calls, which either means an increase in the number of animals singing, an increase in the amount of singing by individual whales, movement of more singing whales into the area, or a combination of these factors.

It is possible that some of the seasonal increase in singing levels in Hecate Strait in mid-winter reflects an increase in the number of animals using the area. For instance, seasonal peaks in FWCI at all other locations outside of Hecate Strait occur one or two months prior to the peak singing intensities in Hecate Strait. This offset suggests that a movement of animals from other nearshore sites into the Hecate Strait region may occur from October through to January. Alternatively, it is possible that whales already in Hecate Strait may simply be moving closer to the Southwest Hecate recorder later in the singing season, causing the call index to rise. However, this does not explain the synchronous decrease in call index at sites outside Hecate Strait – movement of animals into Hecate Strait is a more probable explanation. Otherwise, as noted earlier, the drop in call index post October at sites outside Hecate Strait may be an artifact of the increasing inter-note interval in song over the course of the singing season. However, additional information from a separate analysis of song presence at Brooks Peninsula (Koot, 2015) indicates that the drop in call index post-October at that location in our study is more likely caused by a continual decrease in the number of days with song present post-October, not an artifact of inter-note interval, which further supports the idea of movement away from these sites. Whether movement from these sites is directed towards the Hecate Strait region as suggested by the offset in peak calling, or whether animals are moving to other areas, will need more study and effort to clarify.

The high intensities of singing observed in Hecate Strait between November and January overlaps with the estimated calving and conception period for Fin whales in the North Pacific (Lockyer 1984). Ohsumi et al. (1958) and Lockyer (1984, citing Fujino 1954) noted the peak month of conception to be December, and peak calving months to be November and December. Additionally, Pike (1956, unpubl. data)[1] estimated that 75% of births in the Fin whales inhabiting British Columbia waters occurred between mid-October and mid-February. Although we cannot draw any conclusions about calving from acoustics, these insights, combined with the high levels of singing and the offset peak from everywhere else in this study region suggests that activities associated with breeding (courting and mating) are likely taking place in Hecate Strait during the October to February period.

Beyond January in Hecate Strait, singing levels decline but it is unknown whether this occurs because of changes in calling behaviour in the later stages of the breeding season (fewer animals singing), localized re-distribution of whales within the region, or migration of whales out of the region. This decline is much sharper than would be expected if it was solely due to a change in calling behaviour post-breeding season, which may indicate a movement of animals away from the SW Hecate detection area beginning in late January or early February.

The line of reasoning in this section emphasizes that the Hecate Strait region is unique among the areas in this study in having the highest effort-corrected levels of singing that persist latest into the winter, and also implies the region may be of central importance for Fin whales during the breeding season in the near shore waters of British Columbia. Further insights from genetics, photo-ID, acoustic analyses from elsewhere in BC, tagging studies and improved winter field efforts will help clarify Fin whale population structure and movements in British Columbia and possibly identify other regions of importance.

4.3 DIEL CALLING PATTERNS

It is thought that feeding patterns may influence the daily singing patterns of Fin whales. Fin whales feed largely on zooplankton in British Columbia (Flinn et al. 2002; DFO Cetacean Research Program, unpublished data), which are known to undergo diel vertical migrations towards the surface at night and the depths during the day (Hays 2003). Fin whale feeding may occur more readily during the daytime while prey is concentrated at depth (Nichol et al. 2017), whereas singing or other behaviour may be more prevalent at night when zooplankton become more diffuse in surface waters rendering feeding inefficient (Stafford et al. 2005, Wiggins et al. 2005).

Our results showed that there is no statistical or observable difference between the intensity of singing at night compared to during the day in Southwest Hecate Strait (Figure 15). At Dellwood Knolls and Brooks Peninsula, there seemed to be a very slight observable difference between night and day most obvious in October, with slightly more energy at night than during the day (Figures 13 and 14). The slight diel differences observed in the visualizations were not significant at Dellwood Knolls; however, the difference was significant at Brooks Peninsula for pre-October.

The apparent lack of a diel trend in singing behaviour in Hecate Strait may be due to one or more possible factors. The first possibility is that feeding Fin whales in Hecate Strait may not be

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[1] Pike, G. C. 1956. Age, growth and maturity studies on fin whales from the coast of British Columbia. Fisheries Research Board of Canada, Unpublished Manuscript.

inhibited by the diel vertical migration of zooplankton prey, suggesting other drivers like tidal upwelling, tidal fronts, or complex bathymetric features may allow a consistent supply of food to be available all day, ultimately resulting in evenly distributed singing behaviour. The second possibility is that Hecate Strait may not be used for feeding by Fin whales, but solely for other behaviors like reproduction. However, we have ample observations of foraging Fin whales in Hecate Strait in October and March from ship surveys, as well as from state-space modelling from data logging tags indicating Area-Restricted-Search in the area (inferring feeding behaviour) (Nichol et al. 2017). The third possibility is that only some Fin whales in Hecate Strait sing on a diel cycle, though not enough whales to cause a detectable change in the overall calling intensity that would be detectable by our methods. Relatedly, even though Simon et al. (2010) found a very strong diel trend in Fin whale singing behaviour in Davis Strait (Baffin Bay), they noted that singing did not cease entirely during the day, but only decreased.

An examination of the area's oceanography, as well as further study of Fin whale dive behaviour within and among regions using data logging tags would help provide insight into the above possibilities.

4.4 LIMITATIONS AND ASSUMPTIONS

A number of assumptions were made in modeling site-specific transmission loss. First, we used average monthly site-specific ambient noise levels (within F_{noise}), which meant that short-term changes in noise (i.e. vessel transits, weather systems) that would reduce detectability of fin whale calls, could not be taken into account. Also, the propagation models relied on site-specific environmental data available through ESME, which were from a reputable source but were too coarse temporally and spatially to account for changing conditions among years covered in the study. We determined that differences in monthly environmental data for Dellwood Knolls had negligible effect on transmission loss so we opted to only use October environment data for each site, which was the month whose transmission loss varied least from all other months in the Dellwood test. In future, using two representative environmental data periods (i.e. winter, summer) for each site may account for more seasonal variability.

We assumed a constant source level of 189 dB re 1µPa @ 1m for Fin whale calls, because this is the most recent published average source level for a large sample size of 20-Hz fin whale vocalizations from offshore of British Columbia (Wierathmueller et al. 2013). Although using the average source level does not take into account the full range of variability that could be encountered, it is likely to result in propagation that is acceptable for most calling circumstances.

We also assumed a calling depth of 20m based on a recent tagging study conducted by Stimpert et al. (2015) off California. Multi-sensor acoustic tags with high-rate accelerometry deployed on Fin whales allowed for calls made by the tagged whale to be identified and associated directly with tag depth measurements. The team found that singing Fin whales almost exclusively produced vocalizations within 10-20m of the surface. The closest depth range bin in our propagation loss output was 20m, so we used the latter.

Also, in this study we compared corrected results among all sites regardless of how restricted their overall detection areas were (e.g. Caamaño Sound versus Dellwood Knolls). There may be some merit in only comparing among sites in similar environments (e.g. off-shelf or coastal sites).

By using the most current available information on Fin whale call production, by validating the assumption that differences between monthly propagation models is negligible, and by using site-specific average ambient noise levels for each month available, our analysis attempted to account for sufficient variability to compare results among locations for our purposes. Figure A1 in the Appendix shows the uncorrected daily average FWCIs for comparison to the corrected final results. Future studies with access to more powerful computing could benefit from higher temporal and spatial resolution of ambient noise and environmental variables. A future effort to ground truth site-specific environmental data, such as sound-speed profiles, would also be beneficial.

5 CONCLUSIONS

Of the areas examined in this study, peak singing intensities were recorded in the Hecate Strait region (including Caamaño Sound). Peak singing intensities in the Hecate Strait region (notably on the Southwest Hecate recorder) occurred one to two months later than other sites examined in this study and were sustained for the longest duration into the winter. These observations suggest that movement of some Fin whales from other nearshore locations in our study area towards Hecate Strait may occur mid-winter. However, more evidence for such movement is needed. The period of peak singing intensities in Hecate Strait align with available information on the timing of the reproductive cycle of Fin whales in British Columbia, indicating that activities associated with breeding, such as courting and mating, are likely occurring in Hecate Strait. Dedicated ship survey effort in Hecate Strait in winter has been minimal, which highlights a need for improved visual effort to validate these findings.

High seasonal levels of singing were also observed at two other locations outside of the Hecate Strait region: Brooks Peninsula and Dellwood Knolls. To help identify other areas of importance for Fin whales, geographic gaps in acoustic monitoring coverage should be filled, most notably in, northern British Columbia, offshore waters, and the west coast of Vancouver Island.

6 ACKNOWLEDGEMENTS

We express our gratitude to Tamás Juhász, Lucius Perreault, David Spear, and officers and crew of the CCGS John P. Tully for their hard work and expertise in constructing and deploying the acoustic moorings that allowed for the collection of data for this study. We also thank Ana Širović for her consultation on methodology. Barbara Koot provided a wealth of insight on the topic of Fin whale acoustics in British Columbia through her thesis, as well as in discussion and her comments on the draft. Svein Vagle provided us with the recordings for Eastern Hecate Strait, for which we are very grateful. Jared Towers and Brian Falconer assisted in deploying a recorder in Caamaño Sound, and Graeme Ellis assisted in its retrieval. Graham Voysey provided technical assistance with the ESME software. Finally, we also acknowledge the help of Linda Nichol, Brianna Wright, Lisa Spaven, and Harald Yurk for their thoughts and discussion throughout the stages of this study.

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8 TABLES

Table 1: Acoustic deployment details for deployments included in this study.

Location	ID	Instrument	Sensor Depth (m)	Sensor	Start Date	End Date	Total Days	Duty Cycle (REC:PAUSE) (min)
Anthony Island (W.Cape St James)	AM020	AURAL-M2	100	HTI-96-MIN	2009-09-20	2010-07-15	298	7:23
	AM025	AURAL-M2	100	HTI-96-MIN	2010-07-15	2011-05-17	306	9:21
Brooks Peninsula	AM024	AURAL-M2	105	HTI-96-MIN	2010-07-15	2011-04-02	261	4.5:10.5
	AM029	AURAL-M2	105	HTI-96-MIN	2011-05-18	2012-05-25	373	4.5:10.5
	AM045	AURAL-M2	105	HTI-96-MIN	2013-07-04	2014-06-28	359	4.5:10.5
Southwest Hecate	AM041	AURAL-M2	146	HTI-96-MIN	2012-08-03	2013-03-06	215	4.5:10.5
	AM046	AURAL-M2	146	HTI-96-MIN	2013-07-18	2014-04-23	279	4.5:10.5
Eastern Hecate	HEC1A	SM2M	51	HTI-92-WB	2014-07-01	2015-06-30	365	2:58, on the hour
	HEC1B	SM2M	52	HTI-92-WB	2014-07-01	2014-06-22	356	2:58, on the half-hour
Caamaño Sound	AM052	SM2M	35	HTI-92-WB	2013-10-10	2014-02-03	116	5:10
Triangle Island	AM028	AURAL-M2	135	HTI-96-MIN	2011-05-18	2012-05-18	366	4.5:10.5
	AM036	AURAL-M2	135	HTI-96-MIN	2012-06-11	2013-04-29	322	4.5:10.5
Bowie Seamount	AM031	AURAL-M2	235	HTI-96-MIN	2011-07-24	2012-01-02	162	9:06
	AM032	AURAL-M2	233	HTI-96-MIN	2012-01-16	2012-04-22	97	9:06
	AM039	AURAL-M2	237	HTI-96-MIN	2012-07-31	2013-07-15	349	4.5:10.5
Dellwood Knolls	AM057	AMAR G3	336	Geospectrum M8Q	2014-07-14	2015-07-30	381	5.5:9.5

9 FIGURES

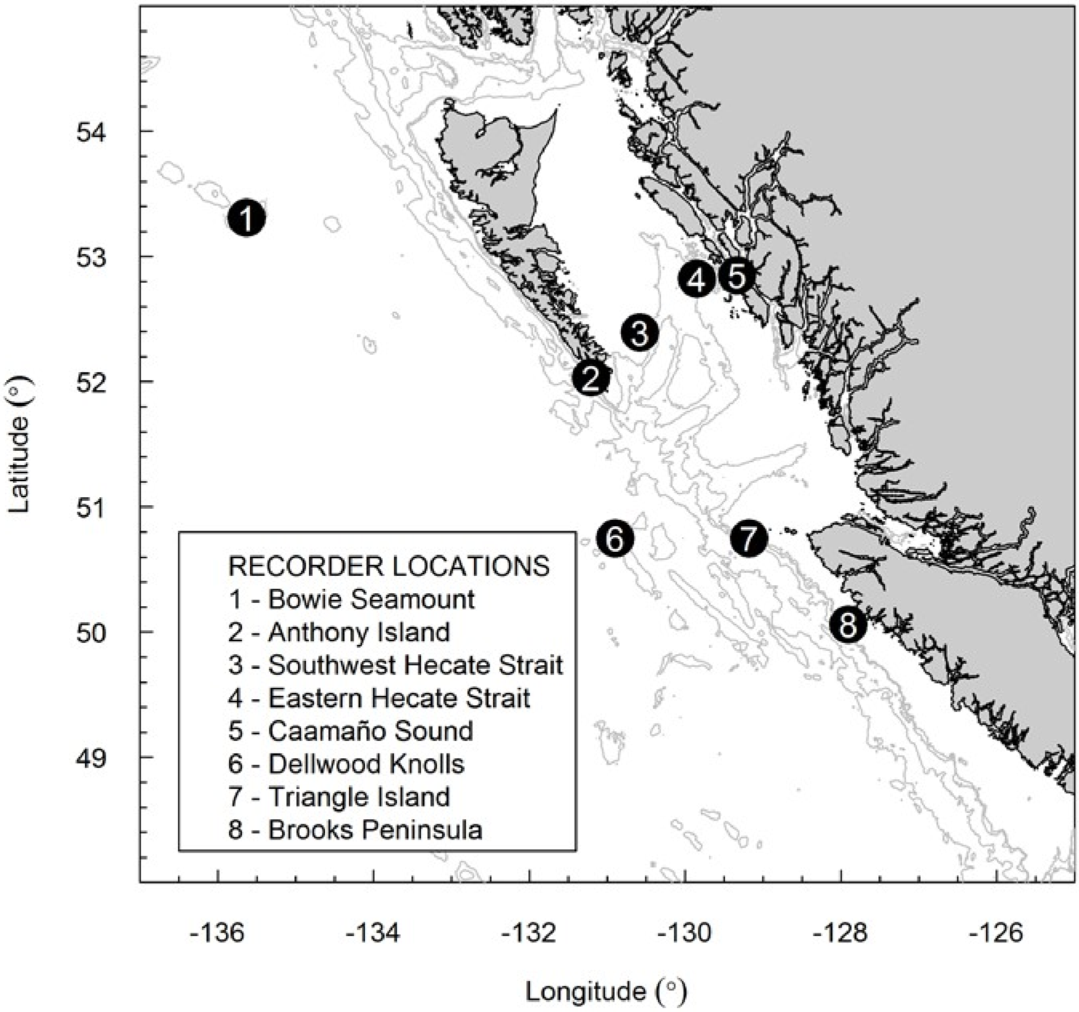

Figure 1: Map of the British Columbia coast showing the locations of data collection for this study. The 200, 300, 1000, and 1500m isobaths are shown.

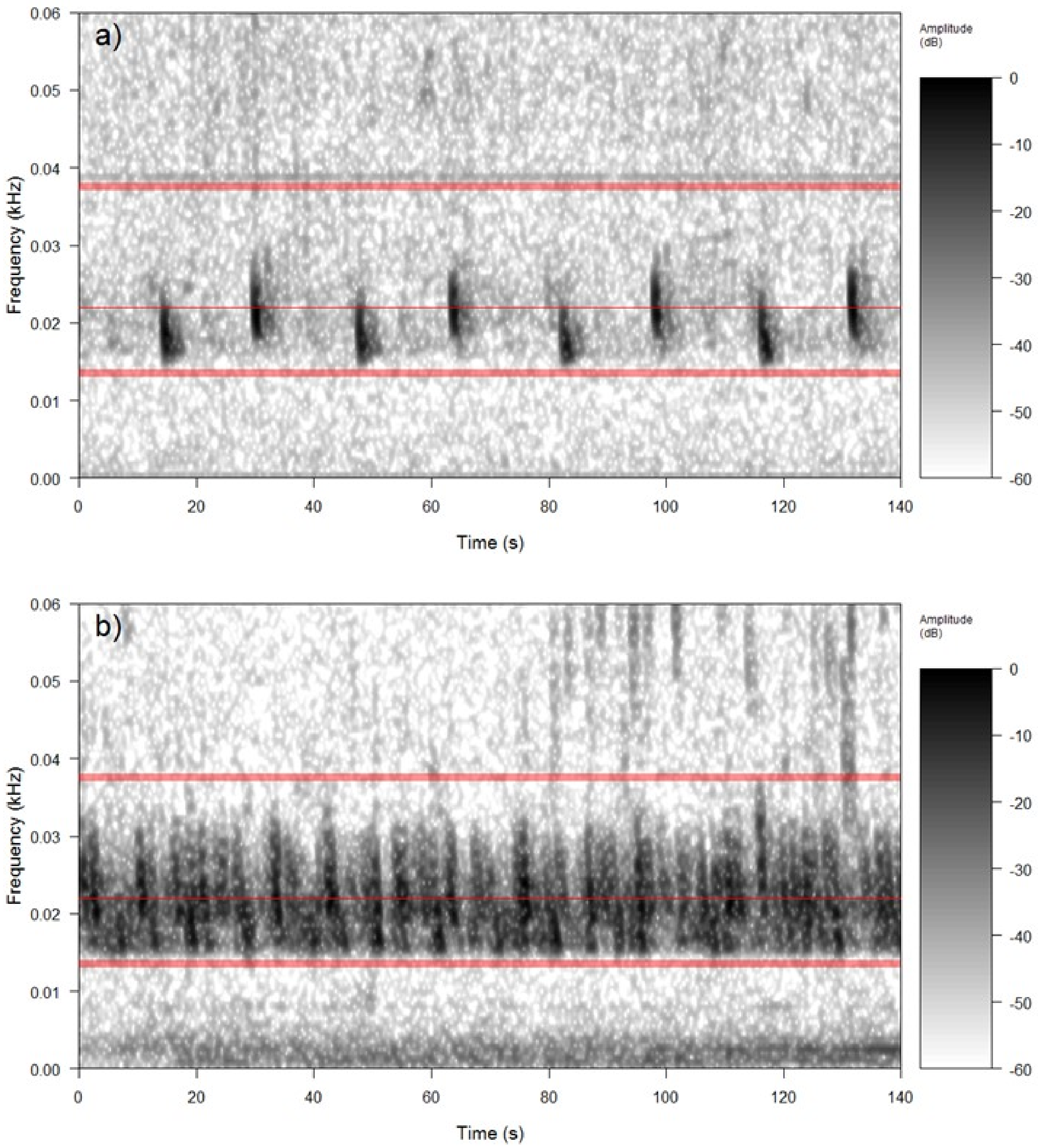

Figure 2: Spectrograms of Fin whale song from: a) Caamaño Sound, and b) Southwest Hecate Strait. Red shaded bands at 13-14Hz and 37-38Hz indicate bands used to represent F_{noise} in the FWCI calculations. Red line at 22Hz represents the F_{fin} band used in the FWCI (Spectrogram parameters: window length = 2048 samples, overlap = 90%).

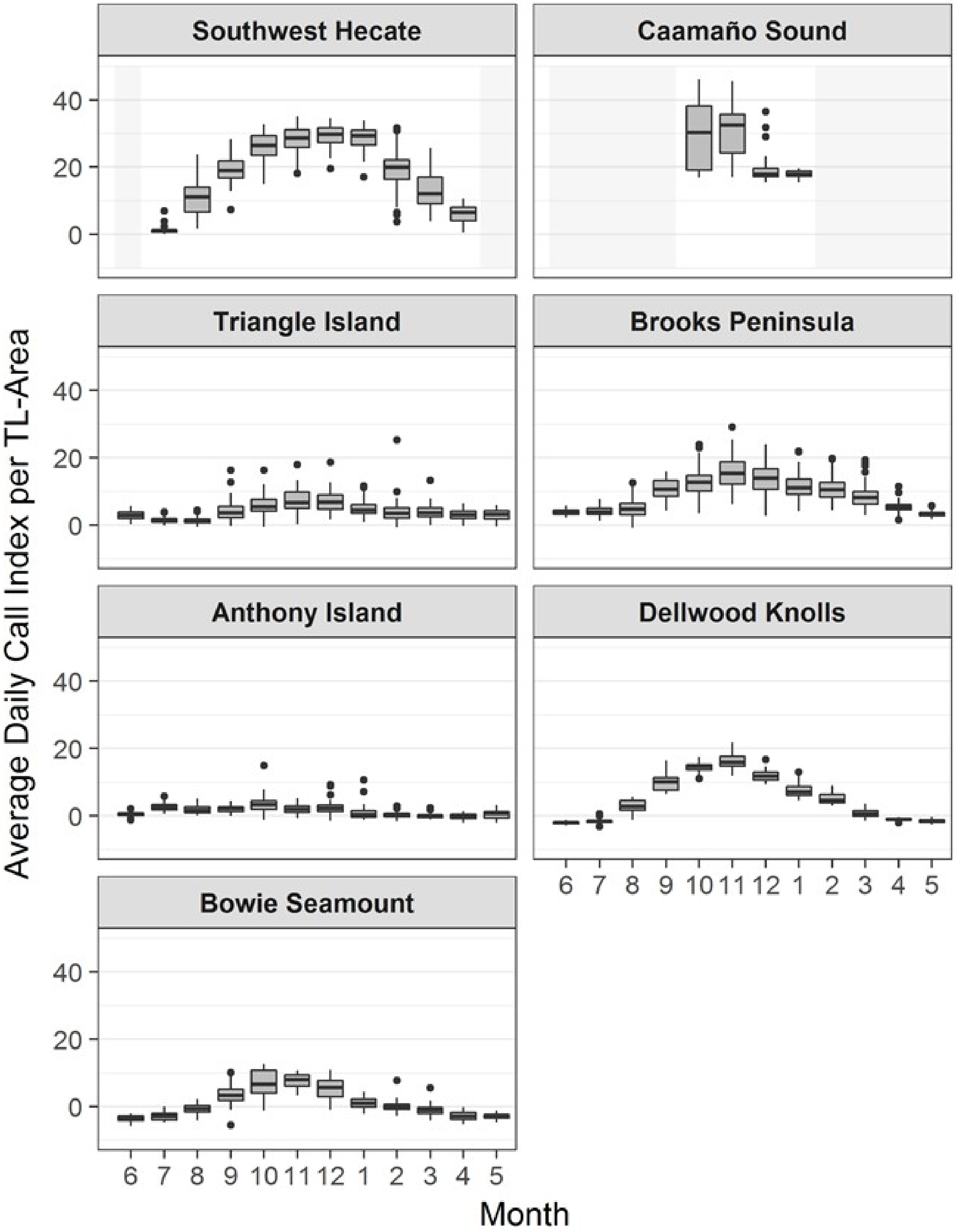

Figure 3: Boxplots showing corrected mean daily call index values by month for each recorder site, corrected for transmission loss-area. The black bar in the boxes represent the median, upper and lower limits of boxes represent 75th and 25th percentiles respectively, whiskers represent highest and lowest values within the 75th and 25th percentiles, and dots are outliers. Note the x-axis: plots have been centered on November (peak calling period). Light grey shaded regions represent months with no data. See Appendix figure A1 for uncorrected values.

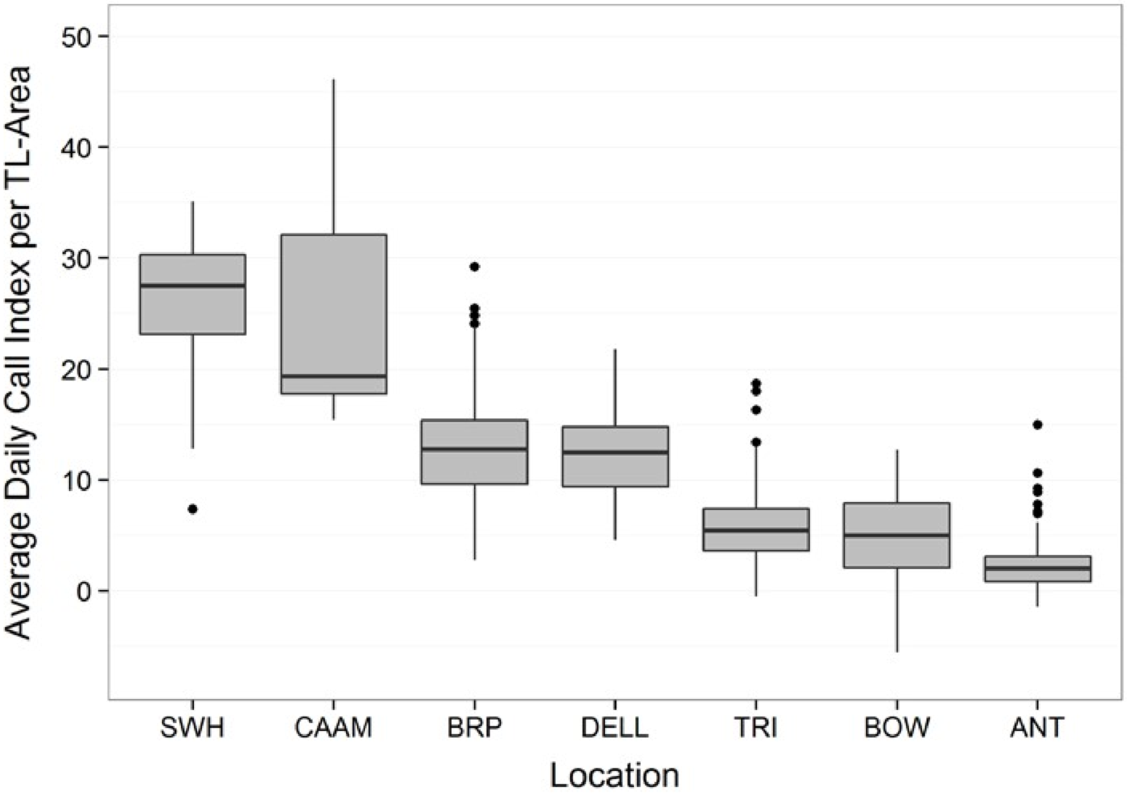

Figure 4: Boxplot showing range of corrected average daily call index values during the period between September 1st and January 31st for all available years and locations; data is corrected for area-transmission loss. This date range encompasses the peak calling periods at all sites. Plots were ordered in descending order (left to right) by median values. SWH=Southwest Hecate, CAAM= Caamaño Sound, BRP=Brooks Peninsula, DELL=Dellwood Knolls, TRI=Triangle Island, BOW=Bowie Seamount, ANT=Anthony Island.

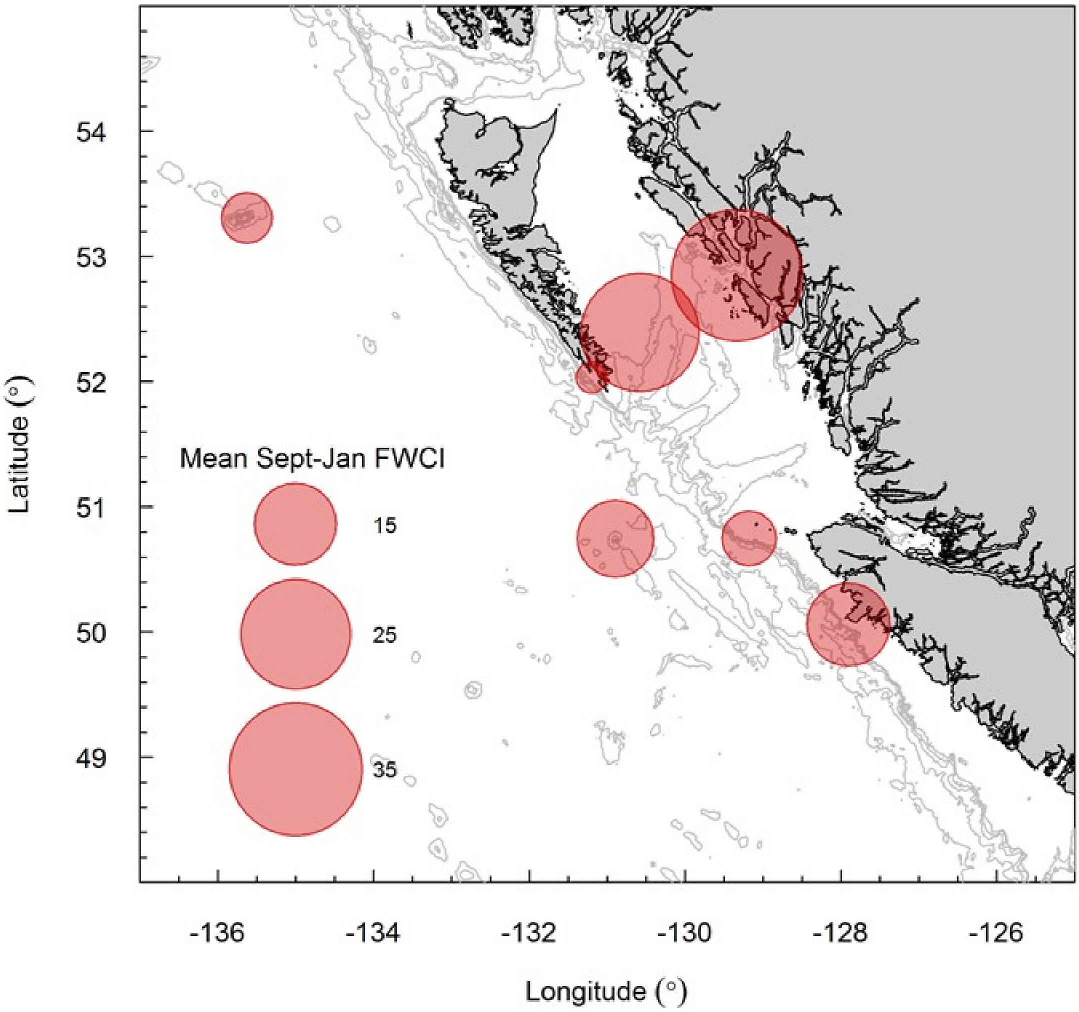

Figure 5: Map showing recorder locations. Size of red circles is proportional to the mean daily call index values (corrected for area and transmission loss) between September 1st and January 31st for all years available at each site. The 200, 300, 500, 1000, 2000 meter isobaths are shown.

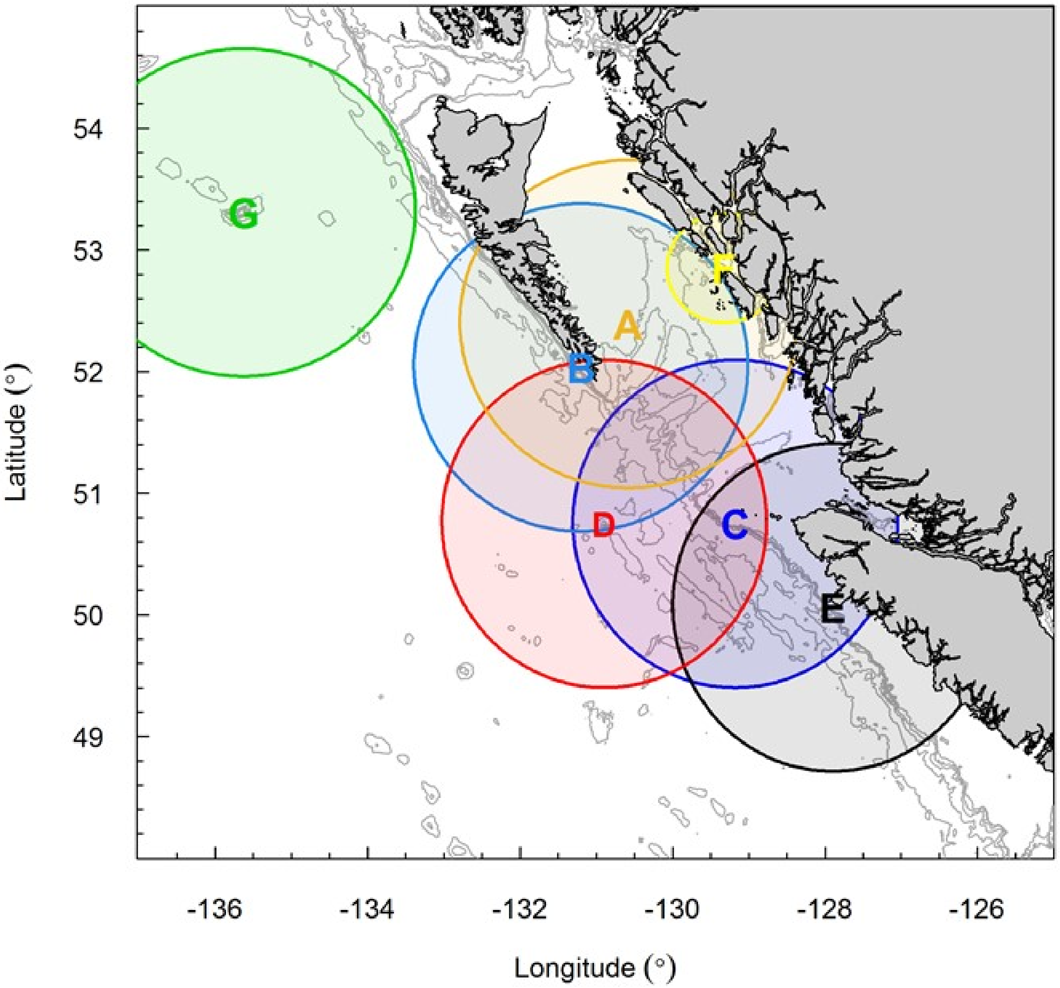

Figure 6: Map showing recorder locations with 150km radius circles that depict the areas over which transmission loss was measured. Note that the radius of F (Caamaño Sound) differs from the other stations (50km radius). Circles show general overlap of the areas, but do not necessarily represent the actual extent of overlap from which Fin whale calls would be received at multiple stations, for details see figure 7. A=Southwest Hecate, B=Anthony Island, C=Triangle Island, D=Dellwood Knolls, E=Brooks Peninsula, F=Caamaño Sound, G=Bowie Seamount. These letters are consistent with the lettered maps in figure 7.

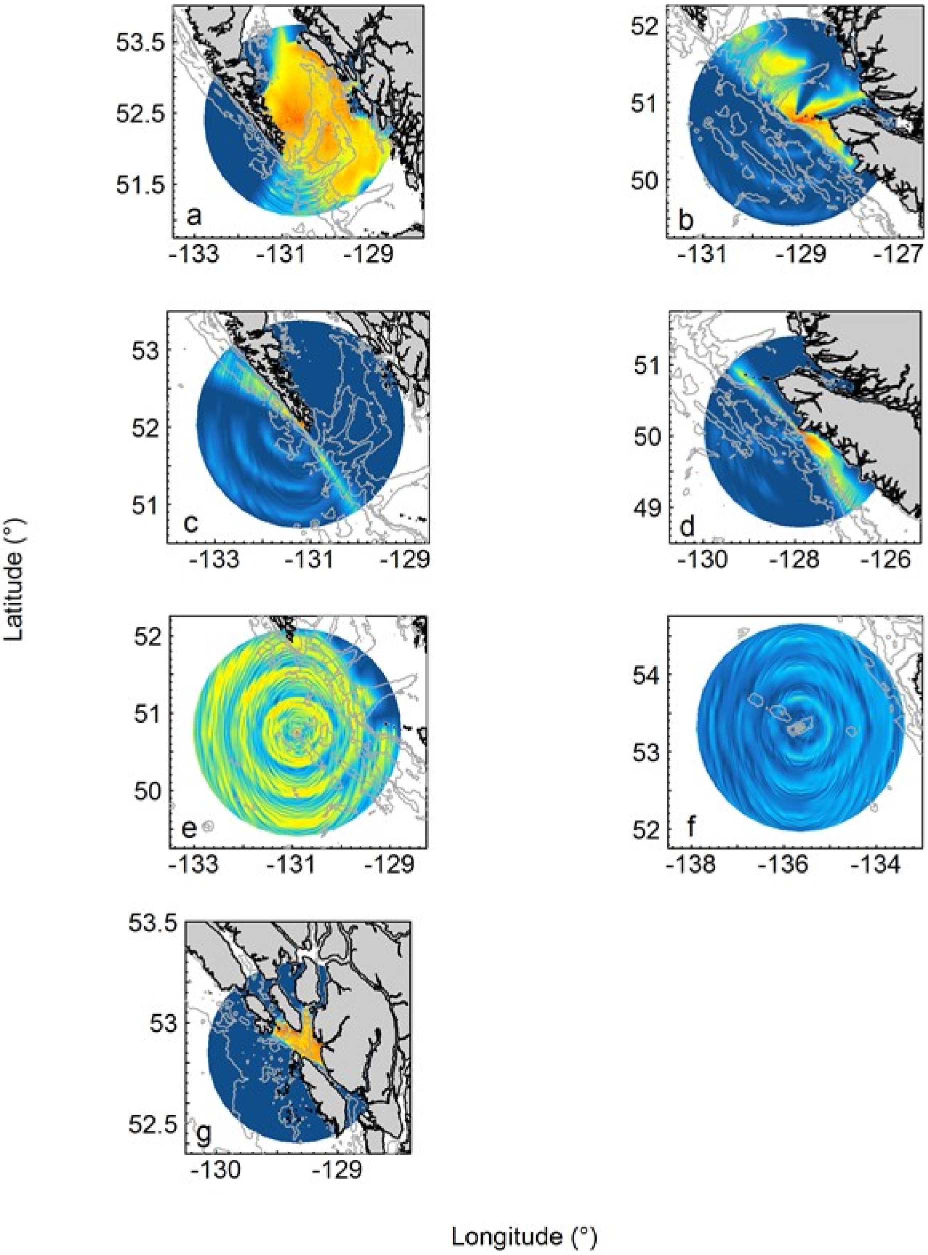

Figure 7: Transmission loss areas for all recorder locations. Each map is scaled to the site-specific MaxTL for October. Dark blue represents areas from which Fin whale calls are not received at the hydrophone site. Hotter colours represent areas from which received calls would be more intense. A=Southwest Hecate, B=Triangle Island, C=Anthony Island, D=Brooks Peninsula, E=Dellwood Knolls, F= Bowie Seamount, G=Caamaño Sound.

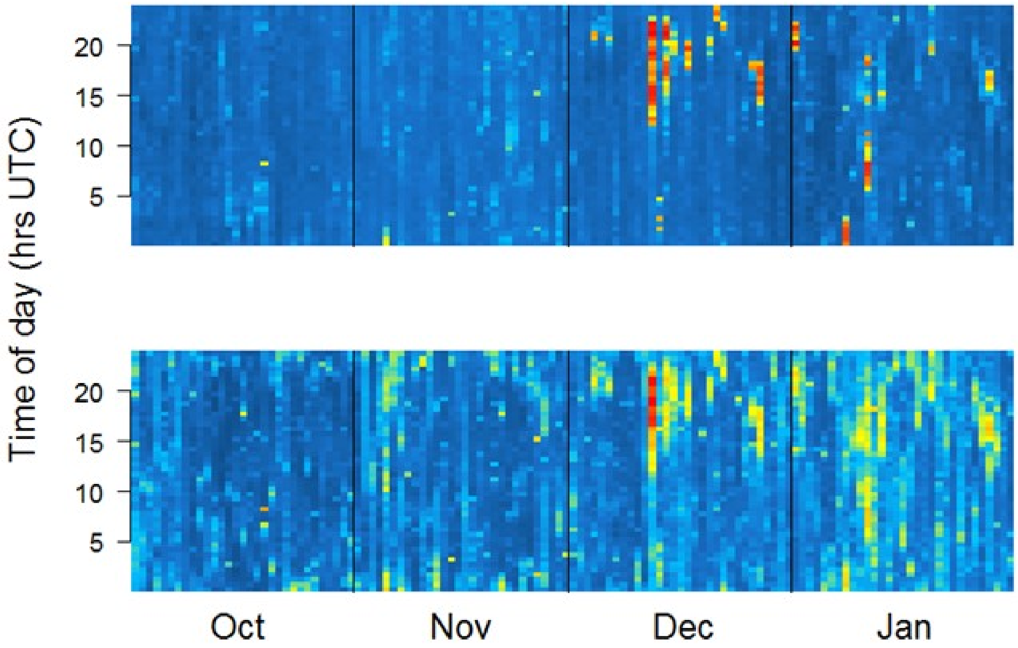

Figure 8: Summed F_{fin} power (top panel) and F_{noise} power (lower panel) in half-hour intervals for each day between October 1st and January 31st at Brooks Peninsula. The colour scale is from blue (lowest levels) to red (highest levels). Note the exceptionally faint difference for October in the F_{fin} band earlier than 0500 UTC (0500 UTC = 2000 PST).

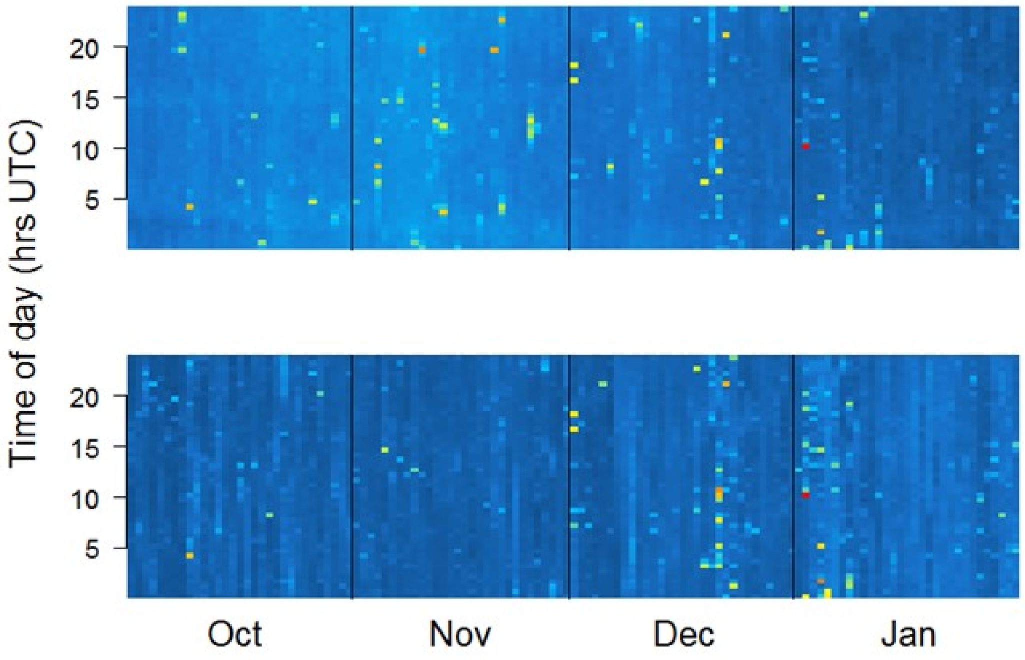

Figure 9: Summed F_{fin} power (top panel) and F_{noise} power (lower panel) in half-hour intervals for each day between October 1st and January 31st at Dellwood Knolls. The colour scale is from dark blue (lowest levels) to red (highest levels). Note the exceptionally faint difference for October in the F_{fin} band earlier than 0500 UTC (0500 UTC = 2000 PST).

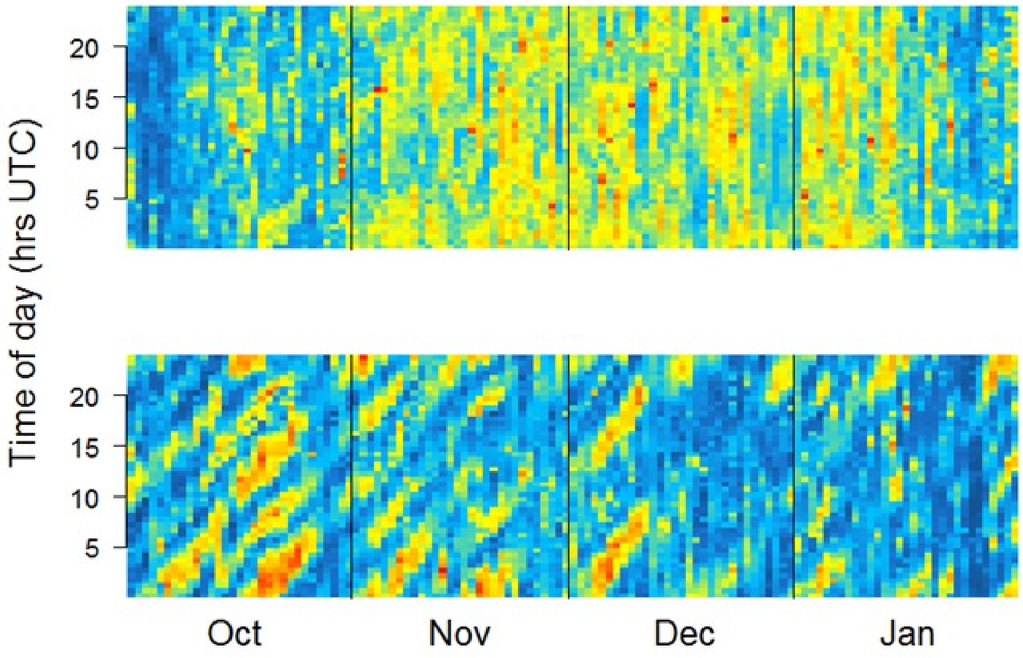

Figure 10: Summed F_{fin} power (top panel) and F_{noise} power (lower panel) in half-hour intervals for each day between October 1st and January 31st at Southwest Hecate Strait. The colour scale is from dark blue (lowest levels) to red (highest levels). Note that there is no obvious trend in day/night levels (0500 UTC = 2000 PST). The diagonal streaks of intense energy in the F_{noise} band are caused by flow noise around the hydrophone from currents.

10 APPENDIX

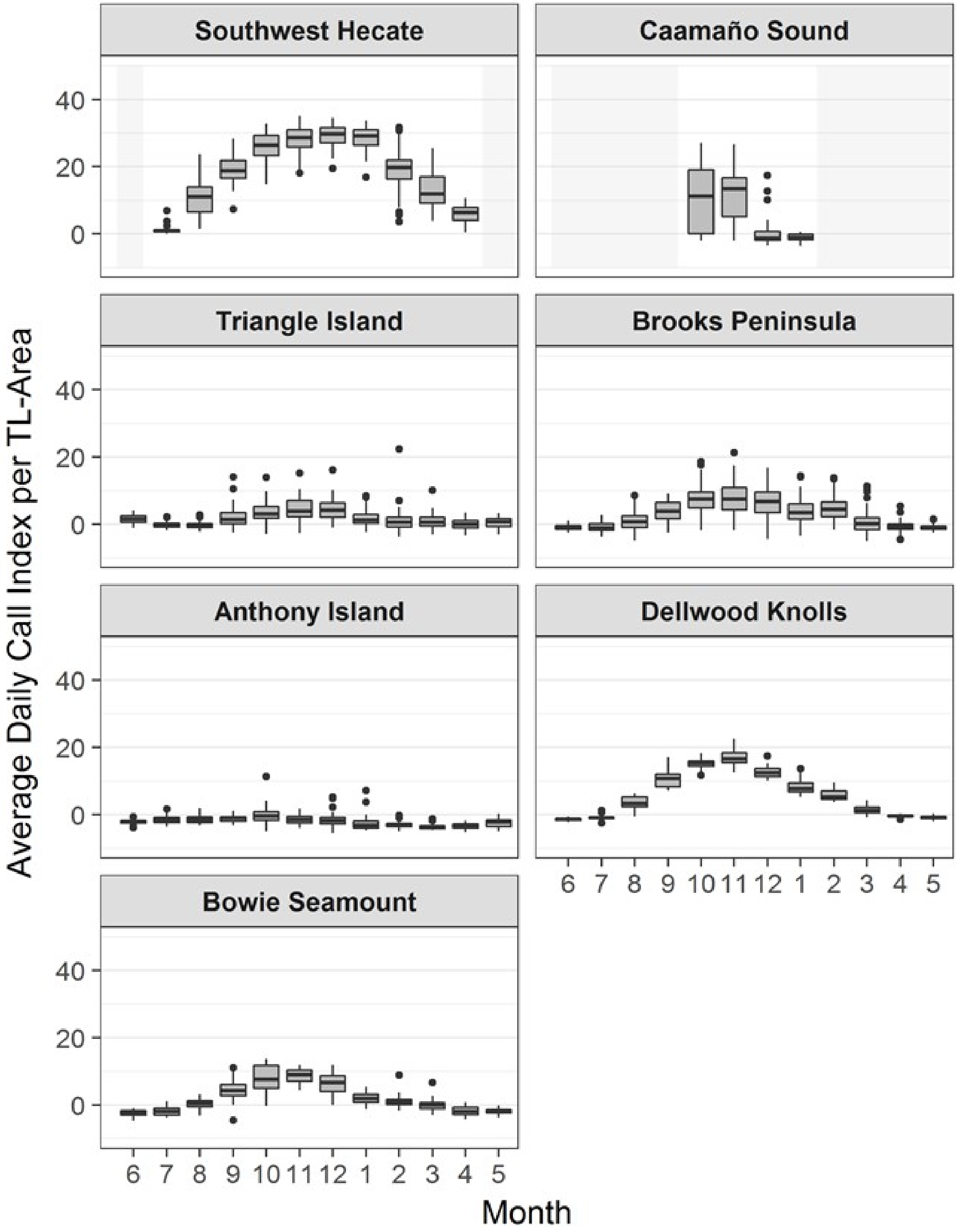

Figure A 1: Average uncorrected daily call indices for reference. These values are to be used in combination with Figure 3 to examine how the correction factor affected the data.