Bryde's whale calls recorded in the Gulf of Mexico

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Bryde's whales (*Balaenoptera edeni*) inhabit tropical and sub-tropical waters worldwide and, unlike most other mysticetes, they are not thought to make long seasonal migrations (Jefferson *et al.* 2008). They are the only Balaenopterid regularly found in the U.S. waters of the Gulf of Mexico (GOM), with their range likely constrained to the shallow, northeastern part of the GOM around DeSoto Canyon (Maze-Foley & Mullin 2006). Bryde's whales are likely the smallest population of cetaceans in the region (Maze-Foley & Mullin 2006). Since the early twentieth century, there have been only four reported Bryde's whale strandings along the coast of the GOM (Mead 1977). National Oceanographic and Atmospheric Administration (NOAA) Fisheries has been conducting regular marine mammal surveys in the GOM since 1990's and the number of individuals found in the U.S. Exclusive Economic Zone (EEZ) was estimated at 35 (CV=1.10) between 1991-1994 (Hansen *et al.* 1995), and 40 (CV=0.61) between 1996-2001 (Mullin & Fulling 2004). Based on the most recent surveys conducted in 2003 and 2004, Bryde's whale population in the US EEZ in the GOM is estimated at 15 (CV=1.98) individuals (Mullin 2007). While it has been suggested that the GOM population is a distinct stock, no evidence exists to confirm their separation from the nearby southern Caribbean or Atlantic stocks (Waring *et al.* 2009).

Evidence for Bryde's whale stock separation within an ocean basin exists in other regions. In the Eastern Tropical Pacific (ETP), two separate Bryde's whale stocks were proposed based on a break in the species distribution between 7 and 9 °N (Wade & Gerrodette 1993). This separation was supported with acoustic evidence by Oleson *et al.* (2003), who reported distinct call types in the two geographic regions and suggested that different Bryde's whale stocks may have distinct call types. This hypothesis is further supported by the large variability in Bryde's whale calls recorded in other regions. In addition to the ETP, distinct low frequency (60 – 950

Hz) pulses, tonals, and moans have been described for free-ranging Bryde's whale adults and calves in the Gulf of California, southern Caribbean, and the western North Pacific off the coast of Japan (Cummings *et al.* 1986, Edds *et al.* 1993, Oleson et al. 2003, Heimlich *et al.* 2005).

No calls have been described previously for free-ranging Bryde's whales in the GOM, but two call types have been recorded from a captive juvenile that stranded on the Gulf coast of Florida in 1988 (Edds *et al.* 1993). One type was a growl-like pulsed moan with amplitude and frequency modulation (200-900 Hz), and highly variable duration ranging between 0.3 and 51 seconds (Edds *et al.* 1993). The second was a sequence of discrete, 10 ms long pulses with the majority of energy between 400-610 Hz and interpulse interval of 50-130 ms (Edds *et al.* 1993). In addition, one call type has been described from free-ranging Bryde's whales in the southern Caribbean. This call has a slight frequency downsweep with a fundamental frequency at approximately 44 Hz with two to four harmonics (the second harmonic is generally the strongest), and a mean duration of 1.6 s (Oleson *et al.* 2003).

Once Bryde's whale calls in the GOM are well described, passive acoustics can be used to learn more about their seasonal presence, range extent, and relative abundance in this region. While it is possible Bryde's whales are present in this area year-round as their strandings have been recorded year-round (Wursig *et al.* 2000), visual surveys have been conducted only during the spring (Waring *et al.* 2009). In this paper, we describe one call type recorded in the presence of Bryde's whales in the GOM and a time series of the call's presence in long-term recordings from DeSoto Canyon in the northeastern GOM from October 2010 to July 2011. One additional, possible Bryde's whale call that was only recorded on the long-term autonomous recordings is also described.

Initial data to identify calls produced by Bryde's whales in the GOM were collected during the 2011 NOAA Southeast Fisheries Science Center's Atlantic Marine Assessment Program for Protected Species (AMAPPS) survey. Between 28 July and 1 August 2011, visual and acoustic surveys for marine mammals were conducted aboard the NOAA ship *Gordon Gunter* from the southeastern edge of the GOM, just south of Florida, to Pascagoula, MI, following the 200 m isobath (Figure 1). Trained marine mammal observers conducted a line transect survey for cetaceans using 25x "Big Eye" binoculars concurrently as a passive acoustic survey was conducted. In addition, Directional Frequency Analysis and Recording (DIFAR) AN/SSQ-53E sononbuoys were deployed in arrays after baleen whale encounters.

DIFAR sonobuoys contain a directional hydrophone with a bandwidth from 10 to 2,400 Hz, which provides a magnetic bearing to the source of the received sound of interest. The signals from the sonobuoy are transmitted via a single radio carrier frequency to a ship-mounted antenna. During AMAPPS cruise, an omnidirectional X500 antenna (Diamond Antenna) with a P160VDG pre-amplifier (Advanced Receiver Research) was used, which transmitted the signal to ICOM radio receivers modified for low-frequency response (Greeneridge Sciences). The signal was digitized using a Sound Blaster Audigy USB sound card (Creative Technology). Incoming signals were monitored aurally via headphones and visually via a scrolling spectrogram in the software program *Ishmael* (David Mellinger, Oregon State University). In addition, digital recordings to wav files were made and annotated using *Logger2000* (Douglas Gillespie, International Fund for Animal Welfare). Times of all potential baleen whale sounds were noted.

During post-analysis, recordings made during the encounters with Bryde's whales were scanned to verify real-time detections and determine bearings to the sounds. Magnetic bearings

to sound sources were extracted from the multiplexed DIFAR signal using an algorithm developed by Charles Greene (Greenridge Sciences), and modified by David Mellinger (Oregon State University) and Mark McDonald (Whale Acoustics). When a bearing to the same call was extracted from more than one concurrent sonobuoy recording, the location of the source of that call was estimated from bearing crossings.

In addition to ship recordings, long-term passive acoustic recordings of Bryde's whales in the region were collected using High-frequency Acoustic Recording Packages (HARPs; Wiggins and Hildebrand 2007). A HARP was deployed in DeSoto Canyon (29º 3.2' N, 86º 5.8' W, depth 260 m), northeastern GOM (Figure 1), from 21 October 2010 until 17 January 2011 and again from 21 March until 6 July 2011, for a total recording effort of 4665 hours. Additionally, HARPs were deployed in southeastern GOM at Dry Tortugas (25º 31.9' N, 84º 38.3' W, depth 1320 m) from 20 July until 26 October 2010 and again from 3 March – 15 May and 12 July – 14 November 2011, and in north-central GOM at Main Pass (29º 15.3' N, 88º 17.8' W, depth 90 m) from 29 June until 29 August 2010, from 2 November 2010 – 19 February 2011, 20 March – 14 April, and 2 May – 21 June 2011 (Figure 1). The HARPs sampled at 200 kHz and data were decimated to a 2 kHz sample rate to enable quicker processing and analysis. First, long-term spectral averages (LTSAs) were created using 2,000-point fast Fourier transforms (FFTs), with 5 s time and 1 Hz frequency resolution (Wiggins & Hildebrand 2007). Custom-made Matlab-based program *Triton* (Wiggins & Hildebrand 2007) was used to visually scan LTSAs for the presence of calls of interest, either those matching recordings collected during the AMAPPS cruise or similar, baleen whale-like (low frequency, short duration, high intensity) sounds. The scrutinized LTSA windows were plotted with 0.5 hours of data, over frequency range 0 to 500 Hz. When sounds of interest were identified in the LTSA, they were examined more closely by zooming in

to 60 s of data and frequency range 0 to 400 Hz. If presence of a call was confirmed, the time of its occurrence was logged.

Time and frequency characteristics of Bryde's whale calls were measured to define their features. The following features were measured manually: minimum and maximum call frequencies were measured from spectrograms, and call start and end times were measured from time series plots (band-pass filter 60-130 Hz). The duration of a call was calculated as the duration between the start of the first and the end of the last pulse. The number of pulses per call also was noted and the interpulse interval (IPI) of each call was calculated by averaging the difference between the end of one call and the start of the subsequent call over the course of each calling bout. All calls recorded on sonobuoys were measured, while a subset of 30 calls was measured from the HARP recordings. Only one call per 24 h period was used for the latter analysis to minimize the over-representation of calls from an individual whale. Averages and standard errors of all measurements are reported.

To determine the call source level (SL), which is the sum of transmission loss and received level, we measured peak-to-peak received level of calls from sonobuoy recordings and corrected them for sonobuoy and receiver sensitivities (Anonymous 1988), and estimated transmission loss from position information from crossed bearings. Transmission loss was calculated empirically by using least squares to estimate the slope of the best-fit line through the scatter of the logarithm to base 10 of calculated range to the source and measured received levels. The range to the source was calculated as the distance between the sonobuoy deployment locations and the location of the crossing of bearings from multiple sonobuoys. This empirical transmission loss was found to be $15*log_{10}(range[m])$. The source level of each call with measured bearing was calculated for each sonobuoy at which the call was recorded. We report

6

the average call SL and its standard error based on calculations, as well as the average difference in the SL calculated for individual calls from multiple sonobuoys.

To investigate if there is a diel pattern in Bryde's whale call production, we divided the call detections from HARPs into four light periods: dawn, day, dusk, and night. Following Wiggins et al. (2005), light periods were defined based on the timings of nautical and civilian sunrise and sunset. These values were downloaded from the U.S. Naval Observatory's Astronomical Application Department (http://aa.usno.navy.mil/) for 29º 3' N, 86º 6' W (DeSoto Canyon) for periods between October 2010 and July 2011. Since the duration of daily light periods varies over the course of a year, we divided the number of calls in each daily light period by the duration of the light period to get the hourly call rate (calls/h). In addition, to remove bias due to the variation in daily call rates through the deployment period, each day's mean call rate was subtracted from the daily call rate for each light period. We used only days when at least one call was detected for this analysis. Since the mean adjusted data failed the Lilliefors' composite goodness-of-fit test for normal distribution, a non-parametric analysis of variance (ANOVA) Kruskal-Wallis test was used to test the null hypothesis that the call rate is constant during each light period. A multiple comparison test was used to evaluate which light periods had significantly different call rates. All statistical tests were conducted using Matlab's statistics toolbox.

Three groups of Bryde's whales were encountered during the AMAPPS survey in the GOM, all on 31 July 2011, but calls of interest (Figure 2a) were recorded only during the encounter with the first group, sighted at 1430 GMT (Figure 3). Three DIFAR sonobuoys were deployed in an array during the sighting: 0, 11, and 42 min after the initial sighting. A small boat was deployed between the second and third sonobuoy deployment. During this encounter, four

Bryde's whales were observed diving, with no other identifiable behavior. At 1610 GMT visual observers noted a decrease in time between dives from 10 minutes to 4-5 minutes. The NOAA ship *Gordon Gunter* and the small boat stayed with the group until 1800 GMT for a total of 3.5 hours and visual observers noted 22 whale position updates during that time period, but there were no updates on sonobouy locations during the period with recorded calls.

One call type, consisting of pulse pairs, was identified as a likely Bryde's whale call based on the location of bearing crossings of the sound sources to the area of whale sightings (Figure 3) and its similarity to recordings of Bryde's whales in other regions. The recorded calls were frequency downswept pulse pairs (from 110 ± 4 to 78 ± 7 Hz), less than one second long $(0.4 \pm 0.1$ s) with an IPI 1.3 ± 0.1 s (Figure 2a). No other baleen whale-like calls were recorded during this time. Seven pulse pairs (14 pulses total) were recorded simultaneously on two sonobuoys. No calls were recorded after the deployment of the small boat, thus no calls were recorded on all three sonobuoys. Of the 14 individual pulses, 12 were localized successfully. The first 9 pulses (recorded between 1443 GMT and 1458 GMT) were localized to an area 1 km west-northwest of the first sonobuoy deployment location (Figure 3). The last three pulses (recorded between 1510 and 1514) were localized to an area northwest of sonobuoy deployment locations (Figure 3). The mean call SL was 155 ± 14 dB re: 1 µPa at 1 m, with an average 15 dB difference in the individual SL values calculated from each sonobuoy for each call. No other whale species were sighted on 31 July, although a group of 4 bottlenose dolphins (*Tursiops truncatus*) was sighted 27 minutes before the first Bryde's whale sighting. No other dolphins were sighted until five hours after the last Bryde's whale recording.

No potential baleen whale sounds were recorded during the second and third Bryde's whale sighting on 31 July. At 1841 GMT the antenna pre-amplification was lost, resulting in a

8

significantly decreased radio signal reception range and may explain the lack of recordings during those sightings.

Calls similar to the downswept pulse pair calls that were recorded during the first Bryde's whale sighting were frequently recorded in the long-term HARP recordings from DeSoto Canyon. These downswept pulses recorded on the HARP had a frequency range from 143 ± 3 to 85 ± 6 Hz, and each pulse was 0.7 ± 0.1 s long, with IPI 0.6 ± 0.2 s (Figure 2b). These pulses, however, came in sequences of varying lengths between 2 and 25 pulses, as well as, occasionally, only as a single pulse, and averaged eight pulses per sequence. The average duration of these pulse sequences was 9.1 ± 8.1 s. A total of 680 Bryde's whale calls were detected on 53 days of HARP recordings from DeSoto Canyon. To maintain the naming scheme first introduced by Oleson et al. (2003), we will refer to these as call type Be9.

Bryde's whales Be9 calls were found in the area of DeSoto Canyon consistently between March and July, as well as in October and January (Figure 4). A peak in calls occurred in late June, but there were also relatively high numbers of calls during late March and early April and in early January. No data were available for periods between mid-July and mid-October and late January to mid-March. The Be9 call rate was significantly higher during dusk and night periods than during dawn and day (Kruskal-Wallis ANOVA = 35.3, df = 3, P =0.000) at DeSoto Canyon (Figure 5). No Bryde's whale calls were recorded at the Dry Tortugas or the Main Pass location during our monitoring effort.

An additional, possible Bryde's whale call was detected in the long-term recordings from DeSoto Canyon in June. This call type also consisted of downsweeps, although they occurred at a higher frequency (approximately 170-110 Hz) and typically consisted of three segments (Figure 2c). They most frequently occurred in doublets, but single downsweeps and triplets were

9

also present, always in a repetitive sequence. This call type was detected 93 times, all during five days in late June, concurrent with the peak in Be9 call detections.

This is the first description of free-ranging Bryde's whale calls in the GOM. The localized sources of the calls during the AMAPPS survey were within a few hundred meters of the visual observations of Bryde's whales around the times of calling bouts. Considering no other whales were sighted around the same time and these pulses are not similar to sounds from the only other species sighted in the vicinity, bottlenose dolphin (Lilly & Miller 1961, Caldwell *et al.* 1990, Baron *et al.* 2008), we are confident these calls were produced by Bryde's whales. There are additional lines of evidence that support Bryde's whales as the source of these calls. First, a fine-scale temporal and spatial offset between visual observations and acoustic detections is frequently observed (Širović *et al.* 2006, Gedamke & Robinson 2010, Oleson *et al.* 2007*a*). Baleen whales generally call at depth and can stay submerged as long as 15 min (Oleson *et al.* 2007*b*, Parks *et al.* 2011, Croll *et al.* 2001), so the calling whale is not likely to surface at the same location where its calls were produced. Second, calls reported here exhibit characteristics similar to those of Bryde's whales from other regions (Oleson *et al.* 2003). Lastly, the combination of the call source levels, depths of the hydrophones at which the recordings were made, and their frequency characteristics, makes them unlikely to be attributable to a fish (Wysocki 2006). While they are not an exact match to the calls recorded from a captive juvenile from this area, both types exhibit pulsed characteristics, albeit in different frequency ranges, over variable duration (Edds *et al.* 1993). Their difference, however, may be explained by the fact that one was produced by a juvenile while the life stage of whales producing the other calls is unknown, although they may represent calls of adults. Alternatively, it could be due to the vastly different context under which the calls were recorded (captive versus free-ranging). However,

based on the concurrent visual observations, temporal and frequency characteristics of these calls, and the lack of other potential sources for this call, we are confident the Be9 calls reported here were produced by Bryde's whales.

The second call reported here as a possible Bryde's whale also has features that are common to baleen whale calls (low-frequency, short duration). In addition, its relative similarity in duration, bandwidth, and pulse patterns to the confirmed Bryde's whale call Be6 recorded in the ETP (Oleson *et al.* 2003), lead us to believe it may also be from a Bryde's whale. Even though it is somewhat higher frequency than the Be9 call, it is within the frequency and temporal range reported from other Bryde's whale populations (Oleson *et al.* 2003, Heimlich *et al.* 2005). Finally, its occurrence during the days when Be9 call was abundant in the data is also an indication that these calls may be an alternative call type produced by Bryde's whales in the GOM.

Relatively consistent presence of Be9 calls in our data from DeSoto Canyon during winter and spring is consistent with the hypothesis that this population is resident in the GOM (Waring *et al.* 2009) and possibly does not move over a large area. Lack of detections in October and November may be explained by its small population size (Mullin 2007); also we would not expect to detect the whales frequently given that the area we were monitoring was relatively small (assuming 10 km detection range as described below, that area is approximately 315 km^2). We should note, however, that passive acoustic data only allow us to detect presence of calling animals, so when no calls are detected it could mean the animals are simply not calling. We do not have long-term passive acoustic data at DeSoto Canyon between late July and mid-October, and the sighting from the AMAPPS cruise only extends Bryde's whale presence in this area to the end of July. Historical visual surveys were conducted only during spring (Waring *et al.*

11

2009), and we are not familiar with any other published information on Bryde's whales presence

in this area between August and mid-October. Since the timing of visual sightings and acoustic

recordings of Bryde's whales in southern Caribbean is concurrent with their detected presence in

the GOM (Oleson *et al.* 2003, Notarbartolo di Sciara 1983), and given the difference between the

calls in those two regions (Oleson *et al.* 2003), it is likely Bryde's whales in the GOM are a

separate, resident population, as exist in other regions (Tershy *et al.* 1990, Best 2001). In

addition, since Be9 calls were not recorded at the other two locations in the GOM, it is possible

this population is geographically limited to the northeastern corner of the GOM. Alternatively,

the population may be constrained to the continental shelf in eastern GOM and thus was not

recorded at the shelf slope location in Dry Tortugas. In any case, more spatial sampling is

required to verify if Bryde's whales are indeed geographically constrained in the GOM.

The size of this population has been estimated previously from visual surveys to be

between 15 and 40 animals (Hansen *et al.* 1995, Mullin & Fulling 2004, Mullin 2007). To

estimate its density from passive acoustic data, we need to know the rate at which calls are

produced (*r*) and the range over which we can detect the calls. We can then apply the density

estimator from Marques *et al.* (2009): $D = n * (1-c) / (a * p * T_K * r)$, where *n* is the total number

of calls detected on the HARP over the recording period T_K, *c* is the proportion of false positive

detections (set to zero in our case since all the detections were conducted manually and thus

verified), *p* is the probability of detecting a call given it is produced within the surveyed area $a =$

$\pi *$ (detection distance)^2, and assumed to be 1 in our calculation (we assume we detected all calls

within the determined detection radius). We can estimate the rate of call production from the

concurrent visual and acoustic encounter during AMAPPS. A total of four Bryde's whales were

sighted and seven calls were recorded during 3.5 hour long encounter, giving a call rate $r = 0.5$

calls/h. Because of compromised recording equipment during the second and third sighting, we did not include those encounters in the calculation of the call rate. Additionally, as there appeared to be a change in the behavior of the whales when the small boat was launched during the first encounter, this call rate may not be a good representative of the overall call rate of the population. Given the estimated source level (155 dB re: 1 μPa at 1 m) and our empirical transmission loss of $15* log_{10}(range)$, we assume these calls can be detected out to a distance of 10 km. Thus we obtain Bryde's whale density of 0.93 whales/1,000 km^2 at the DeSoto Canyon site. While it is not possible to estimate the error in our calculation since it is based on estimation of call rate from recordings from a single encounter and recordings at one instrument, if we assume Bryde's whales in the GOM are bound to the shelf areas (water depth <1,000 m) where they have been previously sighted with visual surveys (approximately 33,000 km^2), we would estimate 31 whales in this region, which is within the range of visual survey estimates over the past 20 years (Waring *et al.* 2009). However, more targeted recordings to obtain a more representative call rate and additional measurements of the call source levels as well as recording at multiple locations within the known range of Bryde's whales in the GOM would greatly improve our ability to produce more reliable estimates.

With this first record of confirmed calls from free-ranging Bryde's whales in the GOM, we have been able to learn about the persistence of Bryde's whales in this region of the Gulf. We presented evidence in support of the hypothesis that this population is isolated and few in numbers. More directed studies of the calling behavior of this Bryde's whale population, along with additional long-term recordings in this area, would provide an even better understanding of their presence in the area and would present an opportunity for more accurate population abundance estimation in the future.

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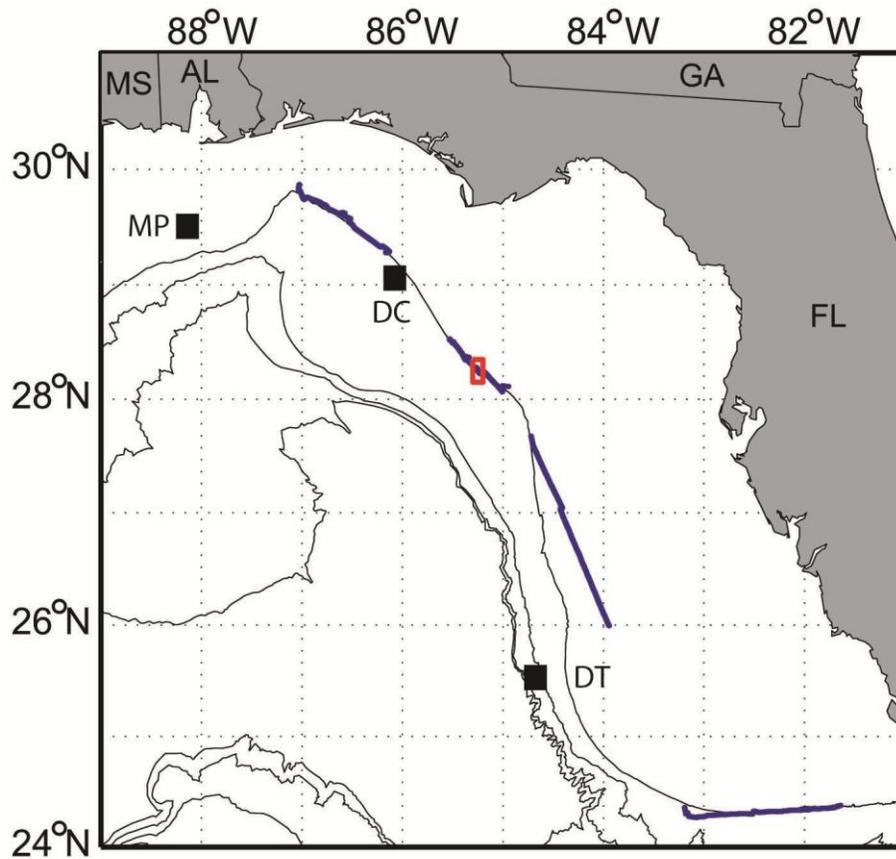
Figure 1. Area of the Gulf of Mexico surveyed from 28 July until 1 August 2011 during AMAPPS cruise (visual survey effort is shown in thick, blue solid lines), with HARP deployment locations at Main Pass (MP), DeSoto Canyon (DC), and Dry Tortugas (DT) marked with black squares. Bathymetry contours shown at 200m, 1000m, 2000m, and 3000m. Red rectangle is the approximate area of Bryde's whale sightings and recordings on 31 July 2011 expanded in Figure 3.
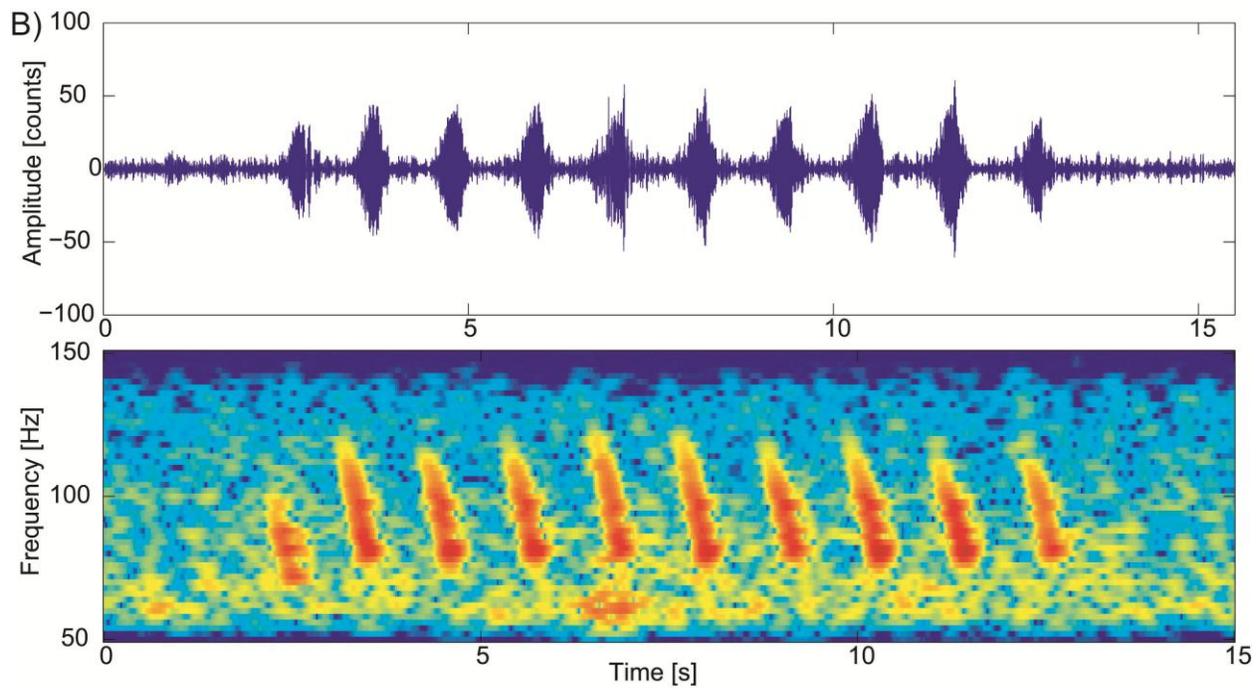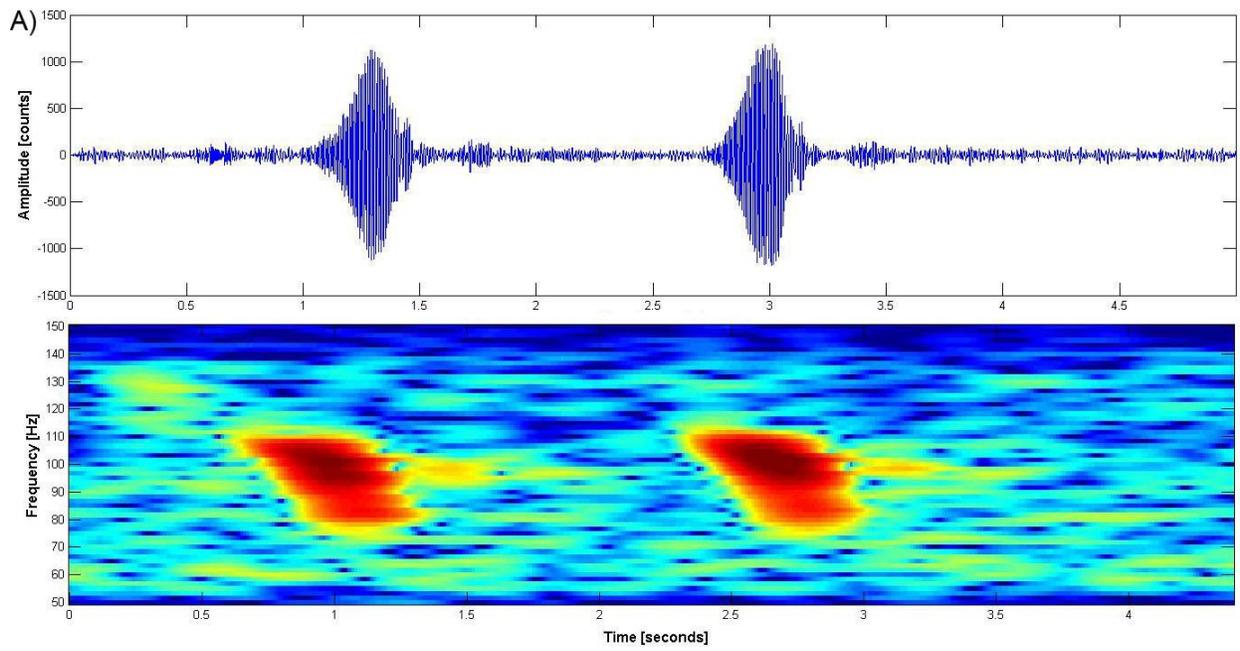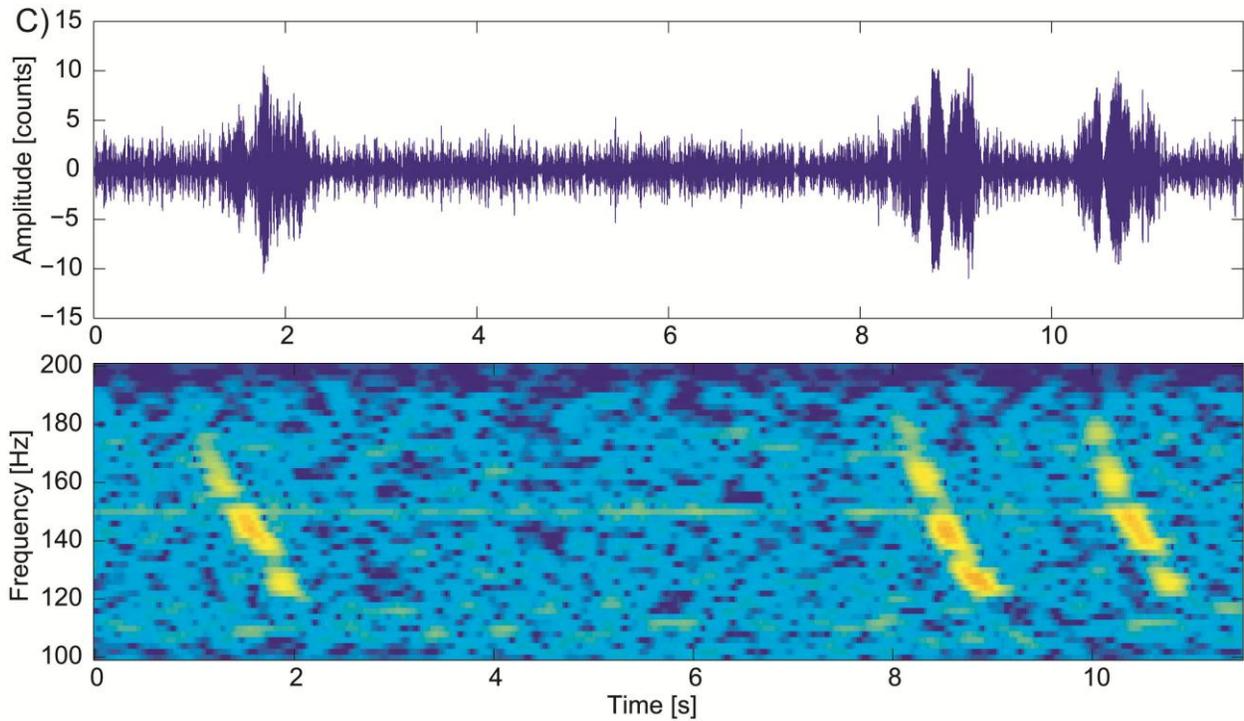
Figure 2. Time series and spectrograms of Bryde's whale calls. A) Be9 pulses recorded with a sonobouy on 31 July 2011 (600-point FFT, 98% overlap, Hanning window, band-pass filter 60-130 Hz), (B) Be9 call sequence recorded on the HARP at DeSoto Canyon on 8 June 2011 (1,000-point FFT, 95% overlap, Hanning window, band-pass filter 60-130 Hz), and C) possible Bryde's whale calls recorded on the HARP at DeSoto Canyon on 24 June 2011 (1,000-point FFT, 95% overlap, Hanning window, band-pass filter 110-180 Hz).
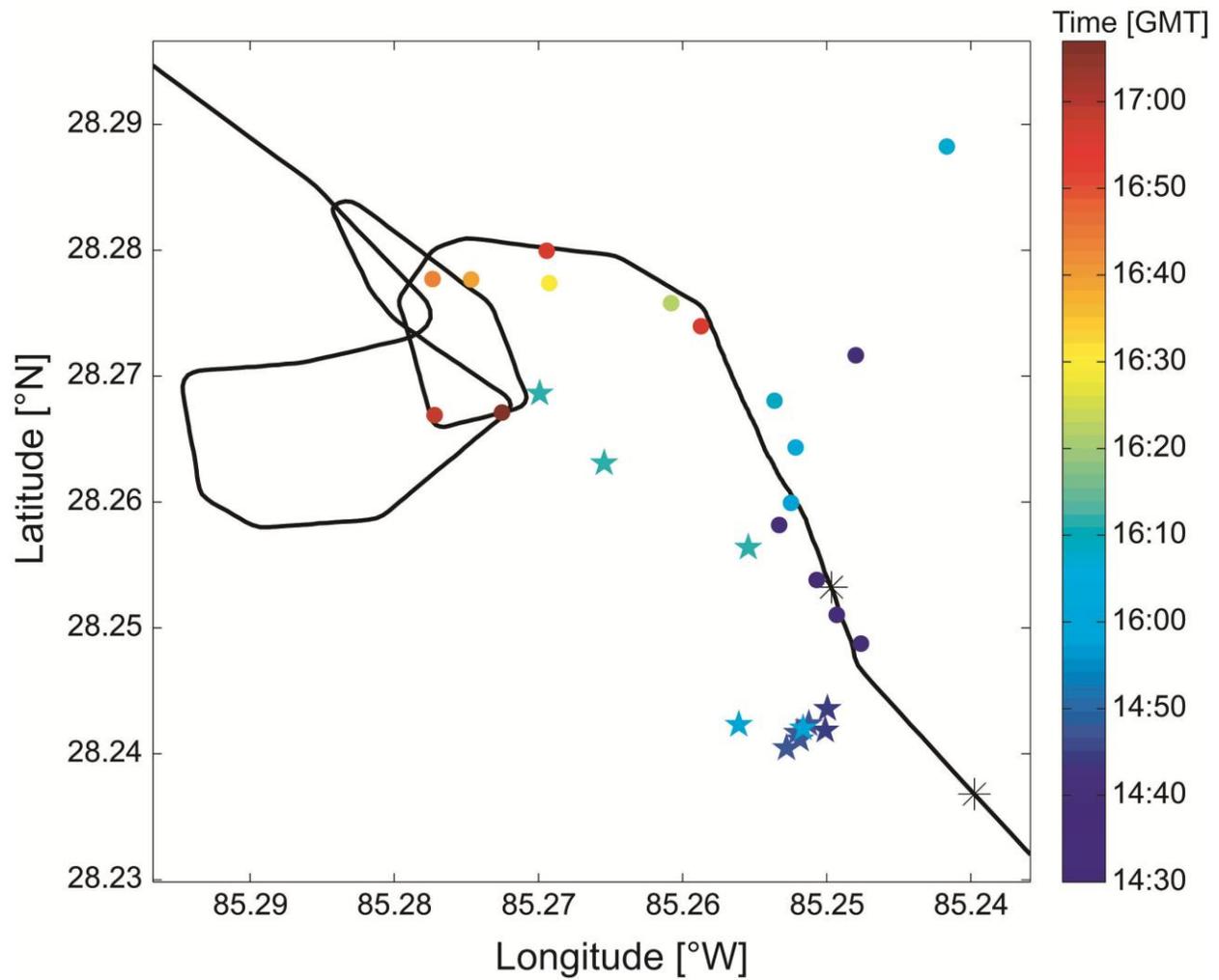
Figure 3. Locations of Bryde's whale calls (stars) and visually observed whale position updates (circles) from the first 97 minutes of the first sighting on 31 July 2011, with time of the event (in GMT) denoted by color. Ship trackline from this section of AMAPPS is shown as a black line and sonobuoy deployment locations used for localizations are black asterisks.
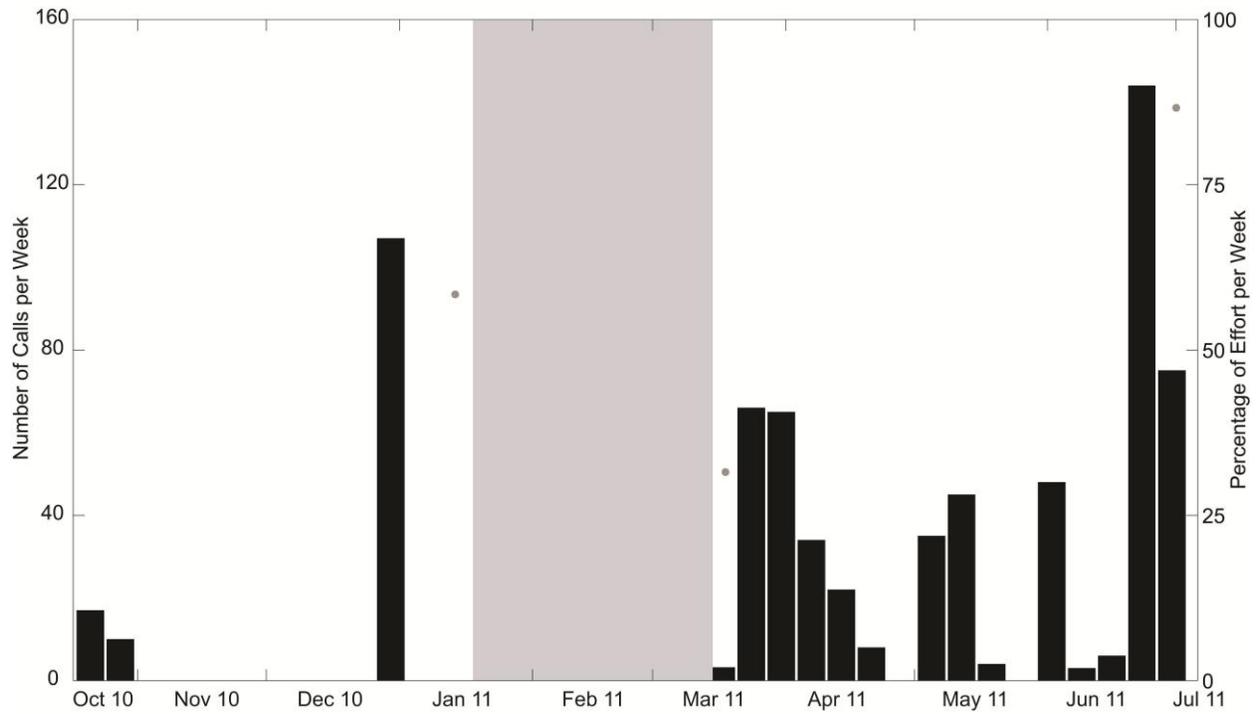
Figure 4. Weekly number of Bryde's whale Be9 calls (black bars) recorded at DeSoto Canyon

between 21 October 2010 and 6 July 2011. Gray shaded area is a period during which there was

no recording effort and gray dots represent times when there was less than 100% recording effort

during the week (right vertical axis).
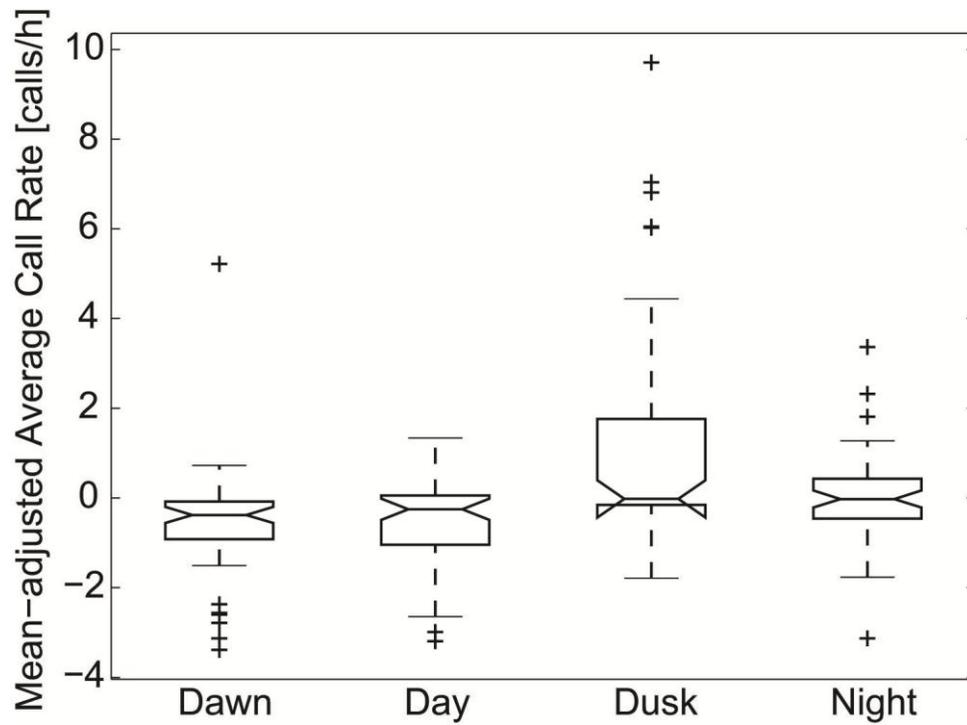
Figure 5. Box-and-whisker plot of mean-adjusted average call rate for Bryde's whale Be9 calls recorded at DeSoto Canyon during four light periods. Whiskers represent the lowest and the highest datum still within 1.5 interquartile range of the lower and the upper quartile, respectively, and plus symbols are outliers.