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Listening in the Ocean

New Discoveries and Insights on Marine Life from Autonomous Passive Acoustic Recorders

Modern Acoustics and Signal Processing

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Chapter 3
Long-Term Monitoring of Cetaceans Using Autonomous Acoustic Recording Packages

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Abstract Autonomous acoustic recorders have advanced our understanding of cetaceans, providing information for better models of species distribution, behavior, ecology, and conservation. For over a decade, Acoustic Recording Packages (ARPs), and its broader-bandwidth successor, High-frequency Acoustic Recording Package (HARP), have been used for Passive Acoustic Monitoring (PAM) providing high-fidelity, long-term acoustic data sets for cetacean studies. Some of these studies are summarized below showing a wide range of applications and results including species signal characterization, seasonal and daily presence patterns, geographic and habitat use, population density and abundance estimations, acoustic stimuli behavioral response, and swimming behavior via array tracking. Species studied include low-frequency baleen whales and high-frequency dolphins and beaked whales.

3.1 Introduction

There are various approaches for passive acoustic monitoring (PAM) of cetacean and other oceanic sounds. One technique uses hydrophones cabled to land-based recording stations. In an early example of recording cetaceans, Thompson (1965) employed a cabled hydrophone array off San Clemente Island, California to record blue (*Balaenoptera musculus*) and fin (*Balaenoptera physalus*) whale sounds on magnetic tape for 8 days. Thompson and Friedl (1982) used hydrophones cabled north of Oahu, Hawaii to study 6 species of cetaceans for about 2 years showing seasonal and migratory patterns. Cabled hydrophones have the advantage of monitoring in real-time, but they also have high installation and operational costs. Portable hydrophone arrays towed or dangled from ships (Thomas and Evans 1982; Barlow and Taylor 2005) are a similar technique that have relatively low hardware costs, but typically only provide short duration recordings because ship and personnel operational costs are high.

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Autonomous acoustic recorders are another PAM tool used to monitor cetacean sounds and are often deployed in remote locations for long periods. They consist of a hydrophone and digital recording device, are battery-powered, and are packaged to withstand the ocean environment, but must be recovered from the ocean to retrieve the data for analysis. These recorders come in many different configurations depending on scientific goals and environmental conditions. For example, instrument design and costs are affected by whether the deployment location is shallow (<100 m) or deep (>1000 m), recording duration is short (1 week) or long (1 year), and focal species is baleen (low sample rate) or odontocete (high sample rate).

Two recording devices that were specifically designed for long-term (months to year) acoustic data acquisition are the Acoustic Recording Package (ARP) (Wiggins 2003) and the High-frequency Acoustic Recording Package (HARP) (Wiggins and Hildebrand 2007). HARPs are essentially enhanced ARPs that record at higher bandwidth and therefore detect a wider range of species. ARPs have been used worldwide since 2000 to study marine mammal sounds offshore of Alaska, California, Hawaii and Antarctica in shallow (<100 m) to deep (>3000 m) water and over long periods (years). From 2000 to 2006, there were 113 ARP deployments resulting in over 38 instrument-years of low-frequency (10–500 Hz) ocean sound recordings (Table 3.1). The maximum sample rate for ARPs was 1 kSamples s^{-1} (kHz), limiting the recorded animals to mysticetes and some pinnipeds. Beginning in 2004, the HARP data logger was developed to record both mysticetes and odontocetes while maintaining the long-term capabilities of ARPs. To record odontocetes, faster sampling (200 kSamples s^{-1}) was employed, which led to the need for increased data storage capacities and the need for lower power electronics to obtain long duration recordings. Since 2006, HARPs have been recording underwater

Table 3.1 ARP and HARP number of deployments, data duration, and data quantity from 13 years of long-duration recordings

	Deployments		Recording Duration (days)		Quantity (bytes × 10^9)	
Year	ARP	HARP	ARP	HARP	ARP	HARP
2000	23		1580		211	
2001	27		3942		441	
2002	26		3669		413	
2003	21		2454		363	
2004	11	9	835	550	119	6117
2005	3	18	863	960	75	20,918
2006	2	23	752	1167	65	26,780
2007		46		2066		61,277
2008		62		2711		86,987
2009		91		4170		125,847
2010		80		5215		167,817
2011		52		5320		184,019
2012		51		6138		230,906
Total	113	432	14,095	28,297	1686	910,668

sounds with high-fidelity from 10 Hz up to 100 kHz, initially with 2 months of continuous data storage (Table 3.1). Development of HARP capabilities continues to advance, for example, in 2010 loss-less data compression was employed with larger data storage devices, boosting recording durations by a factor of five to achieve 10 month continuous recording with 100 kHz bandwidth. As of 2012, HARPs have amassed close to one petabyte (1×10^{15} bytes) of acoustic data, with each year incurring more data than the previous year (Table 3.1).

Processing and analyzing large, long-term acoustic data sets can be challenging. Typical spectrogram evaluation for wideband (100 kHz) data can be conducted by an analyst only near real-time because of human and computational limitations, prohibiting the detailed analysis of long-term data sets. Automated detectors have been useful in finding cetacean sounds in large data sets, but require extensive training to provide good performance and typically only detect sounds with known characteristics, missing new or uncharacterized sounds. As an efficient alternative, Long-Term Spectral Averages (LTSAs) provide an overview of a large data set, along with providing a means to search for and evaluate events of interest such as cetacean calling bouts (Wiggins and Hildebrand 2007). LTSAs are essentially spectrograms with each time slice representing many (1000s) spectra averaged together, allowing multiple hours or days of wideband acoustic data to be displayed on a single page or viewing screen. *Triton* (www.cetus.ucsd.edu) is a software package developed in MATLAB (www.mathworks.com) to analyze ARP and HARP data including calculating and displaying LTSAs, but also works with standard wav audio files. In addition to providing a long-term view of acoustic data, LTSAs provide a means of quickly accessing the original acoustic data for more detailed analysis via cursor selecting events from the LTSA spectrogram. Automated detectors can also be used on LTSAs files, for example, to identify start and end times of calling bouts, which then can be used to define periods upon which to execute fine scale automated detectors for individual calls, reducing overall processing time on large data sets.

Calibrated hydrophones and recording electronics are required to determine accurate received sound pressure levels. Received levels allow estimation of source levels for calling animals when their call detection ranges are known. Understanding detection ranges also can provide insights into animal communication ranges, animal foraging and navigation capabilities, and population density estimations using distance sampling techniques (e.g., Buckland et al. 2001; Marques et al. 2009). All ARP and HARP hydrophone sensors are laboratory-calibrated before deployment and at the end of service life, and representative hydrophones are routinely calibrated at the US Navy's transducer evaluation center, TRANSDEC, in San Diego, California. Calibrated hydrophones also allow for studies on ambient noise and how anthropogenic sources such as ships or airguns may mask whale calls (McDonald et al. 2006a, 2008; McKenna et al. 2009, 2012a, b, 2013; Roth et al. 2012, 2013; Širović et al. 2013a).

What follows is a summary of cetacean-related results from long-term autonomous acoustic recordings using ARPs and HARPs, including studies on temporal and spatial distribution patterns, species call characteristics, and passive acoustic tracking. Focal species include blue and fin whales in the Southern California Bight and around Antarctica, North Pacific right whales (*Eubalaena japonica*) in the Bering Sea, Byrde's whales (*Balaenoptera edeni*) offshore of southern California and in the Gulf of Mexico, dolphins offshore of southern California, and beaked whales throughout the North and Central Pacific.

3.2 Blue and Fin Whales

Blue and fin whales have been recorded worldwide, documenting nine different blue whale regional call types (McDonald et al. 2006b). Some blue and fin whale calls have been characterized as song; these are stereotyped, low-frequency (~10–100 Hz), high-intensity (>180 dB re 1 μPa at 1 m) sounds that are produced in a repetitive pattern. These characteristics make their calls well suited for long range reception and allow for relatively straight-forward detection and classification.

From 2000 to 2004, five ARPs recorded baleen whale calls offshore of southern California at Tanner and Cortez Banks around 200 m water depth. The focal population for this study was Northeast Pacific blue whales, which migrate annually between North American summer feeding grounds and Central American breeding grounds. Offshore of southern California these whales produce three primary call types designated as: A, B, and D. Types A and B are often produced in a repetitive song sequence, are made only by males, and have been associated with reproductive behavior, whereas type D calls are made by both genders during intervals between foraging at depth (McDonald et al. 2001; Oleson et al. 2007a). By monitoring these calls types over 4 years, a temporal separation between type B and D calls was observed both seasonally and daily (Fig. 3.1) (Oleson et al. 2007b). It was found that type D calls occur earlier in a given season than type B calls, and D calls are produced primarily during daylight hours, correlated with feeding behavior on aggregated prey at depth. In contrast, type B song calling was greater during nighttime with peaks during twilight periods, just after sunset and before sunrise, which correlate with the vertical migration of the prey, when they may be less aggregated and foraging is less efficient (Fig. 3.2) (Wiggins et al. 2005).

In a more recent study using a HARP offshore of southern California near a naval test range, it was found that blue whales were less likely to produce D calls when military tactical mid-frequency active sonar was present and that the response was more pronounced when the sonar source was closer (i.e., higher sound levels) to the animals (Melcón et al. 2012). This shows that anthropogenic noise, even at frequencies well above the blue whales' sound production range (Fig. 3.3), can change their vocal behavior; however, the long-term consequences this disruption to blue whale foraging is currently not well understood.

In the Southern Ocean, three long-term ARP studies were conducted to monitor blue and fin whales: from 2001 to 2003 at seven sites off the Western Antarctic Peninsula (WAP), at four circumpolar Antarctic locations during 2003 and 2004, and at two locations off eastern Antarctica for 2005–2007 (Fig. 3.4). These recordings

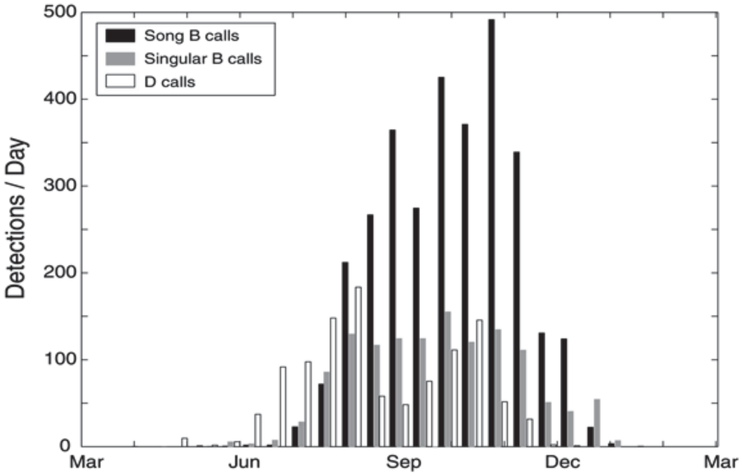


Fig. 3.1 Seasonal calling rates for blue B and D calls at Tanner and Cortez Banks, offshore of southern California. Detections are grouped into 2-week bins and averaged over 4 years. Foraging-related D calls (*white bars*) peak earlier in the season than song B calls (*black bars*) or singular B calls (*gray bars*) (from Oleson et al. (2007b); Fig. 3.4)

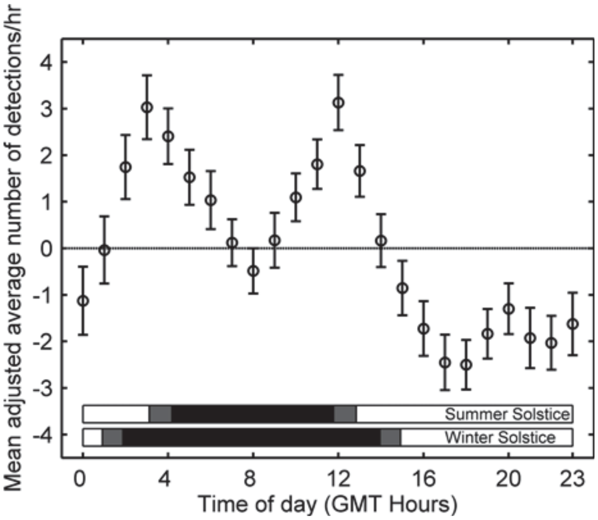


Fig. 3.2 Daily calling rates for blue B calls at Tanner and Cortez Banks, offshore of southern California. Detections are mean adjusted for each day. *Bottom horizontal bars* show day (*white*), dawn and dusk twilight (*gray*), and night (*black*) periods. Peaks occur just after sunset and before sunrise, correlated with the vertical migration times of krill, blue whale's primary food source (from Wiggins et al. (2005); Fig. 3.5)

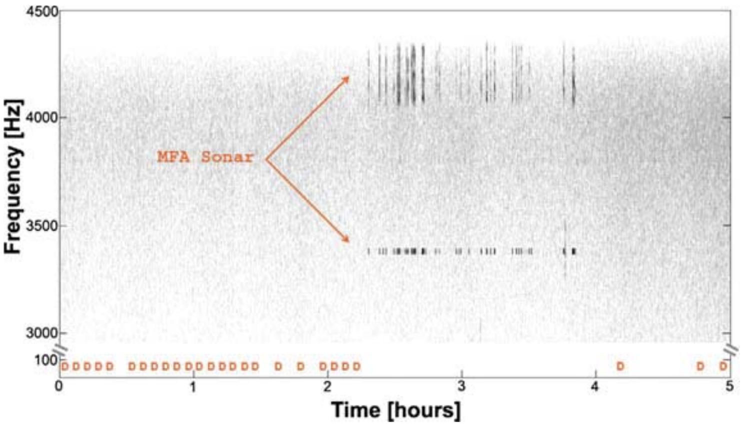


Fig. 3.3 Temporal sequence of Navy tactical mid-frequency active (MFA) sonar and blue whale D calls. Each orange "D" represents the presence of D calls in a 5-min bin. Note D calls do not occur during period of MFA sonar although they occupy different frequency bands (from Melcón et al. (2012); Fig. 3.1)

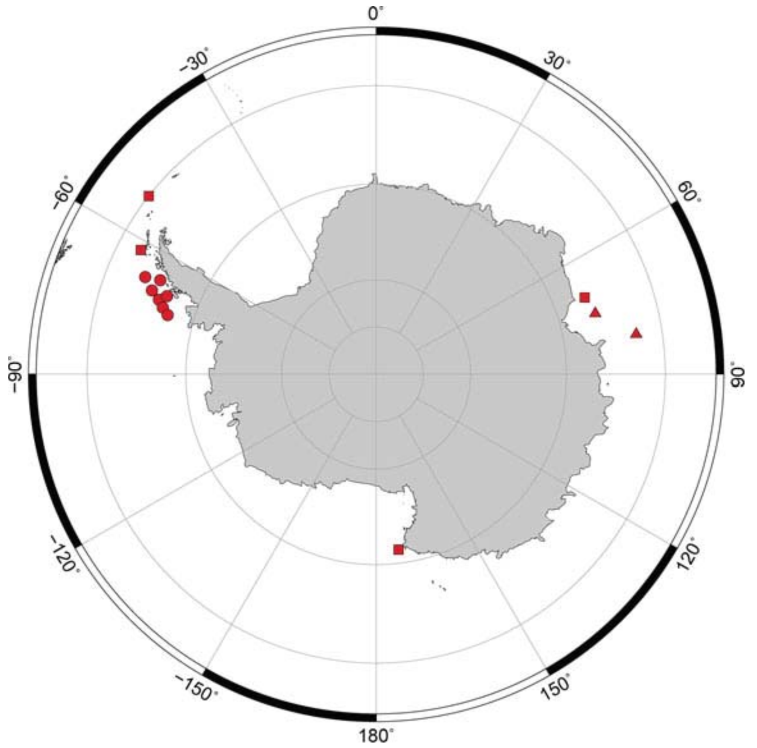


Fig. 3.4 Antarctic ARP deployment locations (*red symbols*) for blue and fin whale call studies. Red circles: ARPs deployed 2001–2003 near the West Antarctic Peninsula (WAP) with two on the shelf and six in deep water (>3000 m) (Širović et al. 2004). *Red squares*: ARPs deployed 2003–2004 around Antarctica at four sites: WAP, Scotia Sea (SS), Ross Sea (RS) and Eastern Antarctic (EA) (Širović et al. 2009). *Red triangles*: two ARPs deployed in eastern Antarctica from 2005 to 2007 (Gedamke et al. 2007)

of blue whales near Antarctica show different patterns than those observed off southern California. Blue whales were detected year round at both the WAP study area and at the four circumpolar locations with peaks in March–May and November suggesting asynchronous migrations of subgroups between feeding and breeding grounds (Širović et al. 2004, 2009). Similar results showing year around blue whale presence and a peak calling in fall were observed using from the 2005–2007 recordings off eastern Antarctica (Gedamke et al. 2007). Daily patterns in blue whale calling were not observed, presumably because light does not affect krill concentrations in the same way as at lower latitudes.

As with blue whales, fin whales have a different acoustic presence near Antarctica than offshore of southern California. ARP multiyear acoustic records offshore of southern California show fin whales call year round, whereas around Antarctica their calling is seasonal between February and June–July for the three study sites (WAP, circumpolar, eastern) from 2001 to 2007 (Širović et al. 2004, 2009; Gedamke et al. 2007). Also, as with blue whales which have different regional call types, fin whales calls from WAP are different than those from eastern Antarctica and different than those offshore of southern California. All three types have a call component that sweeps down in frequency from around 30 to 15 Hz over 1 s, but the WAP type has another component around 89 Hz, the eastern type has a component around 99 Hz, and the southern California type lacks the higher frequency component (Gedamke et al. 2007; Širović et al. 2009).

During the WAP study, ARPs were positioned approximately 100 km apart along the 3000 m depth contour and were intended to be independent monitoring sites. However, because blue and fin whales produce high-intensity calls and propagation conditions are favorable at high latitudes for low-frequency sounds, some calls were received on multiple instruments allowing them to be localized and source levels to be estimated. Blue whale calls were located up to a range of 200 km using time-difference of arrival analysis, and fin whale call ranges were estimated up to 56 km using multipath arrival techniques (Širović et al. 2007). Both average blue and fin whale source levels were 189 dB re: 1 μPa at 1 m with blue calls spanning 25–29 Hz and fin whale calls over 15–28 Hz. These source levels and detection ranges have the potential to be used to estimate population densities from distance sampling techniques and knowledge of calling rates.

In the eastern North Pacific, two, low-frequency downswept fin whale calls are present: 20 and 40 Hz calls. Using HARP recordings from over 5 years in the Bering Sea, offshore of southern California and in the Gulf of California, it was found at all three sites that fin whale 40 Hz calls peaked 3–5 months before 20 Hz calls (Fig 3.5). This temporal offset suggests both call types need to be monitored to provide a more complete description of their seasonal presence, and that the temporal separation may show that these two call types serve different purposes such as foraging (40Hz) and other social interactions (20Hz) (Širović et al. 2013b).

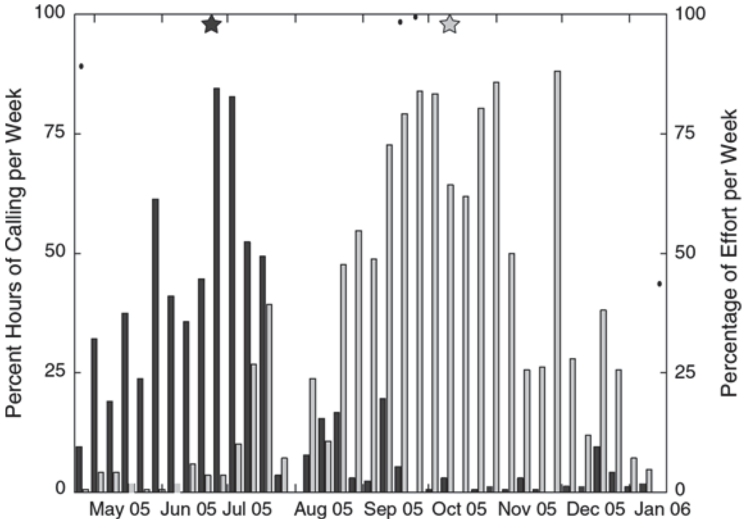


Fig. 3.5 Percent of hours per week with fin whale 20-Hz (*light gray*) and 40-Hz (*dark gray*) calls recorded in the Bering Sea. *Black dots* and *right axes* show percentage of recording effort when less than 100 %, and stars at *top* show mean day of calling presence for both call types (from Širović et al. (2013b); Fig. 3a)

3.3 North Pacific Right Whales

Eastern North Pacific right whale populations were heavily depleted during the commercial whaling era of the nineteenth and twentieth centuries; they are now the world's most endangered large whale species. Population estimates are uncertain, but totals are less than a hundred individuals (Wade et al. 2011). Based on visual sightings of right whales during the summer months in the southeastern Bering Sea (SEBS), ARPs and HARPs were deployed on the Bering Sea shelf and at the shelf break in various configurations from 2000 to 2006.

Right whale calls travel long distances on the Bering Sea shelf because of favorable propagation conditions provided by a uniform shallow water waveguide (Wiggins et al. 2004). Detections ranges of approximately 200 km have been observed, allowing autonomous acoustic recorders to monitor large regions for this sparsely populated species (Munger 2007). Even with large detection ranges, long duration records show calling bouts of a few hundred calls per day, that are often separated by days to months of no calling (Fig. 3.6). These data suggest that right whales may use the SEBS middle shelf intermittently and may be transiting through on their way to other areas (Munger et al. 2008).

Right whales have been associated with several different low-frequency sounds. In the Bering Sea, upsweeping frequency modulated calls from about 90 to 170 Hz over approximately 0.7 s are the most common type. Right whales upswept calling bouts were observed as early as May and as late as December, seasonally much earlier and later than anticipated based on visual encounters. July to October showed

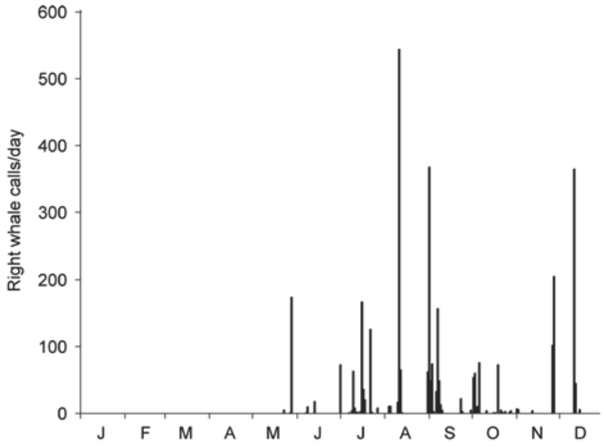


Fig. 3.6 Seasonal calling rates for Northeastern Pacific right whales from 2000 to 2005 on the Bering Sea middle-shelf (depths < 100 m). Upswept calling bouts were observed seasonally much earlier and later than previous visual encounters (from Munger et al. (2008); Fig. 4a)

more days per month of calling (≥6 days/month) than earlier or later (≤3 days/month). Hourly calling rates were significantly higher during nighttime than during day light hours, and most calls were clustered in temporal bouts with intercall intervals between approximately 10 and 500 s (Munger et al. 2008).

The SEBS ARPs were placed as independent sites, but the same calls were recorded on multiple instruments allowing them to be localized. These locations were coupled with detection range estimates from shallow water waveguide modeling to estimate call source levels. Right whale call source levels were approximately 177 dB re 1 µPa at 1 m, acoustic transmission loss was roughly $15 \times \log_{10}$ (range), and ambient noise levels were around 70–90 dB re 1 μPa^2/Hz over the right whale calling band 90–170 Hz (Munger et al. 2011). These parameters along with detection range estimates and calling rates were used for estimating right whale population densities from autonomous acoustic recorders in the SEBS using the distance sampling technique, acoustic cue counting (Marques et al. 2011). A point estimate of 25 animals (CV 29 %; 95 % confidence interval 13–47) agrees well with estimates by others using photographic and genetic data with mark–recapture techniques (Wade et al. 2011).

3.4 Bryde's Whales

Bryde's whales are typically found in tropic and subtropic regions and unlike other mysticetes do not appear to migrate. They produce a variety of low-frequency (65–950 Hz) moans, tones, and pulses which potentially delineate different stocks (Oleson et al. 2003). A small population of ~15 Bryde's whales, the only known group of baleen whales in the Gulf of Mexico, was recorded with a HARP during an

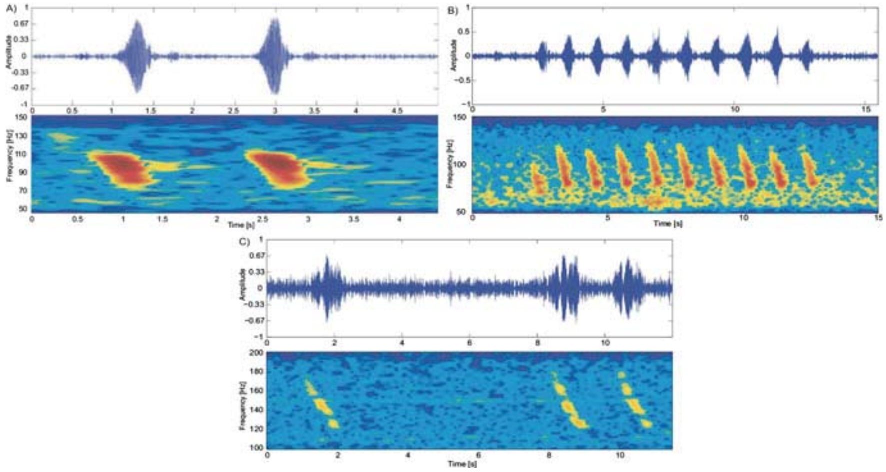


Fig. 3.7 Time series and spectrograms of Bryde's whale calls in the Gulf of Mexico. (**a**) Be9 pulses from sonobuoy recording, (**b**) Be9 pulse sequence recorded on HARP, and (**c**) possible Bryde's whale calls recorded on HARP (from Širović et al. (2013a); Fig. 2)

ongoing experiment to monitor the effects on marine mammals of the Deepwater Horizon oil spill (Širović et al. 2013a). DeSoto Canyon, in the northeast Gulf at about 260 m depth, was the only site of three evaluated to have Bryde's whale calls recorded; the other two sites were about 200 km west and 400 km south. Be9 calls (Fig. 3.7), ~140–80 Hz downswept pulses often in sequences as first described by Oleson et al. (2003) were detected from March to January with a peak in June and an absence in calling in November and December; no recordings were available from late January to mid-March. Significantly more calls were detected at dusk and night than during dawn and daylight hours.

While Bryde's whales are typically found in low latitudes, we have been recording their calls in the temperate waters offshore of southern California using ARPs and HARPs since 2000 (Kerosky et al. 2012). In this study, the calls were observed from summer to early winter and calling presence was found to significantly increase over the study period from 2000 to 2010, but calling was not found to correlate with local sea surface temperature. This seasonal pole-ward range expansion in the Pacific is likely caused by prey availability within the California Current ecosystem, which may be a result of climate change and oceanographic conditions.

3.5 Dolphins

A diverse group of odontocetes are found in the waters offshore of southern California including: sperm whales, beaked whales, porpoises, and dolphins, all of which produce echolocation clicks. The ability to differentiate between click types can provide insights into the foraging and migratory behaviors of these animals from autonomous recordings. Fortunately, some clicks are distinguishable based on their spectral and temporal characteristics allowing for click classification, such as sperm whales. On the other hand, species-level classification of echolocation clicks is still a topic of active research (Roch et al. 2011).

Commonly observed species of dolphins found in the waters offshore of southern California include: short-beaked common (*Delphinius delphis*), long-beaked common (*D. capensis*), bottlenose (*Tursiops truncates*), Pacific white-sided (*Lagenorhynchus obliquidens*), and Risso's (*Grampus griseus*) dolphin. Soldevilla et al. (2008) compared the spectral and temporal properties of echolocation clicks from ship-based single species recordings and found unique spectral peak and notch patterns for Pacific white-sided and Risso's dolphins, allowing species classification in autonomous recordings. Furthermore, two distinct subsets of click types were observed for Pacific white-sided dolphin (designated as types A and B), suggesting two geographically distinct populations of this species occur within the Southern California Bight with differing foraging strategies (Henderson et al. 2011).

As part of a long-term, broadband monitoring effort in the Southern California Bight, acoustic recordings were made at six sites with HARPs sampling at 200 kHz from 2005 to 2007. In these recordings, Risso's dolphin echolocation click bouts were identified based on their unique spectral structure (Fig. 3.8) and evaluated for diel, seasonal, and geographical patterns (Soldevilla et al. 2010a). Out of a cumulative total of 1959 recording days for all sites, Risso's click bouts were observed on 739 days with the majority of bouts occurring inshore and peak occurrence at the southern end of Santa Catalina Island (Fig. 3.9). At the inshore sites, clicks were observed year-round with high seasonal and interannual variability, but typically

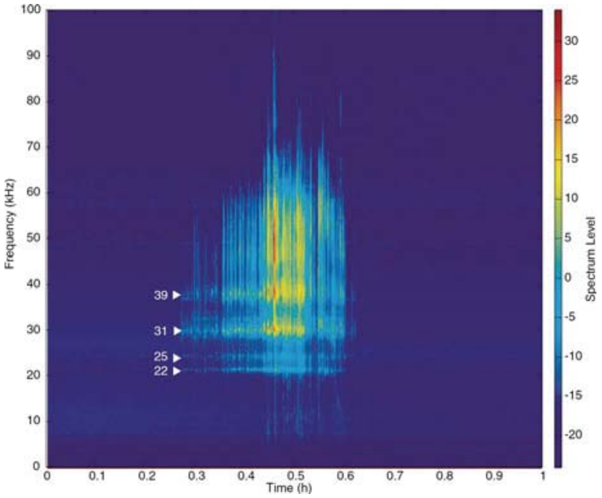


Fig. 3.8 Long-Term Spectral Average (LTSA) of Risso's dolphin echolocation clicks offshore of southern California. Spectral peaks (*horizontal bands*) are at approximately 22, 25, 31 and 39 kHz (from Soldevilla et al. (2010a); Fig. 3)

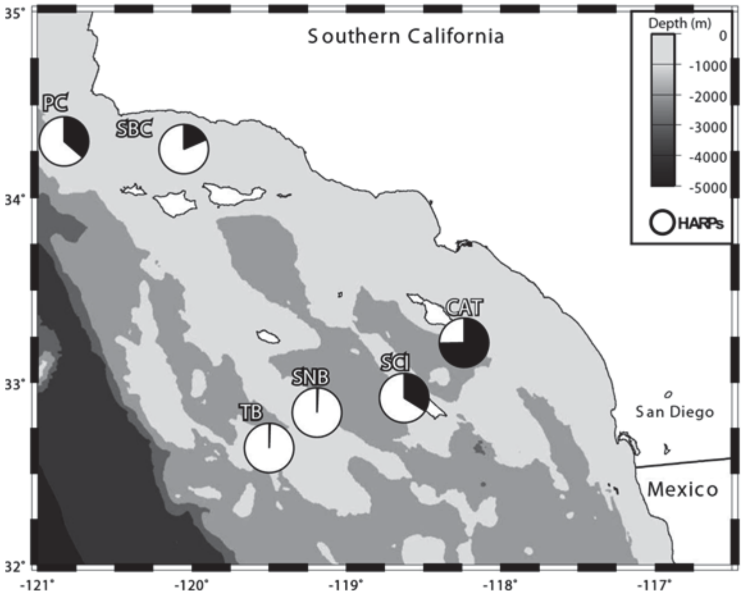


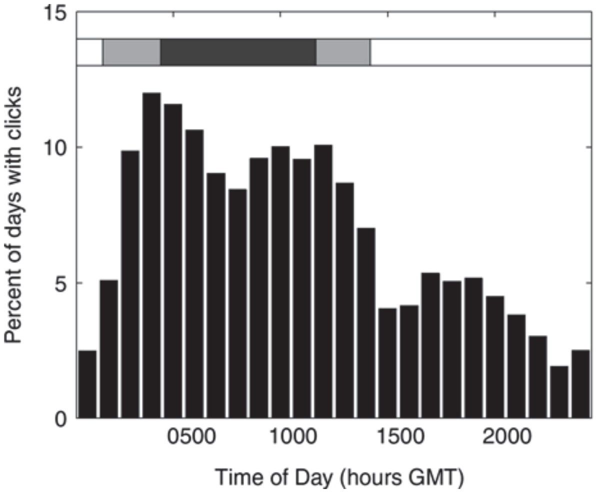
Fig. 3.9 Geographical occurrence of Risso's dolphin in the southern California Bight from 2005 to 2007. Six HARP locations are shown as pie charts with black sections representing percentage of recording days with Risso's dolphin click bouts. Island and near shore sites had Risso's dolphin clicks most often (from Soldevilla et al. (2010a); Fig. 1)

with peak occurrence in the autumn. Click rates and the hourly occurrence of click bouts were both observed to be significantly higher at night than during the day, suggesting increased foraging activity on diel-vertically migrating prey (Fig. 3.10).

Using the same HARP recordings as for the Risso's dolphin study, Pacific white-sided dolphin clicks were identified and their temporal and spatial occurrence offshore of southern California was investigated (Soldevilla et al. 2010b). Both Pacific white-sided type A and type B click bouts were identified (Fig. 3.11). Type A clicks were observed on 317 of the 1959 recording days at all six sites, whereas type B clicks were identified on 130 recording days at only the two southern inshore sites, supporting the hypothesis that there are two separate populations of Pacific white-sided dolphins and that these click types are population-specific (Fig. 3.12). Seasonal patterns show both types peak in fall-winter at the southern sites and peak in spring for type A at the northern offshore site. Inversely related diel patterns were observed for the two click types with type A click bouts and click rates higher at night, and type B with higher click activity during daylight hours, suggesting specialization on different prey by the two populations (Fig. 3.13).

Environmental variables can be combined with cetacean acoustic occurrences to create predictive models for whale and dolphin distributions. Time-lagged predictor variables and hourly occurrence of click types for Risso's and Pacific white-sided dolphins from the 2005–2007 southern California HARP recordings were investigated using generalized additive models (Soldevilla et al. 2011). Various oceanographic

Fig. 3.10 Diel patterns of Risso's dolphin echolocation click bouts for the six sites shown in Fig. 3.9. In the *horizontal bar*, daylight, twilight, and nighttime are represented by *white*, *gray*, and *black*, respectively. Peak clicking occurs during twilight and night (from Soldevilla et al. (2010a); Fig. 4)



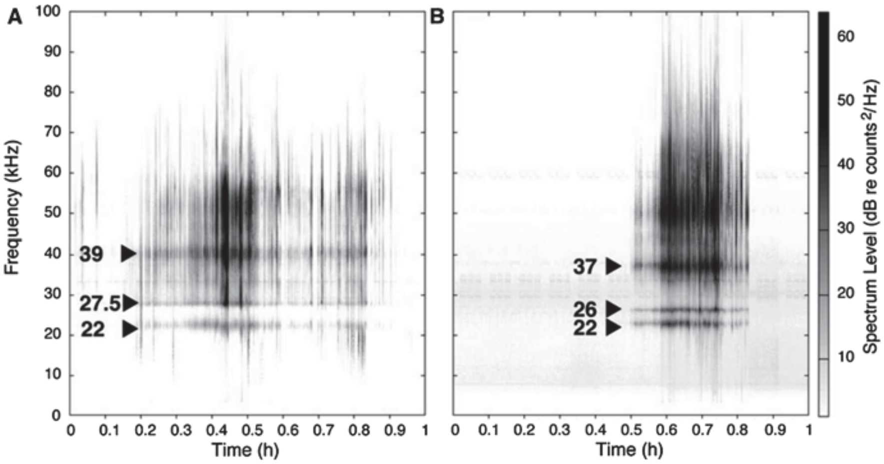


Fig. 3.11 LTSAs of Pacific white-sided dolphin echolocation clicks offshore of southern California. (**a**) Type A and (**b**) type B clicks with different spectral bands may be from different populations (from Soldevilla et al. (2010b); Fig. 3)

variables were evaluated including sea surface temperature (SST), SST coefficient of variation (CV), solar and lunar temporal indices, sea surface chlorophyll concentration (Chl), Chl CV, and upwelling indices. For all click types, SST and SST CV were consistently selected as important variables (i.e., 80–100 % of models) with the addition of solar indices selected for Pacific white-sided types A and B (100 % of models). The best model for Pacific white-sided type B clicks included concurrent environmental data, suggesting oceanographic fronts or convergence zones aggregate prey

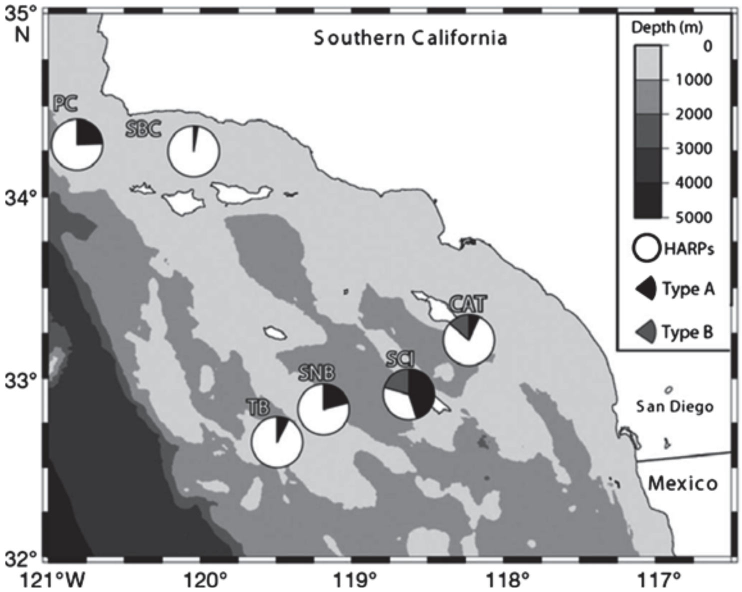


Fig. 3.12 Geographical occurrence of Pacific white-sided dolphin type A and B echolocation clicks in the southern California Bight from 2005 to 2007. Six HARP locations are shown as *pie charts* with *shaded sections* representing percentage of recording days with type A (*black*) and type B (*gray*). Type A clicks were recorded at each site, but type B occurred only at the southern sites near islands (from Soldevilla et al. (2010b); Fig. 1)

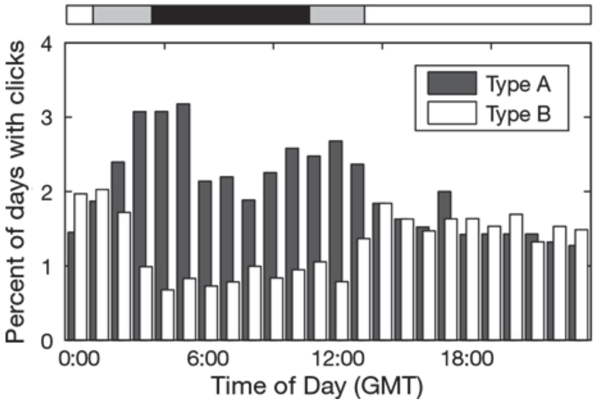


Fig. 3.13 Diel patterns of Pacific white-sided dolphin types A and B echolocation click bouts for the six sites from Fig. 3.12. The *horizontal bar* shows periods of daylight (*white*), twilight (*gray*), and night (*black*). During twilight and night, type A clicking peaks but type B clicking is at a minimum (from Soldevilla et al. (2010b); Fig. 5)

for foraging. Conversely, the best models for Risso's and Pacific white-sided type A clicks included 4-week time lagged variables, suggesting ecological succession processes following events such as upwelling may affect foraging.

Using HARP recordings near the Aleutian Islands, offshore of Washington and southern California, and near the tip of Baja California, high frequency downswept

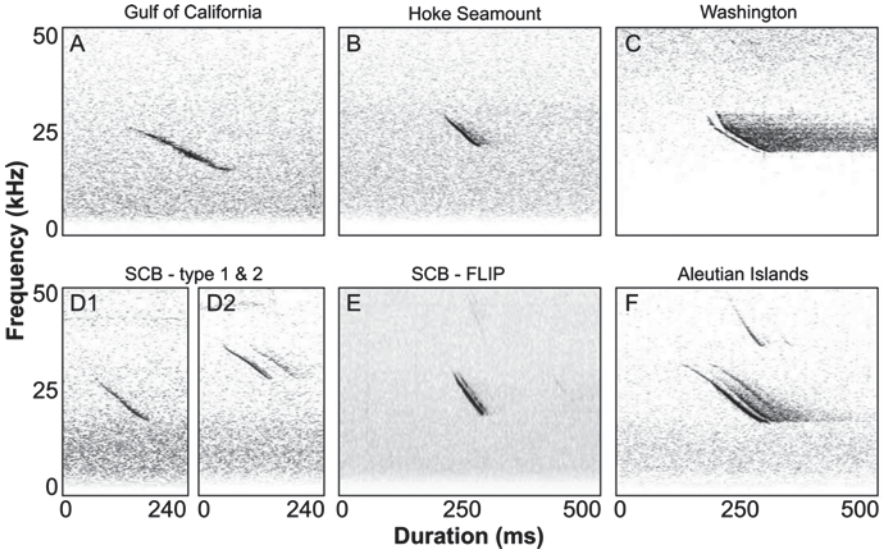


Fig. 3.14 Killer whale high frequency modulated signal spectrograms for five regions in the North Pacific (from Simonis et al. (2012); Fig. 2)

signals from killer whales (*Orcinus orca*) were identified, similar to those reported for Atlantic populations, but not previously described for the North Pacific (Fig. 3.14) (Simonis et al. 2012). Two types of high frequency modulated signals (~25 and ~35 kHz, 50–160 ms duration, source level ~190 $\mathrm{dB_{pp}}$ re 1 µPa at 1 m) were described as similar to bat echolocation signals and potentially could serve the same purpose with a large time-bandwidth product that increases the signal processing gain (Au 1993). As a result, these signals are more suitable than typical echolocation clicks for long range detection tasks such as identifying prey and underwater features for navigation.

3.6 Beaked Whales

More than one-fourth of all cetacean species are in the family Ziphiidae (beaked whales), although until recently not much was known about these animals because they are difficult to observe, spending relatively little time near the sea surface and foraging at great depths. Recent interest in the impact of tactical Navy sonar on beaked whales (Frantzis 1998; Cox et al. 2006) has motivated the development of tools to aid in learning about these animals. For example, the DTAG acoustic archival tag (Johnson and Tyack 2003) has provided details on the behavior of beaked whales, including swimming, diving, foraging, and echolocating behaviors. Furthermore, the wideband (100 kHz), deep water (>1000 m) capabilities of HARPs has provided long duration recordings of beaked whale echolocation foraging dives

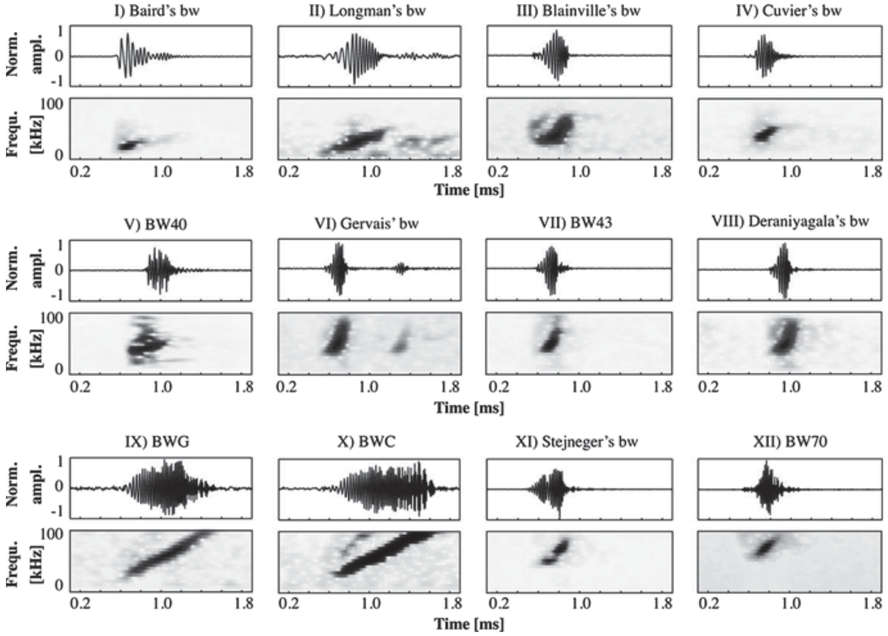


Fig. 3.15 Time series and spectrograms of 12 beaked whale species-specific frequency modulated pulses for known (*I–IV*, *VI*, *VIII*, *X*, *XI*) and unknown (*V*, *VII*, *IX*, *XII*) origin (from Baumann-Pickering et al. (2013a); Fig. 4)

throughout the North Pacific including offshore of southern and central California, off the coast of Washington, near the Aleutian Islands, in the Gulfs of Alaska, Mexico, and California, around the Main and Northwestern Hawaiian Islands, and Saipan (Baumann-Pickering et al. 2013b). These recordings include sounds previous attributed to specific species as well as ones that have been newly associated and others that are beaked whale-like echolocation sounds but from unknown origin (Fig. 3.15) (Baumann-Pickering et al. 2013a).

Wideband recordings were made from April 2005 to May 2006 by a HARP deployed on top of Cross Seamount, west of the island of Hawai'i, at approximately 400 m depth (Johnston et al. 2008). The prominent signal recorded was an approximately 1000 μs, frequency modulated (FM) upswept signal starting around 40 kHz and extending past the HARP Nyquist frequency limit of 100 kHz (Fig. 3.15X). The general high-frequency, upswept character of this signal is similar to Cuvier's (*Ziphius cavirostris*) (Fig. 3.15IV) and Blainville's (*Mesoplodon densirostris*) (Fig. 3.15III) beaked whales echolocation signals (Johnson et al. 2004; Zimmer et al. 2005) suggesting that the Cross Seamount sounds are also from beaked whales, but likely a different species based on its significantly different signal duration, inter-pulse interval and frequency range (McDonald et al. 2009). The Cross Seamount beaked whale echolocation signals were shown to be present year-round with some seasonal variability and occur almost entirely during night at Cross

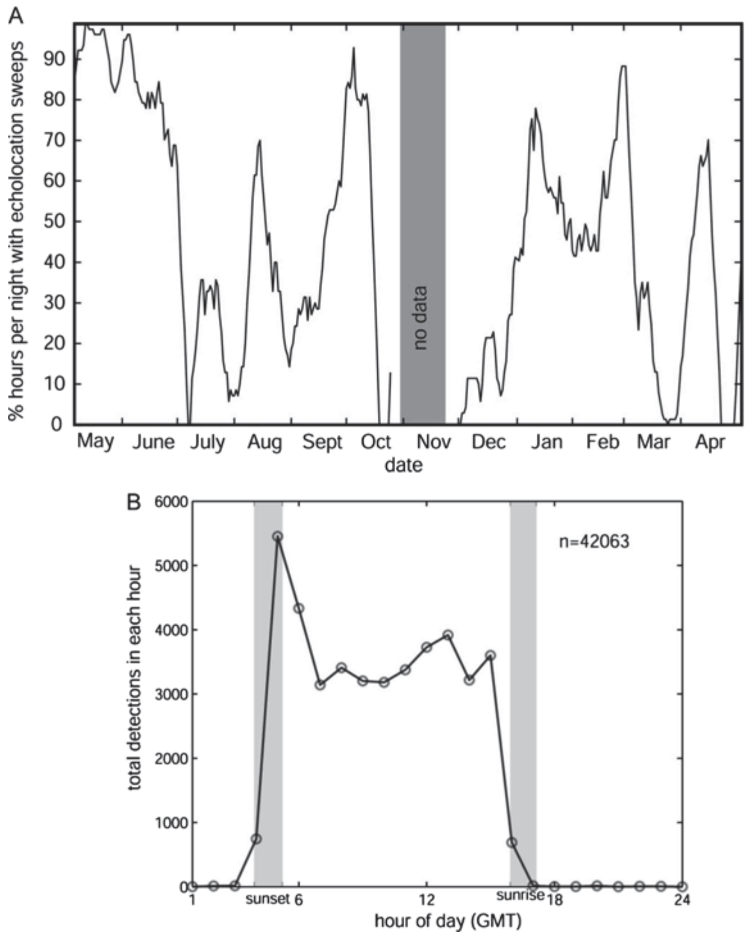


Fig. 3.16 Cross Seamount beaked whale echolocation pulse occurrence. (**a**) Daily and (**b**) hourly presence over 1 year. The diel pattern shows echolocation (foraging) only at night (from McDonald et al. (2009); Figs. 2 and 3)

Seamount and other locations suggesting they forage only at night (Fig. 3.16). These sounds are hypothesized to be from *M. ginkgodens* based on known habitat and comparisons to recordings elsewhere throughout the North Pacific (Baumann-Pickering et al. 2013b).

Similar to the Cross Seamount study, a HARP was deployed at Palmyra Atoll for approximately 1 year from October 2006 to September 2007 at about 600 m depth and recorded FM upswept pulses from another apparent beaked whale with signal characteristics differing from Cuvier's, Blainville's, and Cross Seamount beaked whales (Baumann-Pickering et al. 2010). In addition to the HARP recordings, concurrent visual observations and hydrophone array recordings were made in the presence of an unidentified beaked whale with the array recordings including upswept FM pulses similar to the HARP recordings. The Palmyra Atoll beaked whale signal sweeps from about 34 to 65 kHz, has a pulse duration of about 430 μs and inter-pulse interval of 225 ms (Fig. 3.15VIII). Additional analysis is being conducted to investigate diel and seasonal patterns of beaked whale signals from HARP recordings at Palmyra Atoll from 2006 to 2010. These signals, also recorded at nearby Kingman Reef, may be from Deraniyagala's beaked whale (*M. hotaula*) based on this small geographical distribution and past strandings in the region (Baumann-Pickering et al. 2013a, b).

In 2010, a HARP was deployed in the Aleutian Island region near Kiska, Alaska at over 1000 m deep. This area is a known habitat for three beaked whale species: Baird's (*Berardius beardii*), Cuvier's, and Stejneger's (*M. stejnegeri*). FM upswept pulses were recorded throughout the 3 month data set with no clicks matching the characteristics from Baird's beaked whale (Dawson et al. 1998; Baumann-Pickering et al. 2013d) and only one click sequence from Cuvier's beaked whale (Zimmer et al. 2005); therefore, the pulses were presumed to be associated with Stejneger's beaked whale which had not been previously described. The FM pulses ranged from 40 to 100 kHz with a peak frequency around 48 kHz, pulse duration of 115 μs, and a median inter-pulse interval of 77 ms (Baumann-Pickering et al. 2013c) (Fig. 3.15XI).

Baird's is the largest known beaked whale species and from two encounters were recorded producing whistles, burst pulses, and echolocation clicks (Dawson et al. 1998). Using HARP recordings from southern California and towed array recordings offshore of central and northern California, tens of thousands of detections were used to characterize their echolocation clicks showing two types of signals (Baumann-Pickering et al. 2013d). One of the signals was a beaked whale-like FM pulse with 230 ms inter-pulse interval (Fig. 3.15I). The other signal was a dolphin-like broadband click. Both signals' spectra were composed of multiple frequency peaks consistently around 9, 16, 25, and 40 kHz, but with varying relative amplitude.

In addition to the four species described above, and the well-known Cuvier's and Blainville's beaked whales, HARPs have recorded five additional unique beaked whale-like FM pulses (Baumann-Pickering et al. 2013a). These additional pulses include those from Gervais' beaked whale (*M. europaeus*) and four pulses of unknown origin named BW40, BW43, and BW70 after their peak frequency, and BWG from the Gulf of Mexico (Fig. 3.15). Uniquely identifying the signal characteristics for these pulses allows for intra- and inter-species analysis of spatiotemporal patterns of beaked whale sounds (Baumann-Pickering et al. 2013b), and potentially the evolutionary niche separation that may have caused differences in beaked whale signals.

3.7 Tracking Cetacean

Long-term recordings from ARPs were used to localize calling blue, fin, and right whales (above), however, these results were serendipitous as the ARPs were deployed as independent stations and it was not anticipated that the same call would be recorded on more than one instrument. On the other hand, autonomous acoustic recorders can be configured into preplanned large aperture (~1–5 km) arrays to localize cetacean sounds, providing the recorders are time-synchronized and locations of receiving sensors are well known. While source level and detection range estimates used for population density estimates can be derived from localizations, locations can be combined sequentially to produce tracks which can provide information on cetacean swimming behavior including direction, speed and response to acoustic stimuli.

In the fall of 2007, four time-synchronized HARPs sampling at 200 kHz were deployed in a 2 km × 2 km array on the seafloor about 800 m deep offshore of southern California (Wiggins et al. 2013). Typically, odontocete echolocation clicks are not well suited for localization in this type of array because of their narrow-beam directional character; however, some odontocetes also produce nearly omnidirectional whistles which were localized and tracked (Fig. 3.17). Bouts with large numbers of whistles and clicks were presumed to be from common dolphins based on previous concurrent ship-based single species visual identifications and acoustic recordings. Temporal analysis of these recordings showed dolphins tend to whistle more during day and click more at night. The one month recordings provided tracks of dolphin whistles with typical swimming speeds during daytime transiting behavior of about 2 m/s, and disjointed shorter and slower tracks during nighttime, presumably related to foraging activities. Swimming behavior from tracking could potentially be used to evaluate dolphin responses to various stimuli. Additionally, in the fall of 2008, a similar km-scale HARP array was deployed about 400 m deep in the same region and was used to track high frequency modulated signals from killer whales (Gassmann et al. 2013) showing this approach can be used for other species with nearly omnidirectional, intense signals.

In 2009, a HARP was configured with four hydrophones separated by about 0.5 m each in a small aperture array to track odontocete narrow-beam echolocation clicks (Wiggins et al. 2012). The hydrophones were each sampled at 100 kHz and arranged in a tetrahedron configuration. The small aperture allowed the same click to be received on all four sensors and standard time difference of arrival processing provided three-dimensional angles from the HARP to the sources. About 1 month of recordings provided tracks for both near-surface dolphins and near-seafloor beaked whales (Fig. 3.18). The ability to track free-ranging odontocetes provides a better understanding of habitat use and ranges from these tracks can be used to estimate population densities from distance sampling techniques.

3.8 Summary

Long duration autonomous acoustic recordings have provided insights into the diel and seasonal behaviors of cetaceans. When accumulated over long periods, calls and echolocation pulses show daily trends often related to foraging and seasonal patterns associated with behavior and migration. ARPs and HARPs were designed specifically to provide persistent recordings over long periods using large data storage solutions. They have been used to monitor a wide range of species often in

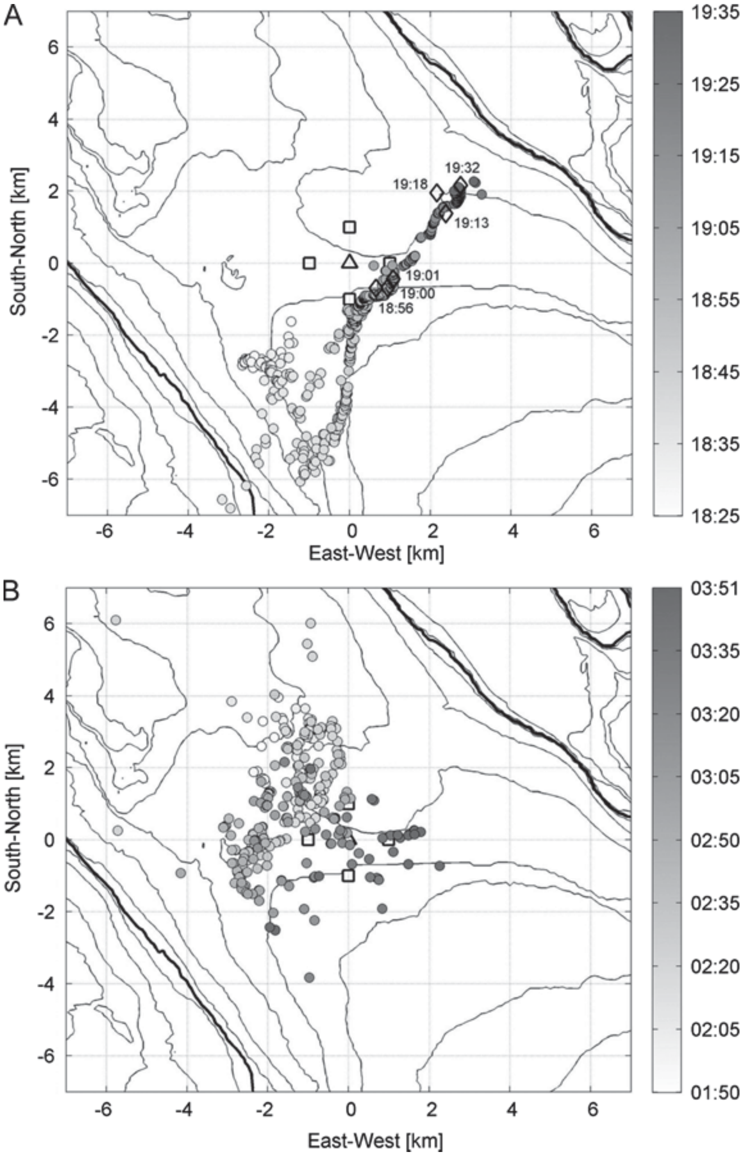


Fig. 3.17 Dolphin tracks from a km-scale HARP array offshore of southern California in 2007. *Filled circles* are dolphin locations with *shading* corresponding to the time scale on the *right*. HARP locations are *squares* on a ridge; *thick contour lines* are 1000 m deep and *thin lines* are at 50 m increments. (**a**) 575 localized whistles over 50 min during daytime hours show *tight clustering* and a directed path. *Diamonds* are visual observed dolphin locations with corresponding times. (**b**) 325 localized whistles over 2 h in the early night show many short tracks over a wide area with slow overall group movement north of the array (from Wiggins et al. (2013); Figs. 5 and 6)

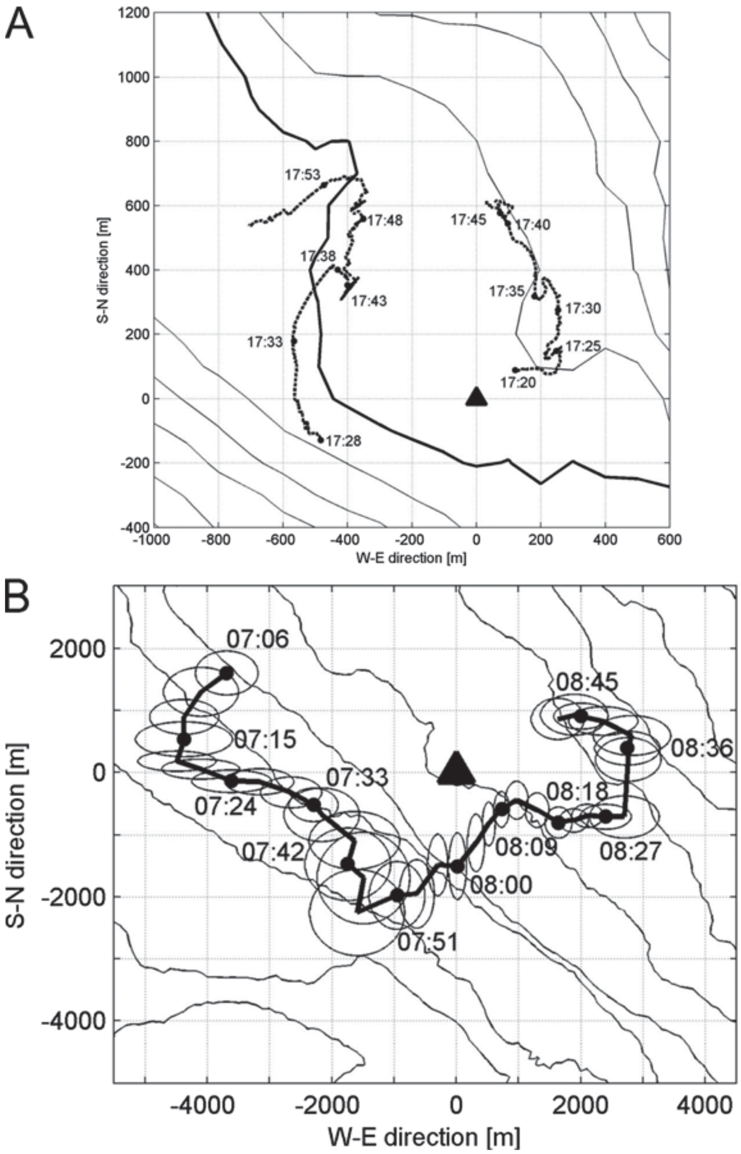


Fig. 3.18 Tracks from echolocation clicks using a HARP configured with a small aperture array offshore of southern California in 2009. (**a**) Two beaked whale tracks show slightly different behaviors, but both appear to follow the seafloor bathymetry. *Dark contour* is 1000 m and *light contours* are 10 m increment, deeper to the northeast. (**b**) Median dolphin group track with standard deviation error *ellipses* showing group spread. *Dark triangle* (HARP) is on 1000 m contour, other contours are 100 m apart with deeper to the northeast (from Wiggins et al. (2012); Figs. 5 and 7)

remote and inhospitable locations for relatively low cost. HARP wideband recordings (100 kHz) include high-fidelity sounds from endangered blue, fin, and right whales, rarely observed and unknown species of beaked whales, and free-ranging dolphins with distinct click types. Long duration temporal and spatial patterns of these sounds are being used with environmental measures to develop predictive cetacean distribution models for ecological studies and conservation and management efforts. In addition, ARP and HARP calibrated hydrophones have provided cetacean source levels and detection ranges as well as ambient noise levels which can be used with distance sampling techniques to estimate population densities.

While HARPs will continue to be used to monitor cetaceans over long periods in fixed-point independent and large aperture array configurations, additional configurations and advanced capabilities are being developed, for example, recently a HARP has been integrated into a Wave Glider and recorded dolphin whistles and clicks while transiting offshore of Kona, Hawaii (Willcox et al. 2009)

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