

Interactions Among Behavioral Responses of Baleen Whales to Acoustic Stimuli, Oceanographic Features, and Prey Availability

Ari S. Friedlaender, PhD
Southall Environmental Associates, Inc.
9099 Soquel Drive, Suite 8
Aptos, CA 95003
phone: (831) 661-5177 fax: (831) 661-5178 email: asf7@duke.edu

Elliott L Hazen, PhD
NOAA SWFSC Environmental Research Division
1352 Lighthouse Ave.
Pacific Grove, CA 93950
phone: (831) 658-3202 fax: (831) 648-8440 email: Elliott.hazen@noaa.gov

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www.sea-inc.net

LONG-TERM GOALS

The long term goals of this collaborative research effort, which is coordinated with other ONR and Navy-funded biological research projects, are two-fold. We aim to first determine how the distribution, abundance, and behavior of prey affects the foraging behavior and ecology of baleen whales off the California coast. Baleen whales employ a variety of feeding strategies that relate to the behavior of their prey and understanding these is paramount to being able to assess changes in their feeding ecology arising from a host of natural and human factors. Second, we will use these empirical findings on how prey affects whale behavior to more completely describe and quantify behavioral responses of baleen whales to controlled exposure experiments and describe the energetic consequences of observed changes in behavior. In order to determine whether and how behavioral changes occurring in baleen whales during controlled exposure experiments are related to sound in their environment, we need to better understand and quantify whether and how changes in their prey environment account for the behavioral change as well. In baleen whales, the behavioral states most commonly observed are feeding, traveling, resting, and socializing. Blue whales visit the southern California Bight in the summer months primarily to forage, and therefore understanding baseline behavior (such as how changes in their prey affect the likelihood of changing behavioral states) is necessary to adequately describe, understand, and effectively mitigate the affects of anthropogenic sound, including military sonar, on these animals.

OBJECTIVES

The overall objectives of this research are to obtain empirical synoptic measurements of fine-scale prey distribution and whale diving and foraging behavior in order to better understand baleen whale foraging ecology and better interpret responses to experimental sound exposure. The current project has already enabled us to obtain basic distribution and density information for prey concurrent with

foraging mysticete cetaceans during tagging with fine-scale movement sensors in the context of behavioral response studies (specifically the Southern California Behavioral Response Study, or SOCAL-BRS). These data on prey and oceanographic variables provide direct insight into the movement patterns and foraging behaviors of the whales and are elucidating how changes in whale behavior can be accounted for by changes in the distribution and abundance of their prey and/or by the presence of human sounds.

APPROACH

The specialized SIMRAD EK60 echosounder units (38 and 120 kHz echosounders and GPTs) and top-side hardware were made available for the project through collaborations with research partners at Duke University (Dr. Doug Nowacek). A specialized echosounder mount and towfish appropriate for the SOCAL-BRS platform was fabricated with support from this award (Figure 1). The smaller orange echosounder is the 120 kHz unit and the larger echosounder is the 38 kHz unit.



Figure 1. Specialized echosounder mount and towfish used in the SOCAL-BRS.

Several computers were required, including a ruggedized laptop computer specific to data acquisition (Dell Latitude E6420 ATG) and a laptop computer for field/lab data analysis (MacBook Pro - 15.4/2.3/2X2GB/750/SD/HR-AG). Additionally, several external data storage drives and other ancillary gear (e.g., handheld GPS unit) were required and obtained with this award. The information from each echosounder is processed in a GPT (general purpose transceiver) that also acts as a power supply. The data are then streamed through Ethernet cables to the laptop where they are processed in customized visualization and analysis software (Echoview). The data are stored directly on the laptop computer and then backed up on external hard drives routinely. A hand-held Garmin GPS unit is connected to the laptop to provide a time and location stamp for the echosounder data as it is acquired.

Finally, a plankton sampling system was obtained for the second leg of the project, given the interesting measurements made initially and the inability to obtain plankton species identifications. This consisted of a triple-stitched plankton net (100 cm X 500 cm X 1000 Microns x 11 cm diam; 4.5”0 COD end aperture), an SS-ring and bridle assembly, a complete 2-PC PVC COD end assembly (1000 microns), and a mechanical flow-meter (Figure 2). In order to quantify the density and biomass of prey measured from the echosounders it is paramount to generate length-frequency estimates of the actual targets that are being measured. Thus, incorporating the net into our sampling protocols will allow for more accurate and quantitative estimates of prey for our analysis.



Figure 2. Net assembly being deployed from the SOCAL-BRS research vessel.

Fine-scale prey density and distribution and individual predator behavior was measured in two phases in SOCAL-11 (late-July to mid-August and September 2011) and in the first phase of SOCAL-12 (July-Aug 2012) using the existing research platform (*R/V Truth*). By analyzing prey and predator at fine scales (100s of meters), we can begin to test for the relationships between prey distribution and predator behavior and understand the ecological decisions made by individual whales when foraging, and how the broader oceanographic environment affects blue whales in southern California.

Prey sampling - Prey distribution and abundance was continuously measured using 38 and 120 kHz SIMRAD EK60 echosounders at fine scales (<10 km). Acoustic data collected in the absence of sighted or tagged whales were treated as a control measure of ambient prey density. Fine scale sampling methods are dependent on the behavior of the tagged whale so an iterative approach to sampling prey is employed. If the tagged whale is traveling (>1km per hour displacement), a zig-zag design was used to survey prey distributions passed over by the whale by sampling in its wake (~1.4km long transects). When focal whales were surface feeding (defined as observing the animal with its mouth gaped or bubbles located where the animal surfaced), a clover leaf sampling design allowed the measurement of prey abundance and distribution, with the center of the sampling box centered around the whale (Figure 3). The sampling design around non-feeding and non-traveling (i.e. resting) individuals is identical, with a cloverleaf used to examine the prey distribution in the absence of feeding. When measuring prey relative to surfacing events, transects were designed to pass within 500 meters of the tagged whale. Correlations between whale behavior, prey data, and environmental data, will only be considered in analysis within a 500m radius of a whale surfacing. This will allow us to quantify the distribution, abundance and dimensions of prey patches in close proximity to foraging and non-foraging whales. We will also compare the two frequencies of acoustic data to differentiate krill from larger fish targets as krill have greater backscatter at 120kHz than 38kHz.



Figure 3. Clover leaf sampling design around tagged whale. Each leaf is 1km from the center.

Whale data - Whale behavior (*e.g.*, feeding/non-feeding) is inferred from the tag record in combination with near continuous daytime focal surface observations. Tags were attached from ~6m rigid-hulled inflatable boats (RHIB) by taggers using hand-held poles from which Woods Hole Oceanographic Institution (WHOI) Digital Acoustic tags (DTAG) were deployed. The DTAG is a small, lightweight, pressure tolerant tag capable of recording data for up to ~20 hours and attached to the whale via suction cups. The DTAG measures the acceleration in the animal's pitch, roll, and heading, as well as depth, and water temperature at 50 Hz. The tags also measure sound and calibrations have been made between vertical acceleration and flow noise to determine when whales lunge underwater. This is determined by increased acceleration as the whale approaches a prey patch and dramatic deceleration when the animal opens its mouth to lunge and engulf prey. This approach has been published and ground-truthed for several species of baleen whales, including blue whales and thus is considered the most accurate way of determining feeding events in baleen whales from tag-derived records. Data from the pitch record also allows for analysis of fluke stroke rates and relative stroke amplitudes and combined with behavioral observation allows the identification of surface feeding bouts and quantification of their duration. All sensor data are stored in flash memory on the tag and are downloaded via an infrared connection to a computer for analysis. The tag has a VHF antenna that transmits when at the surface, allowing us to follow the whale when it is either out of visual range or during nighttime. Focal follows were conducted from RHIBs such that animal's position was recorded by marking a GPS position at the location (foot-print) and time where the tagged whale made a terminal dive. Additionally, we augmented this method by collecting high-resolution range and bearing measurements using a laser range-finder (Leica Vector IV), to georeference the surfacing locations of the tagged whale more frequently. Similar to previous studies using non-linear generalized additive models, in analysis we will quantify the effects of remotely sensed environmental features and prey abundance on the distribution and abundance of whales at the seascape scale. This approach will provide estimates of (1) prey and environment in the functional study area around blue whales and (2) the functional relationships between prey density and school size and predator aggregation size.

WORK COMPLETED

Fine-scale prey mapping and whale tagging was conducted during SOCAL-11 (under a previous award) and the first phase of the SOCAL-12 (July 2012) research study. Phase two of SOCAL-12 is scheduled to occur after the report for the 2012 fiscal year is due. Consequently, no results from this effort will be included, but we fully expect to complete additional baleen whale tagging and concurrent prey mapping efforts during this leg. During SOCAL-11, acoustic prey data concurrent with tagged whales were collected on 7 days. One day of data collection occurred in conjunction with tags being deployed on baleen whales in the first phase of SOCAL-12. In this case, two DTags were deployed: one on a blue whale and one on a fin whale, which is a unique and important opportunity to look at sympatric behavioral responses in relation to prey in individuals of two different species.

Date	Species	Pre-exposure	Post-Exposure	Control
7/29/11	Blue Whale		X	
7/30/11	Blue Whale	X	X	
7/31/11	Blue Whale			X
8/1/11	Blue Whale	X	X	
8/2/11	Blue Whale	X	X	
8/3/11	Blue Whale			X
8/6/11	Blue Whale	X	X	X
8/7/11	Blue Whale			
8/8/11	Blue Whale			X
8/9/11	Blue Whale	X	X	
8/4/12	Blue Whale	X	X	
8/4/12	Fin Whale	X	X	

In collaboration with Jeremy Goldbogen as part of the SOCAL-11 BRS analysis, behavioral metrics were identified from tag sensor data to determine whale behavior (e.g. dive time, angular change). These metrics have been incorporated in our ecological analyses to understand how prey affects various dive parameters.

Tag-derived data have been analyzed to determine general behavioral states continuously during the dive record. Using methods of Goldbogen *et al.* (2006) and Ware *et al.* (2010), flow noise from the tag is calibrated with accelerometer data to generate an estimate of whale speed. This is then used to determine when individual sub-surface feeding lunges occur. Rapid acceleration followed by significant and rapid deceleration is a trademark of lunge feeding in baleen whales. Thus, any dive in which at least one feeding lunge is detected is deemed to be a feeding dive. Dives with no lunges can be classified as either travel, resting, socializing, or other, based in part on the depth and duration of the dive as well as from surface observations collected during focal follows. Within each foraging dive, the number of lunges can be related to the depth of feeding (Goldbogen *et al.* 2006, 2011; Ware *et al.* 2010). Similarly, the rate of ascent and descent (to determine travel time to and from feeding depths) can be used as metrics of foraging. By combining these metrics we can relate any changes in foraging depth, duration, or intensity to concurrent changes in the distribution, abundance, and behavior of their prey using multi-variate analyses (e.g., GAM, CART, see Friedlaender *et al.* 2006, 2009; Hazen *et al.* 2009).

Echosounder data were calibrated on board the *R/V Truth* in 2011 according to Foote *et al.* (1987) using a 38.1 mm tungsten carbide sphere of known target strength to ensure accurate and reliable acoustic measurements. Krill schools were determined by using the ΔSv method (Watkins and Brierley 2002) prior to calculations of acoustic biomass. The DSv method uses differences in modeled krill TS at 120 kHz and 38 kHz to calculate a range of predicted difference in scattering for the smallest and largest krill target strengths. Prey data were processed using Myriax Echoview version 5 in two distinct ways: 1) the traditional line-transect based approach of acoustic biomass/m² and 2) using the school detection module to identify individual patches and calculate size and density parameters that have been shown to be more relevant to foraging whales (Hazen *et al.* 2009).

RESULTS

On 4 August 2012, we deployed a DTag on one fin whale and one blue whale in the vicinity of the Palos Verdes Peninsula. We conducted prey mapping activities before and after a playback that included both whales. The fin whale (bp12_217a) was tagged at 11:07 local time and the tag remained on the whale overnight (Figure 4 - top). This deployment represents a significant milestone as it is the first overnight deployment we have done on a fin whale. The behavioral information from this tag record are therefore extremely valuable. The blue whale (bw12_217a) was tagged at 12:50 local time and the tag remained on the animal until the following morning as well (Figure 4 - bottom). Thus, we have concurrent tag data from two whale species in the same location for an extended period of time, which will allow for significant ecological and behavioral comparisons regarding how these two species forage and interact.

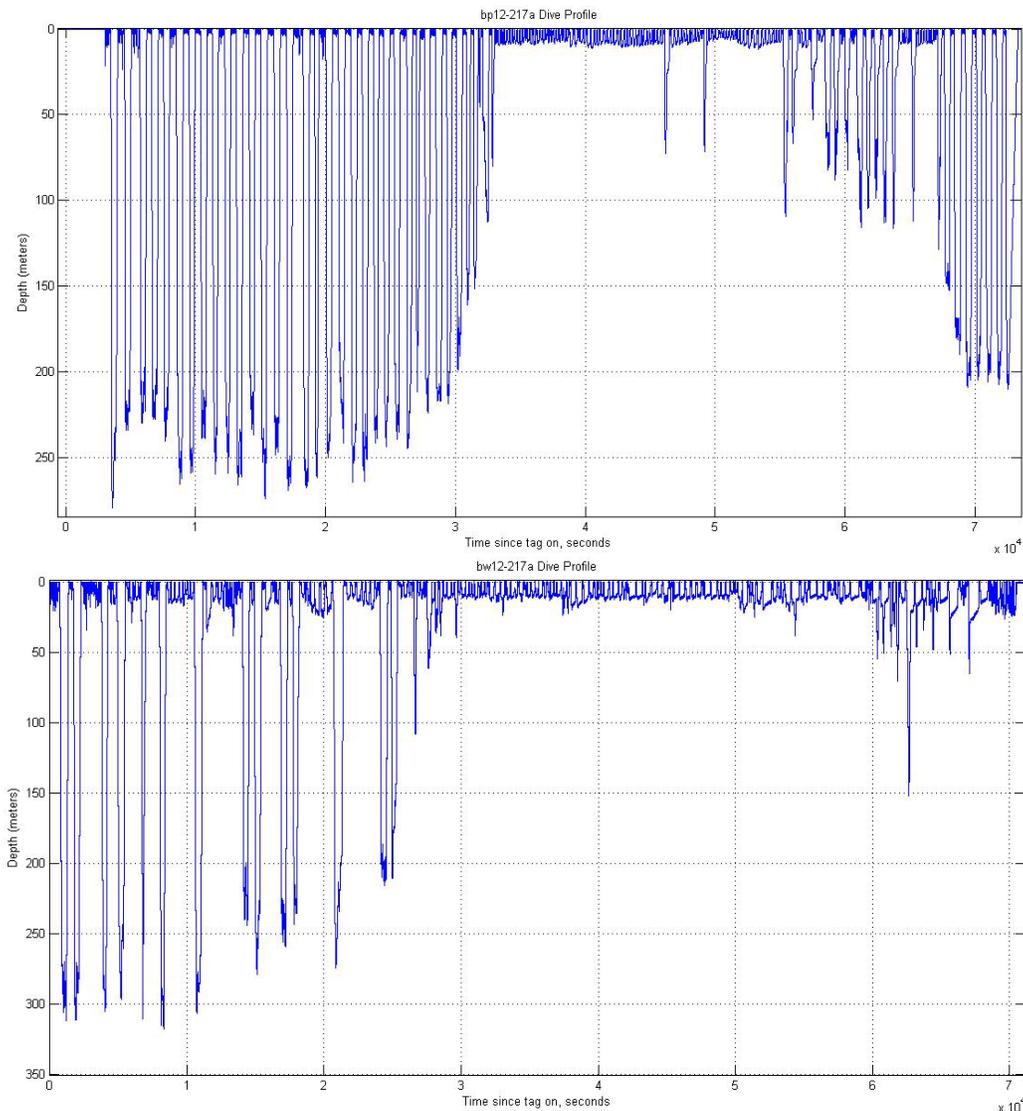


Figure 4. Complete time-depth dive profile for the fin whale (top) and blue whale (bottom) tagged in the same general time and place in SOCAL-12.

The fin whale appears to feed slightly shallower than the blue whale initially and also feeds/dives at an increased rate. It is also significant to compare the overall behavioral patterns for these two whales. Both whales feed intensively during the afternoon at a consistent depth and then gradually feed shallower as evening approaches. This diel change in the depth of diving is likely related to the diel vertical migration of their prey. The cessation of feeding after sunset and the subsequent extended surface durations are also interesting. This behavioral state change may occur based on several factors: prey density at night drops below an energetically efficient density for feeding, the whales may become satiated from feeding or require surface time to regain oxygen stores from intense and high energy feeding bouts, or as visual predators they are unable to locate prey.

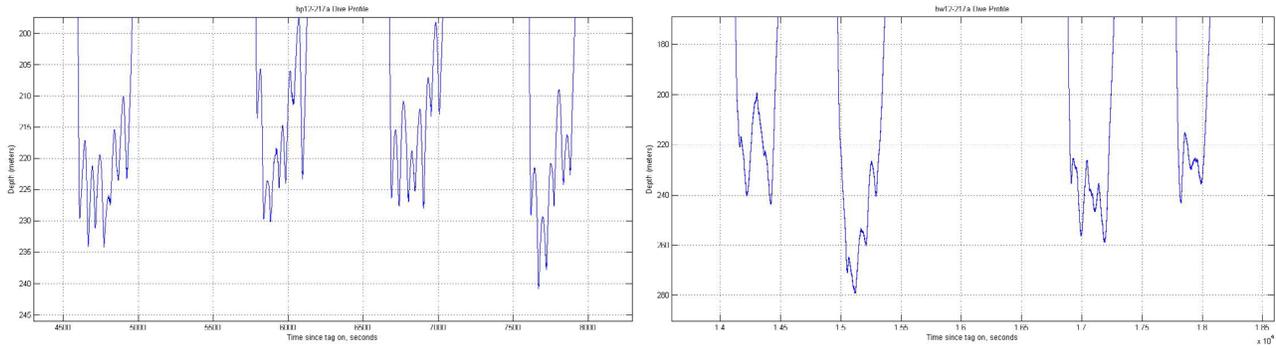


Figure 5. Four foraging dives for the SOCAL-12 fin (left) and blue (right) whales shown in greater detail.

The foraging depths for these dives are relatively similar, while the dive duration for the fin whale is slightly longer than for the blue whale. The rapid vertical transitions seem at the terminal depth for each foraging dive represent individual feeding lunges. It is clear that the fin whale completes more feeding lunges per dive than the blue whale in this instance (Figure 5). As well, the vertical displacement during lunging may reflect differences in the kinematic patterns of feeding for each species. The depth of these lunges is consistent with depths observed of krill schools, with schools at 120 kHz from 90-250 meters deep before and after playback (Figure 6).

The kinematic patterns appear to be similar between the two whales, with vertical lunging occurring repeatedly during the dive. Also evident on the fin whale plot are fluke strokes prior to vertical lunging. These are represented by the fine-scale sawtooth pattern just prior to vertical movement (Figure 7). Ongoing analyses are quantifying how the foraging behavior of each of these tagged whales relates specifically to the distribution and abundance of their prey.

It is clear from the time-depth dive profiles that both blue whales are feeding intensively between 100-250 meters depth (Figure 8). Generally speaking, the whales seem to be feeding consistently deeper at the beginning of the dive record and then shallower towards the end of the record. The echogram is included to qualitatively show school shape. In the top panel from the 38 kHz echosounder, there is a consistent layer from 200-400 meters and we see krill schools from the top of the layer towards the surface (Figure 9). By overlaying spatially and temporally, the whale tracks and prey data we can sample more precisely what the prey abundance was like where the whales were feeding. Generally, it appears that the whales were targeting the upper portion of this consistent prey layer. The bottom panel of the echogram shows individual prey patches shallower in the water column, 100-150 meters deep from the 120 kHz echosounder. This patch structure may relate to the vertical changes observed in the dive patterns of both whales later in the deployment (Figure 10). This enables us to quantitatively compare the feeding rates and foraging behaviors of whales associated with discrete and dense prey patches versus more continuous and uniform prey layers.

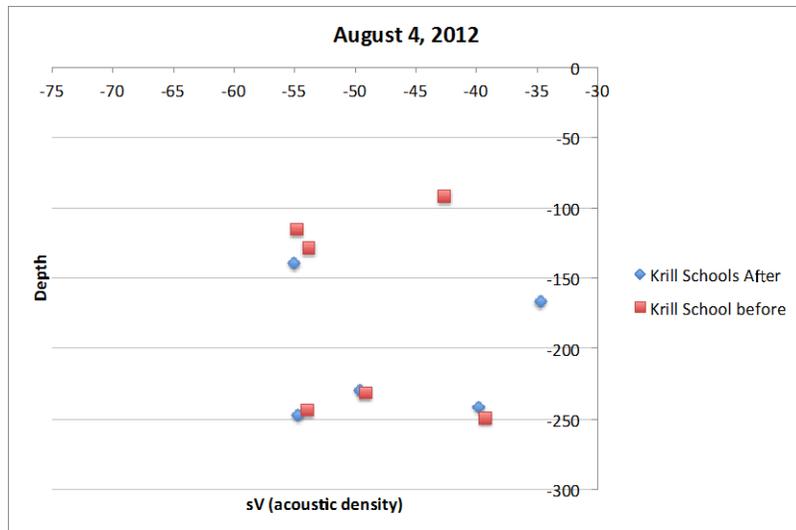


Figure 6. Acoustically detected krill schools for August 4, 2012 before and after CEE with depth in meters on the y-axis and the density (scattering volume – sV) on the x-axis. Denser schools are further right.

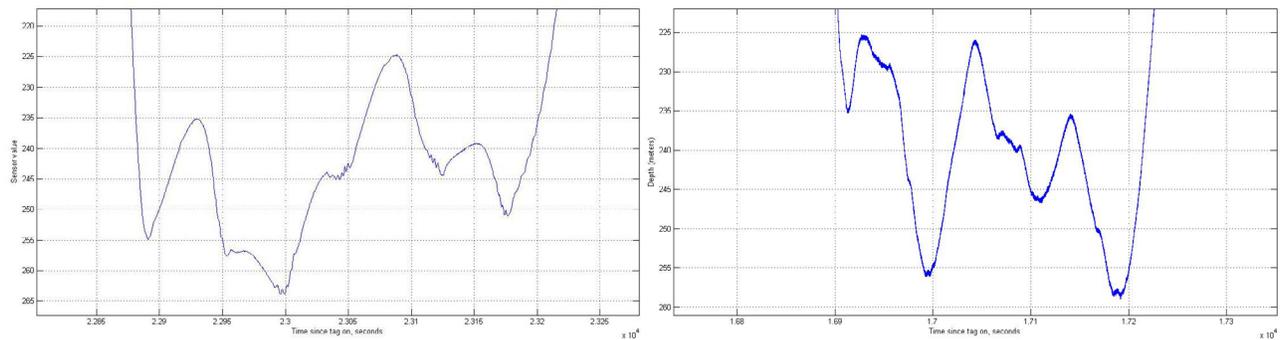


Figure 7. Time-depth profile for a single feeding dive for the SOCAL-12 fin (left) and blue (right) whale.

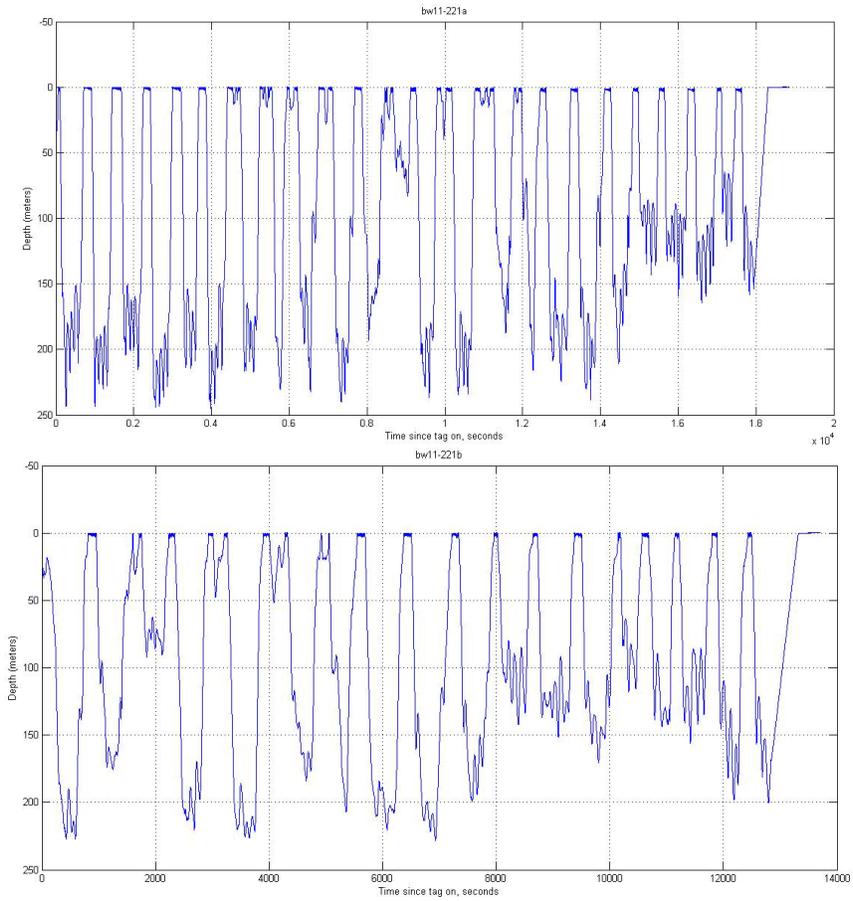


Figure 8. Dive records for two blue whales tagged on 9 August 2011 (simultaneous measures of prey distribution is shown in Fig. 6 below).

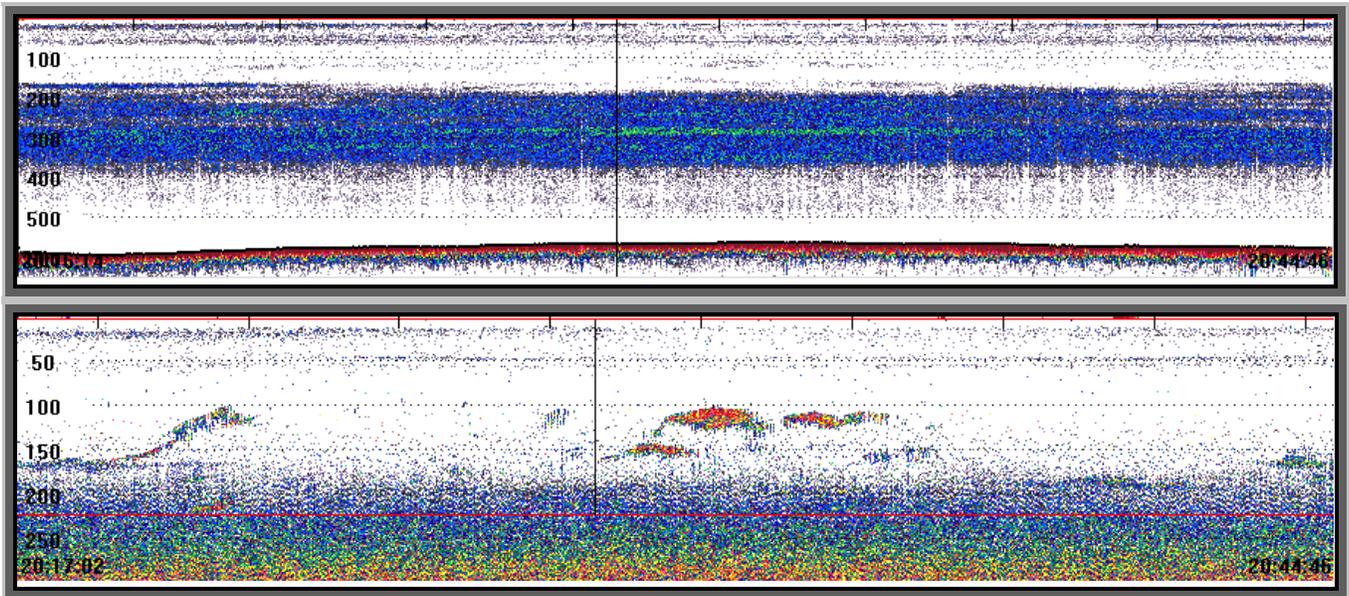


Figure 9. Acoustic echogram of krill schools at a) 38 kHz and b) 120 kHz measured around the two blue whales show in Fig. 5. Depth is on the y-axis and time is on the x-axis. Note that the x-axis for the dive data (in Fig 5) and prey data are at different scales.

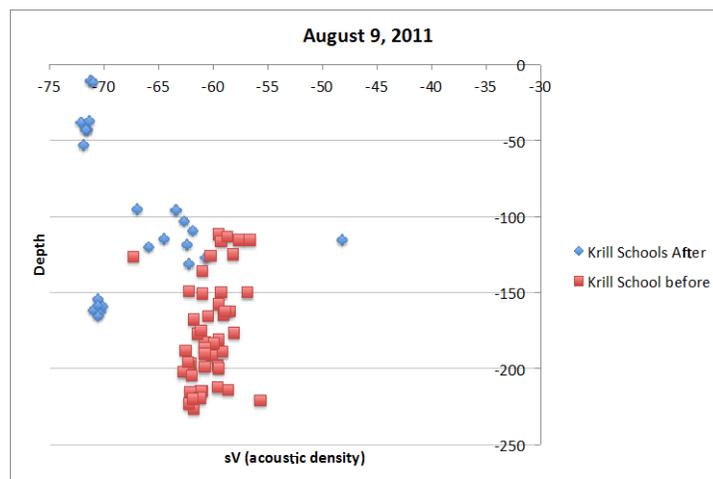


Figure 10. Acoustically detected krill schools before and after CEE with depth on the y-axis and the density (scattering volume – sV) on the x-axis. Denser schools are further right.

Ongoing analyses:

For the remainder of this award, some additional field data (SOCAL-12 phase II) will be collected but most of our efforts will continue to focus on data analysis. The acoustic data from 2011 and the first leg of 2012 have been processed and exported based on school metrics and in 250 x 10 meter bins (horizontal x vertical). These can be directly sampled based on foraging dive location along with interpolated water column data (T, S, thermocline depth, stratification strength) and can be run in a regression model framework. This approach has been used previously to understand the characteristics influencing foraging behavior and distribution patterns (Friedlaender et al. 2009, Hazen et al. 2009).

Dive profiles for each of the animals tagged concurrent with quantitative measurements of prey distribution, behavior, and density have been obtained. Furthermore, we have used principle component analyses (PCA) to combine 84 behavioral metrics for CEE response analyses and we plan on including environmental and prey metrics in this framework. Prey metrics will include patch type (discrete versus layer) shape, size, depth, density, and change from before to after CEE experiment. Changes in these metrics before to after can help determine whether observed behavioral changes were a function of the playback, changes in the prey field, or some interaction between these factors.

IMPACT/APPLICATIONS

Using fine scale foraging behavior in concert with prey and environmental data, this work will greatly enhance our knowledge of blue whale ecology. We will be able to provide new analytical approaches to contribute to the current state of knowledge regarding the foraging ecology and feeding behavior of baleen whales. We will be able to determine how changes in prey affect how baleen whales feed. This is useful for understanding how changes in the marine ecosystem will likely manifest in the distribution, movement and feeding patterns of whales and consequently how best to implement management practices. Additionally, we will be able to contribute significantly to our understanding of how anthropogenic sounds affect baleen whale behavior when feeding. We will be able to determine if there are particular feeding strategies or prey dynamics that whales will abandon or change their behavior in response to anthropogenic sound input and apply this understanding to other locations and marine ecosystems.

RELATED PROJECTS

This project is closely coordinated with the Southern California Behavioral Response Study (SOCAL-BRS – see: www.socal-brs.org) which is measuring behavior and responses to simulated mid-frequency sonar and other signals in marine mammals. The prey-mapping measurements for this project are leveraging boat time and other logistical support from the ongoing SOCAL-BRS project, while providing data that are directly relevant to interpreting the behavioral responses of mysticetes to controlled exposure experiments.

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