Listening for Large Whales in the Offshore Waters of Alaska

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Listening for Large Whales in the Offshore Waters of Alaska

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In 1999, the first phase of a multiyear program was initiated at the National Oceanic and Atmospheric Administration's National Marine Mammal Laboratory and Pacific Marine Environmental Laboratory to advance the use of passive acoustics for the detection and assessment of large whales in offshore Alaskan waters. To date, autonomous recorders have been successfully deployed in the Gulf of Alaska (1999–2001), the southeastern Bering Sea (2000–present), and the western Beaufort Sea (2003–2004). Seasonal occurrences of six endangered species (blue, fin, humpback, North Pacific right, bowhead, and sperm whales) have been documented on the basis of call receptions in these remote ocean regions. In addition, eastern North Pacific gray whale calls were detected in the western Beaufort Sea from October 2003 through May 2004. Here we provide an overview of this suite of research projects and suggest the next steps for applying acoustic data from long-term recorders to the assessment of large whale populations.

Keywords: whales, acoustics, recorders, remote sensing, Alaska

Large whales were severely depleted by commercial whaling from the 18th through the late 20th century, to such an extent that all were included in the initial US listing of endangered species in 1973. Targeted species included blue, fin, humpback, right, Bryde's, and sperm whales (box 1), and although precise numbers are unknown, the removal of at least two million whales over roughly 200 years is well documented (Clapham et al. 1999). While this intensive exploitation underlies the recent controversial hypothesis of top-down ecosystem forcing—the so-called "megafaunal collapse" hypothesis (Springer et al. 2003, Mizroch and Rice forthcoming)—it also sets a challenge to scientists and resource managers charged with estimating current population sizes and habitat protection for these endangered species.

With the end of the cold war and the subsequent willingness of the US government to allow dual use of some military assets (Nishimura and Conlon 1993), a unique opportunity arose to use the US Navy's SOSUS (Sound Surveillance System) underwater hydrophone network to detect and track whales. Biologists welcomed this opportunity, and found in SOSUS an unprecedented tool to detect blue and fin whale calls over long distances in the North Atlantic and North Pacific basins (Clark 1995, Watkins et al. 2000, Stafford et al. 2001) and to track individual whales that produced atypical calls (Watkins et al. 2004). In the North Pacific, the seasonal detection of endangered blue and fin whale calls, using SOSUS, provided a means to correlate call occurrence with habitat features in remote areas off the Kamchatka Peninsula (Moore et al. 2002) and to investigate whale response to ocean climate variability off California (Burtenshaw et al. 2004).

The success of research that used SOSUS to track seasonal occurrence patterns in whale calls fostered the development of autonomous recorders that could be deployed virtually anywhere in the world's oceans (Fox et al. 2001, Wiggins 2003). Two types of recorders have been used off Alaska: (1) autonomous hydrophones developed by the National Oceanic and Atmospheric Administration's (NOAA) Pacific Marine Environmental Laboratory (PMEL) (Fox et al. 2001; *www.pmel.noaa.gov/vents/acoustics/whales/bioacoustics.html*) and (2) acoustic recording packages (ARPs; Wiggins 2003, *http://cetus.ucsd.edu*). The PMEL hydrophone consists of a watertight titanium pressure case containing alkaline batteries, a data logging system with one to six hard disk drives, and a hydrophone outside the case. The ARPs, developed by the Marine Physical Laboratory of the Scripps Institution of Oceanography, consist of a frame that holds the batteries, hard disk drives, and ballast, with a hydrophone suspended about 7 meters (m) above the frame. The recording bandwidth for both recorders ranges from 230 to 880 hertz (Hz) (sample rates 500 to 2000 Hz) depending on the unit, with hard disk drive storage capacity of 36 to 160 gigabytes. They are thus capa-

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Box 1. Large whale species.

These species of large whales, once the target of commercial whaling, are now detected by researchers using passive acoustic methods.

- Blue whale (*Balaenoptera musculus*)
- Bryde's whale (*Balaenoptera edeni*)
- Bowhead whale (*Balaena mysticetus*)
- Fin whale (*Balaenoptera physalus*)
- Gray whale (*Eschrichtius robustus*)
- Humpback whale (*Megaptera novaeangliae*)
- Minke whale (*Balaenoptera acutorostrata*)
- North Pacific right whale (*Eubalaena japonica*)
- Sperm whale (*Physeter macrocephalus*)

ble of continuous recording during 200- to 400-day deployments. Both types of instruments need to be recovered in order to retrieve the acoustic data.

The principal difference between the instruments is that the PMEL recorder is moored with the hydrophone suspended up into the deep sound channel, while the ARP's hydrophone samples sound at roughly 10 m above the seafloor (figure 1). Both instruments have proved to be flexible tools for acoustic observations of large whales in remote areas of the world's oceans, as demonstrated by deployments along the mid-Atlantic ridge (Nieukirk et al. 2004), the eastern tropical Pacific (Stafford et al. 1999a), and the Antarctic Peninsula (Sirovic et al. 2004). As such, they are especially suitable for cetacean detection in the offshore waters of Alaska, where standard visual surveys are often hampered by darkness and bad weather.

Autonomous recorders off the shore of Alaska: The first five years

In 1999, a multiyear program to advance the use of passive acoustics for detection and assessment of endangered whales in the offshore waters of Alaska was initiated by NOAA's National Marine Mammal Laboratory (NMML) and PMEL. The focus of the study was the detection of large whales through the long-term deployment of autonomous recorders to monitor specific ocean regions for their calls. The program began with the deployment of six PMEL recorders in the Gulf of Alaska (GOA) in October 1999, followed in October 2000 by the initial deployment of four ARPs in the southeastern Bering Sea (SEBS). Since then, multiple year-long deployments (figure 2) in the GOA, the SEBS, and the western Beaufort Sea (WBS) have yielded unprecedented information on the seasonal occurrence and calling behavior of endangered blue, fin, humpback, sperm, North Pacific right, and bowhead whales, as well as nonendangered gray whales. Here we review the highlights of detection and seasonal assessments of endangered large whales from data gathered using the PMEL and ARP recorders.

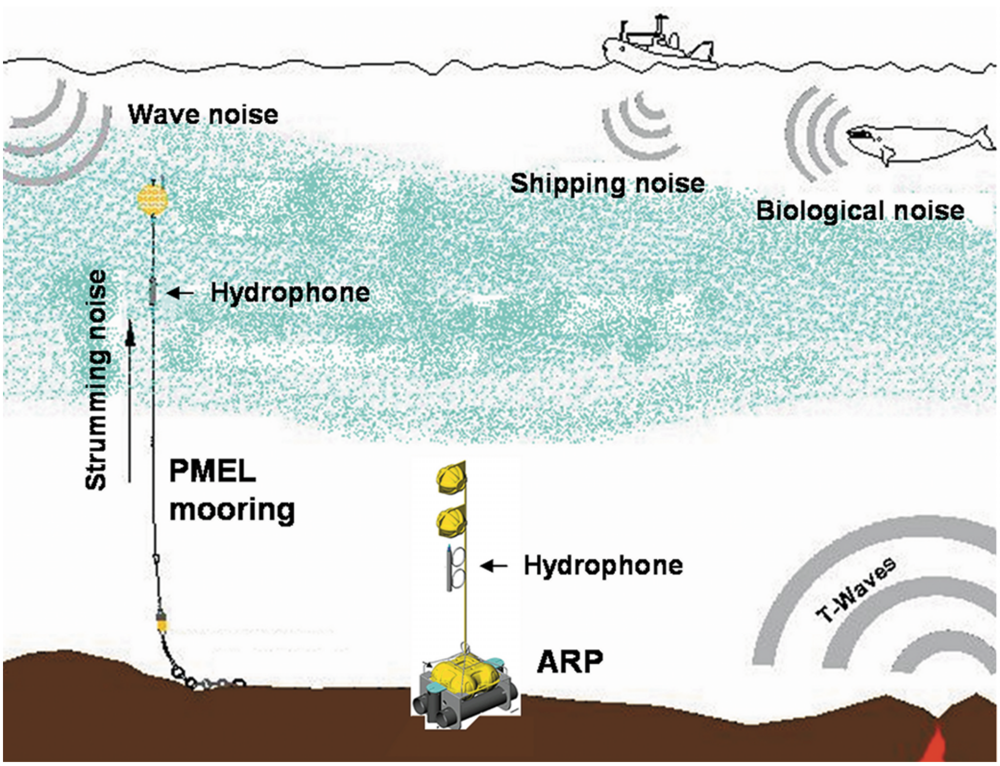

Figure 1. Schematic diagram of a Pacific Marine Environmental Laboratory (PMEL) recorder and an acoustic recording package (ARP) in their most common deployment configuration.

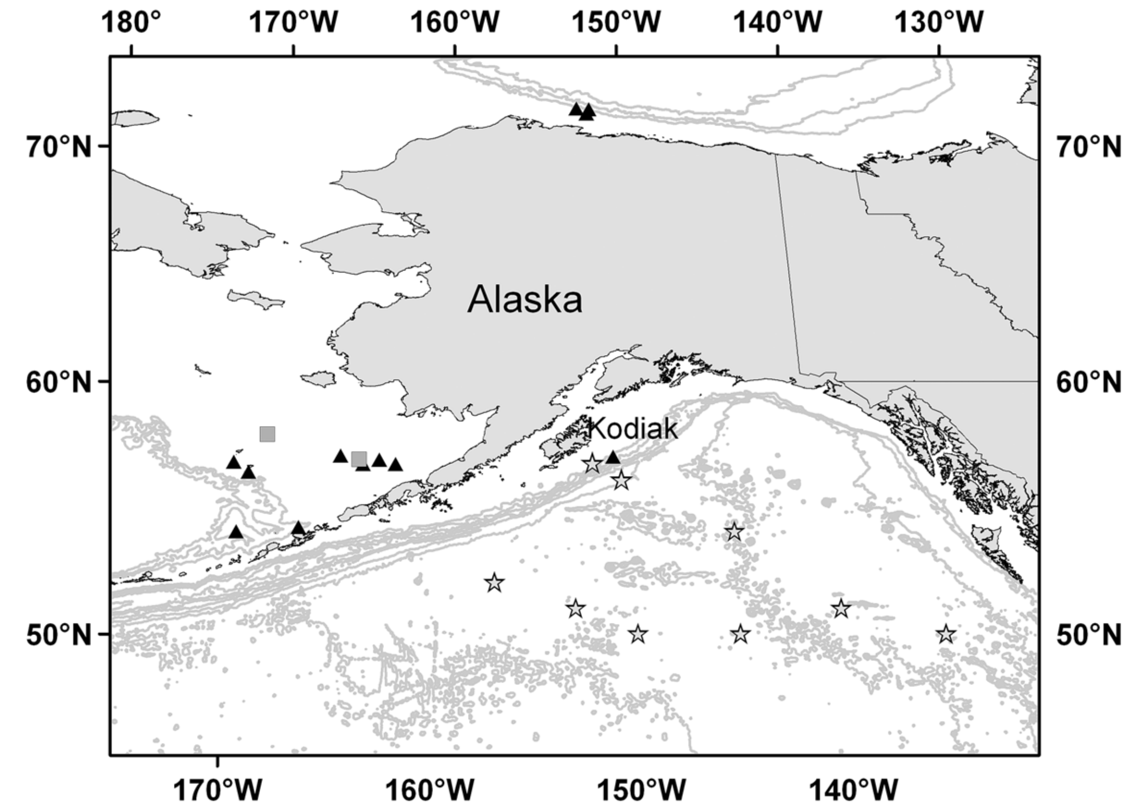

Figure 2. Deployment locations for Pacific Marine Environmental Laboratory recorders (stars), acoustic recording packages (ARPs; triangles), and high-frequency ARPs (squares) in offshore Alaska waters. Deployment periods: Gulf of Alaska, 1999–2001; southeastern Bering Sea, 2000–present; western Beaufort Sea, 2003–2004.

The Gulf of Alaska

Blue whales were the initial focus of acoustic surveys in the GOA. Although blue whales range across the North Pacific, in 1999 nearly nothing was known about their seasonal occurrence in high latitudes, nor about their population structure. On the basis of data from an 18-month deployment of six PMEL recorders, two types of blue whale calls were described, which both confirmed the presence of blue whales in the GOA and also suggested that two populations used the area (Stafford 2003). Both call types showed a strong seasonal pattern, with peak occurrence from August through November (figure 3). Although the northeastern Pacific call type was most prevalent, the western Pacific call type was recorded throughout the calling season, with some evidence of call mimicry during periods when the two call types overlapped (Stafford and Moore 2005).

Data from the six PMEL recorders were subsequently analyzed for the presence of sperm whale clicks (Mellinger et al. 2004a) and fin whale pulses. For sperm whales, recordings were processed using an automatic detector to find the characteristic highly regular clicks produced by this species. The detection algorithm, accurate 98 percent of the time according to manual review, found sperm whale clicks present in the GOA year-round (figure 3). This is a surprising result, given the common belief among researchers and the lay public, based on whaling data and a dearth of sightings, that sperm whales migrate to midlatitudes in winter. Sperm whale clicks occurred roughly half as often in winter as in summer, suggesting that a sizable fraction of the population is present year-round. Surprisingly, fin whale pulses too were detected year-round in the GOA, with most calls detected from August through February (figure 3). A more detailed analysis of these signals and those from humpback whales is under way.

The sighting of a lone North Pacific right whale among humpback whales during an aerial survey southeast of Kodiak Island, Alaska, in July 1998 precipitated the placement of two PMEL recorders in the northern GOA near Kodiak Island (Waite et al. 2003). In May 2000, one instrument was deployed at the location of the sighting (57°08.20′ N and 151°51.00′ W), with a second recorder located at the continental slope to complement the aforementioned array of six recorders in the central GOA. Data from these instruments, and from the five present in the central GOA in 2000–2001, were analyzed for calls from the critically endangered North Pacific right whale (Mellinger et al. 2004b). In this case, automatic detections were used to identify periods of data containing the characteristic "up" call produced by this species (McDonald and Moore 2002). Automatic detections led analysts to periods of data that were visually and aurally examined to determine the likelihood that they were from right whales and not the calls of humpback whales, which can have similar characteristics. Of a total of 654 sounds that re-

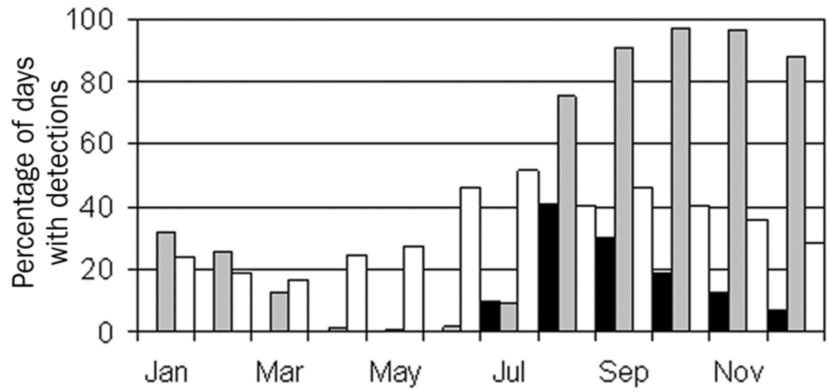

Figure 3. Average monthly call detections for blue whales (black), fin whales (gray), and sperm whales (white) from Pacific Marine Environmental Laboratory recorders in the Gulf of Alaska. Bars indicate the percentage of days in each month in which species' calls were detected.

sembled "up" calls, only 12 were actual right whale calls. However, the detector led analysts to parts of the data in which 60 unambiguous right whale calls were identified, with 10 probable right whale calls found on the instrument at the sighting location near Kodiak Island.

Although very few North Pacific right whale calls were found, it is noteworthy that the unambiguous right whale calls were detected in August and early September on the westernmost recorder in the GOA, and that calls were recorded from locations where right whales were formerly abundant but have not been seen in recent decades (Shelden et al. 2005). Finally, to further gauge the occurrence of right whales near Kodiak Island, an ARP was deployed at the nearshore sighting location in April 2003; the instrument recorded continuously until August 2003, but no right whale calls were apparent in a preliminary analysis of the data.

The southeastern Bering Sea

Detection of North Pacific right whale calls was given highest priority in the SEBS because of the whales' critically endangered status (Shelden et al. 2005). The opportunistic sighting of right whales during an Alaska Fisheries Science Center groundfish assessment cruise in 1996 led to intense photo-identification and vessel surveys conducted there from 1998 to 2004 (LeDuc et al. 2001). The sighting locations indicated that right whales preferred the comparatively shallow waters (approximately 70 m) of the SEBS middle shelf, which dictated deployment locations for the initial suite of four ARPs in October 2000 (figure 4). Of the four original recorders, only two were recovered near the deployment site in August 2001; the other two were opportunistically recovered by residents of Nelson Lagoon, Alaska (March 2002), and by a fisherman who pulled an instrument from the water near the international date line (July 2002). While the latter two recoveries were fortuitous—both instruments contained data—they indicated that the ARPs had trouble maintaining position in shallow deployment sites. This view was later reinforced when an ARP deployed on the middle shelf in August 2001 was recovered on a beach in June 2003, again near Nelson Lagoon.

Provisional analyses of the five ARPs deployed on the SEBS middle shelf found that right whale calls occurred from May through November, with the greatest number of calls recorded in September and October (Munger et al. 2005). Calls occurred in bouts lasting several minutes, followed by long quiet periods, and there were very few calls recorded overall. This pattern suggests either that only a few right whales occupy the SEBS middle shelf, that whales simply pass though the area en route to other destinations, or that whales call infrequently while feeding. One key result from the middle-shelf deployments was the discovery that the distance to calling right whales could be estimated from arrival times of the dispersed waveforms of the "up" call in this comparatively flat shallow-water environment (Wiggins et al. 2004). The acoustic waveguide created by the uniform shallow bottom allowed detection of right whale calls at ranges of up to 50–55 kilometers (km), roughly double the anticipated distance.

To expand the acoustic survey for right whales, three ARPs were deployed along the SEBS shelf break in late spring 2004, with one recorder (called a HARP, or high-frequency acoustic recording package) modified to record to 80 kilohertz attached

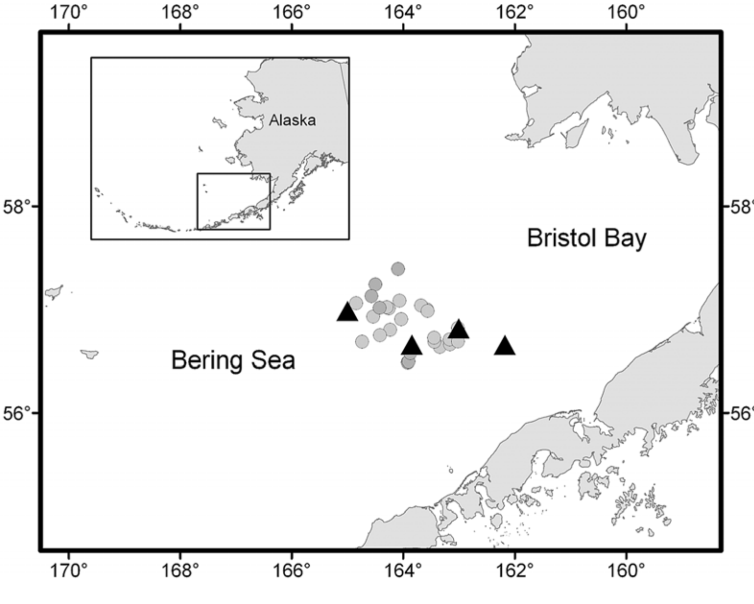

Figure 4. Sighting locations of North Pacific right whales in the southeastern Bering Sea, 1998–2001, with initial deployment locations for four acoustic recording packages (black triangles), October 2000.

to a PMEL mooring on the SEBS middle shelf (figure 2). The middle-shelf HARP was serviced and a new HARP deployed on a second PMEL mooring to the northwest along the 70-m depth contour in autumn 2004. All recorders were recovered and redeployed in spring 2005, with recovery and the initiation of data analysis planned for autumn 2005.

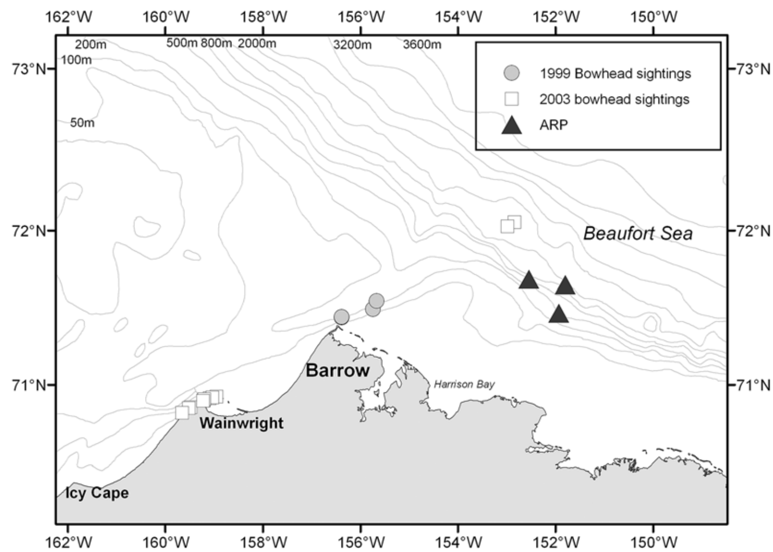

Figure 5. Sighting locations of bowhead whales near Barrow, Alaska, in July 1999 and July 2003, relative to deployment locations for three acoustic recording packages (ARPs) in the western Beaufort Sea.

The western Beaufort Sea

Oceanographic research related to climate variability is expanding in the Arctic, providing opportunities for collaborative investigations of cetacean habitats. One such effort is the Western Arctic Shelf–Basin Interactions (SBI) project (*http://sbi.utk.edu*), a broad, multidisciplinary program investigating the premise that global climate changes influencing biophysical processes have amplified effects in the Arctic ecosystem. With support from the NMML and contributions in kind from SBI principal investigators, three ARPs were deployed in the WBS in early October 2003 and two were recovered in September 2004; the third ARP did not respond to acoustic release commands and could not be recovered.

The recorders, placed near a mooring line operated by Woods Hole Oceanographic Institution, focused on fine-scale sampling of physical oceanographic parameters along the Beaufort Sea slope and in the vicinity of opportunistic sightings of bowhead whales in July 1999 and July 2003 (figure 5). Bowheads usually migrate to the Canadian Beaufort Sea in late spring, and visual and real-time acoustic surveys have censused the migrating population near Barrow, Alaska, every few years since 1978 (Clark et al. 1996, George et al. 2004). Although occasional summertime sightings near Barrow are common (Moore 1992), there is concern on the part of Alaska Native subsistence hunters that changing Arctic climate conditions may be affecting bowhead whale distribution and migration patterns. In addition, hunters have reported increasing numbers of gray whales near Barrow in the late summer and autumn, which may indicate a northward shift in distribution for this species. The two recovered ARPs suffered battery problems, such that a full year of data could not be recovered from either instrument. However, a provisional analysis of extant data confirmed the presence of bowhead whale calls northeast of Barrow during the spring (mid-April through May), with gray whale calls recorded in each month from October 2003 through May 2004. This extended period of occurrence of gray whales in the Beaufort Sea complements observations of feeding whales moving north from the Bering to the Chukchi Sea in summer (Moore et al. 2003), and of a delay of roughly a week in the wintertime southbound migration of gray whales off California (Rugh et al. 2001). All three factors combined suggest that this species may be a good barometer of marine ecosystem variability in the North Pacific.

Future directions: Population assessment, ecosystem modeling, and ocean observation

Because PMEL recorders, ARPs, and HARPs are easily reoutfitted, they can be redeployed anywhere in the world's oceans. This flexibility makes them an ideal tool for basin- to fine-scale assessments of cetacean occurrence and movements. For example, long-distance migration patterns based on call detection have been described for blue whale populations in both hemispheres (Stafford et al. 1999b, 2004). This capability was not available a decade ago. Further development of analytical tools to estimate the distance to calling whales (McDonald and Fox 1999, Wiggins et al. 2004) may one day provide data to support abundance estimation using radial-distance sampling techniques (Buckland et al. 2004). Instrument malfunction remains a concern; with every deployment there have been some recorders that either failed to operate properly or could not be recovered (Stafford 2003, Wiggins 2003). Design improvements will continue on the autonomous instruments, as well as on those that fit on mooring lines.

Since 2003, ARPs have been deployed in tandem with PMEL oceanographic moorings in the Bering Sea (*www.pmel.noaa.gov/foci*), thereby enhancing their capability for modeling the effects of environmental variability on cetacean call detection and seasonal occurrence. Perhaps as important as concurrent acoustic detection and oceanographic measures, however, are the development of call detection tools and the further investigation of whale behavioral ecology. The year-long data sets associated with the recorders demand additional signal processing tools to assist analysts in the timely and accurate identification of calls. To date, spectrogram correlation and neural networks have shown the greatest promise (Mellinger and Clark 2000, Mellinger 2004, Munger et al. 2005). At best, automated detection can accurately identify calls to species, as is the case with sperm whales (Mellinger et al. 2004a); at worst, detectors can identify periods of data for manual examination and call identification, as in the case of North Pacific right whale calls (Mellinger et al. 2004b, Munger et al. 2005).

Although call detection has provided key first-order information on the seasonal occurrence of large whales at unprecedented spatial and temporal scales, the underlying motivation for calling—the behavioral ecology of large whales—remains largely unknown. Initial investigations have revealed diel variation in blue whale calling patterns in the eastern Pacific that may be associated with foraging behavior (Stafford et al. 2005, Wiggins et al. 2005). Long-term studies of fin whales suggest that the patterned 20-Hz pulses often associated with that species may represent a reproductive display, as is thought to be true for humpback whale song and may also be the case for the patterned stereotypic calls of blue and fin whales. Bowhead, right, and gray whales produce a wide variety of calls; some may be simple contact signals, while the meaning of others is unknown (Tyack and Clark 2000). To improve call detection as a tool, researchers need to make additional fine-scale observations, which is possible with tags equipped with acoustic sensors, to provide a baseline for evaluating calling behaviors across a suite of species.

Integrated acoustic systems for ocean observatories are on the horizon (Howe and Miller 2004). Acoustic detection of cetacean calls should become a primary tool incorporated in planned ocean observing systems (*www.ocean.us*) to facilitate the incorporation of these apex predators in marine ecosystem models. A novel effort in this regard could be realized if, for example, PMEL tsunami buoys were outfitted with acoustic sensors, such that whale calls could be received in near real time. Alternatively, acoustic detection capability could be added to extant NOAA weather buoys (*www.ndbc. noaa.gov*), and the aforementioned *ad hoc* program currently in place in the Bering Sea could be augmented by including recorders on PMEL oceanographic moorings. A fundamental difference between conventional acoustic sampling and anticipated ocean observing systems is the potential for real-time or near-real-time sampling across a suite of temporal and spatial scales. Such capability holds promise for (a) quantifying the spatiotemporal distribution of whales, (b) investigating responses to oceanographic variability, and (c) detecting behavioral responses to anthropogenic noise (Howe and Miller 2004). The success of NOAA's nascent program in acoustic detection suggests that such opportunities can be realized as we enter the next decade of ocean exploration.

Acknowledgments

This article is dedicated to the memory of Bill Watkins, a pioneer in open-ocean research on whales and in cetacean call detection and description. Bill was a good friend and mentor, always ready with lively discussions and insights.

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