PAPER

Changing Perspectives in Hawaiian Monk Seal Research Using Animal-Borne Imaging

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ABSTRACT

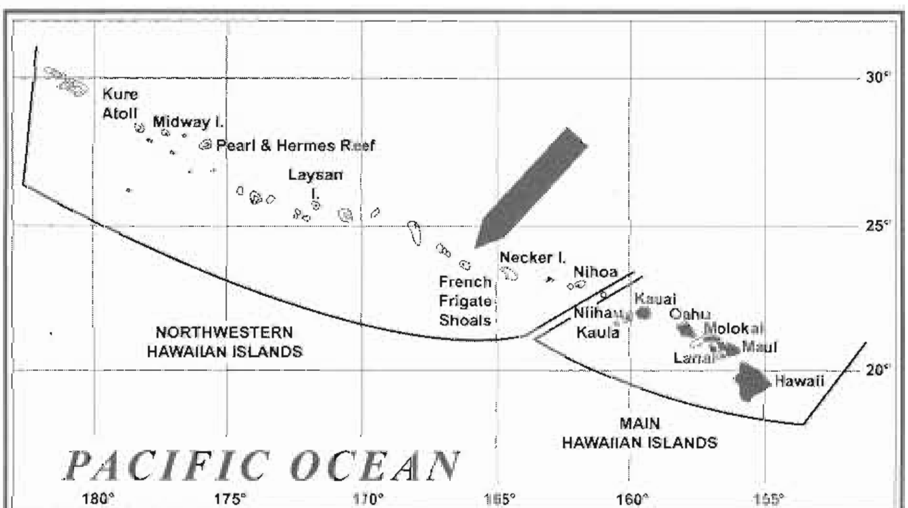
The use of animal-borne imaging devices on the endangered Hawaiian monk seal has greatly helped understand where and how they forage. Those devices provide high-resolution data on the behavior, foraging habitat, and prey of seals, and the ecological community where they live. They have indicated that some monk seals regularly forage in mesophotic (100-300 m) and subphotic (>300 m) habitats rather than just in shallow reef habitats. The collected imagery is also helping to guide the development of further research, conservation, and management plans. Use of animal-borne imaging has resulted in substantial progress in understanding the foraging landscape of monk seals. Any refinements in this technology will certainly inform further population recovery efforts.

Introduction

Animal-borne imaging may be an effective supplemental tool in behavioral research. Indeed, it has greatly enhanced knowledge of the foraging behavior and marine habitat use of Hawaiian monk seals. Hawaiian monk seals are among the last tropical seals on Earth. Retaining similar anatomical features for 13 million years, they are now threatened with extinction. An estimated 1,200 seals live in the Hawaiian Archipelago, virtually all in the remote Northwestern Hawaiian Islands (NWHI) (Figure 1) (Carretta et al., 2006). Since the late 1970s, a considerable amount of effort has been devoted to clarifying the demography and foraging ecology of Hawaiian monk seals using a variety of methods (Baker and Johanos, 2002; Parrish, 2000, 2002, 2005; Stewart et al., 2006). Animal-borne imaging is the latest advancement in research, resulting in important insight about the underwater activities of seals. Here, we review the historical context of monk seal research and then describe the important contributions that animal-borne imaging has made.

FIGURE 1

Map of the Hawaiian Archipelago with major islands and atolls labeled. French Frigate Shoals is the primary breeding colony located in the central portion of the archipelago.



Historical Context

Recovery of Monk Seals

The monk seal population in the NWHI declined substantially during the 20th century owing to direct hunting, disturbance associated with mining of guano, fishing and harvest of bird eggs, the introduction of dogs at seal colonies, and disruption from other human activities. More development and disturbance to the seals came with World War II when airfields, harbors and bases were built to support large-scale military operations. After the war the Hawaiian monk seal population was dangerously low and in need of protection. Consequently, the monk seal was designated as endangered by the U.S. government in 1976. The National Oceanic and Atmospheric Administration (NOAA) was assigned the lead responsibility for research and management of the species.

The earliest monk seal research involved direct and simple classic descriptions of the animals and their habitat by naturalists during expeditions to the remote NWHI (Kenyon and Rice, 1959; Kenyon, 1981). Though some seal species live along continental coastlines, Hawaiian monk seals live on the peaks (islands and atolls) of volcanic pinnacles that rise from the abyssal seafloor of the Pacific plate to form the Hawaiian Archipelago. Seals that populated the six primary colonies in the NWHI seemed isolated and largely restricted to their host atolls. The passing of endangered species and marine mammal protection legislation in the mid-1970s spurred an annual effort of remote field camps to monitor the seal population at each of those sites. Minimizing disturbance initially enhanced the growth of the seal population with the greatest increases at colonies where military or navigational bases closed. For example, French Frigate Shoals (FFS) Atoll, the former site of a Coast Guard station, became a Fish and Wildlife Service research station. FFS rapidly became the primary breeding colony for monk seals in the Northwestern Hawaiian Islands.

Need to Define Critical Habitat

Part of designating the Hawaiian monk seal as an endangered species was to define the critical habitat the seals needed for foraging. The area designated included reef waters (<20 m) adjacent to the sand beaches where the seals hauled out. The seals' diet was thought to be a combination of fish, cephalopods, and crustaceans based on fragments of prey found in seal scats and spews (Delong et al., 1984). In the mid 1980s the population increase at FFS peaked (Figure 2) and in the years since has shown a continuous decline (Gilmartin et al., 1993). Understanding the reasons for that decline became the focus of research investigations in the early 1990s. Eight out of ten pups were dying before their third year (Baker et al., 2006). There was a trap fishery for lobster and a hook and line fishery for deep-slope large bodied snappers and groupers. Both of those fisheries generally operated on the oceanic banks between the atolls that host seal colonies. There was concern that the fisheries might be competing with monk seals for fish.

Emerging telemetry and data logging technology spurred some of the first studies of movement patterns of monk seals. Prior to this, researchers had only been able to attach time depth recorders to seals to see what depths the seals visited most often (Delong et al., 1984). With the availability of seal-mounted satellite transmitters it was determined that many of the seals were routinely making oceanic transits to neighboring banks (Abernathy, 1999; Stewart et al., 2006), movements that had previously been thought uncommon. Complementary studies with captive seals that examined the dynamics of digestion on various prey found that seals digest and pass a meal in less than eight hours, meaning that the scats found on the beach might represent prey only from the closest reefs (Goodman-Lowe, 1998; Goodman-Lowe et al., 1999). Collectively, those data suggested that seals could be feeding at distant locations on different prey types and excreting all the evidence of their meal before they got back to the beach.

Early reports that suggested reef habitats as the primary foraging habitat of endangered Hawaiian monk seals were inconsistent with data emerging from recent telemetry studies. But the spatial resolution of locations derived from satellite tracking of foraging seals was too coarse to document the use of the diverse habitats that occur over very small areas at and near atolls.

Animal-Borne Imaging

Between 1995 and 2003, deployment of CRITTERCAMs (Marshall, 1998) on Hawaiian monk seals was an annual element of studies of their foraging ecology at FFS (Figure 3). For the first time biologists were able to see the habitats the seals were visiting, the fish that lived there, and the tactics that seals used to catch them. Initial deployments focused on adult males, the most robust group of seals. The cameras were glued to the hair on the seals' backs so that the recorded images showed the area in front of the seal and its head visible in the lower central portion of the frame. The CRITTERCAM also recorded sound, and archived measurements of temperature and dive depth and duration. An on-board computer controlled camera operation based on pre-determined recording regimes. The computer could be programmed to record periodically by time interval, or only when wet, or by depth or temperature threshold. Because the foraging habitat of monk seals can range from a meter deep in fringing reefs to several hundred meters at subphotic depths, video recordings were made for 90 seconds every 15 minutes regardless of depth. In general, the CRITTERCAMs were removed from seals when they hauled out within about a week after attachment.

During the years that CRITTERCAMs were deployed on adults the cameras were reduced in size so they could be attached to juvenile seals. The juvenile segment of the seal population suffers the highest mortality and injury from shark predation and entanglement in active or derelict fishing gear (Bertilsson-Friedman, 2002; Henderson, 1984, 2001). Juvenile seals also appeared to be in poorer physical condition than adults, suggesting the limited prey availability might account for their poor condition and low survival at FFS. Emaciated seals are most commonly seen dur-

FIGURE 2

Declining trend in annual beach counts of seals and pups born at French Frigate Shoals. Photo inset is of a starving young monk seal

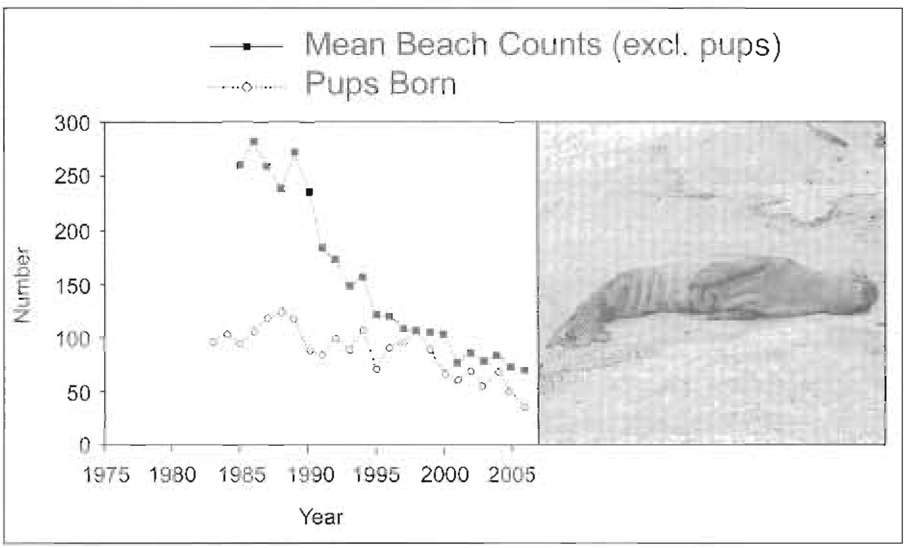
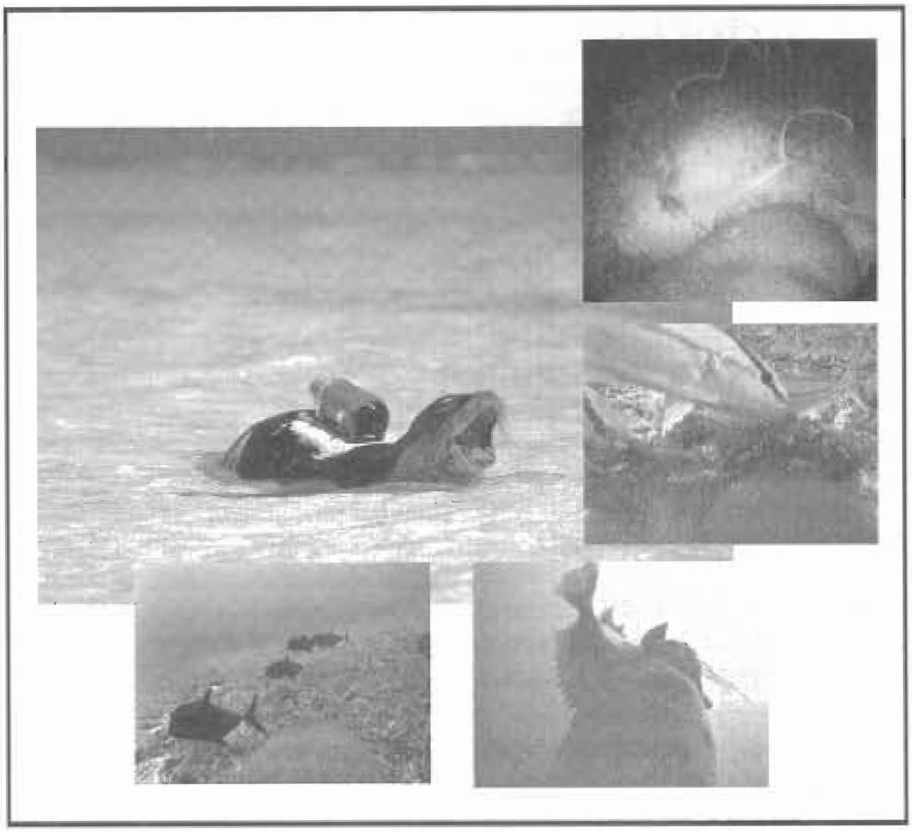


FIGURE 3

Photo of an adult monk seal fitted with the CRITTERCAM animal-borne imaging device. Insets are frame captures from the CRITTERCAM video.



ing their first year and less common by the time they are three for those that survive. The smaller CRITTERCAMs provided an opportunity to document the transition of pups from suckling to foraging independently once weaned when four to six weeks old.

Findings—Adult Males

Foraging time

Thirty five adult males were outfitted with CRITTERCAMs between 1995 and 2000. The resulting data provided new remarkable insight about the foraging behavior and foraging habitats of Hawaiian monk seals. The video images demonstrated that seals spent about half their time, when at sea, interacting with other seals, vocalizing into open water, or sleeping in underwater caves (Parrish et al., 2000). Most seals that were observed feeding traveled outside the atoll onto the deep slope rubble fields and sand terraces to find prey. Some transited through oceanic waters to neighboring banks where they foraged on summits and deep slopes that were thought previously to be too distant to use. Seals often ate the same type of reef fish that they swam by and ignored when in shallow reef habitats. Prey items larger than 20 cm were rarely eaten (Parrish et al., 2002, 2005). Seals were seen to eat octopus, lizard fish, flatfish, sand wrasses, trigger fish, and eels.

Foraging habitat

Seals used different feeding tactics in different habitats. Some seals specialized by searching sand fields and were adept at digging out wrasses and eels by burrowing their heads deep (~45 cm) in the sand to capture the hiding fish. Other seals sequentially searched large loose rocks, sometimes a meter across and weighing more than 20 kg. They would slip their head and shoulders under to move the rock and eat prey hiding beneath. Five of the cameras deployed were equipped with night vision to document feeding activities at night. These cameras had a ring of red light emitting diodes around the lens that was enhanced for recording with an image intensified lens. The five seals were fitted with these cameras and all that fed were seen to travel outside the atoll to find food on the deep slopes. Some feeding occurred in the shallows as the seals were en route to spending most of their time feeding on the slope. Three of the seals visited some patches of filamentous black corals on the slope that sheltered a large number of eels (Parrish et al., 2002). One seal was documented to commute between its favorite resting cave in the atoll lagoon during the day and out to the black coral patch at night and some seals that swam offshore and dove to subphotic depths of 300 m or more. Because those seals were not equipped with night vision cameras, feeding was confirmed by sounds of the seal interacting with the bottom recorded by the hydrophone. One exception was a video segment where a seal ascended into illuminated depths carrying a 30 cm fish in its mouth.

Findings—Juveniles

Nine juveniles (male and female) between the ages of 1 and 3 were instrumented with the smaller camera systems. Unexpectedly, the first year seals (FYS) did not feed in the shallows of the atoll; instead they traveled out on to the deep sand fields at 100 m where the adults feed (Parrish et al., 2005). The two- and three-year-old seals spent more time foraging in shallower habitats including searching under rocks to catch small fish hiding underneath. In one video segment a FYS was observed making an unsuccessful attempt to flip over a large rock.

Camera effects

All the CRITTERCAMs were deployed on healthy juvenile seals, so the data obtained is assumed to represent good foraging habitat and viable feeding strategies. Juveniles that were clearly emaciated couldn't be burdened with the CRITTERCAM and it is unknown what habitats and prey those seals were trying to exploit. Littnan et al. (2004) evaluated the effect of the camera attachment on the seals behavior by deploying 10 time-depth recorders (TDR) to compare dive records of the same seals during and after the CRITTERCAM deployments. A total of six TDR records were available to compare foraging behaviors with and without the camera systems. Dive variables, such as depth, duration, and descent/ascent rates, did not significantly differ. Cumulative effects on foraging trip duration and percent time submerged were not detected. These results suggested the cameras were not a substantial impact to the seals for short deployments (Littnan et al., 2004). The condition and well-being of the seals was verified over successive years of follow-up surveys and all the seals were alive and in good condition (Baker and Johanos, 2002).

New Research Directions

Animal-borne imagery helped interpret data from dive recorders and satellite tags and provided a guide to invest our conventional research tools. CRITTERCAM served as a "compass" which directed how to apply or even develop new research tools. Some examples are listed below.

Sand Trawls and the Link to Changing Oceanography

The sand fields on the terraces of the deep slope were identified as an important forage grounds for the seals. Parrish et al (2005) estimated that FYS that foraged there ate around ~1.0 kg of fish each day when foraging. That quantity is consistent with the daily feed weight of juvenile seals held in captivity. Knowing this, researchers could now use small conventional bottom trawls to estimate the abundance of seal prey in the sand and develop an annual index of prey recruitment. Flounder account for most of the prey in those habitats and range between 5 and 12 cm in length. Larval flounders, which are an abundant component of the plankton, settle at 3 cm and grow quickly, attaining a size of 10 cm (the size seals feed on) in as little as 6 months. The rapid growth of flounders and other sand fish may be the best link yet identified between the abundance of monk seal prey and variable oceanography.

Re-evaluation of Satellite Telemetry

Data from the CRITTERCAMs supported findings from earlier telemetry studies and indicated a greater amount of foraging at deeper depths relative to shallow habitats (Abernathy, 1999; Stewart et al., 2006). This prompted a re-evaluation of the subphotic component of previous satellite dive data (Abernathy, 1999). Even though deeper diving was a small percentage of the diving activity of the seals with satellite tags, the CRITTERCAM data suggested it was all foraging behavior. Review of prior satellite positions in the FFS region revealed that the subphotic dives occurred over the span of months and were made by some seals with a concentration of positions at two locations (Parrish et al., 2002). At shallower depths CRITTERCAM had shown some monk seals to target specific habitats and it was possible that the seals diving to subphotic depths had found some similar patch habitat. Surveys conducted using the Hawaii Undersea Research Laboratory's *Pisces* submersibles revealed beds of deepwater corals (Parrish et al., 2002). Similar surveys made in adjacent areas where seals didn't concentrate their subphotic foraging found no coral and were barren basalt and carbonate bottom. The seals' use of this habitat seemed analogous to the seals with the CRITTERCAM commuting to the patches of whip corals to feed on eels at shallower slope depths.

Prey Biomass Surveys

The seals' use of subphotic depths as feeding grounds prompted a survey of prey resources in the subphotic. Fish assemblages close and distant from the major seal colonies were compared and revealed regional differences in prey where low biomass corresponded with a location close to seal colonies and high biomass was distant from seal colonies (Parrish, in review). It is unknown whether this indicates prey resources are approaching carrying capacity for monk seals, or if these differences are the result of other ecological processes, or if it's some combination of both factors.

Competition with Other Apex Predators

The 42 CRITTERCAMs deployed on monk seals showed that seals were often followed by an entourage of large jacks and sharks. These predators follow the seals closely waiting for them to flush prey from hidden location, which they would then compete for (Parrish et al., in review). It is unknown how much prey seals lose to these uninvited escorts and whether this could partially explain why young seals appear to suffer the worst survivorship.

Conclusions and Future Applications

Our impressions of monk seals as provincial animals that stay close to the beaches on which they rest have clearly changed to that of an animal that travels inter-island and has an enviable knowledge of the archipelagos' submarine landscape. The change in this perspective is largely due to advances in seal-mounted instruments including dive recorders, satellite tags and, most notably, imaging devices such as CRITTERCAM. Several studies remain to better understand the ecology of the species and develop successful conservation strategies. One of the most intriguing observations has been the increase of monk seals in the main Hawaiian Islands—an area with extensive fishing. The seals exhibit better body condition than seals in the remote Northwestern Hawaiian Islands, and telemetry studies indicate that the seals don't have to travel far to obtain their daily ration of food (Littnan, Pers. comm.). Reasons for this difference are unknown. One hypothesis is that fishing in the main islands may have removed many of the jacks and sharks that compete directly or indirectly for the same prey seals eat. Continued development of seal-mounted imaging technology is essential to advance research efforts and assist the recovery efforts of the endangered Hawaiian monk.

The application of CRITTERCAMs to ecological studies of monk seals has proven extremely valuable. Despite the great success of these systems, they could be improved by increasing the functionality and capacity, shifting to solid-state technology, and decreasing the size and mass. Key additions would be: environmental and biological sensors (e.g., temperature, salinity, sophisticated acoustic recorder); high-resolution GPS system, and greater integration of movement data (i.e., dive depth, video, and location). The value of each deployment would be greatly increased by extending the battery life and amount of data that can be recorded. Shifting to solid-state technology will reduce instrument failure resulting from harsh treatment of the cameras when they are deployed (i.e., monk seals continually smashing cameras against rocks as they flip them). However, all of these additions must balance with the need for maintaining a small package that limits drag on study animals and will allow for longer deployments.

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