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# Abundance and densities of beaked and bottlenose whales (family Ziphiidae)

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ABSTRACT

Estimating the abundance and density of beaked whales is more difficult than for most other cetacean species. Consequently few estimates appear in the published literature. Field identification is problematic, especially for the smaller species, and visual detection rates decrease dramatically with Beaufort sea state; prior experience is very important to an observer's ability to detect beaked whales. Passive acoustics may hold future promise for detecting beaked whales from their vocalisations, especially for the larger species. Most published estimates of abundance or density are based on visual line-transect studies that found narrower effective strip widths and lower trackline detection probabilities for beaked whales than for most other cetaceans. Published density estimates range from 0.4-44 whales per 1,000km$^2$ for small beaked whales and up to 68 whales per 1,000km$^2$ for large beaked whales. Mark-recapture methods based on photo-identification have been used to estimate abundance in a few cases in limited geographical areas. Focused research is needed to improve beaked whale abundance and density estimates worldwide.

KEYWORDS: ABUNDANCE ESTIMATE; *g*(0); MARK-RECAPTURE; SURVEY-VESSEL; SURVEY-AERIAL; SURVEY-ACOUSTIC; BEAKED WHALE; MODELLING; DISTRIBUTION; ACOUSTICS; PHOTO-ID

## INTRODUCTION

Despite their nearly ubiquitous distribution in the world's oceans, there are few estimates of the density or absolute abundance of beaked whales. In part, this is because many surveys have concentrated on continental shelf waters, where beaked whales are rare. However the lack of estimates largely reflects the general rarity and difficulty in detecting and identifying beaked whales under typical survey conditions. There is a growing recognition that mass strandings of beaked whales have been associated with loud anthropogenic sounds, such as military sonar (e.g. Anon., 2001) and possibly geophysical research (Peterson, 2003). Consequently, there is a growing need for information about the abundance and density of beaked whales to allow us to better (1) evaluate the risks that anthropogenic sounds pose to specific beaked whale populations and (2) monitor and mitigate those effects at the population level.

In this paper, some of the problems encountered when making quantitative estimates of abundance or density for beaked whales are examined, studies where abundance or density was estimated are reviewed and recommendations for research to help fill gaps in current knowledge are made.

### Field identification

Throughout this paper, large (6-13m) beaked whales (*Berardius* spp., *Hyperoodon* spp., and *Indopacetus pacificus*) and small (4-7m) beaked whales (*Ziphius cavirostris, Mesoplodon* spp. and *Tasmacetus shepherdi*) are differentiated between because their detectabilities differ markedly. Field identification is a major problem in estimating the abundance of small beaked whales. Although Cuvier's beaked whales (*Z. cavirostris*), Tasman beaked whales (*T. shepherdi*), and *Mesoplodon* spp. are physically distinctive at close range, all three genera appear similar at distance; medium-sized, brown to grey in colour, with dorsal fins located closer to flukes than to head. The elusive behaviour of small beaked whales in the presence of survey ships often prevents close approaches to verify species identification. The typical duration of a surfacing series for Cuvier's and *Mesoplodon* beaked whales is only 2-3mins (Barlow, 1999), leaving little time for observation. Their long dives (typically 15-40mins; Barlow and Sexton, 1996) substantially reduce the opportunity to relocate groups and to verify species under average survey conditions. Within the genus *Mesoplodon*, field identification of species is even more problematic. For many species, field identification is impossible for juveniles or females, therefore only groups with mature males may be identified to species. To further compound problems, three to five species of *Mesoplodon* may be sympatric in a given area (MacLeod *et al.*, 2006). Finally, the taxonomy of the genus *Mesoplodon* is still being resolved, with two new species described in the last 15 years (Reyes *et al.*, 1991; Dalebout *et al.*, 2002). Consequently, most *Mesoplodon* sightings are identified only to genus, and many sightings of small beaked whales may be field-classified as 'unidentified ziphiid'.

Species identification is less of a problem for the large beaked whales because the species are physically more distinctive and are often easier to approach. Of the five species, only the southern bottlenose whale (*H. planifrons*) and Arnoux's beaked whale (*B. arnuxii*) overlap in distribution (MacLeod *et al.*, 2006), which eliminates potential confusion in tropical and northern latitudes. However, the external morphology of Longman's beaked whale (*I. pacificus*) was described only recently and many previous sightings of this species were attributed to *Hyperoodon* spp. (Pitman *et al.*, 1999; Dalebout *et al.*, 2003). Although Longman's beaked whales overlap in size with adult Cuvier's beaked whales, we have included the

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former with the large beaked whales because their larger group sizes and conspicuous blows make them more similar in detectability to the other large beaked whales.

## Detecting beaked whales

Small beaked whales are more difficult to visually detect in the field than most other cetaceans, with the exception of *Kogia* spp. and some porpoises. They typically surface inconspicuously, usually without a splash or visible blow and seldom breach or display other aerial activities. In addition, small beaked whales rarely display their flukes when they dive and they occur in small groups, typically 1-5 individuals. Finally, they spend very little time at the surface and then dive for extraordinarily long periods (Barlow, 1999). In contrast, the visual detection of large beaked whales is easier because they have a conspicuous blow and are physically larger. However, large beaked whales also have relatively long dive times compared to other cetaceans (Kasuya, 1986; Barlow, 1999; Hooker and Baird, 1999), which reduces their detectability by visual observers.

### *Sea state*

The group encounter rate (number of groups seen per unit of search effort) can be used as a rough measure of how the ability to visually detect beaked whales changes with sighting conditions. Sea state is the most commonly used measure of sighting conditions for cetacean surveys. Encounter rates can change dramatically with increasing sea states (Table 1), decreasing more than 10-fold from Beaufort 0-1 (glassy or with a few ripples, wind speed 0-3kts) to Beaufort 5 (moderate waves with many whitecaps, wind speed 17-21kts). Visual surveys for cetaceans are generally not conducted above Beaufort 5.

Table 1

Changes in the encounter rates (ER = number of sightings per 1,000 km of survey effort) with Beaufort sea state for small beaked whales (genera *Mesoplodon* and *Ziphius*). Survey effort consisted of a team of at least three observers in all cases*.

| | SWFSC: 1986-2002 | | SEFSC: 1991-2003 | | NEFSC: 1998 | |
|---|---|---|---|---|---|---|
| Beaufort sea state | No. sightings | ER (per 1,000 km) | No. sightings | ER (per 1,000 km) | No. sightings | ER (per 1,000 km) |
| 0 | 16 | 9.8 | 11 | 16.8 | n/a | n/a |
| 1 | 122 | 10.1 | 45 | 7.2 | 32 | 145.0 |
| 2 | 169 | 4.9 | 18 | 1.4 | 44 | 23.9 |
| 3 | 175 | 2.4 | 26 | 1.2 | 18 | 7.2 |
| 4 | 180 | 1.5 | 5 | 0.2 | | |
| 5 | 76 | 0.9 | 6 | 0.5 | | |

*Data are from Southwest Fisheries Science Center surveys in the eastern Pacific (SWFSC: Ballance, Barlow, and Gerrodette, unpubl. data); Southeast Fisheries Science Center surveys in the Gulf of Mexico, Caribbean, and North Atlantic (SEFSC: Hansen, Hoggard, Garrison and Mullin, unpubl. data); and Northeast Fisheries Science Center surveys in slope and offshore waters of the North Atlantic (NEFSC: Palka and Waring, unpubl. data).

### *Experience*

The importance of observer experience in detecting beaked whales has not been examined previously. This paper examines data from Southwest Fisheries Science Center (SWFSC) surveys in the eastern tropical Pacific (ETP) to quantify the effect of experience. The surveys from 1986-1990 and 1998-2000 were used since these covered almost exactly the same study area (Fig. 1), and thus geographic differences in sighting rates is not a confounding factor. Observers were classified by previous experience on SWFSC or Southeast Fisheries Science Center (SEFSC) line-transect surveys as follows: (1) first-time observers; (2) observers with at least four months of previous at-sea experience as a marine mammal observer; and (3) observers with at least 12 months of at-sea experience. Note, however, that even first-time observers had some previous cetacean research experience and in some cases, had considerable at-sea experience (e.g. as fishery observers). Ability to detect beaked whales was estimated as the number of beaked whales (i.e. sightings identified as Cuvier's beaked whales, *Mesoplodon* beaked whales and unidentified ziphiid whales) detected by each observer per 1,000km of transect surveyed by that observer in a given survey year. Analysis of variance (ANOVA) was used to test whether *experience*, *survey year*, or *observer* were significant factors in explaining variation in beaked whale sighting rates, which were weighted by the length of transect surveyed by an observer in a given year.

Results of the ANOVA indicate that *experience* was a significant factor in explaining differences in sighting rates among observers ($p<0.0001$). The effects of *year* ($p=0.90$) and *observer* ($p=0.22$) were not significant when *experience* was included in the model. Mean sighting rates were 0.54 per 1,000km for first-time observers, 0.67 per 1,000km for observers with 4-11 months prior experience and 0.93 per 1,000km for observers with at least 12 months prior experience. The analysis only considered the ability of an observer to detect a beaked whale and not necessarily his/her ability to identify one. Since observers work in teams of three and each team has at least one very experienced observer (the identification expert), the difficult species were often identified by someone other than the observer who made the initial sighting. There were only 20° of overlap in search angles between the right and left observers, so the presence of a more experienced observer should not have appreciably affected the sighting rate of the observer on the opposite side of the vessel. However, this lack of complete independence may have exaggerated the $p$-value in the above comparison of sighting rates, if more experienced observers were also more likely to see beaked whales first.

### *Acoustic detection*

Although visual detection has been used on all previous surveys, passive acoustic detection (listening for sounds produced by beaked whales) offers the potential to detect submerged whales. The value of acoustic detection will depend on how frequently the whales vocalise and how easily those vocalisations can be detected. Until recently, very little was known about beaked whale vocalisations. Studies of captive and stranded whales suggested that beaked whales are capable of producing both pulsed sounds (clicks) and whistles (Dawson *et al.*, 1998). Ljungblad (cited in Dawson *et al.*, 1998) recorded ultrasonic clicks in the vicinity of a *Mesoplodon* whale. Frantzis *et al.* (2002) recorded narrow-banded, 13-17kHz clicks in close proximity to Cuvier's beaked whales and Johnson *et al.* (2004) recorded clicks ranging from 20kHz to over 40kHz using recorders that were physically attached to Cuvier's beaked whales. However, many efforts to record sounds in the vicinity of free-ranging Cuvier's and *Mesoplodon* beaked whales have been unsuccessful (Barlow *et al.*, 1997; Barlow and Rankin, unpubl. data), indicating that sound production may not be common in the smaller beaked whales, or that their sounds do not propagate well to surface hydrophones. Large beaked whales in the genera *Berardius* and *Hyperoodon* make more consistent vocalisations that can be detected at the surface (Hobson and Martin, 1996;

Dawson *et al.*, 1998; Hooker and Whitehead, 2002). Passive acoustics may add appreciably to our ability to detect *Berardius* and *Hyperoodon* species when they are submerged. Two attempts to record Longman's beaked whales (in mixed groups with short-finned pilot whales, *Globicephala macrorhynchus*) failed to detect sounds that could unambiguously be attributed to that species (Rankin and Barlow, unpubl. data). The narrow-banded characteristic of clicks from Cuvier's beaked whale (Frantzis *et al.*, 2002; Johnson *et al.*, 2004), Baird's beaked whale (*B. bairdii*; Dawson *et al.*, 1998), and the northern bottlenose whale (*H. ampullatus*; Hooker and Whitehead, 2002) distinguish them from clicks of many other species and if this pattern holds elsewhere, digital filters could be designed to greatly improve our ability to acoustically detect beaked whales. Currently, however, methods to routinely incorporate acoustic detections into abundance estimation surveys are not well developed (Mellinger and Barlow, 2003) and have never been used for beaked whales.

## Line-transect abundance estimation

Most previous abundance or density estimates for small beaked whales have been based on visual line-transect methods. The basic line-transect equation for estimating density, $D$, in a defined study area is:

$$D = \frac{n \cdot S}{2 \cdot L \cdot ESW \cdot g(0)} \qquad (1)$$

where:
$n$ = number of sightings;
$S$ = expected (or mean) group size;
$ESW$ = effective strip half-width;
$L$ = total length of transects in the study area; and
$g(0)$ = probability of detecting an animal on the trackline.

Abundance, $N$, is estimated by multiplying density by the size of the study area, $A$.

*ESW* is estimated by fitting an empirical function, the detection function, to the distribution of perpendicular sighting distances. A minimum sample size of 60 sightings is recommended for estimating a detection function (Buckland *et al.*, 2001), and ~15 sightings is an absolute minimum. As the encounter rate is typically low for small beaked whales and decreases rapidly with increasing sea state, sample size is often an impediment to estimating beaked whale abundance. Although it is recommended that detection functions are fitted to data from each specific survey (a combination of ship, area, personnel, and sea conditions), 15 beaked whale sightings would not be made during most surveys. As a result, most estimates of beaked whale abundance or density have pooled data from multiple surveys to estimate *ESW*. To obtain an adequate sample size for estimating *ESW*, some authors have used pooled sighting distributions of several species, such as Cuvier's and *Mesoplodon* beaked whales (Forney *et al.*, 1995), all beaked whales (Kasamatsu and Joyce, 1995) or small beaked whales with other small whale species (Barlow, 1995; Mullin and Fulling, 2003). There is a trade-off between the improved precision obtained by pooling species and the potential biases that could result from pooling. Barlow *et al.* (2001) showed that when modelling perpendicular distance (a surrogate for *ESW*) a species-pooling scheme that combined Cuvier's beaked whales, *Mesoplodon* beaked whales and minke whales (*Balaenoptera acutorostrata*) resulted in a more parsimonious model based on Akaike's Information Criterion (AIC) than a model that included all species separately. Thus, at least in some cases, the trade-off appears to favour pooling species of similar size, behaviour and sighting characteristics.

Estimating the probability of detecting an animal on the trackline, $g(0)$, is also critical for estimating abundance or density for most beaked whales. Animals can be missed on the trackline either because they were at the surface and were not seen (i.e. perception bias) or because they were never at the surface within the visual range of the observers (i.e. availability bias) (Marsh and Sinclair, 1989). Both types of bias affect beaked whale density estimates. As discussed above, beaked whales are difficult to detect and to identify, leading to perception bias. They also have long dive times (Kasuya, 1986; Kasamatsu and Joyce, 1995; Barlow, 1999), leading to availability bias. To minimise these biases, line-transect data for the small beaked whales are often limited to the best survey conditions (e.g. Beaufort sea state $\leq 2$; Barlow, 1995). However, even under these conditions and using 25X binoculars to extend sighting distances, many trackline animals may be missed. Two methods have been used to estimate $g(0)$ for beaked whales: independent observer methods using multiple observation locations from a single ship or aircraft (to estimate perception bias only) and model-based methods (to estimate perception and/or availability bias). Barlow (1995) pooled beaked whales with other small whales to obtain an estimated $g(0)$ value of 0.84, using conditionally independent observer methods. Miyashita (1986) estimated a $g(0)$ value of 0.84 to correct availability bias for Baird's beaked whales based on a dive-time simulation model. Kasamatsu and Joyce (1995) and Barlow (1999) made model-based estimates of $g(0)$ for beaked whales that included diving and detection models, thereby accounting for both availability and perception bias during shipboard surveys. Based on the use of 7X binoculars in sea states of Beaufort $\leq 5$, Kasamatsu and Joyce (1995) estimated that $g(0)$ for southern bottlenose whales was approximately 0.27 (CV=0.04). Based on SWFSC surveys using 25X binoculars, Barlow (1999) estimated that $g(0)$ was approximately 0.23 (CV=0.35) for Cuvier's beaked whales and 0.45 (CV=0.23) for *Mesoplodon* whales in Beaufort 0-2 survey conditions and was 0.96 (CV=0.23) for Baird's beaked whales in Beaufort 0-5 conditions. Values of $g(0)$ for Cuvier's and *Mesoplodon* beaked whales have not been estimated for sea states of Beaufort $\geq 3$, but based on the decline in encounter rates, we can infer that values would be dramatically lower in rougher conditions.

Values of $g(0)$ for beaked whales on aerial surveys have only been estimated once and then only to account for perception bias ($g(0)$=0.95; Forney *et al.*, 1995). Given their long dive times and short surface times, availability bias is likely to be an even bigger problem for beaked whale abundance estimates derived from aerial surveys than from vessel-based surveys. A crude estimate of $g(0)$ for availability bias in beaked whales can be made by estimating the fraction of time they spend in surfacing series, assuming that animals are visible from the air during the entirety of a surfacing series. Based on published dive and surface times (Barlow, 1999), these crude $g(0)$ values would be 0.11 for *Mesoplodon* beaked whales, 0.07 for Cuvier's beaked whales and 0.18 for Baird's beaked whales. These small values still probably overestimate the $g(0)$ values for beaked whales on aerial surveys because they do not include corrections for perception bias.

Reactive movement of beaked whales in response to survey vessels can also bias line-transect estimates of density and abundance. Small beaked whales are often referred to as 'shy' (Leatherwood *et al.*, 1988) and may avoid vessels by diving (Heyning, 1989). The perceived shyness and avoidance behaviour may be an erroneous interpretation of their normal short surface and long dive times. Recently, both Bainville's (*M. densirostris*) and Cuvier's beaked whales have been approached by small boats for photo-identification and suction-cup tagging (Johnson *et al.*, 2004; R. Baird, pers. comm.). Northern bottlenose whales are often described as 'curious' and may be attracted to stationary vessels (e.g. Whitehead *et al.*, 1997). Currently it is not possible to say whether movement in response to survey vessels is introducing any appreciable bias in line-transect estimates.

The difficulty in identifying species of beaked whales at sea and the resulting high incidence of 'unidentified beaked whales' on most surveys poses other problems for abundance estimation. The sightings of unidentified beaked whales can be treated as an independent category for estimating *ESW* and *g*(0), or they can be pooled with other sightings that were identified to species or genus for estimating these line-transect parameters. In either case, the abundance of unidentified beaked whales can be prorated into other species categories based on the relative abundance of the other categories, or the abundance of unidentified beaked whales can be reported separately. One problem with separate analysis of *ESW* and *g*(0) is that beaked whales that are seen at greater distance may be more likely to remain unidentified. Barlow *et al.* (2001) showed that unidentified small beaked whales were seen on average at greater perpendicular sighting distances than Cuvier's or *Mesoplodon* beaked whales. Consequently, the line-transect assumption that animals are uniformly distributed relative to the trackline may be violated. For this reason, it may be best to pool all small beaked whales (including unidentified small beaked whales) when estimating line-transect parameters.

Previous line-transect abundance estimates for beaked whales are summarised in Table 2. Estimates from three major ocean basins are discussed below.

### *Pacific Ocean*

Miyashita (1986) and Miyashita and Kato (1993) estimated the abundance of Baird's beaked whales in slope waters west of Japan based on ship surveys in 1984, 1991 and 1992. They used a *g*(0) estimate from Miyashita (1986) to correct for diving whales that were missed. In both of these studies, abundance was only estimated for strata that contained sightings of Baird's beaked whales, so the density estimates in Table 2 (40 to 68 animals per 1,000km$^2$) are higher than the density would be for the entire study area. Wade and Gerrodette (1993) estimated the abundance of Cuvier's and *Mesoplodon* beaked whales in the eastern tropical Pacific based on 1986-90 SWFSC ship surveys. However, their study assumed that *g*(0) was 1.0 and included Beaufort sea states of 0 to 5, so abundances and densities were certainly underestimated. Barlow (1995) estimated the abundance of Cuvier's beaked whales, *Mesoplodon* beaked whales, unidentified small beaked whales and Baird's beaked whales based on a 1991 summer/fall ship survey within 556km (300 n.miles) of the coast of California and Forney *et al.* (1995) estimated the abundance of unidentified small beaked whales based on winter 1991 and 1992 aerial surveys within 185km (100 n.miles) of the coast of California. Both Barlow (1995) and Forney *et al.* (1995) used estimates of *g*(0) to account for perception bias but did not account for availability bias. Barlow (2003b) re-estimated beaked whale abundance in California waters and expanded estimates to Oregon and Washington waters based on new survey data. In this analysis and all subsequent analyses of the Pacific surveys, observations were limited to Beaufort sea states 0-2 and model-based estimates of *g*(0) (Barlow, 1999) were used to account for both perception and availability biases. Ferguson and Barlow (2001) re-analysed all SWFSC ship survey data from 1986-96 (using the new *g*(0) estimates) and estimated abundances and densities stratified by 5° (latitude and longitude) rectangles for the eastern tropical Pacific, Gulf of California, and US west coast study areas. Barlow (2006) estimated the abundance of beaked whales in the US Exclusive Economic Zone (EEZ) around Hawaii using multiple-covariate methods, with *ESW* and *g*(0) estimates that were based on previous SWFSC surveys in the eastern Pacific. For Cuvier's beaked whale in the Pacific, the highest densities were found in the southern Gulf of California (38 animals per 1,000km$^2$). For *Mesoplodon* beaked whales in the Pacific, densities were again highest in the southern Gulf of California (6.4 animals per 1,000km$^2$).

### *Atlantic Ocean and Gulf of Mexico*

Beaked whale abundance and density were estimated from ship surveys around Iceland (Gunnlaugsson and Sigurjónsson, 1990), from aerial surveys along the US northeastern coast (Winn, 1982), from ship surveys along the US eastern coast (Mullin and Fulling, 2003) and from ship and aerial surveys in the Gulf of Mexico (Hansen *et al.*, 1995; Mullin and Hoggard, 2000; Mullin and Fulling, 2004; Mullin *et al.*, 2004). Study areas included shelf, slope and deep waters. In the study around Iceland, abundance was estimated only for northern bottlenose whales; the other researchers estimated abundance only for small beaked whales. All small beaked whales were pooled for estimating *ESW*, and for some studies, beaked whales were also pooled with other 'cryptic species' to estimate *ESW*. In the Atlantic and Gulf of Mexico, the highest beaked whale densities were estimated from aerial surveys in the Gulf of Mexico (1.5 animals per 1,000km$^2$; Mullin *et al.*, 2004).

### *Southern Ocean*

In Antarctic waters, Kasamatsu and Joyce (1995) estimated the pooled abundance of all beaked whales based on ship-based sighting surveys conducted in 1976-88 in Beaufort sea state $\leq$5. The study area ranged from the Antarctic pack ice edge or continental edge northward, with most survey effort being south of 60°S latitude. The majority of identified beaked whale sightings were southern bottlenose whales (*H. planifrons*). They estimated *g*(0) using a model of dive times and a simulation of the sighting process. Overall densities in this enormous study area were very high (20 animals per 1,000km$^2$).

## Mark-recapture abundance estimation

Photo-identification coupled with mark-recapture can also be used to estimate beaked whale population sizes. Many species of beaked whales are highly marked with scars and should be readily identifiable. Extensive photo-identification catalogues have been developed for small beaked whales in the Bahamas (Claridge *et al.*, 2001) and for northern bottlenose whales in 'The Gully' – a submarine canyon off Nova Scotia (Whitehead *et al.*, 1997). To date, mark-recapture abundance estimates have been made only for the Gully population of northern bottlenose whales. In one study (Gowans *et al.*, 2000), 66% of animals were estimated to have reliable long-term marks and the population size was estimated to be about 130 (95% CI=106-166). The range of this population outside the Gully

Table 2

Summary of line-transect abundance and density estimates for beaked whales. Average densities are estimated by dividing the total abundance by the size of the total study area. The basis for *g*(0) estimates include independent observer (IO) and model-based methods and can include corrections for perception bias (PB) and/or availability bias (AB).

| Study region | Total area km$^2$ | Overall abundance | Overall density per 1,000km$^2$ | CV | Beaufort sea state range used | *ESW* km | *g*(0) | *g*(0) basis | Notes |
|---|---|---|---|---|---|---|---|---|---|
| **NORTH PACIFIC** | | | | | | | | | |
| **Japanese eastern slope waters, 1983 (Miyashita, 1986)** | | | | | | | | | |
| *B. bairdii* | 61,970 | 4,220 | 68.1 | ~0.30 | 0-5 | 2.49 | 0.84 | Model, AB | 1 |
| **Japanese eastern slope waters, 1991-92 (Miyashita and Kato, 1993)** | | | | | | | | | |
| *B. bairdii* | 124,606 | 5,029 | 40.4 | ~0.56 | 0-5 | 1.35 | 0.84 | Model, AB | 1 |
| **Eastern tropical Pacific ship surveys, 1986-90 (Wade and Gerrodette, 1993)** | | | | | | | | | |
| *Z. cavirostris* | 19,148,000 | 20,000 | 1.0 | 0.27 | 0-5 | 0.86 | 1.00 | Assumed | |
| *Mesoplodon* spp. | 19,148,000 | 25,300 | 1.3 | 0.20 | 0-5 | 1.26 | 1.00 | Assumed | |
| **California ship surveys, 1991 (Barlow, 1995)** | | | | | | | | | |
| *Z. cavirostris* | 815,000 | 1,621 | 2.0 | 0.82 | 0-2 | 1.63 | 0.84 | IO, PB | |
| *Mesoplodon* spp. | 815,000 | 250 | 0.3 | 0.83 | 0-2 | 1.63 | 0.84 | IO, PB | |
| Unid. sm. ziphiid | 815,000 | 1,322 | 1.6 | 0.89 | 0-2 | 1.63 | 0.84 | IO, PB | |
| *B. bairdii* | 815,000 | 38 | 0.0 | 1.02 | 0-5 | 3.90 | 1.00 | IO, PB | |
| **California aerial surveys, 1991-92 (Forney *et al.*, 1995)** | | | | | | | | | |
| Unid. sm. ziphiid | 264,270 | 392 | 1.5 | 0.41 | 0-4 | 0.40 | 0.95 | IO, PB | |
| **Eastern North Pacific ship surveys, 1986-96 (Ferguson and Barlow, 2001)** | | | | | | | | | |
| *Z. cavirostris* | 25,000,000 | 90,725 | 3.6 | N/A | 0-2 | Various | 0.23 | Model, PB+AB | |
| *Mesoplodon* spp. | 25,000,000 | 32,678 | 1.3 | N/A | 0-2 | Various | 0.45 | Model, PB+AB | |
| Unid. sm. ziphiid | 25,000,000 | 51,365 | 2.1 | N/A | 0-2 | Various | 0.35 | Model, PB+AB | |
| *B. bairdii* | N/A | 1,104 | 0.1 to 1.2 | 0.5 to 1.0 | 0-5 | Various | 0.96 | Model, PB+AB | 1 |
| *I. pacificus* | N/A | 291 | 0.2 to 0.4 | 1.00 | 0-5 | Various | 0.96 | Assumed | 1,3 |
| **US West coast ship surveys, 1996 and 2002 (Barlow, 2003)** | | | | | | | | | |
| *Z. cavirostris* | 1,142,500 | 1,884 | 1.6 | 0.68 | 0-2 | 1.76 | 0.23 | Model, PB+AB | |
| *Mesoplodon* spp. | 1,142,500 | 1,247 | 1.1 | 0.92 | 0-2 | 1.76 | 0.45 | Model, PB+AB | |
| Unid. sm. ziphiid | 1,142,500 | 432 | 0.4 | 1.06 | 0-2 | 1.76 | 0.34 | Model, PB+AB | |
| *B. bairdii* | 1,142,500 | 228 | 0.2 | 0.51 | 0-5 | 2.82 | 0.96 | Model, PB+AB | |
| **Hawaii ship surveys, 2002 (Barlow, 2006)** | | | | | | | | | |
| *Z. cavirostris* | 2,452,916 | 15,242 | 6.2 | 1.43 | 0-2 | 1.64 | 0.23 | Model, PB+AB | |
| *M. densirostris* | 2,452,916 | 2,872 | 1.2 | 1.25 | 0-2 | 2.55 | 0.45 | Model, PB+AB | |
| Unid. sm. ziphiid | 2,452,916 | 371 | 0.2 | 1.17 | 0-2 | 2.02 | 0.35 | Model, PB+AB | |
| *I. pacificus* | 2,452,916 | 1,007 | 0.4 | 1.26 | 0-6 | 2.24 | 0.96 | Assumed | 3 |
| **NORTH ATLANTIC** | | | | | | | | | |
| **Northeastern Atlantic high latitudes - NASS-87 (Gunnlaugsson and Sigurjonsson, 1990)** | | | | | | | | | |
| *H. ampullatus* | 2,284,095 | 5,827 | 2.6 | 0.16 | 0-4 | N/A | 1.00 | Assumed | |
| **U.S. NE coast CETAP summer aerial surveys, 1978-82 (Winn, 1982)** | | | | | | | | | |
| *Z. cavirostris* | 278,350 | 25 | 0.1 | 0.94 | 0-3 | 0.29-0.52 | 1.00 | Assumed | |
| *Mesoplodon* spp. | 278,350 | 121 | 0.4 | 0.70 | 0-3 | 0.29-0.52 | 1.00 | Assumed | |
| **U.S. SE coast ship survey, 1998 (Mullin and Fulling, 2003)** | | | | | | | | | |
| *Mesoplodon* spp. | 573,000 | 348 | 0.6 | 0.76 | 0-4 | 1.78 | 1.00 | Assumed | |
| Unid. sm. Ziphiid | 573,000 | 193 | 0.3 | 0.71 | 0-4 | 1.78 | 1.00 | Assumed | |
| **Gulf of Mexico ship surveys, 1991-94 (Hansen *et al.*, 1995)** | | | | | | | | | |
| *Z. cavirostris* | 398,960 | 30 | 0.1 | 0.50 | 0-5 | 1.79 | 1.00 | Assumed | |
| Unid. sm. ziphiid | 398,960 | 117 | 0.3 | 0.38 | 0-5 | 1.78 | 1.00 | Assumed | |
| **Gulf of Mexico ship surveys, 1996-2001 (Mullin and Fulling, 2004)** | | | | | | | | | |
| *Z. cavirostris* | 380,432 | 95 | 0.2 | 0.47 | 0-4 | 1.67 | 1.00 | Assumed | |
| *Mesoplodon* spp. | 380,432 | 106 | 0.3 | 0.41 | 0-4 | 1.67 | 1.00 | Assumed | |
| Unid. sm. ziphiid | 380,432 | 146 | 0.4 | 0.46 | 0-4 | 1.67 | 1.00 | Assumed | |
| **Gulf of Mexico aerial surveys, 1992-1994 (Mullin *et al.*, 2004)** | | | | | | | | | |
| *Z. cavirostris* | 85,815 | 11 | 0.1 | 0.71 | 0-3 | 0.23 | 1.00 | Assumed | |
| *Mesoplodon* spp. | 85,815 | 52 | 0.6 | 0.30 | 0-3 | 0.23 | 1.00 | Assumed | |
| Unid. sm. ziphiid | 85,815 | 71 | 0.8 | 0.53 | 0-3 | 0.23 | 1.00 | Assumed | |
| **Gulf of Mexico aerial surveys, 1996-1998 (Mullin and Hoggard, 2000)** | | | | | | | | | |
| *Z. cavirostris* | 70,470 | 22 | 0.3 | 0.83 | 0-4 | 0.35 | 1.00 | Assumed | |
| *Mesoplodon* spp. | 70,470 | 59 | 0.8 | 0.51 | 0-4 | 0.35 | 1.00 | Assumed | |
| **ANTARCTIC/SOUTHERN OCEAN** | | | | | | | | | |
| **Southern Ocean ship surveys, 1976-88 (Kasamatsu and Joyce, 1995)** | | | | | | | | | |
| All ziphiid whales | 29,179,839 | 599,300 | 20.5 | 0.15 | 0-5 | 0.80 | 0.27 | Model, PB+AB | 2 |

1. Range of this species is smaller than entire study area; density is estimated for strata which include at least one sighting. 2. Most sightings were of *H. planifrons*. Estimate of *g*(0) was based on that species. 3. *g*(0) estimated based on similar diving patterns of *B. bairdii.*

is not known, but only 34% of the population is estimated to be using the Gully at any one time (Gowans *et al.*, 2000). Work is in progress to estimate abundance of small beaked whales in the Bahamas using mark-recapture methods applied to photo-identification data (Claridge, Durban, Parsons and Balcomb, pers. comm.).

## Review of abundance and density estimation

Line-transect surveys using visual detection methods are currently the only reliable method for estimating density and abundance of beaked whales over broad areas. From previous estimates, average pooled densities of all small beaked whales fall within the range of 0.4-44 animals per

1,000km$^2$, with the *g*(0)-corrected estimates falling in the upper part of that range (2.7-44 animals per 1,000km$^2$). All of these studies include a combination of shelf (less than 200m), slope (200-2,000m), and deep (greater than 2,000m) waters and additional insight could be obtained if estimates were stratified to include only the slope and deep-water habitats of beaked whales. There are no estimates of density from oligotrophic deep-water regions that are far from continents or islands. Areas such as the southern Gulf of California have densities of small beaked whales that are an order of magnitude higher (44 animals per 1,000km$^2$) than the averages found in other study areas. This appears to validate the concept of 'hot spots' with much higher than average beaked whale abundance. The densities of southern bottlenose whales in the Southern Ocean (20 animals per 1,000km$^2$) and Baird's beaked whales in slope waters of Japan (40-68 animals per 1,000km$^2$) are higher than the typical density estimated for the smaller beaked whales. For comparison, global estimates of sperm whale (*Physeter macrocephalus*) densities (0.8-17.4 animals per 1,000km$^2$; Whitehead, 2002) fall within the same range as density estimates for small beaked whales.

Mark-recapture abundance estimates based on photo-identification appear to have limited utility for estimating the population sizes of smaller beaked whales over broad areas, because animals are rarely seen and are difficult to approach and the overall populations appear to be large. There are several locations, however, where beaked whales are more easily approached. Photo-identification studies in those areas may be valuable for estimating local population sizes and for obtaining a wealth of other data, such as residency patterns and social structure (Claridge *et al.*, 2001). Mark-recapture appears to have greater potential for estimating the abundance of entire populations of the larger beaked whales such as northern bottlenose whales and Baird's beaked whales. For both of these species, animals are well marked and easily approached.

When considering current densities of beaked whales, it is important to remember that these may be less than the historic levels of abundance. Northern bottlenose whales have been depleted, perhaps multiple times, by whaling in the Atlantic Ocean (Mitchell, 1977; Christensen and Ugland, 1983) and Baird's beaked whales have been subject to whaling off Japan. Bycatch of small beaked whales has occurred off the US west coast (Julian and Beeson, 1998) and elsewhere, but population-level effects have not been assessed. The potential population-level effects of anthropogenic sounds on beaked whales are poorly understood. Balcomb and Claridge (2001) found that none of the Cuvier's beaked whales that were photo-identified near their Abaco study site in the Bahamas were ever seen again after the beaked whale stranding incident in March 2000, indicating the potential for at least local population-level effects.

## RESEARCH RECOMMENDATIONS

(1) Virtually nothing is known about the population structure within most species of beaked whales. Genetic, morphometric, photo-identification and long-term tagging studies are needed to evaluate how populations are structured.

(2) There are many gaps in our knowledge of the worldwide distribution of beaked whales. Emphasis should be placed on training observers for at-sea identification of beaked whales for all cetacean surveys and on the collection of genetic and other specimen material for the accurate identification of stranded beaked whales.

(3) The estimation of correction factors (*g*(0)) for missed animals is critical for accurately estimating abundance or density for line-transect surveys. Additional research is needed on methods, and additional data (such as dive times) are needed.

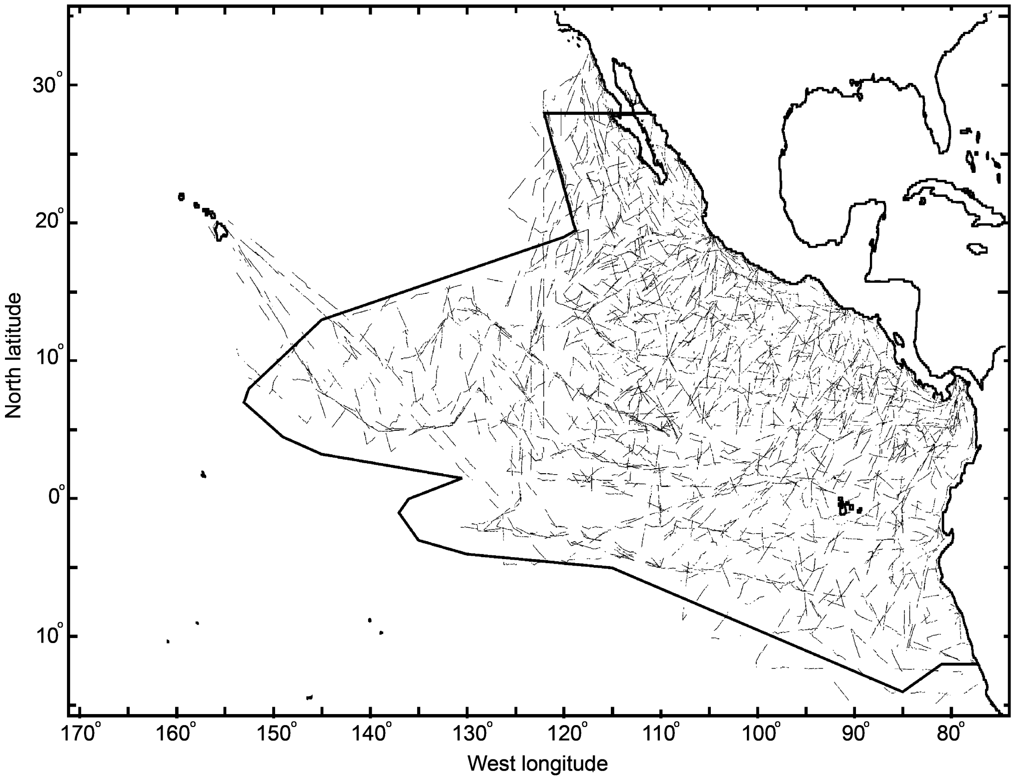

Fig. 1. Transect lines covered during the 1986-1990 and 1998-2000 shipboard cetacean surveys conducted by the SWFSC. Bold line indicates the boundary of the eastern tropical Pacific (ETP) study area.

(4) Most abundance and density estimates for beaked whales exist only where cetacean surveys have been conducted for other reasons, such as for whale stock assessment or where fishery bycatch problems exist (Fig. 1). Densities have not been estimated for vast areas of beaked whale habitat, particularly those areas that are far from shore. Additional surveys are needed to characterise beaked whale densities in these other habitats.

(5) Since beaked whales spend so much of their time submerged and unavailable to visual observers, acoustic detection methods should be investigated. Additional information is needed to characterise the vocal behaviour of beaked whales and to detect those vocalisations from a surface vessel.

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