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CETACEAN ABUNDANCE IN HAWAIIAN WATERS ESTIMATED FROM A SUMMER/FALL SURVEY IN 2002

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ABSTRACT

Cetacean abundance is estimated for the U.S. Exclusive Economic Zone (EEZ) around the Hawaiian Islands based on a ship line-transect survey from August to November, 2002. Sighting detection functions are estimated from this and other NOAA research surveys from 1986 to 2002 using a new, multiple-covariate approach. Twenty-four species were seen on this survey, including two species (Fraser's dolphin [*Lagenodelphis hosei*] and sei whale [*Balaenoptera borealis*]) that had not been previously documented to occur in Hawaiian waters. The most abundant large whales are sperm whales (*Physeter macrocephalus*) and Bryde's whales (*Balaenoptera edeni*). The most abundant delphinids are pilot whales (*Globicephala macrorhynchus*), rough-toothed dolphins (*Steno bredanensis*), Fraser's dolphins, spotted dolphins (*Stenella attenuata*), and striped dolphins (*Stenella coeruleoalba*). Dwarf and pygmy sperm whales (*Kogia sima* and *Kogia breviceps*) and Cuvier's beaked whales (*Ziphius cavirostris*) are also estimated to be quite abundant. Some of the migratory baleen whales (fin whales [*Balaenoptera physalus*], sei whales, minke whales [*B. acutorostrata*], and humpback whales [*Megaptera novaeangliae*]) were seen only late in the survey. Abundance is estimated for 19 cetacean species. The overall density of cetaceans is low in the study area, especially for delphinids. The precision of density and abundance estimates is generally low for all species because of the low number of sightings.

Key words: cetacean, dolphin, whale, abundance, density, *Lagenodelphis hosei,* line-transect survey, multiple covariates, Hawai'i, Pacific.

Most prior studies of cetaceans in Hawaiian waters have concentrated on humpback whales (*Megaptera novaeangliae*) (Darling and McSweeney 1985, Baker and Herman 1987) and spinner dolphins (*Stenella longirostris*) (Norris *et al*. 1994, Östman 1994). The limited information on other cetacean species was summarized by Shallenberger (1981) and Leatherwood *et al*. (1982). These researchers found 21 cetacean species in Hawaiian waters plus unconfirmed sightings of three other species. Blue whales (*Balaenoptera musculus*) can be added to this species list based on vocalizations detected and recorded off Oahu (Thompson and Friedl 1982).

There is little quantitative information on the abundance of cetaceans around Hawai'i. Mark–recapture methods applied to photo-identification data have been used to estimate the abundance of humpback whales around the main Hawaiian Islands (Baker and Herman 1987, Cerchio 1998) and spinner dolphins around the island of Hawai'i (Östman 1994). Aerial line-transect surveys were used to estimate the abundance of these two species plus 11 other species within 46 km (25 nmi) of the main Hawaiian Islands during the months of February to April (Mobley *et al.* 2000, 2001). The abundance of Hawaiian cetaceans has never been estimated for the summer/fall season nor for the entire U.S. Exclusive Economic Zone (EEZ) surrounding Hawai'i.

In this paper, I describe the results of a Summer/Fall 2002 ship survey of cetacean abundance in the U.S. EEZ waters surrounding Hawaii, including all of the Northwest Hawaiian Islands. The motivation for this survey was to determine if cetaceans in this area are sufficiently abundant to support the levels of bycatch estimated for the Hawaii-based longline fishery (Forney 2004). The low density of cetaceans in this area and the low number of sightings pose problems for estimating the line-transect parameters needed for abundance estimation. A method is developed that uses information on detection probability from this and from similar prior surveys. A multiple-covariate line-transect model is used to account for differing sighting conditions in the Hawaiian study area compared with those areas previously surveyed, and abundance is estimated for 19 cetacean species.

METHODS

Field Methods

A survey of cetaceans in Hawaiian waters was conducted in summer/fall of 2002 aboard two National Oceanographic and Atmospheric Administration (NOAA) research vessels.[1] The R/V *David Starr Jordan* conducted surveys in Hawaiian waters from 06 August to 27 November and the R/V *McArthur* surveyed there from 19 October to 25 November. The study area was defined as the U.S. EEZ (Fig. 1). To avoid surveying broadside to, or straight into, the dominant swells (generated by the northeasterly to easterly trade winds), the survey was designed with a series of parallel transect lines oriented in a WNW–ESE direction (Fig. 1). The location of a baseline was selected by choosing a random latitude along a given longitude, and the other transect lines were parallel to this baseline and were spaced 85 km apart. Because the ships returned several times to Honolulu or Hilo for refueling, a stratum with a higher density of survey effort was established within approximately 140 km of the main Hawaiian Islands by adding transect lines that were parallel to and halfway between the main set of transects. The two strata (Fig. 1) will be referred to as the "Main Island stratum" and "Outer EEZ stratum."

Visual line-transect survey methods (Buckland *et al.* 2001) were fundamentally the same as have been used during Southwest Fisheries Science Center (SWFSC) surveys since 1982 (Wade and Gerrodette 1993, Barlow 1995). The ships traveled at 16.7–18.5 km/hr (9–10 kts) during surveys. Survey effort included only those times when the ship was within 9.3 km (5 nmi) of the planned transect lines, when two observers

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[1] A joint Cruise Report for both ships is available by writing to the author or from the website http://swfsc.nmfs.noaa.gov/PRD/cruiseinformation.

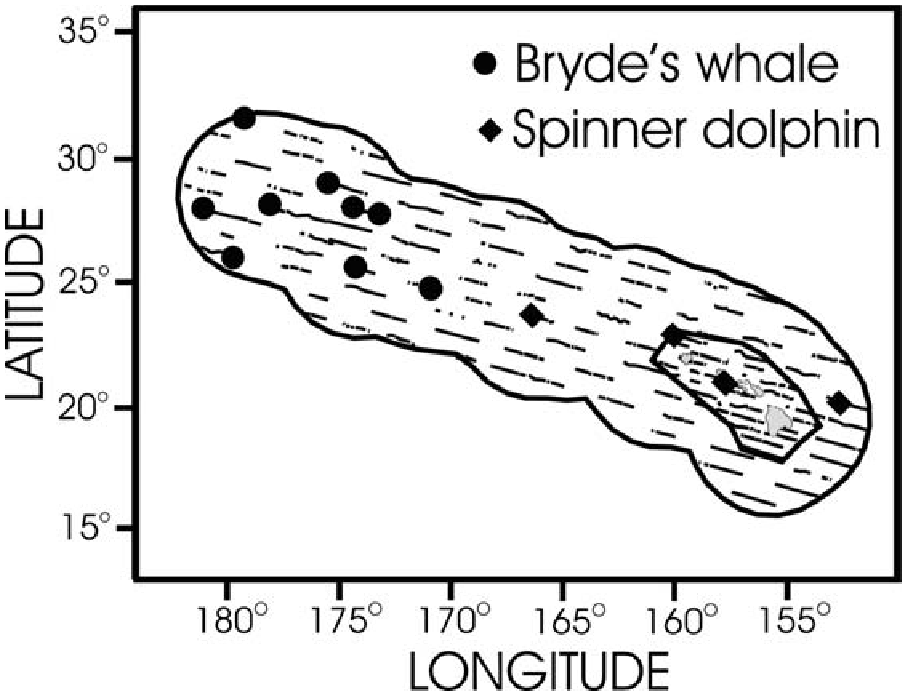

Figure 1. Search effort in Beaufort 0 to 6 conditions (fine lines) and sighting locations of Bryde's whales and spinner dolphins within the Hawaiian EEZ study area. Bold lines indicate the margins of the Main Island and Outer EEZ strata used for abundance estimation.

were searching through port and starboard 25× pedestal-mounted binoculars, and when a third observer/data recorder was searching from a cental position. Observers were selected on the basis of their past experience and skill on cetacean surveys, and the "on-effort" team always included at least one observer who was an expert in field identification of marine mammals. Six observers on each vessel rotated among the three observer stations, with 40 min per station followed by a 2-h rest. Observations were made from the flying bridge deck of both ships at a height of approximately 10.5 m above the sea surface. Observers searched with 25× binoculars from a bearing angle of 90° on their respective side of the vessel to 10° on the opposite side. The center observer/data recorder searched the forward 180° using unaided eyes and, occasionally, a 7× binocular. The data recorder entered searching effort and sightings data on a computer using custom data entry software. Effort data included time and location, a number code for each on-effort observer, Beaufort sea state, swell height (in ft), wind speed (in kts), visibility (in nmi), the presence of rain or fog within 5.5 km (3 nmi) of the ship, and the vertical and horizontal location of the sun relative to the ship's bow.

When marine mammals were seen by one of the three on-effort observers, the ship was typically directed to divert from the trackline toward the animals if they were within 5.5 km (3 nmi) of the trackline. Perpendicular distance from the trackline was estimated from the initial bearing angle relative to the bow (measured to the nearest 1° using a scale on the base of the 25× binoculars) and from the initial distance (measured using the reticle scale in the oculars of the 25 × or 7 × binoculars). Typically the vessel approached the animals to within a sufficient distance and remained in proximity to them for a sufficient time to allow the observers to reliably identify species, determine the proportion of each species present (for mixed species groups), and to estimate the group size. Data recorded for each sighting included species, time and location, initial bearing and distance, a code for the observer making the initial sighting, and independent estimates (from each observer) of the overall group size and the proportion of each species present (in mixed species groups). Animals were identified to the lowest possible taxonomic category, usually species. If species could not be determined with certainty, observers recorded a higher taxonomic category, for example, ziphiid or *Kogia* spp. (see Table 1 for all taxonomic categories used on this survey and all Latin species names). For sightings that could not be identified to species with certainty, the observers' "probable species" designation was also recorded. For some species, photo-documentation and/or biopsy sampling followed after species determination and group size estimation.

A hydrophone array was towed from the *David Starr Jordan* during most daylight hours to detect vocalizing cetaceans that were missed by the visual observer team. The acoustics team worked independently of the visual team and did not notify the visual team of an acoustic detection unless it was past the beam of the ship and was not detected by the visual team. At that time, the ship was occasionally directed to the estimated location of an acoustic detection, particularly for sperm whales. Animals detected acoustically but missed by the visual team are not included in the analyses presented here. Acoustic data will be analyzed in a separate report.

Analytical Methods

Density and abundance for each species are estimated using a Horvitz–Thompson approach to incorporate multiple covariates into the estimation of the detection probability function (Marques 2001, Marques and Buckland 2003). Geographic stratification accounted for different levels of survey effort in the Main Island and Outer EEZ strata. The density D_i of a species within geographic stratum i is estimated as

$$D_i = \frac{1}{2 \cdot L_i} \sum_{j=1}^{n_i} \frac{f(0, c_j) \cdot s_j}{g_j(0)},$$

where L_i is the length of on-effort transect lines in stratum i, $f(0,c_j)$ is the probability density of the detection function evaluated at zero perpendicular distance for sighting number j with associated covariates c_j, s_j is the number of individuals of that species in each group, $g_j(0)$ is the trackline detection probability of sighting j, and n_i is the number of sightings of that species in stratum i.

Only half-normal detection models are considered for estimating $f(0,c_j)$ because hazard-rate models have been shown to give highly variable estimates (Gerrodette and Forcada 2005). The covariates for the detection function are chosen by forward step-wise model building using an $\mathrm{AIC_c}$ criteria (Hurvich and Tsai 1989). The most distant 5%–10% of sightings for each species are truncated to improve the fit near the origin (Buckland *et al.* 2001). The estimates of trackline detection probability, $g(0)$ (Table 2), are based on a variety of methods from other studies (Barlow 1995, 1999; Barlow and Sexton 1996). For some species, $g(0)$ values vary with group size, thus the subscripted $g_j(0)$ in the above equation represents the value of $g(0)$ for group j

Table 1. SWFSC species codes, scientific names, common names, and number of sightings of cetaceans seen on the 2002 Hawaiian survey. N_{TOT} is the total number of sightings (including off-effort sightings), N_{EFF} is the number of on-effort sightings in "acceptable" Beaufort sea states (Beauf 0–2 for *Mesoplodon* spp., *Ziphius cavirostris,* and *Kogia* spp. and Beauf 0–6 for all others), N_{ABUND} is the number of sightings within the truncation distance that were used for abundance estimation. Abundance was not estimated for some species categories (N/A).

SWFSC Species code	Scientific name	Common name	N_{TOT}	N_{EFF}	N_{ABUND}
2	*Stenella attenuata* (offshore)	Offshore pantropical spotted dolphin	14	8	8
13	*Stenella coeruleoalba*	Striped dolphin	15	11	11
102	*Stenella longirostris*	Spinner dolphin	8	5	5
15	*Steno bredanensis*	Rough-toothed dolphin	18	14	14
18	*Tursiops truncatus*	Bottlenose dolphin	15	9	9
21	*Grampus griseus*	Risso's dolphin	7	5	5
26	*Lagenodelphis hosei*	Fraser's dolphin	2	2	1
31	*Peponocephala electra*	Melon-headed whale	1	1	1
32	*Feresa attenuata*	Pygmy killer whale	3	2	2
33	*Pseudorca crassidens*	False killer whale	2	1	1
36	*Globicephala macrorhynchus*	Short-finned pilot whale	25	16	16
37	*Orcinus orca*	Killer whale	2	2	2
46	*Physeter macrocephalus*	Sperm whale	43	28	21
47	*Kogia breviceps*	Pygmy sperm whale	2	2	2
48	*Kogia simus*	Dwarf sperm whale	5	3	3
80	*Kogia simus/breviceps*	Unidentified *Kogia* spp.	1	0	N/A
49	Ziphiid whale	Unidentified beaked whale	3	1	1
51	*Mesoplodon* spp.	Unidentified *Mesoplodon*	4	0	N/A
59	*Mesoplodon densirostris*	Blainville's beaked whale	3	1	1
61	*Ziphius cavirostris*	Cuvier's beaked whale	3	2	2
65	*Indopacetus pacificus*	Longman's beaked whale	1	1	1
70	Balaenopteridae	Unidentified rorqual	2	1	N/A
71	*Balaenoptera acutorostrata*	Minke whale	1	0	N/A
72	*Balaenoptera edeni*	Bryde's whale	13	10	8
73	*Balaenoptera borealis*	Sei whale	6	4	N/A
74	*Balaenoptera physalus*	Fin whale	5	2	N/A
76	*Megaptera novaeangliae*	Humpback whale	1	1	N/A
77	Unid delphinoid	Unidentified dolphin or porpoise	12	8	N/A
177	Unid small delphinid	Unidentified small dolphin	8	3	N/A
277	Unid medium delphinid	Unidentified medium-sized dolphin	2	1	N/A
377	Unid large delphinid	Unidentified large dolphin	1	1	N/A
78	Unid small whale	Unidentified small whale or large dolphin	5	4	N/A
79	Unid large whale	Unidentified large baleen or sperm whale	4	2	N/A
96	Unid cetacean	Unidentified cetacean	4	2	N/A
98	Unid whale	Unidentified large or small whale	4	3	N/A

Table 2. Estimates of trackline detection probability, $g(0)$, coefficients of variation for $g(0)$, and mean group size. Values of $g(0)$ and its CV (in parentheses) are obtained from previous studies[a,b,c] and, for some species, vary with group size. Mean group sizes are the geometric mean of "best" estimates from multiple observers and have not been corrected for bias. Bias-corrected group sizes used for abundance estimation can be obtained by dividing by 0.86.

	$g(0)$ Estimates for group size ranges		
Species	1–20	>20	Mean group size in Hawai'i study area
Offshore spotted dolphin[a]	0.76 (0.14)	1.00 (n/a)	60.0
Striped dolphin[a]	0.76 (0.14)	1.00 (n/a)	37.3
Spinner dolphin[a]	0.76 (0.14)	1.00 (n/a)	31.7
Rough-toothed dolphin[a]	0.76 (0.14)	1.00 (n/a)	14.8
Bottlenose dolphin[a]	0.76 (0.14)	1.00 (n/a)	9.0
Risso's dolphin[a]	0.76 (0.14)	1.00 (n/a)	15.4
Fraser's dolphin[a]	0.76 (0.14)	1.00 (n/a)	286.3
Melon-headed whale[a]	0.76 (0.14)	1.00 (n/a)	89.2
Pygmy killer whale[a]	0.76 (0.14)	1.00 (n/a)	14.4
False killer whale[a]	0.76 (0.14)	1.00 (n/a)	10.3
Short-finned pilot whale[a]	0.76 (0.14)	1.00 (n/a)	22.5
Killer whale[a]	0.90 (0.07)	0.90 (0.07)	6.5
Sperm whale[b]	0.87 (0.09)	0.87 (0.09)	7.3
Pygmy sperm whale[c]	0.35 (0.29)	0.35 (0.29)	1.0
Dwarf sperm whale[c]	0.35 (0.29)	0.35 (0.29)	2.3
unidentified beaked whale[c]	0.34 (0.29)	0.34 (0.29)	1.0
Blainville's beaked whale[c]	0.45 (0.23)	0.45 (0.23)	2.3
Cuvier's beaked whale[c]	0.23 (0.35)	0.23 (0.35)	2.0
Longman's beaked whale[a]	0.76 (0.14)	1.00 (n/a)	17.8
Bryde's whale[a]	0.90 (0.07)	0.90 (0.07)	1.5

[a] $g(0)$ estimates from Barlow (1995) based on his categories of small delphinids, large delphinids, and other large whales. Large and small delphinids are pooled based on the similarity in their $g(0)$ values (0.74 and 0.77, respectively, for groups of less than 20). Longman's beaked whales are included with his large delphinids because they commonly co-occur with short-finned pilot whales and exhibit similar behavior. Killer whales are included in his other large whale category.

[b] $g(0)$ estimates from Barlow and Sexton (1996) for sperm whales with 30-min dives.

[c] $g(0)$ estimates from Barlow (1999) based on his categories of *Kogia* spp., *Mesoplodon* spp., and *Ziphius cavirostris*. The value for unidentified beaked whales was an average of the values for *Mesoplodon* and *Ziphius*.

with group size s_j. The densities of most species are based on search effort in Beaufort sea states of 6 or less. Because they are so difficult to see, the densities of dwarf and pygmy sperm whales and most beaked whales[2] are estimated using search effort in sea states of Beaufort 2 or less.

Because the number of cetacean sightings was so low on the 2002 Hawai'i survey, data from previous SWFSC surveys in the eastern North Pacific are also included in estimating $f(0,c_j)$. These additional data include surveys in the eastern tropical

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[2] Longman's beaked whale (*Indopacetus pacificus*) analyses were done in Beaufort 6 or better conditions because this species has a distinct blow and is much more conspicuous than smaller beaked whale species.

Pacific (ETP, 1986–1990, 1992–1993, and 1998–2000) and surveys off the U.S. west coast (1991, 1993, 1996, and 2001). The same survey methods and the same research vessels (*David Starr Jordan* and *McArthur*) were used for the Hawai'i survey and for these previous surveys. Covariates include factors that have been shown to affect perpendicular sighting distances (Barlow *et al.* 2001): Ship (*Jordan* or *McArthur*), Beaufort sea state (*Beauf*, treated as a continuous variable), total school size (*TotSS*, including all species present in a group), the natural logarithm of total school size (*LnTotSS*), visibility (*Vis*, treated as a continuous variable), the presence of glare on or near the trackline (*Glare*, treated as a logical variable), and the presence of rain or fog obscuring a portion of the forward field-of-view (*Rain/Fog*, treated as a logical variable).[3] Visibility (the estimated distance at which a conspicuous cue could be seen) was not collected prior to 1991, so most of the models are based on data collected from 1991 to 2002. For some species, the number of sightings is insufficient to reliably estimate the detection function, and in those cases models are based on data from 1986 to 2002, and the variable *Vis* is excluded from consideration. In several cases, species are pooled to aid in estimating detection functions, and, in those cases, *Species* is evaluated for inclusion as a categorical covariate to account for real differences among those species.

Group size, s, is estimated as the bias-corrected geometric mean of the "best" independent estimates from each observer who made an estimate. Using direct calibrations from aerial photographic estimates of group size, Gerrodette *et al.* (2002) found that, on average, observers underestimated group size. Aerial photographic estimates of group size are not available to calibrate observers for the Hawai'i survey. Therefore, we correct individual estimates of group size by dividing mean group size by 0.86, the mean correction factor from 52 observers who were calibrated by Gerrodette *et al.* (2002). The observers' designations of "probable species" are used in place of higher taxonomic categories in cases where species could not be determined with certainty.

The overall estimate of abundance, N, for each species is estimated as the sum of the densities multiplied by the areas within each geographic stratum, i:

$$N = \sum_{i=1}^{2} A_i D_i$$

The surface areas, A_i, are 212,892 km^2 for the Main Island stratum and 2,240,024 km^2 for the Outer EEZ stratum (both excluding land areas).

A mixed nonparametric and parametric bootstrap was used to estimate the coefficient of variation for estimated density and abundance. The components of variance contributed by sampling variation and model fitting were estimated with the nonparametric bootstrap. Survey effort was divided into 150-km segments, representing the approximate distance surveyed in one day. Effort segments were sampled randomly with replacement from all survey years, and the sightings associated with those segments were used to fit the multiple-covariate model to estimate $f(0,c_j)$. Bootstrap estimates of density were then made using these $f(0,c_j)$ values and the 2002 effort segments within the Hawai'i study area using the Horvitz–Thompson-like estimator of Marques and Buckland (2003). The bootstrap did not replicate the model selection process and thus excludes this component of the variance. If more than 10% of bootstrap iterations failed to converge on stable density estimates, a

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[3] See Barlow *et al.* (2001) for a more complete description of these covariates.

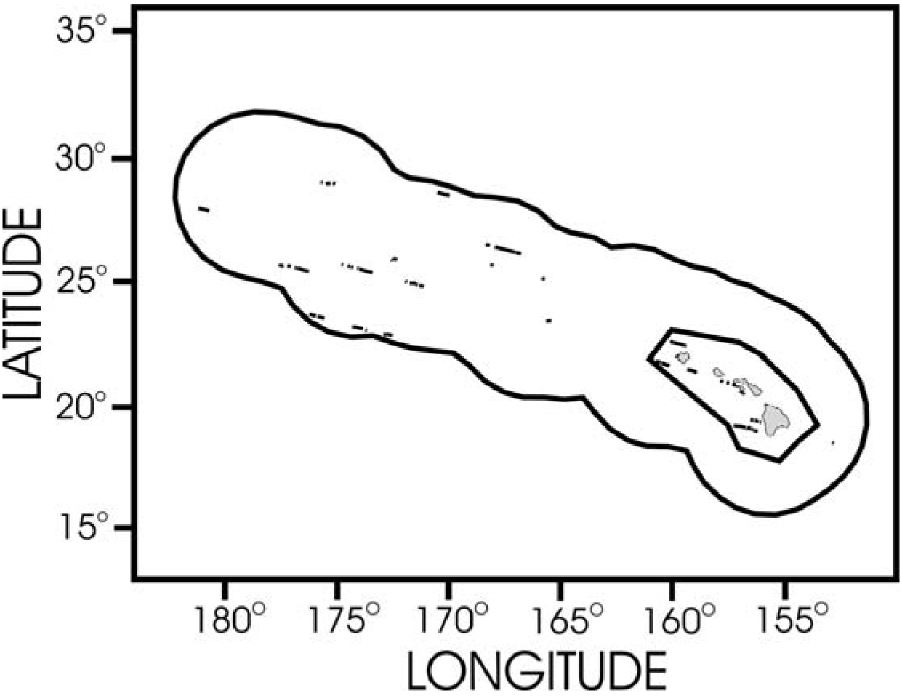

Figure 2. Search effort in Beaufort 0 to 2 conditions (fine lines) within the Hawaiian EEZ study area. Bold lines indicate the margins of the Main Island and Outer EEZ strata used for abundance estimation.

simpler line-transect model (with fewer covariates) was used both for estimating density (*D*) and the CV(*D*). The component of variance contributed by uncertainty in estimates of $g(0)$ was included as a parametric bootstrap embedded within the parametric bootstrap described above. I modeled $g(0)$ as a logit-transformed random normal deviate with a mean and variance chosen to give the estimated $g(0)$ value and its coefficient of variation. The coefficients of variation of $g(0)$ are estimated from prior studies (Barlow 1995, 1999; Barlow and Sexton 1996).

RESULTS

The survey covered a linear distance of 17,050 km in sea state conditions of Beaufort 6 or less; 3,550 km of search effort were in the Main Island stratum, and 13,500 km were in the Outer EEZ stratum. Overall search effort within each stratum covered each area fairly uniformly (Fig. 1), with a higher density of coverage in the Main Island stratum. Conditions during this survey were, on average, quite windy. Only 1,400 km of survey effort were in optimal sighting conditions (Beaufort 2 or less). The survey effort in Beaufort 0–2 conditions (Fig. 2) is much less uniformly distributed than the overall survey effort.

A total of 159 "on-effort" sightings and 68 "off-effort" sightings were made in the Hawaiian study area, and 24 different species were seen (Table 1).[4] With the

[4] Sighting locations for all species are given by Barlow *et al*. (2004).

exception of the North Pacific right whale (*Eubalaena japonica*), all species that have been seen previously in Hawaiian waters were seen during this survey. Two previously undocumented species were also seen: Fraser's dolphins and sei whales. This survey confirms a previous report by Shallenberger (1981) that a tropical bottlenose whale is found in Hawaiian waters.[5] Four seasonally migratory baleen whale species were seen during the survey (minke, sei, fin, and humpback whales). Of these migratory species, fin whales were seen in September and October, and the others were only seen in November. Blue whales, whose vocalizations have been recorded in Hawaiian waters, were not seen.

Line-Transect Modeling

Different sets of covariates were chosen for the best-fit model for different species (Table 3). Total school size (expressed as *TotSS, LnTotSS*, or both, to allow greater flexibility in fitting nonlinear relationships) was the most frequent covariate that was entered in the line-transect models. Other selected covariates included *RainFog, Beauf, Glare,* and *Vis*. In general, models based on a fewer number of sightings were less complex and included fewer covariates. The sample size for estimating multiple-covariate models was very marginal for Fraser's dolphins ($n = 30$) and was less than 100 for eight other species (Table 3), despite having pooled survey data that covered almost two decades and having, in some cases, pooled species. Of the eight models that were based on pooling multiple species or subspecies, the covariate *Species* was not selected for any model.

Density and Abundance Estimation

The mean size of groups that were included in abundance estimates is given in Table 2 for each species. The average of the effective strip widths (given the covariates associated with sightings in Hawaii) are given in Table 3. The numbers of sightings and estimates of abundance and density (individuals per 1,000 km^2) of species in both of the geographic strata are given in Table 4. The more abundant cetaceans species include offshore spotted dolphins, striped dolphins, rough-toothed dolphins, Fraser's dolphins, dwarf sperm whales, and Cuvier's beaked whales. The most abundant large whales are, by a large margin, sperm whales followed by Bryde's whales. Coefficients of variation for the pooled abundance estimates in both strata (Table 4) are generally high, as expected given the low number of sightings of most species.

DISCUSSION

The overall density of cetaceans in Hawaiian waters is lower than in most areas that have been previously surveyed. In surveying low-density areas, the low number of sightings poses a problem for abundance estimation. In the case of the Hawaiian survey, the use of data from previous surveys to estimate line-transect parameters is helpful in estimating abundance for all species and is absolutely essential for some. By using this approach, abundance estimates could be made for 19 species (Table 4) that were seen by observers while searching along established transect lines. Abundance is

[5] Note that Shallenberger (1981) referred to this as an unconfirmed report of *Hyperoodon* sp. The tropical bottlenose whale has only recently been found to be synonymous with Longman's beaked whale (Dalebout *et al.* 2003).

Table 3. Data and specifications used for the estimation of line-transect parameters *f(0,c)* for each species based on 2002 and prior-year survey efforts. The best-fit model indicates the covariates selected for inclusion based on the AIC^{c} criterion and the stability of bootstrap estimates (see text for description of covariates). Average effective strip widths (ESW) are estimated as the product of the truncation distance and the mean probability of detecting a group within this distance for groups of the given species seen in the Hawaiian study area (hence, with the covariates associated with Hawaiian sightings). In some cases, sightings of other species or subspecies were included to improve the ability to fit a model given limited data; in these cases, the number of sightings of all species is included in the sample size.

Species	Years used	Beaufort sea states used	Sample size	Truncation distance km	Best-fit model	Average ESW km	Other species/subspecies included in fitting line-transect model
Offshore spotted dolphin	1991–2002	0–6	581	4.5	*LnTotSS*	2.84	
Striped dolphin	1991–2002	0–6	727	4.5	*TotSS*	2.60	
Spinner dolphin	1991–2002	0–6	376	4.5	*LnTotSS*	2.57	All spinner dolphin subspecies
Rough-toothed dolphin	1991–2002	0–6	156	3.5	*TotSS+RainFog*	1.80	
Bottlenose dolphin	1991–2002	0–6	604	4.5	*LnTotSS+Beauf+Vis*	2.26	
Risso's dolphin	1991–2002	0–6	196	4.5	*TotSS+Beauf+Glare*	2.27	
Fraser's dolphin	1986–2002	0–6	30	4.5	*LnTotSS*	2.70	
Melon-headed whale	1986–2002	0–6	66	4.0	*LnTotSS*	2.92	Pygmy killer whale
Pygmy killer whale	1986–2002	0–6	66	4.0	*LnTotSS*	1.38	Melon-headed whale
False killer whale	1986–2002	0–6	55	4.5	*TotSS*	4.20	
Short-finned pilot whale	1991–2002	0–6	185	5.5	*Beauf+Vis*	2.71	Long-finned pilot whale
Killer whale	1991–2002	0–6	115	5.0	*LnTotSS+Vis*	3.79	
Sperm whale	1991–2002	0–6	114	5.5	*LnTotSS+Beauf*	3.73	
Pygmy sperm whale	1991–2002	0–2	70	2.5	*LnTotSS*	1.15	Dwarf sperm whale
Dwarf sperm whale	1991–2002	0–2	70	2.5	*LnTotSS*	1.62	Pygmy sperm whale
Unidentified beaked whale	1986–2002	0–2	74	4.0	*Beauf*	2.02	
Blainville's beaked whale	1986–2002	0–2	80	4.0	*TotSS*	2.55	All *Mesoplodon* spp.
Cuvier's beaked whale	1986–2002	0–2	56	4.0	Null	1.64	
Longman's beaked whale	1986–2002	0–6	292	5.5	Null	2.24	Short-finned pilot whale
Bryde's whale	1991–2002	0–6	216	4.5	*LnTotSS*	2.67	

Table 4. Number of sightings and estimated abundances of cetaceans in the two geographic strata of the Hawaiian study area. Overall abundances, densities of individuals (per 1,000 km^2), and coefficients of variation (CV) are pooled from both strata. Pooled sighting numbers, densities, and abundances are given for delphinids and beaked whales.

	Main Island stratum		Outer EEZ stratum		Overall		
Species	Sightings *n*	Abundance *N*	Sightings *n*	Abundance *N*	Abundance *N*	Individual density per 1,000 km^2 *D*	CV
Offshore spotted dolphin	6	4,283	2	4,695	8,978	3.66	0.48
Striped dolphin	1	660	10	12,483	13,143	5.36	0.46
Spinner dolphin	3	1,488	2	1,863	3,351	1.37	0.74
Rough-toothed dolphin	7	1,713	7	6,997	8,709	3.55	0.45
Bottlenose dolphin	5	465	4	2,750	3,215	1.31	0.59
Risso's dolphin	2	513	3	1,859	2,372	0.97	0.65
Fraser's dolphin	0	0	1	10,226	10,226	4.17	1.16
Melon-headed whale	0	0	1	2,950	2,950	1.20	1.17
Pygmy killer whale	2	956	0	0	956	0.39	0.83
False killer whale	0	0	1	236	236	0.10	1.13
Short-finned pilot whale	8	3,190	8	5,680	8,870	3.62	0.38
Killer whale	0	0	2	349	349	0.14	0.98
Sperm whale	4	126	17	6,793	6,919	2.82	0.81
Pygmy sperm whale	0	0	2	7,138	7,138	2.91	1.12
Dwarf sperm whale	0	0	3	17,519	17,519	7.14	0.74
Unidentified beaked whale	1	371	0	0	371	0.15	1.17
Blaineville's beaked whale	0	0	1	2,872	2,872	1.17	1.25
Cuvier's beaked whale	0	0	2	15,242	15,242	6.21	1.43
Longman's beaked whale	0	0	1	1,007	1,007	0.41	1.26
Bryde's whale	0	0	8	469	469	0.19	0.45
Delphinids pooled	34	13,267	41	50,087	63,354	25.83	
Beaked whales pooled	1	371	4	19,121	19,492	7.95	

not estimated for migratory baleen whales because the survey did not correspond to their peak period of abundance. Nor is abundance estimated for the various categories of unidentified dolphin and unidentified whale species (Table 1).

Even though abundance could be estimated for most of the species known to exist in Hawaiian waters, the precision of these estimates is generally poor. Abundance estimates for six species are based on only one sighting. All abundance estimates are based on less than 25 sightings of each species in the study area. The lowest estimated coefficient of variation (for short-finned pilot whales) was 33%, and CVs for most species are much higher. The component of variance from parameter estimation is likely underestimated because the bootstrap did not include variation introduced in the model selection process. Furthermore, CVs of $g(0)$ estimates were taken from other studies. Overall, CVs for the densities of all species are likely to be underestimated; however, the variance in encounter rates dominated the overall estimate of the CVs.

Delphinids

It is difficult to define one "most abundant" delphinid species in Hawaiian waters given the imprecision of their abundance estimates; however, several delphinid species in Hawaiian waters can be considered to be approximately equivalent in abundance: offshore spotted dolphins, striped dolphins, rough-toothed dolphins, Fraser's dolphins, and short-finned pilot whales. The number of sightings used to make these estimates varied considerably from 16 sightings of short-finned pilot whales to one sighting of a very large group of Fraser's dolphins. Rough-toothed dolphins are not commonly found to be a dominant component of the cetacean fauna in any study area; however, Baird *et al.*[6] found rough-toothed dolphins to be the second most common delphinid off Kaua'i and Ni'ihau in Hawai'i. The dolphin that people most commonly associate with Hawai'i is the spinner dolphin, but our study indicates that they are mostly concentrated near the main Hawaiian Islands and are not very abundant outside our Main Island stratum (Table 4, Fig. 1). Spotted dolphins, bottlenose dolphins, and short-finned pilot whales also appear to be clustered near the main Hawaiian Islands (Fig. 3, 4), and spotted dolphins and pilot whales appear to be more abundant there than spinner dolphins (Table 4). Striped dolphins are widely distributed, with no apparent affinity to the Main Island stratum (Fig. 3). Although false killer whales are frequently seen taking fish from hooks in the tuna longline fishery based in Hawai'i and are occasionally hooked (Forney 2004), this species was encountered only once during on-effort surveys, yielding an abundance estimate of only 236 (CV = 1.13). This estimate is higher than the estimate of 121 (CV = 0.47) obtained by Mobley *et al.* (2000) based on 14 sightings made within 46 km (25 nmi) of the main Hawaiian Islands. This may suggest that false killer whales are not very common around the Hawaiian Islands, or perhaps that their occurrence in Hawaiian waters is seasonal or concentrated primarily near the main Hawaiian Islands.

Mobley *et al.* (2000) estimated abundance for most delphinids within 46 km of the main Hawaiian Islands, and their estimates for bottlenose dolphins, spotted dolphins, spinner dolphins, and short-finned pilot whales were generally similar to

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[6] Baird, R. W., D. J. McSweeney, D. L. Webster, A. M. Gorgone and A. D. Ligon. 2003. Studies of odontocete population structure in Hawaiian waters: Results of a survey through the main Hawaiian Islands in May and June 2003. Final Contract Report to NOAA Southwest Fisheries Science Center, 8604 La Jolla Shores Dr., La Jolla, CA 92037. 25pp.

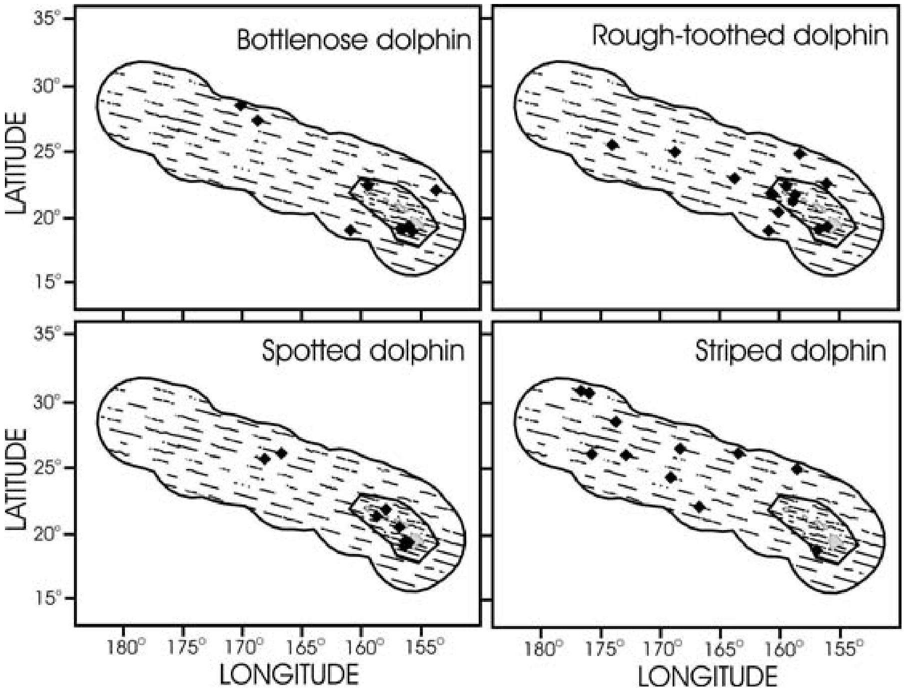

Figure 3. Locations of on-effort sightings of bottlenose dolphins (*Tursiops truncatus*), rough-toothed dolphins (*Steno bredanensis*), spotted dolphins (*Stenella attenuata*), and striped dolphins (*Stenella coeruleoalba*) in the Hawaiian study area.

(within a factor of two) the estimates presented here for abundances within 140 km of these Islands. Their estimates for rough-toothed dolphins and striped dolphins were considerably lower than my estimates for the Main Island stratum, which is consistent with the more pelagic distribution of these species outside of this study area.

The overall density estimate for delphinids in the Hawaiian study area (26 per 1,000 km^2, Table 4) is much lower than the total delphinid density estimated for most warm–temperate and tropical locations worldwide (Wade and Gerrodette 1993; Barlow 1995; Mullin and Fulling 2003, 2004; Mullin *et al.* 2004) and is even lower than all but one stratum in oligotrophic Mediterranean waters (Forcada and Hammond 1998). The total delphinid density for Hawai'i is also far lower than the range of estimates (112–2,342 per 1,000 km^2) for 5° latitude × 5° longitude strata in the eastern tropical Pacific (Ferguson 2005, her table 2.3, excluding strata 111 and 112, which were in the Hawaiian study area and were comparably low in density, 10 per 1,000 km^2). It is likely that the low density of delphinids is related to the low productivity of the subtropical gyre water that bathes most of the Hawaiian Islands.

Beaked Whales

The pooled density estimate for all beaked whale species (8 per 1,000 km^2, Table 4) is dominated by the abundance of Cuvier's beaked whale; however, with just two

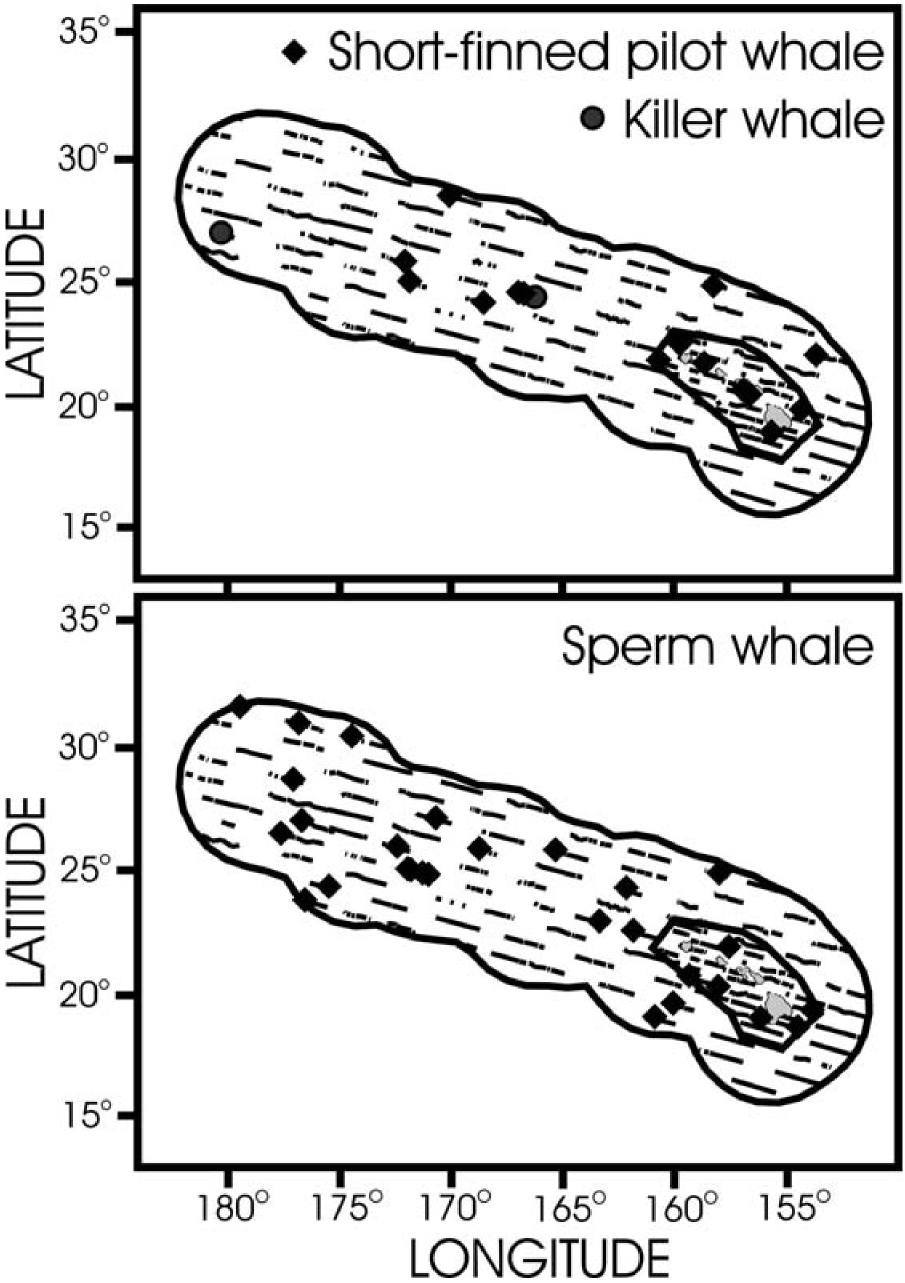

Figure 4. Locations of on-effort sightings of short-finned pilot whales (*Globicephala macrorhynchus*), killer whales (*Orcinus orca*), and sperm whales (*Physeter macrocephalus*) in the Hawaiian study area.

"on-effort" sightings of this species and one of Blainville's beaked whale, it is impossible to say which species is truly more abundant. This total beaked whale density is higher than most published estimates from studies in warm–temperate and tropical waters (Wade and Gerrodette 1993; Barlow 1995; Mullin and Fulling 2003, 2004; Mullin *et al.* 2004; summarized by Barlow *et al.*, in press). However, most of these previous estimates assumed that $g(0)$ was 1.0 and included search effort in Beaufort sea states of 4 and sometimes 5, and therefore these previous studies underestimate true beaked whale abundance. The most comparable estimates of beaked whale abundance are those of Ferguson (2005) and Ferguson and Barlow (2001), which were based on the same $g(0)$ estimates and the same range of Beaufort sea states. The Hawai'i density estimate for Cuvier's beaked whales is slightly greater than the median value (3.6 per 1,000 km^2) of Ferguson's 5° × 5° strata (Ferguson 2005, her table 2.4). The density estimate for Blainville's beaked whales in the Hawai'i study area is toward the upper end of the range of density estimates for any *Mesoplodon* species (Ferguson and Barlow 2001, their table 11).

Dwarf and Pygmy Sperm Whales

The pooled abundance of the two species of the genus *Kogia*, dwarf and pygmy sperm whales, is surprisingly larger than that of any of the delphinid species. However, the overall density (10 per 1,000 km^2) is toward the lower end of the range of density estimates of *Kogia* for 14 strata in the eastern Pacific (2 to 50 per 1,000 km^2, Ferguson and Barlow 2001, their table 8). Records from 1949 to 1982 show that strandings of pygmy sperm whales ($n = 9$) are more common around the main Hawaiian Islands than strandings of dwarf sperm whales ($n = 2$) (Tomich 1986, Nitta 1991). Neither species was seen in the Main Island Stratum of this survey, and the total number of sightings of the two species was similar in the Outer EEZ stratum ($n = 2$ and 5, respectively).

Large Whales

Sperm whales were distributed widely throughout the study area (Fig. 4) and are, by a large margin, the most abundant large whale in Hawaiian waters in summer and fall. The estimated abundance of sperm whales (6,919) is approximately comparable to the estimated abundance of humpback whales in winter (Cerchio 1998). Estimated sperm whale density (~2.8 per 1,000 km^2) is higher in the Hawaiian study area than in the eastern tropical Pacific (~1 per 1,000 km^2, Wade and Gerrodette 1993) and in California offshore waters (~1 per 1,000 km^2, Barlow 1995) and is comparable to the overall density of sperm whales worldwide (Whitehead 2002). The estimate of sperm whale density for Hawaiian waters is slightly lower than the range estimated by Barlow and Taylor (2005) for the eastern temperate North Pacific (3–5 per 1,000 km^2), a study area that included a small part of the Hawai'i study area but which was, for the most part, north and east of this study area. Sperm whale abundance is low in the Main Island stratum, which is consistent with what Mobley *et al.* (2000) found within 46 km of those Islands.

Bryde's whales are the only nonmigratory species of baleen whale found in the tropics and sub-tropics. They are the second most abundant large whale in this study and had an overall density of 0.2 per 1,000 km^2. This density is toward the lower end of the range of Bryde's whale density estimates for 5° × 5° areas in the ETP (0.1–4.3 per 1,000 km^2, Ferguson and Barlow 2001, their table 3). However, all of the Bryde's whales on our survey were found in the western half of the Hawaiian study area (Fig. 1), so their density there would be approximately twice as high as the overall average. This distribution corroborates evidence of a geographic discontinuity between eastern and western Pacific populations of this species (Wade and Gerrodette 1993, their fig. 18). All of the Bryde's whales seen on this survey are likely to belong to a western Pacific population.

Sei, fin, blue, minke, and humpback whales in Hawai'i belong to seasonally migrating populations that feed at higher latitudes. Blue whales were not seen on our survey, and minke whales were acoustically detected (Rankin and Barlow 2005) but were not seen on-effort. However, this survey was not conducted during the expected season of peak abundance, and sei, fin, minke, and humpback whales were seen only late in the survey. No estimates are presented for these species. Abundance estimates for humpback whales in Hawai'i already exist from mark–recapture methods (Cerchio 1998) and from aerial surveys (Mobley *et al.* 2001) during their period of peak abundance. Meaningful estimates of density or abundance for the other migratory baleen whales would require a winter survey.

Status of Cetaceans in Hawaiian Waters

The goal of this research was to gather additional information to help evaluate the status of cetaceans in Hawaiian waters, especially in view of bycatch in the Hawaii-based longline fishery. Preliminary results of this survey (Barlow 2003) were used in the 2003 assessment of cetaceans in Hawaiian waters (Carretta *et al.* 2004). That report concluded that the estimated bycatch in the Hawaiian longline fishery (Forney 2004) was sustainable (bycatch was less than the Potential Biological Removal level as defined by the U.S. Marine Mammal Protection Act, MMPA) for all species except false killer whales. Carretta *et al.* (2004) concluded that the mean annual rate of false killer whale bycatch (mortality and serious injury) in the Hawaiian longline fishery for the period 1998–2002 was 4.4 individuals per year and that given the relatively small size of the population as estimated from this survey, the population should be considered "strategic" under the guidelines of the MMPA. Additional work is currently underway to improve estimates of abundance for this population using photo-identification and mark–recapture methods (Robin Baird, personal communication) and to determine the genetic relationship between the Hawai'i population and more pelagic populations of false killer whales.

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