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**ABUNDANCE AND DISTRIBUTION PATTERNS OF
HAWAIIAN ODONTOCETES: FOCUS ON O'AHU**

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DEDICATION PAGE

This dissertation is dedicated to mum and dad for their love, encouragement and patience.
Grazie di cuore

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ABSTRACT

This dissertation is an assessment of the status of odontocetes in Hawaiian waters focussing on O'ahu. The work builds on available literature, and on data collected by the author and by others in Hawaiian waters.

Abundance and distribution patterns of odontocetes were derived from stranding and aerial survey data. A stranding network operated by the National Marine Fisheries Service, Pacific Area Office collected 187 stranding reports throughout the main Hawaiian Islands between 1937 and 2002. These reports included 16 odontocete species. Number of stranding reports increased over time and was highest on O'ahu. Strandings occurred throughout the year. The difference in number of strandings per month was not significant. Fifteen of the 16 species reported in the stranding record for the main Hawaiian Islands were also reported by aerial survey studies of the area between 1993 and 1998. Only 7 of the species reported were detected during aerial transects around O'ahu between 1998 and 2000. Based on the stranding record, *Kogia* sp., melon-headed whales, striped dolphins and dwarf killer whale appear to be more common than suggested by aerial surveys. Conversely, pilot whales and bottlenose dolphins were more common, according to aerial surveys, than predicted by the stranding data.

Aerial surveys of waters between 0 and 500m around the Island of O'ahu showed that the most abundant species by frequency of occurrence was the pilot whale (30% of sightings), followed by the spinner (16%) and bottlenose dolphin (14%).

Because of small sample size, abundance estimates for odontocetes have a high level of uncertainty. The unavailability of a correction factor for $g(0) < 1$, and the reduced visibility below the aircraft further reduced accuracy and increased the inherent

underestimation in the data. The most abundant species according to distance sampling estimates were spotted dolphins, pilot whales, false killer whales and spinner dolphins.

A natural factor shaping the ecology of odontocete populations is predation pressure both by other odontocetes and, more frequently, by sharks. An account of predation by a tiger shark on a spotted dolphin near Penguin Banks is used as an example of the potential mechanisms of predation by sharks on odontocetes.

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PREFACE

This dissertation is comprised of (1) a preface, (2) a short introductory chapter, (3) three peer-reviewed publications (one published, and two being prepared for submission), and (4) a conclusion section. The work presented focuses on aspects of the ecology of cetaceans, primarily odontocetes, found in waters around the Island of O'ahu.

Chapter 1 is entitled "The Status of Odontocetes in Hawaiian Waters". It introduces the current status of knowledge of odontocetes in Hawai'i and is the premise for this dissertation.

Chapter 2 entitled "Odontocete Strandings as an Indicator of Distribution Patterns in the Main Hawaiian Islands" was written using information obtained from the National Marine Fisheries Service, Pacific Area Office (NMFS-PAO) on historical strandings of odontocetes in Hawaiian waters from 1937 to 2002. A version of this chapter will be submitted for publication in a peer-reviewed journal in collaboration with Lori Mazzuca at the National Oceanic and Atmospheric Administration (NOAA), and Shannon Atkinson at the University of Alaska, Fairbanks (UAF) and the Alaska Sea Life Center (ASLC).

Chapter 3 provides a review of the theory behind the distance sampling method which was used to analyze the line transect data collected during aerial surveys, and Chapter 4, entitled "Abundance and Distribution of Cetaceans in Near-Shore Waters around O'ahu and Penguin Banks" presents preliminary abundance estimates for humpback whales and odontocetes found in waters within the 500m isobath around the Island of O'ahu using the distance-sampling method. This chapter also provides

information on patterns of distribution for some Hawaiian odontocetes. The resulting paper will be submitted for publication in collaboration with Shannon Atkinson at UAF and ASLC and Joseph Mobley at the University of Hawaii West O'ahu.

Chapter 5 entitled "Predation Pressure" summarizes the theoretical framework surrounding the issue of predation on cetaceans. As an example of predation, a section of this chapter presents a case study documenting an attack by a tiger shark (*Galeocerdo cuvier*) on a spotted dolphin (*Stenella attenuata*) in Hawaiian waters and proposes a possible strategy used by sharks to prey upon cetaceans. The case study was accepted in March 2003 for publication in Aquatic Mammals as a note entitled "Evidence of Predation by Tiger Shark (*Galeocerdo cuvier*) on Spotted Dolphin (*Stenella attenuata*) off O'ahu, Hawai'i".

Finally, a conclusion section summarizes the information presented in the other chapters. This section provides a more general understanding of the patterns that influence the distribution of odontocetes in Hawaiian waters.

CHAPTER 1

THE STATUS OF ODONTOCETES IN HAWAIIAN WATERS

In 1981 Shallenberger completed a review of the status of Hawaiian cetaceans for the U.S. Marine Mammal Commission with the objectives of (1) developing a list of all cetaceans found in Hawaiian waters, (2) reviewing the existing literature to extract those facts pertinent to the management of Hawaiian species, and (3) making recommendations as to what additional data were needed to ensure the protection and conservation of cetaceans and their habitat in Hawai'i (Shallenberger, 1981). In his final report Shallenberger writes: "...At present there is no species of Hawaiian cetacean for which adequate knowledge of these five topics [present and past population levels, structure and distribution, factors affecting mortality and natality, basic natural history, factors affecting the resources upon which the species depends, man's effect on the species] is available...".

Nineteen years later, Mobley *et al.* (2000), for the first time, published preliminary estimates of odontocete abundance in waters within 25 nautical miles of the main Hawaiian Islands, obtained using aerial surveys flown between 1993 and 1998. Such study was part of a comprehensive assessment of cetacean populations during the period January to April, when humpback whales are present in Hawaiian waters.

As a result of these efforts, at least 19 species of odontocetes (Table 1) have been identified in Hawai'i (Shallenberger, 1981; Nitta, 1991; Mobley *et al.* 2000). However, a recent National Marine Fisheries Service (NMFS) stock assessment report on the status of knowledge of Hawaiian marine mammals acknowledges that there is still insufficient

information on most species of odontocetes to be able to make a reliable determination of their population size, and trends in abundance and distribution (Carretta *et al.*, 2001).

The Hawaiian Islands Humpback Whale National Marine Sanctuary (HIHWNMS) was instituted on 4 November 1992 to specifically protect humpback whale habitat, and monitor key population parameters (National Marine Fisheries Service, 1991). The focus of sanctuary-funded research on a single species may not be an ideal approach, given the incompleteness of information available on cetaceans as a whole in Hawaiian waters. In fact, many in the scientific community advocate that the health of an ecosystem is directly dependent upon the health of all its parts, and further agree that an ecosystem-based approach is the most appropriate strategy for long-term management (Christensen, 1996; Noss, 1996; Schwartz, 1999; Sherman and Duda, 1999). It is, therefore, imperative to emphasize the importance of adopting a broad research and monitoring plan for Hawaiian waters, which includes multiple species of cetaceans and their prey.

Odontocetes share key areas of concern with humpback whales and often interact with them at multiple levels. In addition, most Hawaiian odontocete species are found in Hawaii' year-round, and are, therefore, intimately tied to the local oceanographic and biological cycles. Odontocetes sit at the top levels of the marine food chain, and may more directly suffer the cumulative effects of harmful substances present in their habitat, or of major shifts in food availability, making them a sensitive indicator of general ecosystem health (DeMaster *et al.*, 2001; Benson and Trites, 2002). Many other factors may influence their spatial and temporal distribution, including anthropogenic factors (Harwood, 2001).

It has been true in the past history of species management that interest in a particular species only peaked at the onset of large documented declines in population levels, and, often, population parameters before the decline were not available. It is clear that this approach is problematic.

Because there is insufficient information on odontocete populations in Hawaiian waters we cannot assume these populations are doing well. Furthermore, if there is a concern that humpback whale populations may be affected by increasing human-related activities in Hawai'i, then we should be equally concerned about some of the same activities affecting odontocetes which reside year-round in these waters.

Many factors may influence the spatial and temporal distribution of odontocetes, including physiographic and hydrographic characteristics, prey distribution, breeding and calving areas, predation and anthropogenic factors (Payne *et al.*, 1986; Richardson *et al.*, 1995; Baumgartner, 1997; Davis *et al.*, 1998; Davis *et al.*, 2002). How any of these factors influence distribution of odontocetes in Hawaiian waters is poorly known.

Davis *et al.* (2002) suggested that cetacean distribution may primarily be explained by prey availability, and, secondarily, by hydrographic features. In addition, the distribution and movement patterns of one species may be related to the distribution and movement patterns of another because of affiliation or competition for resources. For example, schools of spinner dolphins are frequently found in association with spotted dolphins and have been documented to feed in large aggregations across the Pacific Ocean (Leatherwood *et al.*, 1988). Feeding aggregations often include many levels of the trophic chain, and predator-prey relationships can, therefore, be quite complex. Heithaus (2001) reports a significant dietary overlap between sharks and dolphins. The presence of

sharks as potential competitors, and, at times, as predators, may affect the short-term distribution of some species.

Table 1 – List of species identified in Hawaiian waters to date based on published reports.

Common Name	Species Name	Strandings ①	Field Observations ②	Mobley <i>et al.</i> ③
Spinner Dolphin	<i>Stenella longirostris</i>	18	Many	50
Striped Dolphin	<i>Stenella coeruleoalba</i>	17	-	2
Pygmy Sperm Whale	<i>Kogia breviceps</i>	12	Many	2(*)
Pilot Whale	<i>Globicephala macrorhynchus</i>	12	Many	73
Sperm Whale	<i>Physeter macrocephalus</i>	10	Many	21
Melon-Headed Whale	<i>Peponcephala electra</i>	10	Many	3
Bottlenose Dolphin	<i>Tursiops truncatus</i>	8	Many	49
Rough-Toothed Dolphin	<i>Steno bredanensis</i>	6	Many	8
Pygmy Killer Whale	<i>Feresa attenuata</i>	6	Many	-
Spotted Dolphin	<i>Stenella attenuata</i>	5	Many	23
False Killer Whale	<i>Pseudorca crassidens</i>	5	Many	21
Risso's Dolphin	<i>Grampus griseus</i>	5	2	2
Cuvier's Beaked Whale	<i>Ziphius cavirostris</i>	3	-	7
Blainville's Beaked Whale	<i>Mesoplodon densirostris</i>	2	1	7
Killer Whale	<i>Orcinus orca</i>	1	2	1
Dwarf Sperm Whale	<i>Kogia simus</i>	1	Some	-
Common Dolphin	<i>Delphinus delphis</i>	-	1	-
Pacific Whitesided Dolphin	<i>Lagenorhynchus obliquidens</i>	-	1	-
Bottlenose Whale (?)	<i>Hyperoodon sp. (?)</i>	-	1	-

① Stranding information for odontocetes for the period 1937-1987 was taken from Nitta (1991), and from Mazzuca *et al.* (1999).

② Shallenberger (1981).

③ Mobley *et al.* (2000) reported odontocetes sighted during aerial surveys conducted within 25 nautical miles off the main Hawaiian Islands between 1993-1998. (*) Sightings were classified as *Kogia sp.* and could have been either pygmy or dwarf sperm whales. Mobley *et al.* (2001) reported killer whale sightings in Hawaiian waters (three historical reports besides the sighting reported by the authors).

Shallenberger (1981) reported that a significant portion of the diet of Hawaiian odontocetes consists of epipelagic and mesopelagic fish and squid. This primarily includes myctophid fish, some of which migrate at night to between near surface and 400 m depth of the surface (Reid *et al.*, 1991; Benoit-Bird *et al.*, 2001) and several species of squid, including *Abralia trigmura* and *Abralia astrostica*, which also show vertical diurnal migrations (Shallenberger, 1981). The mesopelagic boundary community is an

important factor in shaping the foraging strategy and distribution of odontocete predators, which face physiological limitations and cost-benefit tradeoffs when accessing this resource at depth versus near the surface. Because the availability of the mesopelagic boundary layer changes throughout the night, until, during daylight hours, the layer is too deep (400-700 m) for effective foraging by most odontocetes, these predators may have to limit their foraging to nighttime, and, more precisely, to specific times during the diel cycle when the prey is available closer to the surface or at a depth that maximizes intake and minimizes physiological costs (Benoit-Bird, 2003). This has been studied in spinner dolphins in Hawai'i, which track both vertical and horizontal movements of the shallower mesopelagic boundary prey layer between dusk and dawn (Benoit-Bird, 2003). Many odontocetes also feed on the locally abundant opelu (*Decapterus pinnulatus* and *Decapterus maruadsi*) and akule (*Trachurops crumenophthalmus*) may also be particularly important in smaller odontocetes' diets, while larger odontocetes have been observed eating mahimahi (*Coryphaena hippurus*), yellowfin tuna (*Thunnus albacares*), and skipjack tuna (*Katsuwonus pelamis*) (Shallenberger, 1981). Around the Hawaiian Islands these are the same resources that are important to fisheries. Because movements of odontocetes may be closely tied to movements of commercially important prey species, an understanding of seasonal and diel patterns in abundance and distribution of odontocetes could reveal more subtle patterns in the distribution of economically important resources.

Of the eight Hawaiian Islands, O'ahu is by far the most heavily impacted by human related activities, housing approximately 80% of the state's population and being visited by over five million tourists per year (Hawaii Tourism Authority, 2002). On

O'ahu, whale and dolphin watching are increasingly becoming popular activities and some hotels on the island have started advertising "swim with the dolphins" locations where wild spinner dolphins are known to come close to shore to rest. Long-standing local fisheries target fishes that are also prey to one or more species of odontocetes, and numerous anecdotal reports of adverse interactions between fishermen, bottlenose dolphins and false killer whales have been collected (Nitta and Henderson, 1993). Habitat degradation, in the form of pollution, depletion of resources by fisheries and human-related activities, noise, and increase in human presence on the water, can also negatively impact marine mammals (Harwood, 2001).

Overlaid on the natural cycles are, therefore, a variety of anthropogenic factors with the potential to influence or alter the abundance and distribution patterns of species sharing all or portions of their preferred habitats with humans. For the Hawaiian Islands, and O'ahu in particular, increasing development on land, and increased use of the marine environment for a variety of economic reasons, dictates that the status of all marine resources be assessed before insurmountable problems present themselves. It is therefore a priority to develop management plans based on the sustainable use of waters surrounding the Island of O'ahu, with particular attention to all federally protected marine mammals.

Based on these premises, the present study was undertaken to complete a preliminary assessment of the status of odontocetes around O'ahu. The general objectives of the present work were: (1) to present historical information available on Hawaiian odontocetes and discern, from it, general patterns of distribution, (2) to supplement historical information for O'ahu with a field study of abundance and distribution patterns

using aerial survey techniques, and (3) and to discuss some of the natural factors that may drive abundance and distribution of odontocetes in Hawaiian waters.

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CHAPTER 2

ODONTOCETE STRANDINGS AS AN INDICATOR OF DISTRIBUTION PATTERNS IN THE MAIN HAWAIIAN ISLANDS

Little is known about abundance and distribution patterns of odontocetes around the Hawaiian Islands. Strandings (Shallenberger, 1981; Nitta, 1991; Mazzuca *et al.*, 1998 and 1999), historical records (Tomich, 1986; Shallenberger, 1981), opportunistic sightings (Shallenberger, 1981), and dedicated surveys (Mobley *et al.*, 2000) have helped identify the 19 species of odontocetes, which are currently known to occur in this area. The patterns of abundance and distribution have been recently documented for the winter and spring of 1993-1998 (Mobley *et al.*, 2000), while no studies report about year-round patterns. Until routine scientific monitoring of abundance and distribution patterns of cetaceans is undertaken, strandings documented in the Hawaiian Islands will be a useful resource to fill knowledge gaps.

A few cetacean species have been documented only from stranded specimen (Klinowska, 1985; Goodall, 1977; Mignucci-Giannoni *et al.*, 1999; Pinedo and Polacheck, 1999; Malakoff, 2001). Strandings have been used to provide an indication of distribution for some commonly occurring species and help identify areas of occurrence in regions where systematic scientific effort is lacking (Guerra-Correa *et al.*, 1987).

Because of the rugged topography and low population levels in some parts of Hawai'i, the Hawaiian Islands are not an ideal location to maintain an efficient stranding network (Nitta, 1987). However, strandings have been documented since 1937. Nitta (1991) summarized stranding data between 1937 and 1987, and Mazzuca *et al.* (1999)

analyzed odontocete mass stranding data between 1954 and 1997. However, a complete analysis of odontocete stranding patterns for Hawaiian waters has not been done. The purpose of this study is to summarize the currently available stranding information and deduce generalized patterns of distribution for odontocetes in waters surrounding the main Hawaiian Islands.

STUDY AREA

The Hawaiian Island Archipelago is isolated from any other landmass by approximately 4,600 km of deep oceanic water. It consists of a group of volcanic islands including eight major islands and 124 islets, stretching in a 1,500-kilometer crescent from Kure Atoll in the northwest to the island of Hawai'i in the southeast, encompassing an area of 16,729 square km (Fig. 1).

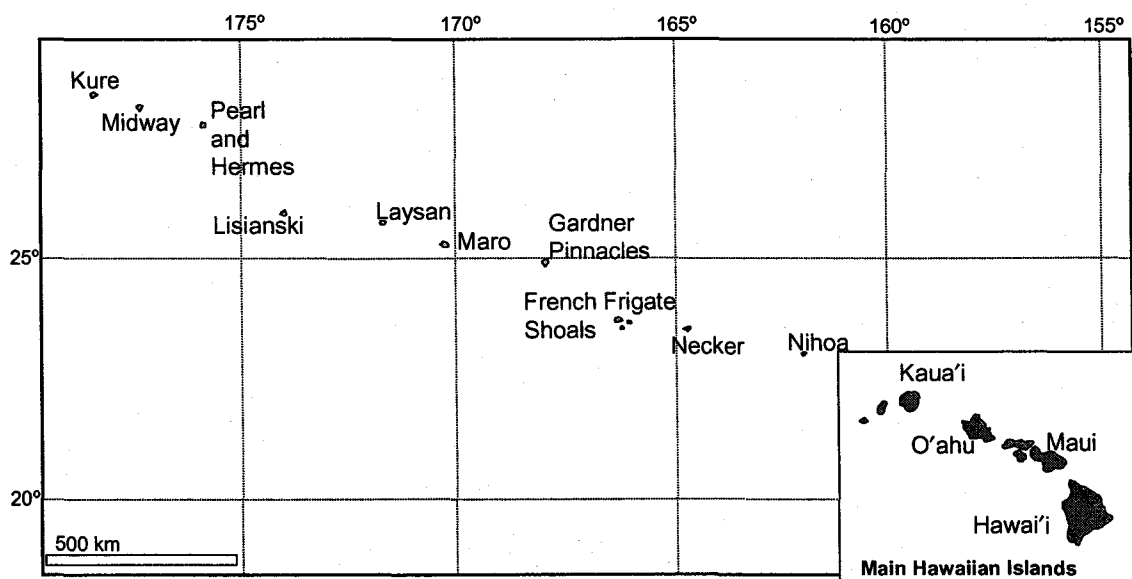


Figure 1 – Map of the Hawaiian Island chain emphasizing the location of the main Hawaiian Islands

Northeast trade winds prevail most of the year. Wind patterns may affect the probability of a carcass being washed ashore. In addition, the islands are surrounded by coral reefs. Shallow reefs can alter the pattern of stranding by preventing carcasses from reaching the shore. Thus, the location of these features may be important when interpreting the patterns of stranding.

METHODS

Stranding information for the period 1937-2002 around the Island of O'ahu was obtained from the National Marine Fisheries Service, Pacific Area Office (NMFS-PAO) and from previously published work (Shallenberger, 1981; Nitta, 1991; Mazzuca *et al.*, 1999).

Stranding reports contained in the NMFS-PAO database reported stranding date, species involved when identifiable, stranding location, number of animals stranded, and name of the responders. Some reports also included gender, estimated age class and status of the carcass, disposition information and samples taken. The database also included reports from news articles and phone calls, and not all carcasses were checked by NMFS-PAO personnel. Ancillary information was provided when available.

Differences in stranding frequency by species, island, sector (each representing a different compass direction as outlined below), and season for all main Hawaiian Islands were investigated. To determine if the distribution of strandings was skewed toward a particular compass direction, each island was divided into eight wedge-shaped sectors (NNE, ENE, ESE, SSE, SSW, WSW, WNW, NNW; Fig. 2). The length of the coastline delimited by each sector was calculated (in kilometers) using a measuring tool included

in the ArcView 3.2© software package. Number of strandings per kilometer of coastline were calculated for each compass direction for each of five islands/regions (Kaua'i, O'ahu, Moloka'i, Maui/Lana'i, Hawai'i). Comparisons among islands and sectors were accomplished using two-way ANOVA.

Species composition in the stranding record for all main Hawaiian islands was compared to that obtained by Mobley *et al.* (2000) during aerial surveys of the main Hawaiian Islands within 25 nautical miles from shore, and to that obtained during aerial survey transects conducted around the island between 1998 and 2000 (Maldini, Chapter 4 of this dissertation). Data for O'ahu were analyzed in details with respect to location and species composition since O'ahu's database was more comprehensive than for all other islands.

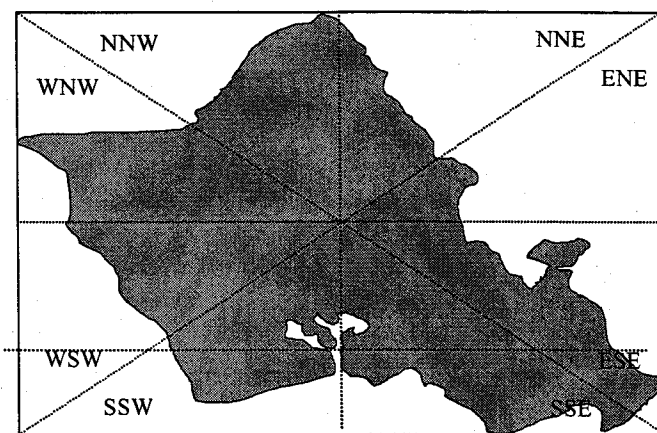


Figure 2 – Diagram of the method used to subdivide each of the Main Hawaiian Islands into sectors according to compass direction, using the Island of O'ahu as an example.

Strandings were not reported for the islands of Nihi'a'u and Kaho'olawe where the federal stranding network is inactive. Access to Nihi'a'u shores is limited to native Hawaiians, while Kaho'olawe is uninhabited. Strandings for Maui and Lana'i were combined because of the small number of strandings recorded on Lana'i (two records).

RESULTS

One-hundred and eighty-seven odontocete strandings were recorded in the main Hawaiian Island region by the NMFS-PAO between 1937 and 2002. Of these, 174 were identifiable to species, seven to genus (six *Kogia* sp. and one *Stenella* sp.), two were unresolved identifications, and 10 were unidentified (Table 1). The trend in the data was best explained by a second order polynomial regression ($R=0.411$; $P<0.001$), and it predicted an increase in the number of strandings throughout the history of the database (1937-2002; Fig. 3).

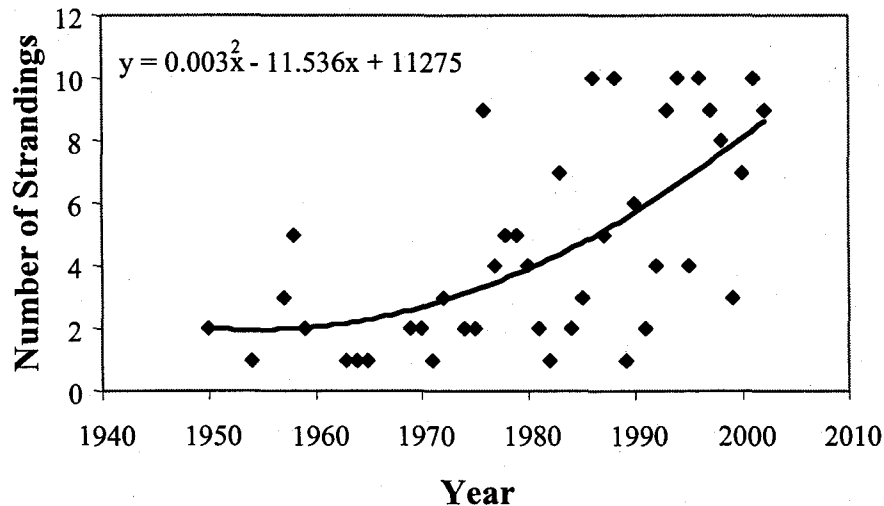


Figure 3 – Number of strandings recorded in Hawaiian waters by the National Marine Fisheries Service, Pacific Area Office between 1937 and 2002. The number of stranding increased significantly throughout the years.

Sixteen species were included in the stranding record, although pygmy sperm whale (*Kogia breviceps*) and dwarf sperm whale (*Kogia simus*) were pooled as *Kogia* sp. for analysis purposes (Table 1). The four most common species in the stranding record were *Kogia* sp. (18%; with pygmy sperm whale being more common), spinner dolphin

(*Stenella longirostris*; 15%), striped dolphin (*Stenella coeruleoalba*; 12%), and sperm whale (*Physeter macrocephalus*; 10%; Fig. 4).

Table 1 – List of odontocete strandings recorded by the National Marine Fisheries Service, Pacific Area Office between 1937 and 2002 in the main Hawaiian Islands. Species names correspond to the following (in alphabetical order): *Feresa attenuata*: Pygmy Killer Whale; *Globicephala macrorhynchus*: Short-Finned Pilot Whale; *Kogia breviceps*: Pygmy Sperm Whale; *Kogia simus*: Dwarf Sperm Whale; *Mesoplodon densirostris*: Blainville's Beaked Whale; *Orcinus orca*: Killer Whale; *Peponcephala electra*: Melon-Headed Whale; *Physeter macrocephalus*: Sperm Whale; *Pseudorca crassidens*: False Killer Whale; *Stenella attenuata*: Spotted Dolphin; *Stenella coeruleoalba*: Striped Dolphin; *Stenella longirostris*: Spinner Dolphin; *Steno bredanensis*: Rough-Toothed Dolphin; *Tursiops truncatus*: Bottlenose Dolphin; *Ziphius cavirostris*: Cuvier's Beaked Whale.

Year	Species	# of individuals	Location	Island
1950	<i>Ziphius cavirostris</i>	1	-	O'ahu
1950	<i>Orcinus orca</i>	1	South Point	Hawai'i
1950	<i>Ziphius cavirostris</i>	1	South Point	Hawai'i
1954	<i>Physeter macrocephalus</i>	1	Kahuku	O'ahu
1955	<i>Peponcephala electra</i>	1	Wailupe Circle	O'ahu
1957	<i>Globicephala macrorhynchus</i>	1	Punalu'u	O'ahu
1957	<i>Globicephala macrorhynchus</i>	2	Waikiki	O'ahu
1957	<i>Kogia</i>	1	Wailupe Circle	O'ahu
1958	<i>Globicephala macrorhynchus</i>	1	Kalihi Beach	Kaua'i
1958	<i>Globicephala macrorhynchus</i>	24	Keomuku Beach	Lana'i
1958	<i>Globicephala macrorhynchus</i>	1	Waikiki	O'ahu
1958	<i>Globicephala macrorhynchus</i>	12	Kalihi Beach	Kaua'i
1958	<i>Stenella coeruleoalba</i>	1	Ala Wai	O'ahu
1959	<i>Globicephala macrorhynchus</i>	28	Anini Beach	Kaua'i
1959	<i>Globicephala macrorhynchus</i>	1	Waimanalo	O'ahu
1963	<i>Kogia breviceps</i>	1	Bellows Beach	O'ahu
1964	<i>Peponcephala electra</i>	1	Kahuku	O'ahu
1965	<i>Peponcephala electra</i>	1	Lahaina	Maui
1969	<i>Steno bredanensis</i>	1	Waianae	O'ahu
1969	<i>Stenella longirostris</i>	1	Sandy Beach	O'ahu
1970	<i>Ziphius cavirostris</i>	1	Makaha	O'ahu
1970	<i>Stenella longirostris</i>	1	Kahului Harbor	Maui

Table 1 – continued

Year	Species	# of individuals	Location	Island
1971	<i>Peponcephala electra</i>	1	Keehi Lagoon	O'ahu
1972	<i>Stenella longirostris</i>	1	Makapu'u	O'ahu
1972	<i>Peponcephala electra</i>	1	Kahuku	O'ahu
1972	<i>Kogia breviceps</i>	1	La'i'e	O'ahu
1974	<i>Kogia breviceps</i>	1	Kalaupapa	Moloka'i
1974	<i>Pseudorca crassidens</i>	1	Kailua Beach	O'ahu
1975	<i>Stenella attenuata</i>	1	Hale'iwa	O'ahu
1975	<i>Feresa attenuata</i>	1	Hawi	Hawai'i
1976	<i>Stenella longirostris</i>	1	SLP	O'ahu
1976	<i>Kogia breviceps</i>	2	Kihei	Maui
1976	<i>Peponcephala electra</i>	1	Punalu'u	O'ahu
1976	<i>Physeter macrocephalus</i>	1	Kahuku	O'ahu
1976	<i>Steno bredanensis</i>	18	Kihei	Maui
1976	<i>Steno bredanensis</i>	1	Ka'anapali	Maui
1976	<i>Steno bredanensis</i>	4	Kihei	Maui
1976	odontocete	1	Ka'anapali	Maui
1977	<i>Stenella longirostris</i>	1	Mokule'i'a	O'ahu
1977	<i>Stenella coeruleoalba</i>	1	Punalu'u	O'ahu
1977	<i>Kogia</i>	1	Waimea	Kaua'i
1977	<i>Grampus griseus</i>	1	Wailuku	Maui
1978	<i>Stenella longirostris</i>	1	Kailua	O'ahu
1978	<i>Stenella longirostris</i>	1	Port Allen	Kauai
1978	<i>Grampus griseus</i>	1	Kahala	O'ahu
1978	<i>Stenella coeruleoalba</i>	1	Hale'iwa	O'ahu
1978	<i>Grampus griseus</i>	1	Papohaku	Moloka'i
1978	<i>Stenella coeruleoalba</i>	1	Reef Runway	O'ahu
1979	<i>Kogia breviceps</i>	1	Kihei	Maui
1979	<i>Pseudorca crassidens</i>	1	Mokapu Peninsula	O'ahu
1979	<i>Globicephala macrorhynchus</i>	1	Haunauma Bay	O'ahu
1979	<i>Stenella coeruleoalba</i>	1	Kahuku	O'ahu
1979	<i>Physeter macrocephalus</i>	1	Barbers Point	O'ahu
1980	<i>Pseudorca crassidens</i>	1	Mokapu Peninsula	O'ahu
1980	<i>Stenella longirostris</i>	1	Ka'a'awa	O'ahu
1980	<i>Kogia breviceps</i>	1	Kihei	Maui
1980	<i>Stenella coeruleoalba</i>	1	Kihei	Maui
1980	<i>Stenella coeruleoalba</i>	1	Kailua Beach	O'ahu
1981	<i>Feresa attenuata</i>	4	Ma'ala'e'a	Maui
1981	<i>Ziphius cavirostris</i>	1	Hilo	Hawai'i
1982	odontocete	1	Kihei	Maui
1983	<i>Feresa Attenuata</i>	1	South Point	Hawai'i
1983	<i>Tursiops truncatus</i>	1	Kepuhi Beach	Moloka'i
1983	Odontocete	1	Waiakalua-Pila'a	Kaua'i
1983	<i>Peponcephala electra</i>	1	Makaha	O'ahu
1983	<i>Stenella coeruleoalba</i>	1	Punalu'u	O'ahu
1983	<i>Physeter macrocephalus</i>	1	Ha'ena	Kaua'i
1983	<i>Grampus griseus</i>	1	Kihei	Maui
1984	<i>Globicephala macrorhynchus</i>	1	Kahana Bay	O'ahu
1984	<i>Stenella coeruleoalba</i>	1	Pauwalu Harbor	Moloka'i

Table 1 – Continued

Year	Species	# of individuals	Location	Island
1985	<i>Tursiops truncatus</i>	1	Mokule'i'a	O'ahu
1985	<i>Peponcephala electra</i>	1	Mokule'i'a	O'ahu
1985	<i>Physeter macrocephalus</i>	1	Kaneohe	O'ahu
1986	<i>Stenella longirostris</i>	1	Kaneohe	O'ahu
1986	<i>Stenella coeruleoalba</i>	1	Lanikai	O'ahu
1986	<i>Pseudorca crassidens</i>	1	Mokapu	O'ahu
1986	odontocete	1	Olowalu	Maui
1986	<i>Stenella attenuata</i>	1	Kaoio Pt.	O'ahu
1986	<i>Globicephala macrorhynchus</i>	1	Kahului	Maui
1986	<i>Tursiops truncatus</i>	1	Bellows Beach	O'ahu
1986	<i>Peponcephala electra</i>	1	Ku'au Bay	Maui
1986	<i>Stenella coeruleoalba</i>	1	Kailua	O'ahu
1986	<i>Kogia breviceps</i>	1	Kalaupapa	Moloka'i
1987	<i>Stenella longirostris</i>	1	Hale'iwa	O'ahu
1987	<i>Tursiops truncatus</i>	1	Wailua	Molokai
1987	<i>Kogia simus</i>	1	Hauola Gulch	Lanai
1987	<i>Stenella attenuata</i>	1	Makaha	O'ahu
1987	<i>Steno bredanensis</i>	1	Waipio Bay	Hawai'i
1988	<i>Peponcephala electra</i>	1	Mokule'i'a	O'ahu
1988	<i>Stenella longirostris</i>	1	Ka'anapali	Maui
1988	<i>Physeter macrocephalus</i>	1	Ahukini	Kaua'i
1988	<i>Feresa attenuata</i>	1	Kihei	Maui
1988	<i>Kogia breviceps</i>	1	Punalu'u	O'ahu
1988	<i>Feresa attenuata</i>	1	Ma'alaea	Maui
1988	<i>Feresa attenuata</i>	1	Kihei	Maui
1988	<i>Tursiops truncatus</i>	1	Pauwahu	Moloka'i
1988	<i>Stenella longirostris</i>	1	Nukumoi Pt.	Kaua'i
1988	<i>Grampus griseus</i>	1	Paia	Maui
1989	<i>Globicephala macrorhynchus</i>	1	Wailau	Moloka'i
1990	<i>Stenella</i>	1	Honolulu	O'ahu
1990	<i>Pseudorca crassidens</i>	1	Ha'ena	Kauai
1990	<i>Tursiops truncatus</i>	1	Kualoa	O'ahu
1990	<i>Stenella coeruleoalba</i>	1	Makaha	O'ahu
1990	<i>Stenella longirostris</i>	1	Mokule'i'a	O'ahu
1990	<i>Physeter macrocephalus</i>	1	Po'ipu	Kaua'i
1991	<i>Tursiops truncatus</i>	1	Kihei	Maui
1991	<i>Stenella longirostris</i>	1	Open Ocean	Hawai'i
1992	<i>Physeter macrocephalus</i>	1	Wailua Beach	Kaua'i
1992	<i>Physeter macrocephalus</i>	1	Anahola Bay	Kaua'i
1992	<i>Kogia</i>	1	Makapu'u	O'ahu
1992	<i>Tursiops truncatus</i>	1	Pounders Beach	O'ahu
1993	<i>Stenella coeruleoalba</i>	1	Kaneohe Bay	O'ahu
1993	<i>Stenella longirostris</i>	1	Waianae	O'ahu
1993	<i>Kogia breviceps</i>	1	Kekaha	Kauai
1993	<i>Stenella coeruleoalba</i>	1	Kihei	Maui
1993	<i>Physeter macrocephalus</i>	1	Cape Kumukai	Hawai'i
1993	<i>Stenella longirostris</i>	1	Koke'e Beach	Kaua'i
1993	<i>Stenella longirostris</i>	1	Anahola	Kaua'i
1993	<i>Kogia breviceps</i>	1	Wa'i'ehu	Maui

Table 1 – Continued

Year	Species	# of individuals	Location	Island
1993	<i>Peponcephala electra</i>	1	Ko Olina Resort	O'ahu
1994	<i>Stenella attenuata</i>	1	KMCAS	O'ahu
1994	<i>Stenella coeruleoalba</i>	1	Ma'ala'e'a	Maui
1994	odontocete	1	Ka'ena Point	O'ahu
1994	<i>Stenella longirostris</i>	1	Hanauma Bay	O'ahu
1994	<i>Stenella longirostris</i>	1	Nanakuli Beach	O'ahu
1994	<i>Kogia breviceps</i>	1	Kailua Beach	O'ahu
1994	<i>Stenella longirostris</i>	1	Kaneohe	O'ahu
1994	<i>Stenella longirostris</i>	1	Mokule'i'a	O'ahu
1994	<i>Stenella attenuata</i>	1	Hau'ula	O'ahu
1994	<i>Physeter macrocephalus</i>	1	Kapa'a	Kaua'i
1995	<i>Kogia</i>	1	Waipio Valley	Hawai'i
1995	<i>Peponcephala electra</i>	1	Breneke's Beach	Kaua'i
1995	<i>Stenella coeruleoalba</i>	1	Papohaku Beach	Moloka'i
1995	<i>Globicephala macrorhynchus</i>	1	Barking Sands	Kaua'i
1996	<i>Stenella coeruleoalba</i>	1	Olowalu	Maui
1996	<i>Kogia</i>	1	Halepalaoa	Lana'i
1996	<i>Kogia breviceps</i>	1	Waikolo'a	Hawai'i
1996	<i>Globicephala?</i>	1	Hilo	Hawai'i
1996	<i>Physeter macrocephalus</i>	1	Laupahoe	Hawai'i
1996	<i>Peponcephala electra</i>	1	Makaha	O'ahu
1996	<i>Stenella attenuata</i>	1	Kailua Beach	O'ahu
1996	<i>Kogia</i>	1	Waihe'e	Maui
1996	odontocete	1	Kailua-Kona	Hawai'i
1996	<i>Ziphius cavirostris</i>	1	Nanakuli	O'ahu
1997	odontocete	1	Nanakuli	O'ahu
1997	<i>Physeter macrocephalus</i>	1	Kahuku	O'ahu
1997	<i>Stenella longirostris</i>	1	Kailua	O'ahu
1997	<i>Stenella coeruleoalba</i>	1	Waimanalo	O'ahu
1997	<i>Physeter macrocephalus</i>	1	Waihe'e	Maui
1997	<i>Pseudorca crassidens</i>	1	Kailua-Kona	Hawai'i
1997	<i>Physeter macrocephalus</i>	1	Kahuku	O'ahu
1997	<i>Stenella longirostris</i>	1	Nanakuli	O'ahu
1997	<i>Stenella coeruleoalba</i>	1	Hale'iwa	O'ahu
1998	<i>Tursiops truncatus</i>	1	Kama'ole Beach	Maui
1998	<i>Stenella longirostris</i>	1	Spreckelsville	Maui
1998	<i>Tursiops truncatus</i>	1	Punalu'u Beach	O'ahu
1998	<i>Physeter macrocephalus</i>	1	Anahola	Kaua'i
1998	<i>Ziphius cavirostris</i>	1	Wailua	Kaua'i
1998	<i>Tursiops truncatus</i>	1	Waialua	O'ahu
1998	<i>Kogia breviceps</i>	1	Lahaina	Maui
1998	<i>Peponcephala electra</i>	1	Keahou Bay	Hawai'i
1999	<i>Globicephala macrorhynchus</i>	1	Kaneohe	O'ahu
1999	<i>Physeter macrocephalus</i>	1	Kaneohe	O'ahu
1999	<i>Kogia?</i>	1	Kaupa Bay	Maui
2000	odontocete	1	Po'ipu Harbor	Kaua'i
2000	<i>Kogia simus</i>	1	Kailua Beach	O'ahu
2000	<i>Tursiops truncatus</i>	1	La'i'e	O'ahu

Table 1 – Continued

Year	Species	# of individuals	Location	Island
2000	<i>Steno bredanensis</i>	1	Pu'ako	Hawai'i
2000	<i>Stenella longirostris</i>	1	Anahola	Kaua'i
2000	<i>Kogia breviceps</i>	1	Hanalei Bay	Kaua'i
2000	<i>Stenella longirostris</i>	1	Ka'ena Point	O'ahu
2001	<i>Kogia breviceps</i>	1	Sugar beach	Maui
2001	<i>Peponcephala electra</i>	1	Mokule'i'a	O'ahu
2001	<i>Physeter macrocephalus</i>	1	Kailua Kona	Hawai'i
2001	<i>Stenella longirostris</i>	1	Mokule'i'a	O'ahu
2001	<i>Kogia breviceps</i>	1	Kihei	Maui
2001	<i>Steno bredanensis</i>	1	Kihei	Maui
2001	odontocete	1	Allan Davis B.	O'ahu
2001	<i>Kogia simus</i>	1	Kihei	Maui
2001	<i>Stenella attenuata</i>	1	La'i'e	Hawai'i
2001	<i>Stenella coeruleoalba</i>	1	Kahuku	Hawai'i
2002	<i>Stenella attenuata</i>	1	Poka'i Beach	O'ahu
2002	<i>Kogia breviceps</i>	1	North Shore	Kaua'i
2002	<i>Kogia breviceps</i>	1	Kihei	Maui
2002	<i>Stenella longirostris</i>	1	Magic Island	O'ahu
2002	<i>Kogia simus</i>	1		Moloka'i
2002	<i>Kogia breviceps</i>	1	Makena	Maui
2002	<i>Mesoplodon densirostris</i>	1	Kama'ole	Maui
2002	<i>Kogia breviceps</i>	1	One'uli Beach	Maui
2002	odontocete	1	Keahau	Hawai'i
2001	<i>Kogia breviceps</i>	1	Sugar Beach	Maui
2001	<i>Peponcephala electra</i>	1	Mokule'i'a	O'ahu
2001	<i>Physeter macrocephalus</i>	1	Kailua Kona	Hawai'i
2001	<i>Stenella longirostris</i>	1	Mokule'i'a	O'ahu
2001	<i>Kogia breviceps</i>	1	Kihei	Maui
2001	<i>Steno bredanensis</i>	1	Kihei	Maui
2001	odontocete	1	Allan Davis B.	O'ahu
2001	<i>Kogia simus</i>	1	Kihei	Maui
2001	<i>Stenella attenuata</i>	1	La'i'e	Hawai'i
2001	<i>Stenella coeruleoalba</i>	1	Kahuku	Hawai'i
2000	<i>Kogia simus</i>	1	Kailua Beach	O'ahu
2002	<i>Stenella attenuata</i>	1	Poka'i Beach	O'ahu

None of the species accounted for more than 18% of the strandings (Fig. 4). The highest proportion of strandings was recorded on O'ahu (47%), followed by Maui/Lana'i (24%), Kaua'i (13%), Hawai'i (11%) and Moloka'i (5%).

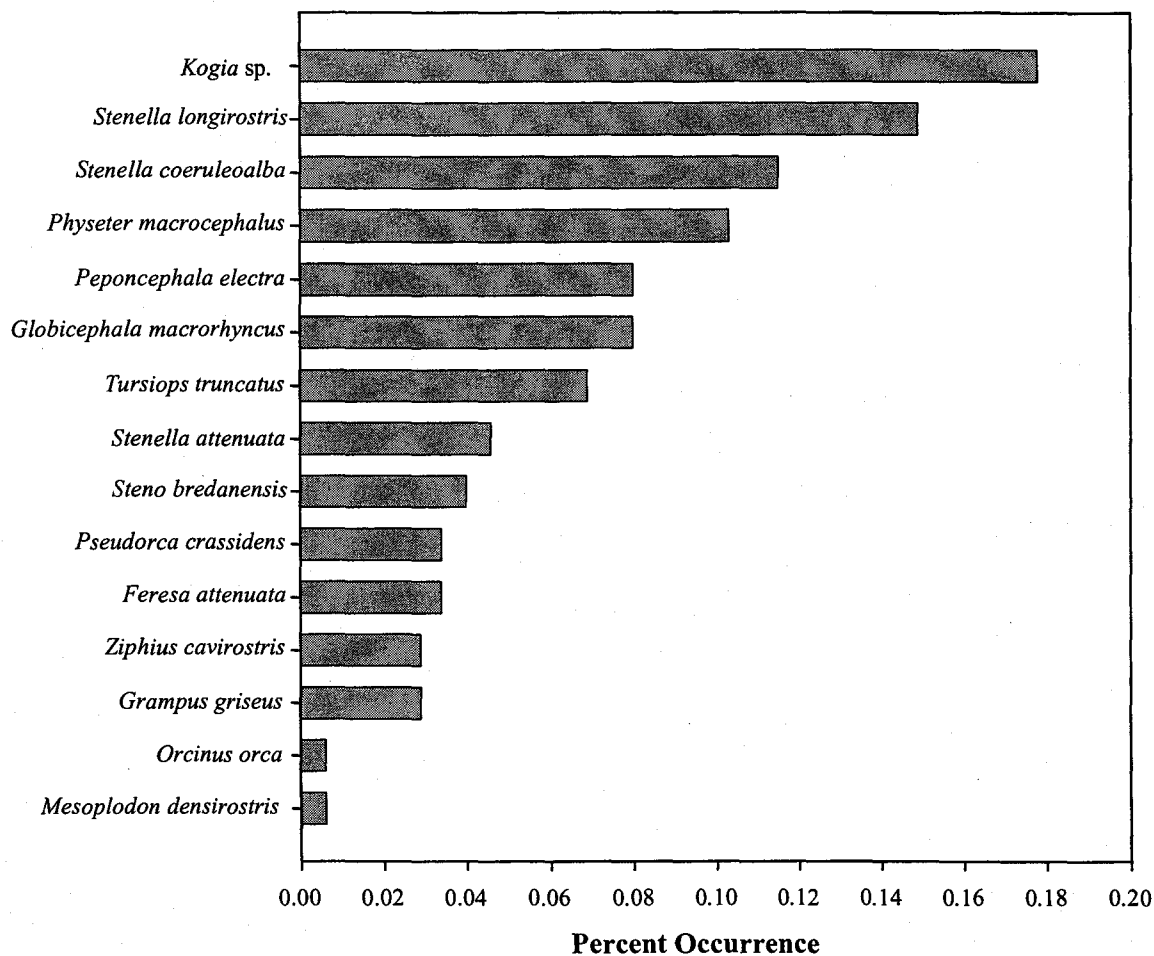


Figure 4 – Proportion of strandings by species recorded by the National Marine Fisheries Service, Pacific Area Office between 1937 and 2002 in the main Hawaiian Islands.

Differences in average number of strandings per kilometer of coastline were significant among islands (ANOVA: $F=0.226$, $P=0.008$; Fig. 5), but not among sectors (ANOVA: $F=1.299$, $P=0.287$; Fig. 6). A Tukey's multiple comparison test supported the conclusion that differences among islands were explained mainly by differences between O'ahu and Hawai'i.

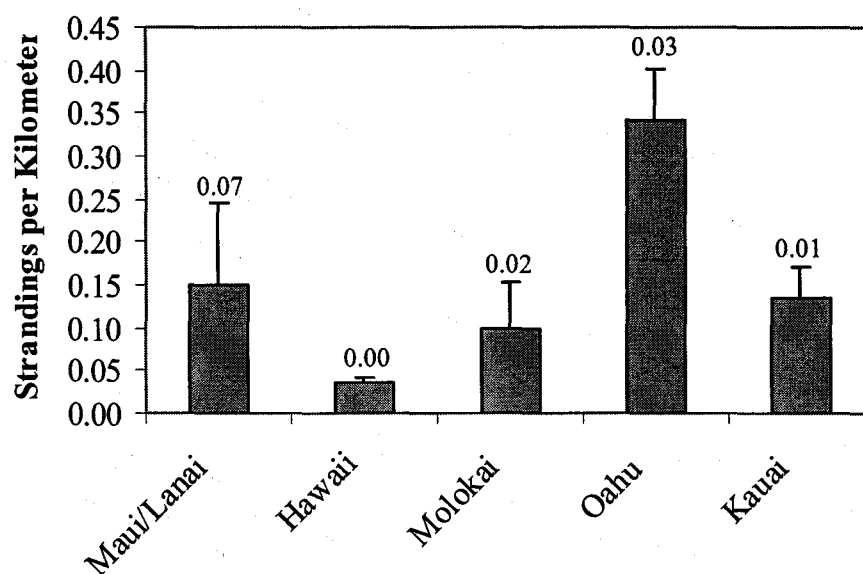


Figure 5 – Comparison of number of strandings per kilometer of coastline among the main Hawaiian Islands between 1937 and 2002. Bars report the Standard Error of the measurements, and numbers at the top of the bars report the Variance.

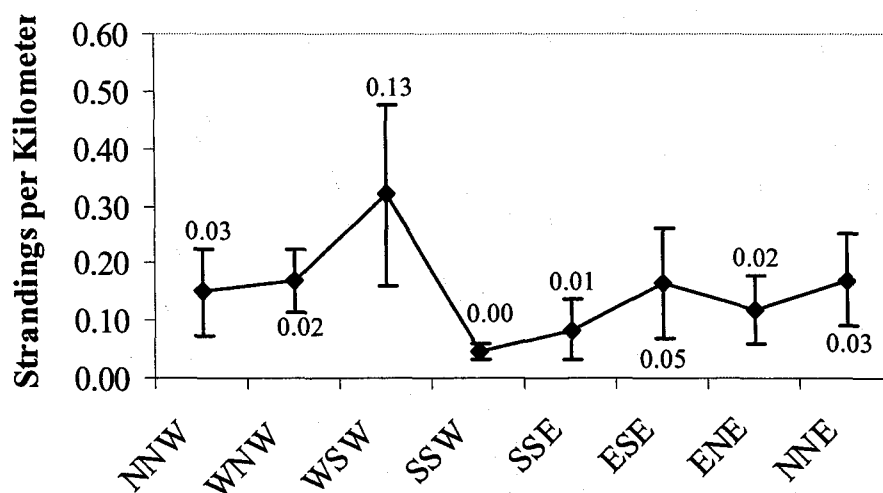


Figure 6 – Differences in number of strandings per kilometer of coastline among sectors of the main Hawaiian Islands between 1937 and 2002. Bars report the Standard Error of the measurements, and numbers above or below the bars report the Variance.

Strandings occurred throughout the year (Fig. 7). The difference in number of strandings per month was not significant (Kruskal-Wallis: $H=17.873$; $P=0.085$).

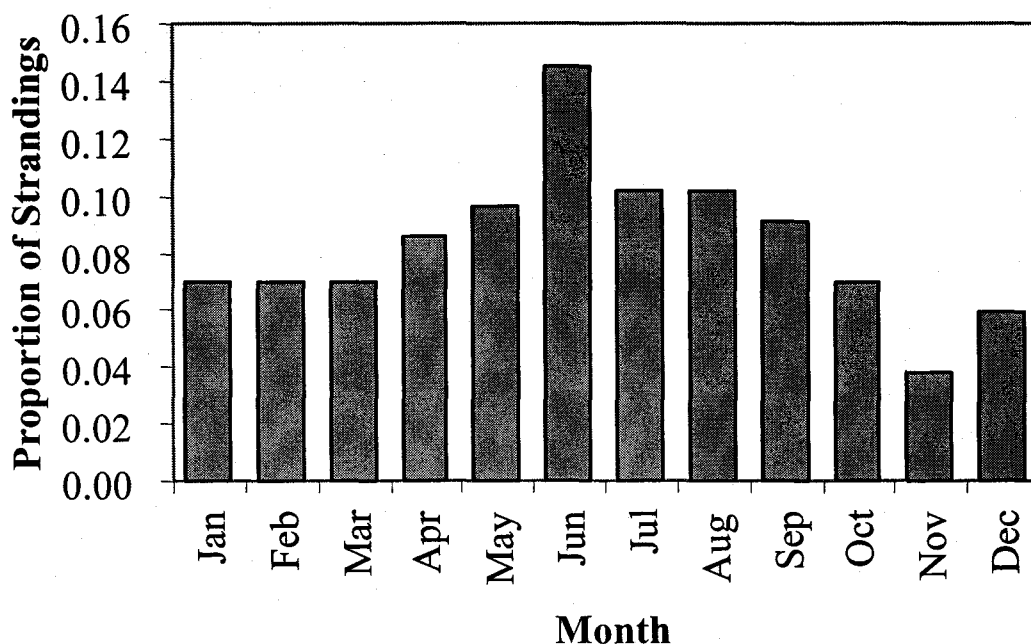


Figure 7 – Proportion of strandings which occurred along the main Hawaiian Islands between 1937 and 2002 throughout the year.

Strandings on O‘ahu occurred along all four main coastlines: north shore, Waianae or west coast, south shore, and windward coast (Fig. 8). Two species (spinner dolphin, and melon headed whale occurred on all four coastlines (Table 2). The false killer whale was localized, stranding only in a small geographical area between the Mokapu Peninsula and Kailua on the windward coastline (four events; Table 2 and 3). All but one stranding of *Kogia* sp. occurred along the windward coast of O‘ahu (five out of six events; Table 2). Sperm whale strandings were concentrated around Kahuku Point between north shore and windward coastline (Table 3). Patterns for all other species were difficult to interpret (Table 2).

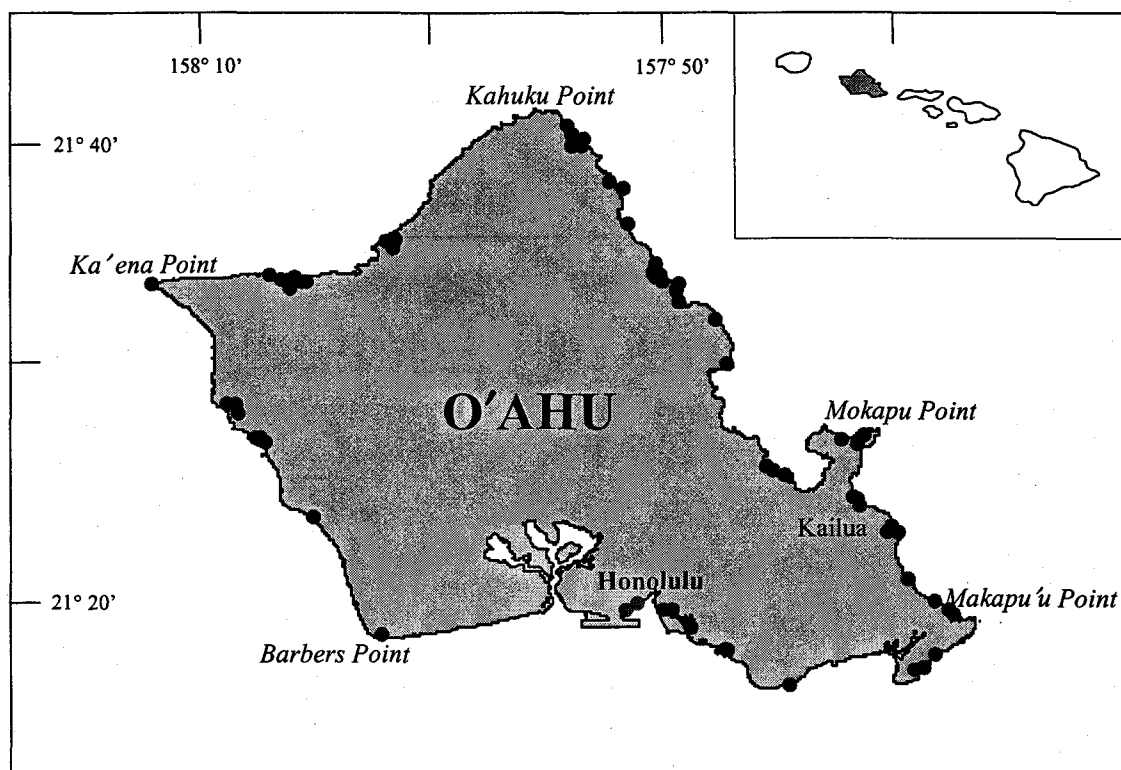


Figure 8 – General location of strandings occurred along O'ahu's coastline between 1937-2000.

Table 2 – Summary of strandings by species reported on the four coastlines of the Island of O'ahu between 1937 and 2002.

Species	South Shore	Waianae	North Shore	Windward
<i>Globicephala macrorhynchus</i>	3			4
<i>Grampus griseus</i>	1			
<i>Kogia sp.</i>	1			6
<i>Peponocephala electra</i>	1	3	3	1
<i>Physeter macrocephalus</i>	1			2
<i>Pseudorca crassidens</i>				4
<i>Stenella attenuata</i>		2		3
<i>Stenella coeruleoalba</i>	2	1		7
<i>Stenella longirostris</i>	4	3	5	4
<i>Steno bredanensis</i>		1		
<i>Tursiops truncatus</i>			2	5
<i>Ziphius cavirostris</i>		2		

Multiple strandings occurred in localized areas such as Mokule'i'a and Hale'iwa along the north shore, Kahuku, Punalu'u, Kane'ohe, and Kailua along the windward coast, and Makaha and Nanakuli along the Waianae coast (Fig. 8; Table 3).

Table 3 – Stranding location and species composition around the Island of O'ahu for locations with four or more strandings between 1937 and 2002. stelo=*Stenella longirostris*; pepel=*Peponcephala electra*; tutru=*Tursiops truncatus*; steco=*Stenella coeruleoalba*; gloma=*Globicephala macrorhyncus*; kogia=*Kogia* sp.; stebre=*Steno bredanensis*; phyma=*Physeter macrocephalus*; steat=*Stenella attenuata*; pscra=*Pseudorca crassidens*; zica=*Ziphius cavirostris*;

	stelo	pepel	tutru	steco	gloma	kogia	stebre	phyma	steat	pscra	zica	Total
Mokule'i'a	4	3	1									8
Kahuku		2		1				4				7
Kailua	1			2		2			1	1		7
Punalu'u		1	1	2	1	1						6
Kane'ohe	2				1			2	1			6
Makaha		2		1					1		1	5
Nanakuli*	2										1	4
Hale'iwa	1			2					1			4

* one of the strandings could not be identified to species

Fifteen of the 16 species reported in the stranding record for the main Hawaiian Islands were also reported by Mobley *et al.* (2000) and Mobley *et al.* (2001) during aerial surveys of the region. Seven of the 13 species reported through strandings throughout the main Hawaiian Islands (and six of those reported for O'ahu) were also detected during aerial transects around O'ahu between 1998 and 2000 (Fig. 9). Based on the stranding record, *Kogia* sp., melon-headed whales, striped dolphins and dwarf killer whale appear to be more common than suggested by aerial surveys (Fig. 9; Table 4). Conversely, pilot whales and bottlenose dolphins were more common, according to aerial surveys, than predicted by the stranding data (Fig. 9; Table 4).

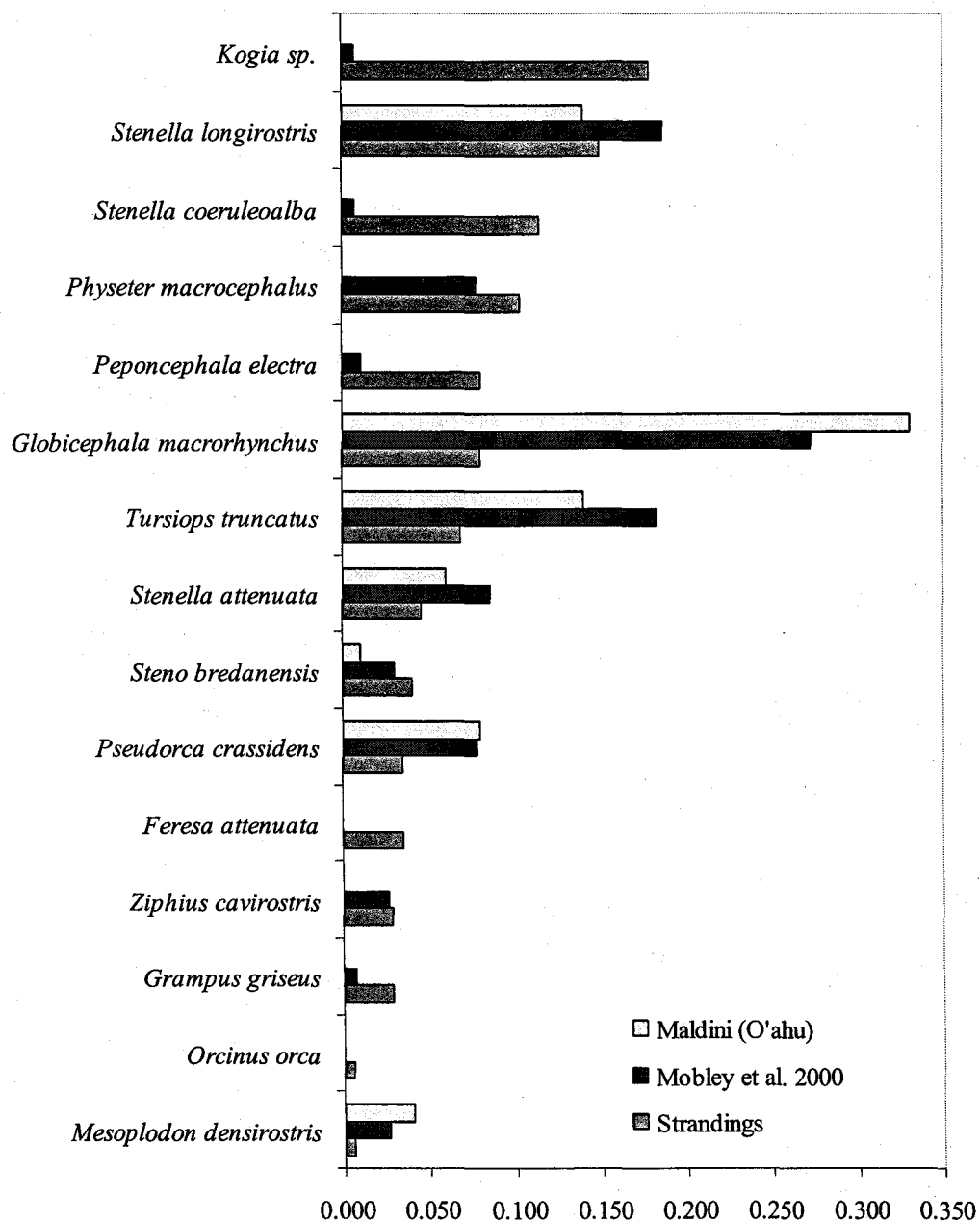


Figure 9 – Comparison of the frequency of occurrence (expressed as a proportion of total) of species stranded around the main Hawaiian Islands between 1937 and 2002 versus species encountered during aerial surveys conducted within 25 nautical miles of the main Hawaiian Islands between 1993 and 1998 (Mobley *et al.*, 2000), and aerial surveys conducted between the 0 and 500 m isobaths around O'ahu between 1998 and 2000 (Maldini, Chapter 4 of this dissertation).

Table 4 – Results of statistical comparison between frequency of occurrence of a species in the stranding record versus its frequency of occurrence in the aerial survey record (using Mobley *et al.*, 2000). The comparisons were analyzed using a z-test for each species. Reported are the values of z and P. Numbers in bold indicate a significant difference.

Species	z-stat	P	Higher Frequency
<i>Mesoplodon densirostris</i>	1.428	0.153	
<i>Orcinus orca</i>	0.863	0.388	
<i>Grampus griseus</i>	1.183	0.237	
<i>Ziphius cavirostris</i>	-0.285	0.775	
<i>Feresa attenuata</i>	2.402	0.016	strandings
<i>Pseudorca crassidens</i>	1.953	0.051	
<i>Steno bredanensis</i>	0.298	0.765	
<i>Stenella attenuata</i>	1.381	0.167	
<i>Tursiops truncatus</i>	3.147	0.002	sightings
<i>Globicephala macrorhynchus</i>	4.841	<0.001	sightings
<i>Peponcephala electra</i>	3.445	<0.001	strandings
<i>Physeter macrocephalus</i>	0.735	0.462	
<i>Stenella coeruleoalba</i>	4.889	<0.001	strandings
<i>Stenella longirostris</i>	0.905	0.365	
<i>Kogia sp.</i>	6.511	<0.001	strandings

Following is a summary of the main findings by species listed in order of frequency of occurrence in the stranding record:

Kogia sp.

Kogia stranded 31 times (32 individuals), including 11 live strandings, a neonate, a calf, and a female with a calf. Twenty-two strandings were confirmed to be the pygmy sperm whale, four were confirmed to be the dwarf sperm whale, while the remaining strandings were not identified to species. Of the 15 sexed animals eight were males and seven were females. *Kogia* stranded on all main Hawaiian Islands, with 14 strandings on Maui, seven on O'ahu, four on Kaua'i, three on Moloka'i, two on Hawai'i, and one on Lana'i. All but one of the strandings on O'ahu and all strandings on Moloka'i occurred along the windward coastline. Strandings occurred in all months of the year. It was first

reported in the stranding record in 1957. Strandings occurred at intervals of 1.42 (SE=0.51) years on average.

Spinner Dolphin: *Stenella longirostris*

Spinner dolphins stranded 26 times (26 individuals) including five live strandings, and the stranding of one pregnant female and one neonate. Of 16 sexed individuals, 10 were males, six were females. Eighteen strandings (72%) occurred on O'ahu (all coastlines), four on Kaua'i, three on Maui and one on Hawai'i. Strandings were distributed across the season occurring in 10 of 12 months of the year. The first recorded stranding occurred in 1969, after which strandings occurred at intervals of 1.06 (SE=0.42) years.

Striped Dolphin: *Stenella coeruleoalba*

Striped dolphins stranded 20 times (20 individuals, five of which were alive at the time of stranding). Of 13 sexed individuals seven were males and six were females. Thirteen of the strandings (47%) occurred on O'ahu, four on Maui, two on Moloka'i and one on Hawai'i. Strandings were distributed across the season occurring in 10 of 12 months. The species was first reported in 1958, and, since then, strandings occurred with intervals of 2.07 (SE=1.14) years on average.

Sperm Whale: *Physeter macrocephalus*

Eighteen strandings (one live in 2001) occurred in Hawaiian waters, during nine of 12 months of the year with no particular seasonality. Of five sexed animals, three were males. Seven strandings (39%) occurred on both Kaua'i, and O'ahu, three on

Hawai'i, and one on Maui. The species was first recorded in the stranding record in 1954. Stranding intervals were 2.27 (SE=1.31) years on average.

Short-Finned Pilot Whale: *Globicephala macrorhyncus*

Pilot whales stranded 14 times (78 individuals) with five mass strandings. At least five events, four of which were reported by Mazzuca *et al.* (1999) were live strandings. In one case (3 Oct 1958), 23 individuals died and one swam away. Seven strandings occurred on O'ahu, four on Kaua'i, and two on Maui/Lana'i, and one on Moloka'i. Pilot whales stranded during seven of 12 months with five strandings in May and three in October. The species was first reported in 1957. Subsequently, stranding intervals ranged from one to 19 years and were 4.11 (SE=1.46) on average.

Melon-Headed Whale: *Peponcephala electra*

Fourteen strandings (14 individuals, three live) occurred in Hawaiian waters mainly around O'ahu (71%) in nine of 12 months. Of the nine animals sexed, five were males and four were females. This species was reported in the stranding record for the first time in 1964 and stranded at intervals of 1.79 (SE=0.53) years.

Bottlenose Dolphin: *Tursiops truncatus*

Twelve strandings occurred (12 individuals, one live), seven on O'ahu, three on Moloka'i and two on Maui, where, in one of the events, a calf was recovered from a gill net. Reports showed no seasonality occurring during nine of 12 months. Of the nine animals sexed seven were males. The species was reported for the first time in 1983 and subsequently stranded at intervals of 1.00 (=0.43) years.

Rough-Toothed Dolphin: *Steno bredanensis*

Eight strandings (32 individuals) occurred, with three mass strandings on Maui and one on O'ahu (Mazzuca *et al.*, 1999). The Maui events occurred in 1976 (two live on 27 and 28 June and a single freshly dead animal on 30 June) suggesting these were related events. Because 12 animals were assisted off the beach on the first mass stranding, it is possible that some of the subsequent strandings were the same animals (Mazzuca *et al.*, 1999).

Of the individuals sexed (12), six were males and six were females. The rough-toothed dolphin was first reported in the stranding record in 1969 and stranded at intervals of 5.80 (SE=1.47) years.

Spotted Dolphin: *Stenella attenuata*

Spotted dolphins stranded eight times (one alive) and only on O'ahu. Four were females and three were males. Two of animals, one male and one female, were calves. Stranding of this species was first reported in 1975 and, subsequently occurred at an interval of 3.50 (SE=1.11) years.

Dwarf Killer Whale: *Feresa attenuata*

Six strandings (nine individuals), four on Maui and two on Hawai'i occurred on five different months. Of the individuals sexed (5), four were males. This species was first reported in the stranding record in 1975 and subsequently stranded at intervals of 9.25 (SE=1.53) years.

False Killer Whale: *Pseudorca crassidens*

Out of six strandings, four occurred on O'ahu, one on Kaua'i and one on Hawai'i. Interestingly, all of the O'ahu strandings occurred in the southeastern portion of the island in a small area between Kailua and the Mokapu Peninsula in January 1974, October 1979 and 1980, and September 1986. Three animals were sexed, a male and two females. The first reported stranding occurred in 1974. Stranding interval was 3.83 (SE=0.59).

Risso's Dolphin: *Grampus griseus*

Five strandings occurred; three were on Maui, all in the month of February, one on O'ahu, and one on Moloka'i. The first stranding was reported in 1977. Subsequently the stranding interval was 5.50 (SE=1.66) years. Of the eight animals sexed four were males and four were females.

Cuvier's Beaked Whale: *Ziphius cavirostris*

The Cuvier's beaked whale stranded five times, twice in January on Hawai'i, twice on O'ahu, and once on Kaua'i. Of three sexed animals, two were males. The first stranding occurred in 1950, and subsequently, stranding events occurred at an interval of 9.60 (SE=2.02) years.

Other Species

A single killer whale stranded at South Point in January 1950 on Hawai'i, a single Blainville's beaked whale stranded in April 2002 on Maui. The beaked whale was alive and it was a male.

DISCUSSION

There are limitations to the information gained by examining strandings. Reports of stranding events are significantly affected by effort, topography of the land, tides and currents, and consistency of a network that systematically documents occurrences (Klinowska, 1985; Mignucci-Giannoni *et al.*, 1999). The increased number of strandings reported over the years around the Hawaiian Islands (Fig. 3) is an example of the effect of increased public awareness and effort on the quantity of information collected. A regional network operated by the NMFS started developing after 1987 (Nitta, 1991), and, in 1994, a more structured response team including several governmental agencies was established in Hawai'i. In addition, the number of people frequenting beaches, including those in more remote locations, increased through the years, as the tourism industry and population levels in Hawai'i grew. Not surprisingly, the island of O'ahu, having the largest population and the most crowded beaches, registered almost half (47%) of the total number of stranding reports. This result suggests that a considerable proportion of strandings may be missed or may go unreported on the other main Hawaiian Islands, where large portions of the coastline are remote. The frequency of strandings recorded standardized by the length of the coastline for each island suggests that considerable effort to expand the stranding network may be most needed on the Island of Hawai'i, where number of strandings per kilometer of coastline was the lowest. In fact, Hawai'i has long stretches of non-easily accessible coastline, and a small population compared to its size.

Despite the increased effort and more organized stranding network, the overall number of strandings recorded for a 58-year period in the main Hawaiian Islands is low compared to other geographic areas. For example, a 200 km stretch of coast between the Loire and Gironde estuaries on the central French Atlantic Coast for the period 1972-1986 yielded 259 odontocete strandings (Duguy and Wisdorff, 1988). On O'ahu, which has a similar (225 km approximately) stretch of coastline, only 30 strandings were recorded during the same period.

Being completely surrounded by a vast stretch of ocean the Hawaiian Islands could present an easily missed target for carcasses floating at sea. Strong currents and winds can alter the trajectory of flotsam. In addition, sharks are abundant in Hawaiian waters and are known to scavenge on marine mammal carcasses, many of which get consumed before they reach land (Long and Jones, 1996; Heithaus, 2001). Furthermore, the presence of offshore reefs may prevent carcasses from reaching the shoreline in certain areas.

The number of strandings per kilometer, for each compass direction, was not significantly different for all islands combined. Because of the low number of stranding events recorded on some of the islands, inter-island differences in stranding patterns by compass direction could not be explored any further. Data for O'ahu alone (Fig. 8) suggest that the windward facing coastlines may experience a higher number of strandings than the leeward coastlines. This may be because of the exposure to trade winds which blow onto shore from the northeast. A visual inspection of the results by sector for all islands suggests that strandings are, in general, less common in the sectors facing south, generally less exposed to onshore wind conditions than in the other sectors (Fig. 6). In general, it is likely that each island, because of its shape and orientation,

experiences a unique combination of exposure to wind and currents, and therefore a unique pattern of strandings.

Strandings occurred during all seasons with no statistically significant trend, although there was a slight spike in occurrences in the month of June. Results of aerial surveys conducted around O'ahu year-round (Maldini, Chapter 4 of this dissertation) indicated, in contrast, an increase in the frequency of occurrence of odontocete sightings in the winter.

All species included in the stranding record were previously documented by Shallenberger (1981), who provided the first report on the status of odontocetes in Hawaiian waters, while Mobley *et al.* (2000) documented 13 of them during aerial surveys of the region in 1993-1998. Aerial surveys around O'ahu between 1998-2000 (Maldini, Chapter 4 of this dissertation) sighted only seven of the species documented in the historical stranding record. These results emphasize that short-term survey studies may not be suitable to describe odontocete species diversity. In addition, long-term stranding databases generally detect the presence of species which may be missed by systematic surveys because of their tendency to be cryptic, either due to their size, surfacing behavior or pelagic life history. This was the case, for example, for *Kogia* sp. and for the Cuvier's beaked whale, which were present in the stranding record, but rarely (if at all) sighted during systematic surveys.

In fact, aerial surveys (Mobley *et al.*, 2000) found *Kogia* sp. only twice, and the Cuvier's beaked whale seven times over an area of 71,954 km. Instead, *Kogia* sp. was never sighted during year-round aerial surveys of waters 0-500 m in depth around O'ahu between 1998 and 2000 (Maldini, Chapter 4 of this dissertation), while the Cuvier's

beaked whale was sighted only three times. The small size of *Kogia* sp. and its tendency to spend short periods at the surface make it difficult to sight in the field, and stranding records, in this case, may provide the best indication of occurrence in a particular area. Based on the high frequency of stranding, these animals appear to be abundant in Hawaiian waters year-round. *Kogia* sp. sightings have occurred in the past near Ka'ena Point, Makapu'u Point, and along the Waianae and south shore coasts of O'ahu, near Laha'ina, Maui, and between Hawai'i and Maui (Shallenberger, 1981; Mobley *et al.*, 2000; pers. obs. by the author, D.M.). Shallenberger (1981) included the dwarf sperm whale as unconfirmed in Hawai'i. Since then at least four specimens have been confirmed in the stranding record.

It is difficult to determine how common Cuvier's beaked whales are in Hawaiian waters. Stranding records are few in Hawai'i suggesting this species to be rare. Being deep divers, these whales are probably difficult to encounter at sea and recorded sightings have been sparse. Shallenberger (1981) reported their presence west of Lana'i and north of Maui, and in the North Western Hawaiian Islands (NWHI). Maldini (Chapter 4 this dissertation) never recorded them around O'ahu, while Mobley *et al.* (2000) reported them near Kaua'i, Ni'ihau and Hawai'i and estimated an abundance of 43 (CV=0.51) within 25 nautical miles of the main Hawaiian Islands.

Other species likely to be cryptic to surveys are the sperm whale, which was fourth in frequency of occurrence in the stranding record, and the Blainville's beaked whale. Sperm whales are classified as endangered and their status in Hawaiian waters is poorly known. Hawai'i marked the center of the nineteenth century whaling grounds for sperm whales (Gilmore, 1959; Townsend, 1935), although actual population estimates

before exploitation are not available. Because sperm whales are generally found in deep waters (Balcomb, 1987), and because their carcasses tend to sink, they are not a good candidate for stranding, which suggests that more strandings than the actual number reported would occur if this was not the case. The frequency of occurrence in the stranding record suggests this species is common around the main Hawaiian Islands. Sperm whales prefer deep waters. Seven strandings occurred on Kaua'i, which is directly adjacent to deep water, as opposed to other areas where the island slope is more gentle and deep waters tend to occur farther offshore. Balcomb (1987) reported sperm whales in the channels around Maui in late spring through fall, most in "nursery herds" of females and calves and in "harem herds" containing one adult male. Sperm whales were also reported off of Hawai'i (Lee, 1993; Mobley *et al.*, 2000), and sperm whale sounds have been recorded off O'ahu throughout the year (Thompson and Friedl, 1982). Mobley *et al.* (2000) estimated the number of sperm whales within 25 nautical miles of the main Hawaiian Islands region at 66 animals (CV=0.56), although this estimate is low because these aerial surveys did not include large areas of deep water around the islands which may be the preferred habitat for this species. Hawaiian sperm whales may be genetically different from sperm whales from the coast of California (Mesnick, unpublished data), although surveys revealed a continuous distribution from California to Hawai'i (Barlow and Taylor, 1998).

Blainville's beaked whales stranded only once in the history of the database, yet it was sighted seven times between 1993-1998 by Mobley *et al* (2000) who estimated the population within 25 nautical miles of the main Hawaiian Islands to be 68 (CV=0.59), and three times around O'ahu between 1998-2000 (Maldini, Chapter 4 of this dissertation).

Because this is a deep water species that is likely to sink when dead, it was certainly underrepresented in the stranding record, but may be relatively abundant around Hawai'i.

The stranding record may also include species that are rarely seen in a particular region such as Risso's dolphins and killer whales (*Orcinus orca*). Stranding and sighting history, in the case of these species, are in agreement.

There have been only a few verified sightings of Risso's dolphins in Hawaiian waters (Shallenberger, 1981; Mobley *et al.* 2000). Since this species is widespread in temperate to tropical waters (Leatherwood *et al.*, 1988) it is possible that it occasionally transits in the vicinity of the Hawaiian Islands. This species may also be confused with others at sea and may therefore go unreported.

Only one killer whale stranding occurred in the history of the database. Killer whales have been sighted occasionally (Shallenberger 1981, Mobley *et al.* 2001) and many encounters by opportunistic observers probably go unreported. In 2002 killer whales have been sighted near Moloka'i, about two miles east of Ka'unakaka'i town (Sykes, S. personal communication). Killer whales transiting Hawaiian waters are probably genetically related to the transient type, based on the small group size recorded (Mobley *et al.*, 2001; Sykes, personal communication), foraging exclusively on other marine mammals from pinnipeds to small odontocetes (Baird, 2000). Transient whales travel thousand of miles in search of their prey and Hawaiian waters may be a better foraging ground as compared to the open ocean. Photographic documentation of these encounters may prove instrumental in matching some of these whales to other populations in the North Pacific.

For most species that are considered common, strandings may or may not reflect the actual distribution or abundance patterns. In fact, bottlenose dolphins and pilot whales appeared with significantly higher frequency in the sighting than in the stranding record (Fig. 9; Table 4).

Bottlenose dolphins are also widespread throughout Hawai'i (Shallenberger, 1981; Mobley *et al.*, 2000; Baird, 2001). This species tends to prefer inshore habitats in Hawai'i and to reside in well-defined communities with high site fidelity to a particular harbor or coastline (Balcomb 1987; Baird, 2001). The reason why bottlenose dolphins do not strand proportionally to their abundance, unless other factors such as wide spread diseases are involved, may be tied to their relative "sturdiness" as a species (which makes them easy to keep in captivity).

Pilot whales stranded less frequently than expected from their relative abundance in Hawaiian waters, where they are considered common (Shallenberger, 1981). They are generally found offshore in deep channels between islands and tend to travel in herds of 20-40 (Balcomb, 1986). Mobley *et al.* (2000) estimated the presence of at least 1,708 (CV=0.32) short-finned pilot whales within 25 nm of the main Hawaiian Islands, and pilot whales were 33% of the odontocete sightings during 13 aerial surveys around O'ahu between 1998 and 2000 (Maldini, Chapter 4 of this dissertation). Mass strandings of pilot whales are a common occurrence in waters where they are present (Geraci, 1993). This was true for Hawaii where 42% of pilot whale's strandings were mass strandings (Mazzuca *et al.*, 1999).

Other mass strandings in Hawai'i involved *Kogia* sp., pygmy killer whales, and rough-toothed dolphins. Mass strandings occurred mainly on Maui, but never north of Kaua'i and south of Maui (Mazzuca *et al.*, 1999). Mazzuca *et al.* (1999) also noted that these strandings occurred along coastlines having an intermediate magnetic field and located near steep gradient anomalies. In addition, mass strandings occurred on the leeward shores, in areas of fringing reefs, shallow or gently sloping bottoms, suggesting that geomagnetic anomalies, coastal configuration and bottom topography may affect the animals' navigation abilities (Mazzuca *et al.*, 1999).

Three species, the pygmy killer whale, the melon-headed whale, and the striped dolphin were found with higher frequency in the stranding record as compared to their frequency during systematic aerial surveys by Mobley *et al.* (2000). These species are not necessarily cryptic (as compared to the species described earlier), although pygmy killer whales and melon-headed whales could be misidentified in the field. Balcomb (1987) describes both pygmy killer whales and melon-headed whales as being not particularly abundant in Hawaiian waters although present year-round. Balcomb (1987) also suggests these species to prefer the open ocean. This information suggests that a carcass may have a lower probability of reaching the shore thereby explaining the low incidence of strandings. Because all aerial surveys conducted in Hawaiian waters to date only covered areas within 25 nautical miles from shore, they may have missed the habitat of these open ocean species.

Strandings suggested a seasonal and localized distribution for melon-headed whales which stranded mainly in the summertime. Melon-headed whales are found in Hawai'i year-round (Balcomb, 1986), and are seen regularly in large herds off the

Waianae coast of O'ahu, the north Kohala coast of Hawai'i, and the leeward coast of Lana'i (Shallenberger, 1981). Only two sightings were recorded during aerial surveys of the main Hawaiian Islands between 1993 and 1998 (Mobley *et al.*, 2000).

In contrast, striped dolphins, which stranded with a frequency second only to that of the spinner dolphin and *Kogia* sp., are rarely observed in Hawaiian waters (Shallenberger, 1981). Thus, the high incidence of striped dolphins in the stranding record is not reflected in the sighting record (Mobley *et al.*, 2000; Maldini, Chapter 4 of this dissertation). This discrepancy is difficult to explain. Schools of striped dolphins may not be properly identified at sea or may be mixed with other species. It is also possible that aerial survey studies to date covered waters too close to shore to detect this species. Its frequency in the stranding record may indicate the presence of a very large population offshore, and may also suggest a potential "fragility" of this species, which causes large but occasional death tolls. If large die-offs were to occur in the open ocean, the probability that a small number of individuals reached the shoreline of Hawai'i would be higher. It is unknown whether striped dolphins in Hawaiian waters are part of the same population found in the Eastern Tropical Pacific (ETP), where the species is widely distributed and for which estimates of population size are available (Wade and Gerrodette, 1993).

For all other species in the stranding database the stranding and the sighting record do not differ significantly, nor there is any reason to suspect that a cryptic life style or other biases may have affected their relative abundance in the records. An exception were spotted dolphins.

Spotted dolphins are considered, by number of individuals, the most abundant odontocete found in nearshore waters around the Hawaiian Islands (Shallenberger 1981), and were estimated at 2,928 ($CV=0.45$) individuals in waters within 25 nautical miles of the main Hawaiian Islands (Mobley *et al.* 2000). Yet, they stranded only eight times in Hawaiian waters and only around O'ahu. The reason for this discrepancy is unclear, and there is no indication so far of a concentration of this species around O'ahu.

False killer whales were reported stranded in a localized area (Kailua) on the Island of O'ahu. Balcomb (1987) reports that they are found around all the Hawaiian Islands although infrequently. Sighting data (Maldini, Chapter 4 of this dissertation) for O'ahu support a localized distribution for this species around this island.

It is evident from the stranding record available for Hawaiian waters that strandings may be a useful tool to determine patterns of occurrence and distribution of marine mammals in a specific geographic area, but not a favorable substitute for properly designed field surveys and long-term studies. In addition, stranding data in Hawai'i suffer from the uneven effort deriving from the remoteness and sometimes inaccessibility of large portions of the coastline, and probably more so from the trade winds creating a bias in strandings towards the windward coasts. Nonetheless, the trend indicated that improved reporting, a more organized stranding network, and/or greater effort due to general education of the public have contributed to an increase in the number of events documented and to a more accurate depiction of the trends in occurrence and distribution.

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CHAPTER 3

ESTIMATING ABUNDANCE USING DISTANCE SAMPLING: A REVIEW OF THE THEORY

Estimating abundance of free-ranging animal populations has been a central question of many ecological studies. To decide how many gray seals to cull in Eastern Canada or what kind of impact a population of transient killer whales is having on endangered Steller sea lions in Alaska, it is necessary to establish how many individuals are found in the population to begin with. This subject has been at the center of much statistical debate because of the difficulties inherent in getting accurate numbers when dealing with free-ranging animal populations. Considerable research has been devoted to solving these issues and a statistical method known as “distance sampling” has been developed to provide fairly robust and reliable estimates of abundance in a variety of situations.

The current status of distance sampling in wildlife management is defined by a few recent publications (Buckland *et al.*, 1993; Buckland *et al.*, 2001; Thomas *et al.*, 2002b), in which a firm statistical base for the topic is established, and areas for future research outlined. The analysis of data collected according to the distance sampling method is usually carried out using the software package DISTANCE (Laake *et al.*, 1996; Thomas *et al.*, 2002a).

This chapter provides the theoretical framework behind the distance sampling theory with special attention to its assumptions, choice of models and modifications of the method used during aerial surveys.

THE DISTANCE SAMPLING THEORY

The use of the line transect method is generally recommended with sparsely distributed populations (such as marine and large terrestrial mammals), with populations that occur in well defined groups (such as herds or schools), and with populations that are detected through a flushing response such as many bird species. Line transect sampling provides a way to measure density and ultimately abundance.

While classic census methods assume all objects in an area are counted and therefore measure density (D) in a straightforward manner as

$$D = n/a$$

where 'n' is number of objects and 'a' is the area sampled, the distance sampling theory allows for the more common situation found when dealing with wild populations where only a proportion of the animals present is counted because many individuals go undetected. The distance sampling theory assumes that the probability of detecting an animal or a group of animals decreases as the distance from an observer increases. In addition, the distance sampling method allows for the size of the sample area to be unknown, as is the case in many studies. To estimate abundance using the distance sampling method, a set of lines or points are placed randomly over the study area, and an observer travels along the lines and measures perpendicular distances from the line to the animal(s) (line transect method), or remains stationary at established points and measures radial distances from a point to detected individuals (point counts). From these sets of measured distances, fairly robust and unbiased estimates of density can be derived if certain assumptions are met. The theory and assumptions behind this methodology are often complex.

The line transect method has proven to be the most useful in studies of cetacean abundance (Leatherwood *et al.*, 1978; Dohl *et al.*, 1986; Barlow *et al.*, 1988; Hiby *et al.*, 1989; Cockcroft *et al.*, 1992; Forney and Barlow, 1998; Mobley *et al.*, 2000; Mobley *et al.*, 2001). For this reason, the review of distance sampling methodology will be limited to line transects.

LINE TRANSECTS

In the line transect method a population of objects is sampled using randomly placed lines, preferably oriented across the expected density gradient. Once a set of lines is placed, an observer travels along a line looking for the objects of interest with the assumption that 100 % detection occurs only on the center line ("i.e.", $g(0)=1$), while away from the line detection drops off according to a detection function $g(x)$ which is the probability of observing an object given that it is ' x ' distance from the line. The value of $g(x)$ is always between zero and one ($0 < g(x) < 1$; Fig. 1) and is without units. This statement is intuitive since it is generally much easier to spot an object closer to the observer, than one at a distance.

In measuring abundance of cetaceans, it is important to recognize that animal size alters detectability, and therefore affects the shape of the detection function. The detection function for a humpback whale, which can be easily spotted a couple of kilometers away, is different from that of a small dolphin for which maximum detection distance maybe less than one kilometer. Detection may also vary depending on other parameters such as cue production (for example a splash or birds overhead in the case of marine mammals), observer effectiveness (visual or hearing acuity, attention span, fatigue, training) and

environmental variables such as poor visibility (fog or rain), glare, sea state, or speed of travel.

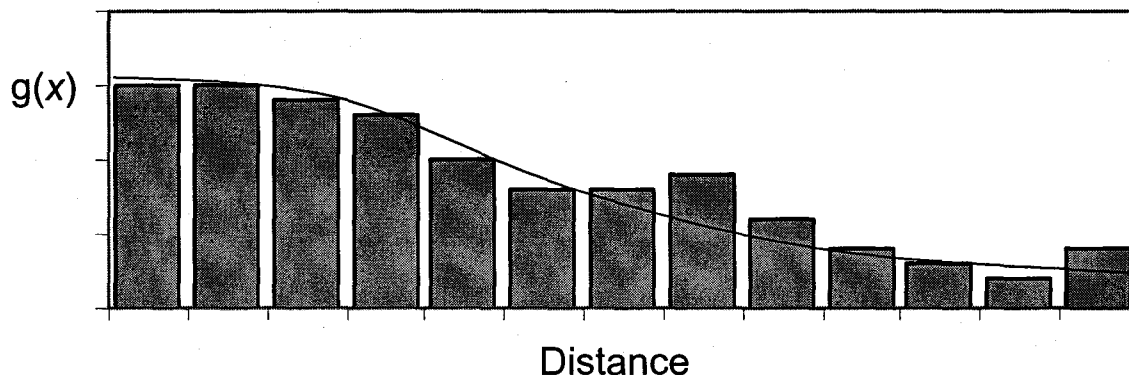


Figure 1 – The detection function $g(x)$ is the probability of detecting an object given it is at a distance x from the transect line.

The practical way to measure perpendicular distances from the centerline to the detected objects in the line transect method is to measure the angle (α) from the observer to the object at the time the observer makes the first detection, then measure the distance (r) from the observer to the sighting (Fig. 2).

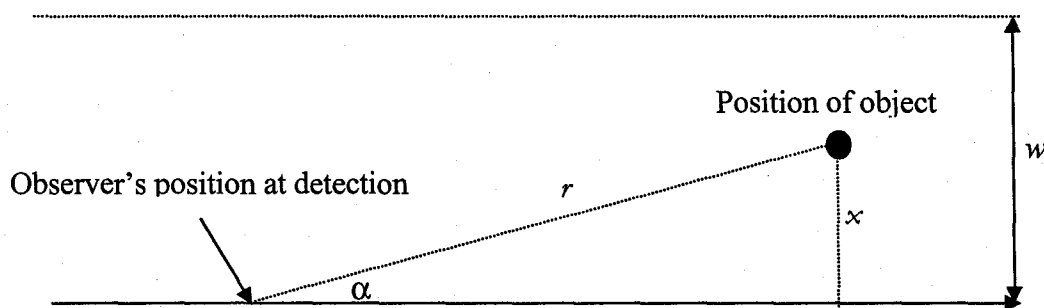


Figure 2 – Schematic view of the line transect sampling method with x being the perpendicular distance from the transect line, α being the angle from the transect line to the object, and r being the linear distance between the observer and the object.

Perpendicular distance can thus be calculated using the trigonometric formula:

$$x = r \sin (\alpha).$$

The detection function $g(x)$ can be used to estimate density (D). Any estimator of density can be expressed as:

$$D = n/2Lw$$

where (n) is the number of objects observed, (L) is the total length of the transect line and (w) is the width of the strip where objects are being detected. By replacing (w) with (a) we get:

$$D = n/2La$$

The constant (a) is simply the total area under the detection function $g(x)$:

$$a = \int_0^\infty g(x)dx.$$

In essence, the basic problem in estimating density is to estimate the parameter (a), or equivalently, ($1/a$).

Underlying any continuous random variable, such as detection distance, there is a probability density function $f(x)$. This function can be thought of as the underlying probability density function from which the observed distance data were generated. It can be shown that $f(x)$ and $g(x)$ are related by:

$$f(x) = g(x)/a.$$

As noted by Burnham *et al.* (1980), this equation shows that $f(x)$ is simply $g(x)$ scaled to integrate to 1.

The critical assumption permitting abundance estimation from distance data is that all objects located directly on the line (distance=0) are detected ("i.e.": $g(0)=1$). If $g(0)$ is unity, then $f(0)=1/a$.

If we can estimate $f(0)$, then we can estimate (a) as:

$$a=1/f(0).$$

The equation for estimating density ($D=n/2La$) can be rewritten in terms of $f(0)$ as:

$$D=nf(0)/2L.$$

We know (n) and (L), so we need to estimate $f(0)$. The main problem in line transect estimation involves developing an appropriate model for $f(x)$ and then using this model to estimate $f(0)$. There are a variety of models and associated estimators that can be used to fit the probability detection function to the detection-distance data (Burnham *et al.*, 1980; Buckland *et al.*, 1993).

ASSUMPTIONS

In order to obtain reliable density estimates a series of assumptions needs to be met:

Assumption 1

Lines are randomly located or a grid of systematically spaced lines is randomly positioned in the study area.

Systematic sampling has often resulted in higher precision than random sampling, provided that grids of systematic lines are also placed randomly (Burnham *et al.* 1993).

Special attention should be given to ensuring that the area of interest is given equal coverage. Zig-zag lines, which are often used when the platform of observation is a plane or a ship, should have equal angles or be placed according to some rule that ensures equal coverage.

Assumption 2**Objects on the line are detected with probability of one.**

This is an important assumption, which, if not met, undermines the reliability of the distance sampling method. If objects on the line are missed the estimated density will generally be biased low. It is important to emphasize that there is no substitute to good design in ensuring that all objects on the line are detected. In the case of marine mammals, despite precautions and extra care taken in sampling the centerline, detection is often less than unity because of the tendency of animals to remain underwater even if present. For this reason, in the marine mammal field, a lot of research has focused on developing methodologies to cope with a $g(0) < 1$. The practice of “guarding the centerline” adopted by shipboard observers during marine mammal surveys can often become counterproductive by altering the shape of the detection function in a way that violates the “shape criterion” (the ideal or desired shape for a detection function to provide reliable estimates). Some animals, such as certain species of dolphins are attracted to the bow of ships and their numbers near the centerline could be overestimated resulting in a curve with a spike near the centerline and a sharp drop-off a short distance away. This type of detection function is hard to model.

Assumption 3**Objects are detected at their initial location.**

At the time the observer makes a detection it is often difficult to determine whether an animal was already present within the observation area or if it moved within it before being detected. If such movement occurs it is important for it to be random and not a consequence of the presence of the observer. In addition, significant problems ensue if the

movement in question is fast compared to the movement of the observer. In most cases the percent of observations not meeting the assumption is low and the effects of movement are not a big problem. If, by collecting ancillary data, it is determined that movements in response to the observer are an issue, the methodology used to collect data should be reviewed carefully.

Assumption 4
Collected measurements are exact.

Only good field technique can ensure that collected angles and distances are exact. Often, this can be obtained by good observer training and careful note taking. Nonetheless, there are situations where some rounding errors occur. During aerial and shipboard surveys, for example, it is often difficult to stabilize the measuring devices because the platform is moving and the display being read oscillates accordingly. The most common observer tendency is that of rounding angles or distances to convenient values (generally multiples of five). This heaping can be minimized later on during data analysis by careful grouping of the data.

In other instances, systematic bias can occur when distances tend to be consistently over or underestimated by some systematic increment. The bias can be estimated and corrected using a calibration equation. When data are collected without a fixed width, a few values may be extreme and difficult to fit. Because these values are of very little use they should be truncated.

Assumption 5**Detections are independent events.**

In general, models assume that objects are randomly and independently distributed throughout the study area. If lines are randomly located this assumption is unnecessary unless objects occur in clusters. Marine mammals tend to travel in schools or herd, and, therefore occur in clusters (see next assumption).

Assumption 6**For clustered populations, the probability of sighting a cluster (pod, school, flock, covey, etc) is independent of cluster size.**

Because distance-sampling techniques sample distances and not objects or animals, each sighting, no matter how many individuals it compromises, is considered one distance if the individuals are aggregated in a cluster. Distance to a cluster is measured to its center, but the number of individuals in the cluster is recorded. Density when clusters are recorded can be easily calculated using the formula:

$$D = (Ds) \times (Es)$$

where (Ds) is the density of the clusters and (Es) the average cluster size. Because the probability of detecting an animal is a function of group size, the detection function can be altered by the presence of large groups. A bias can result by the fact that small clusters may not be detected so (Es) tends to have a positive bias. To deal with data affected by size-bias from clustered populations, which are common in cetaceans, data can be stratified by cluster size, cluster size can be treated as a covariate, or distance data can be truncated.

Assumption 7**The detection curve has a “shoulder”.**

This requirement is also known as the “Shape Criterion”. Burnham et al. (1983) advocate that, in a good model, the shape of the detection function should, ideally, have a “shoulder” near the center line, which means, in terms of distance sampling, that detection remains certain a short distance away from the transect line.

SAMPLE SIZE

Sample size should be large enough to allow for the required precision and for sufficient information so that density can be calculated. Buckland *et al.* (1993) suggest that at least 60-80 distances should be collected in order to obtain a fairly accurate estimator of the detection function $g(0)$.

CRITERIA FOR ROBUST ESTIMATION

To obtain a robust estimation of density and abundance it is preferable to choose a model which is (1) model robust, (2) pooling robust, and (3) conforms to the shape criterion. These three criteria have priority over all others but ideally a model should also be (4) an efficient estimator, and (5) have high precision.

The choice of the appropriate model is often dependent on the quality and quantity of the data collected, and often more than one model describes the data adequately. The experience of the analyzer can play an important role in model choice. However, there are recommended statistical tools to help determine which model best fits the data. One of the most commonly used procedures is the Akaike’s Information Criterion (AIC) which provides a quantitative method for model selection (Akaike 1985).

The AIC is defined as:

$$AIC = -2\log_e(L) + 2q.$$

The expression $-2\log_e(L)$ is a measure of how well the model fits the data while (q) is the number of parameters in the model and a measure of the model complexity. Each added parameter penalizes the model so that the minimum value of the AIC identifies the model that best fits the data without having too many parameters.

There are also other methods to estimate model robustness such as the Likelihood Ratio Test and the Goodness of Fit test. For a thorough review of these methods refer to Buckland *et al.* (1993).

MODELING THE DETECTION FUNCTION

The software package DISTANCE provides three parametric key functions for the detection curve $g(x)$, which provide reasonably good fit for most data sets. These models are: (1) the Uniform Model, ($g(x)=1$ for $x \leq w$), which assumes that everything is equally detectable out to a truncation distance (x), (2) the Half-Normal Model, ($g(x)=\exp(-x^2/2\sigma^2)$ for $x \leq w$), and, (3) the Hazard Rate Model, ($g(x)=1-\exp[-(x/\sigma)^b]$ for $x \leq w$), which is the only model that will fit a variety of shapes for $g(x)$ and is therefore model robust.

SOURCES OF BIAS

There are a variety of factors affecting the sightings of cetaceans at sea, such as weather conditions (“e.g.”: visibility, wind force, sea state and swell), sun glare on the water, observer’s experience and training, the size and height of the observation platform and its method of propulsion, the aids to sighting (“e.g.”: type of binocular used, naked-

eye), the size of the animals and/or their group size, the animals' behavior. Some of these factors can be mitigated during data analysis by using data elimination, truncation, stratification, or by including factors as covariates.

Marsh and Sinclair (1989) recognized two categories of bias: (1) availability bias, and (2) perception bias. Availability bias occurs when abundance of cetaceans tends to be underestimated because animals can only be detected at or near the surface. This bias can be larger for species that spend a considerable time underwater. Correction factors based on the proportion of time a particular species spends underwater can sometimes be applied to reduce this bias (Barlow, 1999), but these corrections are not available for the majority of cetacean species and may be specific to a geographic locality. Perception bias is introduced when animals are missed by an observer even though they are at the surface at the time the survey platform passes by them. This bias is exacerbated by the use of untrained observers, observer fatigue and poor visibility conditions, and may also vary by species being higher with smaller cetaceans or species with more cryptic behavior. A few studies have attempted to correct this type of bias by calculating the proportion of sightings missed using independent platforms along the same transect lines (Cockcroft *et al.*, 1992; Forney *et al.*, 1995; Laake *et al.*, 1997). In the case of poor sighting conditions, the bias can be minimized by excluding data collected during unacceptable conditions.

MODIFICATIONS OF THE METHOD FOR AERIAL SURVEYS

Aerial surveys are just a specialized form of line transect sampling. This technique is generally used as a measure of relative abundance, recognizing that the technique is biased and that the bias cannot be removed or estimated but only held constant.

The difference between aerial transects and land or boat based transects is simply the way perpendicular distance from the line is calculated. In aerial surveys an observer located at an altitude (h) and looking down on an object measures the angle between the object and the horizon typically by using a clinometer. An object at the horizon has $\delta=0^\circ$, while an object directly on the line has $\delta=90^\circ$. The perpendicular distance (x) from the transect line in this case is calculated with the formula:

$$x = h \tan(\delta) \text{ (Fig. 3)}$$

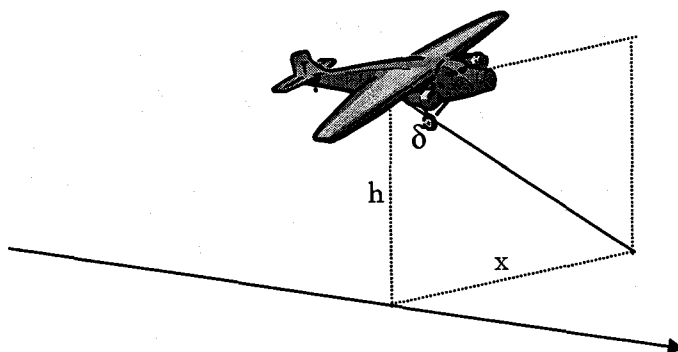


Figure 3 – Schematics of the measurements taken during aerial surveys using the line transect method

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CHAPTER 4

ABUNDANCE AND DISTRIBUTION OF CETACEANS IN NEARSHORE WATERS AROUND O'AHU AND PENGUIN BANKS

The Hawaiian Archipelago is isolated from any other landmass by approximately 4,000 kilometers of deep oceanic water and represents an oasis of productivity surrounded by a relatively unproductive environment with extremely patchy food resources (Venrick, 1969; Gilmartin and Revelante, 1974). In fact, differences in productivity between waters in the vicinity of islands and the open ocean are especially pronounced in tropical climates (Dandonneau and Charpy, 1985). Hawaii's inshore waters should therefore be attractive to local populations of cetaceans by providing an abundance of food as compared to the surrounding ocean.

Twenty-four species of cetacean, nineteen of which are odontocetes have been reported for Hawaiian waters (Shallenberger, 1981; Tomich, 1986; Balcomb, 1987; Nitta, 1991; Mobley *et al.*, 2000). Hawai'i is the breeding ground for a population of humpback whales (*Megaptera novaeangliae*), which summers in British Columbia and Alaska, and, to some degree, Hawaiian waters are visited by whales from throughout the Pacific Basin (Darling, 1983; Payne and Guinee, 1983; Darling and McSweeney, 1985; Baker *et al.*, 1986; Calambokidis *et al.*, 1997, Mate *et al.*, 1998). Mysticetes other than the seasonal humpback whale are considered anomalous or rare in Hawai'i and include fin whales, *Balenoptera physalus* (Shallenberger, 1981; Thompson and Friedl, 1982; Nitta, 1991; Mobley *et al.*, 1996), Brydes whales, *Balenoptera edeni* (DeLong and Brownell, 1977; Shallenberger, 1981), minke whales, *Balenoptera acutorostrata* (Shallenberger, 1981), and right whales, *Balena glacialis* (Herman *et al.*, 1980a).

When reviewing the available scientific literature on cetaceans in Hawaiian waters, it quickly becomes apparent that two species have been the focus of most studies in the region: the seasonal but endangered humpback whale (Cerchio *et al.*, 1998; Mobley *et al.*, 1999 and 2000; Craig and Herman 2000), and the locally abundant coastal spinner dolphin (Norris and Dohl, 1980; Norris *et al.*, 1994; Östman, 1994; Marten and Psarakos, 1999; Benoit-Bird, 2003; Lammers, 2003). Little is known of the other cetaceans, mostly odontocetes, that inhabit Hawaiian waters (Rice, 1960; Pryor *et al.*, 1965; Mobley *et al.*, 1999; Mobley *et al.*, 2000). Baseline population estimates for some odontocete species in inshore waters have been reported by Mobley *et al.* (2000) who have conducted aerial surveys of the main Hawaiian Islands between 1993 and 1998.

In a time when ocean resource management is becoming an issue, knowledge of abundance and distribution of existing biological resources is ever more critical. In Hawai'i, where the tourist industry is seeking new sources of revenue in dolphin watching, and long-standing local fisheries compete with odontocetes for increasingly small catches (Schlais, 1984; Nitta and Henderson, 1993), assessing the status of local species is essential.

Our study focuses on the Island of O'ahu, where anthropogenic impact is highest. Our goals were to: 1) identify species frequenting O'ahu's waters; 2) determine, where feasible, their relative abundance; 3) assess the seasonality of cetacean sightings; and 4) identify significant cetacean habitats around O'ahu.

STUDY AREA

The island of O'ahu has an area of 1,574 square kilometers and is approximately 71x48 kilometers in size, the third largest of the eight main Hawaiian Islands (Fig. 1). The entire coast of O'ahu is fringed by coral reefs 0.8 to 1.6 kilometers in width, except along parts of the west shore between Barber's Point and Ka'ena Point, and from Ka'ena Point to Kahuku Point, where the reefs are not as continuous as along other parts of the island.

The study area, which stretched between the 0 and 500-meter isobaths, was subdivided into five strata (Fig. 1):

1. South Shore – between Makapu'u Point and Barber's Point;
2. Waianae Coast – between Barber's Point and Ka'ena Point;
3. North Shore – between Ka'ena Point and Kahuku Point;
4. Windward Coast – between Kahuku Point and Makapu'u Point; and,
5. Penguin Banks – a 48 kilometer long and nine kilometer wide shallow water embankment (<50 m) surrounded by deep waters located between O'ahu and Moloka'i.

The first four strata identified the four coastlines of the Island of O'ahu, each delimited by two prominent points of land and each enjoying a different exposure to trade winds and wave patterns, and a different coastal relief. The boundary between strata was arbitrarily selected as a line bisecting points of land into equal parts, except for the boundary between the Windward and South Shore, which was drawn as a line connecting

Makapu'u Point to Ili'o Point on Moloka'i. The boundary for Penguin Banks was the 50 m isobath.

Penguin Banks, is a unique environment, being sheltered from trade winds by the Island of Moloka'i and experiencing a unique combination of oceanographic factors because of its shallow waters surrounded by deep oceanic waters. Penguin Banks extends between the Windward coast and the south shore of O'ahu.

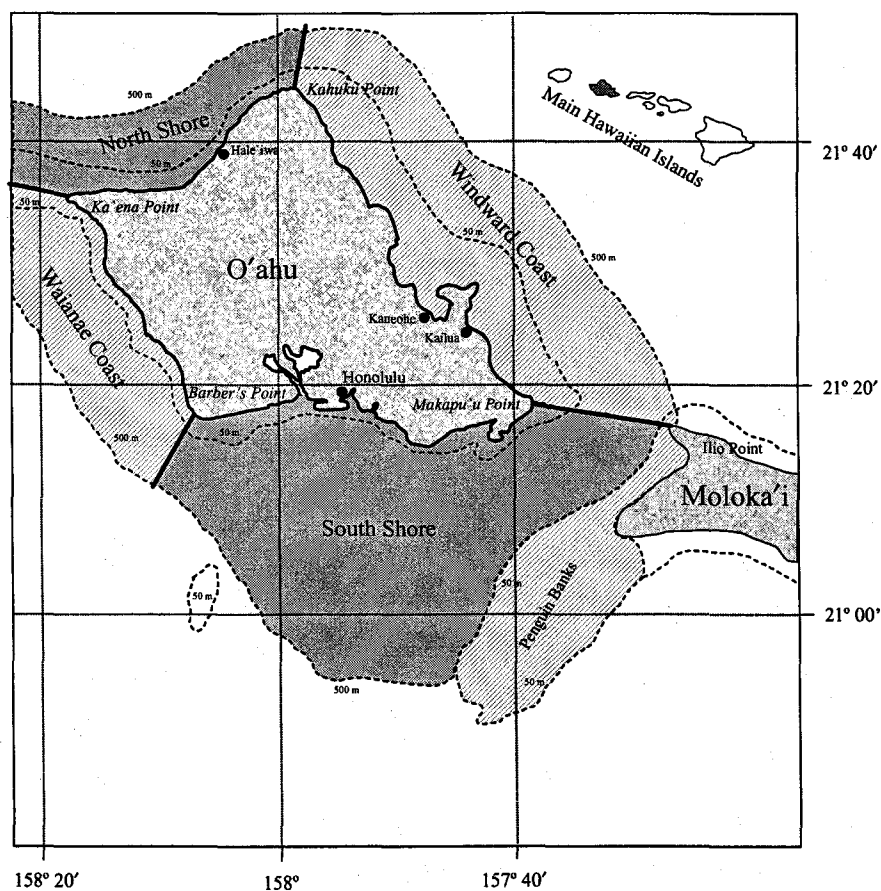


Figure 1 – Map of the Island of O'ahu and of the study area divided into five strata: South Shore, Waianae Coast, North Shore, Windward Coast and Penguin Banks.

METHODS

Aerial surveys are one of the most effective methods of obtaining information about abundance and distribution patterns of wild-ranging populations over large geographic areas and have been widely used for cetacean studies (Leatherwood *et al.*, 1978; Dohl *et al.*, 1986; Barlow *et al.*, 1988; Hiby *et al.*, 1989; Cockcroft *et al.*, 1992; Carretta and Forney, 1993; Forney and Barlow, 1998; Mobley *et al.*, 2000; Mobley *et al.*, 2001). The current study coupled aerial surveys with the line transect data collection method (Buckland *et al.*, 1993).

Waters between the 0 and 500-meter isobath around the Island of O'ahu were surveyed between September 1998 and April 2000. A typical survey departed from Honolulu Airport between 08:00 and 09:00, circumnavigated the Island of O'ahu along pre-determined tracklines, and landed back at Honolulu airport.

Platform and Instrumentation

We used a twin-engine Partenavia P-68 Observer aircraft owned by Tora Flight Adventure Club in Honolulu, Hawai'i (Fig. 2). The plane had a large bubble window in the front, and flat side windows. Despite its bubble-shape, the front window did not allow complete visibility below the aircraft, because of the location of the plane's instrumentation. The flat windows in the back were not suitable for viewing directly below, and this resulted in a blind area estimated to be between 70° and 90° vertical angle below the plane, the equivalent of a 55 m strip on each side of the plane at 152 m altitude. The aircraft was equipped with an Avionics Apollo 50 radar altimeter and a Garmin GPS receiver. The GPS output to a laptop computer, which captured the positional data using

LABVIEW software developed by Michael Feinholz at Oceanwide Science Institute on O'ahu. This software automatically recorded the plane's position at 30-sec intervals. Sighting time and location (as latitude and longitude) were recorded and flagged automatically when pressing the F1 key on the laptop. Altitude, environmental variables and sighting angles were recorded manually and later merged with the computerized data using time information.

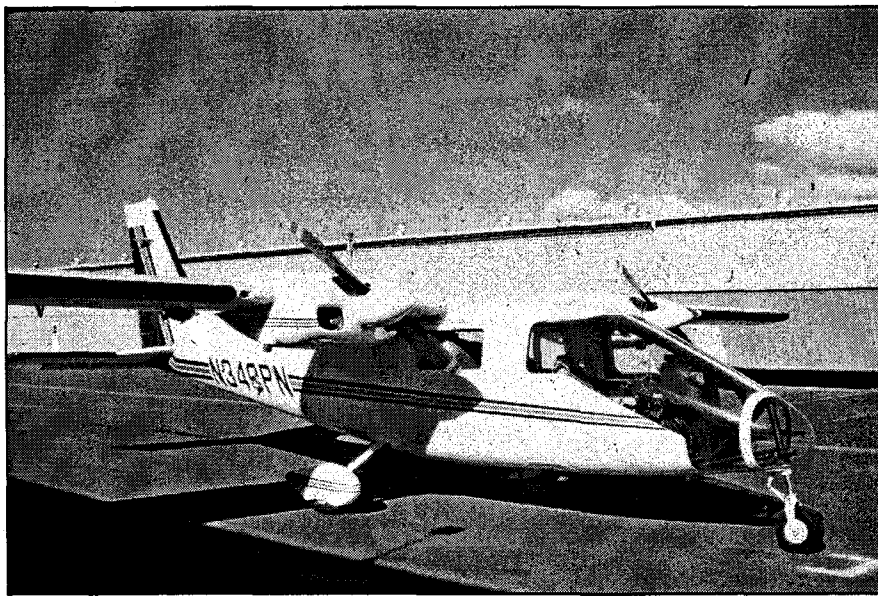


Figure 2 – Partenavia P-68 Observer aircraft owned by Tora Flight Adventure Club in Honolulu, Hawai'i.

The Crew

In addition to the pilot, the plane was staffed with two observers and one data recorder. Sightings were made by the two rear observers, located on each side of the plane, and called out to the data recorder sitting next to the pilot. Two additional people occasionally sat behind the observers. Their role was to take pictures, keep notes or serve as back-ups.

Data Collection Procedures

The aircraft flew in a straight line according to a predetermined route, pre-set on the GPS. Flying altitude, when feasible, was kept constant at 152 meters unless the pilot had to deviate from this pattern by request of the military and of the Honolulu airport control tower. Flying speed was always kept constant at 160 km/h.

The route consisted of several legs of varying length. At the start of each leg, or when conditions changed, the observers called out environmental information, such as glare, visibility, and sea-state, all of which were manually recorded (Table 1). Visibility and glare were rated for each side of the aircraft, while Beaufort sea-state was assessed as a whole.

When a sighting was called out, the recorder immediately hit the F1 key on the laptop, thereby transcribing the time and sighting location onto the hard disk. A sighting angle to a target school or individual was measured (reading the measurement at the center of the school if more than one animal was sighted) using a SUUNTO hand-held clinometer, with 0° corresponding to the horizon and 90° corresponding to the trackline. Angles measured to the nearest degree, and altitude to the nearest meter at the time of sighting were recorded. Sighting angles, in combination with altitude data, allowed for the calculation of perpendicular distance from the sighting to the transect line using simple trigonometry.

After recording positional data, the plane went “off-effort” to allow the observers to investigate all odontocete sightings and determine school size and species identity. Schools were circled over until identification was certain or the animals were lost. The aircraft then resumed effort where it had left off. Sightings of humpback whales were recorded opportunistically but were never investigated (since no federal permit was

available for this species). The plane was moved away from all humpback sightings as quickly as possible to maintain a distance of at least 305 m from this species.

Table 1 – Definition of environmental variables and parameters used to determine the acceptable ranges for data used to generate distance estimates. These definitions were based on Mobley *et al.* (2000). The visibility scale used to judge whether or not to use data for analysis depended on a combination of the Beaufort state and glare. Data were considered acceptable when the visibility was good to excellent.

Visibility Scale	Beaufort	Glare
Excellent	0-1	none
Very Good	0-2	1-10%
Good	0-4	11-25%
Good	0-5	26-50%
Fair	0-5	51-75%
Unacceptable	0-8	76-100%

Survey Design

The flight pattern varied. During the first three surveys, north-south oriented transect lines were flown to explore the area (Mobley *et al.*, 2000; Mobley *et al.*, 2001). The next nine surveys used zig-zag lines because they covered inshore areas better. The pattern had to fit time and budgetary constraints while effectively covering the study area with approximately equal effort. With the start point of each line being in front of Pearl Harbor, randomly generated angles between 5° and 85° were selected to create a zig-zag pattern for each survey. A line connecting two waypoints was defined as a leg. Waypoints intersected the 0 and 500 meters isobaths. The length of each leg was determined by the location of these intersections. This procedure resulted in tracklines 460 to 740 kilometers long, for a total linear distance of 6,916 Km (Fig. 3).

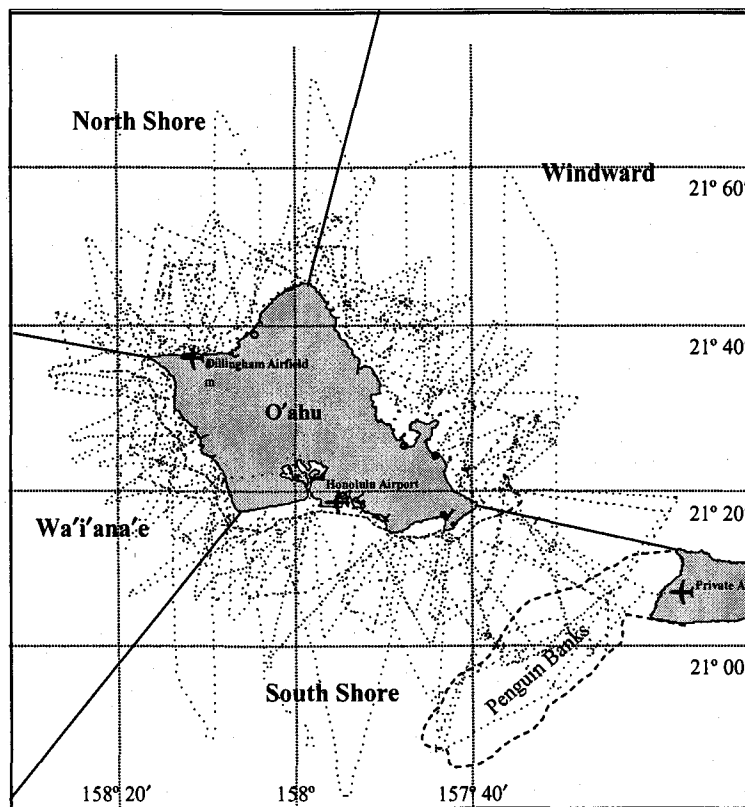


Figure 3 – Tracklines used during 13 aerial surveys around the Island of O‘ahu between July 1998 and June 2000.

Humpback Whale Sightings

Humpback whale sightings were recorded opportunistically and could not be investigated at close range due to the lack of a federal permit for this species, which was not part of the overall research objectives. Nonetheless, humpbacks were counted when sighted and a crude estimate of pod size could be obtained at a distance (over 305 m from any animal). Because sightings could not be investigated at close range, it is expected that school size may have been, at times, underestimated. The average sightings per kilometer of effort, and average number of whales per kilometer of effort (Beaufort <3) were then compared between years (1999 and 2000) and among strata using a Kruskal-Wallis test.

Odontocete Abundance Estimates

Perpendicular distances to odontocete sighting were obtained by multiplying the altitude at which the plane was flying by the tangent of the sighting angle (angle between the trackline and the sighting). Abundance estimates were calculated using the software DISTANCE (Thomas *et al.*, 2002). This program estimates density based of the formula:

$$D = n \cdot f(0) / 2 \cdot L$$

where D = estimated density
 n = number of pods or schools
 f(0) = estimated probability density evaluated at zero perpendicular distance
 L = total length of transect line

Density was then corrected for pod size using the formula:

$$D' = E(S) \cdot D$$

Where E(S) is the estimated pod or school size. Abundance is then calculated as:

$$N = D' \cdot A$$

where N = estimated abundance
 D' = corrected estimated density
 A = total area surveyed

Whale sighting probability tends to drop dramatically as sea state increases beyond Beaufort 3, and, ideally, data analysis should not use distances obtained when conditions are above this sea state (Buckland *et al.*, 1993). In the current study, three odontocete observations were collected during Beaufort > 3 and were, therefore, excluded from the analysis (Table 2).

Visibility, a combination of glare and atmospheric conditions, may affect sightability. Visibility was determined according to the classification in Table 1, and only legs where visibility was good to excellent were used.

To avoid selecting models that were not appropriate, we considered only the Hazard rate, Half-Normal and Uniform as candidate models for the detection function. These models have shown to provide a good fit to cetacean data collected using aerial surveys (Forney *et al.*, 1995; Barlow *et al.*, 1997; Calambokidis *et al.*, 1997; Kingsley and Reeves, 1998; Forney, 1999; Mobley *et al.*, 2000 and 2001). To fit models to the distribution data, 15% of the sightings located farthest from the trackline were removed from analysis as suggested by Buckland *et al.* (1993). The minimum value of the Akaike Information Criterion (AIC) was used to select the best model for the data (Akaike, 1985).

The distance sampling method is based on the assumption that detection probability on the trackline equals one (“e.g.”: $g(0)=1$). For marine mammals this assumption is generally not met because of their tendency to spend the majority of their time underwater, thus creating an “availability bias” (Marsh and Sinclair, 1989). Visibility underneath the plane was also limited, further increasing this bias. In addition, undercounting of sightings by observers is common during aerial surveys (Buckland *et al.*, 1993), due to aircraft speed, poor environmental conditions, and observer fatigue thus creating what Marsh and Sinclair (1989) called a “perception bias”. For these reasons, aerial survey counts generally underestimate abundance.

Correction factors, if available, can be applied to the data to try to model for sightings missed due to these biases. A correction factor was not available for any of the odontocete species sighted in Hawaiian waters, so that any abundance estimate will have considerable uncertainty.

Because the number of sightings for odontocetes was too small to determine the value of $f(0)$ based on differences in the detection function for each species, data were pooled using similar criteria to those used by Mobley *et al.* (2000) during aerial surveys of Hawaiian waters, and by Forney and Barlow (1993) in California. This approach entailed using group size, body size and behavior to determine how to appropriately pool species into similar categories for analysis purposes. Data were pooled in the following groups: small odontocetes (including spinner dolphin, spotted dolphin, bottlenose dolphins and unidentified dolphins), and medium odontocetes (including pilot whale, Blainville's beaked whale, false killer whale and unidentified odontocetes). Mobley *et al.* (2000) placed bottlenose dolphins in a separate category together with rough-toothed dolphins based on significant differences in the Kolmogorov-Smirnov test comparing sighting frequencies versus distance for each species. Because only nine bottlenose dolphin sightings were recorded in our data, we preferred to use Forney and Barlow's (1993) approach and included this species in the small odontocete category. Because of the small sample size for all species combined we chose to perform an unstratified analysis.

Frequency of Occurrence (Overall and by Stratum)

To correct for the lower visibility conditions associated with wind and chop, the number of sightings per unit effort (kilometer) was calculated using data collected only during Beaufort 3 or less (Buckland *et al.*, 1993). The average sightings per kilometer of effort were then compared among strata and season.

Seasons were defined as “humpback whale season” (Jan-Apr) and “off season” (May-Dec). Because abundance estimates for odontocetes in Hawaiian waters are currently only available for the period January to April, when humpback whales are in the area (Mobley *et al.* 2000), and because the presence of humpback whales may influence the distribution of other species, this study tested the hypothesis that there was a significant difference in odontocete sighting frequency between seasons (as defined).

Data were first tested for normality using the Kolmogorov-Smirnov Test, then tested using ANOVA. A Pairwise Multiple Comparison Procedure (Tukey’s Test) was run to compare pairwise between strata and season for odontocete data.

All available odontocete sightings were used to assess number of species present, average school size, spread in the data, and seasonality when possible. Sightings for humpback whales and odontocetes were visually compared to evaluate their occurrence relative to each other. An annotated species account was also included for odontocetes.

RESULTS

Twelve aerial surveys of waters between the 0 and 500 meters isobath around the Island of O’ahu were conducted between July 1998 and June 2000. Surveys covered 10 months of the year, 6,916 kilometers and 47 hrs of flight time (Table 2). Surveys were flown at an altitude which varied between 153 and 213 meters. Surveys were started only in ideal conditions with wind speed less than 15 knots. Nonetheless, weather varied around the island and often the wind picked up offshore and along the Windward Coast during a survey so that some legs experienced winds and seas higher than the accepted range for appropriate sighting conditions. Overall, 5,140 kilometers (or 74 % of the

effort; Table 2) were flown in good to excellent visibility (as defined in Table 1) and Beaufort less than three. The remaining distance was also flown in good to excellent visibility but the Beaufort was greater than three (Table 2).

Table 2 – Summary of survey effort and total sightings recorded around the Island of O’ahu between 1998 and 2000 using aerial surveys. In parenthesis is the number of total sightings made with Beaufort>3. Humpback whale sightings were taken opportunistically and, when sighted humpback whales were circumvented and sightings were not investigated.

Date	Kilometers Flown	Kilometers Flown in Bft 3 or less	Flight Time	Humpback Whale Sightings	Odontocetes Sightings	Average Beaufort
17 Jul 1998	517.02	288.08	3.60	0	2 (1)	3.32
3 Nov 1998	455.87	381.88	2.50	0	3 (1)	3.17
20 Jan 1999	760.35	444.76	5.00	15 (1)	4	2.75
25 Feb 1999	466.39	251.84	4.50	26	20	1.20
14 Apr 1999	545.87	413.83	4.10	2 (1)	3	2.94
4 May 1999	649.03	649.03	4.20	0	8	2.17
12 Jun 1999	1162.85	1121.98	3.75	0	3	1.97
23 Aug 1999	439.05	62.62	2.75	0	3 (1)	3.73
28 Sep 1999	614.37	614.37	3.00	0	3	2.48
1-3 Feb 2000*	718.98	369.11	6.50	54 (3)	15	2.39
11 Mar 2000	656.31	656.31	4.00	78	15	1.81
5 Jun 2000	432.37	187.77	3.10	0	0	3.45

* On 1 Feb 2000 the survey was aborted because of bad weather. The remainder of the survey was completed on 3 Feb 2000

Survey effort was proportional to the size of each stratum surveyed, and affected by the different weather conditions found within each stratum (Table 3). North Shore and Windward Coast surveys were affected by weather conditions more severely than South Shore, Waianae Coast and Penguin Banks (Fig. 4). This is not surprising since these areas are exposed to trade winds throughout the year, as it is typical of the windward and north facing coastlines of all Hawaiian Islands.

When conditions were unacceptable (poor to no visibility as defined in Table 1, and high winds and/or rain making the flight dangerous) a portion of the survey was aborted, as was the case only on 1 Feb 2000, when winds and rain along the Windward

Coast prevented the survey of that area and of Penguin Banks. This portion of the track was completed two days later (3 Feb 2000) in excellent weather conditions. These two days were considered one complete survey.

Table 3 – Summary of aerial survey effort and number of sightings recorded in five geographical strata around O'ahu between 1998 and 2000. In parenthesis is the number of sightings made with Beaufort >3. Humpback whale sightings were taken opportunistically and, when sighted humpback whales were circumvented and sightings were not investigated.

Stratum	Kilometers Covered	Kilometers in Beaufort 3 or less	Number of Sightings	Humpback Whale Sightings	Odontocete Sightings
Jan - Apr					
South Shore	814.99	650.61	27	20	7
Waianae Coast	554.02	554.02	21	13	8
North Shore	507.42	328.61	16	13 (3)	3
Windward Coast	955.8	534.04	36	11 (2)	25
Penguin Bank	315.67	283.12	133	119	14
May-Nov					
South Shore	1097.09	751.9	4		4
Waianae Coast	761.49	727.81	4		4
North Shore	723.67	452.66	7		7 (2)
Windward Coast	1329.16	1059.98	5		5 (1)
Penguin Bank	359.168	313.96	2		2

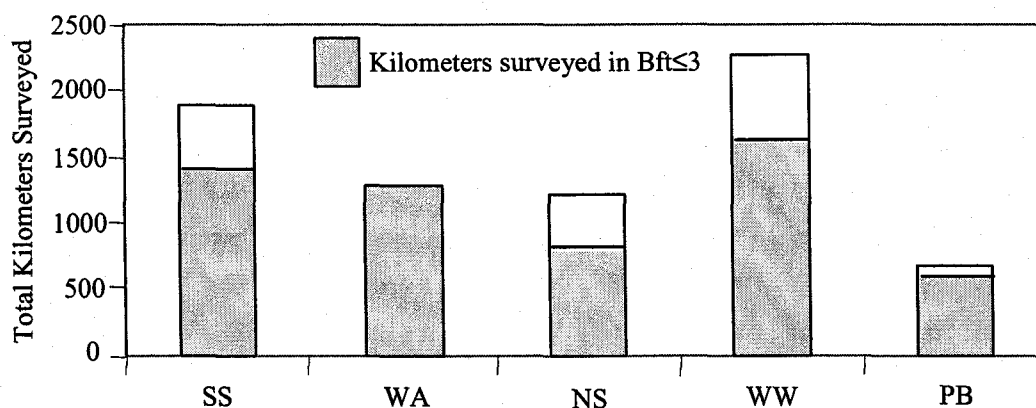


Figure 4 - Comparison of effort spent in all weather conditions versus effort in Beaufort less than 3 for the five geographical strata around the Island of O'ahu during aerial surveys between July 1998 and June 2000. SS=South Shore; WA=Waianae; NS=North Shore; WW=Windward; PB=Penguin Banks.

The overall effort resulted in 255 sightings (not number of animals). The majority of these (175) were humpback whales, 1 was a non-identified mysticete (possibly a humpback whale), 15 were unidentified odontocetes and 64 were odontocetes representing seven different species.

Mysticetes

No mysticetes were sighted other than humpback whales, which were seen only between January and April, their breeding season, when sightings occurred 100% of the time, although occasional sightings may occur earlier or later. The effort during humpback whale season was 3,148 kilometers (2,136 kilometer with Beaufort 3 or less). Such effort yielded 175 sightings (Fig. 5) corresponding to 317 whales (on average 0.082 sightings/km and 0.15 whales/km).

Pod size ranged between 1-8 whales. Ninety-five percent of the sightings were pods of one to three whales, with a single whale being more common (42% of sightings), then two whales (36% of sightings), and lastly three whales (14% of sightings). Average pod size was 2.00 (SE=0.09), and it did not significantly differ between 1999 and 2000 (Mann-Whitney U=3732; P=0.801). Of the 94 multiple whale pods, 10 included a calf. More calves may have been present but were not detected (since sightings were not investigated at close range) and six of the calves were detected in the month of March.

During the March 2000 aerial survey, whales were seen producing clouds of bubbles and moving in a circular manner underwater toward the surface in a manner suggesting bubble netting behavior. This behavior was seen twice in pods of two and four whales respectively.

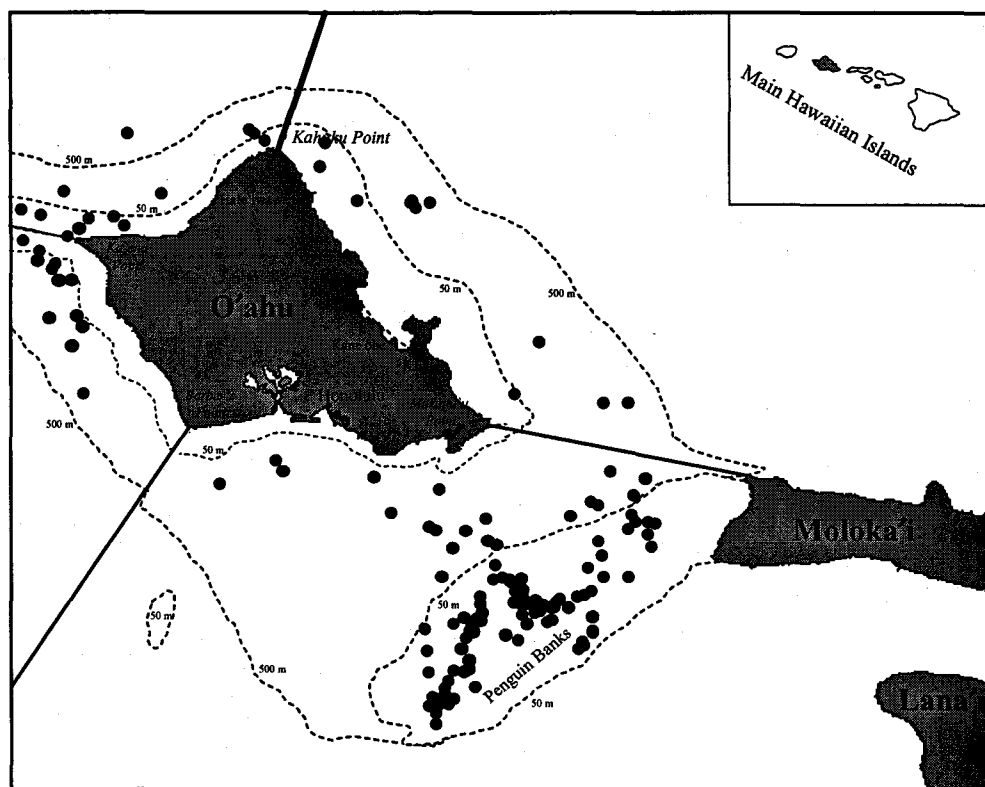


Figure 5 – Geographic location of humpback whale sightings recorded between July 1998 and June 2000 around the Island of O’ahu and Penguin Banks during aerial surveys.

Looking at the 1999-2000 data combined, the number of whales per unit effort (Fig. 6) shows a peak in February and March. The increase from January and subsequent decrease in April coincides well with the progression of the breeding season in Hawaiian waters, and does not deviate from trends observed in previous studies (Herman *et al.*, 1980; Mobley *et al.* 1999; Au *et al.*, 2000).

The differences in number of whales per unit effort by year and by stratum were compared using the surveys conducted on 25 February 1999 and 11 March 2000, since they were the closest in timing with respect to the progression of the humpback whale breeding season in Hawaiian waters, and had a similar Beaufort state across the survey (Table 2).

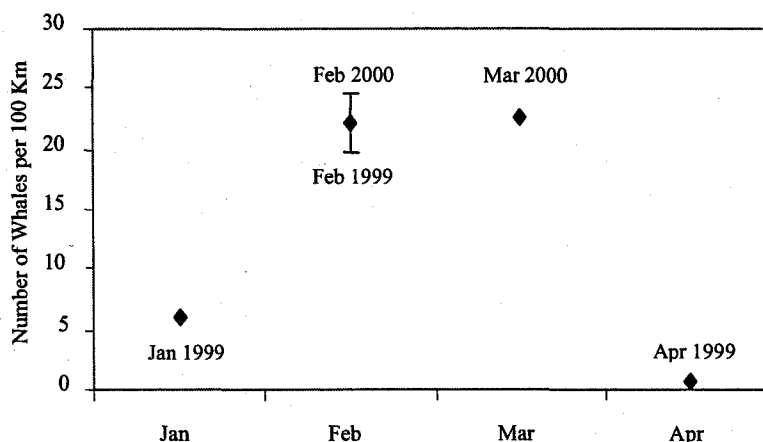


Figure 6 – Number of whales sighted per 100 kilometers of effort during the humpback whale breeding season (Jan-Apr) in O’ahu’s waters. The calculation of an average (and Standard Deviation) was only possible for the month of February, which was sampled in 1999 and 2000.

The difference in the mean values between 1999 and 2000 was not great enough to exclude the possibility that it was just due to random sampling variability after allowing for the effects of differences in strata ($F=0.880$; $P=0.401$). In contrast, the difference in the mean values among strata was greater than would be expected by chance after allowing for effects of differences between years ($F=39.808$; $P=0.002$). The Tukey’s multiple comparison procedure identified the differences between Penguin Banks and all other strata to be responsible for the significance of the result.

In addition, when all humpback season surveys were pooled, number of whales per kilometer of effort was significantly different among strata ($F=6.582$; $P=0.002$) after the data were normalized using the square root transform function. These differences were due to the higher number of whales per kilometer present in the Penguin Banks stratum (Tukey’s multiple comparison).

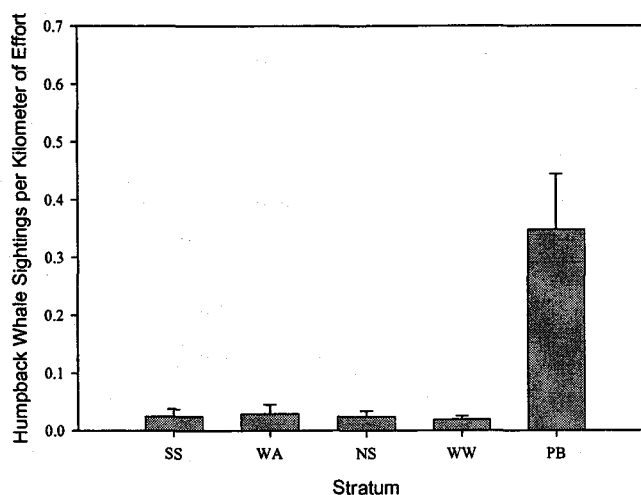


Figure 7 – Humpback whale sightings per kilometer observed along the five geographical strata surveyed aurally between January-March 1999 and January- March 2000. SS=South Shore; WA=Waianae; NS=North Shore; WW=Windward; PB=Penguin Banks. Bars represent Standard Error.

Odontocetes: Community Composition and Occurrence

Odontocetes were encountered on 11 of the 12 surveys for a total of 77 sightings and 1,339 animals (all species pooled). Odontocete sightings included, by frequency of occurrence (Fig. 8), pilot whales (*Globicephala macrorhynchus*; 30%), spinner dolphins (*Stenella longirostris*; 16%), bottlenose dolphins (*Tursiops truncatus*; 14%), false killer whales (*Pseudorca crassidens*; 9%), spotted dolphins (*Stenella attenuata*; 6%), beaked whales (*Mesoplodon densirostris* 4%), and rough-toothed dolphins (*Steno bredanensis*; 1%).

Most abundant by minimum number of individuals encountered was the spotted dolphin (406 animals) and the least was the rough-toothed dolphin (1 animal). In this case, number of animals present was most likely an underestimate since the animal disappeared as soon as it was sighted and was not found again. In fact, rough-toothed

dolphins are generally gregarious animals found in schools of 10-20 individuals (Leatherwood *et al.*, 1988).

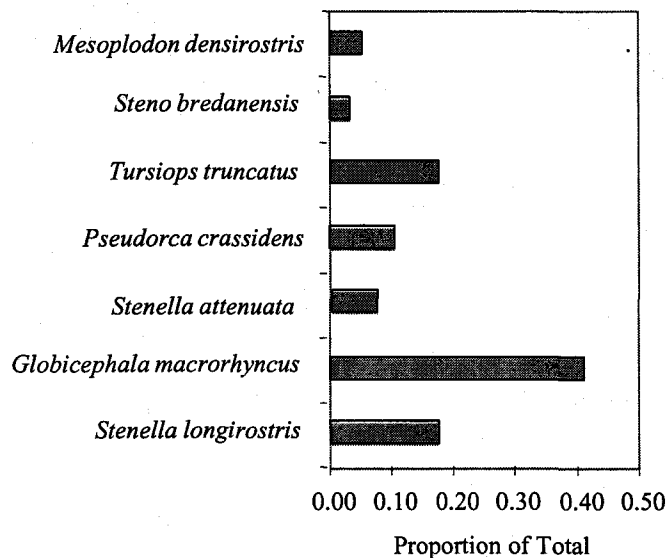


Figure 8 – Frequency distribution of odontocete sightings by species around O’ahu and Penguin Banks collected during aerial surveys between July 1998 and June 2000.

School size is shown as a box plot (Fig. 8), which visually represents the spread in the data and shows the relative position of the median, the minimum and maximum values and the upper and lower quartiles. Spinner (\bar{x} =11; SE=2), bottlenose dolphins (\bar{x} =4; SE=1) and pilot whales (\bar{x} =10; SE=2) had the narrowest spread, while wider spreads, signifying a larger variation in school size were present for spotted dolphins (\bar{x} =61; SE=16) and false killer whales (\bar{x} =11; SE=6). For false killer whales the highest group size encountered (300 animals) was considered an outlier and not used to calculate mean school size. Although false killer whales have been documented in herds of more than 100 individuals (Leatherwood and Reeves, 1988), a more typical group size is 10-50 (Carwardine, 1995).

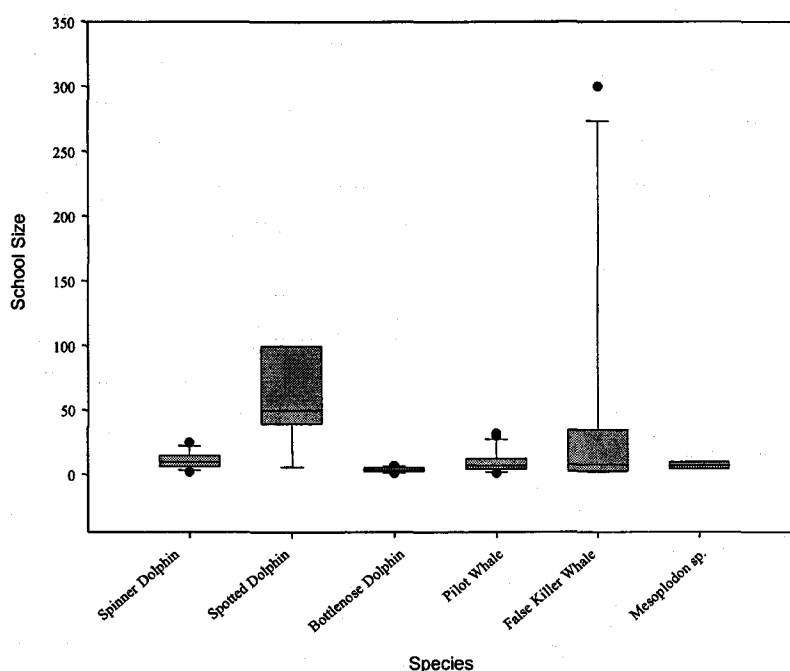


Figure 9—School size for six odontocete species recorded around O’ahu during aerial surveys between 1998 and 2000. The boundary of the box closest to zero indicates the 25th percentile. The line within the box marks the median, and the boundary of the box farthest from zero indicates the 75th percentile. Whiskers above and below the box indicate the 90th and 10th percentiles. The dots represent outliers in the data.

Odontocetes: Distribution

Species richness (defined as the number of species sighted) varied slightly around the island (Table 4). All seven species were sighted in Penguin Banks, six along the Windward coast (all except rough-toothed dolphins), four along the North Shore (spinner dolphins, false killer whales, dense beaked whales, and pilot whales), four along the Waianae Coast (spinner, spotted and bottlenose dolphins, and pilot whales), and only two along the South Shore (spinner and bottlenose dolphins).

Table 4 – Species occurrence around the Island of Oahu by stratum. SS=south shore; WA=Waianae coast; NS=north shore; WW=windward coast; PB=Penguin Banks.

Species	SS	WA	NS	WW	PB
<i>Tursiops truncatus</i>	*	*		*	*
<i>Stenella longirostris</i>	*	*	*	*	*
<i>Stenella attenuata</i>		*		*	*
<i>Globicephala macrorhynchus</i>		*	*	*	*
<i>Pseudorca crassidens</i>			*	*	*
<i>Steno bredanensis</i>					*
<i>Mesoplodon densirostris</i>			*	*	*

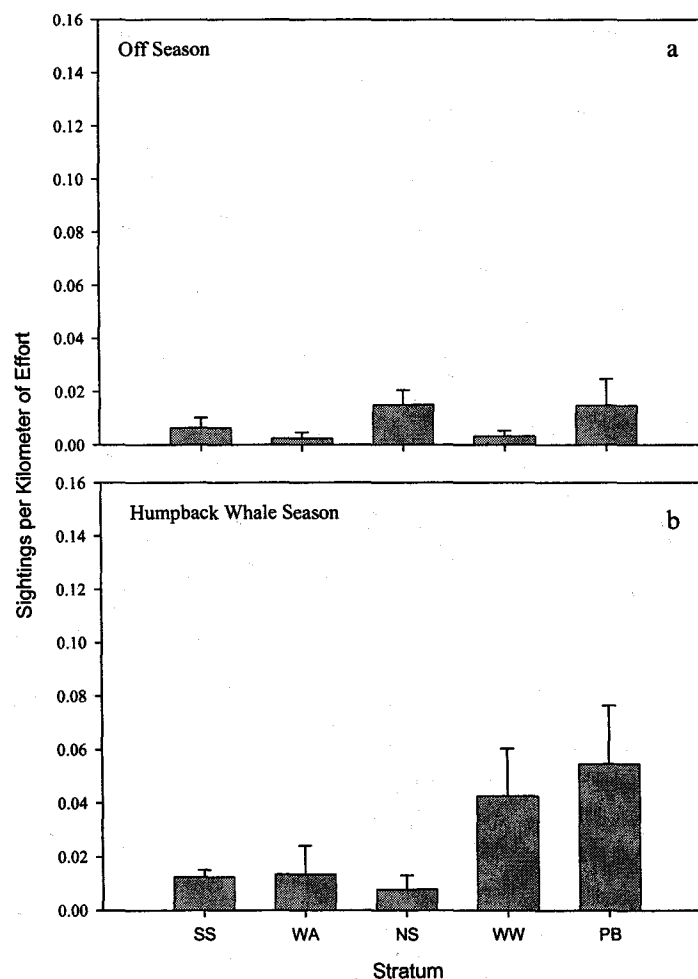


Figure 10 -Sightings per kilometer for seven odontocete species recorded during aerial surveys in the five geographical strata around the Island of O'ahu during off (a) and humpback whale season (b). Sightings per kilometer were calculated only for Beaufort ≤ 3 .

Sightings per 100 kilometers traveled in Beaufort less than three, was overall highest around Penguin Banks (3.59), followed by Windward (2.29), North Shore (1.18), Waianae (1.02) and South Shore (0.92), but the difference was not statistically significant ($F=2.452$; $P=0.061$). The difference in mean value between seasons was significant ($F=7.931$; $P=0.007$). Interactions between stratum and season were not statistically significant ($F=2.139$; $P=0.093$; Fig. 10). However, Windward and Penguin Banks had a higher sighting frequency during humpback whale season.

The frequency of odontocete sightings (expressed as number of sightings per kilometer surveyed) was higher during January-April than the rest of the year and peaked in the month of February, and in general mirrored the peaks in humpback whale presence (Fig. 11).

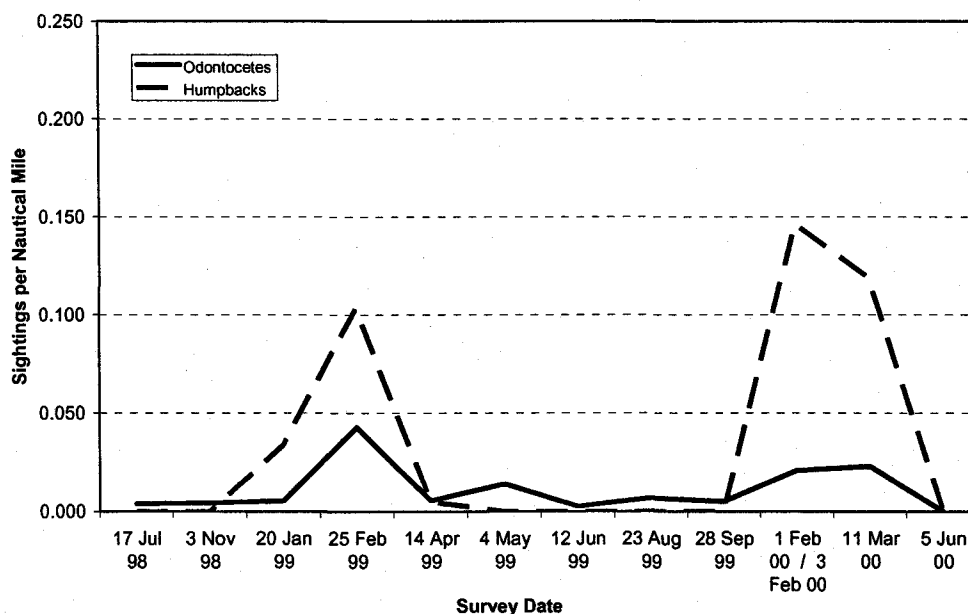


Figure 11- Comparison of sightings per kilometer for humpback whales versus all odontocete species observed around the Island of O'ahu between July 1998 and June 2000. Sightings per kilometer were calculated only using data with Beaufort 3 or less. The line does not suggest a continuum between points but simply serves to enhance differences and similarities between the two categories of data.

The distribution of perpendicular distances for odontocete sighting data showed most distances were within 1000 m from the trackline. There was a blind strip averaging 100 m below each side of the aircraft. This blind area was, in fact, wider than expected based on the maximum angle measurable by the observers. As a result, data were left truncated at 100 m for abundance analysis. In addition, 15% of the observations were right truncated.

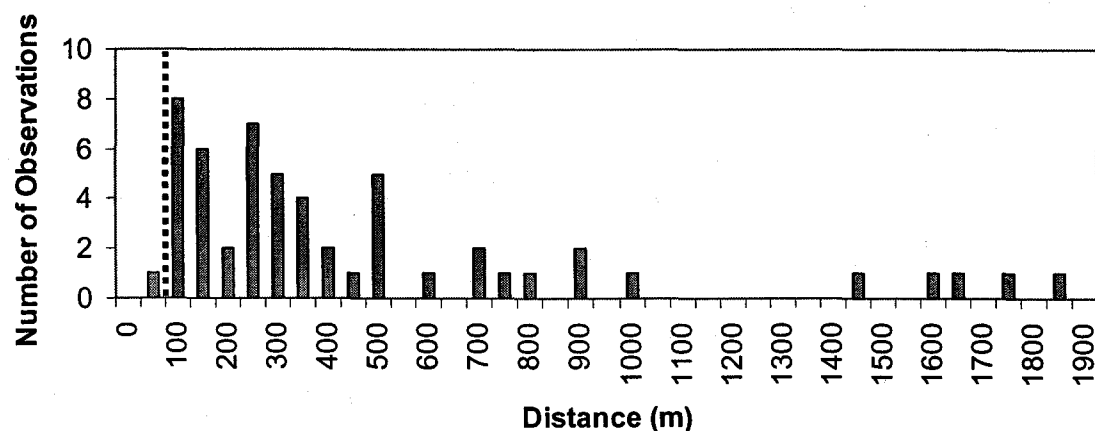


Figure 12 – Distribution of perpendicular distances from the trackline for odontocete sightings collected during aerial surveys of the Island of O’ahu between 1998 and 2000. The perpendicular line at 100 m indicates the average width of the blind spot below the aircraft.

Because of small sample size, abundance estimates for odontocetes have a high level of uncertainty. The unavailability of a correction factor for $g(0) < 1$, and the reduced visibility below the aircraft further reduce accuracy and increase the inherent underestimation in the data. In addition, it is assumed that the model selected accurately describes the behavior of the detection function near the transect line, which may or may not be the case. An overestimate would result if the model estimated the detection on the line to be greater than reality, and conversely, underestimation would result from the

probability of detection dropping off more quickly than the model predicted. Because, in general, cetacean abundance estimates tend to be an underestimate of the true population, a tendency of the model to overestimate should not be a problem. Overall, estimated abundance had wide confidence intervals and large CV%, and should therefore be interpreted with caution. The upper ranges of the confidence intervals are probably better indicators of the relative abundance of each species (Table 5).

Table 5 - Results of distance sampling analysis for six odontocete species recorded around the Island of O'ahu during aerial surveys between 1998 and 2000.

Group/Species	No. of Groups Sighted	No. of Groups in Analysis	Mean Group Size	Density (D)	Abundance (N)	CV (%)	95% CI
<i>Model: Uniform</i>							
<u>Small Odontocetes</u>							
Spinner Dolphin	13	10	17.20	0.032	46	62.65	13-156
Spotted Dolphin	6	3	66.67	0.038	53	104.46	8-344
Bottlenose Dolphin	11	6	3.50	0.003	4	52.48	1-11
Unidentified Dolphin	7	4	12.00	0.009	13	85.01	2-72
<i>Model: Hazard-Rate</i>							
<u>Medium Odontocetes</u>							
Pilot Whale	23	13	10.46	0.047	67	73.99	17-255
False Killer Whale	7	3	14.00	0.015	22	117.75	3-175
Blainville's Beaked Whale	3	1	6.00	0.002	3	88.71	1-15
Unidentified Odontocete	8	4	1.25	0.002	2	68.82	1-9

Annotated Species Account

Following is an annotated species account arranged by frequency of occurrence:

Pilot Whale: *Globicephala macrorhynchus* (Fig. 13)

Pilot whales were common along the Windward and North shore coastline and occurred on Penguin Banks associated with humpback whales. Sightings of one small group were followed by more sightings about a kilometer or so ahead suggesting these events were related. Generally direction of travel was consistent among groups. Overall, sightings occurred in deeper waters and were concentrated around Ka'ena Point and between Moloka'i and windward O'ahu. Pilot whales were seen in association with humpback whales and bottlenose dolphins.

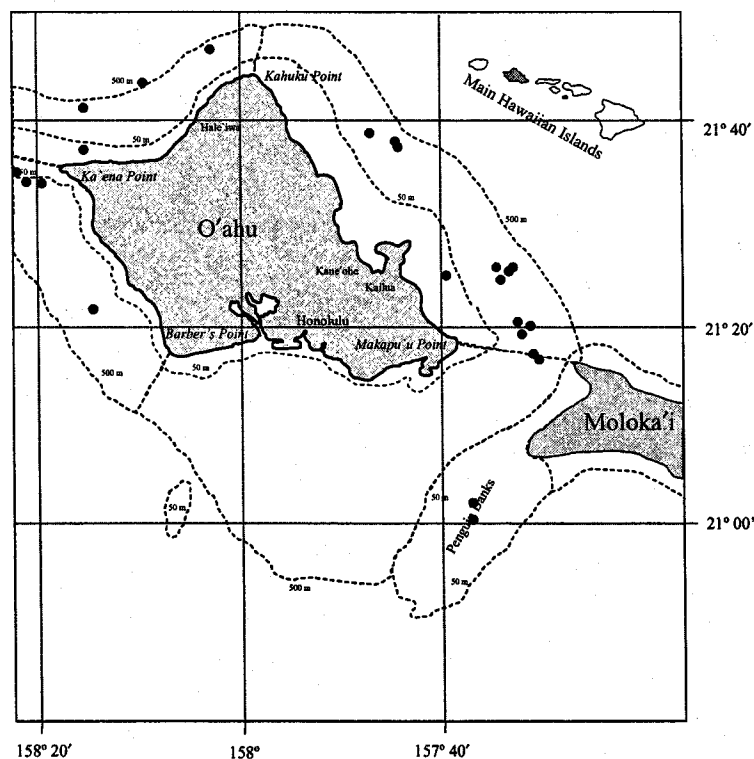


Figure 13 – Location of short-finned pilot whale sightings recorded during aerial surveys of O'ahu and Penguin Banks between 1998 and 2000.

Spinner Dolphin: *Stenella longirostris* (Fig. 14)

Spinner dolphins were found in all *strata* of the study area. Most sightings occurred close to shore mostly in proximity of the coastline, except for sightings in conjunction with spotted dolphins, which occurred in deeper water (>100 m) and for sightings near and around Penguin Banks, which were in approximately 50 meters of water (Fig. 15). Two of the sightings occurred near Makua Beach, which is a known resting site (Marten and Psarakos . Most other sightings were of schools moving along the coastline.

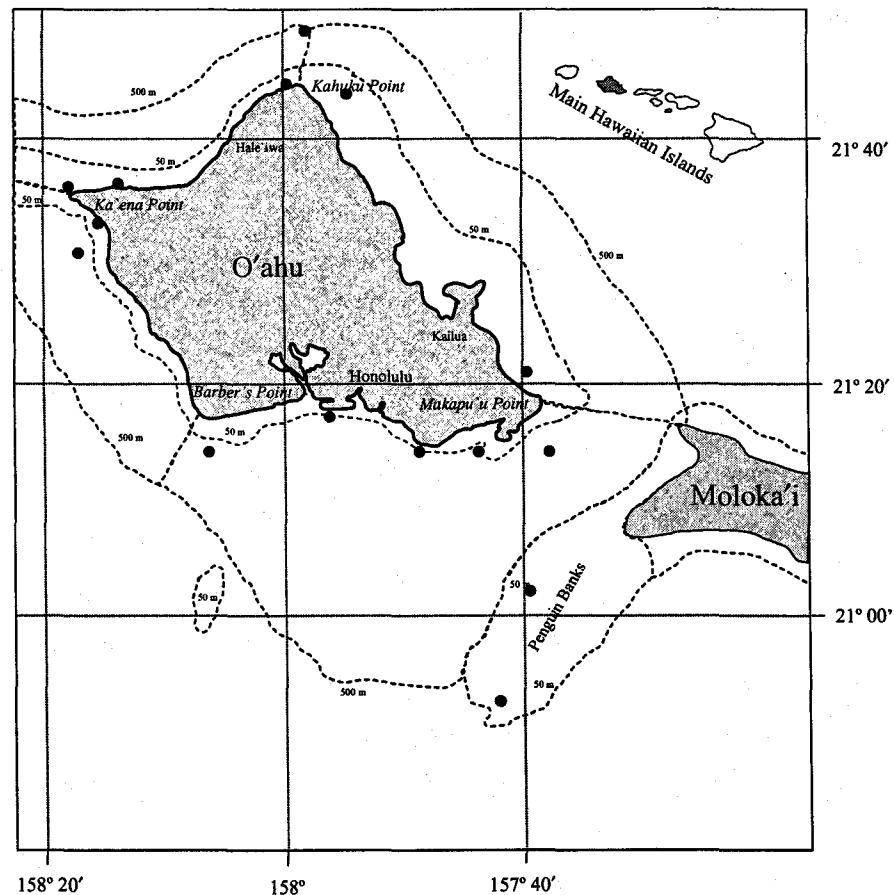


Figure 14 – Location of spinner dolphin sightings recorded during aerial surveys of Oahu and Penguin Banks between 1998 and 2000.

Bottlenose Dolphin: *Tursiops truncatus* (Fig. 15)

Sightings occurred primarily on the south side of O'ahu in open waters. Twice the animals were engaged in high energy surface behavior. Once bottlenose dolphins were associated with the bow wave of a humpback whale and twice with pilot whales. Groups were generally small.

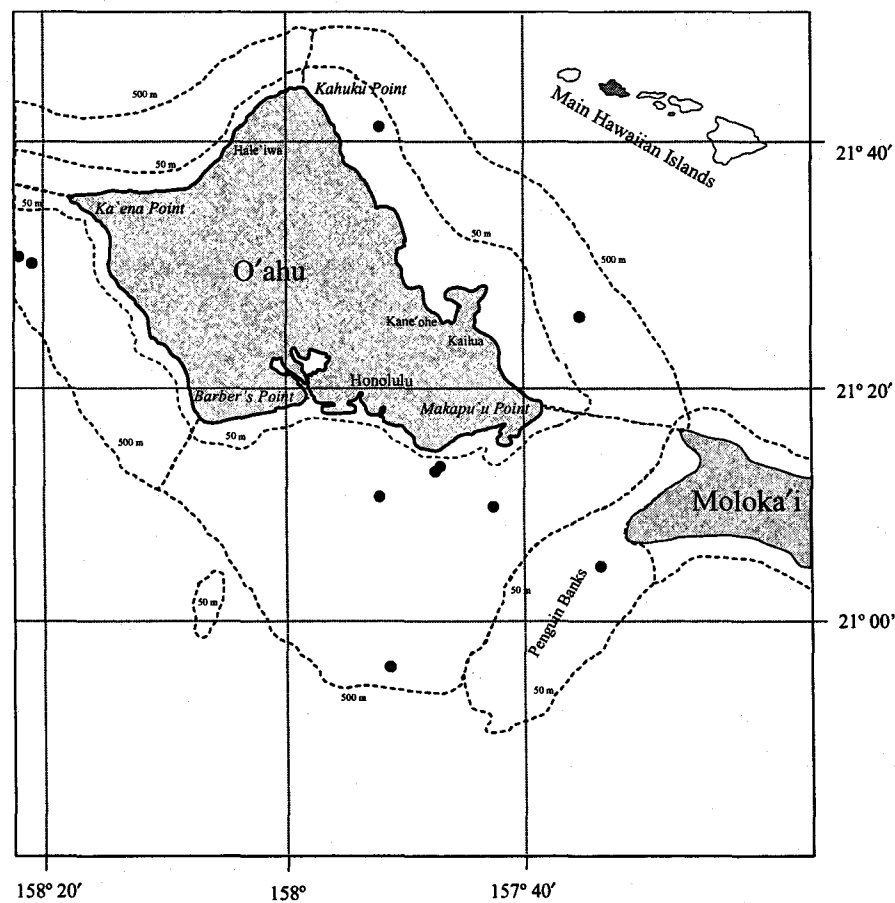


Figure 15 – Location of bottlenose dolphin sightings recorded during aerial surveys of O'ahu and Penguin Banks between 1998 and 2000.

False Killer Whales: *Pseudorca crassidens* (Fig. 16)

False killer whales were seen mainly in the summer time suggesting a seasonality of occurrence. The distribution data are difficult to interpret, since sightings were few, but animals were seen both close to shore and in open waters. A large aggregation of 300 animals was sighted along the windward coast. The animals surfaced synchronously for a short time and dove again not to be resighted. This made it difficult to determine if other species were part of the aggregation.

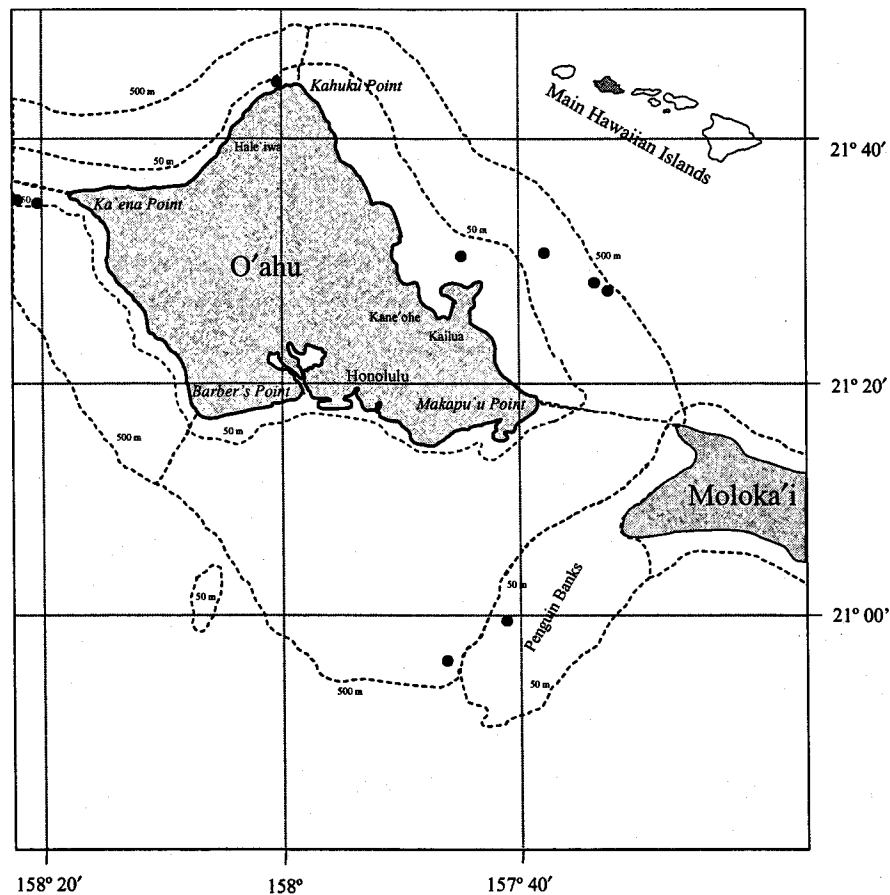


Figure 16 – Location of false killer whale sightings recorded during aerial surveys of Oahu and Penguin Banks between 1998 and 2000.

Spotted Dolphin: *Stenella attenuata* (Fig. 17)

Spotted dolphins were seen along the Waianae coast, Windward and near Penguin Banks, mostly in feeding aggregations. Three times these schools were mixed with spinner dolphins. A fatal attack by a large (3.5-4.0 meters) tiger shark on a juvenile spotted dolphin was witnessed by the author on 11 March 2000 at 12:06 in approximately 50 meters of water at a position of $21^{\circ} 00.85' N$ and $157^{\circ} 40.24' W$ (Maldini, 2003).

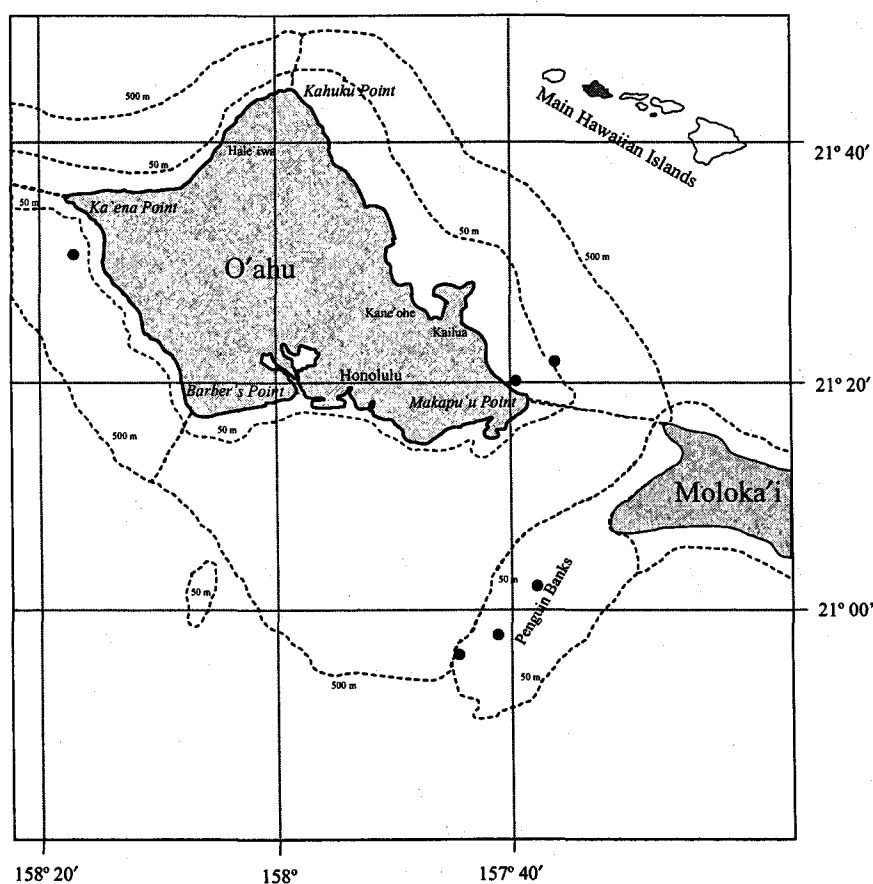


Figure 17 – Location of spotted dolphin sightings recorded during aerial surveys of Oahu and Penguin Banks between 1998 and 2000.

Blainville's Beaked whale: *Mesoplodon densirostris* (Fig. 18)

Blainville's beaked whales are deep divers and are therefore difficult to sight in the field. The fact that three sightings of this species were recorded around O'ahu indicates that it may be more abundant than previously believed. All three sightings occurred in extremely calm seas so that the animals could be easily spotted and observed. Their surface intervals were of 1-2 minutes and the whales hovered at the surface with little forward movement. Once they dove they were not resighted.

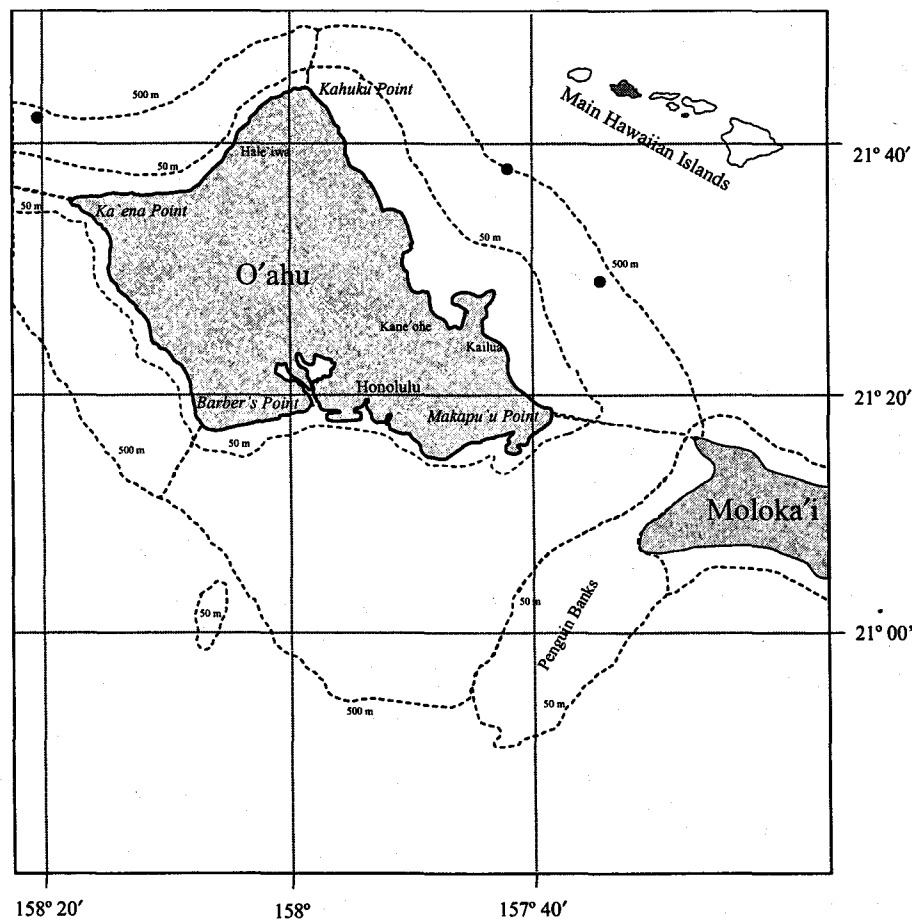


Figure 18 – Location of Blainville's beaked whale sightings recorded during aerial surveys of O'ahu and Penguin Banks between 1998 and 2000.

Rough-Toothed Dolphins: *Steno bredanensis* (Fig. 19)

One sighting occurred on Penguin Banks. This was one individual which disappeared underwater immediately after it was spotted. The presence of only one individual is clearly an underestimate.

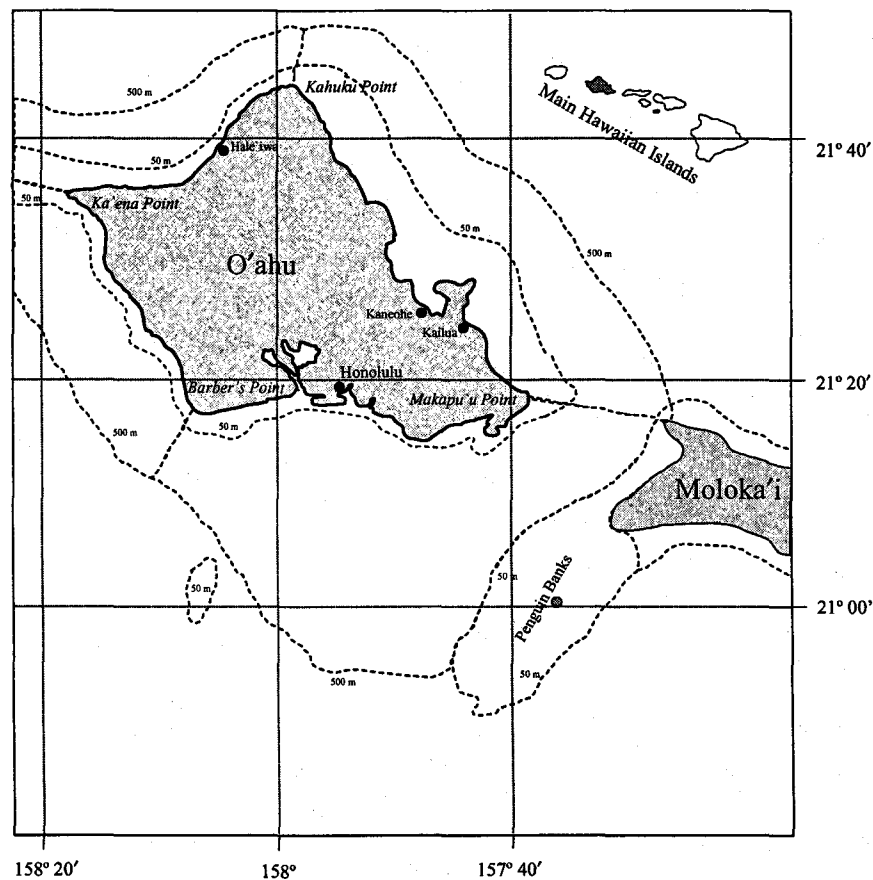


Figure 19 – Location of rough-toothed dolphin sightings recorded during aerial surveys of O'ahu and Penguin Banks between 1998 and 2000.

Interspecific Associations

Most of the sightings were of single species schools. Multi-species schools occurred seven times. Three were spinner-spotted dolphin aggregations were a small number of spinner dolphins was intermixed with a larger school of spotted dolphins. On

Penguin Banks, all cetacean encounters appeared to be correlated in that one encounter soon followed another in a relatively small area.

Of particular interest was the association between pilot and humpback whales. On 25 February, 1999 a group of approximately nine pilot whales was observed surrounding two adult humpback whales. One of the pilot whales was swimming directly on the nose of one of the humpbacks, a second whale appeared to be nudging the humpback whale on its left side, while the other pilot whales surrounded the animal. Because of the difficulty in keeping the scene in view it was difficult to witness the entire encounter but the interaction appeared to be confrontational, with the humpback whale trying to avoid the pilot whales by swimming in a zig-zag pattern. Another group of pilot whales was observed escorting another adult humpback on the same day.

Bottlenose dolphins were seen bow riding humpback whales or in close proximity of whale pods. Bottlenose dolphins were also found in close proximity to spinner dolphins and spotted dolphins or associated with pilot whales.

DISCUSSION

Although other species of mysticetes have been historically recorded around the Hawaiian Islands, our surveys around O'ahu detected only humpback whales. The period between January and April is typically considered the peak of humpback whale presence in Hawaiian waters (Craig *et al.*, 2000), with mid-February to mid-March being the absolute peak in abundance (Herman *et al.*, 1980; Mobley *et al.*, 1999; Au *et al.*, 2000), and sighting data from this study do not deviate from this trend.

Herman and Antinoja (1977) and Mobley *et al.* (1999) reported that humpback whales are mostly found in waters less than 182 m deep. This conclusion is supported by the current study, since the majority of the sightings in the current study occurred in waters <50m deep near Ka'ena Point and Penguin Banks.

The distribution of pod sizes for single animals (42%) and for "threesomes" (14%) in this study is similar to that reported by Herman and Antinoja (1977) during aerial surveys of Hawaiian waters (41.5% "singletons" and 12% "threesomes"), while they found a lower incidence of pairs (26.1%), and a higher incidence of larger pods (20.4%) than in the current study (36% and 9% respectively). Our results for pairs and larger pods, instead, mirror those of Mobley and Herman (1985), who, working from shore stations and small boats, found that pairs (41% of sightings) and "threesome" (23%) occurred more frequently than "singletons" (27%) and larger pods (9%). The differences could be an effect of the methodology used (i.e. aerial surveys versus boat surveys), or the result of variability between years and areas. In general, our results are consistent with the patterns observed in other studies indicating that pod sizes are small (1-3 animals), although social groups of up to seven animals have been reported (Herman and Antinoja, 1977; Mobley and Herman, 1985; Bauer 1986). It is likely that a large portion of our sightings involving two individuals was composed of a mother and her calf and sightings of three individuals of a mother, a calf and a male escort (Herman and Tavorga, 1980; Tyack, 1981; Whitehead, 1982). We were not able to properly investigate all sightings so estimates of calf numbers are based on opportunistic observations at a distance. Overall, few calves were sighted in our study (10) and mostly in March (6). Bauer (1986) found that the percentage of pods with calves and the percentage of calves

compared to total whales was highest on Maui, Penguin Banks and Kaua'i as compared to other islands. In addition, Craig and Herman (2000) found that habitat utilization by female humpback whales varied between the islands of Maui and Hawai'i, and appeared to depend, in part, upon reproductive status, with calves forming a significantly larger proportion of the population off Maui than off Hawai'i. Calves may have been a larger portion of the Penguin Banks population but our inability to investigate sightings did not allow us to answer this question.

Distribution data clearly identify Penguin Banks and Ka'ena Point (Fig. 5) as important habitats for humpback whales. Penguin Banks has been previously noted as an area of high whale concentration (Balcomb, 1987; Leatherwood *et al.*, 1988) although there are no studies conducted directly at this location. The availability of shallow waters (<55m) may be a factor for cow/calf pairs (Glockner and Venus, 1983; Smultea, 1994). While adults without a calf may use deep water to facilitate breeding behavior, cows with calves may use shallower water to avoid harassment and injury to calves from sexually active males, turbulent offshore conditions, or predators (Smultea, 1994). Because of its large area of shallow waters, sheltered from the trade winds by the Island of Moloka'i, and its relative isolation from human related activities Penguin Banks provides an ideal environment for cow/calf pairs. If its characteristics drive maternal females to choose this habitat, then males would choose it as well because of the presence of females.

Recently, Benoit-Bird (2003) argued that humpback whales in Hawaiian waters may engage in feeding activities and provided arguments supporting this hypothesis. One of these arguments is based on the fact that the biomass of the mesopelagic community in some areas of Hawai'i is as large (and sometimes larger) than the biomass available in

humpback whale feeding grounds (Benoit-Bird *et al.*, 2001; Benoit-Bird, 2003).

Furthermore, this biomass is available to the whales within 50-100 m from the surface at night, which may explain why the whales have rarely been seen feeding in Hawai'i (Benoit-Bird *et al.*, 2001). The occurrence of feeding in Hawaiian waters may be supported by the observations of bubble netting behavior on Penguin Banks during the current study, although bubbling may also be associated with agonistic encounters and other social behaviors (Forestell *et al.*, 1977). Several observations of potential feeding behavior have also been reported by opportunistic observers to the Department of Land and Natural Resources in Hawaiian waters (Walters, personal communication) and by Salden (1989). The biological distinction between breeding and feeding grounds has been challenged by other authors (Salden, 1989; Baraff *et al.*, 1991; Gendron, 1993). It is therefore important to start investigating the role of humpback whale habitat in Hawaiian waters in light of these observations.

There was no significant difference in number of whales per unit effort between 1999 and 2000, although an increase of 21% in raw counts per unit effort was registered between 25 February 1999 and 11 March 2000, the two most comparable surveys based on the timing of the humpback whale breeding season in Hawaiian waters. Although raw counts are no substitute for abundance estimates obtained using the distance-sampling method (which was not possible in this study because of permit restrictions) the registered increase provides some support to recent findings that the population in Hawaii is increasing. The rate of increase has been estimated at approximately 7% per year (Mobley *et al.*, 1999; Mobley *et al.*, 2001), a rate much smaller than the increase suggested in this study. The higher rate of increase, which is the result of a rough

estimate rather than the result of appropriately designed surveys, may also be a factor of the constantly shifting distribution of humpback whales, which are known to move between islands so that number of whales seen during one day may be very different than the number of whales seen the next day in the same area. Mate *et al.* (1998) have shown that humpback whales move constantly between islands throughout the season with travel distances per individual ranging from 30 to 1,860 km, and that distribution and abundance shifts faster than previously thought. For example, a whale visited Penguin Banks and five islands (820 km) in 10 days (Mate *et al.*, 1998). For this reason, a number of surveys within the same season may provide improved estimates of abundance, by moderating the effects of these variations.

The frequency of encounter of odontocetes around O'ahu was overall low relative to area surveyed. Only seven of the 19 species of odontocetes reported for Hawaiian waters by Shallenberger (1981) were sighted. Since surveys were limited to waters less than 500 m in depth, much of the sperm whale's habitat, which generally includes waters as shallow as 200 m (Carwardine, 1995), but more typically from 500 to 1800 m or deeper (Balcomb, 1989), may have been missed.

The absence of other species in the sighting record may be an artifact of the methodology used. Pygmy and dwarf sperm whales, for example, were never sighted during our surveys but are known to occur around O'ahu, especially along the Waianae coast (Maldini, personal observation) with possibly higher frequency than predicted. This species small size, dark coloration and generally evasive behavior, spending only brief times at the surface, increases the probability that any occurrence may be missed by an observer at altitude. Pygmy sperm whales are believed to be more common than dwarfs

but distinguishing the two species at sea is almost impossible. Between 1949 and 1995, eighteen strandings of *Kogia* sp. were recorded (Tomich, 1986; Nitta, 1991; Maldini, Chapter 2 of this dissertation). Of these, six occurred along the windward coast O'ahu.

More surprising is the lack of sightings of melon-headed whales which are generally found in large aggregations especially off the Waianae coast of O'ahu (Shallenberger, 1981) and, despite their dark coloration, these whales should not escape an observer at altitude. Eight strandings of melon-headed whales, all around O'ahu, were reported between 1949 and 1995 (Nishiwaki and Norris, 1966; Maldini, Chapter 2 of this dissertation).

The pygmy killer whale is known to occur in Hawai'i but is considered rare. Nitta (1991) documented five strandings on Maui and the Big Island. Pryor *et al.* (1965) reported that pygmy killer whales have been observed several times off the lee shores of O'ahu. Mobley *et al.* (1999) never saw this species during their aerial survey effort between 1993 and 1998, and reported two sightings in 2003 (Mobley, unpublished data), suggesting this species is rare.

The distribution of odontocetes around O'ahu and Penguin Banks needs to be interpreted in the context of the distribution of food patches in the study area. Since waters surrounding Hawai'i constitute a continuum, O'ahu is only a portion of the range used by odontocetes moving within the envelope of the near-island waters. Because of the difference in productivity patterns between the near-island water mass and the barren offshore areas east and west of Hawai'i (Venrick, 1969; Dandonneau and Charpy, 1985), most odontocete species probably move within the water mass directly influenced by the islands, where food availability is higher.

Koslow (1997) points out that the physiology, morphology and behavior of species which are found near seamounts and islands are more similar to species associated with other geographically distant seamounts and islands than to species found in the nearby open ocean. The near-island water mass and its associated productivity create natural geographic boundaries which probably define odontocete movement patterns and seasonal distribution. Although this scenario does not exclude movements outside these natural boundaries, especially by deeper water species, it suggests that the probability of finding odontocetes inside the more productive near-island water mass is higher than the probability of finding them outside of it. This scenario also supports the hypothesis that Hawaiian odontocete stocks are separate from stocks found in the Eastern Tropical Pacific (ETP) and that exchanges between these stocks, although possible, may be infrequent.

Movements of odontocetes within the near-island envelope of productivity are dictated by the fine (meters to a hundred meters) and coarse (one to one hundred kilometers) scale at which mesopelagic community patches are found within the near-island water mass. Benoit-Bird (2003) found that the horizontal component of the movement of the boundary layer in Hawaiian waters may be a more a better predictor of the distribution of potential predators, since its location relative to the shoreline is consistent regardless of night or coastline surveyed. This relative predictability is an advantage to animals that depend on this food resource. Temporal scales overlap with the geographical distribution of mesopelagic food patches. According to Stommel (1963) fine scale geographical patterns correspond to a temporal scale of minutes to hours and coarse scale of hours to a day. This implies that, to find food, odontocetes may have to

move long distances (several to hundreds of kilometers) between patches within a short period of time (hours to a day) and may explain why the probability of finding animals in any particular area at any point in time is low, with some notable exceptions.

The distribution of spinner dolphins is more predictable than that of other species because their existence is tied to the shallow inshore waters where they rest (Norris *et al.*, 1994), and to the diel cycle of the mesopelagic boundary layer closer to shore (Benoit-Bird, 2003) so that their movements may be somewhat restricted by the combination of these two factors. Given that spinner dolphins are generally found close to shore during the day, our ability to detect their presence from aerial surveys was tied to how well the transect lines could cover inshore areas where the animals are generally found. Because of the inshore-offshore zig-zag pattern of the aerial survey tracks, the amount of time spent in areas of shallow water (<50m), with the exception of Penguin Banks, was overall much less than the time spent in waters between 50 and 500m. Spinner dolphin daytime habitat was not properly covered by the aerial survey design and many sightings around O'ahu were probably missed for this reason. To properly address spinner dolphin distribution patterns around O'ahu, boat-based surveys and helicopter surveys circumnavigating the island are probably more suitable. However, the sightings recorded conform to the prediction that spinner dolphins are generally found close to shore, and, when offshore, they are often mixed with schools of spotted dolphins.

Bottlenose dolphins, may rely on a more variable set of resources and may also forage during the day near the slope of the islands or over shallow reefs feeding on medium sized fishes (Balcomb, 1987). Their adaptability and prey switching ability are characteristics that allowed them to become widespread throughout the near-shore waters

of the world's oceans. Bottlenose dolphins are also widespread in Hawaiian waters, both nearshore and offshore (Rice, 1960; Shallenberger, 1981; Baird *et al.*, 2001). Mobley *et al.* (2000) estimated a population of approximately 743 bottlenose dolphins around the main Hawaiian Islands. Baird *et al.* (2001) estimated a population of 134 individuals between Maui, Lana'i and Kaho'olawe. Our study estimated approximately 11-61 individuals between O'ahu and Penguin Banks, although the reliability of this estimate is low. Based on preliminary work by Baird *et al.* (2002), movements between islands may be limited, and bottlenose dolphins may prefer areas of shallow (<200m) water.

Bottlenose dolphins were observed foraging during the daytime in areas of shelf breaks (Maldini, personal observation) near O'ahu and Nitta and Henderson (1983) documented interactions between bottlenose dolphins and the fisheries implicating the dolphins in the stealing of baitfish from fishing gear. Being more opportunistic foragers and traveling in small groups (Baird *et al.*, 2002), bottlenose dolphins are probably less dependent on the mesopelagic boundary layer and on the offshore patchiness of food resources, which allows them to establish high fidelity to restricted areas.

Most other species of odontocetes encountered in Hawaiian waters are pelagic and depend, to a great extent, on shifting productivity patterns within the near-island envelope. Their distribution patterns are therefore less predictable, and may change both daily and seasonally. The number of sightings for most pelagic species in this study's sample was too small to detect particular trends in distribution over time and space. An exception was the pilot whale, which was common and abundant throughout the windward and north shore coasts of O'ahu and was occasionally seen on Penguin Banks

(Fig 14). All sightings were of animals traveling in subgroups suggesting that feeding may occur at night while the daytime is used to move between areas.

Night feeding is consistent with the diel migration of the mesopelagic boundary layer to shallower waters where it becomes available to predators (Reid *et al.*, 1991; Benoit-Bird *et al.*, 2001). This community is not only preyed directly upon by smaller odontocetes such as spinner (Norris *et al.*, 1994), spotted dolphins, and bottlenose dolphins (Barros and Wells, 1998), but is also utilized by larger species of fish such as tuna (He *et al.*, 1997), billfish (Skillman, 1998), and bottom fish (Haight *et al.*, 1993), which are, in turn, food for larger species of odontocetes such as false killer whales (Stacey *et al.*, 1994) and pilot whales (Seagars and Henderson, 1985).

Penguin Banks is an area where sightings of odontocetes occur with significantly higher frequency than in all other areas around O'ahu. On Penguin Banks productivity patterns are higher and more predictable than in surrounding areas. Turbulence and vertical mixing occurring in the deeper channel between O'ahu and Moloka'i (Ka'iwi Channel), which allows large volumes of water to flow through being pushed by the westward current driven by trade winds, cause nutrients from deep water to spill over the shallow bank. The importance of channels between islands in generating turbulence which causes eddies of higher productivity on the leeward side of the islands has been emphasized by Smith (1967).

A large number of cetaceans was concentrated in a small area within Penguin Banks during aerial surveys conducted when humpback whales were present in Hawaiian waters. All sightings appeared to be interrelated, with some degree of association between different species. It is possible that the association between humpback whales

and odontocetes in these waters is caused by humpback whales acting as Fish Aggregating Devices (FADs), and therefore attracting odontocetes to them. In fact, a humpback whale was observed traveling near the north shore preceded and followed by a large school of fish, possibly tuna, swimming directly underneath it. Fish Aggregating Devices (FADs) and other floating structures are known to attract a variety of fish (over 333 species belonging to 96 families have been recorded in the literature) (Castro *et al.*, 2002). In Hawaii, FADs have been successfully used to attract tuna (Higashi, 1994; Brill *et al.*, 1999). These devices are much smaller than a humpback whale, yet they are extremely effective. It is therefore possible that a large whale has the same aggregating effect on fish.

Other associations with humpback whales by odontocetes may be predatory in nature, such as those observed between humpbacks and pilot whales near Penguin Banks. Interactions between humpback whales and pilot whales have been documented by Ciano and Jorgensen (2000), who witnessed several individual pilot whales flanking a humpback whale in Norwegian waters. The interaction described was very similar to the one witnessed in Hawai'i except that the reaction of the humpback whales could not be properly assessed from the plane. It is clear that some of the large odontocete species such as short-finned pilot whales (Ciano and Joergensen, 2000) and false killer whales (Palacios and Mate, 1996) do attack larger whales, but the frequency and extent of these attacks is currently not known.

In conclusion, the factors involved in determining the distribution patterns of Hawaiian cetaceans, odontocetes in particular, are far from simple and are still poorly understood. Although aerial surveys on a consistent basis are a good method to look at

trends in abundance and distribution over time, there is the need for detailed studies on many odontocete species in Hawaiian waters. Without the insights provided by such studies, the complex relationships between these species and their habitats will remain difficult to interpret.

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CHAPTER 5

PREDATION BY TIGER SHARK (*Galeocerdo cuvier*) ON SPOTTED DOLPHIN (*Stenella attenuata*) OFF O'AHU, HAWAII WITNESSED FROM AN AIRCRAFT

On 11 March 2000 an attack by a tiger shark (*Galeocerdo cuvier*) on a spotted dolphin (*Stenella attenuata*) was witnessed at approximately 12:06 from an altitude of 150 meters while on board of a Partenavia P68 Observer aircraft during an aerial survey of cetaceans in the coastal waters around the Island of O'ahu. The plane circled the site of attack for its entire duration (approximately 1 minute), until the animals involved (the shark and the dolphin) disappeared from view. The attack occurred on Penguin Banks, a shallow water embankment between the islands of O'ahu and Moloka'i, (Fig. 1).

The species identification of the animals involved in the interaction was made by the author and relied on several characteristics typical of the two species. The tiger shark, estimated to be approximately 3.5-4.0 meters in length, was identified by its large square head, its blunt nose, its slender body behind the pectoral fins and its size. Spotted dolphins in Hawaiian waters can be distinguished from other *Stenella* species for the presence of faint spots on the body and a prominent white lip at the tip of the rostrum. From an aircraft, observers routinely identify spotted dolphins using the latter characteristic since the presence of spots is not noticeable from a distance.

The attack occurred in approximately 50 meters of water at a position of 21° 00.85' N and 157° 40.24' W. The juvenile spotted dolphin was part of a large (approximately 30-50 individuals) school traveling in a south-easterly direction toward the island of Moloka'i. The school was arranged in a diamond shaped formation.

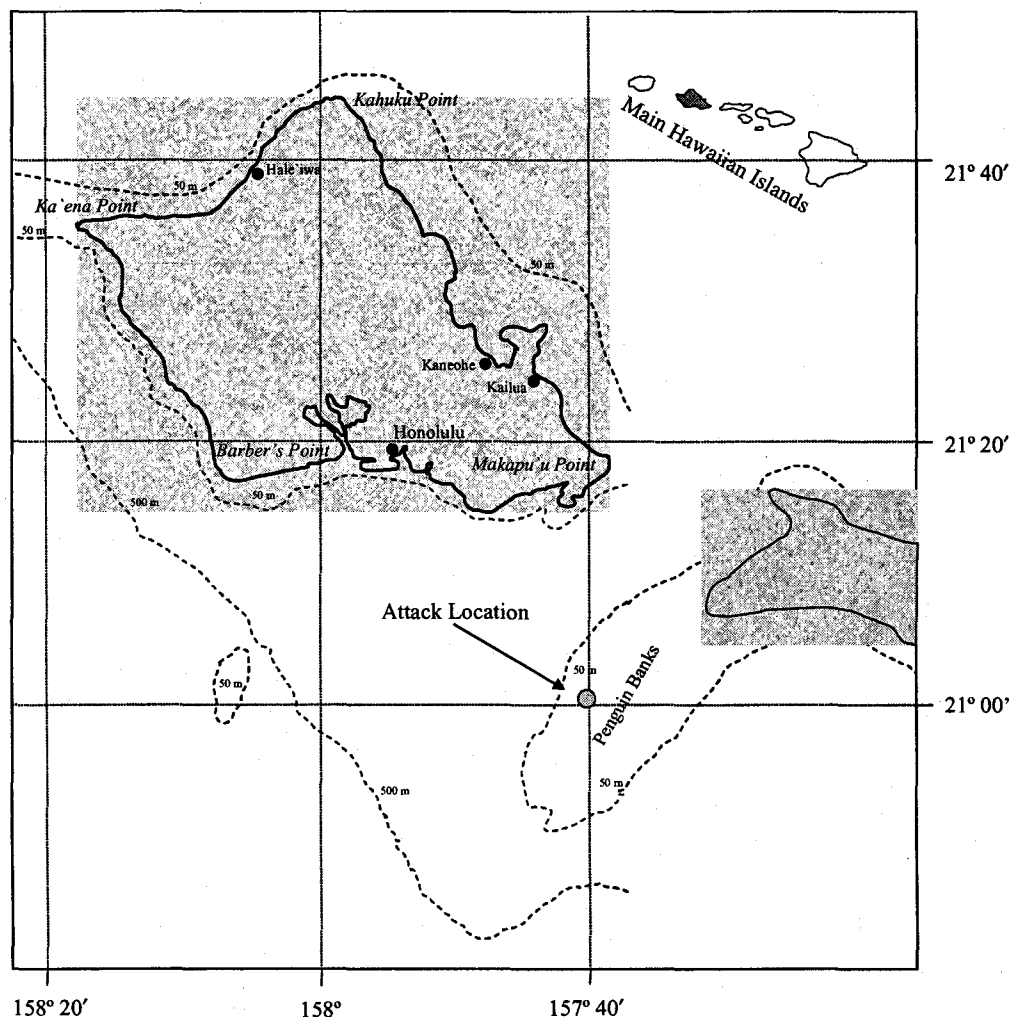


Figure 1 – Map of the Penguin Banks area between the Islands of O’ahu and Moloka’i in the Main Hawaiian Islands Chain showing the exact location of a tiger shark attack on a spotted dolphin.

A juvenile spotted dolphin was observed slowly falling behind the school while a tiger shark quickly approached from the rear-left side. While the shark approached the isolated dolphin, the rest of the school continued on its south-easterly course.

The shark’s approach was fast and deliberate. The tiger shark bit the spotted dolphin in the middle section of the tailstock and completely severed it. The dolphin was thus left unable to escape and was seen thrashing at the surface for a few seconds, allowing one of the observers (DM) a clear view of its missing tailstock. Some blood was

present in the water but the sighting was lost before any of the observers could verify the amount. Given the nature of the injury it was assumed that the dolphin did not survive the attack, which was therefore defined as successful.

In a few seconds the two animals disappeared underwater and we lost the location of the sighting. Subsequently, two attempts were made to reposition the plane on the exact location of the initial sighting to find the shark again with no success.

The strategy used by the tiger shark during the attack seems to confirm previous observations that successful attacks on cetaceans occur more frequently from the side/rear, while the higher incidence of wounds and scars on the back/frontal regions of the body of survivors indicates this is a less effective site of attack (Heithaus, 2001a). In the case reported, the severing of the tailstock effectively ensured the immobilization of the victim which was left unable to escape. Interestingly, another published report of a tiger shark attack on a bottlenose dolphin calf at Monkey Mia, Australia shows a photograph of the dead calf with a severed tail, and witnesses to the attack suspect the tail was severed before the shark took a second fatal bite into the belly of the animal (Mann and Barnett, 1999). Other observations also support the hypothesis that many attacks on odontocetes are directed to the tail (Arnold, 1972; Cockcroft, 1991; Long and Jones, 1996). If successful attacks are generally as quick and flawless as the one witnessed in the current study, it is not surprising attacks are missed by potential observers.

The attacked dolphin appeared to detach from the orderly diamond formation of the school before the attack began. Whatever the reason for this tactical error, it reinforces the importance of school cohesion and coordination as a defense mechanism against predation.

Predation Pressure on Odontocetes: Does it Shape their Behavior?

In general, the mechanisms of predation on odontocetes are not well documented. Most information available is based on anecdotal reports, stomach contents, and indirect evidence from strandings. Nonetheless, predation pressure has been advocated as an important factor in shaping schooling behavior in cetaceans (Norris and Dohl, 1980a).

The incidence of scarring in dolphins indicates that attacks by predators, likely sharks, occur with high frequency. Irvine *et al.* (1973) reported that between 20 and 50% of bottlenose dolphins (*Tursiops truncatus*) living along the shallow waters of Florida and Texas bear scars inflicted by sharks. More recently, Heithaus (2001a) reported a bite scar frequency of 74.2% on adult bottlenose dolphins in Shark Bay, Western Australia, and attributed most of the attacks to large tiger sharks (>3 m). In contrast, dolphins living in the open ocean appear to have a lower incidence of scars (Wood *et al.*, 1970). The difference in scarring frequency could be attributed to the differential mortality in shallow versus open waters. While attacks may be frequent in both environments, shallow waters may afford an animal additional protection, because of the lesser number of directions from which an attack could be launched. For example, spinner dolphins (*Stenella longirostris*) may seek the shallow sandy bottom of protected coves over areas of rocks and corals to be able to see the approach of a shark and better respond to it (Norris *et al.*, 1994). In the open ocean, the school envelope may provide the only protection to an individual against attacks, which could come from several directions.

School coordination becomes an important feature of cetacean societies in light of the possibility of predation. In response to an attack, an individual is safeguarded only within the school envelope where the rapid and coordinated avoidance maneuvers of the

school contribute to “confuse” the predator’s search image and give any individual in the school the advantage of a few precious seconds that may be the difference between life and death. Therefore, some aspects of predator evasion in cetaceans may not be very different than in schooling fish.

On the other hand, cetaceans have developed very sophisticated sonar systems, which allow them to efficiently scan the water ahead in search of prey and as an early warning signal for predators. Besides foraging, predation pressure may have been a shaping force in the development of cooperation in cetacean schools (Norris and Schilt, 1988). Norris and Dohl (1980a) describe a dolphin school as an Sensory Integration System (SIS) where the coordination of perceptions helps each individuals “perceive” at all times the position of all other individuals within the school envelope, and facilitates responses to information gathered outside the envelope (such as the presence of food or of a predator). As part of an SIS each individual depends on the other to contribute information gathered within its sensory distance, and the sum of the information provided by each school member constitutes the framework used to coordinate the movements and reactions of the school as a whole. Without the cooperation of each individual within the school this system would not work. As part of an SIS, a school may become an efficient mechanism for long-range predator detection.

Within this framework other cetaceans may prove to be more efficient predators having the advantage of the same sophisticated long-range detection system. Transient killer whales, for example, which feed exclusively on other marine mammals, counteract the ability of their prey to detect them at a distance by traveling in small, tight groups and by staying completely silent possibly using hearing more than echolocation to find their

food (Barret-Lennard *et al.*, 1996). In addition, cetacean predators may also rely on cooperation to successfully kill their prey.

Sharks on the other hand rely on chemical, electrical and visual cues to find their prey. Their success in killing a dolphin may rely in opportunity, speed and stealth. Heithaus (2002a) during a study in Australian waters using direct observation via a “Cittercam” found that tiger sharks feeding on a variety of prey (mainly fish, turtles and sea snakes) rarely engaged in high-speed chases, and generally did not attack prey that were vigilant.

Norris *et al.* (1994) present a report by Springer, which illustrates a possible cooperative effort by sharks to kill a common dolphin (*Delphinus delphis*) by surrounding a school for several hours and flanking the dolphins until an opportunity is provided. It is common in the open ocean to find multi-species aggregation where sharks and dolphins all follow large schooling fish (Au, 1991). The continued presence of sharks around dolphin schools may provide opportunities for predation although cetaceans do not appear to be the main staple of any shark species. The young, old and debilitated animals are the most likely victims of this opportunistic predation pressure.

In a recent study of the dynamics of tiger shark predation in a subtropical seagrass ecosystem, Heithaus (2002b) found that the presence of tiger sharks may shape the habitat use decisions by bottlenose dolphins (*Tursiops aduncus*). In fact, when sharks were absent in cold winter months, dolphin distribution matched the distribution of their food. Conversely, when tiger sharks were abundant during the summer, the distribution of foraging dolphins significantly deviated from that of their food (Heithaus 2002a). These findings suggest that even a low degree of predation may be enough to shape the

ecology of odontocetes for which, even a low degree of mortality could make a big difference given their relatively low reproductive rates, and their complex social system.

Are Odontocetes an Important Prey for Sharks?

Despite the theoretical framework surrounding the issue, the dynamics of predation on cetaceans by sharks are not well documented or understood. Dietary studies on sharks commonly believed to prey on marine mammals do not show cetaceans to be an important prey item (Heithaus, 2001a and b; Simpfendorfer *et al.*, 2001). Nonetheless, even an occasional successful feeding on a relatively large dolphin may make it worthwhile for a shark to regularly engage in this predatory practice (Heithaus, 2001a).

Heithaus (2001b) recently reviewed predator-prey and competitive interactions between sharks and dolphins. Much of the evidence of shark/cetacean interaction relies on stomach content studies (Bell and Nichols, 1921; Cliff and Dudley, 1991; Simpfendorfer *et al.*, 2001) or on carcasses beached or floating at sea, which often bear signs of shark predation. Still, in some cases, these animals may have died of other causes and have been scavenged after death (Carey *et al.*, 1982; Long and Jones, 1996; Heithaus, 2001b). There are few accounts of direct attacks on live cetaceans (Leatherwood *et al.*, 1972; Mann and Barnett, 1999) and the best indirect evidence is provided by observations of scarring patterns and wounds on live dolphins (Corkeron *et al.*, 1987; Cockcroft *et al.*, 1989; Cockcroft, 1991; Bearzi *et al.*, 1997; Urian *et al.*, 1998; Heithaus, 2001a).

In Hawaiian waters, at least two species of shark that have been implicated in regular predation of marine mammals, primarily the tiger shark (*Galeocerdo cuvier*), and the white shark (*Carcharodon carcharias*). The oceanic white tip shark (*Carcharhinus*

longimanus) has been classified as an occasional predator (Heithaus, 2001a). In Hawai'i, dolphins were found in 7% of stomachs from large tiger sharks (>3m), and in 2% of stomachs from smaller (2-3m) sharks (Lowe *et al.*, 1996). It is unclear what proportion of these dolphin parts is actually consumed alive versus scavenged as there is not published data on the subject. Because tiger sharks are common in Hawaiian waters (Holland, personal communication), predation by a fraction of the population on odontocetes may exert enough pressure to become an important factor in the daily life of these marine mammals. Future research efforts should strive to better understand the relationship between sharks and dolphins, and perhaps be able to derive quantitative information about the impact of shark predation on dolphin populations.

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CONCLUSIONS

Studies of cetacean species in Hawai'i have been limited to humpback whales and spinner dolphins to a large extent. Studies of odontocetes, in general, are necessary to determine baseline parameters, especially in light of the expansion of human related activities in Hawaiian waters.

Information collected using both the historical stranding record (from 1937 to 2002) and 13 aerial surveys of the Island of O'ahu and Penguin Banks identified 16 species of odontocetes present in Hawaiian waters with varying degrees of frequency. Based on these data spinner dolphins, pilot whales, spotted dolphins, bottlenose dolphins, *Kogia* sp., sperm whales, false killer whales and melon-headed whales are common in Hawai'i although some of these species may be cryptic to survey efforts and some may not strand with frequencies comparable to their abundance in the environment. Striped dolphins may be abundant in pelagic waters surrounding the islands. Pygmy killer whales and rough toothed dolphins are present but rare in Hawaiian waters. Risso's dolphins and killer whales appear to be occasional visitors. Two beaked whales, Cuvier's and Blainville's are rarely observed because of their deep-diving habits and tendency to remain in deep waters, but may be common in Hawai'i. In addition, the aerial survey effort covered areas shallower than 500 m, thereby decreasing the probability of encountering these species.

The combination of stranding and sighting information worked well to detect the maximum number of species occurring in Hawaii. Strandings were better at detecting the presence of species but the information provided on their distribution was biased by the quality and extent of the effort, and by the tendency of certain species to strand more

often than others independently from their relative abundance in the natural environment. Aerial surveys provided better information on actual short-term distribution patterns but the extent of the aerial survey effort in this study was insufficient to address long-term distribution and seasonal occurrence in detail. In addition, sightings were biased toward less cryptic species and may have missed common but not readily visible animals depending on sea state, speed of the aircraft, observer training, and general visibility conditions. Sightings were also limited to waters within the 500 m isobath.

Penguin Banks was found to be the most important habitat for humpback whales, and odontocetes in the study area. Its importance may be due to a combination of factors such as its location next to a deep water channel which funnels turbulent waters through from the windward side of the islands to the leeward side, bringing in a well mixed water mass richer in nutrients and spilling it over the shallow bank to create a highly productive environment, more ideal for feeding than other areas around O'ahu. Feeding is more likely to occur at night as the mesopelagic boundary layer migrates to the surface and spills over the shallows of Penguin Banks.

The distribution of humpback whales on Penguin Banks may be related to the availability of shallow waters to maternal females, which may seek these areas to protect the calves from other humpbacks and from predators. However, humpback whale distribution in this area may also be a function of food availability, as whales may also opportunistically feed on the mesopelagic boundary layer.

Odontocete sighting frequency was, overall, low around O'ahu and Penguin Banks, and may have shifted rapidly with the availability of food resources. The most common species by frequency of occurrence was the pilot whale in deeper waters, with

concentrations along the windward side of the Island of O'ahu and an estimated population size of 67 (95% CI: 17-255). Most abundant species by number of individuals may be the spotted dolphin, which occurs in localized aggregations, with estimated abundance of 53 (95% CI: 8-344). Spinner dolphins occurred along all coastlines around O'ahu, mainly near-shore in waters less than 50 m deep during the daytime, with groups found offshore being mixed with schools of spotted dolphins. Population estimates for spinner dolphins were 46 (95% CI: 13-156). Bottlenose dolphins were concentrated around the south shore and Penguin Banks and were seen in small groups. Their occurrence may be localized with high site fidelity to certain areas. Population estimates were 4 (95% CI: 1-11). False killer whales had highly variable school sizes and their occurrence was concentrated in time, most sightings occurring in the summer and during the same survey. The population estimates was 22 (95% CI: 3-175). Blainville's beaked whales were seen three times so data are not sufficient to infer about their distribution. The population estimate should be interpreted with caution and was 3 (95% CI: 1-15).

All abundance estimates were biased low, with $g(0) < 1$ (no correction factor available) and suffered from a low number of sightings. Overall, these estimates are highly uncertain and have large confidence intervals.

Mixed school associations were primarily spinner/spotted dolphins, pilot whales and bottlenose dolphins, and bottlenose dolphins or pilot whales associated with humpback whales. The nature of these associations is unclear, but they may occur because of feeding cooperation/competition. In addition, humpback whales may act as fish aggregating devices and therefore attract other cetaceans to their vicinity. Some

interactions between humpback whales and pilot whales may be predatory, as pilot whales have been documented to harass humpback whales in other areas of the world.

Factors affecting the distribution and abundance of cetaceans around the Hawaiian Islands are food availability, which also depends on habitat characteristics, distribution of competitor species, including other cetaceans, and distribution of predators. The mechanisms and dynamics of predation on cetaceans are poorly understood. An event of predation by a tiger shark on a spotted dolphin on Penguin Banks, witnessed opportunistically, provided some insight into the potential mechanisms of predation and suggested that predatory events may be relatively frequent in Hawaiian waters given the abundance of tiger sharks. Sharks and cetaceans may overlap in distribution and share the same food resources. Predation of cetaceans by larger sharks may be opportunistic and rely on failures of the school envelope to protect an individual from an attack.

Studies focusing on the effects of human related activities on odontocetes in Hawaiian waters are necessary in light of the increasing popularity of dolphin watching and the expansion of tourism on the water. Although coastal species will be the first to feel the effects of these activities, proper species management practices dictate that efforts to understand all the factors affecting cetacean distribution patterns be studied before serious concerns arise.

It is clear that attention should be focused on this issue in Hawaiian waters in the near future. In particular, we need to determine habitat use patterns in relation to food resources, physiography and human related activities. This can only be accomplished with species-specific studies coupled with consistent survey work be it aerial or ship-

board. It is important that survey effort occurs year-round as shifts in distribution between winter/spring and summer may occur. It is also important to understand if and what role humpback whales' presence plays in determining these shifts.

Penguin Banks, which is included in the Hawaiian Islands Humpback Whale National Marine Sanctuary (HIHWNMS) boundaries, should be an area of intense focus being important for all cetaceans. It is critical that the research priorities of the HIHWNMS be shifted toward an ecosystem-based assessment which includes funded studies of odontocetes. Key species in this plan should be spinner dolphins, bottlenose dolphins and pilot whales. The first two species because of their high potential for interactions with humans, the third because of its relative abundance and its importance in determining shifting patterns of offshore food resources.

In conclusion, Hawaiian waters are home to a variety of cetacean species of which little is known to date, despite their relative accessibility and their importance to the Hawaiian ecosystem. It is our duty to make sure future threats to their environment are minimized by adopting preventive measures which include a thorough knowledge of their ecology.