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Does a lack of observed beaked whale strandings in military exercise areas mean no impacts have occurred? A comparison of stranding and detection probabilities in the Canary and main Hawaiian Islands

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ABSTRACT

Anthropogenic activities must be monitored to determine effects on marine mammal species, but the difficulty lies in how to measure impact. Mass strandings of beaked whales have occurred in association with naval exercises, with two species most affected, Cuvier's (*Ziphius cavirostris*) and Blainville's (*Mesoplodon densirostris*) beaked whales. Six such events have occurred in the Canary Islands but there have been no reported mass strandings in Hawai'i. We assess the hypothesis that factors that influence the likelihood of strandings occurring and/or being detected differ between the Canary and main Hawaiian Islands, such that beaked whale stranding/detection probabilities will be lower in Hawai'i. On an archipelago-wide basis, nearshore bathymetric comparisons indicate that the Canaries have a greater proportion and a total greater amount of appropriate beaked whale habitat closer to shore, with a steeper slope. Hawaiian shorelines are more dominated by steep cliffs, human population density is much lower, and human population per kilometer of shoreline is 53% lower than in the Canaries. All of these factors suggest that there is a higher probability of a carcass washing onshore and being detected in the Canary Islands. It cannot be concluded that the lack of mass strandings in Hawai'i is evidence of no impact.

Key words: beaked whale, Canary Islands, Hawai'i, impact, *Mesoplodon densirostris*, sonar, strandings, *Ziphius cavirostris*.

Beaked whales can be found in all of the world's oceans and are still one of the least studied families of odontocetes, in spite of recent advances in the knowledge of their acoustic ecology and behavior (Johnson *et al.* 2004, Madsen *et al.* 2005, Aguilar de Soto 2006, Baird *et al.* 2006, 2008, Tyack *et al.* 2006, McSweeney *et al.* 2007). A number of recent mass strandings of beaked whales have occurred in close temporal and spatial proximity to naval exercises with associated sonar linked as the likely cause of such events (Simmonds and Lopez-Jurado 1991, Frantzis 1998, Balcomb and Claridge 2001, Evans and England 2001, Jepson *et al.* 2003, Fernández *et al.* 2005, Hildebrand 2005, Cox *et al.* 2006). Two species are most affected, Cuvier's (*Ziphius cavirostris*) and Blainville's (*Mesoplodon densirostris*) beaked whales, with strandings in association with military exercises reported for Greece (in 1996), the Bahamas (in 2000), Madeira (in 2000), and the Canary Islands (in 1985, 1988, 1989, 1991, 2002, and 2004) (Vonk and Martín 1989, Frantzis 1998, 2004, Balcomb and Claridge 2001, Freitas 2004, Martín *et al.* 2004, Cox *et al.* 2006, D'Spain *et al.* 2006, International Whaling Commission 2006). While the mechanisms causing the strandings are unclear, mid-frequency sonar associated with the exercises is thought to result in behavioral changes that lead to a suite of physiological impacts (Jepson *et al.* 2003, Fernández *et al.* 2005, Aguilar de Soto 2006, Cox *et al.* 2006, Tyack *et al.* 2006, Hooker *et al.* 2009).

With the exception of Greece, all other locations were oceanic islands. Whether this is a result of more preferred beaked whale habitat surrounding islands than any other type of location, naval military preference for training near oceanic islands, or a combination of these and potentially other factors, remains unknown. Additionally, conditions for mass strandings may be optimized when the sound source travels through deep channels, between islands, or deep canyons such as those near the incident in Greece (Hildebrand 2005).

Within the last 22 yr, there have been 11 mass stranding events involving beaked whales in the Canary Islands; 6 are known to have directly coincided with naval sonar use or with naval maneuvers operating in the area, while there is no information on naval activities for the other events (Simmonds and Lopez-Jurado 1991, Martín *et al.* 2004, Cox *et al.* 2006, Martín and Tejedor 2009). From 1980 through 2006 there were 87 beaked whale stranding events documented in the Canary Islands representing 119 individuals (Martín and Tejedor 2009). There are resident beaked whale populations that can be found year-round very near to the coast around the Canary Islands (Aguilar de Soto 2006, Arranz *et al.* 2008). In recent years management policies have been introduced by the Spanish Ministry of Defense in an attempt to lower the impact of naval exercises on beaked whales. Use of naval sonar in the Canary Islands is permitted no less than 92 km off the coast of the Canary Islands (Aguilar de Soto and Martín 2007). However, naval exercises that have occurred more than 185 km offshore have still resulted in the stranding of beaked whales in the Canary Islands (Aguilar de Soto and Martín 2007). The Hawaiian Islands experience regular naval exercises (Anonymous 2006) and contain resident beaked whale populations (McSweeney *et al.* 2007, Schorr *et al.* 2009). Only nine beaked whale strandings have been documented in the Hawaiian Islands through 2007 (Maldini *et al.* 2005, D. Schofield[2]), and no mass strandings have been reported. Based on this stranding record, the US Navy has stated that it is "extremely unlikely that any significant behavioral response will result from the interaction of beaked whales and the use of

[2]Personal communication from David Schofield, NOAA National Marine Fisheries Service, 1601 Kapiolani Boulevard, Suite 1110, Honolulu, HI 96814, 5 May 2007.

sonar" (Anonymous 2006). However, the absence of evidence (of an impact) is not evidence of absence.

Here we examine a number of variables that could influence the probability of a dead or disorientated beaked whale from reaching the shoreline, such as distance from the coast to typical beaked whale "habitat," occurrence of fringing reefs, large scavenging sharks, sea surface temperature, and currents. In addition, we examined factors affecting the probability of detection once onshore, including shoreline slope and density of human population, in both Hawai‘i and the Canary Islands. Information about frequency, distribution, and intensity of naval activity in either area is classified. However, both areas are known to host large scale naval exercises involving mid-frequency active sonar use (Anonymous 2006, Cox *et al.* 2006, Navy 2006).

Methods

Ocean bathymetry data and coastal land data were obtained from different sources and available at different resolutions. Bathymetry data for the main Hawaiian Islands was obtained with a resolution of 3 arcseconds (approximately 93 m) through the National Geophysical Data Center (Divins and Metzger 2006). The Canary Islands bathymetry data were acquired from the General Bathymetric Chart of the Oceans Digital Atlas system (GEBCO 2003) at a resolution of 1 arcminute (approximately 1.86 km). Information for coastal slope analyses was extracted from digital elevation models (DEM) for both areas. The main Hawaiian Islands DEM's were at a resolution of 10 m and acquired from the Coastal Geology Group at University of Hawai‘i (School of Ocean and Earth Science and Technology 2006). The Canary Islands information was obtained from an online digital mapping service (MapMart 2006), at a resolution of 90 m. Land area information, length of coastline, and human population numbers for the Hawaiian Islands were taken from The State of Hawai‘i Data Book (Hawaii 2005). Comparable information for the Canary Islands was obtained from The National Statistics Institute of Spain (Instituto Nacional de Estadística 2006). Sea surface temperature (SST), sea surface salinity (SSS), surface seawater density, current speed and direction, and wind speed and direction were obtained from various sources (Fofonoff and Millard 1983, Barton *et al.* 1998, 2001, Zhou *et al.* 2000, Navarro-Pérez and Barton 2001, World Ocean Atlas 2005, Ocean Atlas of Hawai‘i 2006, Windfinder 2009).

ArcView GIS 3.3 software was used to analyze various bathymetric and topographic comparisons between the Hawaiian and Canary Islands. Bathymetric data were analyzed at intervals of 1 km extending out from the shoreline of each island to a total distance of 10 km, and then one interval from 10 km to 20 km. From these intervals a mean depth was used to produce mean depth profile graphs for each island and as a collective island chain. Within the main Hawaiian Island chain, four of the islands are in close proximity to one another and separated by shallow (<200 m depth) channels: Moloka‘i, Maui, Lana‘i, and Kaho‘olawe. Distances among these islands range from 11 to 15 km and collectively they make up what is known as "Maui Nui." Due to close proximity and multiple overlaps of depth intervals, overlapping intervals were merged to avoid counting a value more than once. For the entire island chain mean depth profiles, these islands were grouped as one. Depth and slope in the channels between the other islands were recorded associated with the closest island, so that each area was counted only once.

Percent area of suitable habitat for beaked whales surrounding each island at various distances from shore was calculated, for intervals of 0–3 km, 0–6 km, 0–10 km, and from 10 to 20 km from shore. Suitable habitat for beaked whales is defined here as a depth of >650 m. This minimum depth for suitability was chosen because it is the within 20 m of the shallowest depth reported for a beaked whale sighting in Hawai'i (Baird *et al.* 2006), despite substantial survey effort at shallower depths. For interval distances of 0–10 km and 10–20 km, the same island grouping of Maui Nui was used to prevent overlapping intervals and potentially over calculating certain depth ranges when used for an overall island chain total.

Due to similar circumstances as in the Hawaiian Islands, two of the Canary Islands, Fuerteventura and Lanzarote, were merged and calculated as one value amongst the other islands for a general Canary Islands mean depth profile. Beaked whales are reported in shallower water in the Canary Islands (Ritter and Brederlau 1999, Arranz *et al.* 2008), and sighting depths for beaked whales can vary among islands for both archipelagos. However, we used depths of >650 m to calculate the proportion of suitable beaked whale habitat for both areas, to allow direct comparisons. The implications of this to our conclusions are discussed later.

Topographic maps obtained for each individual main Hawaiian Island were loaded into ArcView GIS 3.3 as a DEM file to determine coastline slope from the shore inland. The Spatial Analyst extension was used to derive slope and data were re-classed into nine categories of 10° increments. Slope increments were grouped further, with a higher slope category indicating an increased difficulty of accessing the coast. Accessibility is defined here as the ease at which the shoreline can be reached in a particular area as a factor of the coastline slope in that area. Slope measurements of 0–20° were classified as easy accessibility, 20–50° slopes were classified as moderate accessibility, and 50–90° slopes were classified as difficult accessibility. An interval extending from the shore inland to a distance of 100 m was measured. Within this interval, percent area of slope categories was extracted. Other values related to land area, shoreline length, human populations, and various oceanic features were directly compared.

Results

Waters around the Canary Islands generally reach greater overall depths closer to shore and have a steeper slope than in the Hawaiian Islands (Fig. 1). Within 10 km of shore the main Hawaiian Islands reach a mean depth of 990 m, with a slope of −94.96 m/km, while the Canary Islands reach a mean depth of 1,223 m, with a slope of −133.71 m/km (Fig. 1). As distance from shore increases, water depth and the amount of suitable beaked whale habitat increases for both locations (Table 1). Overall coastline lengths are slightly less for the Canary Islands compared to the main Hawaiian Islands (Table 2); thus, there is less total water area surrounding the islands at any given distance. However, a greater proportion of the area within the distances from shore measured is suitable for beaked whales (depths >650 m) in the Canary Islands (Table 1). Taking into account the shorter coastline lengths between the two areas, within 3 km of shore the Canary Islands have 49.4% more beaked whale habitat than the main Hawaiian Islands, and within 6 km of shore have 31.3% more beaked whale habitat. Topographic measurements of percent area within the different slope categories indicate that the main Hawaiian Islands have a larger amount of area with shoreline slopes of 50–90° (Fig. 2). Although the total

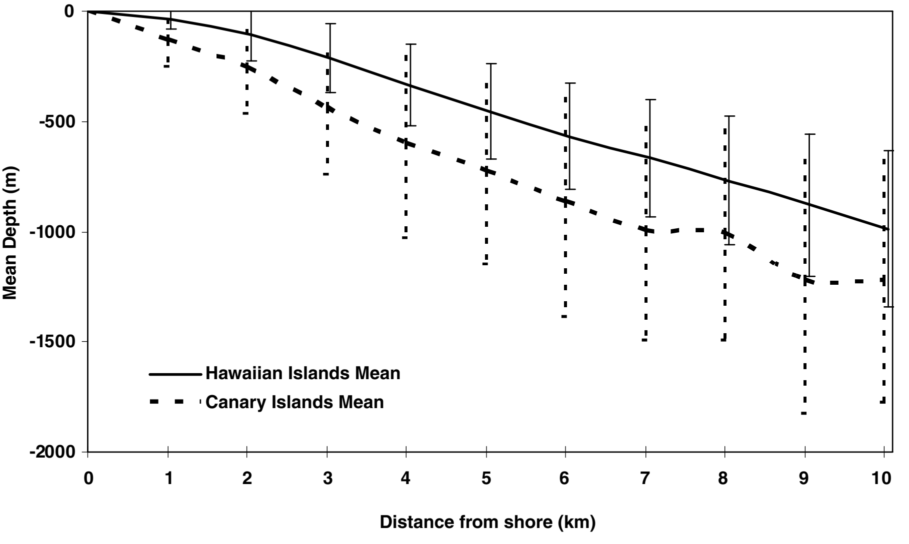

Figure 1. Mean depth comparison between the main Hawaiian and Canary Islands at 1 km intervals from shore. Values shown are averages of the islands within each archipelago and bars represent ±1 SD. The error bars for the two lines are slightly offset for clarity.

land area in the Canary Islands is only about 45% of the area of the main Hawaiian Islands, human population density in Hawai'i is only about 28% of that of the Canary Islands, and population per km of shoreline in Hawai'i is about 53% of that in the Canary Islands (Table 2). The Canary Islands have higher sea surface salinity, lower sea surface temperature, higher surface seawater density, and slower current speeds (Table 3).

Discussion

The Canary Islands reach a greater depth with a steeper slope closer to shore than the Hawaiian Islands (Fig. 1). Beaked whales are known to prefer these deep water habitats and regions of steep slope, so the occurrence of deeper waters close to shore denotes an increased potential for beaked whales presence closer to shore (MacLeod and Zuur 2005, Baird *et al.* 2006). Both the proportion of area closely surrounding the islands that is thus suitable beaked whale habitat (depths >650 m), and the

Table 1. Percent area of suitable beaked whale habitat (defined as depths >650 m) within various distances from shore.

	Distance from shore			
	0–3 km	0–6 km	0–10 km	10–20 km
Main Hawaiian Islands	6.3%	16.5%	29.2%	79.8%
Canary Islands	10.6%	24.4%	36.0%	82.1%

Table 2. Comparison of land areas, coastline length, and human population density between the main Hawaiian Islands and the Canary Islands.

	Length of coastline (km)	Land area per kilometer of coastline (km^2/km)	Human population density (number of individuals/km^2 land area)	Human population per kilometer of coastline (number of individuals/km)
Main Hawaiian Islands	1,236	13.0	72.9	944.3
Canary Islands	1,098	6.8	264.3	1,792.3
Ratio of Hawaiian to Canary Islands (%)		191.2%	27.6%	52.7%

absolute amount of area that is suitable habitat, is greater in the Canary Islands than in the Hawaiian Islands (Table 1). Given that beaked whales appear to be found in shallower waters in the Canary Islands than in Hawai'i (Ritter and Brederlau 1999, Arranz *et al.* 2008), our use of >650 m depth for both areas is conservative, as we likely underestimate the proportion of the near-shore areas in the Canary Islands that are suitable for beaked whales.

In general, cetaceans are known to have higher stranding rates when species inhabit waters that are closer to shore; one example in particular reported beaked whales stranding in areas near locations that contain suitable beaked whale habitat closer to shore along the coast of Washington State (Norman *et al.* 2004). There is more suitable beaked whale habitat closer to shore in the Canary Islands; therefore, beaked whales will have a higher chance of reaching inshore waters and stranding in the Canary Islands rather than in the Hawaiian Islands.

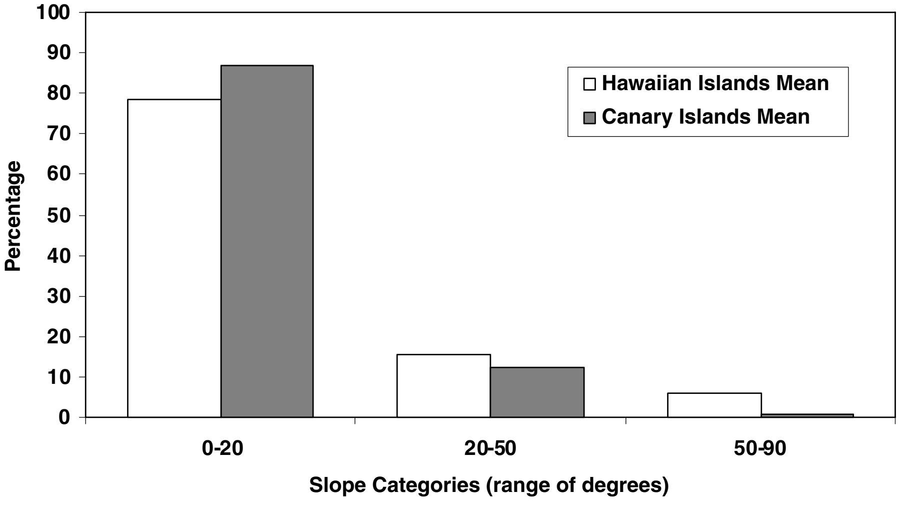

Figure 2. Comparison of shoreline slope within 100 m of shore between the main Hawaiian Islands and the Canary Islands.

Table 3. Comparison of oceanic variables between the Hawaiian and Canary Islands.

	Mean sea surface salinity[a] (pss)	Mean sea surface temperature[a] (°C)	Mean sea surface current speed[b] (cm/s)	Mean density of surface seawater[c] (g/cm^3)
Hawaiian Islands	34.5–35	25–26	25	1.023
Canary Islands	36.8	21	5–20	1.025

[a]World Ocean Atlas 2005.
[b]Barton *et al.* 1998, Navarro-Pérez and Barton 2001, Zhou *et al.* 2000, Ocean Atlas of Hawai‘i 2006.
[c]Fofonoff and Millard 1983.

Both the Canary and Hawaiian islands are of volcanic origin and contain areas of steep mountain coastlines. Direct access to beaches can be a limiting factor in the detection of whale strandings. Within the first 100 m from shore, the main Hawaiian Islands has six times more coastal access dominated by slopes that fall within 50°–90° than the Canary Islands (Fig. 2). In addition, the main Hawaiian Islands have a larger percent area of the coastline that falls into moderate slope or moderate coastal accessibility for the first 100 m inland. The probability of stranding detection is in part due to the ability to access all the locations at which an animal could possibly strand. If there is a large amount of area that is inaccessible to the public, the chance of finding stranded beaked whales drops significantly (Norman *et al.* 2004, Maldini *et al.* 2005). Hawai‘i has some of the highest sea cliffs in the world. Given the near-shore topography of these two island chains, difficulties arising from coastal access issues in the main Hawaiian Islands could lead to a substantial amount of unreported beaked whale strandings, whereas in the Canary Islands a more easily accessible coast likely results in a greater proportion of strandings being detected.

As well as accessibility of shorelines as indicated by the shoreline steepness, the two smallest of the eight main Hawaiian Islands, Ni‘ihau and Kaho‘olawe, have restricted access and very low human populations, thus strandings on those islands are even less likely to be detected. The Hawaiian Islands have a large land area when collectively grouped and compared to the Canary Islands, yet there is a higher human population in the Canary Islands. Therefore, the Canaries contain a higher number of people potentially using the coastline (Table 2). As described in previous stranding studies (Norman *et al.* 2004, Maldini *et al.* 2005), the smaller population to land area and shoreline length ratios in the Hawaiian Islands is a reasonable cause for fewer reported beaked whale stranding events. This implies that stranding records alone do not adequately illustrate potential impacts occurring in an area.

Various oceanic variables could have a large effect on the direction of drift and location of strandings, as well as decomposition rates. Oceanic variables such as SSS and SST play a substantial role in decomposition rates and affect the buoyancy of a carcass (Norman *et al.* 2004). Increased SSS could potentially increase the degree of buoyancy for a floating carcass and increase the time available for wind and currents to push it into shore. Lower SSS levels and less dense surface seawater in the Hawaiian Islands (Table 3) may result in a carcass lying more submerged at the surface or sinking more easily. Increased SST within the main Hawaiian Islands suggests a carcass has a higher probability of faster decomposition and decreased buoyancy. Although data on whale decomposition rates and buoyancy in different water temperatures/densities are not available, these factors could all influence the pattern observed of fewer beaked strandings in the Hawaiian Islands compared to the Canary Islands.

Oceanic surface currents are capable of having a dramatic influence in determining where a carcass will go; a fast current is likely to carry a carcass or weakened beaked whale out to the open ocean faster than it can strand onshore (Norman *et al.* 2004). Surface current speed in Hawai'i is generally faster than found in the Canaries (Table 3), although current speeds vary among the islands in each archipelago and are faster in channels. This increased current speed is therefore another likely factor in the decreased number of beaked whale stranding reports in the Hawaiian Islands as they may be more likely washed out to sea and left unreported in stranding records. Current direction, as well as wind speed and direction, could potentially have an impact; however, very little differences are seen between the two archipelagos. Both locations have current directions generally running toward the southwest with wind direction predominately from north-northeast to east (Zhou *et al.* 2000, Windfinder 2009). Overall annual mean wind speed in the two island chains is very similar, approximately 5.5 m/s (Windfinder 2009). It is therefore likely that surface current speed is a potentially larger factor in the difference of detectable strandings occurring between the two archipelagos. It is important to note that current speed and direction, and also wind speed and direction, are likely to play a much larger role in relation to the location of military exercises around the island chains. In the Canary Islands, most of the naval exercises occurred east of the two islands (Fuerteventura and Lanzarote) most associated with the related beaked whale stranding events (Martín *et al.* 2004). Therefore, both wind and currents worked in favor of pushing dead or moribund beaked whales toward the islands. If military exercises were carried out west of the island chains, strandings for both locations may be less likely to be detected as carcasses will be carried out to the open ocean directly. Information on the location of exercises in the Hawaiian Islands is not available.

Expansive shallow reefs, or any shallow water break, could influence the likelihood of a beaked whale from stranding or being detected by preventing it from reaching near shore waters. It is possible that the extensive coral reefs systems around many of the main Hawaiian Islands influence the occurrence or detection of strandings. Although quantitative information on the amount of coral reef reaching close to the surface is not available for all of the main Hawaiian Islands, on the south shore of Moloka'i, for example, a shallow reef with a significant portion reaching <5 m from the ocean surface extends nearly 1 km perpendicular from shore and stretches virtually across the entire south shore of the island (Logan *et al.* 2005). Due to water temperatures surrounding the Canary Islands, it is possible for some corals to form; however, reefs do not (Brito and Ocaña 2004). No fringing coral reefs and fewer shallow water breaks suggests a higher probability that a moribund beaked whale will reach near shore waters in the Canary Islands.

Scavengers in the sea are an integral part of the ocean ecosystem. Scavenging on cetacean carcasses is an important food source for some sharks (Heithaus 2001). Consumption rates by various scavengers (not just sharks) have been measured at a removal of up to 40–60 kg/d of soft whale tissue (Smith and Baco 2003). Evidence of shark scavenging on cetaceans in Hawai'i was recently reported off the west coast of the Island of Hawai'i (National Oceanic and Atmospheric Administration 2006). A humpback whale (*Megaptera novaeangliae*) was reported as ailing and within hours up to 25 tiger sharks (*Galeocerdo cuvier*) were reported attacking the weakened animal. The whale eventually died and it was hauled offshore and tethered to a fishing buoy; nothing remained of the carcass the following day (National Oceanic and Atmospheric Administration 2006). This event is an example of the scavenging strength, pressure, and immediacy by sharks in the Hawaiian Islands. While there is no information on relative population density of tiger sharks in the two areas, if shark numbers around the Hawaiian Islands are greater than that of the Canary Islands, it is possible beaked whales that die or are disorientated by military sonar exercises have a decreased probability of reaching nearshore waters due to consumption. Limitations due to shark behavior make it difficult to assess populations and determine scavenging pressures in both locations but this could be a factor in the apparent lack of beaked whale mass strandings in the Hawaiian Islands.

Marine mammals inhabiting areas closer to shore are more likely to strand and naval exercises that occur closer to shore have a higher potential to impact nearshore populations of beaked whales. In the Canary Islands, a documented naval exercise occurring over 185 km off the coast of the archipelago still resulted in the stranding of beaked whales (Aguilar de Soto and Martín 2007); it is evident that the distance at which these types of naval exercises occur and their potential impacts are largely unknown. While most naval exercise locations remain classified, it is important to note that even exercises in open-sea environments but relatively near locations of beaked whale populations could potentially cause an impact. It will be inherently more difficult to ascertain the level of impact for open sea exercises, as the likelihood of an animal making it to shore to strand will be even lower.

Oceanic variables discussed are dynamic and complex processes that are considered here fairly simplistically. It is important to note that all of the variables, including bathymetry and topography, are discussed in general at the level of the archipelago for both the Canary and main Hawaiian Islands. While they vary on a small scale within each island chain, an analysis on an island-by-island basis would reveal factors that influence stranding probabilities within each archipelago, such as general wind patterns and speed, which vary on small scales based on topography. All of these factors could play a substantial role in fine scale analyses; however, they are unlikely to affect our general conclusions that bathymetry, topography, human population density, and ocean variables such as currents and sea surface temperature all vary consistently between the two broad archipelagos, such that dead or moribund beaked whales are more likely to strand and be detected in the Canary Islands than in Hawaiʻi.

There is significant potential for underestimating the impact naval sonar use may be having on beaked whales, in the main Hawaiian Islands and elsewhere. The variables analyzed in this study suggest beaked whales are less likely to either strand or be detected in the Hawaiian Islands. Therefore, mortalities and/or strandings may be occurring more frequently than is evident by the limited stranding record, and it is inappropriate to conclude there has been no impact on beaked whales from anthropogenic activity in the Hawaiian Islands.

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