Historic odontocete stranding events in the Hawaiian and Mariana Islands (1848–2023) and how strandings correlate with environmental parameters over an 18 year timespan

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Abstract

This review examines historical data from 535 odontocete stranding events in the Mariana archipelago and Hawaiian Islands by date, location and species and spans the time period of 1848 to 2023. Reports of strandings increased across the two geographic regions that were generally consistent over time. A total of 54 historical stranding events that represent 14 odontocete species are described for the Mariana Islands. A total of 481 stranding events that represent 19 odontocete species are described from the Hawaiian Islands, significantly updating the last published report that examined 202 odontocete strandings that occurred in the main Hawaiian Islands between 1937 and 2002. ArcGIS cluster maps were utilized to identify groupings of stranding events across the geographic regions. The majority of strandings in the Mariana Islands were reported from the west and southeastern coast of Guam, followed by Saipan, Rota and Tinian. Stranding hotspots in the Hawaiian Islands were identified at Mā'alaea Bay, Maui, at windward O'ahu and near Kailua-Kona on Hawai'i Island.

A total of 271 stranding events occurring between 2003 and 2021 were examined in relation to environmental data, including surface temperature and winds, chlorophyll A, bathymetry and the extra-tropical Northern oscillation index using a best-fit model for the Hawaiian and Mariana Islands. An estimated stranding date was generated for events occurring between 2003 and 2021 based on photographs and tissue quality of carcasses at the time of first observation. Estimated stranding date

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A total of 271 stranding events occurring between 2003 and 2021 were examined in relation to environmental data, including surface temperature and winds, chlorophyll A, bathymetry and the extra-tropical Northern oscillation index using a best-fit model for the Hawaiian and Mariana Islands. An estimated stranding date was generated for events occurring between 2003 and 2021 based on photographs and tissue quality of carcasses at the time of first observation. Estimated stranding date was used in the best fit model to better reflect the day of death. The best fit model found sea

surface wind speed and the year of stranding occurrence to be significant factors within this model. Application of the same modeling parameters on a subset focused only on strandings of animals from the genus *Stenella* found significant correlations between sea surface wind speed, average to warm ocean surface temperatures, and the year of stranding occurrence. Sea surface winds were highly significant when related to stranding events, which is likely driven both by general ocean circulation and reversal of prevailing north easterly trade winds in the main Hawaiian Islands, where the majority of stranding events that were examined occurred.
This study provides an updated compilation of historical stranding events in the Hawaiian and Mariana archipelagos, identifies locations of high stranding frequency, and demonstrates that sea surface winds influence the stranding patterns observed in the Pacific Islands. Investigation of stranding events and the determination of factors that contribute to odontocete mortality and the probability of carcass recovery are important elements for the design and implementation of effective conservation strategies for protected species.

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1 Introduction

Cetaceans are recognized sentinels of ocean health and directly impact the overall ecosystem function as top predators through trophic cascades (Bossart, 2006; IJsseldijk et al., 2020; Liu et al., 2019). Necropsy investigations of dead stranded cetaceans are generally the only means to determine causes of morbidity and mortality, but examination of stranding data that is limited to species and location can still provide valuable information. For example, species-specific stranding locations allow for insight into occurrence and has previously been shown to be similar to cetacean surveys from vessel- or aerial-based platforms or from acoustic recorders when determining relative cetacean species distribution (Maldini et al., 2005; West et al., 2024). Additionally, characterization of stranding patterns improves our understanding of the biogeography of populations and may identify important habitat where specific species are found in high abundance (West et al., 2024). Historical stranding data routinely serves as baseline data to evaluate species-specific stranding rates and/or can be utilized to investigate the relationship between stranding events and potential environmental or anthropogenic factors that may contribute to strandings.

The Hawaiian and Mariana archipelagos are a part of the NOAA Fisheries Pacific Islands region. Historical accounts from the Hawaiian Islands detail 60 melon-headed whales (*Peponocephala electra*) that were driven ashore in Hilo Bay in 1848 and used as both a food source and for oil (Peale, 1948 in Shallenberger, 1981), a single melon-headed whale stranding in 1864 on Oʻahu, single strandings of pygmy sperm whales (*Kogia breviceps)* in each of 1923 and 1947 in French Frigate Shoals and Maui, respectively, and a stranding in Waikīkī, Oʻahu of a humpback whale in 1936 (Anonymous, 1936). No other strandings were recorded in the Hawaiian Islands until the 1950's. The Marine Mammal Protection Act of 1972 and Endangered Species Act of 1973 created a framework in the United States where stranding response, treatment and recovery had legal considerations that led to the development of regional stranding networks organized by NOAA Fisheries (Nitta, 1991). In the Hawaiian Islands, the first compilations of historical stranding events included all odontocetes and humpback whales (*Megaptera novaeangliae*) and noted 98 known strandings occurring between 1937 and 1988 (Shallenberger, 1981; Nitta, 1991). An examination of historical records of odontocete strandings that extended an additional 14 years, increasing the range of study from 1937 to 2002, was summarized by Maldini et al. 2005 and included analysis of stranding trends. Despite the growth of increased stranding response capacity within the Hawaiʻi stranding network and an exponential increase in effort to record strandings over the past two decades on a global scale (Lui et al., 2022), no recent analysis of stranding data from the Hawaiian Islands is available in the published literature.

The Mariana Islands archipelago stretches from the island of Guam, which is a separate territory in the South, to fourteen islands in the North that comprise the Commonwealth of the Northern Mariana

Islands. The island of Guam has the highest population density with a significant military presence. The Mariana Islands Range Complex encompasses military training areas that are spread over 500,000 nautical square miles across open ocean and coastal waters in the region. The potential for negative impacts on marine mammals is highlighted by goose-beaked whale (*Ziphius cavirostris*) strandings that were spatiotemporally correlated with naval exercises between 2006 and 2019 (Simonis et al., 2020). The U.S. Navy has significantly invested in research efforts to describe resident cetacean populations in the region, where very little information was available until these dedicated efforts began almost two decades ago. Cetacean line transect surveys have provided baseline distribution and abundance information for 13 species of cetaceans that were sighted around the islands of Guam and Saipan (Fulling et al., 2011). Cetacean vessel surveys in the Mariana Islands have since documented the presence of 20 species of cetaceans through the utilization of visual surveys, photographic identification catalogs, acoustic monitoring, biopsy collections, and satellite tagging to describe individual movement patterns (Hill et al., 2020). Recent investment has focused on the deployment of passive acoustic monitoring tools to better understand relative abundance and estimate beaked whale densities (Simonis et al., 2020; McCullough et al., 2021; Klink et al. 2015; Klink et al., 2020). There has been a tremendous effort in the Mariana Islands to establish cetacean occurrence.

Despite the high interest in stranding events in the Mariana Islands and the increase in information from acoustic recorders, sighting rates at sea, and satellite tagged movements, only stranding rates of beaked whales have been previously examined from the region (Simonis et al., 2020). The first reported stranding in this archipelago was recorded from Saipan and is a report of a human assisted stranding of sperm whales (*Physeter macrocephalus)*, used for food consumption (Costenable, 1905 in Kami and Lujan, 1976). Strandings were reported from Guam in 1962, with a number of published reports of individual stranding events in Guam detailed from the 1970's and 1980's (Kami and Lujan, 1976; Kami and Houser, 1982; Donaldson et al., 1983). In the Northern Mariana Islands, spinner dolphin (*Stenella longirostris*) strandings in the mid-1990's are described, as well as 10 events that represent six species of cetacean on the islands of Saipan and Rota (Trianni and Tenorio, 2012; Trianni and Kessler, 2002). The Simonis 2020 report focused entirely on goose-beaked whales and examined strandings occurring throughout the entire archipelago for this species. Historical cetacean stranding events across cetacean species in the Mariana's archipelago have not yet been compiled in the published literature but would provide valuable baseline information on species-specific stranding rates that would aid in future monitoring efforts for the region.

On a world-wide scale, investigations of spatiotemporal stranding patterns have increased in the 21st century as public interest in sentinel marine species has grown (Liu et al., 2022; Pikesley et al., 2012). Efforts to examine historical cetacean strandings have been conducted in the Atlantic Ocean (Coombs et al., 2019; Nemiroff et al., 2010; Pikesley et al., 2012; Silva and Sequeira, 2003), the Indian Ocean (Foord et al., 2019; Groom and Coughran, 2012), the Mediterranean Sea (Azzellino et al., 2017; Lo Brutto et al., 2021), the North Sea (IJsseldijk et al., 2020), the South China Sea (Liu et al., 2019), and the Pacific Ocean (De Weerdt et al., 2021; Maldini et al., 2005; Mazzuca et al., 1999; Ortiz-Wolford et al., 2021; Trianni and Tenorio, 2012; Warlick et al., 2022). However, an examination of stranding patterns has not been conducted in the Hawaiian Islands that considers the past two decades of collected stranding data, nor have historical stranding patterns across all species been examined to date from the Mariana archipelago.

Specific objectives of the current study are as follows: 1) to describe historical cetacean stranding patterns in the Mariana archipelago and to provide an updated analysis of stranding patterns in the Hawaiian Islands that includes the past two decades of data collection; 2) to describe the baseline stranding frequency for cetacean species that have previously been documented as stranded in both archipelagos; 3) to conduct cluster analysis of historical odontocete strandings by species to identify frequent stranding locations in the Hawaiian and Mariana archipelagos; 4) to conduct an examination of total stranding reports over time in the Mariana and Hawaiian Islands; and 5) to compare historical stranding events in the Hawaiian and Mariana archipelagos with environmental variables that may influence stranding rates, such as sea surface temperature, chlorophyll A, sea surface winds, extra-tropical Northern oscillation index and bathymetry.

METHODS

Study Region:

The geography of the study area includes the Northwestern Hawaiian Islands, the Main Hawaiian Islands and the Mariana Islands. The Mariana Islands region is approximately 12°N to 23°N latitude and 142°E to 148°E longitude. The Hawaiian Islands, including both the Northwestern Hawaiian Islands and the Main Hawaiian Islands, are approximately 13°N to 32°N latitude and 140°W to 179°W longitude.

Sources of Stranding Records:

Historical cetacean stranding records were used to investigate the distribution and biogeography of odontocetes in the waters around the Mariana and Hawaiian archipelagos. Odontocete stranding information was compiled from several different sources. This included cetacean strandings in the Pacific Islands described in the published scientific literature, museum specimens and specimen samples, or unpublished in-house data (West, unpublished). We also obtained historical cetacean stranding data from the Smithsonian Institution's Division of Mammals Collections Stranding Distributional database and the NOAA Fisheries Marine Mammal Health and Stranding Response Program's National Stranding Database.

Stranding events considered in this study were defined as carcasses floating dead or found dead on beaches or shorelines, live stranded cetaceans on beaches or shorelines, and live cetaceans that were distressed, injured, or out of habitat and potentially unable to return to their natural habitat without human assistance. We also included four specimens incidentally caught in fisheries that were collected for necropsies. For this report, human interactions that did not result in the confirmed death of an animal were removed. Excluded interactions involved observations of entangled odontocetes, observations of odontocete vessel strikes, and other reports of human interactions with odontocetes. Additionally, all mysticete species were excluded from analysis, as many historical records include reports of animals trailing or entangled in fishing gear where the outcome of the sighting was unknown. All carcasses that were generally categorized as unidentified large whales that were too decomposed for differentiation between mysticete or odontocete sperm whale were also excluded from our analyses.

Odontocete Stranding Verification by Species:

For all odontocete strandings compiled from the published scientific literature and from historical stranding records entered into the relevant databases, species identifications were assumed to be correct. For in-house stranding records, species identifications are done at the time of a stranding response using coloration, external markings, size, and shape, with a particular focus on lateral examination of the head and rostrum. In some cases, shape of the pectoral fins, tooth counts of both the upper and lower jaw, and ratios between morphometric measurements are used to distinguish between species that are otherwise difficult to identify from one another. Genetic analysis of tissue was used to confirm species identification when species determination may have been questionable for strandings occurring since 2006, with a particular focus on cases where carcasses were too decomposed to use morphological characteristics or where key identifying features were not available at the time of necropsy.

The stranding data examined in this study included the date of the event, location and the number of stranded individuals. Latitude and longitude coordinates were taken directly from the original source when available. In cases with a location but no coordinates, coordinates were generated based on the most detailed information available for each location (island, city, beach, etc.). Stranding records with only the island location available are depicted by coordinates at the island center to not misrepresent locations associated with stranding events. Available latitudes and longitudes were corrected in the NOAA Fisheries National database when the precise locations listed did not match the coordinates given. Many of the historical records had entered the degree, minutes, and seconds locations as decimal degrees without converting (i.e., 12°N 34' 56" was incorrectly entered as 12.3456° when it should be 12.5822°). When a precise location was not provided to support the increased accuracy of the new location, the original location was used. Dates are presented as precise as the original source provided. Stranding databases may have used either the first or last day/month of the month/year when the exact day/month of the month/year of the stranding event was unknown.

Stranding locations were visualized using ArcGIS mapping software (Esri). Cluster maps were generated using Esri ArcGIS Pro to collectively represent stranding data for all species in the Hawaiian and Mariana Islands as well as for the subset of *Stenella* spp. in the Hawaiian Islands. Cluster radius was set to medium to group events at similar latitudes and longitudes.

Estimated Stranding Date as Opposed to Date of First Observation:

To increase the accuracy of the spatial analysis of stranding events and how this may relate to environmental factors, days of death were approximated to allow for an estimated stranding date as opposed to the first observation that is traditionally used as the stranding date. In order to estimate stranding date as opposed to date of first observation, a range of days of death were estimated for each decomposition code. All carcasses were assigned condition codes 1 to 5 to estimate autolysis following the method described by Geraci and Lounsbury (2005). These include Alive (code 1), Fresh Dead (code 2), Moderate Decomposition (code 3), Advanced Decomposition (code 4), and Skeletal/Mummification (code 5). If the animal was seen alive, the stranding date was considered the date of the report. Animals marked as code 2, showed minimal signs of decomposition and likely died that day or within 2 days of the date they were first observed. When no photos or other records were provided, the estimated stranding date was estimated as one day prior to the date reported for code 2 designations. Animals marked as code 3, showed moderate levels of decomposition, including bloating, discolorations, and deflation/inflation of internal organs. These animals were estimated as three to 10 days, and when no photos or other records were available to narrow that window, the estimated date of death was marked as seven days prior to the date of first observation. Animals marked as code 4, showed advanced levels of decomposition, including extensive bloating, openings into the body cavities, and extensive breakdown of internal organs. This code can overlap with code 3 in the description and extends until all soft tissue has disappeared and/or the carcass is mummified. This range was estimated as seven days to 21 days and if no photos or other records were available the day of death was estimated as 14 days. Sperm whales had longer decomposition timeframes due to their immense carcass size. For sperm whales specifically, code 3 was estimated as three to 14 days, and code 4 was extended from 14 to 120 days, which reflects the extreme variation observed during decomposition for this species. When photos or other written findings were included with the records, they were used to increase the accuracy of the estimated stranding date as opposed to date of first observation.

***Environmental Data Collection*:**

Environmental data was selected to examine variables that may influence odontocete stranding frequencies in the Hawaiian and Mariana archipelagos. Data for select environmental variables were obtained from NOAA Environmental Research Division's Data Access Program (ERDDAP) servers. This data included sea surface temperature, chlorophyll-A, extratropical-based Northern Oscillation Index and 10-meter sea surface winds. The data matched the coordinate locations for the month that represented the estimated stranding date for each stranding event. Strandings occurring from 2003 to 2021 were included in the statistical analyses examining environmental variables. This 18-year time period was selected due to this timespan having the most overlap between the covariates and our ability to estimate stranding date based on availability of photos and/or tissue sample collections to assess carcass degradation at the time of first observation.

Monthly means of sea surface temperature (SST) (°C) and chlorophyll-A (CHLA) concentrations were collected from the Aqua Moderate Resolution Imaging Spectroradiometer (MODIS) dataset. SST and CHLA fluctuations can indicate changes in prey availability, with climatic changes influencing primary production and prey availability for odontocete species (Gulland et al., 2022). Monthly extratropical-based Northern Oscillation Index (NOI) data was collected to investigate climate fluctuations. This index utilizes differences in sea level pressure anomalies between locations of activity in the Hadley-Walker atmospheric circulation of the north Pacific, with large positive index values typically associated with La Niña events and large negative values associated with El Niño events (Schwing et al., 2002). Additionally, monthly surface wind (10 m) (SSW) data was collected from the U.S. Navy Fleet Numerical Meteorology and Oceanography Center (FNMOC), a dataset that tracks mean shifts in North-South and East-West directional winds, which potentially influence carcass drift and stranding incidence. An averaged value was calculated from measurements in a 10 km radius for each stranding event for SST, CHLA, NOI, and SSW.

Bathymetric measurements were obtained from the NOAA ETOPO1 database (NOAA National Geophysical Data Center, 2009) to investigate impacts of ocean depth on stranding locations, with a data extraction buffer radius of 5 km using the R package MARMAP (Amante and Eakins, 2009; Pante and Simon-Bouhet, 2013). Slope and aspect values were determined via analysis of the cells adjacent to the depth calculated at the location of each stranding.

Statistical Analysis of Environmental and Stranding Data:

We examined potential relationships between changes in environmental factors with seasonal and annual variations. To that end, we generated generalized additive models (GAMs) to evaluate seasonal changes (via month) over an 18-year time period (Hastie and Tibshirani, 1986). Stranding events were assumed to follow a Poisson distribution for modeling purposes, with cyclic cubic spline smoothing being utilized in the evaluation of monthly variation to account for seasonal cycles (Warlick et al., 2022). Spline smoothing was performed on SST, CHLA, NOI, and bathymetric environmental covariates slope and aspect to capture the flexible overall patterns for incorporation into the GAMs. Depth was not included in the analysis, due to many stranding event locations being documented above sea level with an above zero value. Tensor product smoothing was utilized in the evaluation of SSW, in order to capture the interactive, non-linear relationship between the North-South and East-West components of this covariate. Models were developed using the mgcv package in R statistical programming software (R Core Team, 2023; Woods, 2011).

GAMs for null and base models were developed to provide baseline insight into the impact of environmental covariates inclusion in evaluating stranding occurrences. Models were evaluated through comparison of Akaike's Information Criterion (AIC), which aids in selection of the simplest and most accurate model for interpretation of the data, between progressive permutation of GAMs (Akaike, 1973). From these comparisons, the best fit model was selected for evaluation of the significance of the environmental covariates.

RESULTS

Stranding Events Over Time and by Location and Species:

We examined a total of 535 stranding records for this study that spanned a time period of 176 years. Reliable records of cetacean strandings in the Mariana archipelago began in 1905, and data representing 54 stranding events from this region are included in this study (Table 1). The majority of the marine mammal strandings from the Mariana archipelago were recorded in Guam, with 40 total stranding events and 14 stranding events were reported from the Northern Mariana Islands, two from Rota, nine from Saipan, and three from Tinian. All but five stranding events involved single animals. A stranding of 80 sperm whales was reported from Saipan (Costenable, 1905 in Kami and Lujan, 1976), and three and four spinner dolphins, respectively, stranded in Saipan in 1995 in two separate events, although in the same location (Trianni and Kessler, 2002). A stranding of two to three goose-beaked whales was reported from Merizo, Guam, in 2015, and two goose-beaked whales that stranded in Saipan on two consecutive days in 2011 (Simonis et al., 2020; Table 1).

The earliest records in the Hawaiian Islands were of a large group of melon-headed whales in Hilo Bay in 1848 and a single stranded individual on Oʻahu in 1864. A total of 456 stranding events were recorded in the main Hawaiian Islands, and 25 stranding events were recorded in the Northwestern Hawaiian Islands, an island chain of mostly uninhabited atolls (Table 2). These strandings were comprised of 19 different species. The most populated island among the main Hawaiian Islands is Oʻahu, where 169 stranding events were reported in the 100-year period between 1923 and 2023. A total of 97 stranding events were reported from Maui, followed by 87 stranding events recorded from Hawaiʻi Island, 60 stranding events from Kauaʻi, 23 stranding events from Molokaʻi, 13 events from Lānaʻi, five stranding events from Kahoʻolawe and one stranding event from Niʻihau. Stranding events occurred offshore of the Hawaiian Islands (n=7) at a distance that resulted in these events not being associated with a specific shoreline location. This included a spotted dolphin (*Stenella attenuata*), a false killer whale (*Pseudorca crassidens*), a Risso's dolphin (*Grampus griseus*), and a rough-toothed dolphin (*Steno bredanensis*), where each individual was incidentally by-caught with the carcasses frozen on board a fishing vessel until later examination. Three additional events represented observations of floating dead sperm whale carcasses. The four events that describe the by-caught individuals occurred at great enough distances from the closest islands to not be grouped with the clusters located in the main or Northwestern Hawaiian Islands (Fig. 1a).

A total of 25 stranding events were reported in the Northwestern Hawaiian Islands (Table 2). Midway Atoll, an island in that region with a consistent human presence, had reports of 15 stranding events represented by four species, but reports from the large area of uninhabited atolls in the Northwestern Hawaiian Islands were sparse. Only three stranding events were reported from Laysan

Island, two from French Frigate Shoals, two from Pearl and Hermes Atoll, and one stranded animal each from Trig Island, Lisianski Island and Kure Atoll. Two of the stranding events reported in the Northwestern Hawaiian Islands involved more than one individual, an event involved two Blainville's beaked whales and a goose-beaked whale at Midway Atoll and another event that involved two goose-beaked whales at Pearl and Hermes Atoll.

Total reported stranding events in the Mariana and Hawaiian Islands increased over the time period examined (Fig. 2a; Fig. 3a). With the exception of historical reports in the Hawaiian Islands from the 1800's, we categorized total reported stranding events into each decade for a comparison of stranding frequencies over time. In the Mariana Islands (Fig. 2a), total reported stranding events increased in the 1990 to 1999 decade when compared to the decade 1980–1989. A significant increase in reports in the Mariana Islands occurred in 2000–2009 and then another significant increase in 2010 to 2019 with a drop in the current decade that represents only four years of a 10-year time period. In the Hawaiian Islands, stranding events steadily increased between 1950 and 2000 and then almost doubled between 2000 and 2009 in comparison to the earlier decades (Fig. 3a). There was a slight drop from the peak in total reported stranding events between 2010 and 2019 when compared to the current time period. However, the current decade only covers a four-year period (ended in 2023) and it is projected to be similar to or greater than the total stranding reporting levels in the two prior decades following the year 2000.

Stranded cetaceans in the Mariana Islands comprised 14 species, and spinner dolphins were the most commonly reported species with 11 stranding events. Other stranded dolphins included three stranding events involving pantropical spotted dolphins, one stranding of Fraser dolphins (*Lagenodelphis hosei*), two strandings of striped dolphins (*Stenella coeruleoalba*) and one stranding of a bottlenose dolphin (*Tursiops truncatus*). Goose-beaked whales were the second most stranded species, comprising nine of the ten stranded beaked whales in the dataset, in addition to a single beaked whale of an unidentified species that stranded on Guam. One stranding event of sperm whales occurred in Saipan, six stranding events involved sperm whales in Guam and one sperm whale carcass washed up in Tinian. Three stranding events were reported as pygmy sperm whales and five as dwarf sperm whales (*Kogia sima*). Four false killer whale stranding events were reported in the Mariana's archipelago. Two melon-headed whale stranding events were reported, as well as one stranding event involving each of pygmy killer whales (*Feresa attenuata*), short-finned pilot whales (*Globicephala macrorhynchus*) and killer whales (*Orcinus orca*) (Fig. 2a).

Reported odontocete stranding events in the Hawaiian archipelago include 19 species in the main Hawaiian Islands and five species in the Northwestern Hawaiian Islands, including Midway Island, Kure Atoll, Laysan Island, French Frigate Shoals and Pearl and Hermes Atoll (Table 2). Fig. 3b lists species recorded from strandings reported in the Hawaiian Islands. Spinner dolphins were the most common species that stranded in the Hawaiian Islands with 95 strandings reported. Other *Stenella* species that stranded included 50 stranding events represented by striped dolphins, 18 stranding events involving pantropical spotted dolphins and nine strandings of rough-toothed dolphins. Bottlenose dolphin stranding events were reported 23 times, Risso's dolphins nine times and Fraser dolphins five times. One historical stranding record listed a Pacific white-sided dolphin (*Lagenorhynchus obliquidens*). The most common beaked whale species that stranded were the goose-beaked whale with 15 stranding events, followed by Blainville's beaked whale (*Mesoplodon densirostris*) represented by 12 stranding events and a single Longman's beaked whale stranding. A total of 54 pygmy sperm whale stranding events and 15 dwarf sperm whale stranding events were reported in the Hawaiian Islands. An additional five strandings of the genus *Kogia* were reported where species could not be confirmed; therefore, all *Kogia* species strandings are grouped in Fig. 3b as "*Kogia* spp." Four killer whale stranding events were reported. Large whale reports included 51 sperm whale stranding events. Forty melon-headed whale stranding events were reported in the Hawaiian Islands, as well as 28 short-finned pilot whale stranding events. Ten pygmy killer whale stranding events were reported and 14 false killer whale stranding events. Species that represented stranding events where more than one animal was recorded included pygmy and dwarf sperm whales, short-finned pilot whales, pygmy sperm whales, melon-headed whales and Fraser's dolphins (Table 2).

Stranding Clusters:

We examined the spatial distribution of stranding events utilizing ArcGIS cluster maps of the Hawaiian and Mariana archipelagos (Fig. 1 and Fig. 4). The majority of events in the Mariana archipelago were documented on Guam, primarily along the west and southeastern coasts (Fig. 4b). Six events were reported as occurring on Guam without any location-specific data and are therefore depicted in the center of the island to not bias direction. Yona, Guam, was notable for having a high occurrence of strandings in a small region (three sperm whales and one spotted dolphin). Two events occurred in Songsong, Rota (Fig. 4a). Two events were documented on Tinian, and ten events were documented to have occurred along the western coast of Saipan (Fig. 4a).

We examined spatial distribution of strandings in the Hawaiian Islands (Fig. 1a-e). Clusters and points located in the center of islands indicate stranding events where the island location was available, but exact location was not documented. Kaua‘i had the highest number of stranding events along its north shore, with 19 occurring from the Nā Pali Coast to Kīlauea that included a cluster of 18 stranding events and a single stranding event. Eight stranding events were documented near Anahola, with another 14 strandings along the east coast, between Kalapaki Bay and Keālia Beach (Fig. 1b). Strandings occurred along the south and west shores of the island but in lower numbers, with seven near Po‘ipū and three near Port Allen. Six stranding events clustered on the west side of the island, between Waimea and Polihale State Park. A single stranding event that was represented by a dead floating sperm whale was documented off of Ni‘ihau (Fig. 1b).

On Oʻahu, 106 stranding events were reported on the windward side, with two clusters grouping 44 events near Kailua/Kāneʻohe in the east and 20 near Hawaiʻi Kai in the southeast. Strandings occurred in all areas, with 42 events between Pūpūkea and Kualoa on the north shore which showed two distinct cluster groupings, 18 events clustered near Haleʻiwa and 20 events clustered near Mākaha/Waiʻanae. A total of 14 strandings were clustered together that were reported from east Honolulu beaches (Fig. 1c).

Molokaʻi had documented stranding events along all coasts, with a cluster of 11 stranding events clustered on the north coast around the Kalaupapa Peninsula (Fig. 1d). On Maui, a cluster of 43 strandings occurred in Mā'alaea Bay, with another 27 stranding events clustered into two groups in other areas of the leeward coast. Strandings occurred along the windward coast of Maui between Kahakuloa and Pāʻia, with the majority centralized near Kahului in a cluster of 16 stranding events. Fewer stranding events were reported along the northeast coast and along the road to Hāna (Fig. 1d). Stranding events were only documented on the windward side of Lānaʻi, with the northeast coast being the dominant location for strandings in the two identified groups (Fig. 1d). Clustering diminished the resolution for Kahoʻolawe due to its small size, with three stranding events occurring at the northeast end and two events occurring at the southwest end (Fig. 1d).

On the big island of Hawai'i, the majority of strandings occurred on west facing shorelines, with a cluster of 27 stranding events identified between Kūkiʻo and Kealakekua Bays near Kailua/Kona and an additional 10 events clustering near Puakō, while nine stranding events clustered along the northern tip of the island (Fig. 1e). Thirteen stranding events were clustered around the southern point of the island, with seven of those events occurring at the tip itself near Kalalea Heiau.

A subset of strandings limited to the genus *Stenella* on Oʻahu were examined by location and species (Fig. 5). While all local species of this genus were documented on all sides of the island (Fig. 5a), spinner dolphin stranding clusters were dominant on the west and south shorelines of the island, compared to striped dolphin clusters that were only identified on the east side (Fig. 5b). Pantropical spotted dolphin strandings were reported from each end of the island, and scattered throughout, but the sample size was much smaller than for spinner dolphins and striped dolphins and thus did not present as the dominant species in a cluster group.

Statistical Analysis of Environmental and Stranding Data:

Environmental covariate data was extracted for 271 stranding events that occurred throughout the Hawaiian (n=244) and Mariana Islands (n=27) between 2003 and 2021. Generalized additive models (GAMs) were iterated for all stranding events combined (AE), as well as for all *Stenella* spp. stranding events (SE) (n=103), which were the largest group of animals by genera, and the best model was selected for covariate evaluation based on the lowest AIC value within all permutations of covariate combinations (Table 3).

The best fit model developed for analyzing AE found smooth effects between month, year, NOI, SST, CHLA, and tensor product smoothed SSW. This would suggest that strandings occur under conditions with lower chlorophyll-A concentrations, stronger trade and coastal upwelling winds, average to warm sea surface temperatures, and periods of stronger southwestern 10 m sea surface winds. This model explained 27.7% with the inclusion of environmental factors, an 11.3% increase over the base model alone. Bathymetric covariates did not appear to have relationship effects based on the AE best fit model.

Similarly, the best fit GAM for *Stenella* spp. found smooth effects between month, year, SST, CHLA, and tensor product smoothed SSW, but did not find NOI to have an effect on stranding occurrence. In addition, in the SE model, the additional covariate of slope has an influence on stranding patterns within this genus, with the majority of the documented *Stenella* strandings occurring in areas with slopes less than five degrees (n=83). The best model for SE had a much stronger explanation for deviance at 65.6% (base model = 54.4%).

In both the AE and SE GAMs, tensor smoothed SSW appears to be one of the most significant factors among the potential covariates tested in the developed models (AE and SE p-value<0.001), indicating that southwestern directed winds have a strong impact on the stranding of carcasses. Additionally, the smoothed year of stranding event was found to be a significant factor influencing stranding occurrence (AE and SE p-value<0.001). The year was variable between the two tested groups, with the number of strandings being highest for AE in 2016 (n=21) and lowest in 2017 (n=5), while SE strandings were highest in 2014 (n=11) and lowest in 2015 and 2018 (n=2 each year). Smoothed SST was also found to be significant for the SE model (p-value=0.01), if not as strongly as the other significant covariates. This indicates that there is a lesser, yet still significant, effect of average to elevated temperatures on stranding events.

DISCUSSION

We reviewed 535 stranding events occurring in the Hawaiian and Mariana Islands over a period that covered 176 years (1848-2023). Strandings of 19 different odontocete species were documented across the two archipelagos. The total number of strandings examined across the Pacific Islands is low considering both the extended time period and the expansive area covered in the current study, when compared to stranding analyses of other island locations, such as Sicily (4,880 events over 29 years) and Taiwan (453 events over 68 years) (Liu et al., 2022; Lo Brutto et al., 2021). These findings likely reflect the isolation of both the Hawaiian and Mariana archipelagos, with uninhabited islands and the relatively small human population size on the islands that are inhabited with the exception of the island of Oʻahu. Documentation of stranding reports relies heavily on public reporting, and prior studies have demonstrated a relationship between human population density and the number of reported cetacean strandings (Faerber and Baird, 2010; Maldini et al., 2005). This is further supported by the current study, with the highest stranding reports by occurrence in the Hawaiian archipelago from the island of Oʻahu (35% of stranding reports), where 68% of the human population in the state of Hawaiʻi resides. Mariana Islands strandings were also most frequently reported from Guam (74% of stranding reports), which hosts a strong military presence and has a high human population. A greater number of historical records were recorded for the main Hawaiian Islands (456 stranding events) than the 25 stranding events documented in the Northwestern Hawaiian Islands. The stranding reports from the Northwestern Hawaiian Islands, which generally are not inhabited year-round, are largely due to an impressive effort by scientists, especially those studying Hawaiian monk seals (*Neomonachus schauinslandi*), to obtain stranding data in the Northwestern Hawaiian Islands since the start of field expeditions in the 1960s. In contrast, no stranding data was obtained from uninhabited islands in the Mariana Islands nor from the islands of Agrihan, Pagan, Alamagan and Anatahan that have been sparsely or intermittently populated since World War II (Trianni and Tenorio, 2012).

We report on a total of 54 stranding events from the Mariana Islands, with 40 of the stranding reports from the island of Guam. Prior published reports of Guam strandings include an initial description of the earliest Guam stranding of an albino sperm whale in 1962 and two dwarf sperm whales that stranded in 1970 and 1974 (Kami and Lujan, 1976). Three additional strandings in Guam in 1980 and 1981 add reports of a melon-headed whale, pilot whale and killer whale stranding (Kami and Hosmer, 1982). Further Guam strandings of another dwarf sperm whale, pygmy sperm whale and striped dolphin were also reported (Eldredge, 2003). The first published report examining goose-beaked whales and the spatial temporal relationship to military training activities described eight stranding events between 2006 and 2019 in the Mariana Islands, with seven of the eight events occurring on Guam (Simonis et al., 2020). The prior scientific literature from Guam cumulatively describes eight odontocete species that stranded over 16 stranding events. In the current study, we provide the first compilation of the historical literature from Guam that is combined with 24 additional stranding events that include the first reports of strandings of five additional odontocete species (spinner dolphin, false killer whale, bottlenose dolphin, Fraser's dolphin, spotted dolphin) in Guam.

In the Northern Mariana Islands, published stranding records include descriptions of three spinner dolphin stranding events in 1995 (Trianni and Kessler, 2002) and two additional spinner dolphin stranding events, a striped dolphin, a false killer whale, a dwarf sperm whale and a pygmy sperm whale stranding all from Saipan (Trianni and Tenorio, 2012). There is also a description of a 1905 assisted stranding of 80 sperm whales in Saipan that were consumed as food that are speculated to have been misidentified in the historical description and may possibly represent a species of dolphin (Costenable, 1905). A goose-beaked whale mass stranding of two individuals on Saipan is included in Simonis et al. 2020. In our compilation of historical stranding records in the current study, we report on five additional stranding events from across Tinian, Rota and Saipan with the addition of striped dolphins to the species known to strand in the Northern Mariana Islands.

Our review of historical strandings included 481 stranding events in the main Hawaiian Islands that date back to 1848 and extend until the end of calendar year 2023. Stranding records that comprised 98 historical events in the Hawaiian Islands have previously been reported on by Nitta et al. (1991), with the last update including 202 odontocete records from the main Hawaiian Islands that covered a time span of 1950 to 2002 (Maldini et al., 2005). We provide 20 further years of stranding data collected from the main Hawaiian Islands and include 25 additional records of stranding events occurring in the Northwestern Hawaiian Islands, those occurring before 2003 were not considered by Maldini et al. (2005). In total, we added 279 additional stranding events to the examination of stranding patterns in the Hawaiian Islands from the last published report. This represents the most recent and complete compilation of stranding records to our knowledge from the Hawaiian archipelago.

The current study conducted stranding analysis of the dataset that was similar to the smaller sample size examined by Maldini et al. (2005), where strandings are reported by species and location based on the total occurrence of events. Both the current study and Maldini et al. (2005) reported the same top four species with the highest stranding frequency, but the proportion of strandings by species and the rank order differed. We found spinner dolphins to have the highest stranding frequency among species in the Hawaiian Islands (19.8%) with *Kogia* spp. as the second most commonly stranded genera (18%) where Maldini et al. (2005) reported *Kogia* spp. as the most commonly stranded genera (18%) and spinner dolphins as the second most common (15%). Striped dolphins and sperm whales were the third and fourth most commonly stranded species in both studies (although in reversed rank order), where percentages were almost identical between the species and studies (10–11%). The current study reports on 19 stranded odontocete species in the Hawaiian Islands, where the earlier Maldini et al. (2005) study does not include a 1976 stranding of a Pacific white-sided dolphin calf that may have been misidentified at the time of examination that was included in the current study. Additionally, the first Longman's beaked whale *(Indopacetus pacificus)* stranding in Hawai‘i occurred in 2010 (West et al., 2013) and is included in our stranding analysis. Our stranding data set of increased sample size indicated slight differences in stranding occurrences by island compared to Maldini et al. (2005). Specifically, we found lower stranding frequency on O‘ahu at 35% of stranding occurrences compared to 48% in Maldini et al. (2005). Grouping Maui and Lāna‘i together, the island of Moloka‘i and the island of Kaua‘i each indicated very similar stranding frequencies between the two studies.

Reports of stranding events progressively increased over time in both the Mariana Islands and in the Hawaiian Islands. In the first decade of the 2000s, stranding reports increased significantly in both island archipelagos compared to stranding data obtained during the decades spanning the late 1800's to 2000. Stranding reports continued to increase during the 2010 to 2019 decade in both archipelagos and although stranding events appear to drop in the current decade, this only represents four years (2020 through 2023) and at current stranding rates, they are projected to exceed the number of stranding events reported previously in earlier decades in both locations.

The formation of stranding networks and advanced training of wildlife personnel and volunteers has contributed to increased reporting of strandings over the last several decades from other locations across the globe (Evans et al., 2005; Norman et al., 2004; Coombs et al., 2019) and we anticipate that this is also the case in the Mariana and Hawaiian Islands. Increased strandings reported in Australia were attributed to improved reporting secondary to development of stranding networks and numbers of observers (Evans et al., 2005). It is likely that exponential advances in access to information through the internet and rapid long-distance communications have resulted in increased interest in stranding events when they occur and a higher probability of events being documented and recorded as of the 2000's, when total stranding reports increased significantly in the NOAA Fisheries Pacific Island region that includes the Hawaiian and Mariana Islands. Specifically, increased capacity in Hawaiʻi to support U.S. Pacific Island territories and outlying islands began in 2006 to include stranding response training, rapid communication during stranding events, sampling guidance, shipping of tissues and follow-up analysis, which likely contributed directly to the increase in total stranding reports observed in the Pacific Islands after the year 2000.

Our efforts to generate best fit models of a subset of stranding data from 2003 to 2021 were based on availability of environmental data in conjunction with the ability to better represent day of death through an examination of photographs and tissue quality from strandings. Month and year were included in the stranding event examination as model parameters. Month of stranding was not found to be significant for either the grouped total stranding events examined across both the Hawaiian and Mariana Islands, nor for the subset of *Stenella* spp. strandings examined from the Hawaiian Islands, which suggests that seasonality at the resolution of monthly does not influence stranding patterns in the region. However, year was significant for both the total strandings examined and for the subset of

Stenella spp. strandings in our best fit models and is in agreement with the importance of time as a factor in examining stranding patterns in the region. In the case of the best fit models, specific years with increased stranding reports were identified in both the total stranding data set (2014) and the *Stenella* spp. subset of data (2016). The *Stenella* spp. subset of data also identified sea surface temperature as a significant factor, with average to warmer temperatures being correlated with increased stranding events, but this relationship was not apparent in the total stranding data set and warrants further investigation considering anticipated impacts to marine mammals as a result of climate change (Gulland et al., 2022).

Analysis of cetacean stranding patterns in other regions has investigated environmental factors as they may specifically relate to strandings, including ocean temperature, chlorophyll status, surface winds and bathymetry (Warlick et al., 2022; Johnston et al., 2012; Soulen et al., 2013; Truchon et al., 2013; Evans et al., 2022; Berini, 2015). Large-scale climate processes are now assessed using environmental data and result in an understanding of oceanic conditions during La Niña and El Niño events where data can be examined in relation to marine mammal mortality. We examined potential correlations between ocean surface temperature, surface winds, chlorophyll density and estimated date of death by stranding location and the total number of stranding events reported from the Mariana and Hawaiʻi archipelagos between 2003 and 2021. An additive statistical model showed significant correlation between sea surface winds and year and all stranding events. For the Hawaiian Islands, an analysis of stranding data limited to historical *Stenella* spp. stranding events on the island of Oʻahu (n=85) and environmental parameters demonstrated the significance of year, sea surface winds and sea surface temperature. Sea surface winds were highly significant, whether examined in relation to total strandings grouped together across the Hawaiian and Mariana archipelagos or on the limited scale of *Stenella* spp. stranding events on the island of Oʻahu. We do not know if the significance of sea surface winds driving carcasses washing ashore that was evident in our best fit models would be lost with smaller sample sizes that would result if the data were further broken down by island archipelagos/locations and/or by other species or species groups.

Upper ocean circulation is predominantly formed by wind stress (Pickard and Emergy, 1990). The Hawaiian Island chain transects the southernmost part of the North Pacific convergence zone of the Northern Equatorial Current (NEC) flowing westward. The NEC splits at Hawaiʻi island and forms the Northern Hawaiian Ridge current northwestward along the eastern side of the island chain and continues to the southwest around South Point of Hawaiʻi Island. The Hawaiian lee counter current from east to west splits and circulates on the leeward sides of the island chain northward and southward. Surface ocean currents combined with windshear from the mountain ranges of the islands result in formation of multiple eddies and varying local conditions (Trujillo et al., 2018; Jia et al., 2011). Cetaceans that die in these areas would be generally carried towards leeward shores, consistent with clusters of strandings in Maui between Kahakuloa and Pāʻia, in Hawaiʻi Island between Kūkiʻo and Kealakekua Bays near Kailua/Kona and on the leeward coast of Oʻahu.

Larger marine debris is carried by surface ocean currents and pushed by surface winds. Coastal marine debris has been mapped to beaches in the major Hawaiian Islands, where there are concentrations of washed-up marine debris in specific areas that have been identified despite marine debris found throughout all islands and on all coasts. Larger pieces of marine debris are likely to mimic movement of marine mammal carcasses, and there is some overlap of marine debris collection sites and stranding clusters. (Fig. 1, Moy et al. 2018). Stranding clusters and areas of marine debris overlap on Oʻahu's north shore, near the south point of Hawai'i Island, the northern and eastern shores of Kauaʻi, Kalaupapa peninsula in Molokaʻi and the windward side of Lānaʻi. However, in Maui, the majority of strandings occurred on the leeward coast (72 strandings), and 16 strandings were recorded on the northeast coast, the location with the highest accumulation of larger marine debris. Local eddies where animals die at sea, the shallower depths on the western side of the island, or preferred habitat may be factors influencing the frequency of strandings in Maui, where marine debris washed ashore is generally low but stranding events are commonly reported.

The Hawaiian archipelago experienced a weakening of traditionally strong and consistent north-east trade winds over the course of several decades leading up to 2009, while during that same time period the island chain had an increase in the frequency of winds from the easterly direction (Garza, 2012). Southern and southwest onshore winds prevail when storm systems approach the island chain from the northwest, predominantly during the winter months or when tropical storm systems move past the islands chain to the south. The majority of strandings of *Stenella* spp. occurred along coastlines perpendicular to northeastern trade winds and southwestern Kona winds (Fig. 5a). This supports the idea that strong onshore SSW would result in the stranding of floating carcasses as they encounter increasing surf that aids in pushing them towards shore, rather than where shoreline runs parallel to the typical wind direction on O'ahu, causing animals to move past the island rather than towards it. Evans et al. (2022) found increased stranding events of cetaceans during times of persistent zonal and meridional winds in southern Australia, where winds drove colder and nutrient rich waters towards the coast during spring months resulting in higher biological activity. A study of pygmy sperm whale strandings along the east coast of the United States showed an increased likelihood of a stranding after periods of high wind speed, low barometric pressure and high swell waves (Berini, 2015).

This study demonstrates the value of detailed stranding reports in investigating odontocete biogeography, distribution and causes contributing to stranding events that can be applied beyond the Pacific Islands. The current study provides an example of the type of biological data that can be collected from stranding investigations in isolated and/or remote archipelagos when strong communication, rapid real-time support during events, shipping of tissues and follow-on analysis is available, as Hawai'i has served as an investigative hub for many of the strandings that occurred in the Hawaiian and Mariana Islands since 2006. We recommend increased support for detailed future stranding investigations that includes maintaining and strengthening capacity for stranding responses in the Pacific Island region where much remains to be learned. The high value of stranding reports and necropsy to better understand cetacean distribution, life history and the threats that these protected species face is globally well-recognized. This is reflected in initial efforts by several international entities (i.e. International Whaling Commission Stranding Initiative, Global Stranding Network, South Pacific Regional Environmental Programme) to increase training, collaboration, coordination and the science gained from stranding events occurring world-wide.

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