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Cover: A humpback whale flukes with the NOAA Ship *Oscar Elton Sette* in the background. Photo by Andrea Bendlin, Pacific Islands Fisheries Science Center, National Marine Fisheries Service (Permit No. 20311).

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Abstract

Twenty-four cetacean species (18 odontocetes and 6 mysticetes) regularly occur in the waters around the Hawaiian Islands. Abundance estimates are needed to evaluate the impacts of human activities on these species in population assessments and management plans. Most ship-based, line-transect surveys for cetaceans in Hawaiian waters have occurred during the summer−fall period, including the recurring Hawaiian Islands Cetacean and Ecosystem Assessment Survey (HICEAS) that took place in 2002, 2010, and 2017. There are no recent abundance estimates of cetaceans in Hawaiian waters during winter, when seasonally-migrating baleen whales are at peak abundance. A winter HICEAS (WHICEAS) was conducted in Jan−Mar 2020 to estimate the abundance and distribution of cetaceans around the main Hawaiian Islands during winter. An established multiple-covariate approach, which involves pooling data from previous line-transect surveys to estimate detection functions and using trackline detection probabilities that consider the effect of survey sighting conditions, was used to produce design-based abundance estimates for 17 species (14 odontocetes and 3 mysticetes). Across all species, abundance point estimates range from 115 fin whales to 26,627 melon-headed whales. Low encounter rates led to high CVs (range=0.40−1.06) for most estimates and low statistical power to detect seasonal trends in abundance for 9 odontocete species sighted around the main Hawaiian Islands during both HICEAS 2017 and WHICEAS 2020. Only the paired sperm whale estimates had non-overlapping 95% confidence intervals, suggesting a significant increase in abundance within the study area in winter 2020 compared to summer−fall 2017, but random variation in the encounter rate may be a contributing factor. The WHICEAS 2020 estimates are of the pelagic populations for species where both pelagic and insular populations are recognized, although the abundance of three island-associated populations (Hawai‘i Island pantropical spotted dolphins and Kaua‘i/Ni‘ihau spinner and common bottlenose dolphins) was estimated using the limited data available as a proof of concept. This study represents the first multi-species assessment of winter abundance around the main Hawaiian Islands. Model-based density estimation incorporating the WHICEAS 2020 data provides finer-scale seasonal and spatial inference for 9 species (8 odontocetes and humpback whales). Additional winter survey effort beyond the main Hawaiian Islands and other types of data collection (e.g., satellite tagging) may be needed to more fully evaluate seasonal differences in the abundance and distribution of cetaceans in Hawaiian waters.

Introduction

The waters surrounding the Hawaiian Islands support the regular occurrence of 24 cetacean species, including 18 odontocetes and 6 mysticetes. Early work on cetaceans around the main Hawaiian Islands focused on spinner dolphins (*Stenella longirostris*) (e.g., Norris and Dahl 1980) and humpback whales (*Megaptera novaeangliae*) (e.g., Herman and Antinoja 1977) because of their distributions in shallow waters close to shore (during winter months in the case of the seasonally-migrating humpback whale). While earlier efforts, which were largely conducted from land-based and small-boat platforms, occasionally generated information on less accessible species such as pygmy killer whales (*Feresa attenuata*) (e.g., Pryor et al. 1965), small-boat surveys for a wider variety of cetacean species in main Hawaiian Islands waters were not consistently conducted until 2000 (e.g., Baird et al. 2013). These ongoing surveys regularly include deeper waters farther from shore inhabited by a number of odontocete species, although they are generally confined to nearshore waters on the leeward sides of islands where sea conditions are workable. Collectively, these efforts have provided important insights into the occurrence, distribution, population structure, abundance, and social organization of cetaceans, particularly of island-associated odontocete populations (e.g., Baird et al. 2022) and humpback whales (e.g., Pack et al. 2017), in the nearshore waters of the main Hawaiian Islands.

Within the broader U.S. Hawaiian Islands Exclusive Economic Zone (EEZ), 39 populations of cetacean species are currently recognized in the Stock Assessment Reports (SARs) mandated by the U.S. Marine Mammal Protection Act for marine mammal populations in U.S. waters (Carretta et al. 2021). Island-associated populations have been differentiated for 5 odontocete species (Carretta et al. 2021), and putative insular populations have been established for at least 6 more (Albertson et al. 2017; Baird 2016; Oleson et al. 2013; Van Cise et al. 2017). Of the mysticete species that regularly occur in Hawaiian waters, only humpback whales demonstrate a strong island association. Although island processes clearly exert a strong influence on the occurrence and distribution of cetacean populations in the Hawaiian Islands EEZ (e.g., Abecassis et al. 2015; Woodworth et al. 2012), each species includes a population that spends some part or most of its time in pelagic waters. Concerted efforts that included offshore waters of the Hawaiian Islands began in 2002, when the first Hawaiian Islands Cetacean and Ecosystem Assessment Survey (HICEAS) was carried out by the NOAA Fisheries Southwest Fisheries Science Center (SWFSC) (Barlow 2006). The HICEAS is a recurring ship-based, line-transect survey designed to estimate cetacean abundance in the entirety of the Hawaiian Islands EEZ. To date, the HICEAS has been conducted a total of three times, with the latter two efforts occurring in 2010 and 2017 as a collaborative effort between the SWFSC and the Pacific Islands Fisheries Science Center (PIFSC) (Bradford et al. 2017; Yano et al. 2018).

Abundance estimates are needed to evaluate the impacts of human activities on cetacean populations and are an important component of the SARs and management plans. The HICEAS of 2002, 2010, and 2017 resulted in design-based abundance estimates of 21 (18 odontocete and 3 mysticetes), 19 (15 odontocetes and 4 mysticetes), and 18 (15 odontocetes and 3 mysticetes) cetacean species, respectively (Bradford et al. 2021), and model-based estimates of 9 (8 odontocetes and 1 mysticete) species (Becker et al. 2021). Given the broad spatial survey coverage of each HICEAS and the related lack of sightings from insular populations, these estimates are of the pelagic populations for species where both are differentiated, with the exception of the design-based estimates for the Northwestern Hawaiian Islands population of false killer whales (*Pseudorca crassidens*) (Bradford et al. 2020) and the model-based estimates of pantropical spotted dolphins (*Stenella attenuata*) and common bottlenose dolphins (*Tursiops truncatus*), which are based on sightings from both the pelagic and insular populations (Becker et al. 2021). Small-boat surveys in the nearshore waters of the main Hawaiian Islands have generated longitudinal photo-identification datasets that have been used to produce mark-recapture abundance estimates for island-associated populations of several species, including melon-headed whales (*Peponocephala electra*) from 2002 to 2009 (Aschettino 2010), spinner dolphins from 2002 to 2007 (Hill et al. 2011) and 2011 to 2012 (Tyne et al. 2016), false killer whales from 2000 to 2015 (Bradford et al. 2018), and bottlenose dolphins from 2000 to 2018 (Van Cise et al. 2021). Line-transect data from aerial surveys and photo-identification data from small boat surveys were used to make design-based abundance estimates from 1993 to 2003 (Mobley 2004) and mark-recapture abundance estimates from 2004 to 2006 (Calambokidis et al. 2008), respectively, for humpback whales.

Most ship-based, line-transect surveys for cetaceans in Hawaiian waters, including the HICEAS of 2002, 2010, and 2017, have occurred during the summer−fall period when sea conditions are most conducive to visual survey effort. Thus, the resulting estimates reflect the abundance of cetaceans in the Hawaiian Islands EEZ during that time. The mark-recapture estimates for the various island-associated odontocete populations represent annual abundance and are not specific to a season. The previous abundance estimates for humpback whales are from winter, although those estimates are now outdated. Overall, there are no recent abundance estimates of cetaceans in Hawaiian waters during winter, when the abundance of seasonally-migrating mysticetes is at its peak (e.g., Mobley 2004). Therefore, a winter HICEAS (WHICEAS) was conducted in Jan−Mar 2020 to estimate the abundance and distribution of cetaceans around the main Hawaiian Islands during winter (Yano et al. 2020). Like HICEAS 2017, WHICEAS 2020 was conducted as part of the Pacific Marine Assessment Program for Protected Species (PacMAPPS), a collaborative effort between NOAA Fisheries, the U.S. Navy, and the Bureau of Ocean Energy Management to support ship surveys and estimate cetacean abundance in regions of joint interest. Although WHICEAS 2020 did not span the Hawaiian Islands EEZ and instead focused on the main Hawaiian Islands, the survey was designed to collect data on both pelagic and insular populations, including island-associated populations of pantropical spotted dolphins, for which photo-identification work has been too limited to support mark-recapture estimation (Baird and Webster 2020).

This paper presents design-based, line-transect abundance estimates of cetaceans sighted around the main Hawaiian Islands during WHICEAS 2020. A desirable property of design-based abundance estimates is that they should be unbiased (Thomas et al. 2007). However, these estimates are derived from a single estimate of average density for the study area, whereas management plans often require spatially-explicit density estimates at finer spatial scales (Redfern et al. 2017). Model-based line-transect methods estimate density as a function of habitat or spatial covariates so that abundance can be estimated at spatial scales relevant to management (Hedley and Buckland 2004) and have generally become the preferred way to analyze cetacean line-transect data (Bouchet et al. 2019). Updated model-based abundance estimation incorporating data from WHICEAS 2020 was pursued for 9 cetacean species (7 odontocetes and 2 mysticetes) (Becker et al. 2022). Design-based estimates can serve as useful points of comparison to model-based estimates (Thomas et al. 2007). Additionally, sample sizes do not permit the use of a model-based approach for all species sighted, so design-based estimates are needed for the remaining species. To evaluate potential seasonal differences in cetacean abundance between winter and summer-fall, estimates were also generated using a subset of HICEAS 2017 data collected within the WHICEAS study area, acknowledging that interannual variation in distribution and abundance could be a confounding factor. While the abundance of seasonally-migrating baleen whales was expected to be higher in winter, differences in the abundance of most odontocete species were considered unlikely based on findings from previous studies of cetacean occurrence (e.g., Baird et al. 2013) around the main Hawaiian Islands.

Methods

Data Collection

The design and execution of WHICEAS 2020 is described in detail in Yano et al. (2020). Briefly, WHICEAS 2020 was conducted aboard the 68-m NOAA research vessel *Oscar Elton Sette*, which surveyed the study area from 18 January to 12 March 2020. The study area was defined as a convex hull around a 100-nmi (185.2-km) radius of the main Hawaiian Islands, which was truncated at the easternmost edge of the Papahānaumokuākea Marine National Monument (Figure 1). The systematic survey design consisted of parallel transect lines spaced 46 km apart and oriented WNW to ESE, providing comprehensive coverage of the study area. An additional fine-scale survey grid was established to allow for more intensive coverage of the nearshore areas used by island-associated populations (Yano et al. 2020). This grid included additional WNW−ESE transect lines placed halfway between the main lines in all nearshore areas along with NNW−SSE lines spaced 18.5 km apart around the islands of Kaua‘i, Ni‘ihau, and Hawai‘i. Although HICEAS 2017 data collected within the WHICEAS study area were reanalyzed for the purposes of seasonal comparisons (Figure 1A), the corresponding design details of HICEAS 2017 are well-documented elsewhere (Bradford et al. 2020; Bradford et al. 2021; Yano et al. 2018) and thus not reiterated here.

Otherwise, the implementation of WHICEAS 2020 was consistent with that of HICEAS 2017. The ship surveyed the study area at a speed of 10 kt (18.5 km/h). In addition to the systematic effort on established design-based transect lines, the team of visual observers remained on-effort and followed standard observation protocols when the vessel transited to and from ports, between transect lines, and during other survey-specific activities (e.g., deploying and retrieving drifting acoustic recorders). This nonsystematic effort was differentiated from off-effort periods when the observers were not following standard observation protocols (e.g., after sighting a cetacean or during inclement weather). Cetacean sightings made during nonsystematic effort and while off-effort were not used to estimate cetacean abundance because those sightings were not detected on the established transect lines. However, given that the same observation protocols were in place during all on-effort periods, sightings made during nonsystematic effort were used to estimate detection functions.

The SWFSC and PIFSC have been using consistent observation protocols (Kinzey et al. 2000) to collect cetacean data on line-transect surveys throughout the Pacific Ocean since 1986 and 2009, respectively. Visual observation teams comprised 6 observers who rotated through 3 positions while searching for cetaceans from the flying bridge of the ship. The observers searched from 90° left to 90° right forward of the vessel, with the port and starboard observer each using 25× binoculars, and the center data recorder using unaided eyes. When an observer sighted a cetacean group, the initial bearing and radial distance to the group were recorded and used to compute the perpendicular distance from the sighting to the ship's trackline. If the sighting was within a strip width of 3 nmi (5.6 km) from the trackline, the observers suspended search effort, and the ship diverted from the trackline toward the group so that species, species composition (for mixed-species groups), and group size (recorded as an independent "best," high, and low estimate for each observer) could be determined (Kinzey et al. 2000). This "closing mode" survey effort predominated, although high densities of humpback whales in some areas during WHICEAS 2020 required the use of 'passing mode' effort, such that the ship remained on the trackline following a sighting. Environmental data, including Beaufort sea state, were also collected for each sighting. For some sightings, photos were taken from the ship to confirm species identification or to document rare species or interesting behavior. Once group size estimates were obtained, and if animal behavior and weather conditions allowed, a small boat was launched from the ship for some sightings to collect photo-identification images and biopsy samples of individuals in the group.

The species of some sightings could not be identified. In those cases, the lowest possible taxonomic category was applied (Table 1). As with HICEAS 2017, an acoustics team worked independently of the visual observation team during WHICEAS 2020, detecting cetacean vocalizations from a hydrophone array towed behind the ship during daylight hours. The observers were not alerted to acoustic detections, and these detections were not incorporated in the abundance estimation. However, sightings that were not identified to species were compared to the species classification results from simultaneous acoustic detections (if available) to gain possible insights into species identification.

Abundance Estimation

Cetacean abundance in the WHICEAS study area was estimated using the multiple-covariate line-transect methods (Buckland et al. 2001; Marques and Buckland 2004) that have previously been used to estimate the abundance of cetaceans in the Hawaiian Islands EEZ (Barlow 2006; Bradford et al. 2017; Bradford et al. 2021). In summary, given the low encounter rates of cetaceans in Hawaiian waters, sample sizes for each sighted species were insufficient for estimating detection functions. Therefore, systematic- and nonsystematic-effort sightings were pooled with on-effort sightings made during other SWFSC and PIFSC line-transect surveys since 1986. The pooled sightings were limited to the central Pacific (defined as the area from 5°S to 40°N, and from 175°E to 120°W) to minimize heterogeneity resulting from geographical differences in species behavior and associations. Even with pooling sightings across surveys, sample sizes for many species were still inadequate for estimating a detection function. Thus, sightings of species with similar detection characteristics were combined using the same multi-species pools established in Bradford et al. (2017) and updated in Bradford et al. (2021). An additional pool was formed for humpback whales, who have been excluded from previous abundance estimations because of insufficient coverage of nearshore areas during each HICEAS.

After truncating the 5−10% most distant sightings in each species pool to improve model fit (Buckland et al. 2001), a half-normal model (with no adjustments) was used to estimate detection probability as a function of perpendicular distance from the trackline and of relevant covariates. Half-normal models were used because of their greater stability when fitting cetacean sightings data (Gerrodette and Forcada 2005). The following covariates were evaluated: *Beaufort* (Beaufort sea state), *group size* (the natural logarithm of the sighting group size, which includes the total number of individuals in mixed-species groups), *cruise number* (the number assigned to each survey on a given ship in a given year), *ship* (the survey ship), *year* (the survey year), and *species* (the most abundant species within a group). *Beaufort* and *group size* were incorporated as continuous variables, and the other covariates as categorical variables, which were tested only when there were at least 10 observations per factor level. Covariate models were built using a forward stepwise procedure, and the best-fit models were selected using Akaike's information criterion corrected for small sample size (AICc; Hurvich and Tsai 1989).

Individual observers tend to underestimate cetacean group sizes (e.g., Gerrodette et al. 2019), so correction factors were applied to the "best" estimates of sighting group size made by observers who were calibrated during previous SWFSC surveys (Gerrodette and Forcada 2005). Non-calibrated observers were calibrated relative to the calibrated observers using an indirect regression-based calibration method (Barlow 1995; Barlow and Forney 2007). The sighting group size then used to model the detection function was the weighted geometric mean of the calibrated group size estimates made by each observer (weighted by the inverse of the mean squared estimation error). For mixed-species sightings, the sighting group size was multiplied by the proportion of each species present (averaged over all observers) to calculate the number of individuals by species as needed to estimate density. For mixed-species sightings in which the most abundant species was not one of the pooled species, the factor level for the *species* covariate was labeled as "other" to account for the collective influence of non-pooled species when estimating the detection function (Table 2). If there were too few "other" sightings to test the *species* covariate within a multi-species pool, the set of "other" sightings was inspected more closely. If the set of sightings was deemed unnecessary for detection function estimation (e.g., sightings were made outside the study area or while on nonsystematic effort), the set was removed from the pool so that a species effect could be tested (Table 2).

The estimated covariate detection function and the systematic-effort sightings within the established truncation distance were used within a Horvitz-Thompson-like estimator (Marques and Buckland 2004) to estimate the density (D) of each species in the WHICEAS study area in winter 2020 and in summer−fall 2017:

$$D = \frac{1}{2 \cdot L \cdot g(0)} \sum_{j=1}^{N} f(0, \boldsymbol{c}_j) \cdot s_j \tag{1}$$

Where:

- L is the length of the systematic-effort transect lines completed in the study area;
- $g(0)$ is the probability of detection on the trackline (i.e., perpendicular distance = 0);
- N is the number of systematic-effort sightings of the species within the truncation distance;
- $f(0,\boldsymbol{c}_j)$ is the probability density of the detection function evaluated at zero distance for sighting j with associated covariates $\boldsymbol{c}$; and
- s_j is the number of individuals of the species in the sighting (i.e., species group size).

The value of $f(0,\boldsymbol{c}_j)$ incorporated was a weighted average of all covariate models within 2 AICc units of the best-fit model. Hereafter, $f(0,\boldsymbol{c}_j)$ is referred to by its inverse, the effective strip width (*ESW*), which is the distance from the trackline beyond which as many sightings were detected as were missed within.

The $g(0)$ estimates used in the density estimation were derived from Beaufort-specific estimates of $g(0)$ (Barlow 2015). The relative values of $g(0)$ reported in Barlow (2015) were assumed to be absolute values (i.e., $g(0) = 1$ in Beaufort sea state 0) for all sighted taxa, with the exception of *Mesoplodon* and *Kogia* spp., for which Barlow (2015) provides scaled absolute values of Beaufort-specific $g(0)$ that account for availability bias at low Beaufort sea states. Not all species occurring in Hawaiian waters were covered in Barlow (2015) because of insufficient sample sizes. The Barlow (2015) approach was used with additional data to estimate relative values of

Beaufort-specific *g*(0) for pygmy killer whales (Bradford et al. 2021). For the remaining species, the Beaufort-specific *g*(0) estimates of an associated species in the detection function multi-species pools were used as a proxy following Bradford et al. (2017). Single estimates of *g*(0) for each species in each year were obtained by taking a weighted average of the Beaufort-specific *g*(0) values from Barlow (2015), where the weights were the proportion of systematic effort in each Beaufort sea state category (0-6) within the WHICEAS study area. The coefficient of variation (CV) for each *g*(0) weighted average was computed via the Monte Carlo method applied in Moore and Barlow (2017), which uses a simple exponential function to approximate the relative *g*(0) values and associated CVs from Barlow (2015) and accounts for the lack of independence in the Beaufort-specific *g*(0) values.

The abundance of the relevant population for each species was calculated by multiplying the density estimate by the area of the WHICEAS study area minus the area of the land masses of the main Hawaiian Islands (Table A1). However, the ranges of the pelagic populations of pantropical spotted and common bottlenose dolphins are not considered to overlap with the respective island-associated populations of each species (Carretta et al. 2021). Therefore, the area of the insular population boundaries was subtracted from the larger area for the pelagic populations of these species (Table A1). The fine-scale survey grid designed for WHICEAS 2020 was largely unrealized due to poor weather conditions and the prioritization of the broad-scale transect lines (Yano et al. 2020). Thus, instead of considering the fine-scale effort as systematic and conducting a stratified analysis (i.e., estimating density in both the fine-scale effort stratum and the broader study area), the fine-scale effort was treated as nonsystematic in the abundance estimation (i.e., systematic survey effort was unstratified and thus uniform throughout the study area). However, a small amount of fine-scale survey effort was made within the boundaries of the Hawaiʻi Island pantropical spotted dolphin population and the Kauaʻi/Niʻihau spinner and common bottlenose dolphin populations (Yano et al. 2020), and population-specific sightings were made within these boundaries (Table 1). Thus, the abundance of these three populations was estimated as a means of evaluating the performance of the design-based estimator given limited data for an island-associated population. The estimation followed the aforementioned approach except that the study area was restricted to the boundary of each population (Table A1, Figure 2), and the fine-scale effort within was treated as systematic. Stratification was not necessary given the overlap of the fine-scale grid and the Kauaʻi/Niʻihau spinner and common bottlenose dolphin populations, but was required for the Hawaiʻi Island pantropical spotted dolphin population because its boundary extends beyond the fine-scale grid (Yano et al. 2020).

Abundance estimates were also generated for unidentified cetaceans encountered in the study area, including unidentified *Mesoplodon* spp.; unidentified beaked whales; rorquals identified as sei (*Balaenoptera borealis*) or Bryde's (*B. edeni*) whales; rorquals identified as fin (*B. physalus*), sei, or Bryde's whales; unidentified rorquals; unidentified small, medium, and large dolphins; unidentified dolphins; unidentified small and large whales; unidentified whales; and unidentified cetaceans (Table 1). Sightings of unidentified small, medium, and large dolphins and unidentified dolphins were combined into a single category of "unidentified dolphins" in the estimation. Similarly, sightings of unidentified small and large whales and unidentified whales and cetaceans were combined into an "unidentified cetaceans" category. Estimating the detection function and g(0) for each unidentified species category followed the approach established in Bradford et al. (2017) and updated in Bradford et al. (2021). However, those studies did not include sightings of rorquals identified as fin, sei, or Bryde's whales. In the present analysis, such sightings were pooled with associated species for modeling the detection function (Table 2), and the g(0) estimate for this category was an average of the estimates for fin whales and sei or Bryde's whales, using the standard formula for calculating the CV of the average of independent estimates.

A mixed parametric and nonparametric bootstrap routine was used to estimate the CV for each abundance estimate (Barlow 2006; Barlow and Rankin 2007). Survey effort from all years (1986-2020) was divided into 150-km effort segments, which is the distance generally surveyed in one day. The bootstrap randomly sampled these effort segments with replacement (n=1,000 iterations) and accounted for the variance associated with sampling variation, estimating the detection function (including model selection and averaging), and uncertainty in the $g(0)$ estimate. Uncertainty in $g(0)$ was estimated by modeling $g(0)$ as a logit-transformed deviate with a mean and variance chosen to give the estimated $g(0)$ and CV.

Results

Survey Sightings

Cetacean search effort during WHICEAS 2020 spanned 5,231 km in Beaufort sea states 0−6 leading to sightings of 311 cetacean groups across all effort types. Accounting for mixed-species groups (n=15), these group sightings represent 328 sightings of 19 species (15 odontocetes and 4 mysticetes) and 13 unidentified species categories (Table 1). The systematic survey effort relevant to the abundance estimation spanned 4,415 km in Beaufort sea states 0−6 (Figure 1B), although this effort largely took place during windy conditions (94.3% in Beaufort sea states 3−6 and 87.3% in sea states 4−6; Table A2). A total of 168 cetacean groups were sighted while on systematic survey effort during WHICEAS 2020. Factoring in mixed-species groups (n=8), these group sightings correspond to 178 sightings of all 19 species and 13 unidentified species categories (Table 1). Systematic-effort sightings were made throughout the study area, with higher concentrations of sightings in close proximity to the main Hawaiian Islands and the northern half of the study area (Figure 1B). Of the 39 systematic-effort sightings of cetaceans initially unidentified to species during WHICEAS 2020, comparisons to the species classification results from available simultaneous acoustic detections (n=10) resulted in one improvement in species identification. Specifically, a sighting of unidentified *Mesoplodon* was identified as Blainville's beaked whale (*M. densirostris*), and the sighting record was updated accordingly. This update allowed for the estimation of Blainville's beaked whale abundance, as the existing sightings were not made while on systematic survey effort (Table 1).

Using the 152 systematic-effort sightings from WHICES 2020 within the established truncation distances (N_{EST} in Table 1), abundance was estimated for 17 species (14 odontocetes and 3 mysticetes) and 13 unidentified species categories (combined into 7 taxonomic categories as described in the Methods). There were two species sighted while on systematic survey effort that were not included in the abundance estimation. Only two of the three systematic-effort sightings of false killer whales could be assigned to the pelagic population, with the other sighting potentially of the pelagic or main Hawaiian Islands insular population. Given the uncertainty in population assignment, estimating the abundance of false killer whales during WHICEAS 2020 would not have improved upon previous efforts, including design- and model-based line-transect estimation of the pelagic population (Bradford et al. 2020) and mark-recapture estimation of the main Hawaiian Islands insular population (Bradford et al. 2018), and thus was not pursued. Finally, the single systematic-effort sighting of minke whales (*Balaenoptera acutorostrata*) was outside the truncation distance (and the trackline strip width) and therefore was not used to estimate abundance.

Of the 325 cetacean groups sighted across all effort types within the Hawaiian Islands EEZ during HICEAS 2017 (Bradford et al. 2021), 142 (43.7%) were sighted within the WHICEAS study area. Accounting for mixed-species groups (n=6), these group sightings represent 148 sightings of 15 species (14 odontocetes and 1 mysticete) and 11 unidentified species categories (Table 1). The systematic survey effort in the WHICEAS study area during HICEAS 2017 spanned 2,791 km in Beaufort sea states 0−6 (Figure 1A), with only marginally better sea conditions than during WHICEAS 2020 (89.6% in Beaufort sea states 3−6 and 78.7% in sea states 4−6; Table A2). A total of 30 cetacean groups were sighted in the WHICEAS study area while on systematic survey effort during HICEAS 2017. With 3 mixed-species groups, these group sightings correspond to 33 sightings of 10 odontocete species and 6 unidentified species categories (Table 1). Systematic-effort sightings were made throughout the study area, with higher concentrations of sightings in the southern half of the study area (Figure 1A). The objective of estimating cetacean abundance in the WHICEAS study area during HICEAS 2017 was to provide a seasonal point of comparison to the WHICEAS 2020 estimates. Thus, 29 systematic-effort sightings from HICEAS 2017 within the established truncation distances (N_{EST} in Table 1) were used to estimate abundance for the 9 odontocete species and 6 unidentified species categories (combined into 5 taxonomic categories) that were covered in the WHICEAS 2020 estimation. While dwarf sperm whales (*Kogia sima*) were not sighted on systematic survey effort in the WHICEAS study area during 2017 as they were in 2020, a systematic-effort sighting of unidentified *Kogia* in the study area in 2017 (Table 1) allowed for a comparison of *Kogia* spp. abundance between the 2 years. Only false killer whales (of the pelagic and main Hawaiian Islands insular populations) were not included in the HICEAS 2017 estimation given the lack of comparable estimates from WHICEAS 2020, but more comprehensive abundance estimates are available for these populations (Bradford et al. 2018; Bradford et al. 2020).

Line-transect Estimates

Only 4 of the 6 covariates of interest (*Beaufort*, *group size*, *ship*, and *species*) were tested in the 12 models of detection function, with only *Beaufort* and *group size* tested in all cases (Table 2). Sample sizes were inadequate to test for the effect of *cruise number* and *year* on any of the detection functions. *Beaufort* and *species* most frequently contributed to the model-averaged estimates of detection function, with *Beaufort* and *species* selected in 8 and 5 detection functions, respectively. *Group size* was the most frequently selected covariate in previous detection functions estimated for earlier versions of the current species pools (Bradford et al. 2017; Bradford et al. 2021), but this covariate was only selected in 4 cases in the present analysis (Table 2).

The line-transect parameter estimates of mean *ESW* and *s* vary across species sighted during WHICEAS 2020 (Table 3). Mean *ESW* values range from 1.33 to 4.34 km, are lowest for bottlenose dolphins and dwarf sperm and Blainville's beaked whales, and are highest for sperm (*Physeter macrocephalus*) and humpback whales and the small delphinids with relatively large group sizes (multi-species pool 1 in Table 2). Mean species group sizes range from 1 to 207 individuals, are lowest for dwarf sperm whales and the rorqual species, and are highest for melon-headed whales and the small delphinid species. By species, the HICEAS 2017 estimates of mean *ESW* are generally similar in magnitude to the WHICEAS 2020 estimates, although the estimates of *s* are on average 2−3× higher in 2020 than in 2017 (Table 3). Given the proportions of systematic survey effort are highest in Beaufort sea states 3-6 (Table A2), the resulting weighted-average estimates of *g*(0) for each species during WHICEAS 2020 are relatively low, ranging from <0.01 to 0.68 (Table 3). The estimates are lowest for dwarf sperm whales and rough-toothed dolphins (*Steno bredanensis*) and highest for humpback and sperm whales. The *g*(0) estimates for corresponding species during HICEAS 2017 followed the same pattern, but are slightly higher (Table 3) reflecting the marginally better sea conditions during that survey (Table A2).

Excluding the island-associated populations of pantropical spotted, spinner, and common bottlenose dolphins, the density estimates of species during WHICEAS 2020 are less than approximately 70 individuals per 1,000 km^2, although half of the estimates are less than approximately 10 individuals per 1,000 km^2 (Table 4). Density point estimates for species in the WHICEAS study area during HICEAS 2017 were generally similar in magnitude to the paired point estimates during WHICEAS 2020, with the exception of pygmy killer, short-finned pilot (*Globicephala macrorhynchus*), and sperm whales, which were less than half of the 2020 estimates. However, the density point estimates in the WHICEAS study area during 2017 were over twice as high for most species as the corresponding estimates from the Hawaiian Islands EEZ (Table 4 in Bradford et al. 2021), although the EEZ estimates were marginally higher for striped dolphins (*Stenella coeruleoalba*) and short-finned pilot whales and over 30× higher for sperm whales. Species abundance point estimates for WHICEAS 2020 range from 115 fin whales to 26,627 melon-headed whales (Table 4). Given the low number of sightings of most species, the CVs for the WHICEAS 2020 density and abundance estimates are generally high, ranging from 0.40 to 1.06 (Table 4). The CVs for the species sighted within the WHICEAS study area during 2017 were similarly high, ranging from 0.50 to 1.06 (Table 4), obscuring the ability to detect seasonal trends in abundance (Figure 3). Similar to the density point estimates, the abundance point estimates of pygmy killer, short-finned pilot, and sperm whales in the WHICEAS study area during HICEAS 2017 were less than half of the 2020 estimates, but only the sperm whale estimates had non-overlapping 95% confidence intervals (CIs; Table 4, Figure 3), suggesting a significant difference in sperm whale abundance around the main Hawaiian Islands in summer-fall 2017 and winter 2020.

The density estimates of the Hawaiʻi Island pantropical spotted dolphin population and the Kauaʻi/Niʻihau spinner and common bottlenose dolphin populations are 2−5× higher than the highest density point estimate from WHICEAS 2020 (Table 4). The resulting abundance estimates of 8,241 (CV=0.83, 95% CI=1,987-34,173) Hawaiʻi Island spotted dolphins, 1,110 (CV=1.11, 95% CI=191-6,459) Kauaʻi/Niʻihau spinner dolphins, and 1,007 (CV=0.70, 95% CI=291-3,488) Kauaʻi/Niʻihau common bottlenose dolphins, while imprecise, are higher than expected given previous mark-recapture abundance estimates for spinner dolphin (Hill et al. 2011; Tyne et al. 2016), common bottlenose dolphin (Van Cise et al. 2021), and other island-associated odontocete (e.g., Aschettino 2010; Bradford et al. 2018) populations around the main Hawaiian Islands. Omitting these estimates, approximately 4% of the estimated cetacean abundance during WHICEAS 2020 was not identified to species, with most of this abundance associated with unidentified dolphin and beaked whale species. About 2% and 3% of the estimated delphinid and rorqual abundance, respectively, represents unknown species, while 61% of beaked whale abundance was unidentified to species. The abundance of cetaceans not identified to species in the WHICEAS study area in 2017 was approximately 21% given the relatively high estimate of unidentified *Kogia* (Table 4). About 1% of the delphinid abundance estimated for 2017 represents unknown species, similar to WHICEAS 2020, but in contrast only 23% of beaked whale abundance and all *Kogia* and rorqual abundance was unidentified to species. The estimated abundance of cetaceans in the WHICEAS study area with unknown taxonomic status (i.e., "unidentified cetaceans") is relatively low in both years (around 0.1%).

Discussion

This study estimated the abundance of cetaceans around the main Hawaiian Islands during winter 2020 and compared the results to available estimates from the same area during summer-fall 2017. Comparisons between these sets of estimates are complicated by the relatively low encounter rates characteristic of the region (Barlow 2006; Bradford et al. 2017). With these low encounter rates, random variation in the sampling process (e.g., survey conditions) and sighting attributes (e.g., group sizes) can have an outsized impact on the resulting abundance estimates. For example, random variation could potentially explain the relatively larger group sizes during WHICEAS 2020 or why some species were not sighted around the main Hawaiian Islands during HICEAS 2017 (e.g., Fraser's dolphins, *Lagenodelphis hosei*), particularly given that there was less effort in the study area in 2017 compared to 2020. More importantly, the low encounter rates lead to high variance in the estimates, which results in poor precision and low statistical power to detect seasonal trends in abundance. Predictably, the paired seasonal estimates for almost all nine odontocete species compared had wide and overlapping 95% CIs (Figure 3). Other than an unidentified rorqual, there were no baleen whales sighted during systematic survey effort in the WHICEAS study area during 2017. While this absence of baleen whale sightings could be due to random variation in the encounter rate or interannual variation in distribution and abundance, it more likely reflects a true decline in abundance given seasonal migration patterns. For the odontocete species for which comparisons could be made, interpreting a lack of difference in the seasonal abundance estimates is challenging. Insights from previous studies on the occurrence of cetaceans (e.g., Baird et al. 2013) around the main Hawaiian Islands suggested that such seasonal differences are unlikely. However, any true differences in seasonal abundance are most likely obscured by the low precision of the estimates.

Sperm whales are the one exception among the compared odontocetes, with the resulting paired estimates suggesting a significant increase in abundance around the main Hawaiian Islands in winter 2020 compared to summer−fall 2017 (Figure 3H). Given that random variation in the encounter rate has been shown to at least partially explain the observed variation in design-based abundance estimates of cetaceans in Hawaiian waters (e.g., Bradford et al. 2020), a post-hoc simulation study was conducted to examine whether the increase in sperm whale encounter rate from HICEAS 2017 to WHICEAS 2020 could have occurred by chance if the overall abundance in the study area did not change between seasons (Appendix B). While this study found that the observed encounter rates could have occurred by chance given constant seasonal abundance, the estimated probabilities were low enough that an actual increase in abundance or a shift in distribution toward the main Hawaiian Islands in winter 2020 cannot be ruled out. Changes in abundance could represent seasonal migration patterns, particularly among males, that are known for some populations of sperm whales (Whitehead 2003), but are not well understood for the population in Hawaiian waters. A separate or concurrent distributional shift is supported by the estimate of sperm whale density from the broader Hawaiian Islands EEZ during HICEAS 2017 (Table 4 in Bradford et al. 2021), which is more than 30× higher than the density estimate for the WHICEAS study area in 2017, although still less than half of the estimate from 2020 (Table 4). An analysis of long-term passive acoustic data from the central Pacific found a significant seasonal trend in sperm whale detections at all monitoring sites around the Hawaiian Islands, with lower detections occurring during the summer and early fall, leading the authors to also suggest seasonal changes in population composition or geographic shifts (Merkens et al. 2019). More information on sperm whale demography, migration patterns, and habitat associations in

Hawaiian waters is needed to interpret the potential changes in seasonal abundance found in the present study.

Habitat associations are addressed to some degree by model-based abundance estimation, and an updated model-based estimation incorporating data from WHICEAS 2020 (Becker et al. 2022) provides useful insight into the design-based results. Nine cetacean species were modeled, including pantropical spotted, common bottlenose, striped, rough-toothed, and Risso's (*Grampus griseus*) dolphins and short-finned pilot, sperm, Bryde's, and humpback whales. There were too few sightings to test for a seasonal signal in the WHICEAS study area for common bottlenose dolphins and Bryde's whales, but after evaluating the remaining species, a seasonal signal was only detected for humpback whales (Becker et al. 2022). For the six tested species without a seasonal signal, models were used to make average (2017−2020) seasonal predictions of distribution and abundance in the WHICEAS study area, although one or more dynamic variables (allowing seasonal comparisons) were selected only for Risso's dolphins and short-finned pilot and sperm whales. The density of sperm whales and especially Risso's dolphins demonstrated a northward shift in the study area during winter (Becker et al. 2022). The model-based point estimates of abundance for these three species in winter (Table 4 in Becker et al. 2022) are very similar to the design-based estimates from WHICEAS 2020 (Table 4). While the model-based abundance estimates for these species are not significantly different between winter and non-winter, the model-based estimates for sperm whales are also consistent with a winter increase in the WHICEAS study area. However, the habitat models predicted higher non-winter abundance for short-finned pilot whales, in contrast to the design-based results (Figure 3F). Although encounter rate variation could be playing a role in the reduced estimate of short-finned pilot whale abundance in the WHICEAS study area during 2017, Becker et al. (2022) suggest that winter data from a broader area might be needed to make inference about seasonal differences in cetacean distribution and abundance. For all modeled species except humpback whales, non-winter survey data were used to provide updated model-based density and abundance estimates throughout the Hawaiian Islands EEZ (Becker et al. 2022). Unfortunately, the null model was selected for sperm whales, precluding spatially-explicit predictions that could be used to explore the potential for greater offshore distribution in summer-fall. However, the preceding model-based analysis predicted the highest densities of sperm whales away from the main Hawaiian Islands and especially in the western portion of the Hawaiian Islands EEZ during each HICEAS year (Becker et al. 2021).

The design-based estimates of abundance for the Hawaiʻi Island pantropical spotted dolphin population and the Kauaʻi/Niʻihau spinner and common bottlenose dolphin populations in 2020 are imprecise but are higher than expected given the magnitude of existing mark-recapture abundance estimates of island-associated odontocete populations around the main Hawaiian Islands (Aschettino 2010; Bradford et al. 2018; Hill et al. 2011; Tyne et al. 2016; Van Cise et al. 2021). Becker et al. (2022) also estimated abundance for insular pantropical spotted dolphin populations, producing an average (2017−2020) model-based estimate for the Hawaiʻi Island population (7,324, CV=0.292, 95% CI=4,183-12,823) that is similar to the design-based estimate (Table 4) and estimates for the Oʻahu and 4-Islands populations that are also higher than expected. The systematic survey effort in the boundary of the Hawaiʻi Island pantropical spotted dolphin population, particularly within the inner stratum, appears to over-represent the leeward side of the island (Figure 2A), where a previous effort to model habitat associations of spotted dolphins around the main Hawaiian Islands suggested spotted dolphins are more abundant

(Pittman et al. 2016). Although this modeling effort pointed out that a leeward bias in survey effort may have biased the predictions, the possibility remains that the design-based estimate of Hawaiʻi Island pantropical spotted dolphins is biased high because of the more limited sampling in areas of lower density. There are no mark-recapture abundance estimates available for the island-associated populations of pantropical spotted dolphins in Hawaiian waters, but mark-recapture estimates for spinner (Hill et al. 2011; Tyne et al. 2016) and common bottlenose dolphin (Van Cise et al. 2021) populations in the main Hawaiian Islands provide a useful reference point for interpreting the design-based insular abundance estimates. The design-based estimate of Kauaʻi/Niʻihau spinner dolphin abundance is higher than all available mark-recapture estimates of spinner dolphins in the main Hawaiian Islands (Hill et al. 2011; Tyne et al. 2016), including an estimate for the leeward coast of Kauaʻi in 2005 (601, CV=0.20, 95% CI=407-887; Hill et al. 2011), although given the imprecision of the design-based estimate, its 95% CI overlaps that of each mark-recapture estimate. However, each mark-recapture spinner dolphin estimate is specific to leeward portions of the coastline, with the degree to which each estimate extends to the full island-wide population unknown, limiting comparisons with the design-based estimate. Similarly, Van Cise et al. (2021) likely underestimated the abundance of common bottlenose dolphins in the main Hawaiian Islands, given the leeward bias in survey effort and encounter data. Nevertheless, survey effort was more consistent within the range of the Kauaʻi/Niʻihau population, with the mark-recapture estimate for 2018 (112, SE=27, 95% CI=70-180) only a fraction of the design-based estimate from 2020 and fully below the 95% CI. Ultimately, the design-based estimation for these insular dolphin populations was based on limited effort and sightings data and conducted more as a proof of concept. The resulting abundance estimates should not be used for assessment and management purposes until potential biases can be addressed. However, the exercise speaks to the challenges of ship-based, line-transect abundance estimation for island-associated populations in the main Hawaiian Islands. That is, even though the survey design of WHICEAS 2020 included fine-scale effort to account for these populations, the effort could not be fully realized because of inclement weather conditions and the prioritization of the broad-scale transect lines. Line-transect surveys from small vessels in coastal areas (e.g., Williams et al. 2017) may be a more suitable alternative. Finally, this effort highlights the importance of mark-recapture estimation when data are available and especially when associated sampling bias can be addressed (Bradford et al. 2018; Van Cise et al. 2021).

The density estimates of cetacean species in the WHICEAS study area in 2017 and 2020 (Table 4) are higher than corresponding estimates for the Hawaiian Islands EEZ from HICEAS 2017 (Table 4 in Bradford et al. 2021), although the latter estimates are not stratified to allow for an exact comparison. However, HICEAS 2002 was a stratified survey and quantified by species the relatively higher densities around the main Hawaiian Islands (Barlow 2006; Bradford et al. 2021), a density gradient that has been further demonstrated by model-based efforts (Becker et al. 2022; Becker et al. 2021) and is apparent from effort-corrected sighting rates in relation to depth from small-boat surveys (Baird et al. 2013). Higher densities of cetaceans around the main Hawaiian Islands are likely driven by enhanced productivity associated with the islands, although densities from the WHICEAS study area are still low compared to more productive regions (Barlow and Forney 2007; Wade and Gerrodette 1993). The estimated proportional densities of dolphin, *Kogia*, beaked whale, and large whale (i.e., sperm and baleen whale) species within the WHICEAS study area in summer−fall 2017 and winter 2020 were 79.9%, 18.7%, 1.3%, and <0.1% and 87.6%, 5.1%, 2.9%, and 4.4%, respectively. While seasonal differences in the abundance of most small cetaceans in the study area are unlikely (or unlikely to be detected), the winter survey did detect an increase in the relative abundance of large whales. The resulting abundance estimate for humpback whales (2,975, CV=0.40, 95% CI=1,407-6,291) is the first estimate from the main Hawaiian Islands since the SPLASH project of 2004-2006 (Calambokidis et al. 2008). However, Becker et al. (2022) produced a model-based estimate of peak humpback whale abundance throughout the Hawaiian Islands EEZ during 2020 (11,278, CV=0.56, 95% CI=4,049-31,412) that is more relevant to specific assessment and management contexts than the design-based estimate. Overall, this study provides the first multi-species assessment of winter abundance around the main Hawaiian Islands. Additional winter survey effort beyond the WHICEAS study area and insight from other data streams (e.g., satellite tag data) may reveal seasonal differences that could not be identified in the present estimation.

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Tables

Table 1. Names and number of sightings of cetacean species and taxonomic categories visually observed in the winter Hawaiian Islands Cetacean and Ecosystem Assessment Survey (WHICEAS) study area during the HICEAS in 2017 and the WHICEAS in 2020. Table continues on following page, and notes follow end of table.

			2017			2020		
Common name	**Scientific name**	**Population name**	**NTOT**	**NSYS**	**NEST**	**NTOT**	**NSYS**	**NEST**
Pantropical spotted dolphin	*Stenella attenuata*	Hawai‘i Pelagic	10	7	6	6	4	4
Pantropical spotted dolphin	*Stenella attenuata*	4-Islands	2	0	-	0	0	-
Pantropical spotted dolphin	*Stenella attenuata*	Hawai‘i Island	9	0	-	6	1	2[1]
Striped dolphin	*Stenella coeruleoalba*	Hawai‘i	4	3	3	8	3	3
Spinner dolphin	*Stenella longirostris*	Kaua‘i/Ni‘ihau	0	0	-	1	1	1
Spinner dolphin	*Stenella longirostris*	O‘ahu/4-islands	1	0	-	0	0	-
Spinner dolphin	*Stenella longirostris*	Hawai‘i Island	1	0	-	0	0	-
Rough-toothed dolphin	*Steno bredanensis*	Hawai‘i	18	4	4	7	4	4
Common bottlenose dolphin	*Tursiops truncatus*	Hawai‘i Pelagic	1	0	-	3	3	3
Common bottlenose dolphin	*Tursiops truncatus*	Kaua‘i/Ni‘ihau	0	0	-	3	1	2[1]
Common bottlenose dolphin	*Tursiops truncatus*	O‘ahu	0	0	-	2	0	-
Common bottlenose dolphin	*Tursiops truncatus*	4-Islands	2	0	-	0	0	-
Common bottlenose dolphin	*Tursiops truncatus*	Hawai‘i Island	0	0	-	1	0	-
Risso’s dolphin	*Grampus griseus*	Hawai‘i	5	2	2	5	4	4
Fraser’s dolphin	*Lagenodelphis hosei*	Hawai‘i	0	0	-	3	2	2
Melon-headed whale	*Peponocephala electra*	Hawaiian Islands	3	2	2	5	3	3
Melon-headed whale	*Peponocephala electra*	Hawaiian Islands or Kohala Resident	1	0	-	1	0	-
Pygmy killer whale	*Feresa attenuata*	Hawai‘i	2	1	1	3	3	3
False killer whale[2]	*Pseudorca crassidens*	Hawai‘i Pelagic	2	1	-	2	2	-
False killer whale	*Pseudorca crassidens*	Hawai‘i Pelagic or Main Hawaiian Islands Insular	5	0	-	2	1	-
False killer whale	*Pseudorca crassidens*	Main Hawaiian Islands Insular	5	1	-	0	0	-
Short-finned pilot whale	*Globicephala macrorhynchus*	Hawai‘i	27	1	1	6	5	5
Sperm whale	*Physeter macrocephalus*	Hawai‘i	5	1	1	14	10	8
Dwarf sperm whale	*Kogia sima*	Hawai‘i	0	0	-	1	1	1
Unidentified *Kogia*	*Kogia sima/breviceps*	-	2	1	1	0	0	-

			2017			2020		
Common name	**Scientific name**	**Population name**	N_{TOT}	N_{SYS}	N_{EST}	N_{TOT}	N_{SYS}	N_{EST}
Blainville's beaked whale	*Mesoplodon densirostris*	Hawai'i	3	0	-	3	1	1
Cuvier's beaked whale	*Ziphius cavirostris*	Hawai'i	3	0	-	0	0	-
Longman's beaked whale	*Indopacetus pacificus*	Hawai'i	3	2	2	1	1	1
Unidentified *Mesoplodon*	*Mesoplodon* spp.	-	1	0	-	2	1	1
Unidentified beaked whale	Ziphiid whale	-	4	1	1	4	4	4
Minke whale	*Balaenoptera acutorostrata*	Hawai'i	0	0	-	1	1	0
Sei whale	*Balaenoptera borealis*	Hawai'i	0	0	-	5	3	3
Fin whale	*Balaenoptera physalus*	Hawai'i	0	0	-	1	1	1
Humpback whale	*Megaptera novaeangliae*	Central North Pacific	3	0	-	164	85	72
Sei or Bryde's whale	*Balaenoptera borealis/edeni*	-	0	0	-	6	4	4
Fin, sei, or Bryde's whale	*Balaenoptera physalus/borealis/edeni*	-	0	0	-	1	1	1
Unidentified rorqual	Balaenopterid whale	-	2	1	1	15	4	2
Unidentified small dolphin	Small delphinid	-	10	2	1	9	4	3
Unidentified medium dolphin	Medium delphinid	-	4	0	-	4	1	1
Unidentified large dolphin	Large delphinid	-	0	0	-	1	1	0
Unidentified dolphin	Delphinid	-	4	2	2	9	5	4
Unidentified small whale	Small whale or large dolphin	-	1	0	-	2	2	2
Unidentified large whale	Large baleen or sperm whale	-	3	0	-	16	7	4
Unidentified whale	Small or large whale	-	1	0	-	4	3	2
Unidentified cetacean	Cetacean	-	1	1	1	1	1	1

[1] One sighting was added when fine-scale effort was treated as systematic when estimating the abundance of this island-associated population.

[2] Abundance estimation of false killer whale populations is covered in Bradford et al. (2020) for the Hawai'i Pelagic population and Bradford et al. (2018) for the Main Hawaiian Islands Insular population (see text for more details).

Population names refer to those used in the NOAA Fisheries Stock Assessment Reports (e.g., Carretta et al. 2021). N_{TOT} is the number of sightings across all effort types; N_{SYS} is the number of sightings made while on systematic effort in Beaufort sea states 0–6; and N_{EST} is the number of sightings made while on systematic effort that were within the truncation distance and used in the abundance estimation. The abundance of some species could not be estimated (-). Numbers of sightings for WHICEAS 2020 reflect improvements in species identification (n=1) following classification of acoustic data.

Table 2. Detection functions modeled by using pooled sightings collected in the central Pacific during line-transect surveys conducted in 1986−2020 by the NOAA Fisheries Southwest and Pacific Islands Fisheries Science Centers. Table continues on following page, and notes follow end of table.

Detection function	NTOT	NDET	TD	Covariates tested	Best-fit model
Pantropical spotted dolphin	333	311	5.0	*Beaufort*, *group size*, *ship*, species	*Beaufort*+*group size*+*species*
Pantropical spotted dolphin	244	228			
Other	89	83			
Spinner dolphin	249	229	5.0	*Beaufort*, *group size*, species	*Group size*(+*species*)
Spinner dolphin	175	159			
Other	74	70			
Multi-species pool 1	349	323	5.0	*Beaufort*, *group size*, *ship*, *species*	*Beaufort*+*ship*
Striped dolphin	296	275			
Fraser's dolphin	28	27			
Melon-headed whale	22	21			
Other[1]	3	0			
Multi-species pool 2	312	294	5.0	*Beaufort*, *group size*, *species*	*Group size*+*species*
Rough-toothed dolphin	83	79			
Common bottlenose dolphin	79	73			
Risso's dolphin	82	79			
Pygmy killer whale	20	20			
Other	48	43			
Multi-species pool 3	222	208	5.0	*Beaufort*, *group size*, *species*	*Beaufort*(+*species*)
Short-finned pilot whale	199	188			
Longman's beaked whale	11	10			
Other	12	10			
Multi-species pool 4	212	178	5.5	*Beaufort*, *group size*, *species*	Null(+*species*)
Killer whale	39	37			
Sperm whale	171	141			
Other[1]	2	0			

Detection function	N_{TOT}	N_{DET}	TD	Covariates tested	Best-fit model
Multi-species pool 5	243	229	4.5	*Beaufort*, *group size*	*Beaufort*+*Group size*
Pygmy sperm whale	5	5			
Dwarf sperm whale	27	27			
Unidentified *Kogia*	7	7			
Blainville's beaked whale	17	16			
Cuvier's beaked whale	61	55			
Unidentified *Mesoplodon*	50	50			
Unidentified beaked whale	70	64			
Minke whale	3	2			
Other	3	3			
Multi-species pool 6	170	156	5.0	*Beaufort*, *group size*	Null(+*Beaufort*)
Bryde's whale	84	79			
Sei whale	15	13			
Fin whale	7	7			
Blue whale	4	4			
Sei or Bryde's whale	52	46			
Fin, sei, or Bryde's whale	1	1			
Other	7	6			
Humpback whale	235	194	5.5	*Beaufort*, *group size*	*Beaufort*
Humpback whale	230	189			
Other	5	5			
Unidentified rorquals	89	61	5.5	*Beaufort*, *group size*	Null
Unidentified dolphin	424	348	5.5	*Beaufort*, *group size*, *ship*	*Beaufort*
Unidentified cetacean	210	165	5.5	*Beaufort*, *group size*	*Beaufort*

[1] The “other” sightings in this pool were within the TD but were removed for other reasons (see text for more details).

Left-justified entries in the first column are the detection functions estimated; indented entries are the factor levels for the *species* covariate, with the “other” factor level representing mixed-species sightings for which the most abundant species was not one of the pooled species. N_{TOT} is the number of available systematic- and nonsystematic-effort sightings in Beaufort sea states 0–6, and N_{DET} is the number of sightings that fell within the truncation distance (TD; in km). If a model with an additional covariate was within 2 AICc units of the best-fit covariate model, the second covariate is shown in parentheses.

Table 3. Estimates of line-transect parameters for cetacean species and taxonomic categories sighted while on systematic survey effort in the winter Hawaiian Islands Cetacean and Ecosystem Assessment Survey (WHICEAS) study area during the HICEAS in 2017 (if available) and the WHICEAS in 2020. Table continues on following page, and notes follow end of table.

	2017			2020		
Species or category	**Mean *ESW***	**Mean *s***	***g*(0) (CV)**	**Mean *ESW***	**Mean *s***	***g*(0) (CV)**
Pantropical spotted dolphin – Hawai‘i Pelagic	2.33	61.9	0.28 (0.11)	2.85	111.2	0.25 (0.13)
Pantropical spotted dolphin – Hawai‘i Island (inner stratum)[1]	-	-	-	3.33	123.4	0.27 (0.12)
Pantropical spotted dolphin – Hawai‘i Island (outer stratum)	-	-	-	2.93	73.2	0.28 (0.11)
Striped dolphin	3.97	32.4	0.35 (0.19)	3.66	49.5	0.31 (0.22)
Spinner dolphin – Kaua‘i/Ni‘ihau	-	-	-	2.06	35.8	0.27 (0.12)
Rough-toothed dolphin	2.62	23.5	0.09 (0.45)	3.23	25.7	0.07 (0.51)
Common bottlenose dolphin – Hawai‘i Pelagic	-	-	-	1.33	6.9	0.24 (0.38)
Common bottlenose dolphin – Kaua‘i/Ni‘ihau	-	-	-	1.61	14.8	0.26 (0.36)
Risso’s dolphin	2.56	31.6	0.57 (0.18)	2.19	21.7	0.52 (0.21)
Fraser’s dolphin	-	-	-	3.59	141.5	0.31 (0.22)
Melon-headed whale	3.46	158.8	0.35 (0.19)	3.50	207.0	0.31 (0.22)
Pygmy killer whale	1.89	18.4	0.14 (0.25)	2.19	16.1	0.11 (0.28)
Short-finned pilot whale	2.00	13.3	0.58 (0.15)	2.88	36.6	0.52 (0.19)
Sperm whale	4.34	1.0	0.63 (0.34)	4.34	13.9	0.61 (0.37)
Dwarf sperm whale	-	-	-	1.74	1.0	0.004 (0.15)
Unidentified *Kogia*	2.25	3.5	0.005 (0.15)	-	-	-
Blainville’s beaked whale	-	-	-	1.77	2.3	0.11 (0.30)
Longman’s beaked whale	4.01	19.3	0.58 (0.15)	2.88	30.2	0.52 (0.19)
Unidentified *Mesoplodon*	-	-	-	1.94	3.3	0.11 (0.30)
Unidentified beaked whale	1.52	1.0	0.13 (0.20)	1.63	1.6	0.11 (0.21)
Sei whale	-	-	-	3.12	1.4	0.38 (0.21)
Fin whale	-	-	-	3.04	2.3	0.30 (0.29)
Humpback whale	-	-	-	3.72	2.3	0.68 (0.36)

Species or category	2017 Mean *ESW*	 Mean *s*	 *g*(0) (CV)	2020 Mean *ESW*	 Mean *s*	 *g*(0) (CV)
Sei or Bryde’s whale	-	-	-	3.03	1.8	0.38 (0.21)
Fin, sei, or Bryde’s whale	-	-	-	3.04	1.3	0.34 (0.17)
Unidentified rorqual	4.01	1.0	0.35 (0.18)	4.01	1.7	0.32 (0.20)
Unidentified dolphin	4.06	7.2	0.33 (0.08)	3.00	4.2	0.29 (0.10)
Unidentified cetacean	2.58	2.3	1.00 (NA)	3.10	1.2	1.00 (NA)

[1] A stratified analysis was used to estimate the abundance of this island-associated population (see text and Figure 2 for more details).

Mean effective strip width (*ESW*) is the average *ESW* of the sightings used in the abundance estimation (N_{EST} in Table 1), was computed from the covariates associated with each sighting, and represents the distance from the trackline (in km) beyond which as many sightings were made as were missed within. Mean species group size (*s*) is the average estimated sighting group size calibrated and proportioned to species of the N_{EST} sightings. The probabilities of detection on the trackline (*g*(0)) were derived from Barlow (2015) as described in the text; the coefficients of variation (CV) for the *g*(0) estimates are included in parentheses.

Table 4. Estimates of density (individuals per 1,000 km^2) and abundance for cetacean species and taxonomic categories sighted while on systematic survey effort in the winter Hawaiian Islands Cetacean and Ecosystem Assessment Survey (WHICEAS) study area during the HICEAS in 2017 (if available) and the WHICEAS in 2020. Table continues on following page, and notes follow end of table.

	2017				2020			
Species or category	**Density**	**Abundance**	**CV**	**95% CI**	**Density**	**Abundance**	**CV**	**95% CI**
Pantropical spotted dolphin – Hawai‘i Pelagic	79.02	27,559	0.58	9,541-79,604	61.25	21,360	0.87	4,896-93,191
Pantropical spotted dolphin – Hawai‘i Island[1,2]	-	-	-	-	208.75	8,241	0.83	1,987-34,173
Striped dolphin	11.82	4,772	0.58	1,653-13,774	14.94	6,034	0.60	2,043-17,825
Spinner dolphin – Kaua‘i/Ni‘ihau[1]	-	-	-	-	153.60	1,110	1.11	191-6,459
Rough-toothed dolphin	65.67	26,517	0.50	10,446-67,312	50.42	20,362	0.73	5,694-72,810
Common bottlenose dolphin – Hawai‘i Pelagic	-	-	-	-	7.06	2,698	1.06	493-14,767
Common bottlenose dolphin – Kaua‘i/Ni‘ihau[1]	-	-	-	-	364.50	1,007	0.70	291-3,488
Risso’s dolphin	7.18	2,900	0.97	585-14,385	7.44	3,004	0.68	897-10,065
Fraser’s dolphin	-	-	-	-	28.82	11,638	0.96	2,377-56,983
Melon-headed whale	43.42	17,534	0.86	4,105-74,894	65.94	26,627	0.71	7,653-92,646
Pygmy killer whale	11.69	4,721	1.06	860-25,917	23.68	9,561	0.66	2,925-31,254
Short-finned pilot whale	1.93	781	1.00	152-4,016	13.95	5,632	0.49	2,267-13,989
Sperm whale	0.06	25	1.01	5-128	4.76	1,924	0.41	894-4,143
Dwarf sperm whale	-	-	-	-	16.27	6,571	1.04	1,224-35,272
Unidentified *Kogia*	52.41	21,166	1.10	3,693-121,315	-	-	-	-
Blainville’s beaked whale	-	-	-	-	1.34	539	1.02	103-2,825
Longman’s beaked whale	2.79	1,125	0.95	234-5,399	2.28	921	1.00	180-4,722
Unidentified *Mesoplodon*	-	-	-	-	1.75	706	1.03	113-3,739
Unidentified beaked whale	0.85	345	1.00	67-1,775	3.87	1,563	0.57	550-4,438
Sei whale	-	-	-	-	0.41	166	0.78	43-645
Fin whale	-	-	-	-	0.29	115	0.99	23-581
Humpback whale	-	-	-	-	7.37	2,975	0.40	1,407-6,291
Sei or Bryde’s whale	-	-	-	-	0.72	290	0.57	102-823
Fin, sei, or Bryde’s whale	-	-	-	-	0.14	57	1.00	11-293
Unidentified rorqual	0.12	48	0.97	10-240	0.29	118	0.98	23-591
Unidentified dolphin	3.02	1,219	0.69	357-4,158	4.22	1,702	0.45	738-3,926

	2017				2020			
Species or category	**Density**	**Abundance**	**CV**	**95% CI**	**Density**	**Abundance**	**CV**	**95% CI**
Unidentified cetacean	0.15	61	0.98	12-304	0.40	162	0.40	75-347

[1] The abundance of this island-associated population was estimated as a proof of concept and should not be used for assessment and management purposes until potential biases can be addressed (see text for more details).

[2] The stratified estimates of density and abundance are 409.60 individuals per 1,000 km^2 and 4,277 individuals (CV=1.29, 95% CI=613−29,823) for the inner stratum and 136.50 individuals per 1,000 km^2 and 3,964 individuals (CV=1.03, 95% CI=752−20,893) for the outer stratum (Figure 2).

The coefficients of variation (CV) apply to estimates of both density and abundance. Log-normal 95% confidence intervals (CIs) for the abundance estimates are shown.

Figures

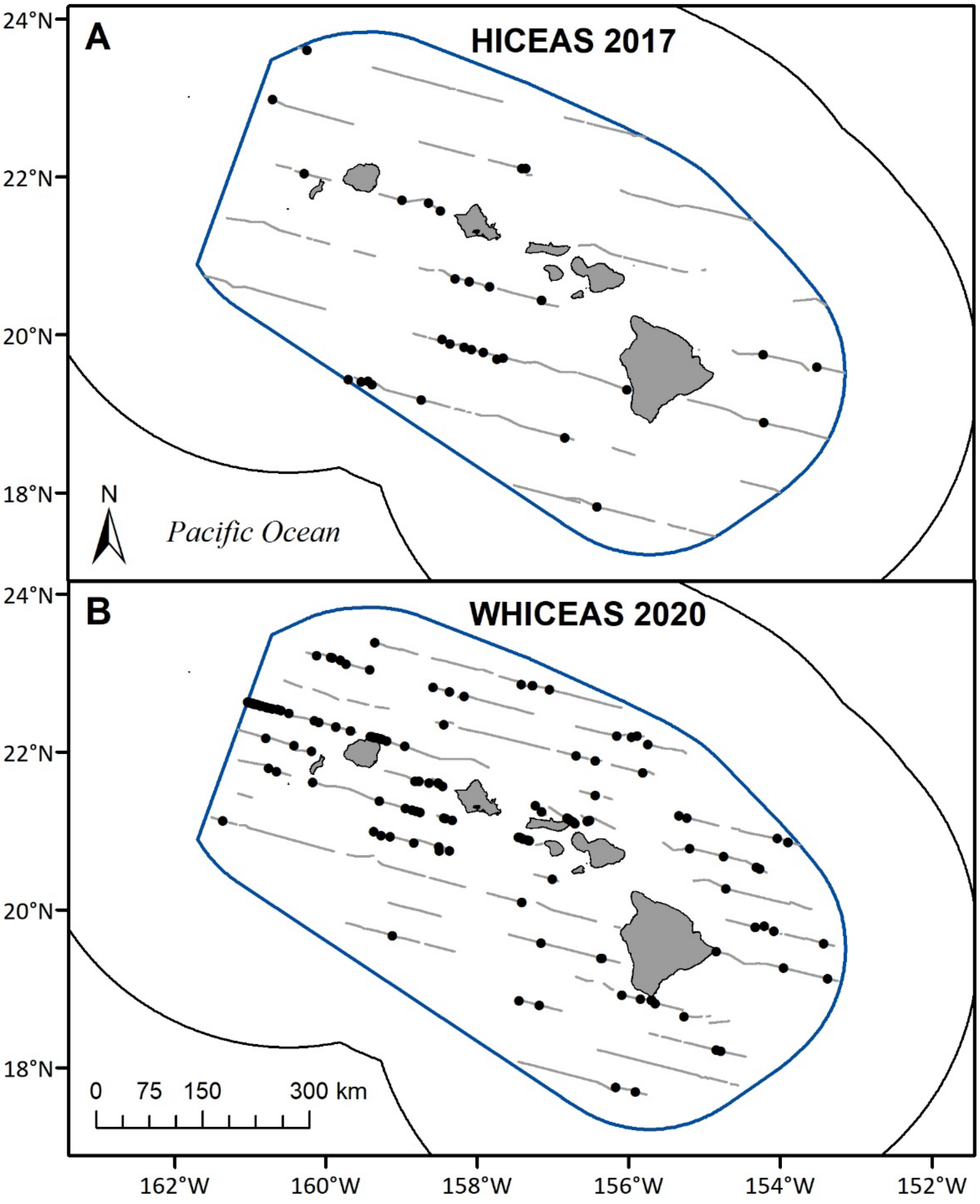

Figure 1. Locations of cetacean groups (black dots; n=198) sighted during systematic line-transect survey effort (fine lines) in Beaufort sea states 0−6 within the winter Hawaiian Islands Cetacean and Ecosystem Assessment Survey (WHICEAS) study area (inner blue outline) during the (A) HICEAS in 2017 (n=30) and (B) the WHICEAS in 2020 (n=168).

A total of 11 sightings across both years were of mixed-species groups, in which at least 2 species were seen. The main Hawaiian Islands are shown in gray with a thin black outline. The outer black outline is the U.S. Hawaiian Islands Exclusive Economic Zone.

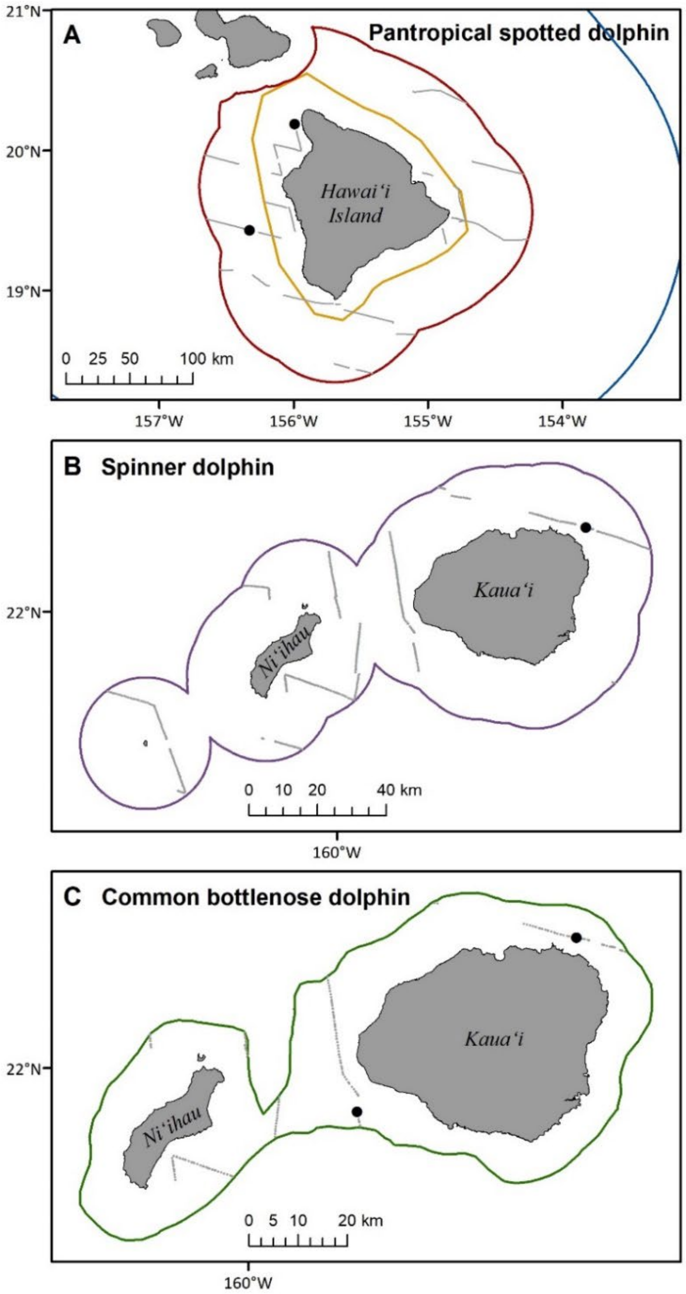

Figure 2. Locations of dolphin groups (black dots) sighted during systematic and fine-scale line-transect survey effort (fine lines) in Beaufort sea states 0-6 during the winter Hawaiian Islands Cetacean and Ecosystem Assessment Survey (WHICEAS) in 2020 and used to estimate the abundance of (A) the Hawaiʻi Island pantropical spotted dolphin population (n=2 groups), (B) the Kauaʻi/Niʻihau spinner dolphin population (n=1 group), and (C) the Kauaʻi/Niʻihau common bottlenose dolphin population (n=2 groups).

The population boundaries are shown as red (represents the outer analysis stratum), purple, and green outlines, respectively. In panel A, the inner yellow outline is the fine-scale grid area (represents the inner analysis stratum), and the outer blue outline is the WHICEAS study area.

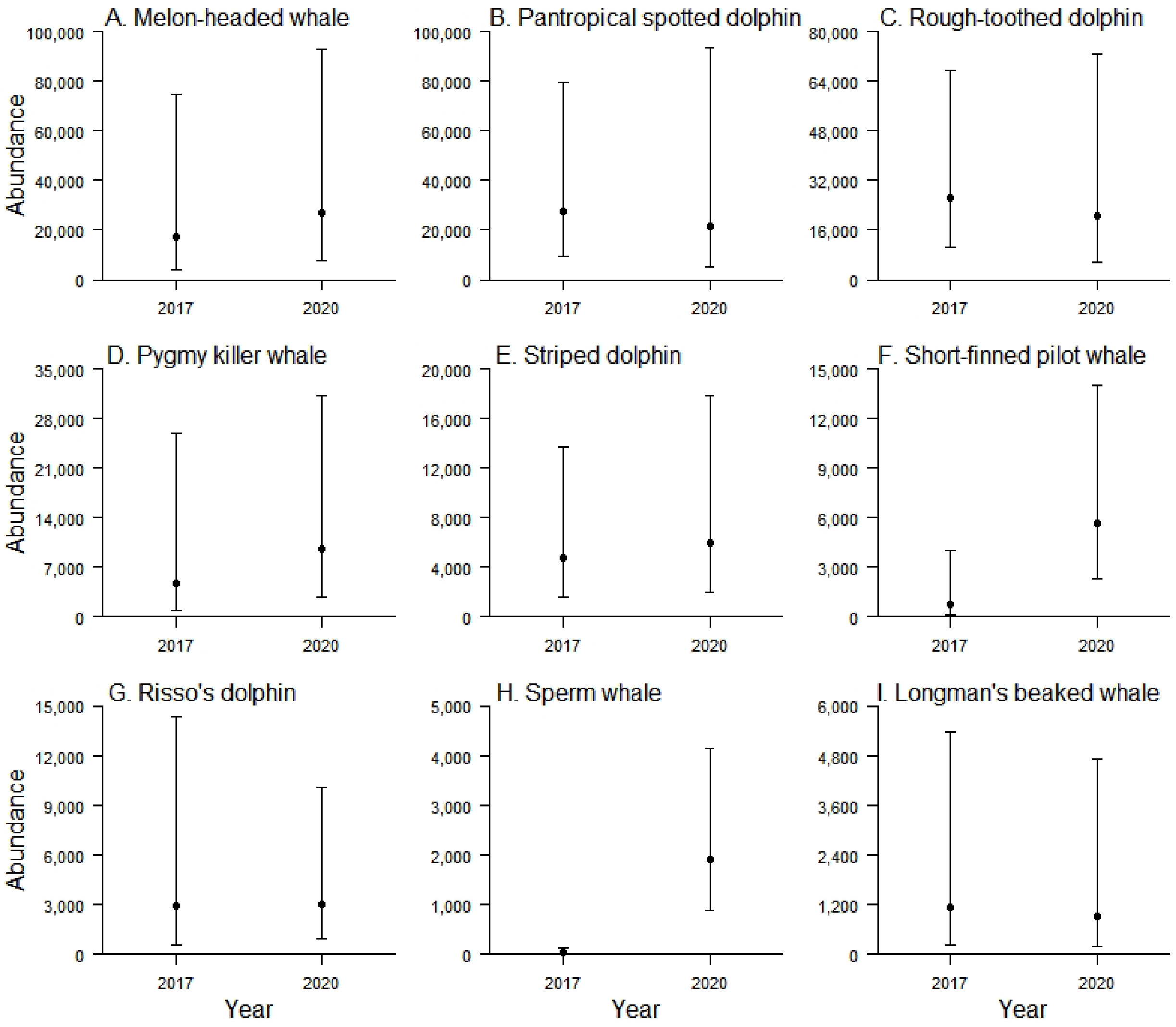

Figure 3. Estimated abundance (with 95% confidence intervals) of the 9 odontocete species sighted within the winter Hawaiian Islands Cetacean and Ecosystem Assessment Survey (WHICEAS) study area during the HICEAS in 2017 and the WHICEAS in 2020: (A) melon-headed whales, (B) pantropical spotted dolphins (pelagic population), (C) rough-toothed dolphins, (D) pygmy killer whales, (E) striped dolphins, (F) short-finned pilot whales, (G) Risso's dolphins, (H) sperm whales, and (I) Longman's beaked whales.

Species are shown in order of highest to lowest abundance during WHICEAS 2020.

Appendix A: Supplementary Tables

Table A 1. Area values (km^2) within the winter Hawaiian Islands Cetacean and Ecosystem Assessment Survey (WHICEAS) study area used to scale relevant HICEAS 2017 and WHICEAS 2020 line-transect density estimates to abundance.

Species	Area
Pantropical spotted dolphin – Hawai‘i Pelagic	348,763
Pantropical spotted dolphin – Hawai‘i Island	39,479
Pantropical spotted dolphin – Hawai‘i Island (inner stratum)	29,036
Pantropical spotted dolphin – Hawai‘i Island (outer stratum)	10,442
Spinner dolphin – Kaua‘i/Ni‘ihau	7,224
Common bottlenose dolphin – Hawai‘i Pelagic	381,982
Common bottlenose dolphin – Kaua‘i/Ni‘ihau	2,763
All others	403,822

The ranges of the pelagic populations of pantropical spotted and common bottlenose dolphins and the island-association populations of pantropical spotted, spinner, and common bottlenose dolphins do not span the entirety of the WHICEAS study area, which was the area value applied to all other cetacean species and taxonomic categories.

Table A 2. Systematic survey effort in total (km) and proportionally by Beaufort (B) sea state within the winter Hawaiian Islands Cetacean and Ecosystem Assessment Survey (WHICEAS) study area used to obtain weighted estimates of trackline detection probabilities (*g*(0)) for HICEAS 2017 and WHICEAS 2020.

Species	Year	Effort	B0	B1	B2	B3	B4	B5	B6
Pantropical spotted dolphin – Hawai‘i Pelagic	2017	2,726	0.000	0.013	0.101	0.112	0.302	0.377	0.096
Pantropical spotted dolphin – Hawai‘i Pelagic	2020	3,924	0.000	0.015	0.038	0.072	0.273	0.402	0.200
Pantropical spotted dolphin – Hawai‘i Island (inner stratum)	2020	168	0.000	0.000	0.108	0.070	0.348	0.384	0.090
Pantropical spotted dolphin – Hawai‘i Island (outer stratum)	2020	326	0.000	0.051	0.035	0.045	0.379	0.449	0.041
Spinner dolphin – Kaua‘i/Ni‘ihau	2020	210	0.000	0.043	0.004	0.180	0.368	0.045	0.358
Common bottlenose dolphin – Hawai‘i Pelagic	2020	4,248	0.000	0.017	0.039	0.072	0.281	0.407	0.184
Common bottlenose dolphin – Kaua‘i/Ni‘ihau	2020	85	0.000	0.014	0.000	0.267	0.415	0.014	0.290
All others	2017	2,971	0.000	0.012	0.093	0.109	0.318	0.378	0.091
All others	2020	4,415	0.000	0.017	0.041	0.070	0.281	0.409	0.183

The ranges of the pelagic populations of pantropical spotted and common bottlenose dolphins and the island-association populations of pantropical spotted, spinner, and common bottlenose dolphins do not span the entirety of the WHICEAS study area, which required the use of different proportions for those populations in relevant years.

Appendix B: Random Variation in Sperm Whale Encounter Rate

The abundance estimates of sperm whales in the winter Hawaiian Islands Cetacean and Ecosystem Assessment Survey (WHICEAS) study area during HICEAS 2017 and WHICEAS 2020 had non-overlapping 95% confidence intervals (Table 4; Figure 3H) suggesting a significant increase in sperm whale abundance around the main Hawaiian Islands, in winter 2020 compared to summer−fall 2017. The difference in the estimates is reflected in the encounter rate of sperm whales in the WHICEAS study area during each year, with the encounter rate based on 1 systematic-effort sighting from HICEAS 2017 and 8 systematic-effort sightings from WHICEAS 2020. A simulation study was conducted to evaluate whether the variation in sperm whale encounter rate between the two years could have occurred by chance if the overall abundance of sperm whales in the WHICEAS study area did not, in fact, vary between these two seasons.

Consistent with the bootstrap routine used in the abundance estimation, 150-km segments of systematic survey effort in the WHICEAS study area were created for HICEAS 2017 and WHICEAS 2020 (Table B1). These effort segments were linked to their associated number of systematic-effort sperm whale sightings used in the abundance estimation (N_{EST} in Table 1) and then pooled for use in a bootstrap procedure. These pooled effort segments with sightings represented constant abundance conditions and were sampled with replacement 1,000 times according to the number of segments surveyed in the study area in each year. For each bootstrap iteration, the number of sperm whale sightings were summed over all effort segments in the sample.

The simulated number of sperm whale sightings during HICEAS 2017 and WHICEAS 2020 has a similar distribution, with a peak between 3-4 and 4-5 sightings, respectively (Figure B1). However, the simulated number of sperm whale sightings in 2017 and 2020 was notably higher and lower, respectively, than what was observed, with only 9.8% of iterations containing ≤1 sightings in 2017, and 14.2% of iterations containing ≥8 sightings in 2020. While these simulated probabilities are relatively small, they indicate the observed encounter rates could have occurred by chance when abundance in the study area was constant between surveys. Thus, random variation in encounter rate may be playing a pronounced role in the seasonal estimates of sperm whale abundance in the WHICEAS study area. However, the low values of these probabilities suggest that other factors may also be influencing the estimates, including an overall increase in abundance or a shift in distribution toward the main Hawaiian Islands in winter.

Table B 1. Number of systematic survey effort segments, total survey distance (km), and sperm whales sighted in the winter Hawaiian Islands Cetacean and Ecosystem Assessment Survey (WHICEAS) study area during HICEAS 2017 and WHICEAS 2020.

Year	No. segments	Distance	No. sightings
2017	27	2,971	1
2020	32	4,415	8

The number of sperm whale sightings observed in each year was compared to the simulated distributions in Figure B1.

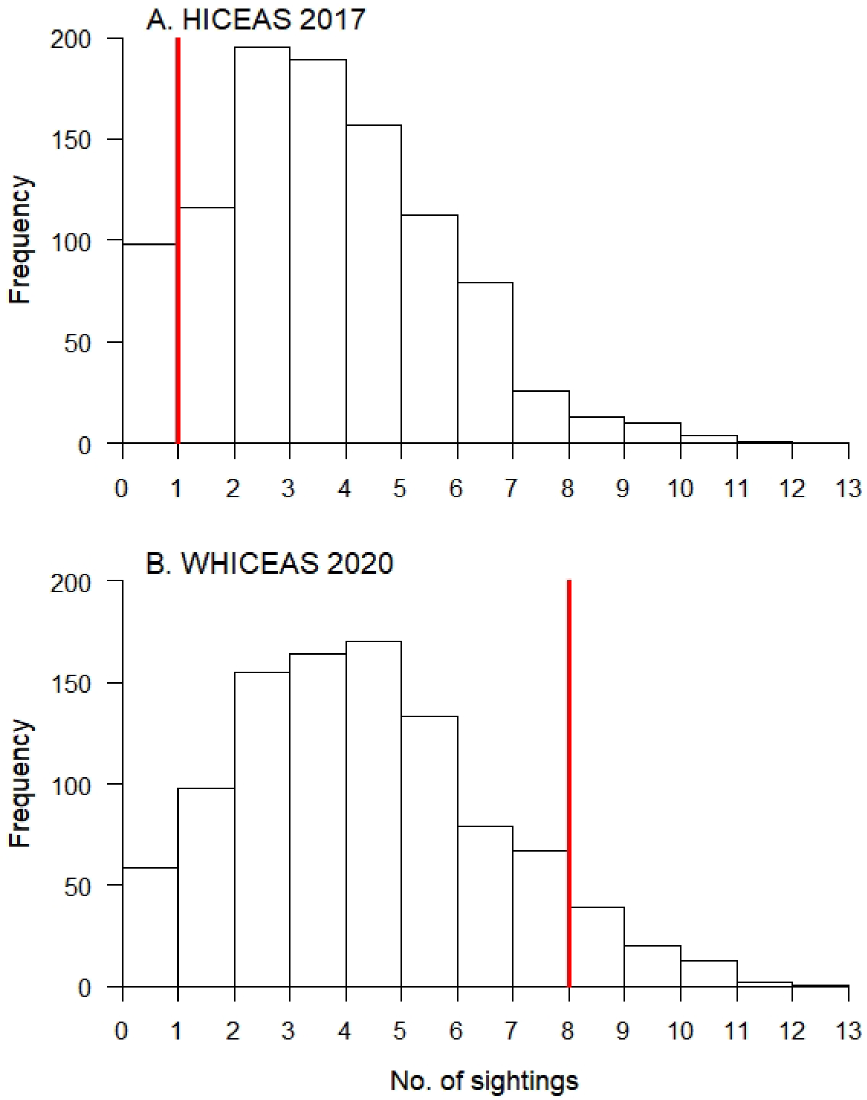

Figure B 1. Distribution of the simulated number of sightings of sperm whales in the winter Hawaiian Islands Cetacean and Ecosystem Assessment Survey (WHICEAS) study area resulting from the bootstrap for (A) HICEAS 2017 and (B) WHICEAS 2020, representing the distribution of sightings that could be expected if sperm whale abundance was constant during each survey.

The number of systematic-effort sightings used in the abundance estimation for each year is represented by the red line.