

# Chapter 6 Marine Mammals

## CETACEANS

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## HAWAIIAN MONK SEAL

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False killer whale. Photo credit: Robin W. Baird (Cascadia Research Collective)

### ABSTRACT

Marine mammals are ecologically, economically and culturally important to Hawai'i. Reliable information on species space-use patterns is required to inform marine spatial planning, particularly for offshore renewable energy installations. This chapter provides distribution maps for marine mammals observed in the U.S. waters of the Main Hawaiian Islands from 1993 to 2014 using data integrated from multiple sources and spatial predictive modeling. At least 26 species of marine mammal (one seal and 25 cetaceans) have been recorded across the project area, of which eight species are listed as Endangered. This chapter has two sections: 6.1 Cetaceans, and 6.2 Hawaiian monk seal. For cetaceans, maps are provided for 22 species, including 15 showing locations of sightings and seven showing predicted spatial distributions. Sighting data from aircraft, ships and small research vessels were integrated and modeled using non-linear algorithms to map summer and winter distributions. These models were based on the statistical relationships between cetacean abundance and environmental variables at the locations of sightings. Model performance ranged from 17 to 59 percent PDE (percentage deviance explained). Highest performing models were achieved for common bottlenose dolphin (*Tursiops truncatus*; 59% summer), spinner dolphin (*Stenella longirostris*; 56% winter) and humpback whale (*Megaptera novaeangliae*; 37% winter). All categories of predictors (survey platform, temporal, climatic, atmospheric, geographic, physical and biological oceanographic, and topographic), contributed to models, with depth, slope, surface current direction and the strengths of temperature and chlorophyll fronts being relatively important environmental predictors across models. For Hawaiian monk seal (*Monachus schauinslandi*), we provide maps of sighting locations, individual space-use patterns and the newly released critical habitat maps, followed by discussion of priorities for future data collection to support marine spatial planning.

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# Marine Mammals

## 6.1. CETACEANS

### 6.1.1. Introduction

This section of the marine mammal chapter provides concise background information on the cultural significance, conservation status and distributions of cetacean species observed in the waters of the Main Hawaiian Islands (MHI). We then describe our synthesis of the best available sighting data across a 20 year period (1993 to 2013) in U.S. waters around the MHI. These data are used to build spatial predictive models for mapping suitable habitat as new representations of species distributions. This study is unique in its combination of broad geographical scale (project area = 860,250 km<sup>2</sup>) and relatively fine spatial resolution distribution maps (1.2x1.2 km grid cells), and because of the integration of a large number (n=46) of diverse predictors including: survey characteristics, temporal variables including climate indices, geographic variables such as distance to features, seafloor topography variables, and physical and biological oceanographic variables. Our study is also unique in its integration of sighting data from multiple research groups using different survey platforms (i.e., ships, small vessels, and aircraft).

#### *Cultural significance*

Whales, called koholā in Hawaiian, hold a sacred place within native Hawaiian spirituality, as illustrated by their inclusion in the Kumulipo, the native Hawaiian chant of creation. Whales represent the largest ocean manifestation of Kanaloa, god of the ocean realm, ocean animals, and fresh water underground (Lebo, 2010). The cultural importance of the koholā is also prominent in Hawaiian oral and written history through legends, place names, artifacts and rock carvings (petroglyphs). The sperm whale (*Physeter macrocephalus*), palaoa, were highly prized for their ivory which were used as fishhooks and pendants. Whale ivory from animals that washed ashore was considered sacred and garlands made of whale tooth, lei niho palaoa, were symbols of status.



Sperm whale, *Physeter macrocephalus*. Photo credit: Robin W. Baird (Cascadia Research Collective)

#### *Cetacean population status and spatial distributions*

Twenty-five species of cetacean (seven baleen whales and 18 toothed whales and dolphins) have been sighted in Hawaiian waters, of which seven are listed as Endangered, eight recognized as depleted under the Marine Mammal Protection Act (MMPA) and six listed on Convention on International Trade in Endangered Species (CITES) Appendix I as threatened with extinction (Table 6.1).

The calving and breeding population of humpback whales (*Megaptera novaeangliae*) is the most seasonally abundant large whale in Hawaiian waters traveling from Alaska to overwinter in Hawai'i. Commercial whaling began in the Hawaiian Islands in 1819 when two New England ships became the first whaling ships to arrive, and by 1846 as many as 596 ships were actively whaling in the region. By the 20th century, the population of large whales, particularly humpback whales, was severely depleted with an estimated population of approximately 1,000 animals, compared with a pre-whaling population of 15,000 animals (Rice, 1978). In 1966, the International Whaling Commission gave legal protection to humpback whales from commercial whaling and in 1972 and 1973, the MMPA and the U.S. Endangered Species Act (ESA) recognized humpback whales as endangered, making it illegal to hunt, harm, or disturb them. In 1992, U.S. Congress established the Hawaiian Islands Humpback Whale National Marine Sanctuary, recognizing the important role that the Hawaiian Islands play in the



Humpback whale, *Megaptera novaeangliae*. Photo credit: Robin W. Baird (Cascadia Research Collective).

Table 6.1. Conservation status of twenty-five species of cetacean sighted around the Main Hawaiian Islands. ESA= Endangered Species Act, MMPA= Marine Mammal Protection Act, CITES= Convention on International Trade in Endangered Species. \* Refers to CITES appendices.

Family	Scientific Name	Common Name	ESA Status	MMPA Status	CITES*
Delphinidae	<i>Stenella attenuata</i>	Pantropical spotted dolphin	None	Protected	Appendix II
	<i>Stenella coeruleoalba</i>	Striped dolphin	None	Protected	Appendix II
	<i>Stenella longirostris</i>	Spinner dolphin	None	Protected	Appendix II
	<i>Steno bredanensis</i>	Rough-toothed dolphin	None	Protected	Appendix II
	<i>Tursiops truncatus</i>	Common bottlenose dolphin	None	Protected	Appendix II
	<i>Grampus griseus</i>	Risso's dolphin	None	Protected	Appendix II
	<i>Lagenodelphis hosei</i>	Fraser's dolphin	None	Protected	Appendix II
	<i>Peponocephala electra</i>	Melon-headed whale	None	Protected	Appendix II
	<i>Feresa attenuata</i>	Pygmy killer whale	None	Protected	Appendix II
	<i>Pseudorca crassidens</i>	False killer whale	Endangered <sup>1</sup>	Depleted <sup>1</sup>	Appendix II
	<i>Globicephala macrorhynchus</i>	Short-finned pilot whale	None	Protected	Appendix II
	<i>Orcinus orca</i>	Killer whale	None	Protected	Appendix II
Physeteridae	<i>Physeter macrocephalus</i>	Sperm whale	Endangered	Depleted	Appendix II
Kogiidae	<i>Kogia breviceps</i>	Pygmy sperm whale	None	Protected	Appendix II
	<i>Kogia sima</i>	Dwarf sperm whale	None	Protected	Appendix II
Ziphiidae	<i>Mesoplodon densirostris</i>	Blainville's beaked whale	None	Protected	Appendix II
	<i>Ziphius cavirostris</i>	Cuvier's beaked whale	None	Protected	Appendix II
	<i>Indopacetus pacificus</i>	Longman's beaked whale	None	Protected	Appendix II
Balaenopteridae	<i>Balaenoptera acutorostrata</i>	Minke whale	None	Protected	Appendix I
	<i>Balaenoptera edeni</i>	Bryde's whale	None	Protected	Appendix I
	<i>Megaptera novaeangliae</i>	Humpback whale	Endangered <sup>2</sup>	Depleted	Appendix I
	<i>Balaenoptera physalus</i>	Fin whale	Endangered	Depleted	Appendix I
	<i>Balaenoptera borealis</i>	Sei whale	Endangered	Depleted	Appendix II
	<i>Balaenoptera musculus</i>	Blue whale	Endangered	Depleted	Appendix I
Balaenidae	<i>Eubalaena japonica</i>	North Pacific right whale	Endangered	Depleted	Appendix I

<sup>1</sup> Refers to insular population.

<sup>2</sup> There is a current proposal to divide North Pacific humpback whales into four distinct population segments (DPS), with the Hawai'i DPS no longer being listed as endangered or threatened under the ESA (Federal Register, 2015a).

preservation and long-term viability of the humpback whale. The size of the Central North Pacific population visiting Hawaiian waters has now been estimated at over 10,000 individuals and Hawai'i has been recognized as a distinct breeding area for whales that migrate to summer feeding grounds in Alaska, northern British Columbia and the Bering Sea (Barlow et al., 2011). There is a current proposal to divide North Pacific humpback whales into four distinct population segments (DPS), with the Hawai'i DPS no longer being listed as endangered or threatened under the ESA (81 FR 14820; Federal Register, 2015a).

Not all cetaceans are seasonal visitors. Several studies have identified island-associated populations within wide-ranging pelagic species, such as spinner dolphins (*Stenella longirostris*; Andrews et al., 2010), rough-toothed dolphins (*Steno bredanensis*; Baird et al., 2008a), and false killer whales (*Pseudorca crassidens*; Baird et al., 2008b). In fact, three discrete populations of false killer whales have been identified in Hawaiian waters: a main Hawaiian Islands insular population, a Northwestern Hawaiian Islands insular population, and a pelagic population (Baird et al., 2013b; Bradford et al., 2015; Carretta et al., 2015). Among these false killer whale populations a large proportion of individuals have been documented moving among islands at distances up to 283 km (Baird et al., 2008b). Melon-headed whales (*Peponocephala electra*) also have discrete sub-populations which appear to exist as a smaller, resident population over shallower nearshore waters and a larger population, seen throughout the MHI over deeper waters (Aschettino et al., 2012; Woodworth et al., 2012).

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In total, 11 species of odontocetes (toothed whales) are known to have, or there is some evidence to support the existence of, resident populations in the MHI on the basis of sighting data, genetic studies and satellite tagging including: dwarf sperm whale (*Kogia sima*), Blainville's beaked whale (*Mesoplodon densirostris*), Cuvier's beaked whale (*Ziphius cavirostris*), pygmy killer whale (*Feresa attenuata*), short-finned pilot whale (*Globicephala macrorhynchus*), melon-headed whale, false killer whale, pantropical spotted dolphin (*Stenella attenuata*), spinner dolphin, rough-toothed dolphin and common bottlenose dolphin (*Tursiops truncatus*; Baird et al., 2015). Three species (common bottlenose dolphin, spinner dolphin, and false killer whale) are regularly found in shallow (<50 m) nearshore waters, and four species (striped dolphins [*Stenella longirostris*], sperm whales, rough-toothed dolphins and pantropical spotted dolphins) are more commonly associated with deep (>3,000 m) offshore waters (Baird et al., 2013a).



Striped dolphins, *Stenella longirostris*. Photo credit: Greg Schorr (Cascadia Research Collective)

Several previous studies have focused on multi-species cetacean distributions to identify priority areas. Becker et al. (2012) and Forney et al. (2015) modeled cetacean distributions using National Oceanic and Atmospheric Administration (NOAA) sighting data associated with 10 km transect segments across the central Pacific Ocean. Using information from extensive studies of odontocete distributions and behavior in Hawaiian waters since 2000, Baird et al. (2015) designated 20 biologically important areas (BIAs) for resident populations of the 11 species of odontocetes, as well as a seasonal BIA representing important reproductive areas for humpback whales. All BIAs can be viewed via an online interactive map (<http://cetsound.noaa.gov/important>). Metadata tables detail the type and quantity of information used to define the BIAs (Van Parijs et al., 2015).



Cuvier's beaked whale, *Ziphius cavirostris*. Photo credit: Daniel Webster (Cascadia Research Collective)

## Environmental context

The MHI (Figure 6.1) exist in a subtropical biogeographic region (Insular Pacific-Hawaiian Large Marine Ecosystem) characterized by relatively stable ocean conditions, low oceanic productivity, seamounts and a diverse narrow insular shelf (Chapter 2). Little is known about the seascape patterns and processes that drive cetacean distributions in the MHI. In deeper offshore waters, oceanic frontal zones, eddies and seamounts are likely to be important features of biophysical convergence (Scales et al., 2014). Closer to shore, sheltered inshore habitats such as coral reefs, shallow banks, seagrass beds and nearshore hydrodynamic features that aggregate prey are likely to be important. For example, studies on movements of toothed whales suggest that eddies in the leeward side of islands are used by melon-headed whales (Woodworth et al., 2012), and offshore populations of false killer whales feed at seamounts where large prey fish are abundant (Baird et al., 2008c). The study presented here quantified a wide range of spatial predictors to represent offshore and nearshore oceanographic characteristics, as well as seafloor topography and shallow-water habitat types to examine correlations with locations of species sightings. Distance to land and distance to seamounts were also included as geographic predictor variables.

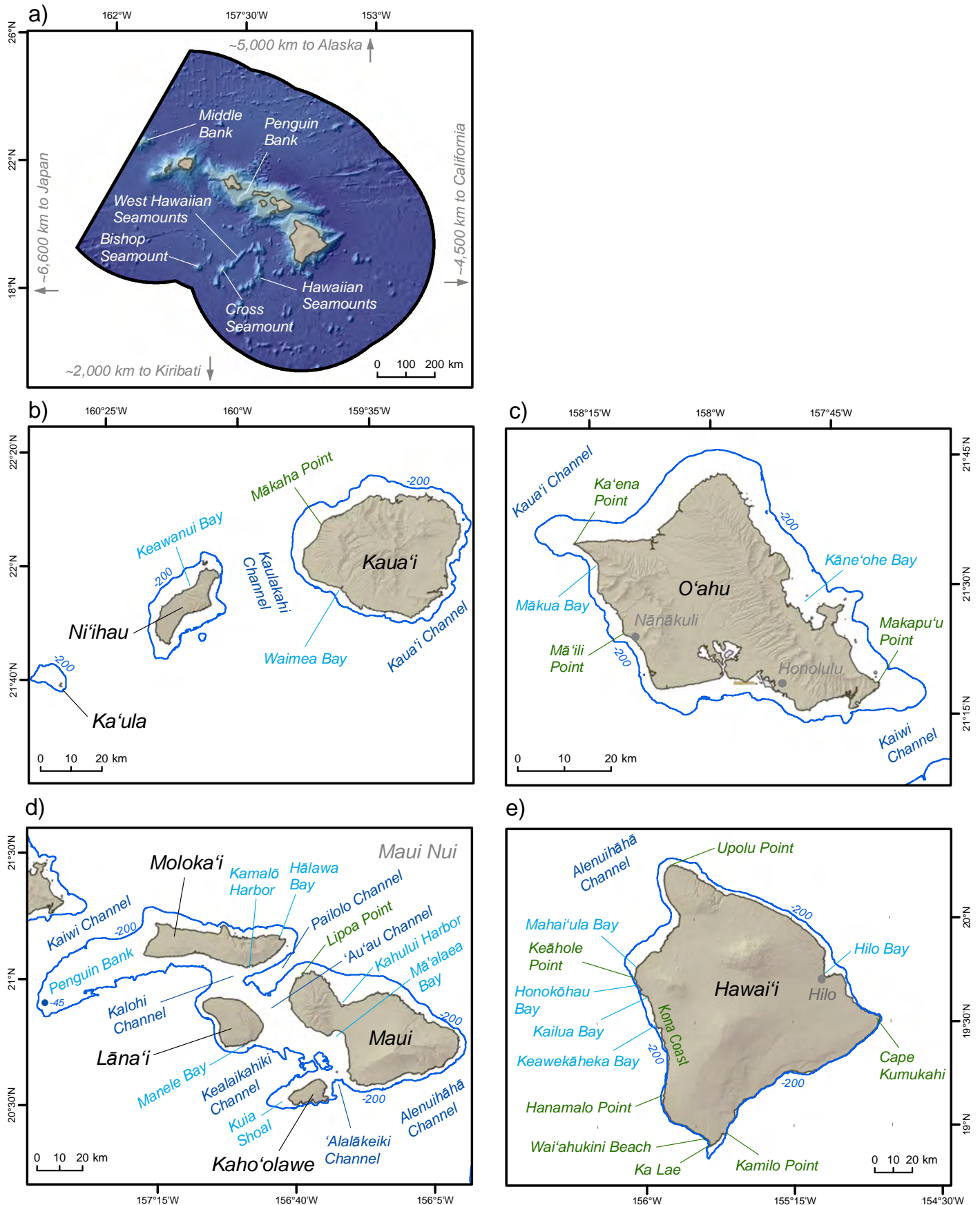


Figure 6.1. Key geographic features and place names around the MHI. These maps depict geographic features that are referenced in this chapter for: a) the project area; b) Ka'ula, Ni'ihau and Kaua'i; c) O'ahu; d) Maui Nui, which includes Moloka'i, Lāna'i, Maui and Kaho'olawe; and e) Hawai'i. All depths are in meters. Data sources: shoreline (Battista et al., 2007), elevation (USGS, 2015) and depths (NOAA NCEI, 2005; GEBCO, 2008)

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## 6.1.2. Methods

### *Survey data*

We analyzed visual at-sea cetacean sighting data from three sources: 1) NOAA National Marine Fisheries Service (NMFS) Pacific Islands Fisheries Science Center (PIFSC) and Southwest Fisheries Science Center (SWFSC), 2) Cascadia Research Collective, and 3) J. Mobley (University of Hawai'i at Mānoa). The combined dataset provided cetacean sightings across a 20 year period (1993 to 2013). Here we describe the data sets from each source, data processing to standardize data, and the spatial modeling techniques.

### NOAA National Marine Fisheries Service data

NMFS survey data used here were collected between 2002 and 2013 (Figure 6.2a). The majority of these data were collected on two systematic ship surveys conducted in 2002 and 2010, the Hawaiian Islands Cetacean and Ecosystem Assessment Surveys (HICEAS; Barlow, 2006; Bradford et al., 2014), which covered the study area with widely spaced transects (Figure 6.2a). The NOAA vessel data were the only spatially extensive surveys for offshore U.S. managed waters. There were also data from other NOAA ship surveys that transited in and out of the study area en route to other survey locales, and from small boat surveys conducted between 2007 and 2013. The small boat surveys were conducted closer to shore with more limited geographic coverage. Most of the NMFS survey effort was from February, May, and September to November (Forney et al., 2015). Data from ship surveys were collected continuously using line transect distance-sampling protocols (Buckland et al., 2001; Barlow, 2006), while small boat surveys generally followed less structured transects recording continuous sighting data. Following NMFS analyses of their line transect data (e.g., Barlow, 2006), we excluded sightings of dolphins, small whales, and large whales whose perpendicular distance from the trackline exceeded 5.5, 4.0 and 5.5 km, respectively.

### Cascadia Research Collective

Multi-species surveys of odontocetes were conducted from small boats (5.5 to 18 m length) between 2000 and 2012. These data are the most geographically intensive surveys for resident populations of odontocetes. Survey vessels operated from approximately 15 to 30 km h<sup>-1</sup>, with two to six observers scanning 360° around the vessel. A global positioning system (GPS) logged locations every 5 minutes while on effort (Baird et al., 2013a). Survey effort was distributed throughout the year, with most effort in April, May, August, October, and December, and the least in January, February, March and September (Figure 6.2b). The surveys were mainly conducted on the leeward sides of all eight of the MHI islands in Beaufort sea states of 3 or less. Greatest effort was applied in three regions: southwest coast of the island of Hawai'i (Kona), west Maui and west Kaua'i (Figure 6.3). The survey transects did not follow a systematic design and often included periods of approaching or following animals for the purposes of species identification, group size estimation, photo-identification of individuals and tagging (Baird et al., 2008a, b). Sighting data were recorded continuously. Sighting cues were sometimes non-visual (e.g., reports from other vessels or acoustic detections; Baird et al., 2008b), so we excluded those sighting data from our analysis. The species focus was mainly odontocetes, but baleen whale sighting data were also collected. Humpback whales were not recorded consistently so this species was not included in this dataset. Cascadia Research Collective has also conducted tracking studies of multiple cetacean species (common bottlenose dolphin, Blainville's beaked whale, Cuvier's beaked whale, false killer whale, short-finned pilot whale, pygmy killer whale, melon-headed whale, rough-toothed dolphin and sperm whale) in Hawaiian waters (Baird et al., 2009b, 2010, 2012a, b, 2015; Schorr et al., 2009; Woodworth et al., 2012; Rone et al., 2015). For this project, only visual sighting data were included in the analyses.



*Melon-headed whale, Peponocephala electra (left) and pygmy killer whale, Feresa attenuata (right). Photo credit: Robin W. Baird (Cascadia Research Collective; left) and NOAA NMFS/SWFSC (right).*

## Aerial surveys

Aerial surveys by light aircraft led by Professor J. Mobley of the University of Hawai'i at Mānoa were conducted in 1993, 1995, 1998, 2000 and 2003 during the peak season (February to April) for humpback whales (Figure 6.2c). Surveys were conducted relatively nearshore (<50 km from shore) around all eight main islands, with standardized effort collecting continuous sighting data (Mobley et al., 2001). The MHI were divided up into four main regions: 1) Hawai'i; 2) Moloka'i, Maui, Lāna'i and Kaho'olawe; 3) O'ahu and Penguin Bank; and 4) Kaua'i/Ni'ihau where surveys typically covered one region per day covering depths from less than 100 fathoms to more than 1,000 fathoms. Greatest effort due to overlapping flight paths across multiple years occurred in a region southeast of O'ahu (Figure 6.3). Surveys were flown at an average altitude of 816 feet ( $\pm 124$  standard deviation [SD]) along north-south lines placed 26 km apart and extending from shore to

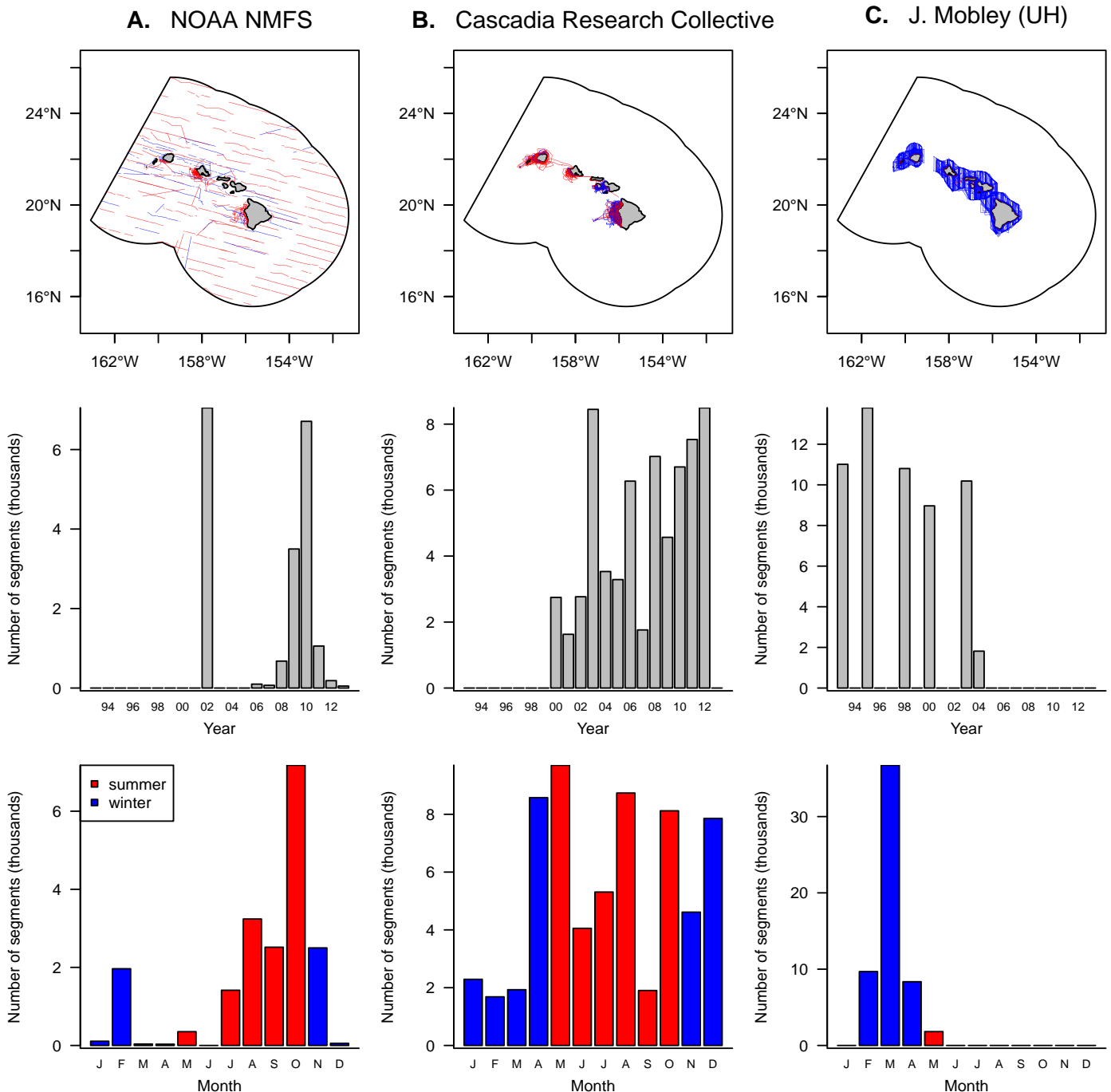


Figure 6.2. Cetacean survey effort showing transects and number of 1.2 km transect segments by season (summer and winter) for the Main Hawaiian Islands conducted by: a) NOAA NMFS ship and small boat surveys, b) Cascadia Research Collective small boat surveys, and c) aerial surveys led by J. Mobley, University of Hawai'i at Mānoa.

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13 km past the 1,000 fathom limit (average of 46 km offshore). Location data from an onboard GPS receiver and altitude data from a radar altimeter were downloaded directly onto a laptop computer. One observer searched on each side of the aircraft and communicated verbally with a data recorder. Identification of species of a given sighting was made only when diagnostic features could be clearly identified. In cases where such features were not clearly visible, or when there was a dispute over species identity, the sighting was recorded as an unidentified dolphin, whale, or cetacean. In total, 16 cetacean species were identified. For more details see Mobley et al. (2001). In addition, a discrete spinner dolphin-focused survey was conducted during May 2004 on the northwest coast of Hawai'i, the Kealaikahiki Channel between Lāna'i and Kaho'olawe, 'Au'au Channel between Maui and Lāna'i, Kalohi Channel separating Lāna'i and Moloka'i, the entire coast of O'ahu, north Kaua'i, and nearshore Ni'ihau.

Figures 6.3 and 6.4 highlight the differences and overlap of sampling effort distributions by depth strata and distance to shore among survey platforms. The Cascadia Research Collective data and aerial surveys show a nearshore bias compared with NOAA ship-based surveys that covered a far greater geographical extent and sampled over deeper waters.

## Data processing

To standardize across datasets, the data were discretized into 1.2 km transect 'segments' corresponding to the dimensions of a Bureau of Ocean Energy Management (BOEM) aliquot (Appendix B). Cetaceans were recorded on 138,813 transect segments (84,513 winter and 54,300 summer). The number of individuals of each species sighted was summed for each segment, and these 'counts' were the response variable for modeling. In the case of the NMFS survey data, our counts represented the sum of rounded mean group size estimates (average of observers' 'best' group size estimates). The midpoint of a segment was used as the location of the summed counts.

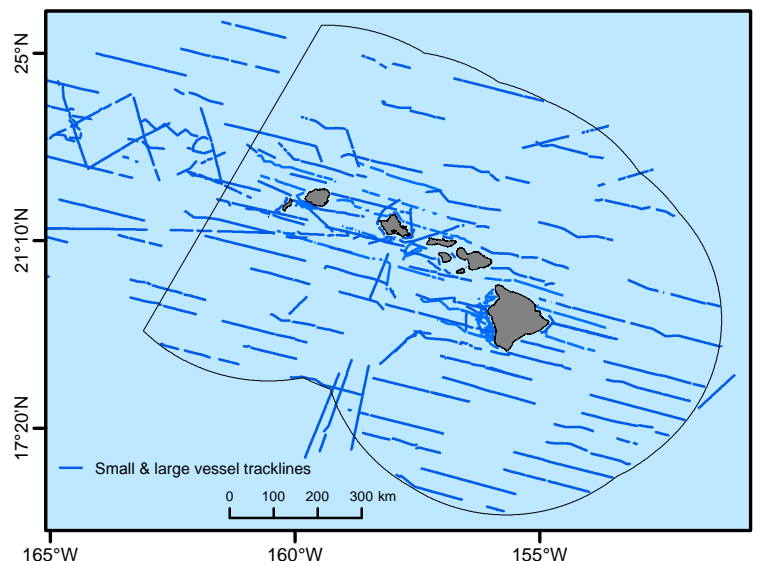
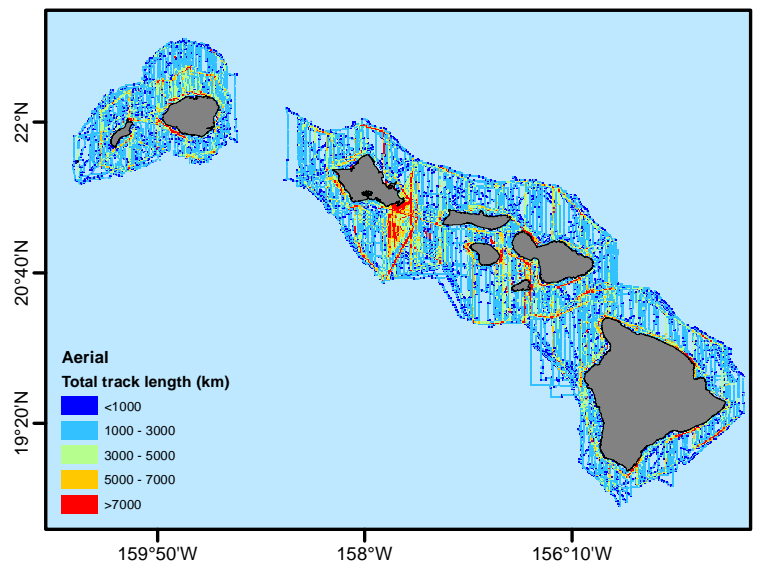
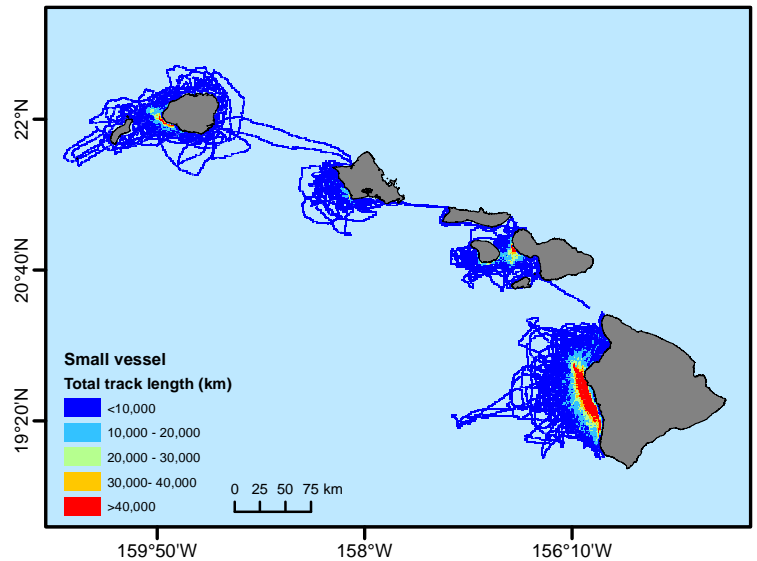


Figure 6.3. Survey effort as total track length per 1.2 km grid cell for: small vessels used by Cascadia Research Collective (top), aerial surveys led by J. Mobley, University of Hawai'i at Mānoa (middle), and individual tracklines for vessels used by NOAA NMFS (bottom).



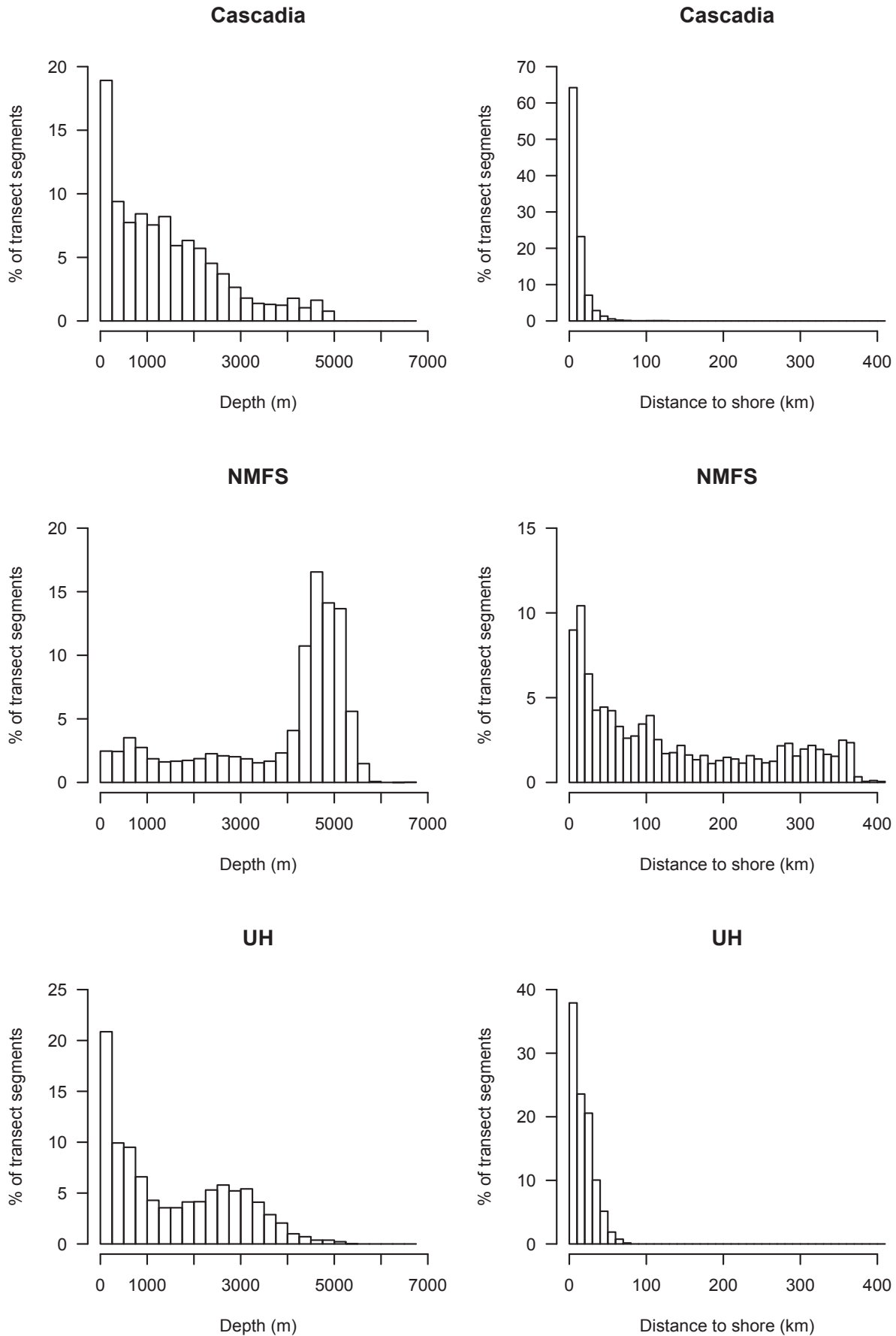


Figure 6.4. Distribution of sampling effort across depth strata and with distance to the nearest coastline for Cascadia Research Collective (top); NOAA NMFS (middle); and J. Mobley, University of Hawai'i at Mānoa (bottom).

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## Spatial predictive modeling and mapping

In Hawaiian waters, most species of cetaceans occur at low density with survey effort being patchy in time and space, resulting in a limited ability to reliably determine distribution patterns across the entire project area from sightings alone. To address this challenge, spatial predictive models were used to create maps of distributions based on habitat suitability. We created seasonal (summer or winter) models for species-season combinations that had  $\geq 50$  transect segments per season with sightings of  $\geq 1$  individual. By this criterion, seven species and 12 species-season combinations were considered (Table 6.2). Other species with fewer sightings were mapped as points showing where the sightings were located (Table 6.2). Several species that occur in the region were not recorded within the dataset used here, including blue whale (*Balaenoptera musculus*), North Pacific right whale (*Eubalaena japonica*), and minke whale (*Balaenoptera acutorostrata*).

Table 6.2. Number of transect segments with cetacean sightings used to identify species suitable for spatial predictive modeling of distributions around the MHI. Source: NOAA NMFS, Cascadia Research Collective and University of Hawai'i at Mānoa sighting data.

Common Name	No. of Transect Segments with Sightings		Assessment Technique
	Summer	Winter	
Humpback whale	7	2098	Winter model
Short-finned pilot whale	327	235	Summer & winter models
Pantropical spotted dolphin	212	226	Summer & winter models
Common bottlenose dolphin	144	142	Summer & winter models
Rough-toothed dolphin	166	74	Summer & winter models
Spinner dolphin	103	121	Summer & winter models
Sperm whale	18	54	Winter model
Cuvier's beaked whale	29	41	Point data map
Dwarf sperm whale	46	24	Point data map
False killer whale	24	40	Point data map
Melon-headed whale	33	25	Point data map
Striped dolphin	36	14	Point data map
Blainville's beaked whale	29	24	Point data map
Pygmy killer whale	24	15	Point data map
Risso's dolphin	13	4	Point data map
Pygmy sperm whale	4	3	Point data map
Bryde's whale	4	1	Point data map
Sei whale	1	3	Point data map
Killer whale	2	1	Point data map
Fraser's dolphin	1	1	Point data map
Longman's beaked whale	2	0	Point data map
Fin whale	0	2	Point data map
Minke whale	0	0	None
Blue whale	0	0	None
North Pacific right whale	0	0	None

## Predictor variables

A wide range of predictor variables was used to model variation in the number of individuals sighted per transect segment, and to predict relative abundance throughout the study area. Categories of predictor variables included: survey, temporal, geographic, seafloor topography, physical and biological oceanographic, and atmospheric (Appendix B). Details of environmental variables are provided in Chapter 2.

Survey predictor variables were designed to account for variation in the type and characteristics of survey platform (e.g., observation height and method), observer identity and expertise, species focus, and sighting conditions. Temporal predictor variables were designed to account for variation in counts over time (i.e., day and year). Three climate indices (i.e., Pacific Decadal Oscillation, North Pacific Gyre Oscillation and Multivariate El Niño-Southern Oscillation) were also included as temporal predictor variables. Geographic predictor variables were designed to account for variation in counts arising from spatial location (i.e., longitude and latitude, distance to land, distance to seamounts). Seafloor topography variables (i.e., depth, slope, topographic complexity and curvature), physical and biological oceanographic variables, and atmospheric variables were developed from a range of data sources (see Chapter 2) to characterize the environmental conditions across the project area. The midpoint of a survey transect segment was used to spatially extract environmental predictor values from the corresponding project grid cell.

## Modeling algorithm

A Boosted Zero-inflated Count (BZIC) Generalized Additive Modeling framework (Bühlmann and Hothorn, 2007; Hofner et al., 2014) was used to relate the survey count data to predictor variables (Appendix B, Figure B.1.). The estimated relationships between the number of individuals of each modeled species counted on each transect segment and the predictor variables were then used to predict the ‘relative abundance’ of these species across the entire study area. Relative abundance was defined as the expected number of individuals that would be counted per km travelled. Spatially explicit predicted values were calculated for each cell of the study grid from the values of the spatially explicit predictor variables for that cell. Thus, the predicted relative abundance in a given grid cell corresponded to predictions for a transect segment whose mid-point falls within that grid cell. For winter models, a 50 km buffer around a minimum convex hull of the survey effort locations was used to exclude predictions which were adversely effected by the absence of survey effort near the edges of the study area.

Our primary modeling objective was to provide the best estimates of at-sea distributions. The statistical modeling framework that we chose had several key features, that in combination provided advantages over alternative modeling approaches given this objective. First, the framework used appropriate statistical distributions to model counts of potentially aggregated animals. Second, the framework allowed for highly flexible relationships between expected counts and a large number (n = 46) of predictor variables, including complex multi-way interactions between predictor variables. Third, the framework accounted for differences in the data collection process between and within datasets.

It is important to recognize that modeled relative abundance does not equate to absolute abundance because individual animals may be missed during visual surveys, and animal movement can bias estimates of abundance. Our model predictions should only be interpreted as indices of abundance.

## Model performance

The performance of each model was evaluated from a suite of performance metrics. The key performance metric was percent deviance explained (PDE) which indicates overall model fit and is analogous to the more familiar R<sup>2</sup> metric for a linear regression. The model with the highest PDE was chosen as the final model. Three additional performance metrics were calculated for each of the final models to provide a more complete assessment of model performance (Table 6.3). Model performance is displayed in the top right corner of each map figure (i.e., Figures 6.10-6.13, 6.15-6.22). The model performance metrics reflect the statistical fit of the models to the data. Performance categories were defined for each performance metric and assigned a numeric code (5 = highest to 1 = lowest). The performance of each final model was assigned an

Table 6.3. Model performance metrics. Metrics reflect the statistical fit of a model to the data; they do not necessarily reflect the accuracy of predictions away from the data.

Name	Description	Data	Stage	Performance categories
PDE	percent deviance explained <sup>1</sup>	all	final fit	5: ≥60% 4: 40-60% 3: 20-40% 2: 10-20% 1: <10%
AUC	area under the receiver operating characteristic curve	all, converted to presence/absence	final fit	5: >0.9 4: 0.8-0.9 3: 0.7-0.8 2: 0.6-0.7 1: <0.6
Rank r	Gaussian rank correlation coefficient <sup>2</sup>	non-zero	final fit	5: >0.6 4: 0.4-0.6 3: 0.2-0.4 2: 0.1-0.2 1: <0.1
Percent error	median absolute residual error as percentage of data mean	non-zero, out-of-bag	during tuning of the number of boosting iterations <sup>3</sup>	5: <25% 4: 25-50% 3: 50-100% 2: 100-200% 1: >200%

<sup>1</sup> To calculate percent deviance explained, the saturated likelihood was assumed to be the maximum possible likelihood value, and the null likelihood was calculated from an intercepts-only zero-inflated model fit to the data (unpublished).

<sup>2</sup> Boudt et al. (2012) and Bodenhofer et al. (2013)

<sup>3</sup> Median value across cross-validation replicates

# Marine Mammals

overall performance equal to the average performance across the four performance metrics. Precision of model predictions was determined using a bootstrap procedure (Appendix B). Specifically, the coefficient of variation (CV) for all spatial predictions was mapped to the analytical grid to allow examination of relative precision in the predicted relative abundance maps.

## Predictor variable importance

While our primary objective was not to determine the ecological drivers and mechanisms behind the spatial distributions of cetaceans in the study area, our model results do provide measures of variable importance. The relative importance of each predictor variable in a given model essentially reflects the amount of variation in the data explained by each variable. Relative variable importance was re-scaled so that it summed to 1 across predictor variables.

### 6.1.3. Results and Discussion

First, we show mapped locations for cetacean species with occurrence observed on less than 50 transect segments within a season (*Non-modeled species distributions*). Next, we present the results of spatial predictive models (*Modeled species distributions*) using data on species sighted on more than 50 transect segments in a season.

#### *Non-modeled species distributions*

The data presented here for non-modeled species represent the midpoints of survey transect segments on which each species was sighted in each season. It is important to note that the distributions of these sightings partially reflects the amount and distribution of effort in each season. Differences in the distribution of sightings for a single species between seasons, or in the number of sightings between areas within a season, do not necessarily indicate differences in the distribution of relative abundance of that species. These sighting data were not effort-corrected, so comparison of sightings between seasons should not be attempted due to differences in winter and summer survey effort. Furthermore, there was less survey effort offshore (Figure 6.3), so even if the abundance of a species offshore was similar to the abundance nearshore, the expected number of sightings would be lower.

Several species of toothed whales exhibited year round (winter and summer) nearshore spatial occurrence around all island groups including: Cuvier's beaked whale (142 animals across 70 segments), Blainville's beaked whale (193 animals across 50 segments), dwarf sperm whale (184 across 69 segments), pygmy killer whale (411 across 37 segments), pygmy sperm whale (*Kogia breviceps*; 25 across 7 segments) and melon-headed whale (13,164 across 53 segments). The highest number of sightings was observed in an area with high survey effort off the west coast of the island of Hawai'i. All of the less frequently sighted cetacean species ( $n = 11$ ) have been observed off the west coast of the island of Hawai'i, suggesting that this area has high importance for cetacean diversity regardless of the bias in survey effort. As such, waters off the west coast of Hawai'i have been identified as a year-round BIA for 11 odontocetes (Baird et al., 2015). Although most effort and sightings were leeward of the islands, several windward sightings were also recorded for Cuvier's and Blainville's beaked whales (Figure 6.5). In contrast, striped dolphin (1,590 across 47 segments) appeared to exhibit a wider distribution than other species, with more sightings offshore, including the southern and northern extremities of the project area (Figure 6.5). Similarly, Risso's dolphin (*Grampus griseus*; 243 across 17 segments) appeared to be more widely distributed offshore, at least in summer months, notably with sightings in the deeper waters and near seamounts to the south and southwest of the island of Hawai'i (Figure 6.6). It is difficult to interpret seasonal differences in the number of offshore sightings because there was less survey effort offshore in winter (Figure 6.2).

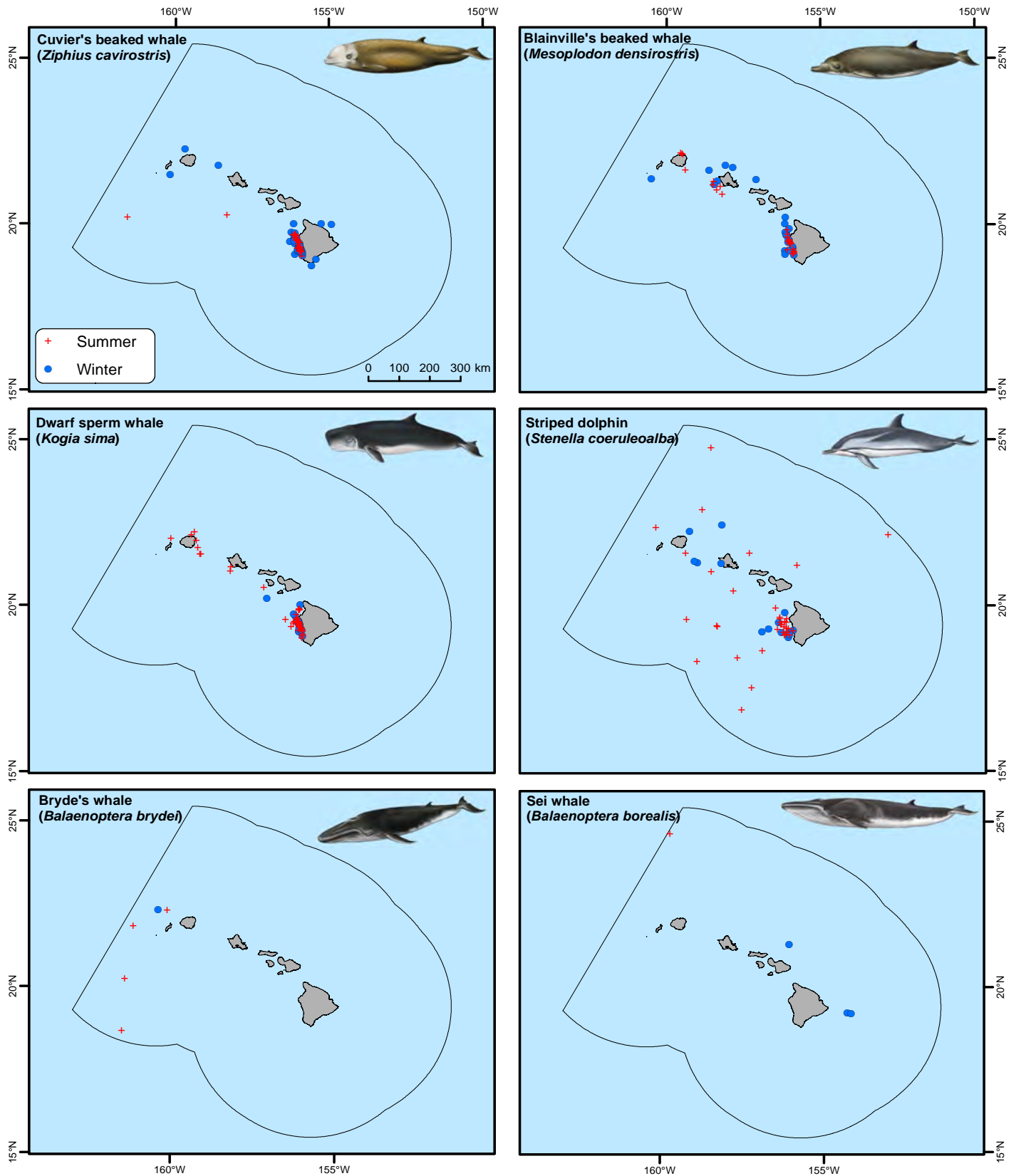


Figure 6.5. Cetacean sighting locations for non-modeled species for summer (May to October) and winter (November to April) seasons across the Main Hawaiian Islands project area (years 1993-2013). The amount and distribution of survey effort differed between seasons and between nearshore and offshore areas (Figures 6.2 and 6.3), so seasonal and spatial differences in the number of sightings do not necessarily reflect differences in relative abundance. Sighting data sources: Cascadia Research Collective, NOAA NMFS/SWFSC and PIFSC, and J. Mobley, University of Hawai'i at Mānoa. Artwork adapted from original by Justin Hart.

# Marine Mammals

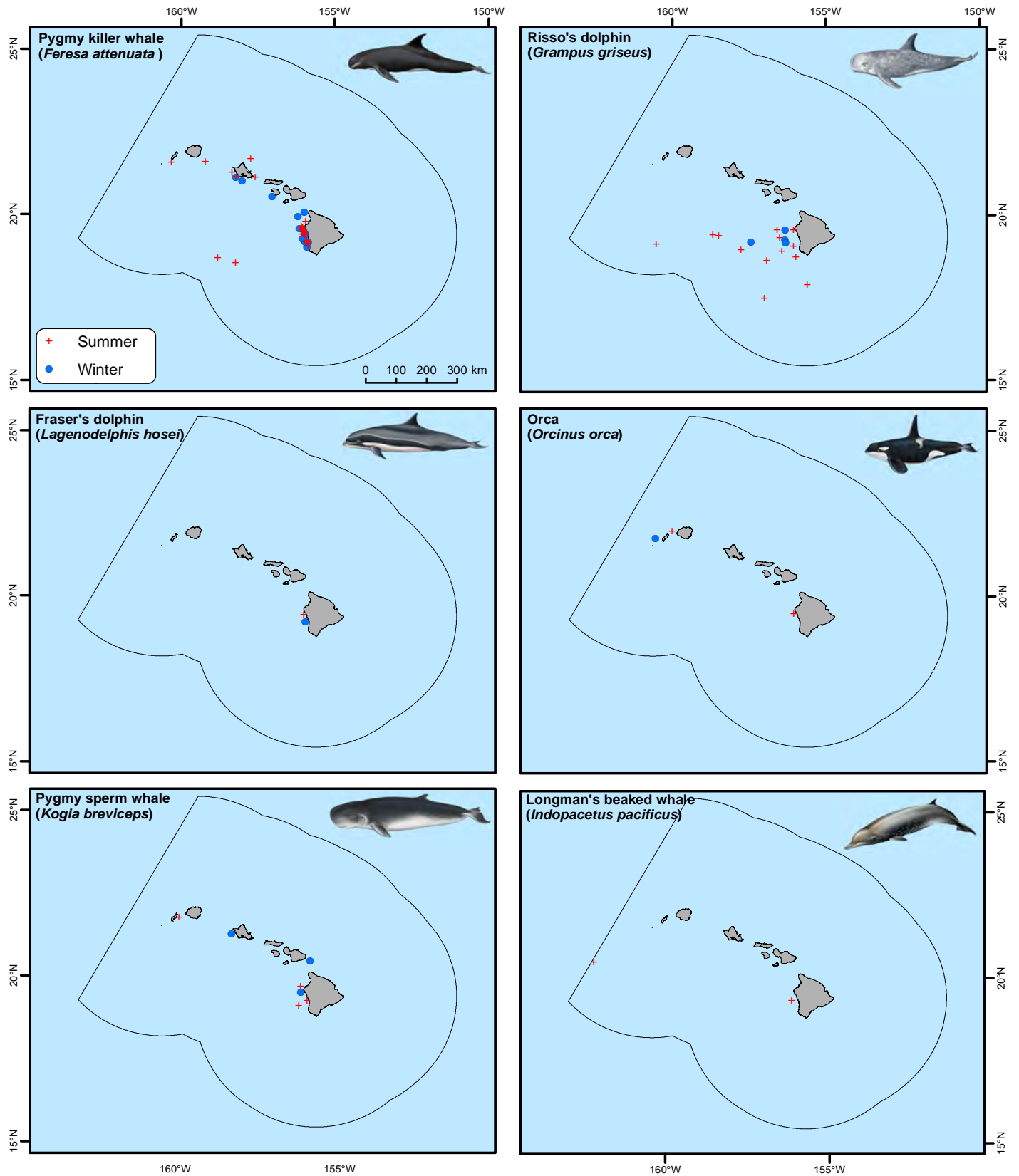


Figure 6.6. Cetacean sighting locations for non-modeled species for summer (May to October) and winter (November to April) seasons across the Main Hawaiian Islands project area (years 1993-2013). The amount and distribution of survey effort differed between seasons and between nearshore and offshore areas (Figures 6.2 and 6.3), so seasonal and spatial differences in the number of sightings do not necessarily reflect differences in relative abundance. Sighting data sources: Cascadia Research Collective, NOAA NMFS/SWFSC and PIFSC, and J. Mobley, University of Hawai'i at Mānoa. Artwork adapted from original by Justin Hart.

Two of the beaked whale species are thought to have distinct insular and offshore populations. The data presented here show two sightings of Cuvier's beaked whales located 100 and 200 km from land (Figure 6.5). Although this nearshore-offshore population distinction is not clearly articulated in the sighting data, previous photo-identification and tracking suggest high spatial association to individual islands for Cuvier's beaked whale (McSweeney et al., 2007; Baird, 2016). For Blainville's beaked whale, one tagged individual from the offshore population traveled from Hawai'i over 900 km to the edge of the Hawaiian Exclusive Economic Zone (EEZ; Baird et al., 2011a), while individuals from the resident population remained associated with the islands of Hawai'i, Maui and Moloka'i (Schorr et al., 2009; Baird, 2016).

There is some evidence to support the occurrence of a small resident population of pygmy killer whales in MHI (McSweeney et al., 2009) that primarily remains within 20 km of the shore (Baird et al., 2011b). Inter-island movements for the resident population are rare (Baird, 2016). Sightings for pygmy killer whales presented here show two sightings (31 and 19 individuals) in summer located more than 200 km from the nearest land (Figure 6.6). It is likely these represent individuals from an offshore (pelagic) population.

Three sightings in the summer season for false killer whale occurred offshore, while the majority of sightings were nearshore in both winter and summer seasons (Figure 6.7). Previous analyses using a combination of sightings, genetic studies and telemetry records indicate that these offshore sightings are individuals from a pelagic population which overlaps in places with the insular nearshore MHI population (Oleson et al., 2010). The discrete MHI insular false killer whale population is considered more vulnerable to extinction than the pelagic population due to statistically significant evidence of recent decline (Baird, 2009; Reeves et al., 2009; Oleson et al., 2010) and threats from human activity (e.g., fisheries and pollutants).



Pod of false killer whales, *Pseudorca crassidens*. Photo credit: NOAA NMFS/SWFSC

Sightings of melon-headed whales were mostly in nearshore waters in summer and winter (Figure 6.7). There were no sightings of individuals in offshore waters more than 50 km from shore, although satellite tracked individuals have been found to travel to more distant deeper offshore waters (Woodworth et al., 2012). Photo-identification, telemetry and genetic analyses suggest there are two demographically-independent populations of melon-headed whales: the Kohala resident stock with high fidelity to the waters (less than 2,500 m depth) off the northwest of the island of Hawai'i, and a broader Hawaiian Islands population with little or no interchange between populations (Aschettino et al., 2012; Oleson et al., 2013; Baird, 2016).

Dwarf sperm whales were only sighted in nearshore waters, with the largest number of sightings west of the island of Hawai'i (Figure 6.5). Studies by Baird et al. (2013a) and Baird (2016) highlight long-term site-fidelity in this region suggesting an island-resident population with all encounters less than 20 km from shore.

Several species were sighted very rarely (winter and summer) and only in offshore waters, such as the Bryde's whale (*Balaenoptera edeni*; far western region of the project area) and sei whale (*Balaenoptera borealis*; north of the island chain; Figure 6.5). Longman's beaked whale (*Indopacetus pacificus*) was sighted twice in summer at one nearshore (west of the island of Hawai'i) and one offshore location (Figure 6.6). Fin whales were only recorded twice during winter months (Figure 6.7).

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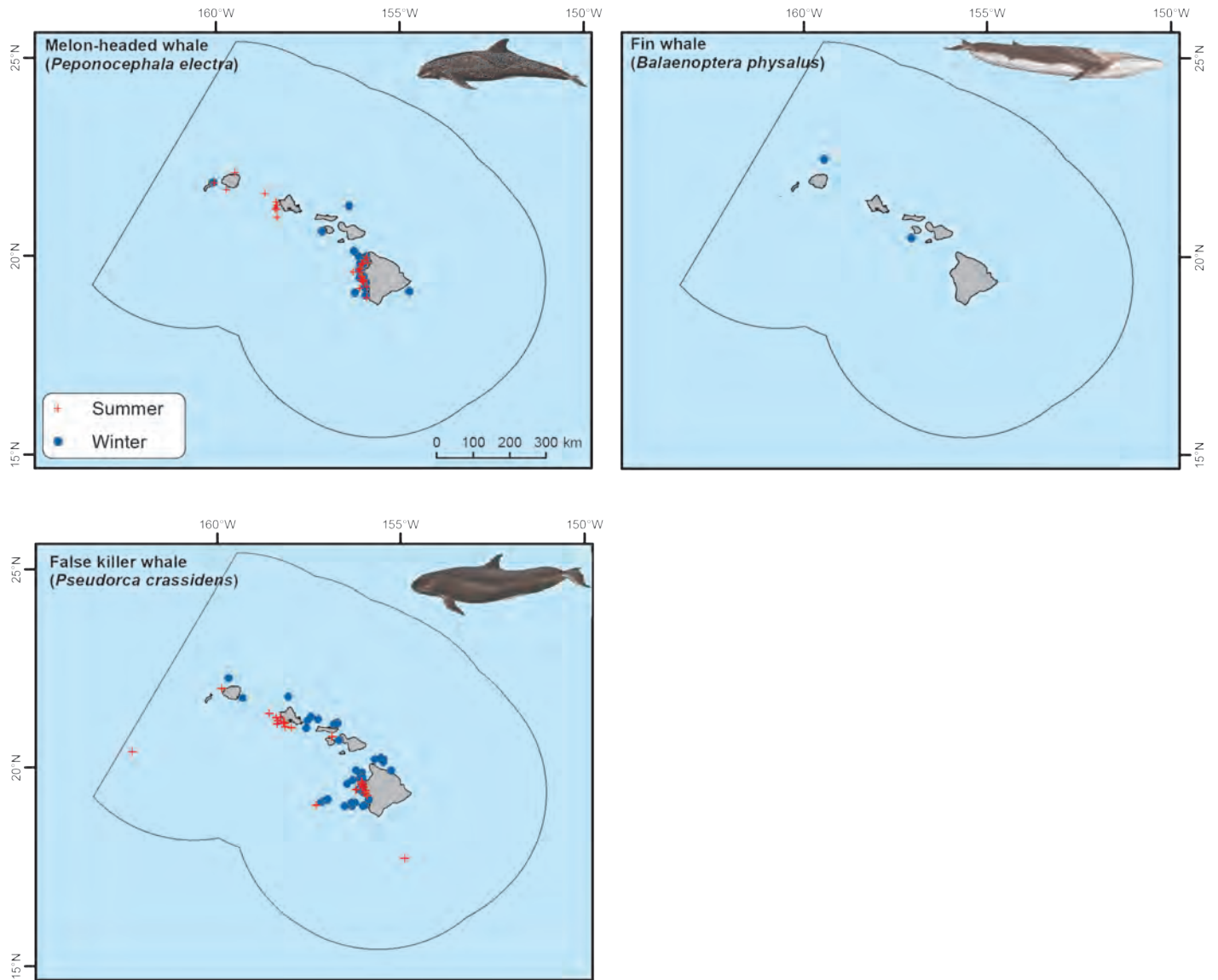


Figure 6.7. Cetacean sighting locations for non-modeled species for summer (May to October) and winter (November to April) seasons across the Main Hawaiian Islands project area (years 1993-2013). The amount and distribution of survey effort differed between seasons and between nearshore and offshore areas (Figures 6.2 and 6.3), so seasonal and spatial differences in the number of sightings do not necessarily reflect differences in relative abundance. Sighting data sources: Cascadia Research Collective, NOAA NMFS/SWFSC and PIFSC, and J. Mobley, University of Hawai'i at Mānoa. Artwork adapted from original by Justin Hart.



## *Modeled species distributions*

A total of 12 spatial predictive models were computed and evaluated resulting in predicted distributions of relative abundance in winter and summer for five species (short-finned pilot whale, pantropical spotted dolphin, common bottlenose dolphin, rough-toothed dolphin and spinner dolphin) and in winter only for two species (humpback whale and sperm whale). Across all final models, the PDE ranged from 17 to 59 percent. Highest (37-59%) PDE was achieved for the summer model (59%) for common bottlenose dolphin, winter (56%) and summer (48%) models for spinner dolphin and the winter model (37%) for humpback whale, with the remaining models ranging from 17-35 percent PDE. Considering a second performance metric, the area under the receiver operating characteristic curve (AUC), most of the models with the highest AUC (=0.91-0.92) were also those with the highest PDE.



*Pantropical spotted dolphin, Stenella attenuata. Photo credit: NOAA NMFS/SWFSC*

Considering all four performance metrics, the statistical fit of seven models had a performance category of 4 (Appendix B), while the performance category of the remaining five models was 3. It is important to recognize that the model performance metrics and badge mainly reflect the statistical fit of the models to the data. They reflect only the data that were analyzed, and they do not reflect the quality of model predictions away from the data.

The modeling results revealed useful information about the contribution of predictor variables to each model (Figures 6.8 and 6.9). For example, sea state was a reasonably important predictor in most models. The probability of zero-inflation almost always showed a strong increase with sea state (i.e., a lower probability of sighting). It is important to note that this result was likely because the probability of detection is lower in higher sea states, not because true abundance is likely to be different. However, these two processes can be confounded and it is not possible to separate them in our analysis. Some of the more important environmental spatial predictor variables included: depth, slope (10 km), slope-of-slope (10 km), distance to shore, distance to seamounts, surface current direction (sine), chlorophyll-*a* concentration and front probability and strength, sea surface temperature front strength, and wind speed and divergence. Temporal predictor variables (year and day of year) were reasonably important in many models. Overall, climate indices played only a minor role and contributed most (Pacific Decadal Oscillation, one year lag) to the summer model for common bottlenose dolphin.

It is important to reiterate that the main objective of our modeling was to provide the best estimates of distributions. The models were not designed to determine which environmental predictors were most ecologically relevant in determining the distribution of cetaceans, nor to determine the functional relationships between environmental predictors and the distribution of cetaceans. Furthermore, many of the environmental predictor variables are likely to be proxies for unmeasured ecological processes linking cetaceans to their prey, rather than being variables that cetaceans respond to directly. Ecological inference from our model results should be cautious. Nevertheless, our results may suggest interesting hypotheses for future research.

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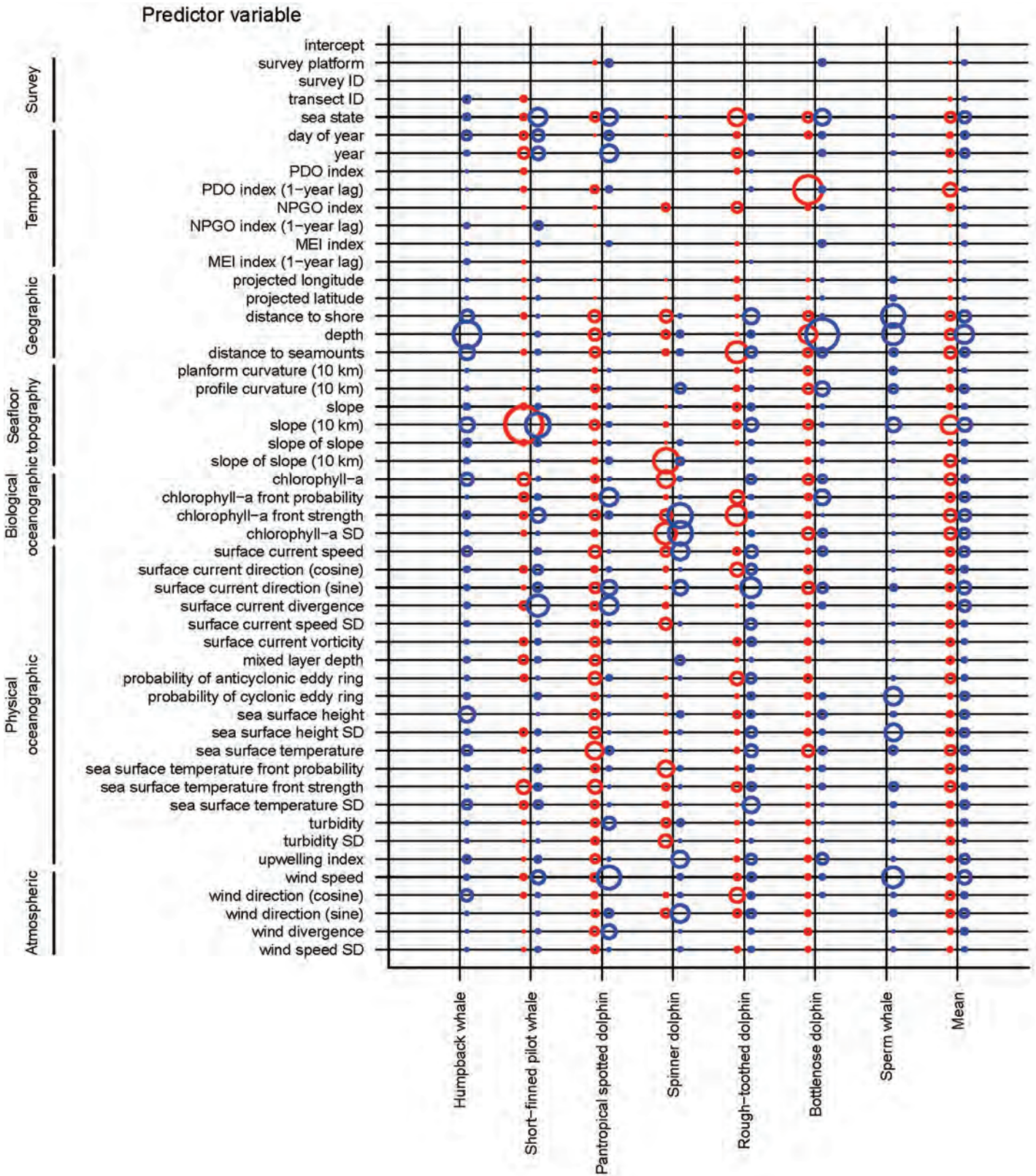


Figure 6.8. Predictor variable importance for the 'zero-inflation' component of each species' model. The area of a circle is proportional to relative variable importance, and the color indicates season (red = summer, blue = winter). Models had two components: a zero inflation and a count component (Appendix B). This figure displays the relative importance of each predictor variable for modeling the probability of zero inflation in the former component.

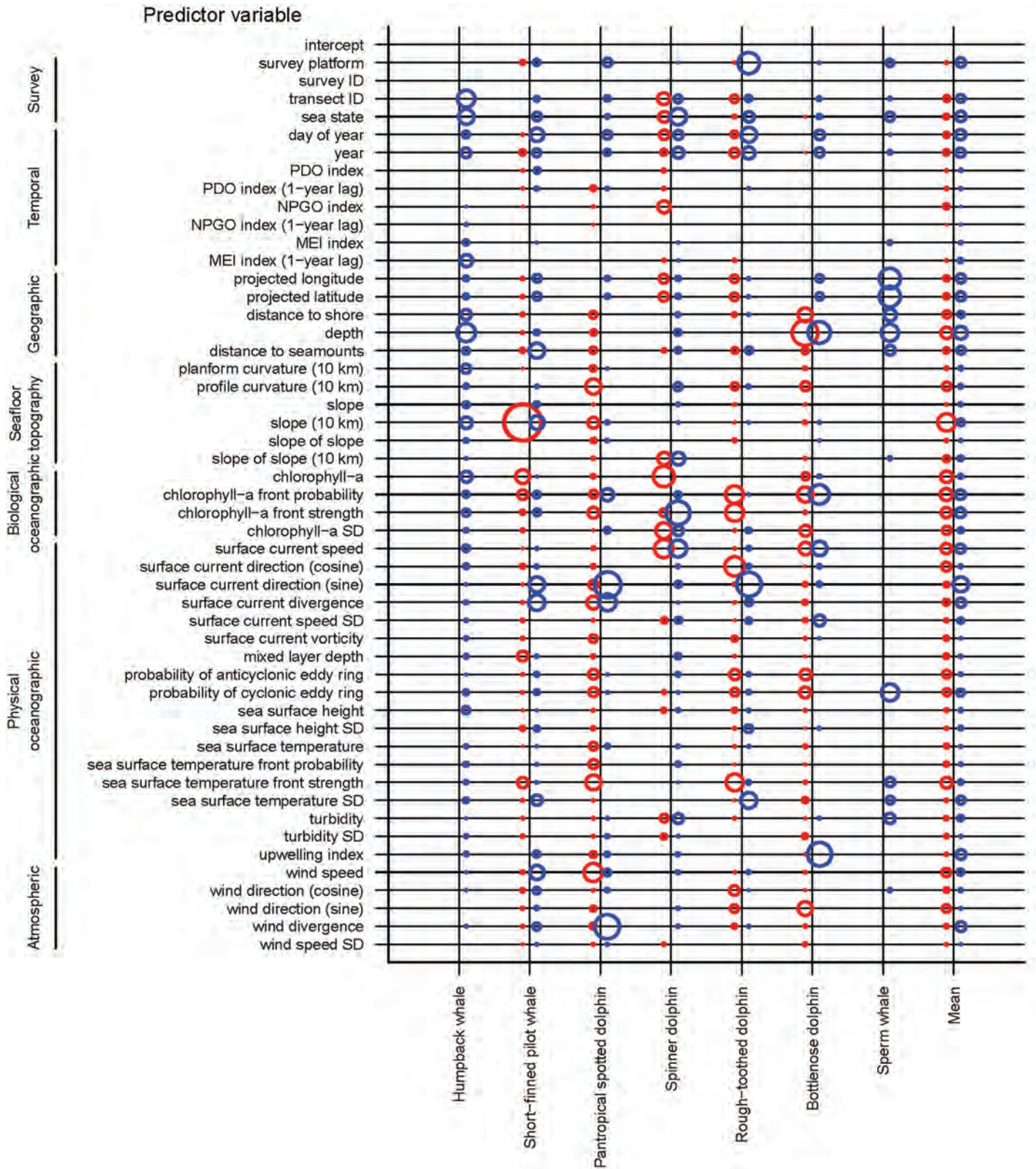


Figure 6.9. Predictor variable importance for the 'mean count' component of each species' model. The area of a circle is proportional to relative variable importance, and the color indicates season (red = summer, blue = winter). Models had two components: a zero inflation and a count component (Appendix B). This figure displays the relative importance of each predictor variable for modeling the mean count in the latter component.

# Marine Mammals

## Humpback whale (*Megaptera novaeangliae*) winter season

The winter model (Figure 6.10) for humpback whale (PDE=37% and AUC=0.91) shows a nearshore distribution across all island groups of the MHI, with highest relative abundance predicted for sheltered, warmest waters primarily within the 200 m isobaths. This habitat preference has been documented in previous studies (e.g., Johnston et al., 2007). Important areas include Penguin Bank off Moloka'i and the Kalohi, 'Au'au and Alalākeiki Channels between Maui, Moloka'i and Lāna'i. High relative abundance was also predicted for the island of Ni'ihau, Ka'ula and the offshore Middle Bank region. For O'ahu and Hawai'i, the north and northeast insular shelf waters were predicted to support higher abundance than the south coast. In general, these high relative abundance areas align with the areas selected for the Hawaiian Islands Humpback Whale National Marine Sanctuary. Depth contributed most to the predicted distribution maps with a steep increase in abundance at the shallowest depths. The day-of-year predictor indicated an increase then decrease in abundance during the winter period, with a peak in early March. Low coefficient of variation (CV) across the areas of predicted high abundance indicates high precision of model predictions.



Humpback whale. Photo credit: NOAA NMFS/SWFSC.

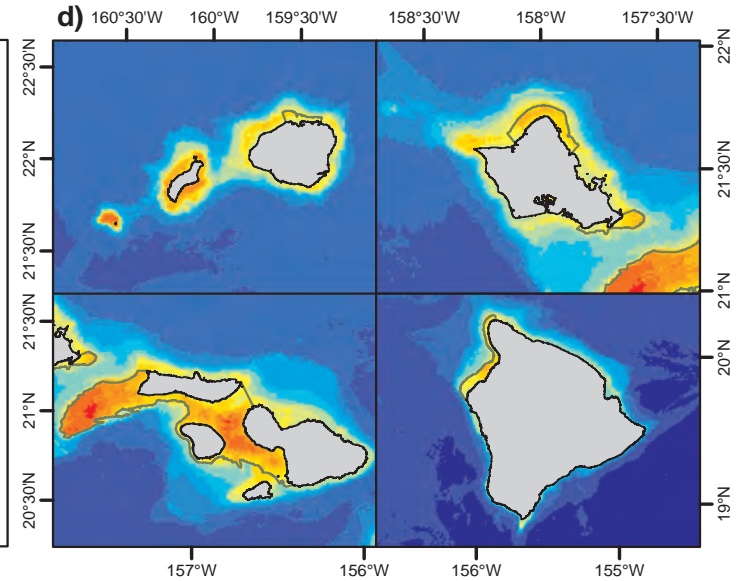
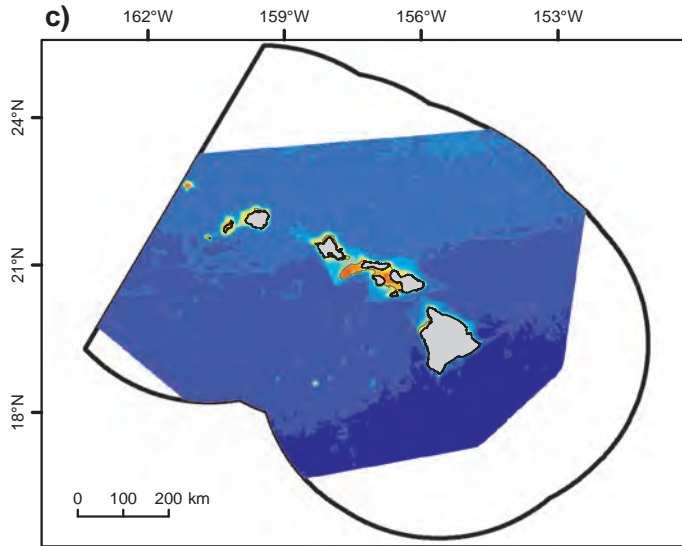
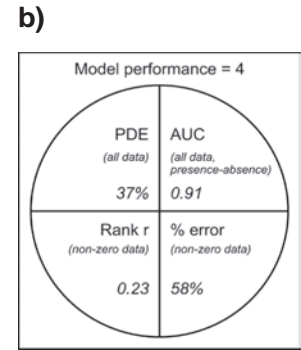
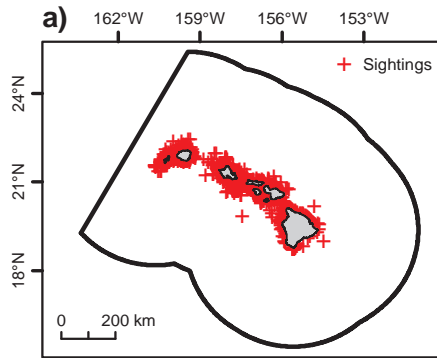
## Sperm whale (*Physeter macrocephalus*) winter season

The winter model for sperm whale (Figure 6.11; PDE=24% and AUC=0.91) shows an offshore distribution with higher predicted relative abundance over deeper waters far from shore. This pattern emerged despite a number of spatially clustered sightings in relatively deep waters off the southwest coast of Hawai'i, where high survey effort has taken place (Figure 6.3), suggesting that the model was not greatly biased by nearshore concentrations of survey effort. Clusters of sightings off the north coast of Kaua'i and the northeast coast of Hawai'i were also in areas of predicted low relative abundance, but these areas had less survey effort (Figure 6.3), potentially indicating that modeled relative abundance in at least some nearshore areas was lower than expected. High relative abundance was predicted for the Middle Bank region and the regions surrounding the Hawaiian and West Hawaiian seamounts, and a region of high probability of cyclonic eddies west of the island of Hawai'i. Depth, distance to shore and probability of cyclonic eddy rings were the environmental predictors with the most influence on the predicted distribution of sperm whale relative abundance. Predicted relative abundance increased with depth and probability of cyclonic eddy rings. The predicted spatial distribution pattern is expected on the basis of analyses of sighting rates in relation to depth (Baird et al., 2013a), and satellite tag data available for sperm whales in Hawaiian waters (Rone et al., 2015). Acoustic monitoring of whale vocalizations indicates that sperm whales occur in the MHI throughout the year (Au et al., 2014), which is also indicated in the sighting data presented here.

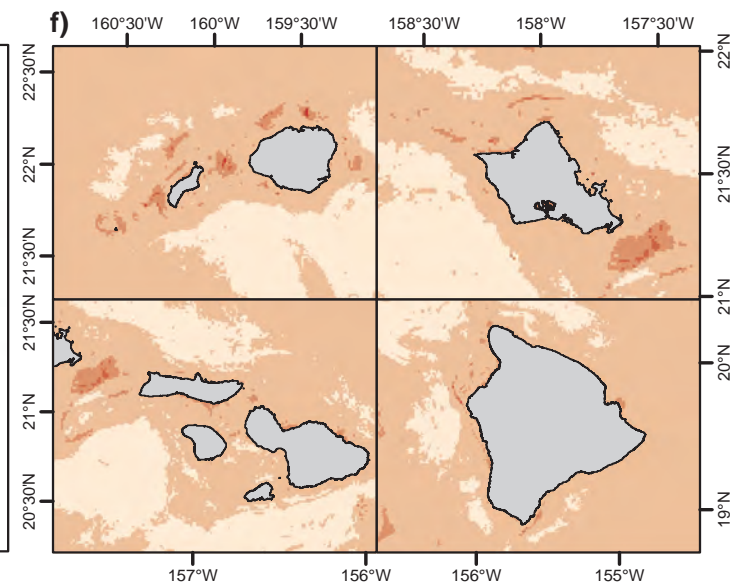
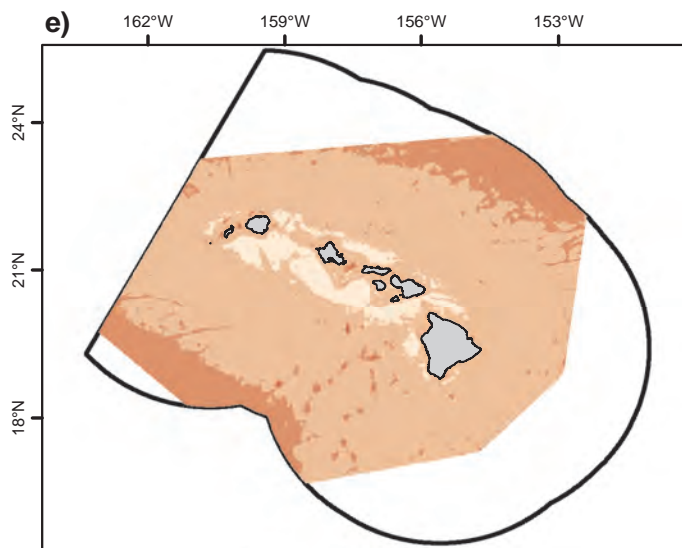


Sperm whales. Photo credit: NOAA

## Humpback whale *Megaptera novaeangliae* (winter)



Relative abundance Min Max



Coefficient of variation 0 0.25 0.5 0.75 1 >1

Figure 6.10. Modeled long-term relative abundance of Humpback whale in winter. Spatial predictive modeling was applied to at-sea sighting data from 1993-2011 provided by J. Mobley (University of Hawai'i at Mānoa), NOAA NMFS/PIFSC and SWFSC. A total of 59,442 transect segments were analyzed, on 2,098 of which this species was sighted for a total of 4,015 individuals sighted. Figure panels are: a) locations of sightings; b) model quality as a function of four performance metrics (Table 6.3); c,d) median bootstrapped estimates of relative abundance; and e,f) bootstrapped coefficients of variation. Predictions were circumscribed by a 50 km-buffered minimum convex polygon around survey effort locations; areas outside this polygon appear blank. Green lines indicate the boundaries of the Hawaiian Islands Humpback Whale National Marine Sanctuary. Artwork adapted from original by Justin Hart.

# Marine Mammals

## Sperm whale *Physeter macrocephalus* (winter)

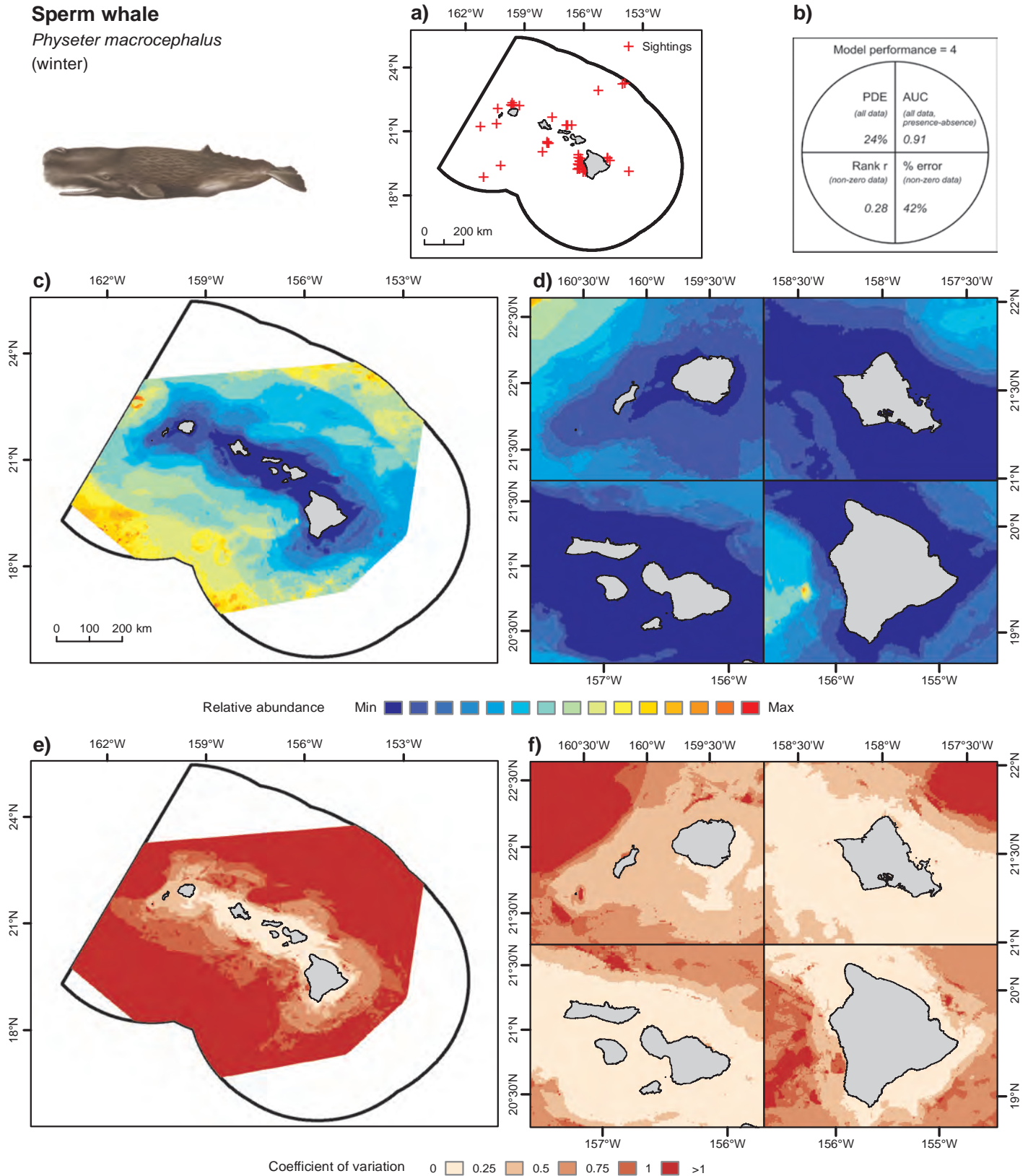


Figure 6.11. Modeled long-term relative abundance of Sperm whale in winter. Spatial predictive modeling was applied to at-sea sighting data from 1993-2012 provided by Cascadia Research Collective, J. Mobley (University of Hawai'i at Mānoa), NOAA NMFS/PIFSC and SWFSC. A total of 84,513 transect segments were analyzed, on 54 of which this species was sighted for a total of 257 individuals sighted. Figure panels are: a) locations of sightings; b) model quality as a function of four performance metrics (Table 6.3); c, d) median bootstrapped estimates of relative abundance; and e, f) bootstrapped coefficients of variation. Predictions were circumscribed by a 50 km-buffered minimum convex polygon around survey effort locations; areas outside this polygon appear blank. Artwork adapted from original by Justin Hart.

## Spinner dolphin (*Stenella longirostris*) summer and winter seasons

Both winter (Figure 6.12; PDE=56% and AUC=0.86) and summer (Figure 6.13; PDE=48% and AUC=0.91) models predict a similar inshore distribution, but with a higher abundance for embayments and leeward island locations in the winter season. Given the predicted inshore distribution, areas of predicted high relative abundance are best visualized at a scale of tens of kilometers (e.g., Figure 6.14). The predicted higher relative abundance inshore is consistent with the known behavior of spinner dolphins in the MHI that rest in sheltered inshore waters during the day (Norris et al., 1994). NMFS recognizes a number of separate insular stocks of spinner dolphins in the MHI (Carretta et al., 2015), largely on the basis of genetic differentiation (Andrews et al., 2010). On Kaua'i, the Waimea Bay region on the southwest coast and the Makaha Point region emerged as important areas and have also



Spinner dolphin, *Stenella longirostris*. Photo credit: Robin W. Baird (Cascadia Research Collective).

been identified as resting areas by expert knowledge (TNC, 2009). Keawanui Bay on Ni'ihau is also highlighted by the model as a year round high potential use area. Around O'ahu, high relative abundance was predicted for Makua Bay and Nanakuli on the west coast (Figure 6.14). Kāne'ohe Bay on the east coast was predicted to be an area of high relative abundance in winter. Around the Maui Nui island group, the models predicted several suitable areas for spinner dolphins, including Kahului Harbor and Mā'alaea Bay and the Lipoa Point area on the north shore adjacent Pailolo Channel on Maui; Kamalō Harbor and the south shore of Moloka'i particularly in winter; and the south shore of Lāna'i, including Manele Bay and west Lāna'i in the Nanahoa area. Around the island of Hawai'i highest relative abundance was predicted for nearshore areas south of Upolu Point on the west coast, Mahaiula Bay, Keahole Point, Honokohau Bay in winter and Kailua Bay. Several of these predictions

agree with expert knowledge on important resting areas (TNC, 2009). These west coast resting areas have also been identified through field surveys (Norris et al., 1994, Östman-Lind et al., 2004) and modeling (Thorne et al., 2012). The southeast shore from Wai'ahukini to Cape Kumukahi is an area of predicted high relative abundance, particularly in the summer months. In addition, Hilo Bay on the east coast of the island of Hawai'i has many high abundance cells in the summer months. Previous predictive models using presence only data showed that spinner dolphin resting habitat was associated with proximity to deep water foraging areas, water depth, the proportion of bays with shallow depths and seafloor rugosity (Thorne et al., 2012). Our models, which focused on a broader spatial scale, were influenced most by slope-of-slope (10 km); chlorophyll-*a* concentration, SD, and front strength; and surface current speed. These results suggest that spinner dolphins may be associated with high complexity seafloor (high slope of the slope values). The chlorophyll-*a* related predictors were likely important because of their ability to discriminate between nearshore and offshore conditions. For example, predicted relative abundance was negatively correlated with chlorophyll-*a* front strength.

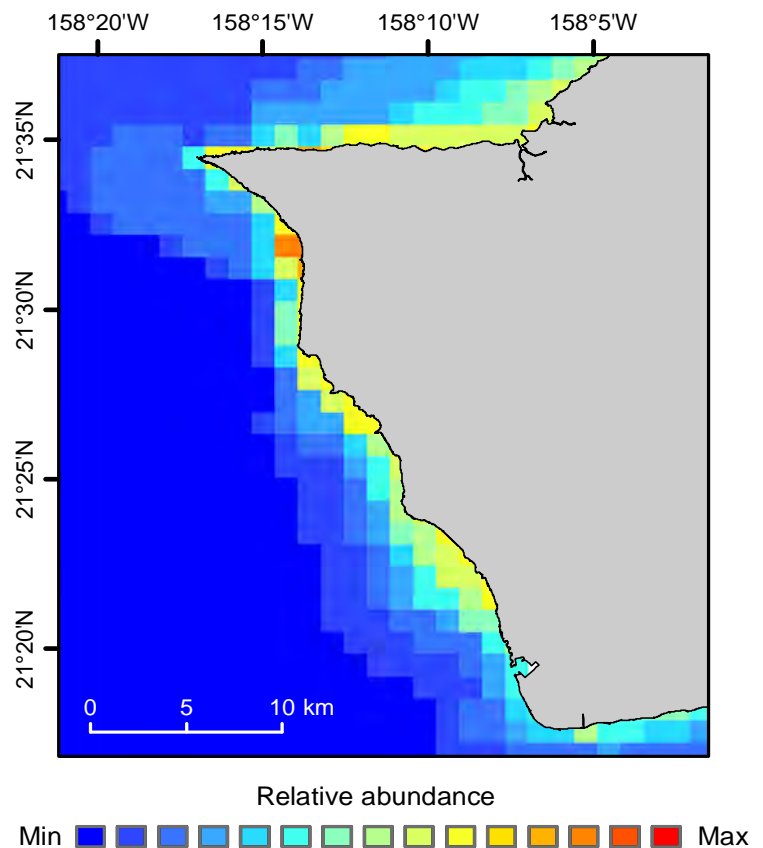


Figure 6.14. Modeled long-term relative abundance of Spinner dolphin in summer along west coast of O'ahu. Spatial predictive modelling was applied to at-sea sighting data from 2002-2013. Data provided by Cascadia Research Collective, J. Mobley (University of Hawai'i at Mānoa), and NOAA NMFS/PIFSC and SWFSC.

# Marine Mammals

## Spinner dolphin *Stenella longirostris* (winter)

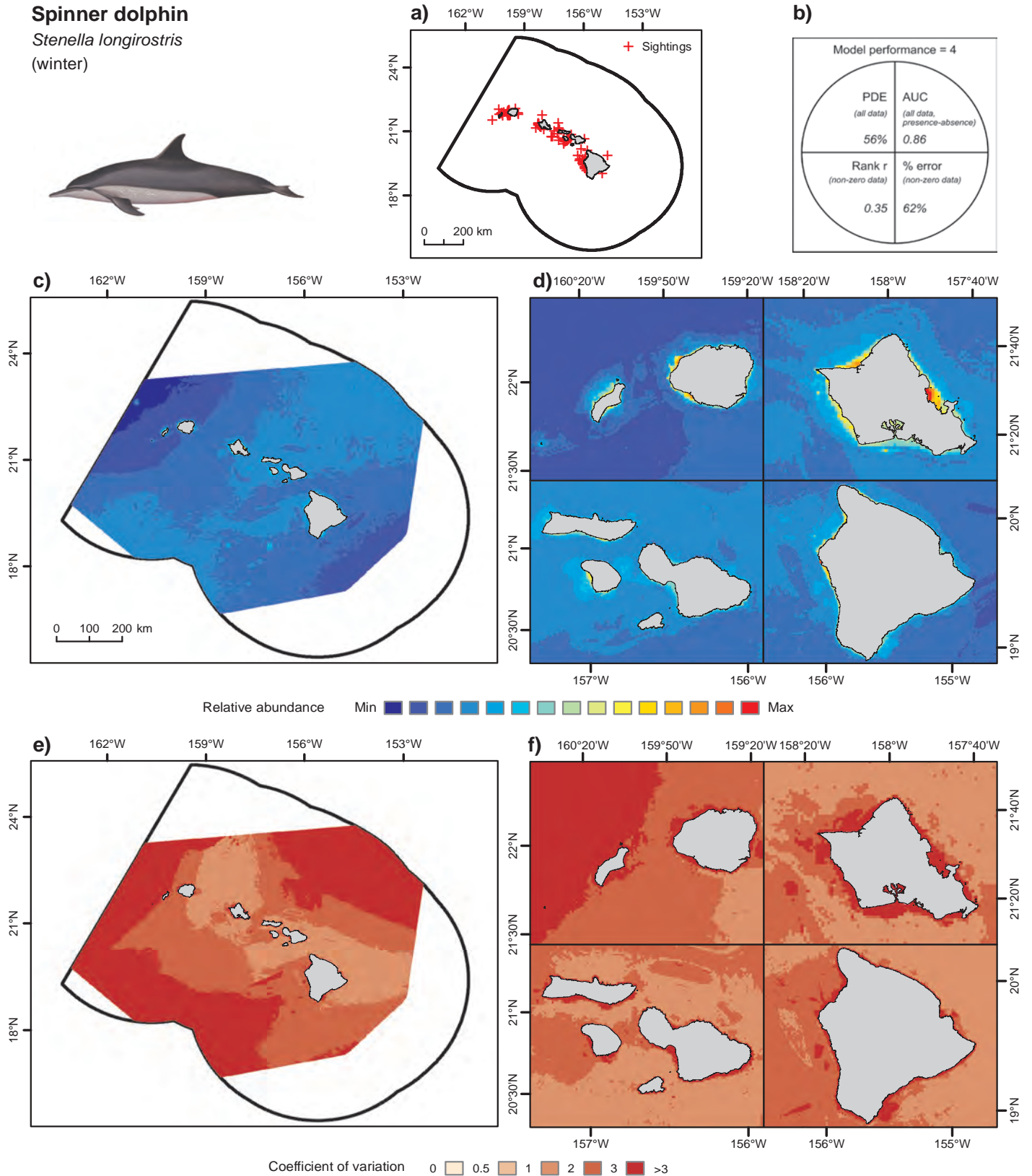


Figure 6.12. Modeled long-term relative abundance of Spinner dolphin in winter. Spatial predictive modeling was applied to at-sea sighting data from 1993–2012 provided by Cascadia Research Collective, J. Mobley (University of Hawai‘i at Mānoa) and NOAA NMFS/PIFSC and SWFSC. A total of 84,513 transect segments were analyzed, on 121 of which this species was sighted for a total of 4,943 individuals sighted. Figure panels are: a) locations of sightings; b) model quality as a function of four performance metrics (Table 6.3); c, d) median bootstrapped estimates of relative abundance; and e, f) bootstrapped coefficients of variation. Predictions were circumscribed by a 50 km-buffered minimum convex polygon around survey effort locations; areas outside this polygon appear blank. Artwork adapted from original by Justin Hart.



## Spinner dolphin *Stenella longirostris* (summer)

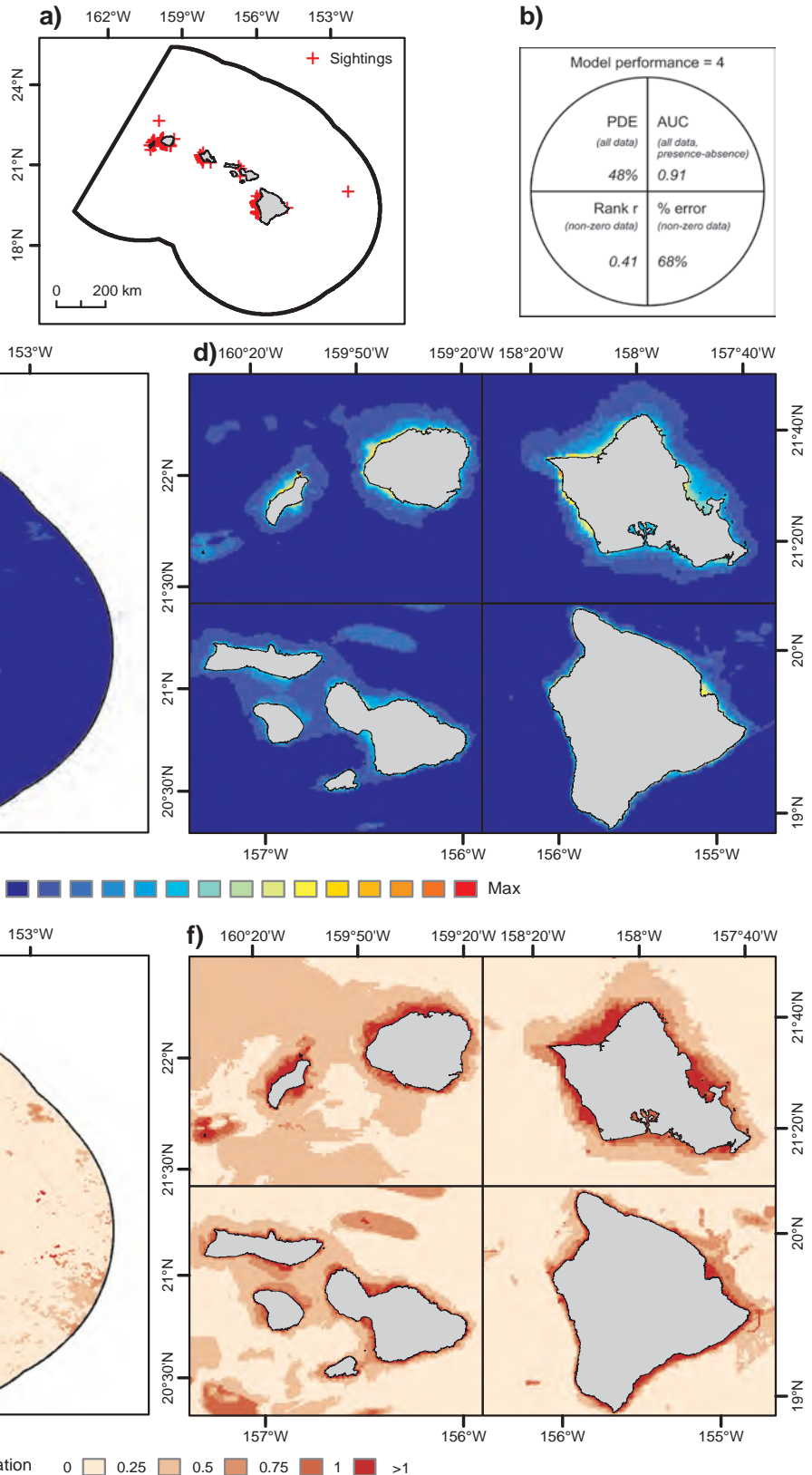


Figure 6.13. Modeled long-term relative abundance of Spinner dolphin in summer. Spatial predictive modeling was applied to at-sea sighting data from 2002-2013 provided by Cascadia Research Collective, J. Mobley (University of Hawai'i at Mānoa) and NOAA NMFS/PIFSC and SWFSC. A total of 54,300 transect segments were analyzed, on 103 of which this species was sighted for a total of 3,795 individuals sighted. Figure panels are: a) locations of sightings; b) model quality as a function of four performance metrics (Table 6.3); c,d) median bootstrapped estimates of relative abundance; and e,f) bootstrapped coefficients of variation. Artwork adapted from original by Justin Hart.

# Marine Mammals

## Common bottlenose dolphin (*Tursiops truncatus*) summer and winter season

Winter (Figure 6.15; PDE=17% and AUC=0.85) and summer (Figure 6.16; PDE=59% and AUC=0.92) models predicted similar nearshore distribution patterns, with additional high relative abundance at Middle Bank and seamounts. Depth was the most consistently important predictor across summer and winter models, possibly explaining the predictions at Middle Bank and seamounts. With the exception of tagged false killer whales (Baird et al., 2013b), very little is known about cetacean use of Middle Bank. The summer model also predicted relatively high abundance southwest of the island of Hawai'i. Previous studies using photo-identification, genetic analyses and satellite tagging suggest limited movement of common bottlenose dolphins between islands and between nearshore and offshore waters, indicating the existence of demographically distinct resident populations at each of the four main Hawaiian Island groups, and a distinct offshore pelagic population beyond the 1,000 m isobaths (Baird et al., 2009a; Martien et al., 2012; Baird, 2016). In summer, models showed highest nearshore abundance across the shallow (<200 m) insular shelf of Ka'ula, Keawanui Bay on Ni'ihau, the sloping shelf off Makaha Point on west Kaua'i and Waimea Bay on south Kaua'i. On O'ahu, highest relative abundance is predicted for the sloping shelf off Ka'ena Point, off Maili Point west O'ahu, Makapu'u Point, Kaiwi Channel and Penguin Bank. Relative abundance is moderate through the channels of the Maui Nui islands. Off the island of Hawai'i, two areas emerge with highest abundance: shelf waters straddling the 200 m isobath north of Upolu Point, and north of Keahole Point, which experiences high upwelling and persistent chlorophyll-*a* fronts (Chapter 2, Figures 2.23 and 2.20, respectively). Chlorophyll-*a* front probability was an important predictor, especially in the winter model, with abundance increasing with increasing front probability. Winter models show a similar all-island distribution, but with lower abundance and occurrence in the more exposed locations offshore, such as the Hawaiian Seamounts and areas such as Upolu Point (north island of Hawai'i), which experiences greater wind speeds in winter than summer (Chapter 2 Figure 2.7). The sheltered channels of Maui Nui are predicted to be relatively more suitable habitat for common bottlenose dolphins in winter than in summer, particularly the 'Au'au Channel between Maui and Lāna'i. Another discrete location highlighted as a higher abundance area only in the winter model was the Kuia Shoal (<200 m depth) off the western tip of Kaho'olawe.



*Common bottlenose dolphin. Photo credit: Robin W. Baird (Cascadia Research Collective)*

## Common bottlenose dolphin *Tursiops truncatus* (winter)

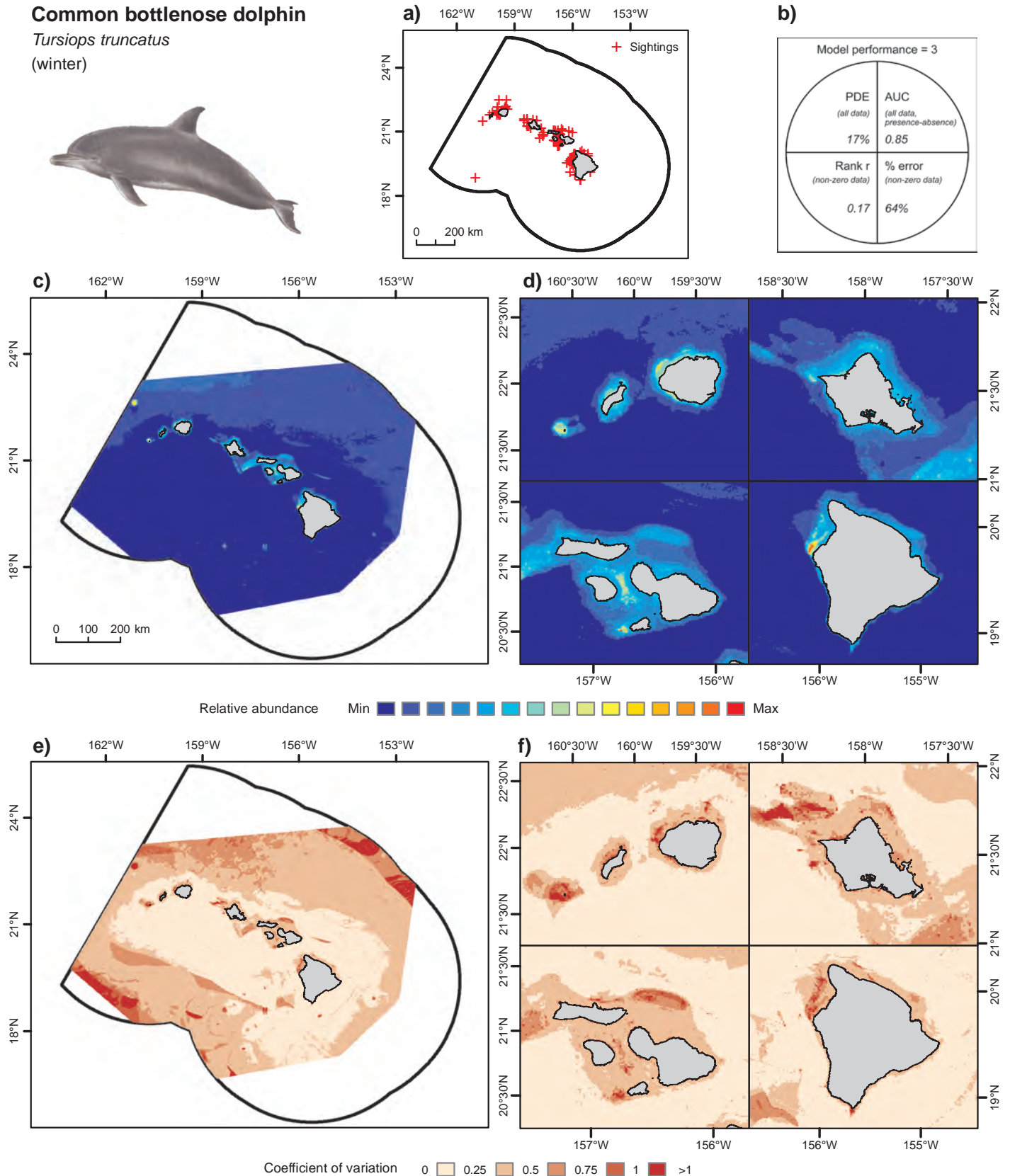


Figure 6.15. Modeled long-term relative abundance of Common bottlenose dolphin in winter. Spatial predictive modeling was applied to at-sea sighting data from 1993–2012 provided by Cascadia Research Collective, J. Mobley (University of Hawai‘i at Mānoa) and NOAA/NMFS PIFSC and SWFSC. A total of 84,513 transect segments were analyzed, on 142 of which this species was sighted for a total of 1,261 individuals sighted. Figure panels are: a) locations of sightings; b) model quality as a function of four performance metrics (Table 6.3); c, d) median bootstrapped estimates of relative abundance; and e, f) bootstrapped coefficients of variation. Predictions were circumscribed by a 50 km-buffered minimum convex polygon around survey effort locations; areas outside this polygon appear blank. Artwork adapted from original by Justin Hart.

# Marine Mammals

## Common bottlenose dolphin

*Tursiops truncatus*  
(summer)

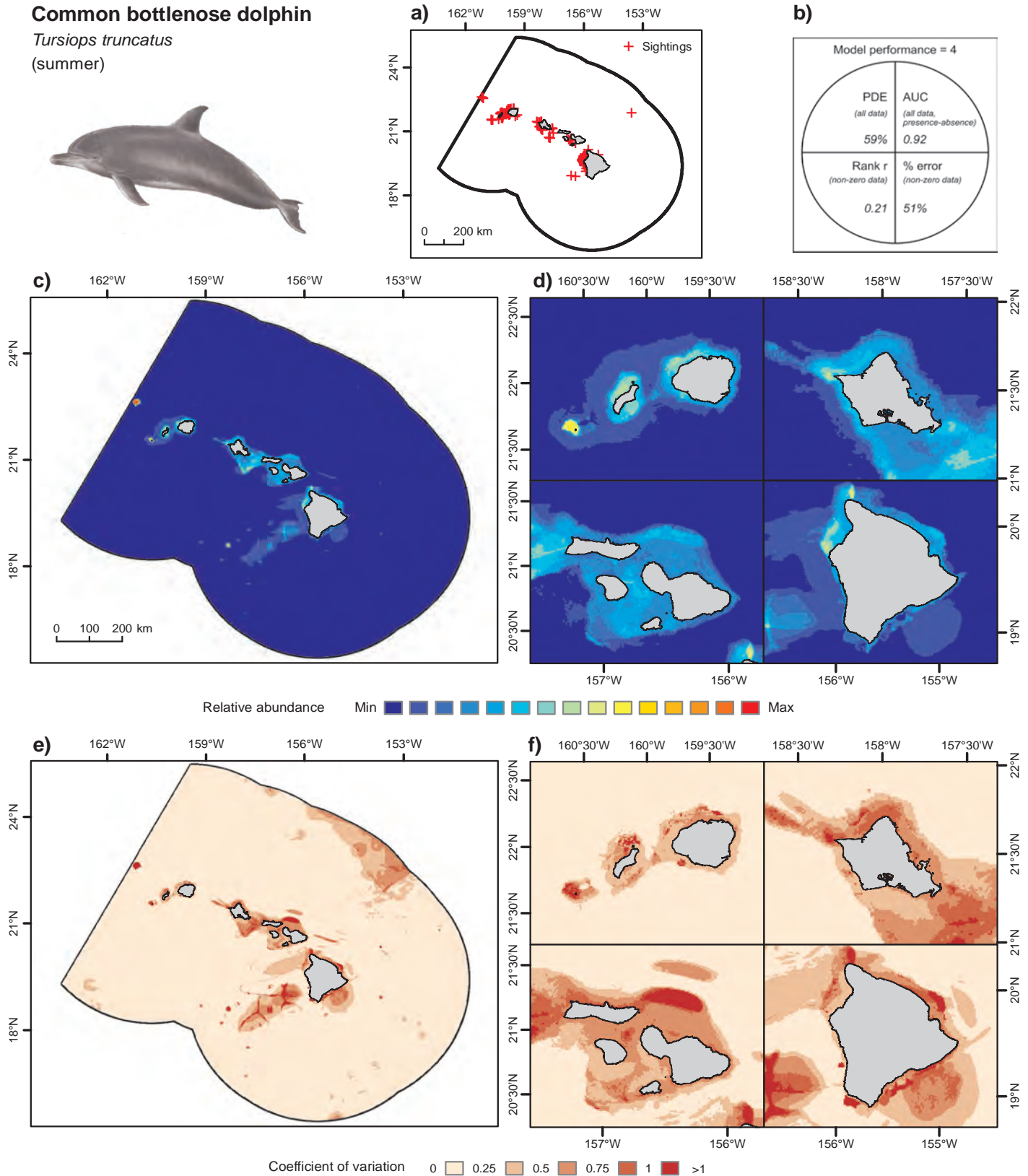


Figure 6.16. Modeled long-term relative abundance of Common bottlenose dolphin in summer. Spatial predictive modeling was applied to at-sea sighting data from 2002-2013 provided by Cascadia Research Collective, J. Mobley (University of Hawai'i at Mānoa) and NOAA/NMFS PIFSC and SWFSC. A total of 54,300 transect segments were analyzed, on 144 of which this species was sighted for a total of 1,395 individuals sighted. Figure panels are: a) locations of sightings; b) model quality as a function of four performance metrics (Table 6.3); c,d) median bootstrapped estimates of relative abundance; and e,f) bootstrapped coefficients of variation. Artwork adapted from original by Justin Hart.

## Pantropical spotted dolphin (*Stenella attenuata*) summer and winter seasons

Winter (Figure 6.17; PDE=35% and AUC=0.86) and summer (Figure 6.18; PDE=26% and AUC=0.78) models predicted that spotted dolphin relative abundance was higher on the leeward side of the islands than on the windward side, with a considerably more restricted leeward distribution in winter. There were several distinct areas with predicted high relative abundance in summer. On O‘ahu, the steeply sloping shelf waters beyond the 200 m isobath south of Ka‘ena Point had high predicted relative abundance. This area has a high probability of anti-cyclonic eddies in the summer and winter months (Chapter 2 Figure 2.20). Around Maui Nui, highest abundance was predicted for Kuia Shoal west of Kaho‘olawe, Alenuihāhā and ‘Au‘au Channels, and the sloping shelf waters leeward of Lāna‘i. Around the island of Hawai‘i, a large high relative abundance area exists for summer and winter along the west coast shelf with highest abundance in a band offshore from Keaweakaheka Point. In the summer only, an additional high relative abundance area is predicted west of Upolu Point. These areas are characterized by a high persistence of chlorophyll-*a* fronts west and south of the island of Hawai‘i, as well as low wave height and low mean current speed, with high variation and warmer seas than surrounding areas in both seasons. In winter, high relative abundance was also predicted for a windward area east of Kaua‘i, but where no sightings occurred. It was not clear why this area would be suitable habitat, so that prediction requires future verification with field data. A range of predictors contributed to the models, with surface current direction and wind speed and divergence being most influential in winter, and wind speed, sea surface temperature and front strength, and profile curvature (10 km) being most influential in summer. Abundance was predicted to decrease with increasing wind speed, which could be a habitat preference for calmer areas or a result of decreased sightability or effort in windier areas. Circular patterns in predicted summer abundance at Middle Bank and seamounts southwest of the island of Hawai‘i were likely a result of estimated relationships with bathymetry (e.g., profile curvature). The predicted higher relative abundance of spotted dolphin on the leeward side of the islands raises the question of whether this pattern was due, in part, to the larger amount of survey effort in those areas (Figure 6.3). While our modeling framework theoretically accounted for effort, it is still possible that geographic variation in effort contributed to the predicted spatial patterns, especially when offshore effort was relatively low (e.g., winter). Further, NMFS recognizes three insular stocks and a pelagic stock for this species in Hawaiian waters (Carretta et al., 2015) on the basis of genetics (Courbis et al., 2014). Our model results reflect the unspecified stock composition of the sighting data used. For example, if most of the sightings were of individuals belonging to insular stocks, then our results would mainly reflect the spatial distribution of the insular stocks.



*Pantropical spotted dolphins. Photo credit: Robin W. Baird (Cascadia Research Collective)*

# Marine Mammals

## Pantropical spotted dolphin

*Stenella attenuata*  
(winter)

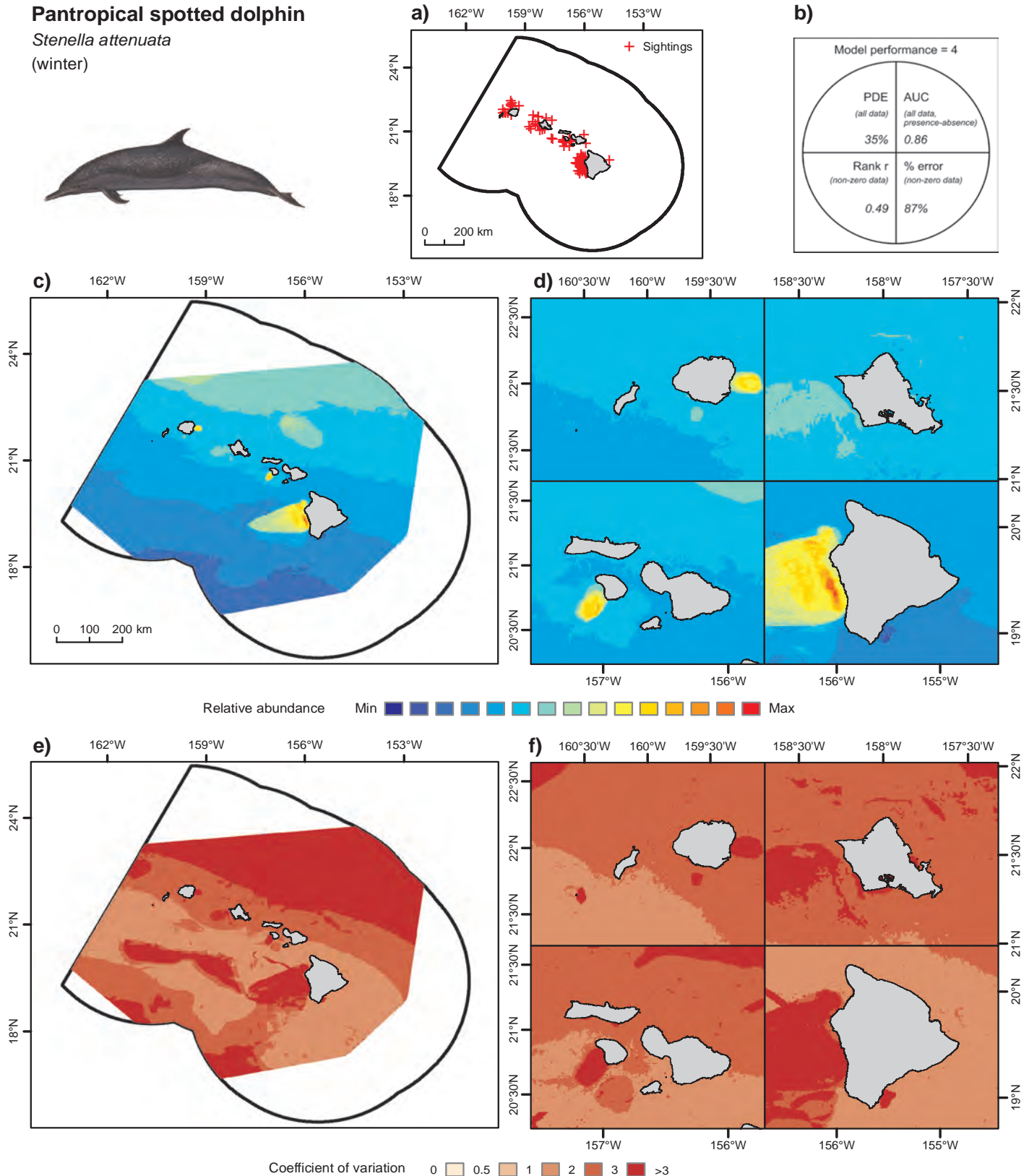


Figure 6.17. Modeled long-term relative abundance of Pantropical spotted dolphin in winter. Spatial predictive modeling was applied to at-sea sighting data from 1993-2012 provided by Cascadia Research Collective, J. Mobley (University of Hawai'i at Mānoa) and NOAA/NMFS PIFSC and SWFSC. A total of 84,513 transect segments were analyzed, on 226 of which this species was sighted for a total of 14,181 individuals sighted. Figure panels are: a) locations of sightings; b) model quality as a function of four performance metrics (Table 6.3); c,d) median bootstrapped estimates of relative abundance; and e,f) bootstrapped coefficients of variation. Predictions were circumscribed by a 50 km-buffered minimum convex polygon around survey effort locations; areas outside this polygon appear blank. Artwork adapted from original by Justin Hart.

## Pantropical spotted dolphin

*Stenella attenuata*  
(summer)

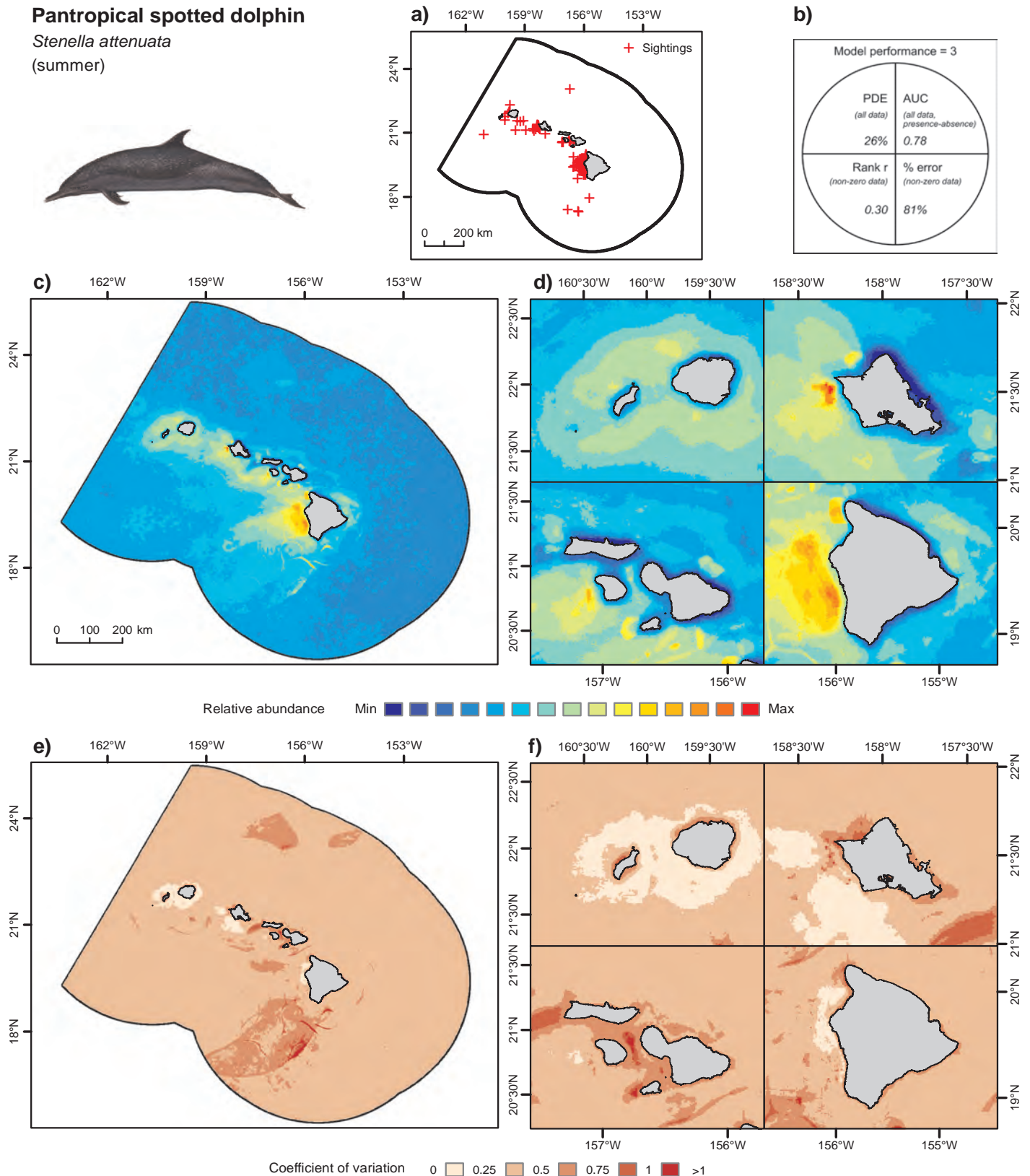


Figure 6.18. Modeled long-term relative abundance of Pantropical spotted dolphin in summer. Spatial predictive modeling was applied to at-sea sighting data from 2002-2013 provided by Cascadia Research Collective, J. Mobley (University of Hawai'i at Mānoa) and NOAA/NMFS PIFSC and SWFSC. A total of 54,300 transect segments were analyzed, on 212 of which this species was sighted for a total of 13,695 individuals sighted. Figure panels are: a) locations of sightings; b) model quality as a function of four performance metrics (Table 6.3); c, d) median bootstrapped estimates of relative abundance; and e, f) bootstrapped coefficients of variation. Artwork adapted from original by Justin Hart.

# Marine Mammals

## Rough-toothed dolphin (*Steno bredanensis*) summer and winter season

Winter (Figure 6.19; PDE=18% and AUC=0.81) and summer (Figure 6.20; PDE=33% and AUC=0.87) models both predicted highest relative abundance in offshore waters generally beyond the 200 m isobath, yet resulted in different spatial patterns in the predicted distributions. The winter model performed less well than the summer model, and the modeled winter distribution was more concentrated and did not correspond as well with the locations of sightings, suggesting that the modeled winter distribution for this species should be interpreted with caution. The winter model predicted that waters around the central MHI (O'ahu and Maui Nui) are less frequently used by rough-toothed dolphin, although there were quite a few sightings in these areas. The largest area with predicted high relative abundance in the winter was over the Hawaiian Seamounts in the lee of the island of Hawai'i, an area characterized by calmer, productive (persistent chlorophyll-*a* fronts), warmer water than surrounding areas. Two of the most important predictors in the winter model were current direction (sine) and sea surface temperature SD. The large area of predicted high relative abundance coincides with the Hawaiian Lee Counter Current (Chapter 2, Figures 2.9 and 2.10). A smaller area of predicted high relative abundance in winter was in the Kaulakahi Channel between Kaua'i and Ni'ihau. These two areas with higher density (Kaua'i and the island of Hawai'i) have been suggested as reflecting two different populations on the basis of genetic analyses and photo-identification (Baird et al., 2008a; Oleson et al., 2013; Albertson, 2014; Baird, 2016). Chlorophyll-*a* front strength and probability were among the most important predictors in the summer model resulting in a more dispersed but also speckled distribution. Summer relative abundance was predicted to be highest in the deep waters of the Kaulakahi Channel between Kaua'i and Ni'ihau; deep waters off Ka'ena Point off west O'ahu; Kaiwi Channel and offshore of Hālawā Bay, Moloka'i, 'Au'au Channel; Alalākeiki Channel southeast of Kaho'ulawe; and west of the island of Hawai'i offshore of Hanamalo Point and Keahole Point.



*Rough-toothed dolphin, Steno bredanensis. Photo credit: Robin W. Baird (Cascadia Research Collective)*



## Rough-toothed dolphin

*Steno bredanensis*  
(winter)

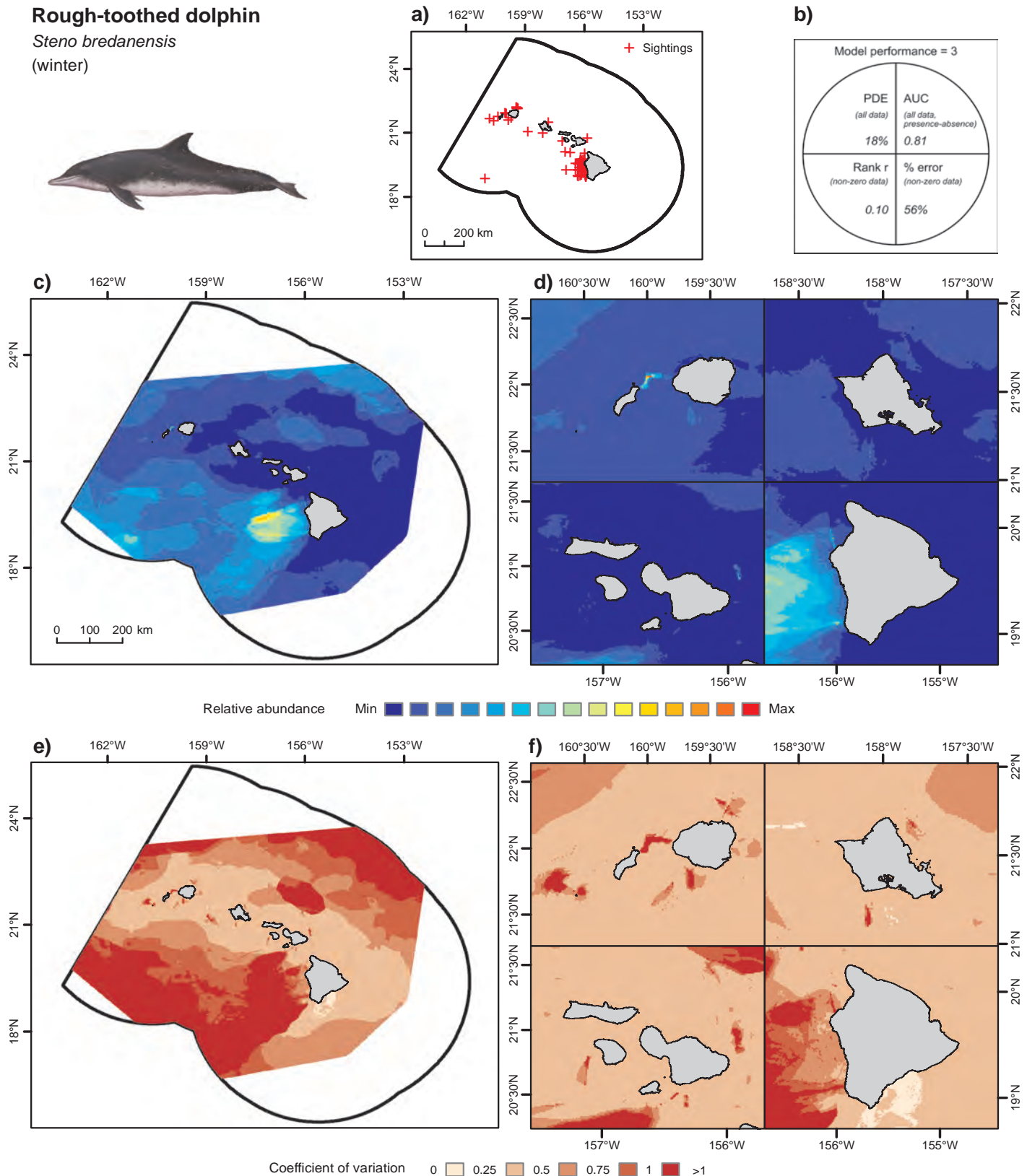


Figure 6.19. Modeled long-term relative abundance of Rough-toothed dolphin in winter. Spatial predictive modeling was applied to at-sea sighting data from 1993-2012 provided by Cascadia Research Collective, J. Mobley (University of Hawai'i at Mānoa) and NOAA NMFS/PIFSC and SWFSC. A total of 84,513 transect segments were analyzed, on 74 of which this species was sighted for a total of 919 individuals sighted. Figure panels are: a) locations of sightings; b) model quality as a function of four performance metrics (Table 6.3); c,d) median bootstrapped estimates of relative abundance; and e,f) bootstrapped coefficients of variation. Predictions were circumscribed by a 50 km-buffered minimum convex polygon around survey effort locations; areas outside this polygon appear blank. Artwork adapted from original by Justin Hart.

# Marine Mammals

## Rough-toothed dolphin

*Steno bredanensis*  
(summer)

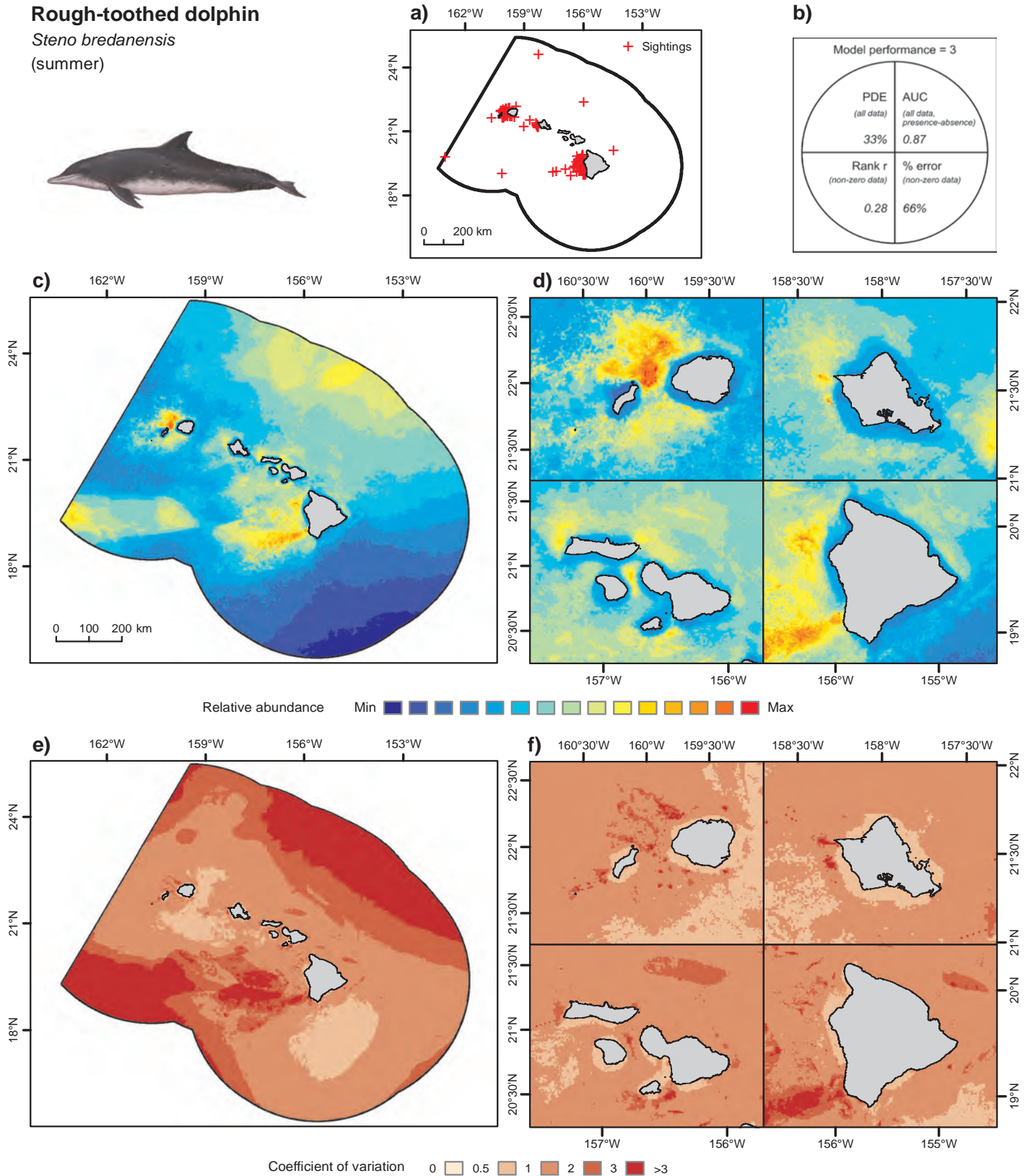


Figure 6.20. Modeled long-term relative abundance of Rough-toothed dolphin in summer. Spatial predictive modeling was applied to at-sea sighting data from 2002-2013 provided by Cascadia Research Collective, J. Mobley (University of Hawai'i at Mānoa) and NOAA NMFS/PIFSC and SWFSC. A total of 54,300 transect segments were analyzed, on 166 of which this species was sighted for a total of 2,009 individuals sighted. Figure panels are: a) locations of sightings; b) model quality as a function of four performance metrics (Table 6.3); c,d) median bootstrapped estimates of relative abundance; and e,f) bootstrapped coefficients of variation. Artwork adapted from original by Justin Hart.

## Short-finned pilot whale (*Globicephala macrorhynchus*) summer and winter seasons

Winter (Figure 6.21; PDE=34% and AUC=0.83) and summer (Figure 6.22; PDE=22% and AUC=0.84) models showed fairly different spatial distribution patterns. High relative abundance in winter was predicted for a band of deep offshore water north of the MHI. A distinct gradient of southward declining abundance was predicted across the project area. Although low relative abundance was predicted for offshore waters north and south of all islands, several notable exceptions were predicted, including a patch of moderate relative abundance off the southern tip of Penguin Bank, the deep shelf at the lee of Lānaʻi and a small patch east of Kahoʻolawe. A striking band of high relative abundance was also predicted along the Kona coast of Hawaiʻi, well beyond the 200 m isobath, but including where the deep shelf waters exist near the coast off Keawekeheka Point. This area was also identified as a high-use area for tracked short-finned pilot whales (Abecassis et al., 2015). In addition, high relative abundance is shown over deep water off the southern tip of the island of Hawaiʻi, between Kalae and Kamilo Point. The summer model predicted distinct bands of higher abundance over deeper sloping shelf waters both north and south of the islands, as well as the Hawaiian Seamounts, including the slopes of Cross Seamount and Middle Bank. The summer model was strongly driven by slope at a 10 km resolution. Slope (10 km) was also a relatively important predictor in the winter model, and some of those same areas can be seen to have higher than average predicted relative abundance in winter. It is possible that the strong estimated relationship between slope and relative abundance was driven by data from certain areas (e.g., off the west coast of the island of Hawaiʻi) and that the predicted high relative abundance in other areas with similar slope are not realistic. For example, there were fewer data from the windward side of the islands to inform the models. Field observations and tracking studies suggest there may be inshore and pelagic populations of short-finned pilot whales in Hawaiian waters, and that island-associated populations exist with strong social cohesion and limited inter-island movements (Abecassis et al., 2015; Mahaffy et al., 2015; Baird, 2016). As with the other species, our model results reflect the unspecified stock composition of the sighting data used.



Short-finned pilot whale. Photo credit: Robin W. Baird (Cascadia Research Collective)

Becker et al. (2012) and Forney et al. (2015) developed habitat-based models of the distributions of our modeled species in the central North Pacific, including waters around the MHI. Their models were fit only to some of the data analyzed here (NOAA ship survey data), so their survey dataset was less concentrated in nearshore and leeward areas. Also, their models differed from ours in several ways. First, their models covered a wider geographic area and used a coarser spatial resolution. Second, their models considered a smaller set of environmental predictor variables but matched these dynamic variables to the sighting data in time ('contemporaneous' approach) allowing their models to capture inter-annual differences in species distributions. Third, their models employed a different statistical framework and incorporated species-specific detection rate parameters that allowed them to estimate absolute density, rather than relative abundance, which was estimated by our models. The predicted distributions presented by Becker et al. (2012) and Forney et al. (2015) reflect larger scale patterns than ours do, and it is difficult to make detailed comparisons. Nevertheless, there are perhaps some instances of broad correspondence between their predicted distributions and ours; for example, common bottlenose dolphin.

# Marine Mammals

## Short-finned pilot whale

*Globicephala macrorhynchus*  
(winter)

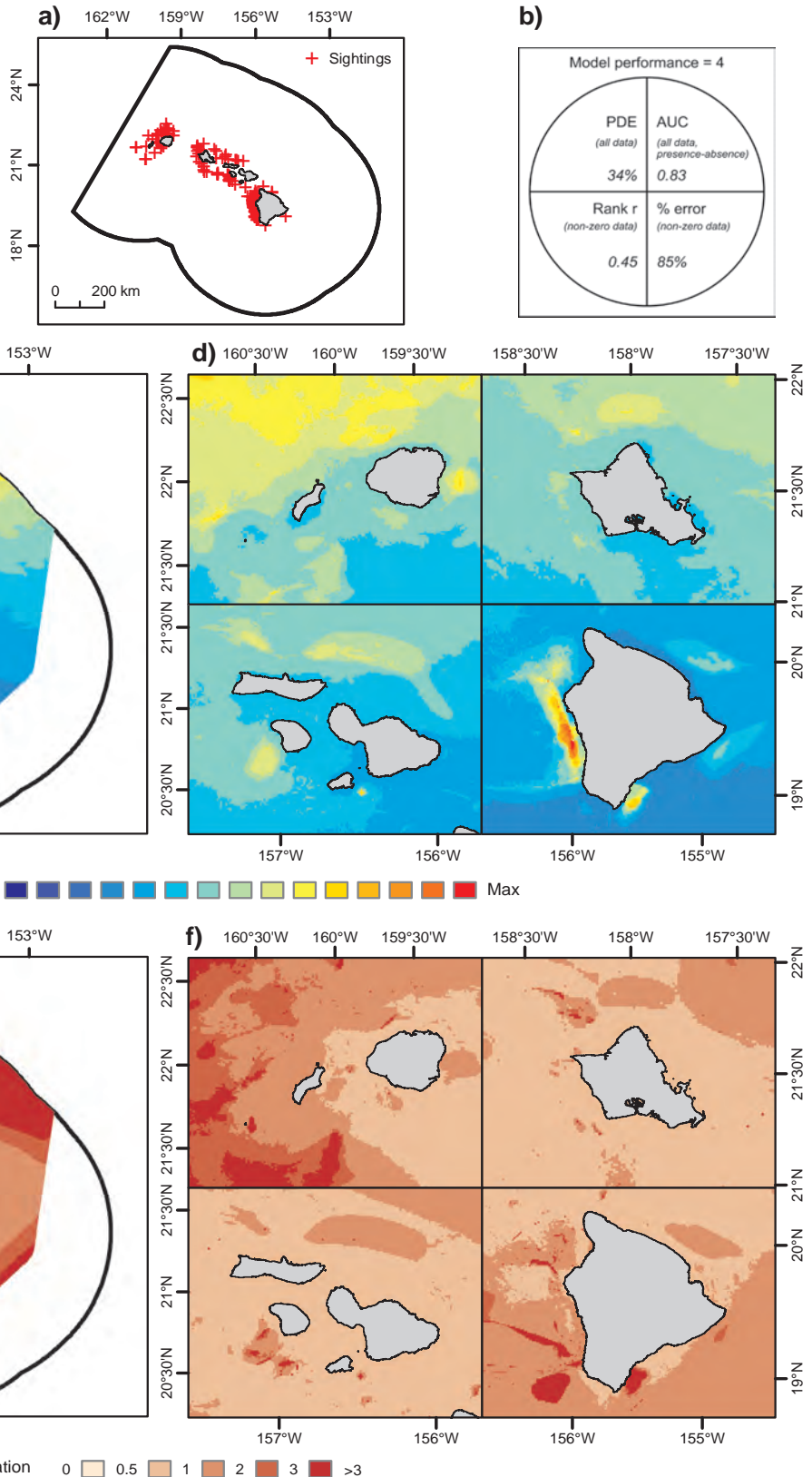


Figure 6.21. Modeled long-term relative abundance of Short-finned pilot whale in winter. Spatial predictive modeling was applied to at-sea sighting data from 1993-2012 provided by Cascadia Research Collective, J. Mobley (University of Hawai'i at Mānoa) and NOAA NMFS/PIFSC and SWFSC. A total of 84,513 transect segments were analyzed, on 235 of which this species was sighted for a total of 4,397 individuals sighted. Figure panels are: a) locations of sightings; b) model quality as a function of four performance metrics (Table 6.3); c,d) median bootstrapped estimates of relative abundance; and e,f) bootstrapped coefficients of variation. Predictions were circumscribed by a 50 km-buffered minimum convex polygon around survey effort locations; areas outside this polygon appear blank. Photo credit: Robin W. Baird (Cascadia Research Collective)

## Short-finned pilot whale

*Globicephala macrorhynchus*  
(summer)

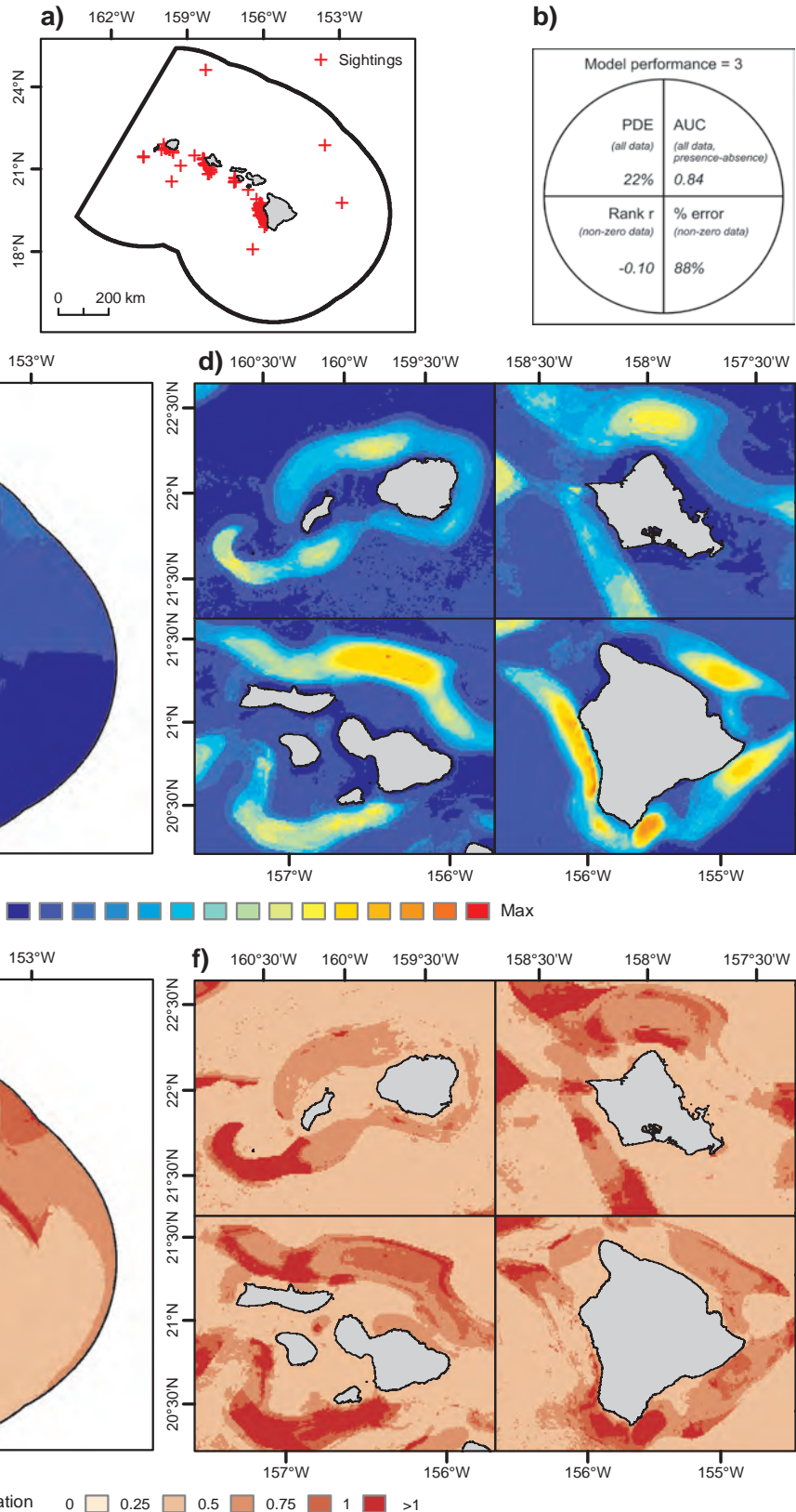


Figure 6.22. Modeled long-term relative abundance of Short-finned pilot whale in summer. Spatial predictive modeling was applied to at-sea sighting data from 2002-2013 provided by Cascadia Research Collective, J. Mobley (University of Hawai'i at Mānoa) and NOAA/NMFS PIFSC and SWFSC. A total of 54,300 transect segments were analyzed, on 327 of which this species was sighted for a total of 6,244 individuals sighted. Figure panels are: a) locations of sightings; b) model quality as a function of four performance metrics (Table 6.3); c, d) median bootstrapped estimates of relative abundance; and e, f) bootstrapped coefficients of variation. Photo credit: Robin W. Baird (Cascadia Research Collective)

# Marine Mammals

## 6.1.4. Data Limitations and Information Gaps

Our assessment analyzed some of the best available at-sea visual survey data for cetaceans in the MHI from recent decades. Each dataset had particular strengths and limitations, many of which are discussed in publications by the data providers: NOAA (Barlow, 2006; Becker et al., 2012; Forney et al., 2015), Cascadia Research Collective (Baird et al., 2013a) and University of Hawai'i at Mānoa (Mobley, 2001). The data spanned 20 years with some survey effort in all months of the year. Nevertheless, given the size of the study area and the relatively low sighting rates for many species, additional years of survey effort especially in windward and offshore waters would help improve estimates of cetacean distributions around the MHI and could be used to validate our model predictions (Forney et al., 2015).

The combining of multiple survey datasets was a unique aspect of our assessment, and it posed special challenges. For example, the different datasets had different spatial coverages and densities. The Cascadia Research Collective data provided relatively intensive coverage of nearshore waters on the leeward sides of the islands using non-systematic transects. The aerial survey data were also from nearshore waters, but with more even coverage of the leeward and windward sides using systematic transects. The NOAA data had the most geographically extensive coverage with systematic transects, but effort was less dense. For species that we modeled, the predictive modeling framework theoretically accounted for these differences in survey effort, but it is still possible that the predicted distributions of relative abundance are biased because of imbalances in survey coverage among datasets.

Another important difference among datasets was the survey platform and protocol. The visual range of observers and the probability of sighting animals vary depending on a number of survey factors, including the height of the observation platform, use of binoculars and area of focus. These factors differed among the datasets, so species-specific sighting rates would also be expected to vary. For species that we modeled, the predictive modeling framework allowed for differences in mean sighting rates among survey platforms, but it is still possible that the predicted distributions of relative abundance are biased because of differences in survey platform and protocol among datasets.

It would be useful to further investigate apparent differences between the results of our habitat-based spatial models and those of Becker et al. (2012) and Forney et al. (2015) to determine the extent to which the additional datasets and the different modeling framework in our study contributed to those differences.

For many of the cetacean species in our assessment, population structure has been documented in the MHI with island-associated populations, and inshore and offshore pelagic populations with different levels of exchange (McSweeney et al., 2007, 2009; Aschettino et al., 2012; Martien et al., 2012; Courbis et al., 2014). Our assessment treated all sightings for a given species the same, so our results reflect the unspecified population composition of those sightings. For example, if most of the sightings were of individuals belonging to an insular population, then our results would mainly reflect the spatial distribution of the insular population.

Electronic tracking studies provide a complementary source of information about the at-sea distribution of cetaceans, and we would encourage current and future such efforts in the MHI. Tracking data provide detailed information about behavior, movements, and space use of individuals through time. It is also more feasible to assign tracked individuals to specific populations, and thereby obtain population-specific information about spatial distributions. Cascadia Research Collective has collected tracking data for 12 cetacean species (common bottlenose dolphin, Blainville's beaked whale, Cuvier's beaked whale, false killer whale, melon-headed whale, pygmy killer whale, killer whale, pantropical spotted dolphin, rough-toothed dolphin, short-finned pilot whale, Risso's dolphin and sperm whale) in Hawaiian waters, and has assessed spatial distributions and habitat

associations for some (Baird et al., 2009b, 2010, 2012a, b; Schorr et al., 2009; Woodworth et al., 2012; Baird, 2016). A comparison of our predicted spatial distributions with these tracking data would be a valuable contribution to the understanding and characterization of cetacean spatial distributions in the MHI (e.g., Figure 6.23).

Acoustic detections from surveys of cetacean vocalizations in Hawaiian waters are now available for many species, particularly odontocetes (e.g., Johnston et al., 2008; Baumann-Pickering et al., 2015), and those data could also be used to validate and improve our estimates of spatial distributions.



Risso's dolphin, *Grampus griseus*. Photo credit: NOAA NMFS/SWFSC

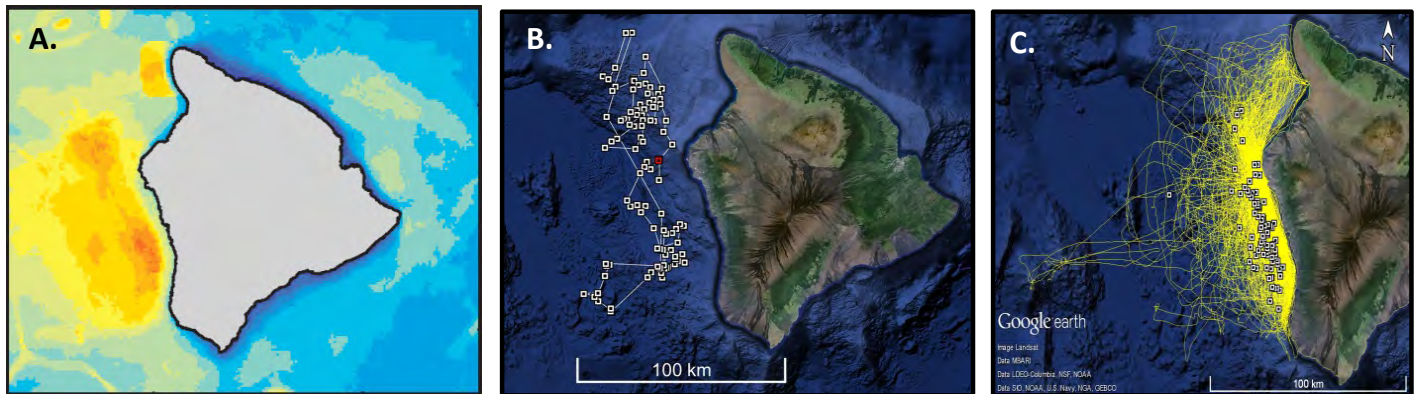


Figure 6.23. Pantropical spotted dolphin space use patterns off the island of Hawai'i. a) Predictive map of spotted dolphin relative abundance distribution in summer months; b) One individual spotted dolphin movement track from satellite telemetry over 11 days in April and May 2015 (from Baird, 2016); c) Survey tracks of Cascadia Research Collective (yellow lines) and spotted dolphin sightings (white squares). Data shown in panels B and C are from Cascadia Research Collective.

# Marine Mammals

## 6.2. HAWAIIAN MONK SEAL (*Neomonachus schauinslandi*)

### 6.2.1. Introduction

This section of the marine mammal chapter provides background information on the cultural significance of Hawaiian monk seals (*Neomonachus schauinslandi*), and their biology, behavior, population ecology and conservation status. We then present data on the distribution of monk seals around the MHI and some examples of movement patterns of individual seals. The data and associated methods are described in detail followed by interpretation of spatial patterns. We map the locations of monk seals recorded in a NOAA sighting database, which includes public sightings and scientific survey data. We present maps of individual seal movements from tracking studies. Critical habitat maps developed to meet requirements of the Endangered Species Act identify important terrestrial and at-sea areas used by monk seals. The ESA critical habitat maps are based on a synthesis of the best-available information on the distribution of monk seals. Data gaps are highlighted and evaluated to inform future data collection strategies.



Hawaiian monk seal, *Neomonachus schauinslandi*. Photo credit: NOAA

The Hawaiian monk seal, Hawaiian language name ‘ilio holo i ka uua (dog that runs in rough waters), is the only native pinniped in Hawaiian waters. Monk seals are mentioned in Hawaiian traditional literature and oral histories and have been associated with the god Lono and Kū, and referenced in many geographical place names (Pūkui et al., 1974; Kittinger et al., 2011).

The Hawaiian monk seal is one of the world’s most endangered mammals, designated as ‘depleted’ under the Marine Mammal Protection Act in 1972, and then listed as an Endangered Species under the U.S. Endangered Species Act (41 FR 51611; November 23, 1976). A high magnitude of threat, high recovery potential and rapid decline that has persisted for over 20 years resulted in the species receiving highest priority in the Recovery Priority Guidelines (55 FR 24296, June 15, 1990). The extinction of the Caribbean monk seal (*Neomonachus tropicalis*) in the 1950s, due to decades of unrestricted hunting, has resulted in the Hawaiian monk seal becoming the last remaining species of its genus (McClenachan and Cooper, 2008; Scheel et al., 2014).



Hawaiian monk seal. Photo credit: NOAA

The maximum age for the species is thought to be 25-30 years, with females reaching reproductive age at between 5 and 10 years of age. Adult monk seals reach lengths of 2.3 m and weigh up to 273 kg. Monk seals occur throughout the Hawaiian archipelago, with most residing in the NWHI and a smaller portion in the MHI (Baker and Johanos, 2004). Monk seal births have been documented in all months of the year (NOAA NMFS, unpublished data), but are most common between February and August, peaking in March and April (Johanos et al., 1994).

Hawaiian monk seals feed on a wide variety of prey, primarily benthic species (including eels and flatfish), crustaceans (lobster, crab, shrimp) and molluscs (octopus; Kenyon and Rice, 1959). Fecal and regurgitate samples collected across the NWHI and MHI revealed a diet that was little different between regions and comprised of fish (78-97%), followed by cephalopods (11-16%) and crustaceans (1-6%; Goodman-Lowe et al., 1998; Cahoon et al., 2013; NOAA NMFS, unpublished data). Telemetry tracking of seal foraging movements has shown that most foraging occurs in waters less than 100 m depth, with occasional excursions to deeper water foraging grounds beyond 300 meters depth (Parrish et al., 2002; Cahoon, 2011; NOAA NMFS, 2014).



Hawaiian monk seals are a wide-ranging species, with some individuals recorded to have travelled distances equivalent to the entire length of the Hawaiian archipelago, although this scale of movement is considered rare, with most seals foraging in shallow waters close to haul-out sites. Underwater observations have shown that seals rest in shallow tidal areas and sleep in underwater ledges close to shore (Wilson, 2015).

Monk seals commonly swim between neighboring islands. Analyses of re-sightings of tagged seals from 1981 to 2011 have shown that seals also travel between the NWHI and the MHI. Johanos et al. (2015) reported 10 seals from a total of 373 individuals making 14 trips between the NWHI, MHI and Johnston Atoll. Two percent of seals observed on Nihoa were also seen in the MHI at least 250 km away. The majority of movements are between locations less than 100 km apart, with comparatively very few movements between locations greater than 400 km apart.

The biogeographic range of the Hawaiian monk seal includes the entire Hawaiian Archipelago and Johnston Atoll. In 2000, the estimated minimum population of monk seal in the MHI was 45, increasing to 52 in 2001 (Baker and Johanos, 2004), 77 individuals in 2005 (NOAA NMFS, 2007) and an estimated minimum of 146 seals in 2011 (Carretta et al., 2013; Baker et al., 2011). Estimated survival from weaning to age 1 year is 77 percent in the MHI, compared with recent NWHI estimates ranging from 42-57 percent (Baker et al., 2011). Furthermore, females begin reproducing at a younger age and attain higher birth rates in the MHI than observed in the NWHI (Baker et al., 2011). As such, the establishment of reproductively sustainable seal subpopulations in the MHI is thought to provide an important role in the recovery of species and reduction of extinction risk (Ragen, 2003). Recovery strategies have focused on protection of vulnerable young female seals to increase the proportion of females surviving to reproductive maturity (NOAA NMFS, 2007). Low genetic variability across the population is an additional risk factor for the long term viability of the species (Kretzmann et al., 1997; Shultz et al., 2009).

Across its range, Hawaiian monk seal abundance has declined 60 percent in the last 40 years and continues to decline at an estimated rate of 3.4 percent per year for the NWHI population (Caretta, 2013), with the current population size at approximately 1,100 individuals. In the MHI, however, the species has been described as recolonizing, and the population growth rate was estimated to be about 7 percent per year in 2008 (Baker et al., 2011), yet it is this segment of the population that is most threatened by direct anthropogenic impacts (Watson et al., 2011).

Female monk seals are also increasingly pupping on popular recreational beaches. These “pupping events” entail mother-pup pairs remaining on the beach to nurse for up to 7 weeks, during which time they are particularly vulnerable to human disturbance. The species is threatened by multiple human stressors, including intentional killing, entanglement in fishing gear, competition with fisheries for food, loss and disturbance of coastal habitats, ocean pollution, collision with vessels, and emerging diseases (NOAA NMFS, 2007; Lowry and Aguilar, 2008). Predicted sea level rise is expected to gradually reduce the availability of breeding locations at the lowest elevation atolls during the next 100 years (Baker et al., 2006). One of the greatest recent constraints to population growth is thought to be food limitation due to its negative impact on the survival of juvenile seals, age of sexual maturity, and fecundity. At one location, French Frigate Shoals in the NWHI, predation of pups by sharks has reduced the sub-population dramatically (Gobush and Farry, 2012).



*Female monk seal with pup. Photo credit: NOAA*

# Marine Mammals

Under the Endangered Species Act (ESA), federal agencies have a legal mandate to promote the recovery of endangered species. Specific agencies with marine and wildlife management duties support implementation of the ESA as specified in the Monk Seal Recovery Plan, including U.S. Fish and Wildlife Service (USFWS), NOAA National Ocean Service (NOS), Hawai'i Department of Land and Natural Resources (DLNR), U.S. Coast Guard and the U.S. Navy. NOAA NMFS Pacific Islands Regional Office (PIRO) is responsible for coordination of the implementation of the Main Hawaiian Islands Monk Seal Recovery Plan (released January 2016) through the Marine Mammal Branch of the Protected Resources Division. NOAA NMFS's Office of Law Enforcement-Pacific Division (OLE-PD) investigates illegal acts against seals and pursues legitimate cases in partnership with the State Division of Conservation and Resources Enforcement (DOCARE) within DLNR. State agencies have responsibilities under state law, specifically the Hawai'i Endangered Species Act to protect monk seals (Chapter 195 D-4 Endangered species and threatened species). For the State, jurisdiction over monk seal protection is with the Marine Wildlife Program (MWP) of the Division of Aquatic Resources in the DLNR. Research and monitoring, as well as rescue and rehabilitation of injured seals, is led by the Protected Species Division of NOAA NMFS Pacific Island Fisheries Science Center (PIFSC).



Hawaiian monk seal. Photo credit: Mark Sullivan (NOAA NMFS/PIFSC/PRD)

Studies on the behavioral response of seals to marine infrastructure, such as renewable energy installations, are rare. A recent tracking study of harbor and grey seals in the North Sea, in Europe, however, showed that infrastructure, including wind turbines and pipelines, influenced the foraging patterns of individual seals (Russell et al., 2014). Some seals concentrated their activity at individual turbines and individuals were found to move along pipelines. Based on very few studies, the impact of wind farms on seals is thought to be a positive influence on abundance due to an increase in food and reduced risk of mortality from bycatch (Hammar et al., 2016).

## 6.2.2. Methods

### *Individual monk seal tracking data*

Global positioning system (GPS) location points for 19 individual monk seals were provided by PIFSC and Duke University from cell phone telemetry studies conducted between 2007 and 2014 (Littnan and Wilson, 2015). These data included data logger information on time spent at the surface and out of water, as well as dive depths and duration. Data on animal behavior are stored for up to six months and transmitted via the cell phone network (Wilson, 2015). When at the surface, the tags were programmed to record a GPS position (< 30 m accuracy) every 20 minutes. Fifteen male and four female monk seals were tracked. Monk seal tracks were mapped by creating lines between the location points. In addition, location point density was mapped as a simple way of representing the intensity of space use across a grid of cells (1.2x1.2 km) for all tracked seals combined.

### *Monk seal location data (NOAA PIFSC)*

PIFSC provided our Biogeographic Assessment with a dataset composed of monk seal location data from various sources, including opportunistic sightings, tagged seal locations and sightings from aerial surveys (Littnan and Maison, 2015). These data were gridded as the sum of seal locations in 5 km cells surrounding all major land masses of the MHI (2007-2011). This dataset includes many opportunistic sightings collected through the public sightings hotline and observer programs ([http://www.pifsc.noaa.gov/hawaiian\\_monk\\_seal/sightings.php](http://www.pifsc.noaa.gov/hawaiian_monk_seal/sightings.php)). These data have some inherent bias due to some sites having greater access to the public than others, yet offer

benefit by providing seal locations across a broad geographical area. For instance, absence of sightings could be related to poor accessibility or low reporting. The bias is difficult to correct and therefore spatial uncertainty is not easily mapped when visualizing the spatial distribution of seal abundance. In some cases, it is likely that the data also include multiple sightings for the same seal at the same time and place. However, due to their broad geographical coverage and richness of observations, the data are a valuable and important source of information and contributed to the delineation of critical habitat. NMFS researchers carefully evaluated the data to identify significant haul-out areas to inform the critical habitat mapping process. Comparisons among the individual sources of data demonstrated that the voluntary sighting data successfully identified areas used by monk seals, and provide a reliable dataset for identifying significant haul-out areas. Since point locations provided insufficient spatial resolution to encompass space use for highly mobile animals, a pragmatic solution was to group sightings into 5 km grid cells over each island to create a standardized grid. Seal location data were binned into grid cells along the coast of each island, and counts within coastal grids were then evaluated to determine frequency of monk seal use within these squares. Areas of significance were defined as those coastal grid cells where the count equaled 10 percent or more of the grid cell with the highest count value for each island. This description of significant haul-out areas allows stretches of coastline used contiguously by monk seals to be included in the description of essential features, accommodates for data that may be underrepresented in frequency due to a lower likelihood of reporting, and in areas with lower seal numbers provides adequate habitat for monk seals to use as the population expands (NOAA NMFS, 2014).

In addition to the 5 km grid of seal locations, here we have provided the same spatial grid, but with the data reduced to presence only data. Where the 5 km cell contains one or more seal sightings, or has been visited by a tracked seal, then it receives a value of 1 to indicate that the site has been used by the species. If no location data were available then the cell received a value of zero to indicate absence of use. This simplification of the data presents a rapid visualization of confirmed seal habitat use patterns around the coastline and nearshore waters of MHI.

### *Monk seal critical habitat maps*

Critical habitat is defined in Section 3 of the ESA, and refers to areas that contain habitat features that are essential for the survival and recovery of a listed species, and which may require special management considerations or protections. Critical habitat areas may include: areas occupied by the species; an area that the species is not currently using, but will need to use for its population to grow and recover; and special management, like protection from development. To map critical habitat, NMFS experts used the best scientific data and knowledge available to identify habitat features essential to the conservation of the species, delineate specific areas within the geographical area occupied which contain at least one essential habitat feature, including those features that support resting, reproduction, molting, predator avoidance, and foraging. Areas of proposed terrestrial critical habitat within the MHI were delineated by including all significant haul-out areas and preferred pupping and nursing sites within the designation (Figure 6.24; NOAA NMFS, 2015). The end points for the stretches of coastline were identified by using haul-out data, pupping and nursing data, natural geographic features, and/or hardened shorelines which lack the features of monk seal critical habitat (80 FR 50925; Federal Register, 2015b).



*Hawaiian monk seal scratching nose. Photo credit: NOAA NMFS/PIFSC/PRD*

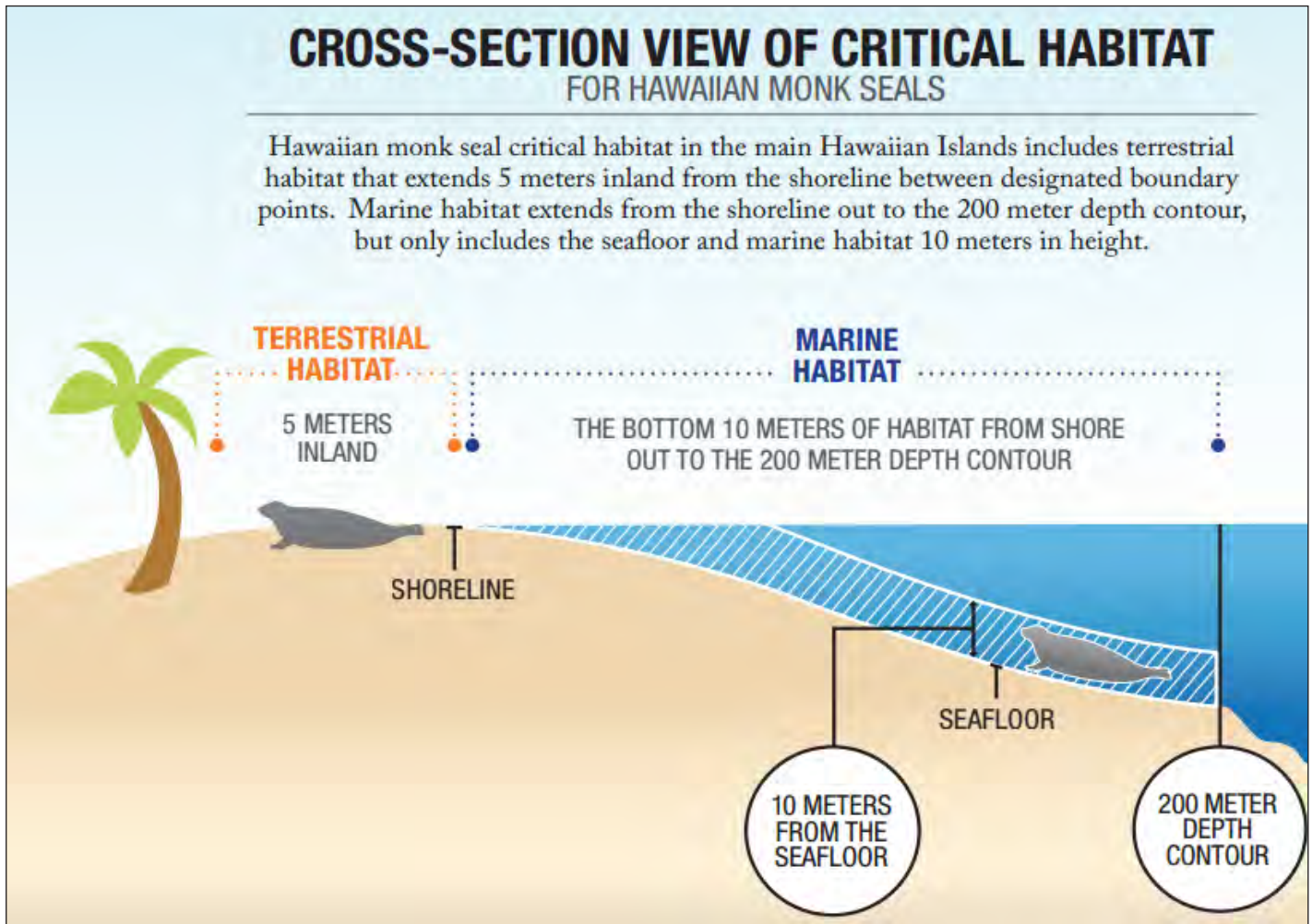


Figure 6.24. Infographic explaining the marine and terrestrial critical habitat dimensions (NMFS, 2014).

### 6.2.3. Results and Discussion

#### *Key space use patterns*

Monk seals have been sighted around all major islands of the MHI (leeward and windward sides; Figure 6.28). Haul-out sites are located on all MHI, but more sites were identified on the westernmost islands that are closest to the NWHI, where most monk seals reside. For example, eight haul out and pupping sites were known to experts on Kaua'i, but only three on Hawai'i. Examination of geographical patterns in the movement data revealed a high frequency of alongshore movements within a single island, but also high connectivity between neighboring islands (Figure 6.25). For instance, the telemetry data highlight the importance of Penguin Bank to monk seals which are known to forage over the shallow sandy banks (Figure 6.26). Although most seal movements are confined to State waters, one individual travelled across the EEZ into international waters and then returned to the MHI.

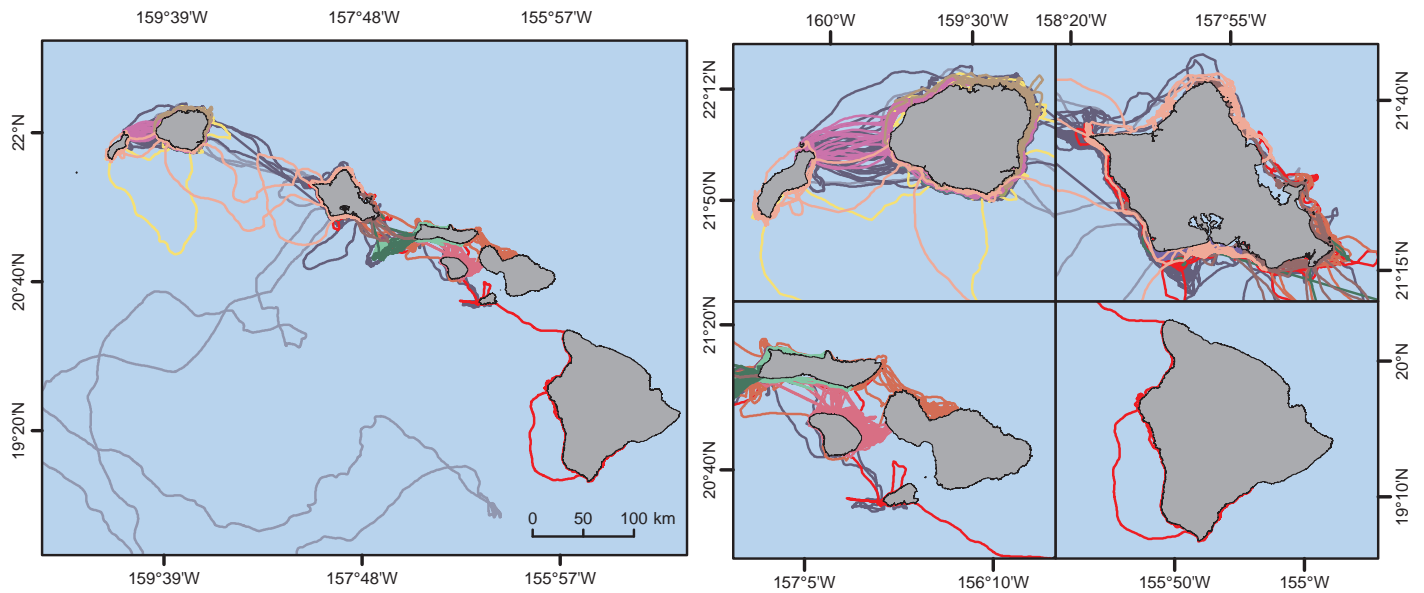


Figure 6.25. Track lines for individual Hawaiian monk seal (*Monachus schauinslandi*) during the period 2007 to 2014. Movement pathways for individual monk seals tagged with GPS/cell phone transmitters across MHI between 2007 and 2014 (left) and by island group from western islands to eastern islands (right; top - Ni'ihau and Kaua'i, and O'ahu; bottom - Moloka'i, Lāna'i, Maui and Kaho'olawe, and Hawai'i). Data source: NOAA NMFS/PIFSC

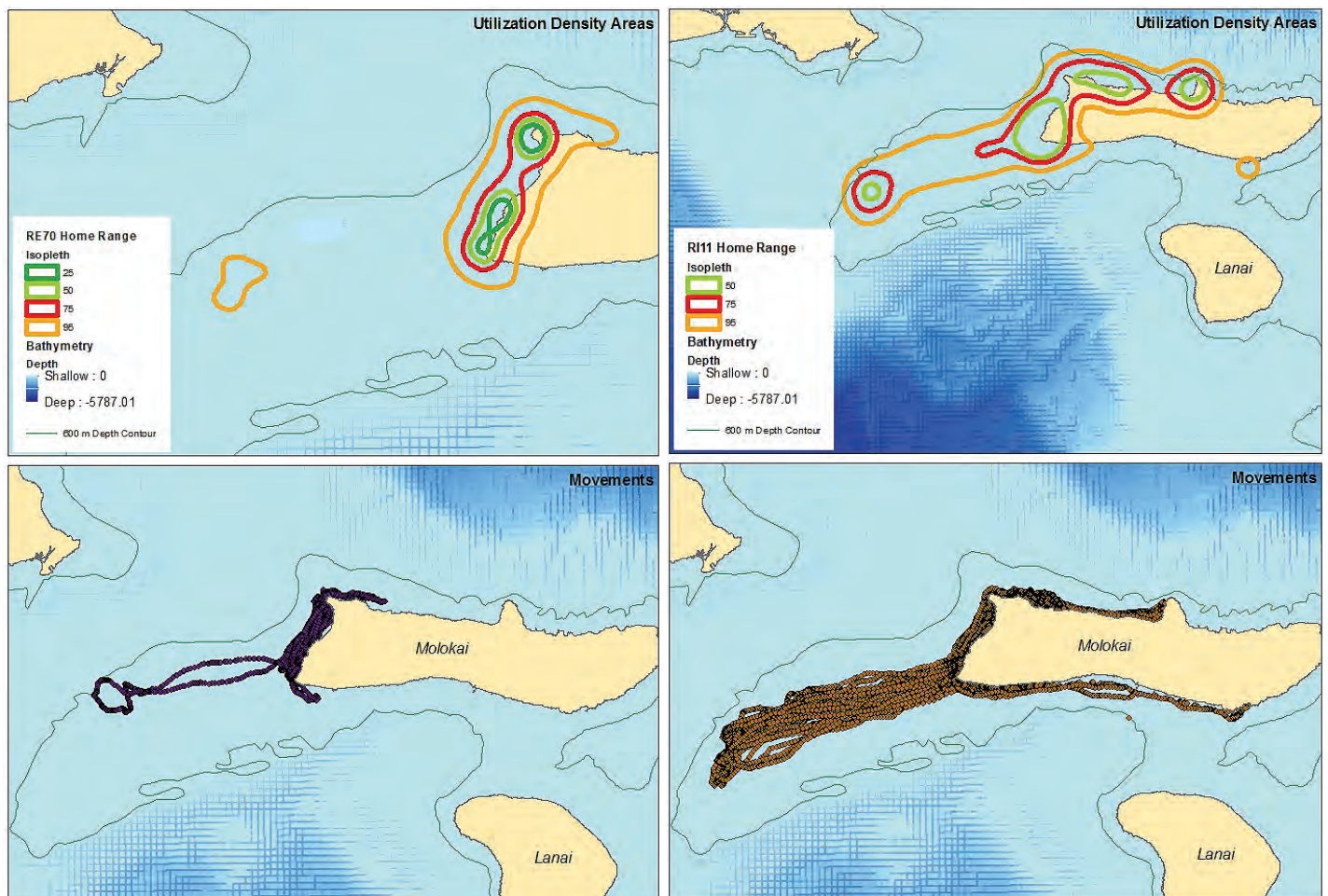


Figure 6.26. Movement tracks and space-use patterns of individual monk seals (id: RE70 and RI11) from Moloka'i, and the high use area of Penguin Bank, an important foraging area for Hawaiian monk seals. Data source: Wilson, 2014

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## Individual monk seal tracking data

On average, monk seals spent 51.1 percent of their day diving, 19.6 percent at the surface, and 29.3 percent of the day hauled-out on land (Wilson, 2015). Analyses of these data by Wilson (2015) revealed two distinct movement modes: near shore and offshore/inter-island movements (Wilson, 2015). Wilson (2015) provides the following description: “There was a high level of individual variation in the movements of monk seals, but general descriptions of their behavior were accurate at the population level. On average, foraging trips lasted  $0.81 \pm 1.38$  days and seals traveled  $28.5 \pm 82.0$  km per trip. Most seals began benthic dives shortly after entering the water, with most dives occurring between 20 to 40 m. The median home range and core area size for seals in the MHI was 265.6 km<sup>2</sup> and 1,564.6 km<sup>2</sup>, respectively”. Maps of the density of location points for multiple individual seals indicate that some high-use areas exist and are shown in warmest colors (i.e., red cells were the highest use areas and blue the lowest; Figure 6.27). This simple snapshot of space use includes inherent bias, for example, seals were tracked for different durations and location data were not necessarily regular in time.

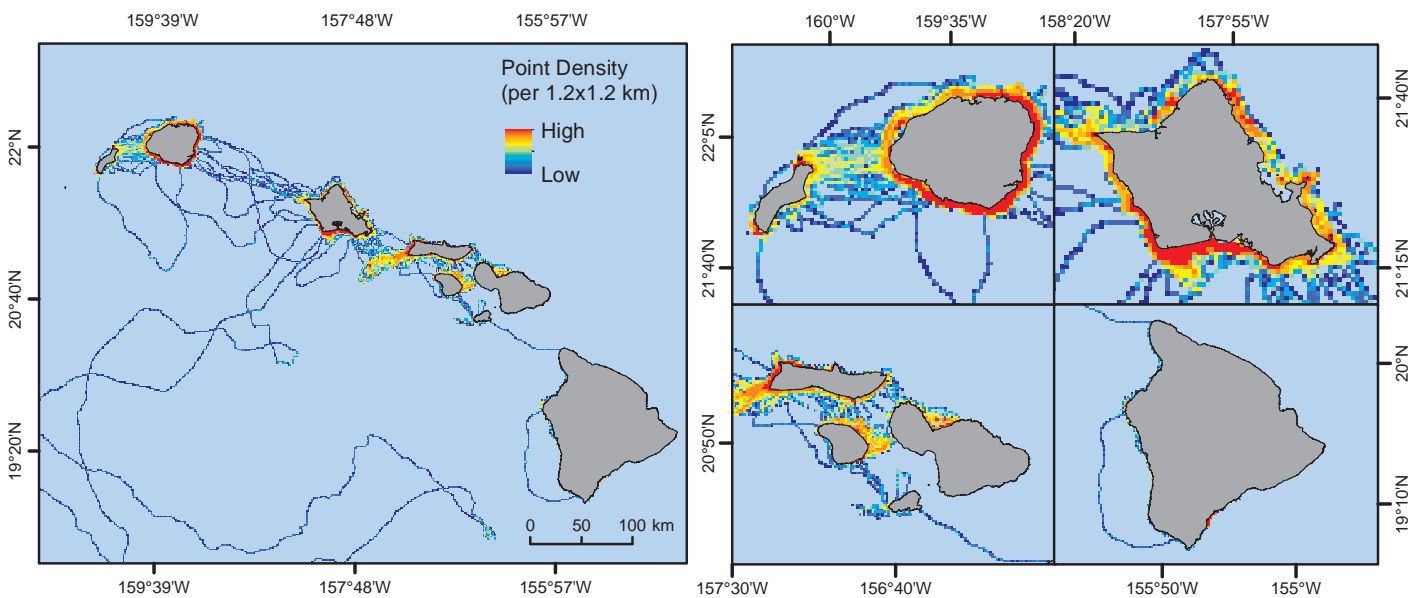


Figure 6.27. Density of location points for individual Hawaiian monk seal tracked between 2007 and 2014. Maps showing the total density of location points recorded from all tagged seals within each 1.2x1.2 km grid cells across the project area (left) and by island group from western islands to eastern islands (right; top - Ni'ihau and Kaua'i, and O'ahu; bottom - Moloka'i, Lāna'i, Maui and Kaho'olaw, and Hawai'i). Data source: NOAA NMFS/PIFSC

## Distribution of monk seal sighting locations

The proportion of coastline with at least one seal located decreases from west to southeast across the MHI (Figure 6.28). Around Ni'ihau, the most western of the MHI, 15 (of 17) of the 5 km cells had seal presence recorded between 2007 and 2009. Only two cells that intersect the coastline have no seals recorded, resulting in an almost entire coastline with seal presence. Kaua'i had 37 (of 40) 5 km cells with seal presence recorded between 2007 and 2010 covering almost all of the cells that intersect the coastline. The continuous coastal use patterns displayed at Kaua'i were only separated by three coastal cells where no seals have been recorded. Given that monk seals are highly mobile, it is highly unlikely that the cells with no sightings represent true absence. The coasts of Ni'ihau and Kaua'i are dominated by sand and rocky beaches providing suitable haul-out sites for seals. O'ahu showed 46 (of 57) 5 km cells with seal presence recorded between 2007 and 2010, with 11 cells that intersect the coastline having no presence recorded. Regardless, seal presence cells form an almost continuous area surrounding the entire island. No sightings were recorded for cells covering the inner Pearl Harbor, O'ahu-Keahi Lagoon and the lagoon adjacent Kāhala'u – embayment areas with a high proportion of wetlands and artificial structure (NOAA ORR, 2001) unsuitable or providing low quality as haul-out sites.

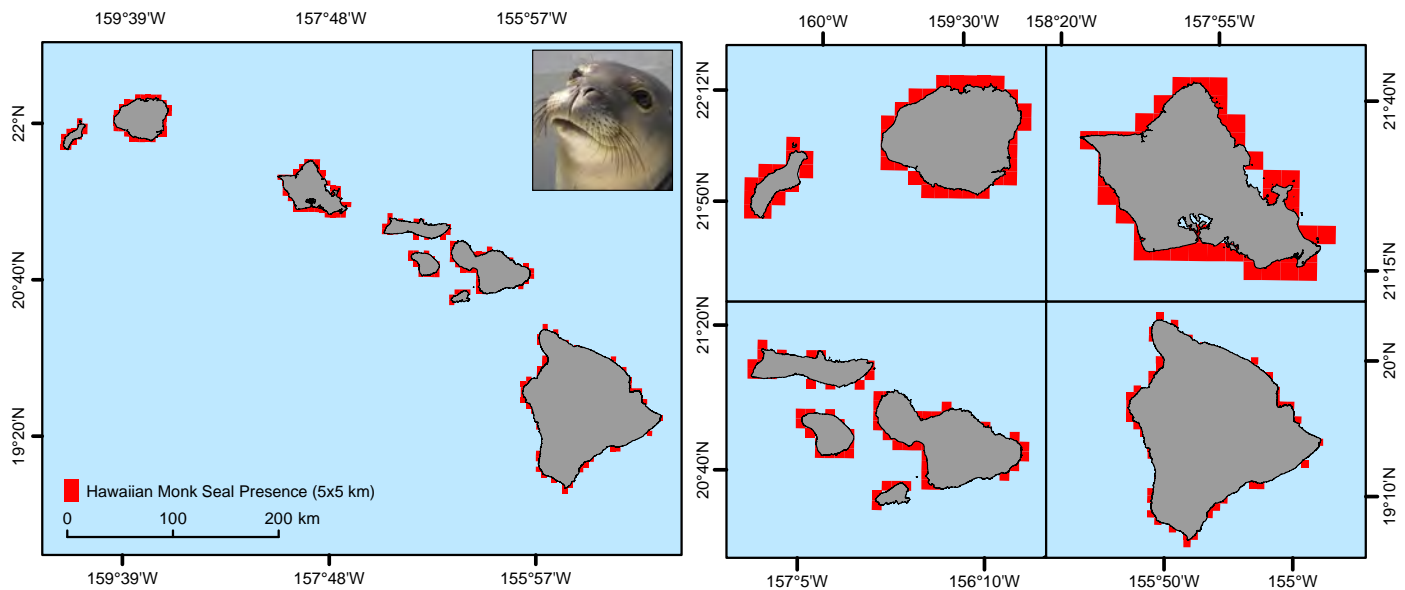


Figure 6.28. Areas used by Hawaiian monk seal. Presence of seals within 5 km cells across MHI (left) and by island group from western islands to eastern islands (right; top - Ni'ihau and Kaua'i, and O'ahu; bottom - Moloka'i, Lāna'i, Maui and Kaho'olawe, and Hawai'i). Data source: NOAA NMFS/PIFSC

Moloka'i had 15 (of 35) 5 km cells with seal presence recorded between 2007 and 2009, and 20 cells having no recorded presence. Presence was generally associated with the areas where sand and rocky shorelines dominated the coast, particularly on exposed rocky shores at the east and west ends of the island. However, with a gradual eastward expansion of the growing MHI Hawaiian monk seal population, it is likely that more sightings have been recorded there since 2009. It is also important to note that data were not adjusted for sightability relative to coastal relief. That is, cells were not excluded from the mapped data where monk seals were unlikely to be seen because of hardened shoreline, sheer cliffs or other factors that would prevent hauling out, and where shorelines are inaccessible to people resulting in no sightings.

Lana'i had 13 (of 18) 5 km cells with seal presence recorded between 2007 and 2011, with five cells intersecting the coastline which showed no recorded seal presence. Kaho'olawe had only half of its coastal cells with seal presence recorded between 2007 and 2010, with five coastal cells having no recorded seal presence. Location data for Maui showed that 25 (of 45) 5 km cells have seal presence recorded between 2007 and 2010, with 20 cells intersecting the coastline that showed no seal presence. Cells without sightings co-occurred with exposed rocky shores on the south and east coast of Maui. For the island of Hawai'i, the farthest east in the archipelago, 55 (of 118) 5 km cells had seal presence recorded between 2007 and 2010, with more than half of the coastal cells (63 cells) with no recorded seal presence. A gap in presence was noted on the exposed rocky shores on the northeast coast.

### Critical habitat maps

Marine areas of critical habitat include a 10 m deep band along the seafloor from shore out to 200 m from shore (Figure 6.24), where the majority of monk seal foraging is known to occur. Specific areas designated include 16 areas within the range of the Hawaiian monk seal, six of which are in the MHI. These areas contain one or a combination of the features essential to seal conservation, including: preferred pupping and nursing areas, significant haul-out areas, and marine foraging areas out to 200 m in depth. In the MHI, monk seal critical habitat includes the seafloor and marine habitat to 10 m above the seafloor from the 200 m depth contour through the shoreline and extending into terrestrial habitat 5 m inland from the shoreline between identified boundary points around the following islands: Ka'ula Island (includes marine habitat only); Ni'ihau (includes marine habitat from 10-200 m in depth); Kaua'i; O'ahu; Maui Nui (including Kaho'olawe, Lāna'i, Maui, and Moloka'i); Hawai'i (Figure 6.29). Boundary coordinates for designated areas are provided here.

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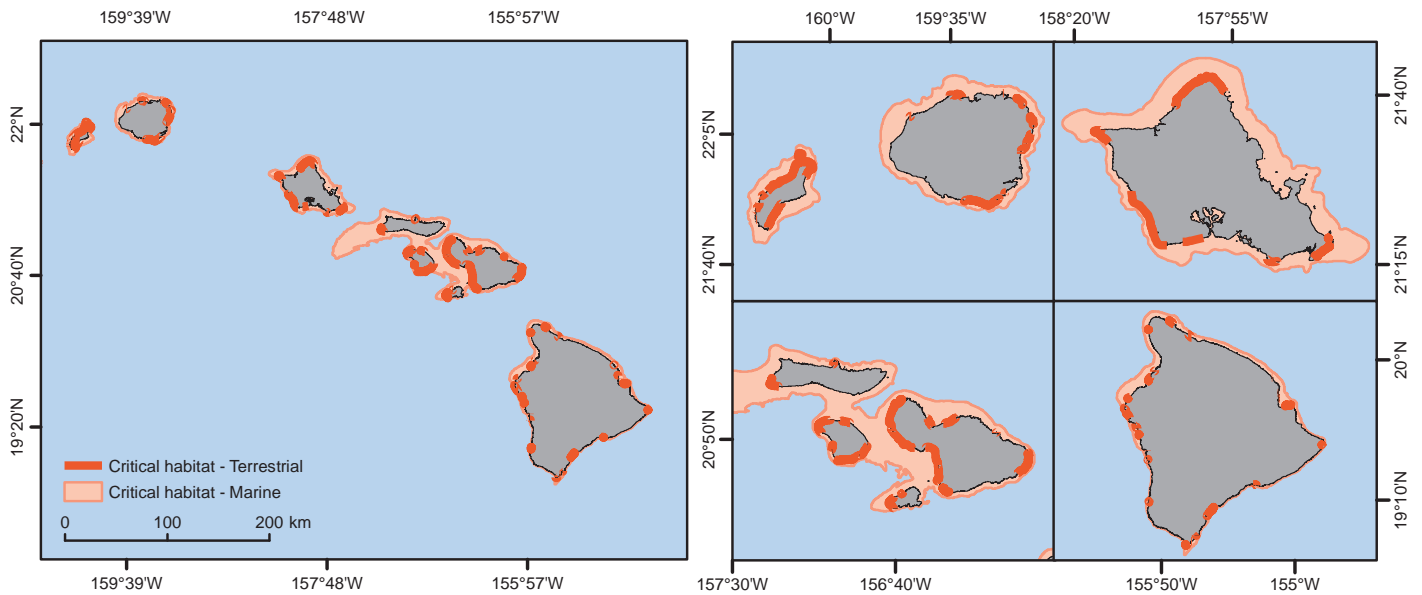


Figure 6.29. Areas used by Hawaiian monk seal. Maps showing terrestrial and marine critical habitat designations for Hawaiian monk seal across MHI (left) and by island group from western islands to eastern islands (right; top - Ni'ihau and Kaua'i, and O'ahu; bottom - Moloka'i, Lāna'i, Maui and Kaho'olawe, and Hawai'i). Data source: NOAA NMFS/PIFSC

Section 4(b)(2) of the ESA requires consideration of economic impacts, impacts to national security, and any other relevant impacts of designation prior to designating any area as critical habitat. As such, several military facilities are excluded from designation as critical habitat (NOAA NMFS, 2015b). In addition, cliffs and manmade shorelines and structures in existence are not included in the designation because these areas do not meet the definition of critical habitat. Examples of manmade shorelines include docks, seawalls, piers, fishponds, roads, pipelines, boat ramps, platforms, buildings, ramparts and pilings. More details on the designations can be found in 'Revision of Critical Habitat for Hawaiian Monk Seals' (NOAA NMFS, 2015b).

## 6.2.4. Data Limitations and Information Gaps

Expansion of the distribution of Hawaiian monk seals across the MHI is a dynamic process which will require continual monitoring to determine the need for expansion of the critical habitat beyond those mapped areas presented here. Some features are known as foraging grounds (i.e., Penguin Bank), but a more complete geographical knowledge of areas important for foraging is needed across the entire MHI region. Telemetry combined with devices that record pressure, temperature, heart rate and video observations of prey will provide the necessary data to better understand foraging and resting activities. Where detailed data on seal behavior are available, in most cases, geographic/habitat/prey availability data are missing or have been sampled at a scale that is not compatible with the fine scale movements of monk seals. Detailed prey and habitat surveys throughout the MHI would be useful for modeling foraging with telemetry and biologging instruments. Furthermore, the telemetry dataset is biased towards males and juvenile animals. Due to a conservative sampling regime, potentially pregnant females are not handled for these studies. The ecology and habitat use of females may be different from other age-sex classes and should be a focus of study in the future. Tracking data also demonstrate that some individuals will undertake extensive excursions into deep waters considerable distance from the islands. Very little is known about the importance of deeper water areas to the recovering seal population. The absence of information about the potential response of monk seals to artificial structure and coastal development is another major knowledge gap. Continued reporting of sightings and telemetry will provide the necessary data to understand seal responses through mapping of space use patterns.



Shifts in foraging habitat use may occur in more densely populated areas. For instance, as the population of seals continues to grow on Kaua'i and O'ahu, resident seals may forage further afield or use deeper areas to search for prey resources. This could change diet, foraging success, and habitat use and should be a focus of future research. With particular relevance to the present project is a need for more information to understand the potential impacts of wind turbine construction (i.e., noise) and operation (i.e., introduction of subsurface structure) on monk seal behavior, foraging and distributions. A review of noise impacts from construction and operation of wind farms in Europe concluded that the disturbance to marine mammals is more severe during the construction of wind farms than during their operation (Madsen et al., 2006). More research is needed to assess the potential impacts to Hawaiian monk seals of noise from wind farm construction and operation.

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