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Final Report of the California Current Ecosystem Survey (CCES) 2018: A PacMAPPS Study

US Department of the Interior
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DISCLAIMER

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REPORT AVAILABILITY

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ABOUT THE COVER

School of common dolphins (*Delphinus delphis delphis*). Photo taken under permit by Adam Ü.

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Contents

List of Abbreviations and Acronyms

AIS	Automatic Identification System
AUC	Area Under the (Receiver Operator Characteristic) Curve
BOEM	Bureau of Ocean Energy Management
CCE	California Current Ecosystem
CCES	California Current Ecosystem Survey
CTD	Conductivity-Temperate-Depth
CV	Coefficient of Variation
DASBR	Drifting Acoustic Spar Buoy Recorder
eDNA	Environmental DNA
ESA	Endangered Species Act
ESW	Effective Strip Width
EEZ	Exclusive Economic Zone
FRD	Fisheries Resources Division
GAM	Generalized Additive Model
GPS	Global Positioning System
HICEAS	Hawaiian Islands Cetacean and Ecosystem Assessment Survey
IAA	Interagency Agreement
MLD	Mixed Layer Depth
MMPA	Marine Mammal Protection Act
MMTD	Marine Mammal and Turtle Division
NBHF	Narrow Band High Frequency
NOAA	National Oceanic and Atmospheric Administration
NMFS	National Marine Fisheries Service
OMAO	Office of Marine and Aviation Operations
OOD	Officer of the Day
PacMAPPS	Pacific Marine Assessment Program for Protected Species
PASCAL	Passive Acoustics Survey of Cetacean Abundance Levels
PBR	Potential Biological Removal
REML	Restricted Maximum Likelihood
RHIB	Rigid Hull Inflatable Boat
ROMS	Regional Ocean Modeling System
SCS	Scientific Computer System
SDM	Spatial Density Model
SNR	Signal to Noise Ratio
SSH	Sea Surface Height
SST	Sea Surface Temperature
ST	Survey Technician
SWFSC	Southwest Fisheries Science Center
UCTD	Underway Conductivity-Temperate-Depth

1 Report Summary

In the summer and fall of 2018, NOAA Southwest Fisheries Science Center conducted the California Current Ecosystem Survey (CCES). CCES was a line-transect survey for coastal pelagic fisheries stocks, marine mammals (cetaceans), seabirds, and ecosystem data, spanning the entire continental shelf and slope off the US West Coast, from Vancouver Island, Canada, to the California-Mexico border. Additional survey coverage for marine mammals and seabirds (but not fisheries stocks) was obtained off northern Baja California, Mexico, and in offshore areas beyond the continental shelf (out to approximately 200 nautical miles). CCES also included an extensive small-boat effort focused on collecting photo identification and tissue biopsies for large whales (especially humpback whales), and passive acoustic monitoring for deep-diving cetaceans (e.g., beaked whales) that are difficult to survey effectively using traditional visual line-transect survey methods. This report describes the collection, summarization, and analysis of cetacean and, to a lesser extent, seabird data from CCES.

CCES was a survey of the Pacific Marine Assessment Partnership for Protected Species (PacMAPPS), a partnership between NOAA, BOEM, and the US Navy. PacMAPPS facilitates the regular collection and analysis of protected species data to service the shared monitoring and assessment requirements of all three agencies throughout the northeastern Pacific.

This final report is a compendium of three NOAA Technical Memoranda, each provided as a separate Appendix. Appendix A (Henry et al. 2020) is the CCES cruise report, describing the methods for cetacean and seabird data collection and providing basic data summaries (e.g., maps and quantification of survey effort, numbers and maps of visual sightings for cetaceans and seabirds, number of photographs and biopsy samples). Appendix B (Simonis et al. 2020) provides an in-depth description of the passive acoustic component of CCES. Passive acoustic data were collected using Drifting Acoustic Spar Buoy Recorders (DASBRs). These data require extensive post-survey processing to identify which species were detected and where. Appendix B describes the methods for post-survey data processing and summarizes results in terms of the numbers of detection for deep diving cetaceans and their locations. Appendix C (Becker et al. 2020) presents the spatial density modeling (SDM) analysis based on visual line transect data collected from all California Current surveys conducted from 1991 through CCES 2018. Outputs include density surface maps for all modeled cetacean species and population size estimates for the survey area.

Visual line-transect data (cetacean sightings and effort) for all California Current surveys from 1991 through 2018 have been or are in the process of being uploaded to OBIS-SEAMAP (Halpin et al. 2009; http://seamap.env.duke.edu/), from where they can be viewed and downloaded by the public. Spatial density surface layers based on survey data collected through 2014 will soon be available through NOAA's CetMap webpage (https://cetsound.noaa.gov/cda-index) and through Density Mapper (https://seamap.env.duke.edu/models/Pacific-GOA/), a web-based mapping tool developed by Duke University.

2 Summary of Results

A total of 12,857 km of transect line was surveyed for marine mammals and seabirds. For the small-boat work, 65 vessel-days of effort were dedicated to collecting large whale photo identification and biopsy samples. In total, 2,122 marine mammal groups were sighted by marine mammal observers. This is a record for a California Current cetacean stock assessment survey. Of these, 2,004 were recorded while 'on-effort' and 118 were 'off-effort'. 328 biopsy samples were collected via projectile sampling. For seabirds, 133 species were sighted. Ardenna shearwaters were the most common genus counted (54.1%), followed by Puffinus shearwaters (16.4%) and Uria murres (8.6%). Fourteen seawater samples were collected for eDNA analysis. Good quality photographic IDs were obtained for >1,000 unique individuals, mostly for humpbacks (895) but also blue whales (100), fin whales (22), and gray whales (11). Seven DASBRs were successfully deployed and retrieved in US West Coast waters and another 8 were successfully deployed and retrieved in Mexican waters. Eight additional DASBRs were deployed in US West Coast waters but not successfully retrieved. The total recording time of the recovered DASBRs was ~1,900 hours. Most of the lost DASBRs were deployed early in the survey in the northernmost section of the study area, which resulted in a paucity of coverage in those areas.

Acoustic data recorded by DASBRs were examined using a semi-automated approach to find echolocation pulses from beaked whales, sperm whales, and species that produce NBHF (narrow band high frequency) pulses such as dwarf and pygmy sperm whales. Six distinct beaked whale signals were detected, including those from Cuvier's, Baird's, and Stejneger's beaked whales, as well as the BW43, BW37V, and BWC signal types (these are signal types that are recognizable and distinct but have not yet been positively attributed to a species). There were no detections of Blainville's beaked whales or BW70 signals. Sperm whales were detected across 11 of the 15 drifts. NBHF clicks were also detected in 11 of 15 drifts.

Habitat-based density models were developed for 14 cetacean species and one guild (Mesoplodonts and Cuvier's beaked whale) using 92,214 km of on-effort survey data collected between 1991 and 2018 within the CCE study area. The number of sightings within the species-specific truncation distances available for modeling ranged from 39 to 1,034. Models were used to generate yearly and multi-year average density surface maps.

3 Conclusions

The 2018 CCES survey generated data and data products of unprecedented quality, due to many factors, including:

- The nature of the 2018 survey (data collection concentrated over the continental shelf) resulted in record sighting numbers for species occupying shelf and slope waters.
- A dedicated small-boat effort resulted in record sample sizes for large whale photo ID and biopsy (these data have been used to generate precise mark-recapture abundance estimates for humpback and blue whales).
- This was the first California Current cetacean stock assessment survey to make use of DASBR technology, which provided our best acoustic data to date for deep-diving species (a peer-reviewed article is in preparation, generating the first passive acoustic-based abundance estimate for Cuvier's beaked whales).
- Species density surface models made use of new variance estimation methods developed over the past couple of years.

4 References

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5 Appendices

Appendix A: Cruise Report for the California Current Ecosystem Survey (Henry et al. 2020, NOAA Technical Memorandum NMFS-SWFSC-636)

This appendix describes the methods for cetacean and seabird data collection and provides basic data summaries (e.g., maps and quantification of survey effort, numbers and maps of visual sightings for cetaceans and seabirds, number of photographs and biopsy samples).

REPORT OF THE CALIFORNIA CURRENT ECOSYSTEM SURVEY (CCES):
Cetacean and Seabird Data Collection Efforts
June 26 – December 4, 2018

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PROJECT OVERVIEW AND OBJECTIVES

The 2018 California Current Ecosystem Survey (CCES) was a joint project of the Marine Mammal and Turtle Division (MMTD) and the Fisheries Resources Division (FRD) of National Oceanographic and Atmospheric Administration's (NOAA) Southwest Fisheries Science Center (SWFSC). The survey was conducted over the course of 7 legs aboard the NOAA ship *Reuben Lasker* between 26 June and 4 December 2018 (Table 1). CCES was an assessment survey for coastal pelagic fish stocks, marine mammals, seabirds, and oceanography along the west coasts of southern Canada (Vancouver Island), US, and northern Mexico (Baja California), out to a distance of approximately 200 nautical miles offshore (Fig. 1). MMTD and FRD worked jointly aboard the vessel during Legs 1 through 4 (OMAO Project No. RL-18-03) (Tables 1, 2a, and 2b), during which the vessel surveyed off the coasts of Vancouver Island and the US West Coast. Only MMTD operations were conducted during Legs 5 through 7 (OMAO Project No. RL-19-01), during which the vessel surveyed off the US West Coast and Mexico. This document covers the work conducted by MMTD (MMTD Survey No. 1651). Work conducted by FRD is presented separately (Stierhoff et al. 2019).

CCES 2018 was the second survey conducted under PacMAPPS, the Pacific Marine Assessment Program for Protected Species[1], an initiative by NOAA, the US Navy, and Bureau of Ocean Energy Management (BOEM), to conduct annual cetacean and ecosystem surveys throughout the North Pacific and generate data products used by all three agencies to meet regulatory requirements pertaining to protected species. The first PacMAPPS survey was the Hawaiian Islands Cetacean and Ecosystem Assessment Survey (HICEAS) 2017 (Yano et al. 2018; Bradford et al. *In press*).

The primary MMTD objectives of CCES 2018 were to collect visual sightings data for marine mammals and seabirds, passive acoustic detection data for cetaceans, photo identification, and biopsy tissue samples for cetaceans, and additional ecosystem data (e.g., oceanographic and prey distribution data). These datasets will be used in a suite of analyses that support MMTD's fulfillment of regulatory requirements and scientific initiatives (e.g., marine mammal stock assessments, integrated ecosystem assessments, mapping cetacean distributions for stakeholders such as the US Navy and BOEM).

CCES 2018 differed markedly – by virtue of its inclusion of a coastal pelagic fish stock survey – from MMTD's marine mammal and ecosystem assessment surveys conducted between 1991 and 2014 (VonSaunder and Barlow 1999, Philbrick et al. 2003, Appler et al. 2004, Forney 2007, Barlow 2010, Barlow et al. 2010, Becker et al. 2012, Moore and Barlow 2017). Whereas the typical MMTD survey design consists of a regular intersecting grid of transect lines (spaced at 60 nmi) throughout the entire US West Coast EEZ (and out to 300 nmi from shore), the first four legs of the CCES 2018 survey design, driven primarily by needs for the fish stock survey, consisted of closely spaced (10 nmi) parallel transects, running perpendicular from shore, concentrated predominantly over the continental shelf (Fig. 1). This resulted in a relative wealth of data over the continental shelf and slope, but a relative paucity of data from distant offshore

[1] https://www.fisheries.noaa.gov/west-coast/science-data/pacmapps-pacific-marine-assessment-program-protected-species

regions, compared to data collected during previous California Current cetacean assessment cruises. In the second part of the study (Legs 5 – 7), transect distribution was dictated in large part by routes taken to retrieve drifting passive acoustic devices (called DASBRs) that had been deployed during the first four legs and to deploy (then eventually retrieve) additional DASBRs. These DASBR-tied routes were modified to some extent to obtain as much far-offshore effort as possible, given the lack of data collected from such areas during Legs 1 – 4. The 2018 survey also differed from past marine mammal stock assessment surveys of the area by its inclusion of northern Baja California as part of the study area. Given the uneven sampling throughout the study area, the 2018 study design will require model-based (rather than design-based) analytical approaches for updating population size estimates for US West Coast marine mammal stocks (Becker et al. 2019, Forney et al. 2010)).

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SURVEY OPERATIONS

1.0 CETACEAN RESEARCH

Weather permitting, visual watches were conducted by the marine mammal observer team on the flying bridge during daylight hours (from sunrise to sunset) along predetermined tracklines (Fig. 1); actual effort completed is shown in Figure 2.

1.1 Cetacean Survey – Standard line-transect survey methods, as implemented on past California Current cetacean surveys (Barlow and Forney 2007), were used to collect information for CCES 2018 . A watch for cetaceans was maintained on the flying bridge during daylight hours by six (6) mammal observers aboard the ship (three were on watch at a time). Each mammal observer worked in 2-hour rotations, manning each of the following three stations on the flying bridge for 40 minutes: a portside 25 x 150 binocular station, a center-line data recorder position, and a starboard 25 x 150 binocular station. During Legs 1 through 4, the visual team was in communication (via satellite phone, cell phone, and VHF radio) with a shore-based small-boat research team from Cascadia Research Collective (Cascadia), which coordinated with personnel on the NOAA Ship *Lasker* to locate groups of marine mammals (especially large whales) to conduct photo identification and biopsy sampling.

At the beginning of each day, search effort started on a trackline determined in advance in consultation between the Cruise Leader and the Command. The ship traveled at ~10 knots (speed over ground) along the designated trackline.

1.1.1 Logging of Data – A log of observation conditions and sightings (e.g., effort status, environmental variables, sighting details) was entered using WinCruz software into a computer connected to the ship's Global Position System (GPS) and Scientific Computer System (SCS, for weather and heading information).

1.1.2 Breaking Trackline and Recording Sighting Details – Surveys were conducted in "closing mode." This means that, upon sighting a marine mammal school or other feature of biological interest, and after recording initial location information for the sighting, the Cruise Leader or marine mammal observer team on watch might take the team 'off effort' and request that the vessel be maneuvered to approach the school or feature for investigation (to determine size and species composition of the school, attempt biopsy and photo identification collection, etc.). When the ship approached the cetaceans (or from the trackline if no approach was needed), the observers made independent estimates of the number of animals (school size). If biopsy and photography operations were to be conducted, these would commence from the bow, based on directions from the Cruise Leader or Senior Marine Mammal Observers. In some instances, during Legs 5 through 7 (MMTD only), the Cruise Leader requested the deployment of a small boat for biopsy, photography, or other operations. During Legs 1 through 4, when sharing the vessel with FRD, the sum duration of the excursions from the trackline was not to exceed an average of 2 h per day; this precluded small-boat operations being conducted from the *Lasker* during these legs (instead, a shore-based small-boat team was used, as described below).

It was occasionally desirable to divert the ship's course from the established trackline during regular effort due to glare or adverse sea conditions. Under these circumstances, during Legs 5 through 7 (when not working with FRD), the ship could divert up to 30 degrees from the established course. This deviation would continue until the ship was 5nm from the trackline, at which point the ship turned back toward the trackline.

1.1.3 Resuming Effort – When the observers completed scientific operations for the sighting, the ship resumed the same course and speed as prior to the sighting and returned to an 'on-effort' state. During legs 1 through 4, this followed the ship's return to the point where the ship had departed from the trackline. During Legs 5 through 7, if the pursuit of the sighting took the ship more than 5nmi from the trackline, the observers were notified and the Cruise Leader or Senior Marine Mammal Observers may request, rather than proceed directly toward the next waypoint, that the ship take a heading of 20 degrees back toward the trackline or return to the position at which the ship diverted before resuming effort.

1.2 Biopsy Sampling – Samples for genetic and hormone analyses of cetaceans were collected on an opportunistic basis. The animals biopsied were approached by the research vessel during normal survey operations, approached the vessel on their own, or were approached by a small boat. Cetacean biopsy samples collected using a dart fired from a crossbow. During Legs 1 – 4, small boat work was conducted by a shore-based team led by Cascadia (see "4.0 Small Boat Work"). During Legs 5 – 7, small boat deployment from the *Lasker* was requested by the Cruise Leader on an opportunistic basis during all daylight hours, occasionally multiple times in a single day. Unless the Captain allowed otherwise, the *Lasker's* small boat always remained within sight and radio contact while deployed.

1.3 eDNA Samples – Via small boats, seawater samples were collected for environmental DNA (eDNA) by Cascadia and NOAA Ship *Lasker* in areas where large whales and large dolphin groups were present. The whale's fluke print, as well as areas of the greatest density of the dolphins' schools, were the target areas. Seawater samples were collected in sterilized Nalgene bottles and stored in a cool, dark place until the water could be filtered. Aboard *Lasker*, samples were vacuum filtered within 24 hrs of collection and then stored in 5 ml of Longmire's lysis buffer at ambient temperature for storage and transport to SWFSC laboratory for DNA extraction.

1.4 Photography –Photographs of marine mammals were taken on an opportunistic basis from aboard the *Lasker* and its small boat. Photographs collected over the course of many years have been and continue to be used to study social behavior, geographic variation in morphology, stock structure, and movement patterns of identified individuals. The animals photographed were approached by the research vessel during normal survey operations, approached the vessel on their own, or were approached by a small boat. Small boat deployment requested by the Cruise Leader on an opportunistic basis during all daylight hours, occasionally multiple times in a single day, providing the Captain concurs that operating conditions are safe. Unless the Captain allowed otherwise, the *Lasker's* small boat always remained within sight and radio contact while deployed. More dedicated photographic data were collected during Legs 1 - 4 by the Cascadia's small-boat team (see "4.0 Small Boat Work"), for the purposes of informing a long-term photo identification study for large whales.

1.5 Passive Acoustics –

1.5.1 Drifting Autonomous Spar Buoy Recorders (DASBRs) – DASBRs are used to collect passive acoustic data for cetaceans, in particular for deep-diving species such as beaked whales (Griffiths and Barlow 2016, Keating et al. 2018, Griffiths et al. 2020). DASBRs consisted of a black ABS spar buoy, bungee and nylon line, a submerged recorder, and hydrophone system at ~100 depth, an 11" sub-surface buoy, and a 30-lb weight at 100-150 m depth (see Simonis et al. 2020 for details). The spar buoys were attached to a secondary round buoy using a 10 m floating line to aid in detection and retrieval. Buoys included two SPOT geo-locators (inside the spar buoy) and were marked with reflective tape. Deployment and retrieval were in accordance with *Lasker's* Ship Specific Instructions (SSI 1102-16.1RL) for DASBR deployment. Deployments and retrievals occurred during day and night. DASBRs were retrieved after a period of weeks to months by a member of the scientific team and a member of the ship's crew. A 12-volt line-puller was used to aid retrieval.

Buoys were tracked with a satellite geolocator. During daylight, they were relocated visually with the assistance of observers on big-eye binoculars (typically at 5 nmi range). At night, they were relocated visually using the ship's spotlight and reflective tape on the buoys (typically at 0.5 nmi range). Usually, deployment or retrieval (once buoys were located) required approximately 30 minutes. Extreme care was taken to ensure that the vessel did not drift over the top of the line. The Officer of the Day (OOD) or Survey Technician (ST) recorded the time of DASBR deployment or retrieval in the SCS event logger.

1.5.2 Sonobuoys – Sonobuoys were deployed opportunistically in the presence of large whales at the request of the Cruise Leader or Sr. Marine Mammal Observer and the OOD or ST recorded the time of sonobuoy deployment in the SCS event logger.

1.5.3 Towed Acoustic Recorder – During daylight hours, an experimental autonomous acoustic recorder was towed approximately 150-180 m behind the ship. The instrument package included a single-channel SoundTrap ST300HF recorder or a SoundTrap ST4300 recorder with two HTI-96-min hydrophones inside a streamlined tow body (10 cm diameter x 1.2 m length). The instrument was deployed from the stern on the starboard side each day before marine mammal operations began and retrieved each night after marine mammal observations ended. The line was deployed and retrieved by hand or with a 12-v battery-powered winch at steerage speed. Data were downloaded weekly by the cruise leader or marine mammal personnel. The OOD or ST recorded the time of towed array deployment or retrieval in the SCS event logger.

After loss of the prototype on Leg 5, the system was re-designed and tested again on Leg 7. The 1/8" stranded stainless cable leading into the tow body was replaced with a stronger and more flexible 1/2" Dyneema cable or with a 1/2" stainless steel rod. A longer 30-m 1/2" tail rope was added to reduce side-to-side motion. The 150-m 1/8" Kevlar tow cable was replaced by a 180-m, 3/16" Dyneema tow cable to provide a greater margin of safety. This new system was successfully deployed and retrieved seven times on Leg 7.

1.6 Salvage of Marine Mammals, Birds, and Turtles – During CCES 2018, six (6) bird carcasses were salvaged and stored in the ship's scientific freezer. Permits to salvage and import birds were on the vessel and all bird specimens were turned over to the San Diego Natural History Museum.

2.0 SEABIRD RESEARCH

2.1 Seabird Surveys – Visual surveys of seabirds were conducted using strip-transect methodology from the flying bridge during daylight hours. On Legs 1 through 4, one seabird observer was on duty; two hours on watch was followed by two hours rest. There were two seabird observers on Legs 5 through 7 which provided continual coverage. A log of visibility conditions, effort, sightings, and other required information was entered into a computer interfaced with the ship's GPS (for course, speed, and position information) and SCS (for weather and heading information). Science computers were connected to the same ship's GPS when possible. Seabird observers primarily used handheld binoculars; 25 x 150 binoculars were available when needed.

3.0 OCEANOGRAPHIC AND OTHER DATA

3.1 Oceanography –The ship's SCS maintained a chronological record of oceanographic stations including locations, dates, and times.

3.1.1 Thermosalinograph (TSG) Sampling – The ship provided and maintained a thermosalinograph (TSG) for continuous measurement of surface water temperature and salinity. The TSG continuously collected surface water temperature and salinity from the ship's clean seawater system.

3.1.2 UCTD Stations (Legs 1 through 4) – Underway Conductivity-Temperature-Depth (UCTD) stations were fixed for Legs 1 through 4. The UCTD (Teledyne Oceanscience Underway CTD) was deployed one to five times along each acoustic transect, during the daytime, at preassigned locations which were spaced approximately 15-nmi apart and staggered on adjacent transect lines to improve sampling coverage. If the waypoint provided did not occur precisely on the acoustic transect, the OOD chose the point on the transect closest to the UCTD waypoint. The vessel speed during UCTD casts was nominally 10 knots but was reduced further at the request of the UCTD operator to achieve the desired cast depth. The OOD recorded the time that the UCTD is deployed and recovered in the SCS event logger. If the Underway CTD could not be used, weather permitting, two CTD stations were occupied each day. A morning CTD was completed 15 minutes before sunrise. A second CTD station was occupied each night no earlier than one hour after sunset. No bottle samples were collected. Additional information on the

CTD casts during Legs 1 through 4 in the FRD Technical Memorandum (Stierhoff et al. 2019).

3.1.3 CTD Stations (Legs 5 through 7) – An evening CTD station was occupied at the end of each day no earlier than one hour after sunset and after sonobuoy deployments. No bottle samples were collected. The CTD was equipped with both a WetLab profiling sensor and redundant dissolved oxygen sensors.

All casts were engaged to a depth range of 500 m, where bottom depths permitted. When bottom depths were too shallow for the 500 m cast, the Cruise Leader and ship's Survey Technician determined a safe depth and notified the bridge prior to operations. Cast descent rates were 30 m/min for the first 100 m of the cast, then 60 m/min after that, including the upcast. Cast times were subject to change given daily operations schedules. Additional CTD stations may have been requested by the Cruise Leader in areas of special interest while other CTD stations might have been omitted due to time constraints or proximity to the last station.

The ship provided the Sea-Bird CTD system, which they maintained and was operated by the ship's Survey Technician. The crew of the vessel operated the winch and other deck equipment and was responsible for the termination (and any necessary reterminations) of the CTD cable pigtail to the conducting cable of the winch. All instruments, their spares, and spare parts provided by the ship were maintained in working order and, if applicable, had current (within the previous 12 months) calibrations. The ship provided two sets of sensors for all casts; conducting CTD casts with dual sensors provided immediate feedback about the performance of the sensors and the validity of the data.

3.2 Active Acoustics – An acoustic calibration of Simrad EK60 and EK80 echosounders was conducted while the ship was dockside in San Diego prior to the start of the Juvenile Rockfish survey (RL-18-02). Prior to the calibration, the transducer faces were cleaned of all barnacles or any other bio-fouling that might have hindered the calibration operations and degraded echosounder data. Additional details can be found in Technical Memorandum 609 (Stierhoff et al. 2019).

The EK60 and EK80 echosounders were operated at 18, 38, 70, 120, 200, and 333 kHz (note: the 18 kHz frequency was secured during Legs 5 through 7 because of possible interference with cetacean detections). Extensive information about echosounder use during Legs 1 through 4 was provided by Stierhoff et al. (2019).

3.3 Loggerhead Turtle Tagging – Loggerhead turtle tagging was scheduled for Legs 6 and 7 when the ship was in the Southern California Bight region; however, no loggerhead turtles were observed in US waters during these legs and so no tagging occurred.

4.0 SMALL BOAT WORK

A small boat was necessary for biopsy sampling, photography, and collecting eDNA. During Legs 1 through 4, this work was conducted by Cascadia, who would launch their rigid-hull inflatable boats (RHIBs) from shore in the morning (when conditions allowed) and return to the launch site by end of day. The Cascadia team (typically two persons) transported their RHIBs down the coast by ground to different launch sites as the *Lasker* progressed south through the survey area. Daily communication between Cascadia and the marine mammal cruise leader on the *Lasker* (from ship to shore, and from ship to RHIBs working on the water) facilitated coordination (e.g., the *Lasker* team would inform Cascadia of the area they anticipated working for the day or where they had recently spotted concentrations of whales). The Cascadia team would find whales and collect skin and blubber biopsy samples and photo identification data. The emphasis was on collecting data for large whales and, in particular, humpback whales.

During Legs 5 through 7, all data were collected from the *Lasker* or from a NOAA small boat launched from the *Lasker*. Deployment of the small boat was requested by the Cruise Leader on an opportunistic basis, provided that the Commanding Officer concurred that operating conditions were safe.

RESULTS

SURVEY EFFORT

A total of 12,857 km of transect line was surveyed by the *Lasker* for marine mammals and seabirds (Table 3, Fig. 2). Most of these data will be used for the model-based analysis to construct density surfaces and estimate population size for as many marine mammal stocks as possible (depending on sample size). Some spatial gaps in survey coverage (Fig. 2) occurred in areas of extended periods of poor weather (wind, fog). The *Lasker* generally continued its progress along FRD study lines during these conditions, in which it was not possible to collect marine mammal visual-survey data.

Cascadia conducted 65 vessel-days of effort dedicated to collecting large whale photo identification and biopsy samples as part of this study (Fig. 3).

MARINE MAMMAL SIGHTINGS

In total, 2,122 marine mammal groups were sighted by *Lasker* observers (Table 4). This is a record for a California Current cetacean stock assessment survey. Of these, 2,004 were recorded while 'on-effort' and 118 were 'off-effort'. Sightings of all positively identified species are displayed in Figures 4 through 15. Additional sightings not identified to at least the family level or sub-family level in the case of delphinids have not been mapped but are noted in Table 4.

BIOPSY DATA

Off the US West coast, 328 biopsy samples were collected via projectile sampling (Table 5). Cascadia collected the vast majority of these samples (323) and the remainder (5) were collected by scientists aboard *Lasker*, including a single biopsy collected from an encountered dead humpback whale. An additional 20 samples were collected in Mexican waters, all from the *Lasker*.

eDNA

Fourteen seawater samples were collected for eDNA analysis by the Cascadia (six samples) and *Lasker* (eight samples).

PHOTOGRAPHY DATA COLLECTED *from Lasker and Cascadia Research Collective*

Photographs were obtained by *Lasker* observers for 231 of the marine mammal sightings (Table 6). Cascadia obtained good quality photographic IDs for > 1000 unique individuals, mostly for humpbacks (895) but also blue whales (100), fin whales (22), and gray whales (11) (Table 7). Additional photo identifications and biopsies were obtained opportunistically during the course of other Cascadia projects (e.g., dedicated to tagging, entanglement response) conducted within the same study area and date frame as the CCES survey.

PASSIVE ACOUSTICS

Seven DASBRs were successfully deployed and retrieved in US West Coast waters and another 8 were successfully deployed and retrieved in Mexican waters (Fig. 16). Eight additional

DASBRs were deployed in US West Coast waters but not successfully retrieved (Fig. 16). The total recording time of the recovered DASBRs was 1,888 hours (Table 8). Most of the lost DASBRs were deployed early in the survey in the northernmost section of the study area, which resulted in a paucity of coverage in those areas (Fig. 16). For the current DASBR design, the number of days at sea was determined to have increased the risk of losing a DASBR before retrieving it. Shorter deployment times or a more robust DASBR design is recommended for future surveys. Acoustic data from the DASBRs has been analyzed to identify detections of beaked whales, sperm whales, and dwarf and pygmy sperm whales (Simonis et al. 2020).

Due to competing priorities, sonobuoy deployment was rare during CCES 2018; the total number of deployments with data is 10.

The prototype autonomous towed array was tested on Leg 5 and performed well during two 1-day test deployments. However, the tow body and recorder (a single-channel ST300HF) were lost during a third trial when the stainless steel cable parted at the point where it entered the nose section of the tow body. The loss was attributed to metal fatigue, likely caused by side-to-side movement of the tow-body.

The redesigned autonomous towed hydrophone array was successfully deployed 7 times. Very clear dolphin whistles and clicks were recorded in calm sea conditions with little noise; however, high noise levels were recorded in high swell conditions. Greater depth is needed in such conditions, which likely could be achieved with a combination of greater weight and a longer tow cable.

OCEANOGRAPHY

During Legs 1 through 4, the FRD from SWFSC conducted CTD measurements using an Underway CTD (n = 239) or CTD rosette (n = 59). On Legs 5 through 7, 98 CTDs were conducted by the Marine Mammal and Turtle Division.

SEABIRDS

During the 609.4 hours seabird observers spent on effort, 133 species of birds were sighted. *Ardenna* shearwaters were the most common genus counted (54.1%), followed by *Puffinus* shearwaters (16.4%) and *Uria* murres (8.6%) (Table 9).

DISPOSITION OF DATA

Table 10 specifies points of contact for the various datasets collected during CCES 2018.

ANALYSES

The scope of this report is limited to a description of the survey methods and work completed, and basic data summaries. Most analyses of these data will be conducted using separate sources of funding support, on varying timetables. Some data, for lack of such support, may not be analyzed for some time. Here is a brief overview of some analyses that are planned or underway.

- Support from BOEM or the Navy (for the CCES 2018 survey) did include funds to process the DASBR data, i.e., to extract detections of different deep-diving cetacean species (such a beaked whales) from the passive acoustic data files, so that these can be summarized and mapped. This work is summarized in a separate Technical Memorandum (Simonis et al. 2020).

- The DASBR data summaries will subsequently be used to estimate population density and abundance for Cuvier's beaked whales. Progress toward doing this for *Mesoplodon* species will also be attempted.
- Support from BOEM or the Navy (for the CCES 2018 survey) also included funds to construct spatial density models (SDMs) for as many cetacean species as possible (depending on the amount of data available). This work will be communicated in a separate report.
- The SDMs will be subsequently used to estimate population size and trends for many cetacean species in the California Current.
- The photo identification data collected for humpback whales is currently being analyzed to inform several population assessment analyses for this species in the region
- Humpback whale biopsy samples have already been assayed for hormonal and genetic information

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PERMITS

NMFS Permit No. 19091, issued to Southwest Fisheries Science Center by the National Marine Fisheries Service, Office of Protected Resources – this permit covers marine mammal and turtle research.

FWS Permit No. MB033305-0, issued to Southwest Fisheries Science Center by the U.S. Fish and Wildlife Service Migratory Bird Permit Office, Region 8.

NMS Permit No. MULTI-2013-009, issued to Southwest Fisheries Science Center to collect biopsies in National Marine Sanctuary waters

NMS Permit No. MULTI-2017-001, issued to Southwest Fisheries Science Center to deploy DASBRs in National Marine Sanctuary waters

Washington State Scientific Collection Permit No. MOORE 18-179 issued by Washington Department of Fish and Wildlife to biopsy whales in Washington State waters

Canadian Marine Mammal Licence No. XMMS 5 2018 issued by Fisheries and Oceans, Canada (DFO) for collection of cetacean biopsies in Canadian waters

Canadian Permit No. IGR-708 issued by Canadian Global Affairs; Authorization for NOAA Ship *Reuben Lasker* to collect DASBRs in Canadian waters (note: not used)

Mexican Permit No. Oficio Nº SGPA/DGVS/ 009395 /18 issued by SEMARNAT for cetacean and ecosystem assessment research in Mexican waters

Mexican Permit No. CTC/06770/18v issued by Secretaría de Relaciones Exteriores for cetacean and ecosystem assessment research in Mexican waters

Mexican Permit No. Oficio núm. 400./331/2018 INEGI.GMA 1.03 issued by Instituto Nacional Estadística y Geografía for cetacean and ecosystem assessment research in Mexican waters

Mexican Permit No. PPFE/DGOPA-198/18 issued by Conapesca for cetacean and ecosystem assessment research in Mexican waters

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Table 1. Survey itinerary for NOAA Ship *Lasker* during CCES 2018.

NOAA Ship *Lasker*	Ports	Dates	Days at Sea	In Port Days
RL-18-03 Leg 1	San Francisco	26-Jun-18	21	
	Newport	16-Jul-18		3
RL-18-03 Leg 2	Newport	20-Jul-18	21	
	San Francisco	09-Aug-18		3
RL-18-03 Leg 3	San Francisco	13-Aug-18	19	
	San Diego	31-Aug-18		4
RL-18-03 Leg 4	San Diego	05-Sep-18	19	
	San Diego	23-Sep-18		10
RL-19-01 Leg 5	San Diego	04-Oct-18	21	
	San Diego	24-Oct-18		4
RL-19-01 Leg 6	San Diego	29-Oct-18	17	
	San Diego	14-Nov-18		5
RL-19-01 Leg 7	San Diego	20-Nov-18*	15	
	San Diego	04-Dec-18		–

* Sailing day lost because foreign national clearances were not issued in a timely manner for Mexican observers.

Table 2a. Cetacean and Ecosystem Assessment participating scientists aboard NOAA Ship *Lasker* during CCES 2018.

Position	Name	Leg 1	Leg 2	Leg 3	Leg 4	Leg 5	Leg 6	Leg 7
CCES Chief Scientist and Chief Scientist Leg 1	Jeff Moore	X						
MMTD Cruise Leader	Jim Carretta		X					
Chief Scientist for Leg 3	Lisa Ballance			X				
MMTD Cruise Leader	Eric Archer				X			
Cruise Leader	Jay Barlow					X		
Cruise Leader	Barb Taylor						X	
Cruise Leader	Karin Forney							X
Assistant Cruise Leader	Brittany Hancock-Hanser							X
Sr. Marine Mammal Observer	Juan Carlos Salinas	X	X	X	X	X	X	X
Sr. Marine Mammal Observer	Paula Olson	X	X					
Sr. Marine Mammal Observer	Suzanne Yin			X	X	X	X	X
Marine Mammal Observer	Dawn Breese	X	X	X	X			
Marine Mammal Observer	Chris Hoefer	X	X	X	X	X	X	X
Marine Mammal Observer	Felipe Triana	X	X	X	X	X	X	X
Marine Mammal Observer	Jim Gilpatrick	X	X	X				
Marine Mammal Observer	Joel Schumacher				X	X	X	X
Marine Mammal Observer	Adam Ü					X	X	
Marine Mammal Observer	Carrie Sinclair							X
Seabird Observer	Michael Force	X	X	X	X	X	X	X
Seabird Observer	Dawn Breese					X	X	X
Visiting Scientist	Lindsey Peavey					X		
Visiting Scientist	Mridula Srinivasan						X	
Mexican Observer	LT Paola Moreno Quintana						X	X
Mexican Collaborator	Sergio Martinez Aguilar						X	X

Table 2b. Fisheries Resources Division participating scientists aboard NOAA Ship *Lasker* during CCES 2018.

Position	Name	Leg 1	Leg 2	Leg 3	Leg 4	Leg 5	Leg 6	Leg 7
Chief Scientist/FRD Lead	David Demer	X						
Chief Scientist Leg 2/Acoustician	Juan Zwolinski		X					
FRD Lead/ Acoustician	Josiah Renfree			X				
Chief Scientist Leg 4/Biologist	David Griffith				X			
Fishery Acoustician	Daniel Palance	X	X					
Fishery Biologist	Dave Griffith	X						
Fishery Biologist	Lanora V. del Mercado	X						
Fishery Biologist	Anne Freire	X						
Fishery Biologist	Megan Human	X						
Fishery Biologist	Kevin Runge	X						
Fishery Biologist	Amy Hays		X					
Fishery Biologist	Lanora V. del Mercado		X					
Fishery Biologist	Emily Gardner		X					
Fishery Biologist	Bill Watson		X					
Fishery Acoustician	Thomas Sessions			X				
Fishery Biologist	Rachel Pound		X					
Fishery Biologist	Bryan Overcash			X				
Fishery Biologist	Debra Winter			X				
Fishery Biologist	Emily Gardner			X				
Fishery Biologist	Sherri Charter			X				
Fishery Acoustician	David Murfin				X			
Fishery Biologist	Tor Mowatt-Larssen			X				
Fishery Biologist	Bryan Overcash				X			
Fishery Biologist	Scott Mau				X			
Fishery Biologist	Alyssa Mische				X			
Fishery Biologist	Melissa Mayaraga				X			
Fishery Biologist	Sue Manion/Lanora V. del Mercado*				X			

Table 3. Transect effort accomplished during CCES 2018 by Beaufort state.

Beaufort	Effort (km)
0	147
1	816
2	1,972
3	3,188
4	3,775
5	2,959
Total	12,857

Table 4. Cetacean sightings during CCES 2018 from NOAA Ship *Lasker*.

Common name	Scientific name	On effort	Off effort	Total
Grey whale	*Eschrichtius robustus*	15	3	18
Common minke whale	*Balaenoptera acutorostrata*	16	4	20
Sei whale	*Balaenoptera borealis*	4	0	4
Bryde's whale	*Balaenoptera edeni*	8	0	8
Sei or Bryde's whale	*Balaenoptera borealis/edeni*	10	2	12
Blue whale	*Balaenoptera musculus*	31	10	41
Fin whale	*Balaenoptera physalus*	139	13	152
Fin or sei or Bryde's whale	*Balaenoptera physalus/borealis/edeni*	73	2	75
Humpback whale	*Megaptera novaeangliae*	644	36	680
Unidentified rorqual (*Balaenoptera* or *Megaptera*)		132	8	140
Sperm whale	*Physeter macrocephalus*	13	3	16
Dwarf or pygmy sperm whale	*Kogia* sp.	2	0	2
Baird's beaked whale	*Berardius bairdii*	10	0	10
Mesoplodon beaked whale	*Mesoplodon* sp.	4	0	4
Cuvier's beaked whale	*Ziphius cavirostris*	11	2	13
Unidentified Beaked whale	*Ziphiid* sp.	6	0	6
Eastern north Pacific long-beaked common dolphin	*Delphinus delphis bairdii*	35	0	35
Common dolphin	*Delphinus delphis delphis*	161	5	166
Unidentified *D. delphis* subspecies	*Delphinus* sp.	128	5	133
Short-finned pilot whale	*Globicephala macrorhynchus*	1	0	1
Risso's dolphin	*Grampus griseus*	46	1	47
Pacific white-sided dolphin	*Lagenorhynchus obliquidens*	98	10	108
Northern right whale dolphin	*Lissodelphis borealis*	27	2	29
Killer whale	*Orcinus orca*	9	1	10
Offshore spotted dolphin	*Stenella attenuata*	1	0	1
Striped dolphin	*Stenella coeruleoalba*	15	0	15
Bottlenose dolphin	*Tursiops truncatus*	13	1	14
Harbor porpoise	*Phocoena phocoena*	108	6	114
Dall's porpoise	*Phocoenoides dalli*	95	1	96
Unidentified dolphin or porpoise		17	0	17
Unidentified small whale		3	0	3
Unidentified large whale		38	0	38
Unidentified cetacean		2	0	2
Unidentified whale		12	0	12
Unidentified small delphinid		71	3	74
Unidentified medium delphinid		1	0	1
Unidentified large delphinid		1	0	1
Unidentified porpoise		4	0	4
Total		2004	118	2122

Table 5. Cetacean biopsy samples collected during CCES 2018 by SWFSC and Cascadia Research Collective, by country of collection.

Common Name	Species	United States	Mexico
Gray whale	*Eschrichtius robustus*	1	0
Blue whale	*Balaenoptera musculus*	33	1
Fin whale	*Balaenoptera physalus*	6	1
Unidentified rorqual	*Balaenoptera* sp.	0	1
Humpback whale	*Megaptera novaeangliae*	286	1
Pacific white-sided dolphin	*Lagenorhynchus obliquidens*	2	10
Unidentified dolphin	---	0	6
Total		328	20

Table 6. Number of sightings photographed from aboard the *Lasker* during CCES 2018.

Common name	Scientific name	Total
Gray whale	*Eschrichtius robustus*	*1*
Common minke whale	*Balaenoptera acutorostrata*	6
Sei whale	*Balaenoptera borealis*	4
Bryde's whale	*Balaenoptera edeni*	7
Rorqual identified as a sei or Bryde's whale	*Balaenoptera borealis/edeni*	5
Blue whale	*Balaenoptera musculus*	20
Fin whale	*Balaenoptera physalus*	38
Unidentified rorqual	*Balaenoptera* sp.	2
Humpback whale	*Megaptera novaeangliae*	18
Sperm whale	*Physeter macrocephalus*	3
Mesoplodon beaked whale	*Mesoplodon* sp.	1
Cuvier's beaked whale	*Ziphius cavirostris*	5
Eastern north Pacific long-beaked common dolphin	*Delphinus delphis bairdii*	8
Common dolphin	*Delphinus delphis delphis*	61
Unidentified *D. delphis* subspecies	*Delphinus* sp.	1
Short-finned pilot whale	*Globicephala macrorhynchus*	1
Risso's dolphin	*Grampus griseus*	6
Pacific white-sided dolphin	*Lagenorhynchus obliquidens*	13
Northern right whale dolphin	*Lissodelphis borealis*	6
Killer whale	*Orcinus orca*	6
Offshore pantropical spotted dolphin	*Stenella attenuata* (offshore)	1
Striped dolphin	*Stenella coeruleoalba*	8
Bottlenose dolphin	*Tursiops truncatus*	3
Harbor porpoise	*Phocoena phocoena*	1
Dall's porpoise	*Phocoenoides dalli*	1
Northern fur seal	*Callorhinus ursinus*	4
Steller sea lion	*Eumetopias jubatus*	1
Total sightings photographed		231

Table 7. Sightings (animal groups observed), number of animals comprising these groups, and number of unique individuals identified (or estimated IDs for species not yet processed) from good quality photos collected during small boat effort by Cascadia and their collaborators from June to November 2018 on the US West Coast. WA = Washington, OR = Oregon, NCA = Northern California, GF = Gulf of Farallones region, MB = Monterey Bay region, SC = Southern California.

Species/Region	1-WA	2-OR	3-NCA	4-GF	5-MB	6-SC	Total
Gray whales							
Sightings	9	1					10
Animals	12	1					13
Estimated IDs	10	1					11
Blue whales							
Sightings		25	2	25	111	8	171
Animals		42	4	42	219	16	323
Unique IDs		26	4	23	42	12	100
Fin whales							
Sightings	1	5			16	2	24
Animals	1	7			17	2	27
Estimated IDs	1	7			12	2	22
Humpback whales							
Sightings	179	109	97	207	214	15	821
Animals	578	614	263	438	682	28	2,603
Estimated IDs	174	242	177	186	134	0	895

Table 8. Deployment and retrieval times and locations for Drifting Acoustic Spar Buoy Recorder (DASBR) deployments. The number of 2-minute files recorded during each deployment is also given. Deployment and retrieval times & locations are taken from electronic bridge logs and may include small errors due to delays in communicating this information from the deck to the bridge. The count of files includes a small number recorded before and after the deployment. A more accurate file count will be available after the acoustic data are analyzed. Seven DASBRs could not be found (NA). Drift 3 was retrieved twice and re-deployed; the first time it was retrieved (3A), equipment was accidentally lost. It was re-deployed with a different recorder (3B), but its satellite locator was not transmitting regularly. Additional floatation was added a few days later and it was re-deployed again (3C).

	Deployment				Retrieval				
DASBR Drift	Date GMT	Time GMT	North latitude	West longitude	Date GMT	Time GMT	North latitude	West longitude	#2-min files recovered
1	7/4/18	19:33	48.3440	126.7029	NA	NA	NA	NA	NA
2	7/10/18	3:04	47.5919	128.5120	NA	NA	NA	NA	NA
3A	7/14/18	0:52	46.2560	125.3746	NA	NA	NA	NA	NA
3B	7/15/18	21:50	46.0893	125.3746	7/21/18	21:56	45.6098	125.2710	NA
3C	7/21/18	21:56	45.6098	125.2710	NA	NA	NA	NA	NA
4	7/25/18	3:30	45.0834	128.2082	10/13/18	0:36	41.7569	127.1545	11,167
5	7/27/18	2:37	44.0938	125.0046	NA	NA	NA	NA	NA
6	7/31/18	2:37	43.0957	127.9195	NA	NA	NA	NA	NA
7	8/5/18	14:48	41.2604	125.0157	10/22/18	9:00	42.0400	124.4850	4,246
8	8/16/18	2:34	38.9485	126.6449	10/10/18	16:53	34.3774	128.3174	3,323
9	8/17/18	18:40	38.7919	124.3891	NA	NA	NA	NA	NA
10	8/22/18	2:11	36.7607	125.0584	10/22/18	0:21	35.9671	122.9397	4,400
11	8/27/18	2:43	36.1534	122.6094	NA	NA	NA	NA	NA
12	8/30/18	2:34	34.8303	123.8146	10/6/18	17:08	34.0316	124.3911	2,716
13	9/11/18	20:35	33.8980	120.9078	10/23/18	14:34	31.4444	119.7754	3,025
14	10/5/18	5:46	32.2688	118.2563	11/1/18	16:55	31.9507	119.2481	1,981
16	10/30/18	14:33	31.3534	117.4199	11/21/18	4:18	32.1253	118.0337	2,428
17	10/31/18	0:02	30.7250	118.6933	11/24/18	4:31	28.2857	118.4385	9,077
18	10/31/18	9:58	30.0108	120.1815	11/23/18	18:41	29.5059	118.8216	2,519
19	11/1/18	2:11	30.0477	117.4605	11/27/18	14:20	28.4041	115.5497	2,519
20	11/5/18	14:04	29.4590	118.3930	11/22/18	19:21	29.3920	116.3355	2,530
21	11/6/18	3:43	29.4677	116.0120	11/11/18	9:29	29.8233	116.0796	1,279
22	11/7/18	14:04	28.7247	116.4778	11/27/18	4:55	28.2846	116.6829	2,337
23	11/22/18	8:10	30.9285	117.3812	12/3/18	0:25	31.0542	119.0123	3,098
								Total files	56,645
								Total minutes	113,290
								Total hours	1,888

Table 9. Summary of seabird sightings during CCES 2018.

Common Name	Scientific Name	No. Individuals	Comments
Greater White-fronted Goose	*Anser albifrons*	1	
Brant	*Branta bernicla*	116	
Cackling Goose	*Branta hutchinsii*	22	
Northern Pintail	*Anas acuta*	85	
Unidentified duck	*Anatinae sp.*	10	Scaup sp. (9)
Greater Scaup	*Aythya marila*	3	
Surf Scoter	*Melanitta perspicillata*	42	
Eared Grebe	*Podiceps nigricollis*	1	108 nmi SW of Cape Flattery; unusual this far offshore
Western Grebe	*Aechmophorus occidentalis*	4	
Eurasian Collared-Dove	*Streptopelia decaocto*	1	
White-winged Dove	*Zenaida asiatica*	1	
Mourning Dove	*Zenaida macroura*	19	
Unidentified hummingbird	*Trochilidae sp.*	2	
Black-bellied Plover	*Pluvialis squatarola*	11	
Semipalmated Plover	*Charadrius semipalmatus*	1	
Whimbrel	*Numenius phaeopus*	72	
Marbled Godwit	*Limosa fedoa*	2	
Black Turnstone	*Arenaria melanocephala*	2	
Least Sandpiper	*Calidris minutilla*	8	
Sanderling	*Calidris alba*	2	
Baird's Sandpiper	*Calidris bairdii*	1	
Western Sandpiper	*Calidris mauri*	2	
Short-billed Dowitcher	*Limnodromus griseus*	1	ship-strike fatality
Spotted Sandpiper	*Actitis macularius*	1	
Wandering Tattler	*Tringa incana*	4	
Lesser Yellowlegs	*Tringa flavipes*	1	
Greater Yellowlegs	*Tringa melanoleuca*	1	
Red Phalarope	*Phalaropus fulicarius*	1,330	
Red-necked Phalarope	*Phalaropus lobatus*	519	
Unidentified phalarope	*Phalaropus sp.*	76	
Unidentified shorebird	*Scolopacidae sp.*	43	
South Polar Skua	*Stercorarius maccormicki*	42	
Pomarine Jaeger	*Stercorarius pomarinus*	84	
Parasitic Jaeger	*Stercorarius parasiticus*	65	
Long-tailed Jaeger	*Stercorarius longicaudus*	77	
Parasitic/Long-tailed Jaeger	*Stercorarius parasiticus/longicaudus*	1	

Common Name	Scientific Name	No. Individuals	Comments
Unidentified jaeger	*Stercorarius sp.*	4	
Common Murre	*Uria aalge*	4,666	
Pigeon Guillemot	*Cepphus columba*	11	
Marbled Murrelet	*Brachyramphus marmoratus*	1	
Scripps's Murrelet	*Synthliboramphus scrippsi*	12	
Guadalupe Murrelet	*Synthliboramphus hypoleucus*	16	Includes first photographically confirmed sighting for Canada
Scripps's/Guadalupe Murrelet	*Synthliboramphus scrippsi/hypoleucus*	5	
Craveri's Murrelet	*Synthliboramphus craveri*	3	
"Xantus's"/Craveri's Murrelet	*Synthliboramphus scrippsi/hypoleucus/craveri*	23	
Ancient Murrelet	*Synthliboramphus antiquus*	4	
Cassin's Auklet	*Ptychoramphus aleuticus*	1,337	
Parakeet Auklet	*Aethia psittacula*	1	
Rhinoceros Auklet	*Cerorhinca monocerata*	353	
Horned Puffin	*Fratercula corniculata*	1	Off Estevan Point, Vancouver Island
Tufted Puffin	*Fratercula cirrhata*	25	
Unidentified small alcid	*Ptychoramphus/Aethia/Synthliboramphus sp.*	6	
Sabine's Gull	*Xema sabini*	148	
Bonaparte's Gull	*Chroicocephalus philadelphia*	183	
Laughing Gull	*Leucophaeus atricilla*	1	first cycle
Heermann's Gull	*Larus heermanni*	46	
Mew Gull	*Larus canus*	4	
Western Gull	*Larus occidentalis*	1,626	
Herring Gull	*Larus argentatus*	54	
California Gull	*Larus californicus*	269	
Iceland Gull	*Larus glaucoides*	7	"Thayer's" Gull
Glaucous-winged Gull	*Larus glaucescens*	178	
Western x Glaucous-winged Gull	*Larus occidentalis x L. glaucescens*	42	
Unidentified *Larus*	*Larus sp.*	237	
Caspian Tern	*Hydroprogne caspia*	5	
Common Tern	*Sterna hirundo*	12	
Arctic Tern	*Sterna paradisaea*	181	
Forster's Tern	*Sterna forsteri*	5	
Arctic/Common Tern	*Sterna paradisaea/hirundo*	15	
Unidentified *Sterna* tern	*Sterna sp.*	42	
Royal Tern	*Thalasseus maximus*	14	
Elegant Tern	*Thalasseus elegans*	57	
Red-billed Tropicbird	*Phaethon aethereus*	15	

Common Name	Scientific Name	No. Individuals	Comments
Red-tailed Tropicbird	*Phaethon rubricauda*	1	~40 nmi SW of Point Sur
Pacific Loon	*Gavia pacifica*	7	
Common Loon	*Gavia immer*	5	
Laysan Albatross	*Phoebastria immutabilis*	69	
Black-footed Albatross	*Phoebastria nigripes*	367	
Wilson's Storm-Petrel	*Oceanites oceanicus*	1	Over Vizcaino Canyon
Fork-tailed Storm-Petrel	*Oceanodroma furcata*	682	
Leach's Storm-Petrel	*Oceanodroma leucorhoa*	704	Includes 12 "Chapman's" Storm-Petrels
Townsend's Storm-Petrel	*Oceanodroma socorroensis*	21	
Ashy Storm-Petrel	*Oceanodroma homochroa*	166	
"Leach's" Storm-Petrel	*Oceanodroma sp.*	32	Leach's complex
Black Storm-Petrel	*Oceanodroma melania*	76	
Least Storm-Petrel	*Oceanodroma microsoma*	28	Unseasonally far N (off Pigeon Point)
“White-rumped” storm-petrel	*Hydrobatidae sp.*	2	
“Dark-rumped” storm-petrel	*Hydrobatidae sp.*	3	
Unidentified storm-petrel	*Hydrobatidae/Oceanitidae sp.*	2	
Northern Fulmar	*Fulmarus glacialis*	842	
Murphy's Petrel	*Pterodroma ultima*	3	
Mottled Petrel	*Pterodroma inexpectata*	1	
Hawaiian Petrel	*Pterodroma sandwichensis*	17	
Cook's Petrel	*Pterodroma cookii*	47	
Unidentified Cookilaria	*Pterodroma sp.*	6	
Unidentified *Pterodroma*	*Pterodroma sp.*	1	
Buller's Shearwater	*Ardenna bulleri*	1,706	One bird off Estevan Point, Vancouver Island; early date for this location
Short-tailed Shearwater	*Ardenna tenuirostris*	27	
Sooty Shearwater	*Ardenna grisea*	4,284	
Sooty/Short-tailed Shearwater	*Ardenna grisea/tenuirostris*	20,231	
Pink-footed Shearwater	*Ardenna creatopus*	1971	
Flesh-footed Shearwater	*Ardenna carneipes*	4	

Common Name	Scientific Name	No. Individuals	Comments
Unidentified shearwater	*Ardenna sp.*	1,069	
Manx Shearwater	*Puffinus puffinus*	1	7 nmi W of Point of Arches, WA
Black-vented Shearwater	*Puffinus opisthomelas*	8,853	
Masked Booby	*Sula dactylatra*	11	Adult and subadult seen of San Nicolas Island
Nazca Booby	*Sula granti*	9	Sub-adult seen in Oregon (rare)
Nazca/Masked Booby	*Sula granti/dactylatra*	4	
Brown Booby	*Sula leucogaster*	52	
Red-footed Booby	*Sula sula*	3	
Unidentified booby	*Sula sp.*	1	
Brandt's Cormorant	*Phalacrocorax penicillatus*	248	
Double-crested Cormorant	*Phalacrocorax auritus*	12	
Pelagic Cormorant	*Phalacrocorax pelagicus*	2	
Brown Pelican	*Pelecanus occidentalis*	110	
Snowy Egret	*Egretta thula*	1	
Black-crowned Night-Heron	*Nycticorax nycticorax*	2	
Barn Owl	*Tyto alba*	1	
Merlin	*Falco columbarius*	1	
Peregrine Falcon	*Falco peregrinus*	1	
Yellow-bellied Flycatcher	*Empidonax flaviventris*	1	
Western Wood-Pewee	*Contopus sordidulus*	1	
Unidentified wood-pewee	*Contopus sp.*	1	
Say's Phoebe	*Sayornis saya*	1	
Purple Martin	*Progne subis*	1	
Barn Swallow	*Hirundo rustica*	3	
Unidentified swallow	*Hirundinidae sp.*	1	
House Wren	*Troglodytes aedon*	1	
Ruby-crowned Kinglet	*Regulus calendula*	2	
European Starling	*Sturnus vulgaris*	3	
Cedar Waxwing	*Bombycilla cedrorum*	1	
Red-throated Pipit	*Anthus cervinus*	1	
Lesser Goldfinch	*Spinus psaltria*	3	
House Finch	*Haemorhous mexicanus*	1	
Lapland Longspur	*Calcarius lapponicus*	2	
Cassin's Sparrow	*Peucaea cassinii*	1	

Common Name	Scientific Name	No. Individuals	Comments
Lark Sparrow	*Chondestes grammacus*	1	
Savannah Sparrow	*Passerculus sandwichensis*	1	
Dark-eyed Junco	*Junco hyemalis*	2	
Bobolink	*Dolichonyx oryzivorus*	1	
Western Meadowlark	*Sturnella neglecta*	2	
Bullock's Oriole	*Icterus bullockii*	2	
Brown-headed Cowbird	*Molothrus ater*	94	
Common Yellowthroat	*Geothlypis trichas*	3	
American Redstart	*Setophaga ruticilla*	1	
Northern Parula	*Setophaga americana*	2	
Blackburnian Warbler	*Setophaga fusca*	1	
Yellow Warbler	*Setophaga petechia*	1	
Palm Warbler	*Setophaga palmarum*	5	
Yellow-rumped Warbler	*Setophaga coronata*	2	
Townsend's Warbler	*Setophaga townsendi*	12	
Hermit Warbler	*Setophaga occidentalis*	13	
Warbler sp. (*Parulidae* sp.)	*Parulidae* sp.	2	Unidentified *Setophaga*
Canada Warbler	*Cardellina canadensis*	1	
Wilson's Warbler	*Cardellina pusilla*	10	
Western Tanager	*Piranga ludoviciana*	3	
Lazuli Bunting	*Passerina amoena*	1	
Unidentified Passerine		3	
Total Individual Birds		54,136	

Table 10. Disposition of data collected aboard NOAA Ship *Lasker* during CCES 2018 for analysis and further distribution.

Data	Primary Investigator	Affiliation	Contact
Marine mammal sightings	Dr. Jeff Moore	NOAA Fisheries – SWFSC	Jeff.E.Moore@noaa.gov
Biopsy and eDNA samples	Dr. Barbara Taylor	NOAA Fisheries – SWFSC	Barbara.Taylor@noaa.gov
Passive acoustics (DASBRs)	Shannon Rankin	NOAA Fisheries – SWFSC	Shannon.Rankin@noaa.gov
Seabird sightings	Dr. Trevor Joyce	NOAA Fisheries – SWFSC	Trevor.Joyce@noaa.gov
Oceanographic data	Dr. Paul Fiedler and Dr. David Demer	NOAA Fisheries – SWFSC	Paul.Fiedler@noaa.gov David.Demer@noaa.gov
Active acoustic data	Dr. David Demer	NOAA Fisheries – SWFSC	David.Demer@noaa.gov
Photographic ID data collected from small-boat operations during Legs 1-4	Dr. John Calambokidis	Cascadia Research Collective	Calambokidis@CascadiaResearch.org

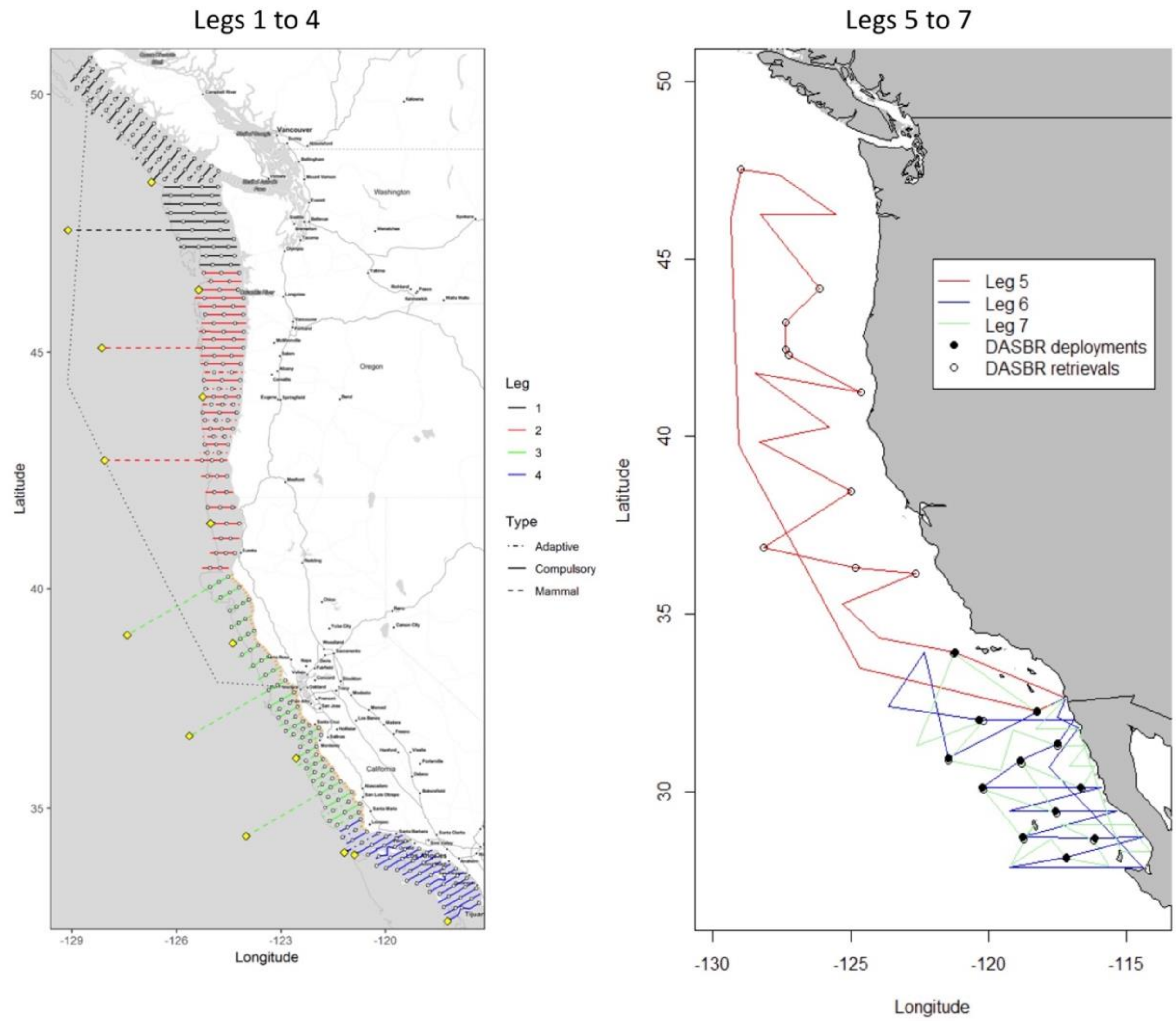

Figure 1. Planned tracklines for Legs 1-4 (left) and Legs 5-7 (right). Map for Legs 1-4 includes planned compulsory (solid lines) and adaptive (dashed lines) active-acoustic transects. Some of these were extended far offshore for marine mammal survey. The long dotted line segments connecting San Francisco to the north end of Vancouver Island represents the initial transit route of the ship. Also shown are UCTD stations (small points), planned DASBR deployment stations (yellow diamonds), and Saildrone transects (orange lines right along the Central California coast), which were part of the FRD study and are not discussed in this report. For Legs 5-7, planned transects were tied to DASBR deployment and anticipated retrieval locations. Actual tracklines for Legs 5-7 varied from the planned lines, as dictated by routes taken to retrieve DASBRs in real time.

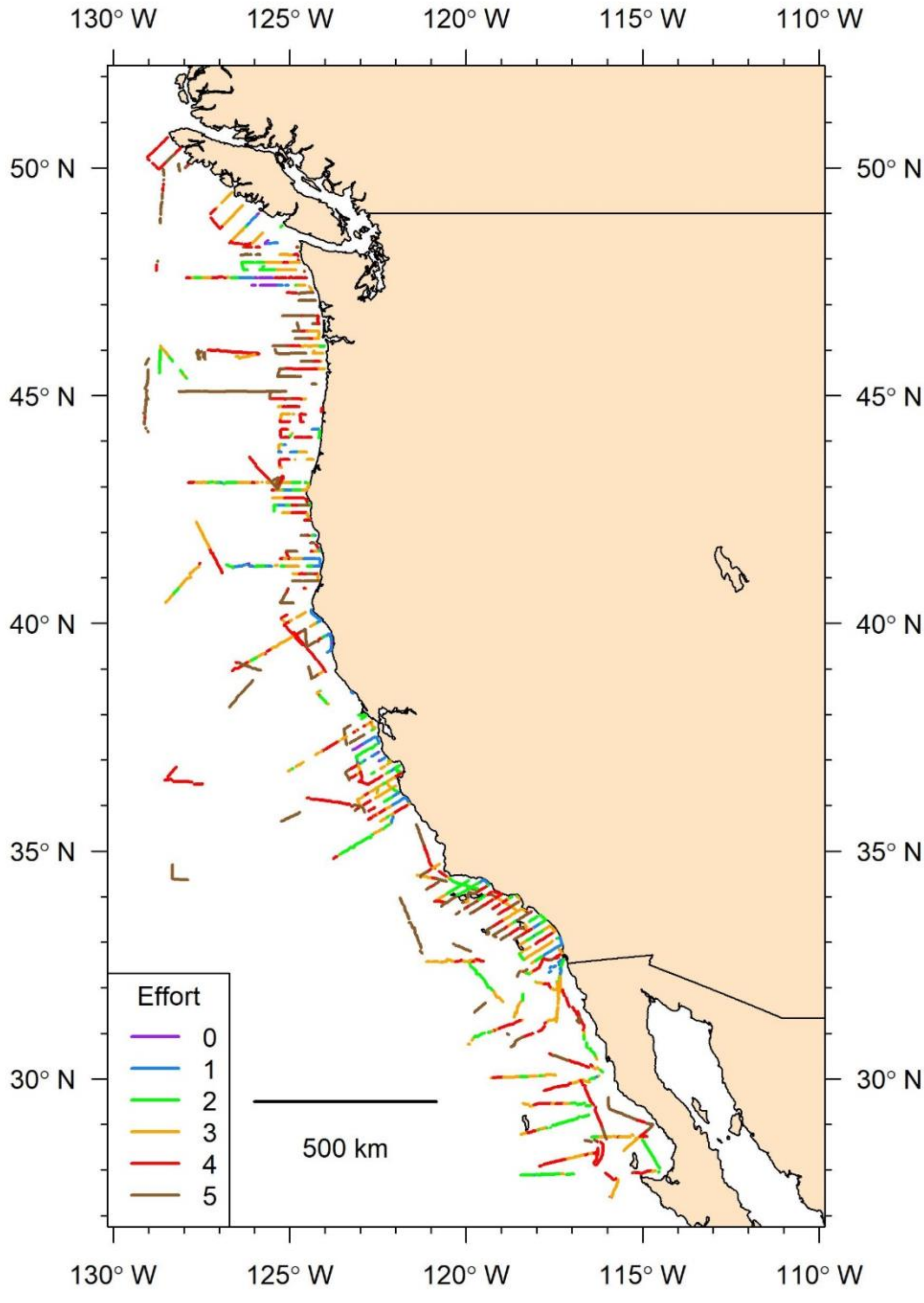

Figure 2. Transect lines completed during CCES 2018 by NOAA Ship *Lasker* that included marine mammal and seabird effort. Colors indicate Beaufort state.

Figure 3. Tracks of small-boat survey effort conducted by Cascadia Research Collective (left), and humpback whale tissue samples collected (right).

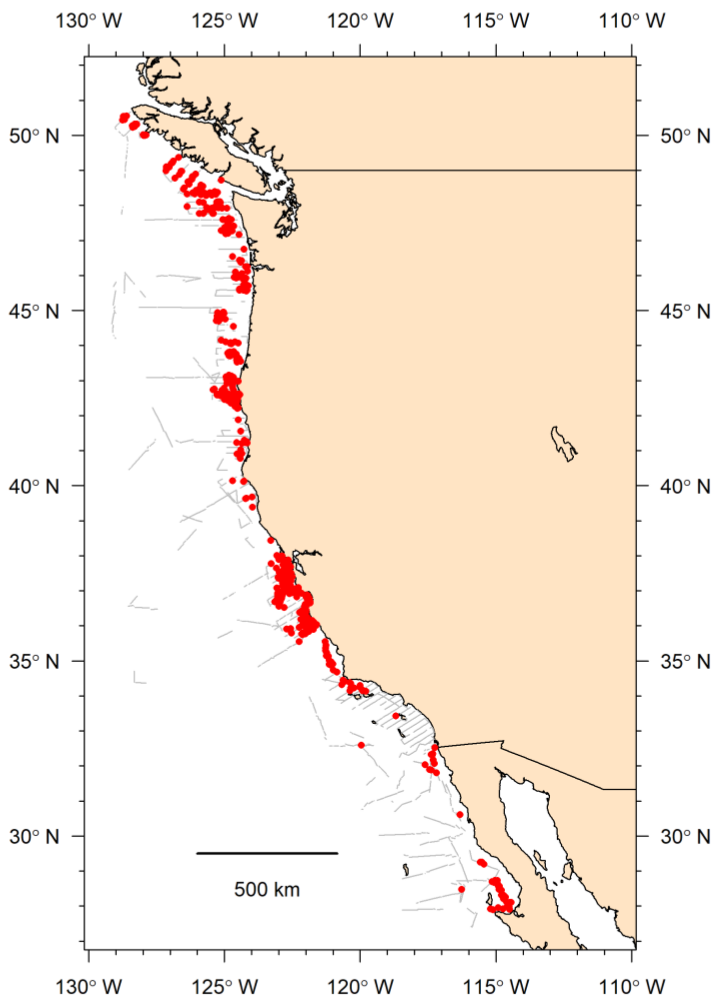

Figure 4. Sightings of humpback whales (red).

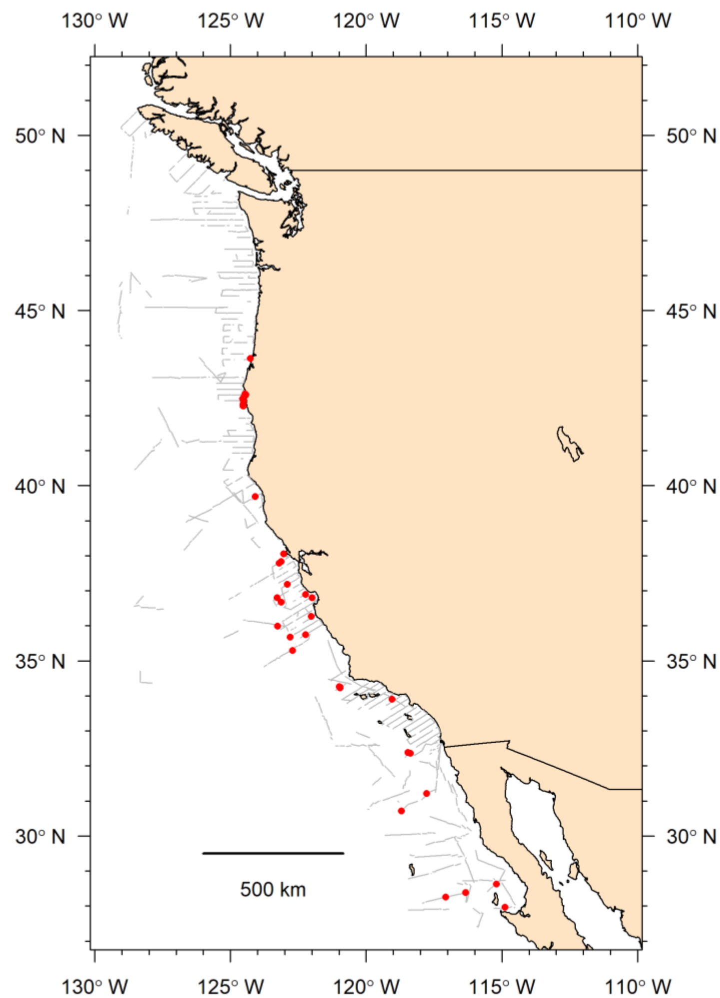

Figure 5. Sightings of blue whales (red).

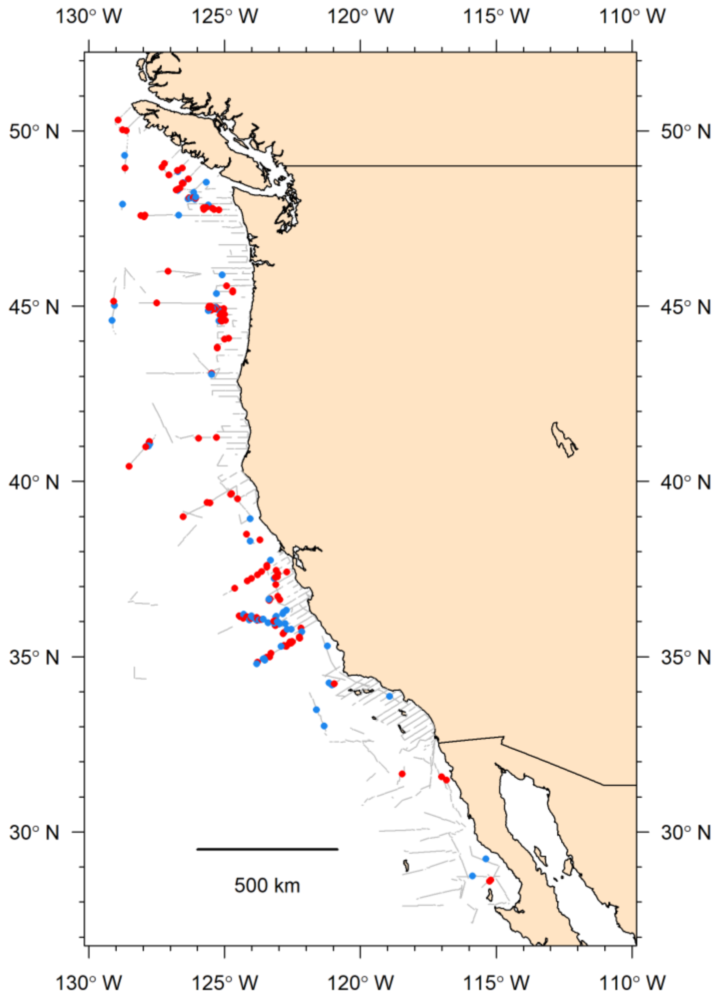

Figure 6. Sightings of fin whales (red) and unidentified *Balaenoptera* species (blue), most of which are likely fin whales.

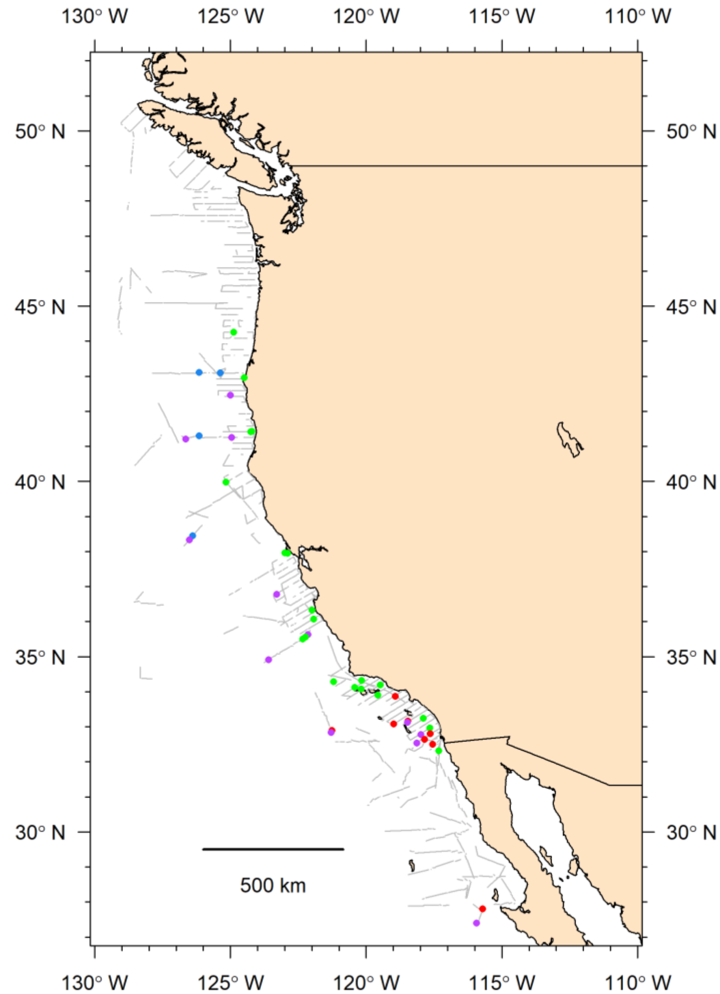

Figure 7. Sightings of Bryde's (red), sei (blue), and minke whale (green). Purple = Bryde's or sei whale.

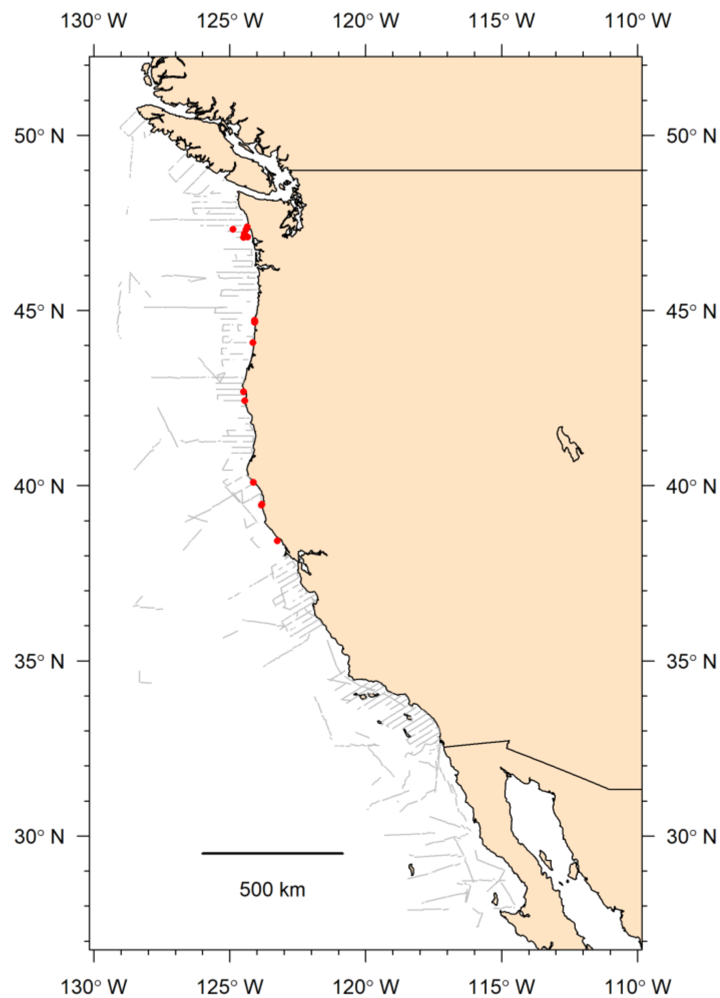

Figure 8. Sightings of gray whales (red).

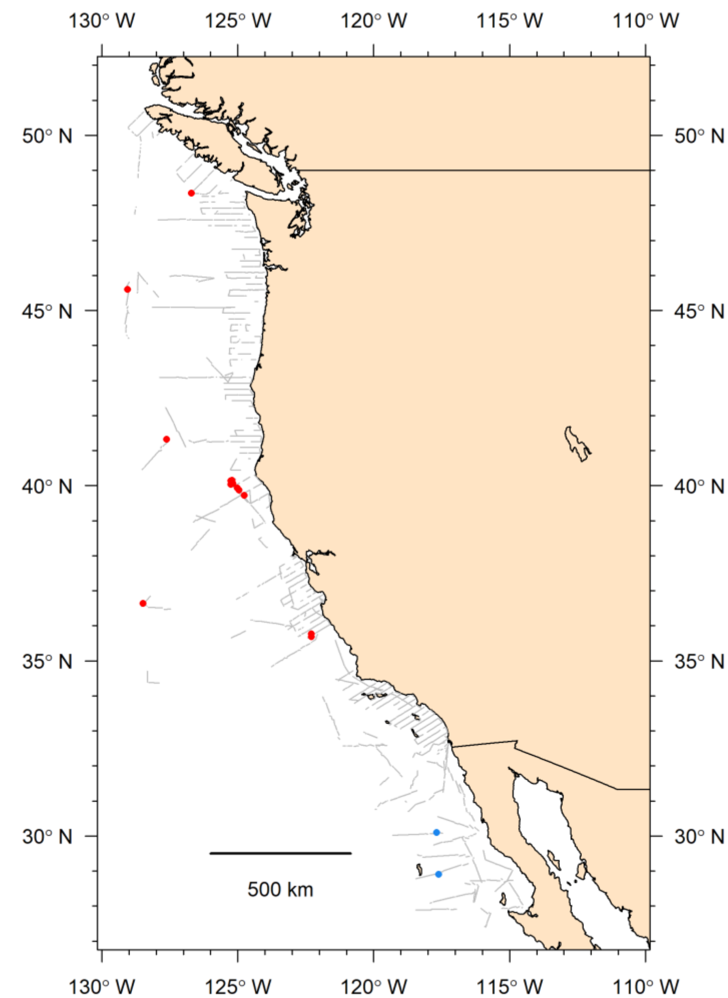

Figure 9. Sightings of sperm whale (red) and *Kogia* species (blue).

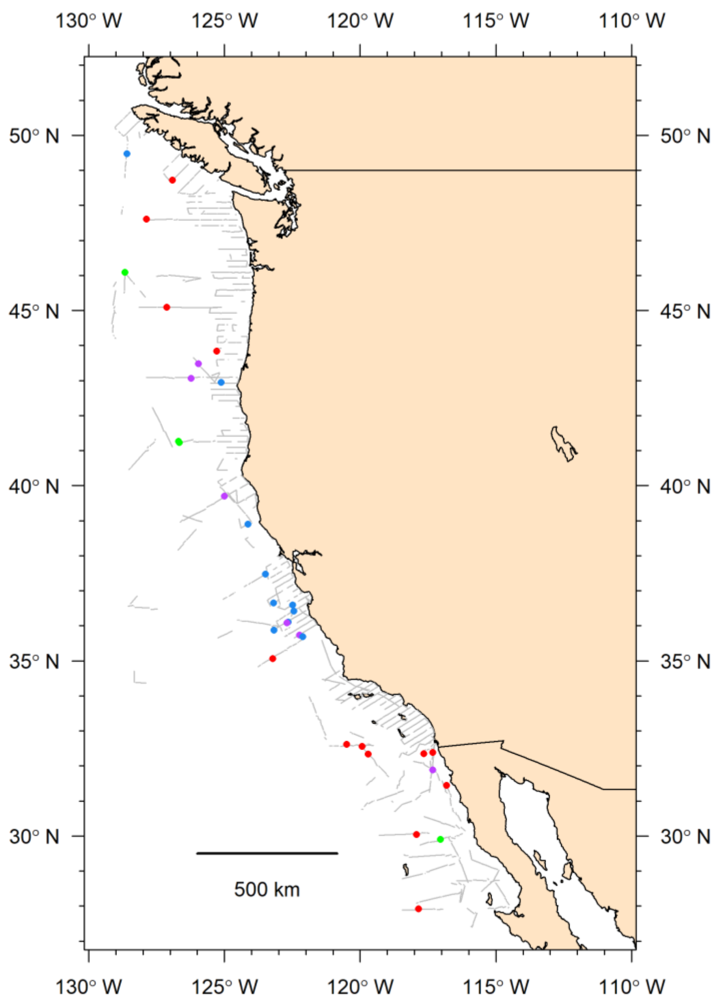

Figure 10. Sightings of beaked whales, including Cuvier's beaked whale (red), Baird's beaked whale (blue), *Mesoplodon* species (green), and unidentified Ziphiids (purple).

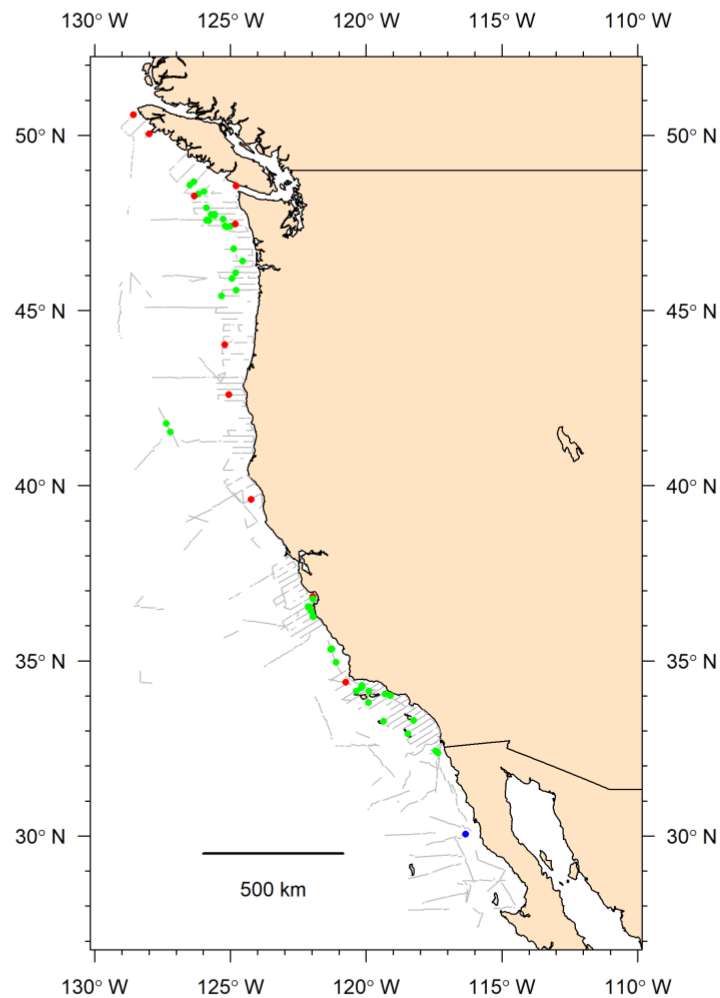

Figure 11. Sightings of "blackfish": killer whales (red), Risso's dolphins (green), and short-finned pilot whales (blue).

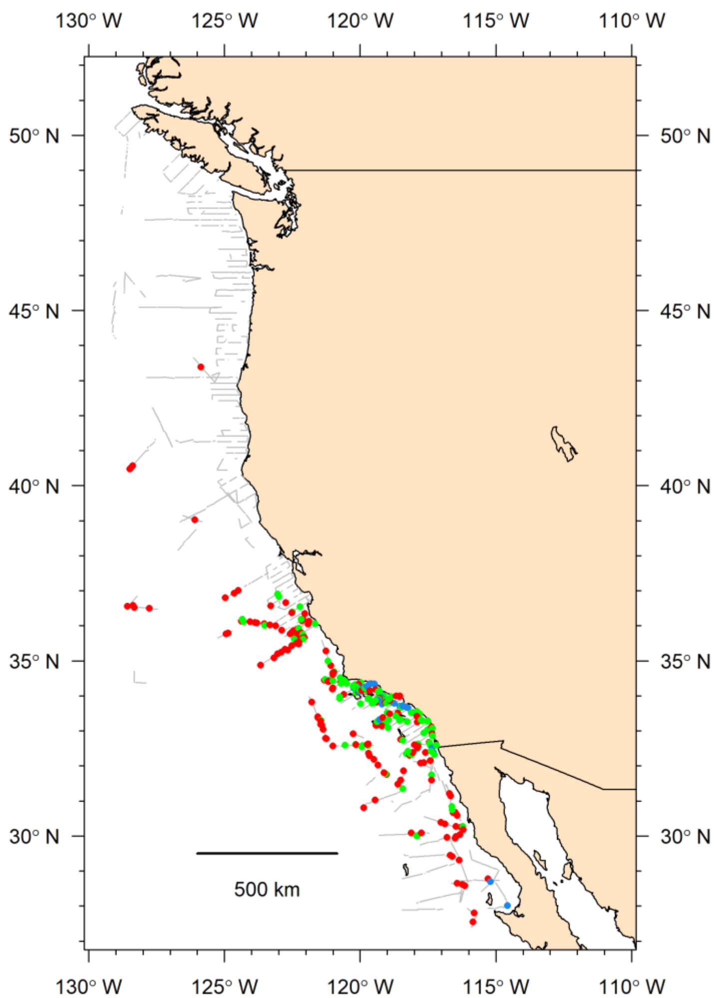

Figure 12. Sightings of common dolphin: *D. delphis*, common dolphins (red), *D. delphis bairdii*, eastern Pacific long-beaked common dolphins (blue), and *D. delphis* not identified to subspecies (green).

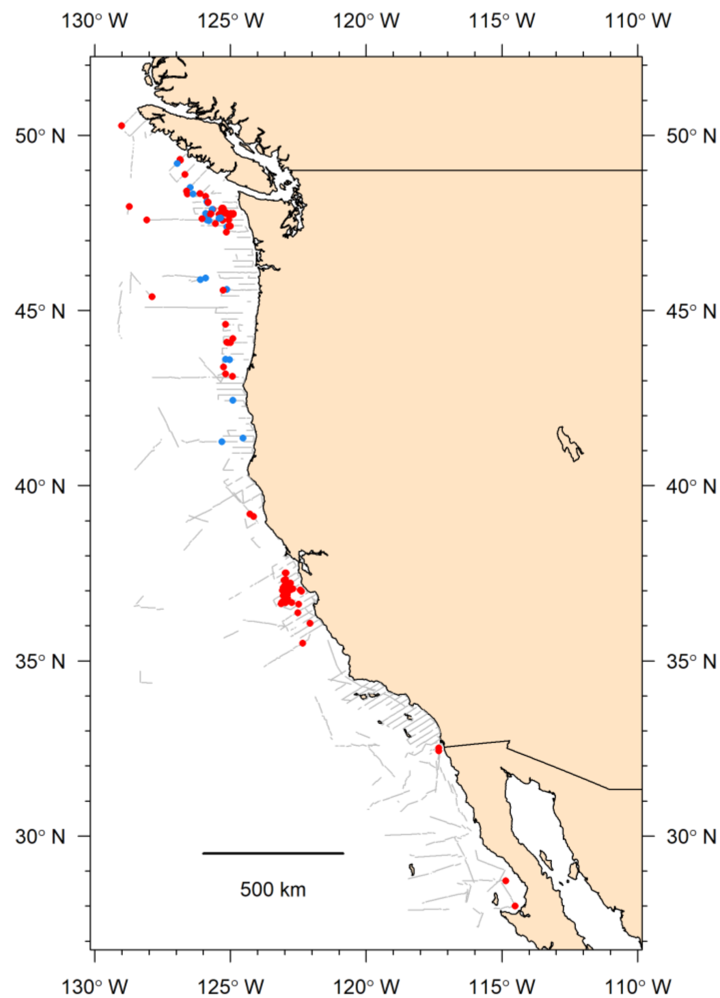

Figure 13. Sightings of Pacific white-sided dolphins (red) and northern right whale dolphins (blue).

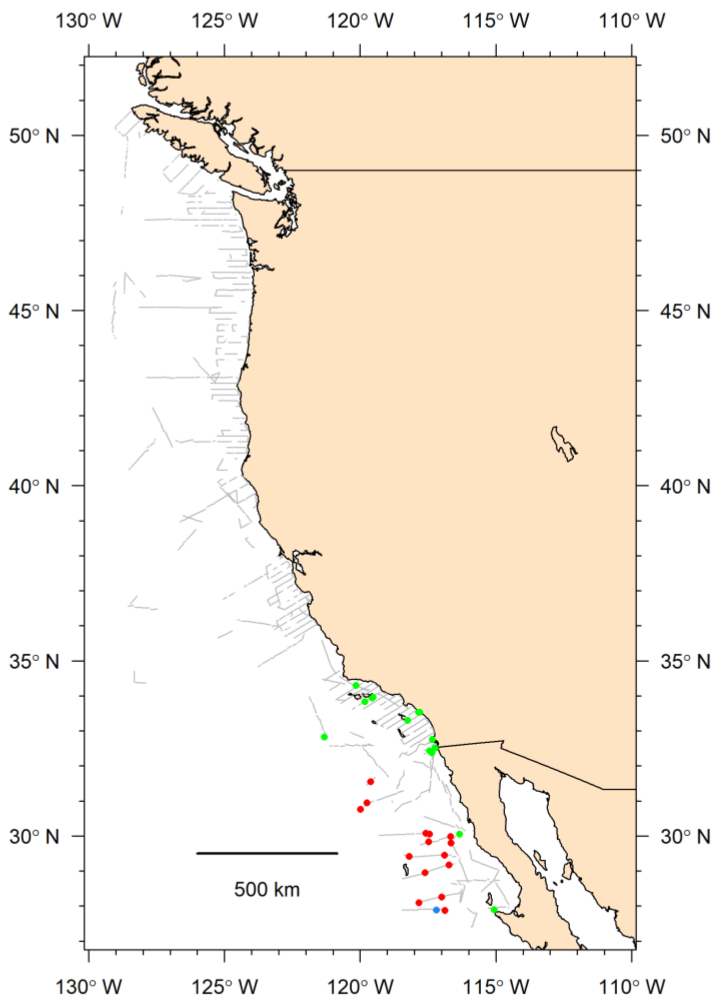

Figure 14. Sightings of other delphinids: striped dolphin (red), offshore spotted dolphin (blue), and bottlenose dolphin (green).

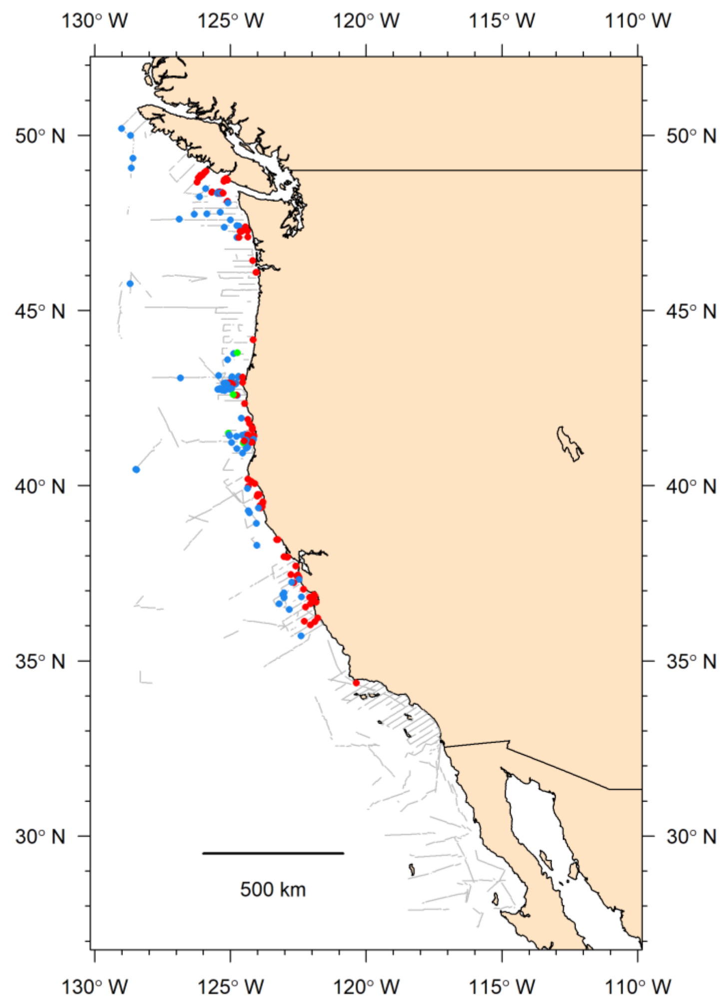

Figure 15. Sightings of porpoise: Harbor porpoise (red), Dall's porpoise (blue), and unidentified porpoises (green).

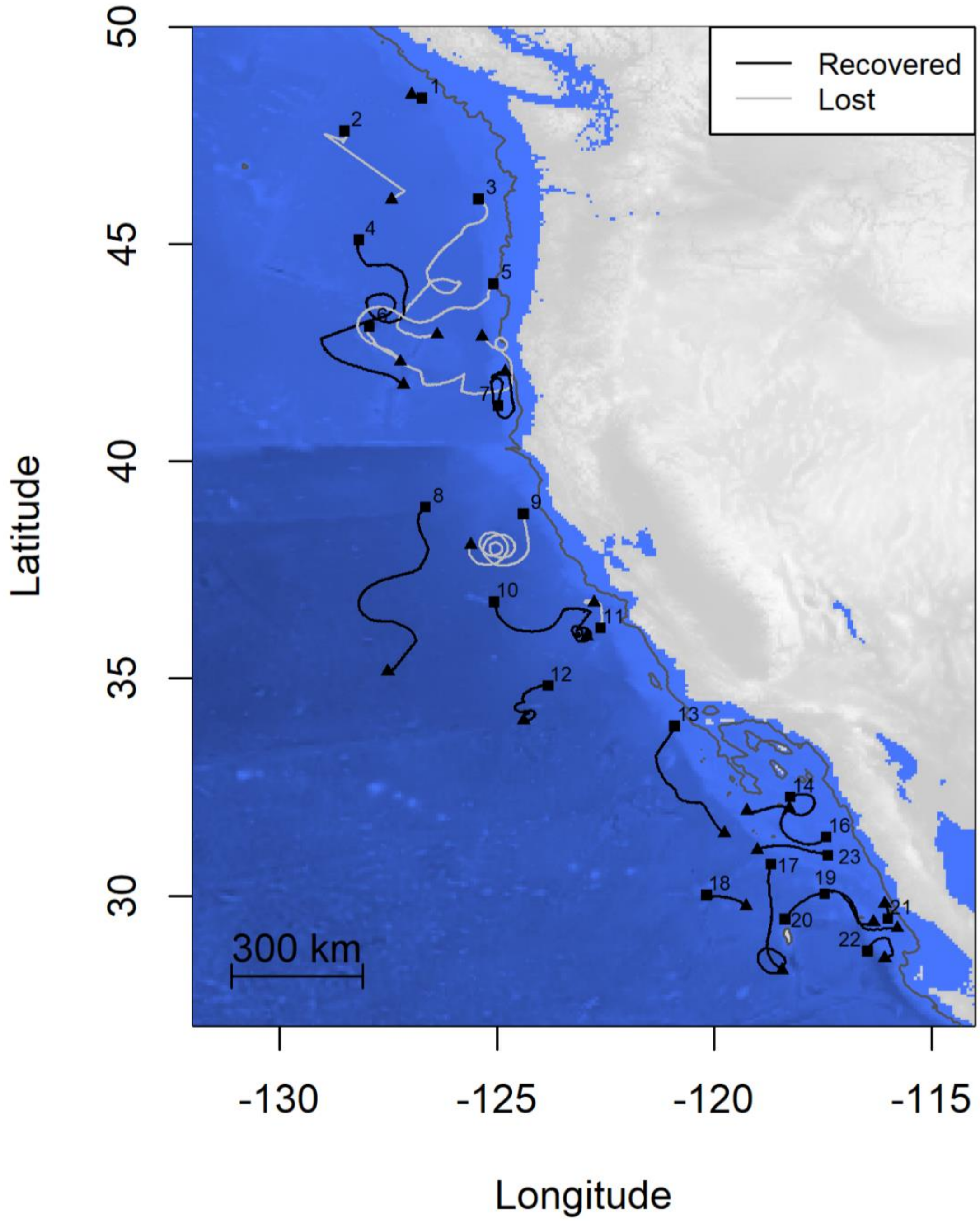

Figure 16. Locations of DASBR deployments (black squares), retrievals or last known location (black triangles), and buoy drifts (recovered = black lines, lost = light gray lines). Medium gray line is the 500-m isobath.

Appendix B: Detailed Report on the Passive Acoustic Monitoring Component of the California Current Ecosystem Survey for Deep-diving Cetaceans (Simonis et al. 2020, NOAA Technical Memorandum NMFS-SWFSC-630)

This appendix provides an in-depth description of the passive acoustic component of CCES, including a description of the methods for post-survey data processing, as well as a summary of the detections and locations for deep-diving cetaceans.



PASSIVE ACOUSTIC SURVEY OF DEEP-DIVING ODONTOCETES IN THE CALIFORNIA CURRENT ECOSYSTEM 2018: FINAL REPORT

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NOAA-TM-NMFS-SWFSC-630
June 2020

NOAA Technical Memorandum NMFS

JUNE 2020

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Cover Photos (top to bottom):
Cuvier's beaked whales (*Ziphius cavirostris*), credit: NOAA, A. Simonis
Sperm whale (*Physeter macrocephalus*), credit: NOAA, P. Olson
Dwarf sperm whale (*Kogia sima*), credit: NOAA, J. Barlow

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1 Introduction

The 2018 California Current Ecosystem Survey (CCES) was a multidisciplinary survey of the marine ecosystem from southern British Columbia, Canada to northern Baja California, Mexico. This survey was a collaboration between the Southwest Fisheries Science Center's (SWFSC) Fishery Resource Division (FRD) and Marine Mammal and Turtle Division (MMTD). CCES 2018 was conducted from 26 June to 4 December 2018 aboard the NOAA ship *Reuben Lasker*. The survey included oceanographic measurements, use of multi-frequency echosounders, surface trawls, vertically and obliquely integrating net tows, continuous underway fish egg sampling, visual line-transect surveys for marine mammals, photographic capture-recapture studies of marine mammals, strip transect surveys for seabirds, and passive acoustic surveys of marine mammals using Drifting Acoustic Spar Buoy Recorders (DASBRs). MMTD and FRD worked jointly aboard the vessel during Legs 1 through 4 (OMAO Project No. RL-18-03) when the vessel surveyed off the coasts of Vancouver Island and the US West Coast. MMTD conducted operations alone during Legs 5 through 7 (OMAO Project No. RL-19-01) when the vessel surveyed off the US West Coast and Mexico. Preliminary results from the oceanographic, fisheries, and krill investigations by FRD are presented in Stierhoff et al., (2019). Preliminary results from the visual surveys for marine mammals and seabirds by MMTD are presented in Henry et al., (in press). In this report we present the preliminary results of the passive acoustic monitoring efforts using DASBRs.

DASBRs were first used in a broad-scale Passive Acoustics Survey of Cetacean Abundance Levels (PASCAL) in the California Current during 2016, (Keating et al., 2018). They are free-floating acoustic recording instruments that include two hydrophones (configured as a vertical hydrophone array) and a digital recorder. DASBRs are tracked with two satellite geo-locators in a spar buoy at the surface, and the archival recorders must be recovered to download acoustic data. In that earlier study, DASBRs were deployed 30 times for a total of 421 recording days. Acoustic recordings were analyzed to detect echolocation signals from beaked whales, sperm whales (*Physeter macrocephalus*), and dwarf and pygmy sperm whales (*Kogia* spp.). In 2016, the most common beaked whale echolocation pulses were from Cuvier's beaked whale (*Ziphius cavirostris*), Baird's beaked whale (*Berardius bairdii*), Stejneger's beaked whale (*Mesoplodon stejnegeri*), and two unidentified species of beaked whales whose echolocation pulses were referred to as BW43 and BW39V. In a subsequent paper describing it, the name for the BW39V signal type was revised to BW37V (Griffiths et al., 2019). Keating et al., (2018) mapped the DASBR drifts from the 2016 cetacean survey along the U.S. West Coast, including the distributions of echolocation detection events of each identified species or signal type. Analysis of narrow-band high frequency (NBHF) signals from Dall's porpoise (*Phocoenoides dalli*), and presumed dwarf and pygmy sperm whales detected during the 2016 survey were presented by Griffiths et al., (2020).

Here we present analyses of the DASBR deployments from the CCES 2018 project. We provide information on the times and locations of drift deployments and retrievals. Each drift is also illustrated on maps of the study area. We present analyses of cetacean echolocation detections from DASBR recordings including those from beaked whales, sperm whales, and NBHF species. As in the previous 2016 study, beaked whale detections were dominated by Cuvier's beaked whale. All the beaked whale species detected in 2016 were also detected in this 2018 study, plus the addition of a signal, designated BWC that had been previously detected in the central and western Pacific, but not previously in the eastern Pacific. Sperm whales and NBHF species were detected throughout the study area.

CCES 2018 was the second survey conducted under the Pacific Marine Assessment Program for Protected Species (PacMAPPS), supported by the National Oceanographic and Atmospheric Administration (NOAA), the US Navy, and the Bureau of Ocean Energy Management (BOEM). This study conducts annual cetacean and ecosystem surveys throughout the North Pacific and generates data products used by all three agencies to meet regulatory requirements pertaining to protected species. Funding is provided in part by the US Department of the Interior, BOEM, Environmental Studies Program, Washington, DC through Interagency Agreement (IAA) M17PG00025 with NOAA/National Marine Fisheries Southwest Fisheries Science Center, and the US Department of Navy US Pacific Fleet through IAA N00070-18-MP-4C560. This report has been technically reviewed by BOEM, US Navy, and NOAA/NMFS, and has been approved for publication. The views and conclusions contained in this document are those of the authors and should not be interpreted as representing the opinions or policies of the US government, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

2 Methods

2.1 Drifting Acoustic Spar Buoy Recorders

Acoustic recordings were collected from DASBRs deployed at 22 predetermined locations distributed approximately uniformly throughout the California Current study area, offshore of the continental shelf (Figure 1). Each DASBR includes a pair of hydrophones, vertically separated by approximately 5-10 m, with the midpoint positioned approximately 100-150 m below the surface (Figure 2). Acoustic recordings were collected on one of two types of instruments, including the SoundTrap ST4300 (Ocean Acoustics, Auckland, New Zealand) and the Song Meter SM3M (Wildlife Acoustics, Maynard, MA) (Table 1). The hydrophones and recorder were attached to a line below a surface spar buoy and terminated at depth with an anchor, which maintained the vertical orientation of the hydrophones in the water column (Figure 2). Some of the deployments also had a ½" elastic "bungee" line in parallel with the ¼" nylon line to reduce the effect of wave action on recording data quality.

The sampling rate and duty cycle varied across all deployments (Table 1), however all acoustic recordings were collected with a minimum sampling rate of 256 kHz and used a 2-minute file size. All devices recorded stereo signals from two hydrophones. The hydrophone sensor types, sensitivities, and other relevant settings are shown in Table 2.

A pressure and 3D accelerometer logger (Loggerhead Computers OpenTag) or a temperature and depth recorder (Lotek Archival Tag LAT-1400) was included in all deployments except drift 16, (Table 1) to measure hydrophone depth and (for the former) array tilt. All SoundTrap ST4300 recorders were also set to record 3D accelerometry. Array depth is critical for estimating the range to vocalizing animals. Array tilt is also critical for estimating range when the array is not vertical in the water column (Barlow and Griffiths 2017).

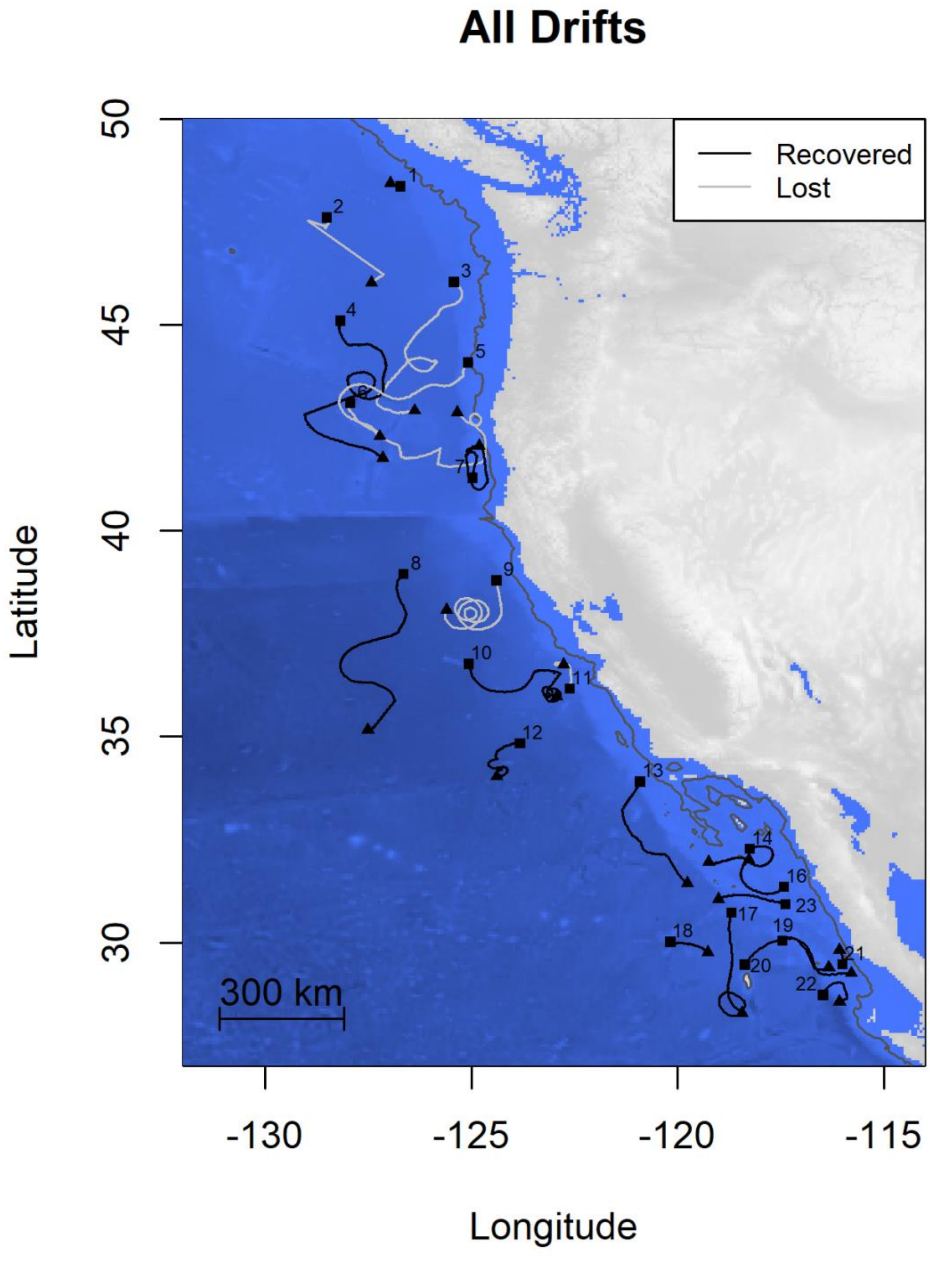

Figure 1. Locations of DASBR deployments (black squares), retrievals or last known location (black triangles), and buoy drifts (recovered = black lines, lost = gray lines). Darker gray line indicates the 500 m isobath.

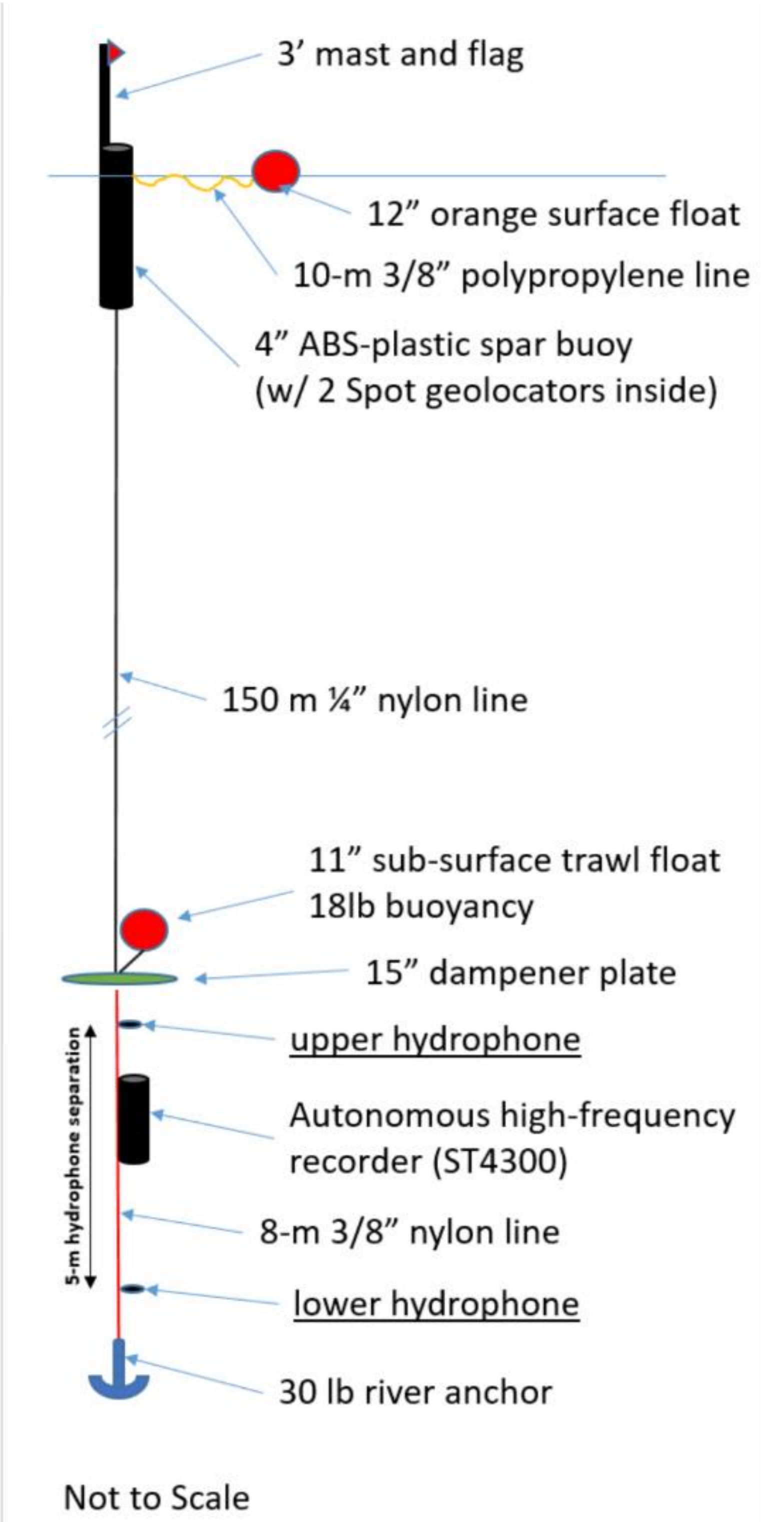

Figure 2. Schematic of DASBR. Note, the SM3M deployments used only 100m of ¼” nylon line, with a 10-m hydrophone separation. See Table 2 for details on configuration of each DASBR.

Table 1. Deployment details for each DASBR deployment during CCES 2018. Seven DASBRs could not be found and data was lost (drifts 1, 2, 3, 5, 6, 9, 11). Acoustic recorder types included ST=SoundTrap, SM3M = Song Meter 3 Marine, with each instrument serial number given. Two types of depth recorders were used: LAT= Lotek Archival Tag LAT1400 and OT= Loggerhead OpenTag.

Cruise Leg	DASBR Drift	Deployment Position	Recovery Position	Recorder Type and ID	Sample Rate (kHz)	Hydrophone Array Label	Duty Cycle On/Off (mins)	Depth Recorder	SPOT Labels
1	1	48. 3440 N, 126. 7029 W	N/A	ST4300 L-256	288	A	2/18	LAT-1	AB, AC
1	2	47. 5919 N, 128. 5120 W	N/A	SM3M #1	256	1	2/2 for 20d, then 2/18	OT-4	H, V
2	3A	46. 2560 N, 125. 3746 W	N/A	ST4300 M-256	288	B	2/18	LAT-2	N, O
2	3B	46. 0893 N, 125. 3746 W	45. 6098 N, 125. 2710 W	ST4300 J-128	288	I	2/18	LAT-12	G, AI
2	3C	45. 6098 N, 125. 2710 W	N/A	ST4300 J-128	288	I	2/18	LAT-12	G, AI
2	4	45. 0834 N, 128. 2082 W	41. 7569 N, 127. 1545 W	SM3M #3	256	3	2/2 for 20d, then 2/18	OT-6	E, K
2	5	44. 0938 N, 125. 0046 W	N/A	ST4300 N-256	288	11	2/18	LAT-3	L, M
2	6	43. 0957 N, 127. 9195 W	N/A	ST4300 D-128	288	C	2/18	LAT-4	P, Q
2	7	41. 2604 N, 125. 0157 W	42. 0400 N, 124. 4850 W	ST4300 O-256	288	12	2/18	LAT-5	R, S
3	8	38. 9485 N, 126. 6449 W	34. 3774 N, 128. 3174 W	ST4300 F-128	288	D	2/18	LAT-6	T, U
3	9	38. 7919 N, 124. 3891 W	N/A	ST4300 P-256	288	13	2/18	LAT-7	I, J
3	10	36. 7607 N, 125. 0584 W	35. 9671 N, 122. 9397 W	ST4300 Q-256	576	E	2/18	LAT-8	Z, AA
3	11	36. 1534 N, 122. 6094 W	N/A	ST4300 E-128	288	F	2/18	LAT-9	AJ, AK
3	12	34. 8303 N, 123. 8146 W	34. 0316 N, 124. 3911 W	ST4300 G-128	288	G	2/18	LAT-10	C, D
4	13	33. 8980 N, 120. 9078 W	31. 4444 N, 119. 7754 W	ST4300 I-128	288	H	2/18	LAT-11	X, Y
5	14	32. 2688 N, 118. 2563 W	31. 9507 N, 119. 2481 W	ST4300 O-256	576	J	2/18	LAT-5	A, B
6	16	31. 3534 N, 117. 4199 W	32. 1253 N, 118. 0337 W	ST4300 K-128	576	12	2/8	none	R, S
6	17	30. 7250 N, 118. 6933 W	28. 2857 N, 118. 4385 W	SM3M #3	256	3	2/2	OT-6	E, K
6	18	30. 0108 N, 120. 1815 W	29. 5059 N, 118. 8216 W	ST4300 Q-256	576	E	2/4	LAT-8	Z, AA
6	19	30. 0477 N, 117. 4605 W	28. 4041 N, 115. 5497 W	ST4300 F-128	576	D	2/8	LAT-6	T, U
6	20	29. 4590 N, 118. 3930 W	29. 3920 N, 116. 3355 W	ST4300 I-128	576	G	2/8	LAT-11	X, Y
6	21	29. 4677 N, 116. 0120	29. 8233 N, 116. 0796 W	ST4300 O-256	576	J	2/4	LAT-5	A, B
6	22	28. 7247 N, 116. 4778 W	28. 2846 N, 116. 6829 W	ST4300 G-128	576	H	2/8	LAT-10	C, D
7	23	30. 9285 N, 117. 3812 W	31. 0542 N, 119. 0123 W	ST4300 O-256	576	J	2/3	LAT-5	A, B

Table 2. Sensor and pre-amp characteristics for each recovered DASBR array (corresponding to the hydrophone array numbers in Table 1).

Hydrophone Array	Element #	Hydrophone				Array Characteristics		Soundtrap		Wildlife Acoustics Board	
		Hydrophone Type	Serial Number	Hydrophone Sensitivity	High-pass Filter (Hz)	Line Type	Hydrophone separation (m)	Gain (dB)	High-pass Filter (Hz)	Gain (dB)	High-pass Filter (Hz)
3	0	HTI-92-WB	856073	-154. 8	20	nylon	9. 1	n/a	n/a	12	2
	1	HTI-96-min	856040	-164. 7	20			n/a	n/a	12	2
12	0	HTI-92-WB	856049	-154. 5	20	nylon	9. 9	High	OFF	n/a	n/a
	1	HTI-96-min	856068	-165. 1	20			High	OFF	n/a	n/a
D	0	HTI-92-WB	856095	-155. 2	20	nylon/poly	4. 88	High	OFF	n/a	n/a
	1	HTI-96-min	856041	164. 5	20			High	OFF	n/a	n/a
E	0	HTI-92-WB	856096	-155. 6	20	nylon/poly	4. 89	High	OFF	n/a	n/a
	1	HTI-96-min	856044	-164. 7	20			High	OFF	n/a	n/a
G	0	HTI-92-WB	856097	-155. 2	20	nylon/poly	4. 82	High	OFF	n/a	n/a
	1	HTI-96-min	856017	-181. 4	100			High	OFF	n/a	n/a
H	0	HTI-92-WB	856051	-154. 7	20	nylon	4. 7	High	OFF	n/a	n/a
	1	HTI-96-min	856067	-164. 9	20			High	OFF	n/a	n/a
J	0	HTI-92-WB	856048	-155. 6	20	Falmat cable	5. 03	High	OFF	n/a	n/a
	1	HTI-96-min	856059	-165. 0	20			High	OFF	n/a	n/a

2.2 Analyses of Acoustic Survey Data to Detect Deep-Diving Whales

Acoustic data recorded by DASBRs were examined using a semi-automated approach to find echolocation pulses from beaked whales, sperm whales, and species that produce NBHF pulses. The NBHF species in our study area include *Kogia* (dwarf and pygmy sperm whales), Dall's porpoise, and harbor porpoise (Barlow 2016; Kyhn et al., 2013; Madsen et al., 2005; Merkens et al., 2018; Griffiths et al., 2020). Our approach generally follows that used by Keating et al. (2018). All DASBRs used a 2-minute recording time with varying duty cycles among deployments based on the expected battery life and duration of the deployment (Table 1). An acoustic detection event is defined as the presence of three or more echolocation clicks from a given species group within a 2-minute recording file.

2.2.1 Identification of Beaked Whales and Sperm Whales

Echolocation pulses were automatically detected using the Click Detector module in PAMGuard software (version 2.00.16e Beta) (Gillespie et al., 2008). A 1st order IIR Butterworth high-pass filter with a corner frequency of 80 kHz was used to flatten (or whiten) the ocean ambient noise spectrum (which is normally dominated by lower frequencies) which helps identify the true peak frequency of faint pulses. Prior to click detection and classification, a digital high-pass pre-filter was used (4th order Butterworth with a 10 kHz corner frequency) to prevent false-triggering on low-frequency sounds. Click detection for these species was based only on signals from the upper, more sensitive hydrophone (HTI-92-WB) using a 12 dB signal-to-noise ratio (SNR) threshold. Echolocation pulses were classified into categories based on peak frequency, and pulses in each category were color-coded with different symbol shapes for viewing in the PAMGuard Viewer click detector window (using a system similar to that described by Keating and Barlow 2013). The peak frequency categories for the click classification were 2-15, 15-30, 30-50, 50-80 and >80 kHz. Within the 30-50 kHz peak frequency category (the typical category for most beaked whale pulses), pulses were further classified based on the presence of a frequency sweep characteristic of beaked whale pulses (Baumann-Pickering et al., 2013; Keating and Barlow 2013). The initial PAMGuard processing also automatically estimated the vertical angle at which echolocation pulses were received using the time-difference-of-arrival of signals at the two elements of the vertical hydrophone array.

After the initial click detection and classification in PAMGuard, the Matched Template Classifier module was used to re-classify clicks based on idealized waveforms from six recognized categories of beaked whales found in the study area (Cuvier's, Baird's, and Stejneger's beaked whales, BW43, BW70, (Baumann-Pickering et al., 2013), and BW37V (Griffiths et al., 2019)). Relatively high thresholds (0.06 for Cuvier's beaked whale and 0.15 for all others) were used with the Matched Template Classifier to minimize the rate of false positive detections of beaked whales, so relatively few clicks were reclassified with this secondary classification method. All clicks above the Matched Template Classifier threshold were displayed in the same color and shape in the PAMGuard Viewer click detection window.

Analysts (AES and JST) used the click detector window with a Bearing-Time display in PAMGuard Viewer to distinguish echolocation pulses of beaked whales and sperm whales from the much greater number of clicks detected from other sources (primarily dolphins). This click detector window displays all detected clicks as symbols in a plot with time on the x-axis and bearing angle on the y-axis. Potential signals were initially identified based on the shape and color of the displayed symbols (corresponding to the peak frequency or Matched Template classification schemes described above). Additional contextual information that contributed to species recognition included bearing angles (the direct-path signals from beaked whales and sperm whales are typically received from depths below the hydrophones and bearing angles are relatively constant over a 2-minute recording period) and pulse repetition rate. Once potential echolocation signals were identified, the analyst could click on the symbol representing a pulse and display its waveform, frequency spectrum, and Wigner plot of frequency versus time (which typically shows a frequency upsweep for beaked whales). After probable beaked whale and sperm whale clicks were identified, all similar clicks within a 2-minute recording were grouped as an event within PAMGuard Viewer.

Initial screening of the data indicated that at times, sperm whale click trains were detected continuously over many hours, creating an enormous analysis challenge. The detection range for sperm whale clicks has been reported as out to 37 km on towed hydrophone arrays (Barlow and Taylor 2005), the low self-noise of DASBRs may result in an even greater detection range. Due to limited available time for data analysis in this study, sperm whale events were only recorded if the direct-path signal arrived from below the hydrophone array at an angle greater than 20° declination relative to horizontal. This eliminated the majority of distant sperm whale signals, which are received at horizontal angles of 0 to -10°, and greatly reduced the time that would have been required to mark all clicks within sperm whale events. Accordingly, the effective survey area was also reduced, which will be accounted for in future density estimates.

During an initial training period, both analysts independently identified beaked whale and sperm whale events for the same DASBR drift (#23) and compared results. Subsequently, a single analyst examined all other drifts. Beaked whale and sperm whale acoustic events were identified by AES in drifts 4-16 and by JST for drifts 17-23. When events were identified, the analyst also recorded an initial species classification based on an identification guide for beaked whale echolocation pulses, utilizing inter-click intervals, with spectral and Wigner characteristics of pulses as seen in PAMGuard (Appendix A). After the initial species classifications were made by a single analyst, the PAMGuard database was stripped of species identification information and then reviewed by the second analyst to independently label species classifications.

After both analysts (JST & AES) independently made their initial species classifications for all beaked whale events (including categories of “unidentified beaked whale” and “possible beaked whale”), all discrepancies were reviewed. Each analyst independently reviewed the subset of discrepancies to determine whether, based on additional scrutiny, they would change their species classification. If the discrepancy remained, events were re-examined in PAMGuard Viewer during a joint session with a third experienced analyst (JB) to reach unanimous approval of all three analysts. If any analyst felt that the species-classification could not be determined with certainty, the event would be re-labeled with the highest level of certainty based on the consensus of all analysts (for example “unidentified beaked whale”).

2.2.2 Identification of NBHF pulses from *Kogia* and porpoise species

NBHF pulses were initially identified by each analyst while scanning the data for beaked and sperm whale events. Subsequently, all recordings from SoundTrap ST4300 recorders were re-analyzed using specialized PAMGuard settings that were optimized for NBHF pulses. These PAMGuard settings were different from those used by Keating et al., (2018) in their analyses of NBHF pulses from the 2016 PASCAL project. The SM3M recordings (sampled at 256 kHz) did not have adequate bandwidth to cover all NBHF pulses and were not analyzed for NBHF pulses. To eliminate low-frequency noise, the acoustic data was filtered with a 6th order IIR Butterworth high-pass filter with a corner frequency of 100 kHz. Preliminary analyses indicated that some NBHF signals were only received on one hydrophone; therefore, signals from both hydrophones were included while searching for NBHF signals, using a click detector with a 12 dB SNR threshold. Echolocation pulses with peak frequencies outside of the range of 100-144 kHz were discarded, leaving a reduced set of detections, which could be more efficiently reviewed in PAMGuard Viewer. Analyst JST identified distinct NBHF events based on pulses with a narrow peak frequency above 100 kHz and a Wigner plot showing a relatively long duration signal at a relatively constant frequency. Because NBHF signals were frequently received on only one hydrophone, which prevented an accurate bearing calculation, the Amplitude-Time display was substituted for the usual Bearing-Time display when reviewing clicks in PAMGuard viewer.

3 Results

3.1 DASBR survey effort

High-quality acoustic data was obtained from 15 of 23 deployments, resulting in 1,910 cumulative hours of recordings (Table 3). Of these, 14 DASBRs were recovered at sea by the *Lasker*. One drift (#7) grounded off Brookings, Oregon and was recovered by a small boat launched locally. For recovered deployments, the distance traveled by individual drifts ranged from 46 to 961 km, with an average distance traveled of 370 km (Table 3). Acoustic recordings on the SM3M recorder (Drifts 4 and 17) had a higher level of instrument noise than the ST4300 recorders, particularly within the frequency range of 55-70 kHz. In general, beaked whales were harder to detect and to identify in the SM3M recordings due to the instrument noise. In future analyses of detection probability, separate analysis of SM3M recordings may be prudent.

Seven drifts were not recovered due to a loss of geolocation information (lost drifts included: 1, 2, 3, 5, 6, 9, and 11; Table 1; Figure 1). The reasons for these losses are unclear, but each DASBR had two SPOT geolocation devices and the pattern of signal loss provides some clues, which are discussed further in section 4.4. The SPOT geolocation transmissions from Drift 1 stopped abruptly after 2 days on one SPOT and after 6 days on the other. Transmissions from Drift 2 became very intermittent on both SPOTs after the second day but continued to be received occasionally for another 93 days. Drift 3 was problematic for several reasons. Initially (Drift 3a) the mast was entangled with the floating line which prevented the spar buoy from floating vertically. During a retrieval attempt, the line became entangled in the ship's propeller and the recorder and hydrophones were lost. A second deployment (Drift 3b) with different instruments also resulted in an entanglement of the mast in the floating line. This DASBR was recovered a few days later and was deployed a third time (Drift 3c). Transmissions from this last deployment stopped abruptly after 8 days on one SPOT and after 58 days on the other. Transmissions from Drift 5 became intermittent after 15 days on one SPOT (but continued to be received occasionally for another 14 days) and stopped abruptly after 79 days on the other SPOT. Transmissions from Drift 6 stopped abruptly after 3 days on one SPOT and after 13 days on the other. Transmissions from Drifts 9 and 11 stopped abruptly on both SPOTs on the same day. The last transmissions from Drifts 2 and 5 were just 2-3 days prior to their scheduled pickup dates; attempts were made to search for these lost DASBRs using the 25X binoculars on the ship, but search conditions were poor and they were not found. An AIS ship track coincided closely with the sudden loss of Drift 9 and thus a ship strike is strongly suspected. Because four of the five most northern deployments were lost, acoustic survey effort is skewed towards the southern portion of the study area.

3.2 Beaked whale detections

Six distinct beaked whale signals were detected, including those from Cuvier's, Baird's, and Stejneger's beaked whales, as well as the BW43, BW37V, and BWC signal types. There were no detections of Blainville's beaked whales or BW70 signals. The numbers of detections of each signal type are shown in Table 4.

After reviewing the species classifications made by each analyst, there was agreement on 90% of species classifications for two-minute files containing beaked whale clicks, and all remaining discrepancies were resolved during the cooperative analyst review (Table 5). Most discrepancies (115/134) were the result of one analyst initially using a more conservative classification (e.g., “beaked whale”, “possible beaked whale”), which was later reclassified to the species level by both analysts. Many of these reclassifications were based on the context of having detections with clear species identification before and after the two-minute file with nondescript characteristics. Eight two-minute files were classified to a more general level than initial analyst decisions, resulting in detections of Cuvier’s (n=7) and Baird’s (n=1) beaked whales to be labeled as “possible beaked whales”. These files often contained low amplitude clicks, with long duration waveforms and consistent inter-click intervals, but undistinguishable spectral features.

Cuvier’s beaked whales were the most frequently detected beaked whale, with detections in 925 two-minute files across 14 drifts throughout the California Current (Figure 3). Baird’s beaked whales were detected in 31 two-minute files across 5 drifts, with 97 % (n=30) occurring in the southern California Current and 3% (n=1) in the northern California Current, offshore of Oregon (Figure 4). Stejneger’s beaked whales were detected in 42 two-minute files in one drift (#4) in the northern, offshore area of the California Current (Figure 4). The BW37V signal type was detected in 66 two-minute files across 2 drifts, with 98% (n=65) occurring on drift 4 in the northern, offshore region of the California Current, and 2% (n=1) in the offshore, central California Current (Figure 5). The BW43 signal type was detected in 135 two-minute files across 10 drifts, all of which occurred in the central and southern California Current (Figure 5). The BWC signal type was detected in 6 two-minute files across two different drifts (17 and 18) offshore of Baja California (Figure 5). All unidentified and possible beaked whale detections are shown in Figures 6 and 7, respectively. The diversity of beaked whale acoustic events per drift is shown in Figure 8 (drifts 4, 7, 8 and 10), Figure 9 (drifts 12-16), Figure 10 (drifts 17-20), and Figure 11 (drifts 21-23).

Table 3. Deployment and retrieval dates (UTC time zone), total deployment duration in days, number of 2-minute recording files, cumulative recording durations, and distance traveled. Differences in total deployment durations and cumulative recording durations are due to duty cycle schedules and/or expiration of memory/battery.

DASBR Drift	Deployment Date/Time (UTC)	Recovery Date/Time (UTC)	Deployment Duration (days)	# 2-min files	Cumulative Recording Duration (hh:mm)	Cumulative Recording Duration (days)	Distance Traveled (km)
4	7/25/2018 03:30	10/13/2018 00:36	79.9	11161	372:02	15.5	961
7	8/5/2018 14:48	10/22/2018 09:00	77.8	4187	139:34	5.8	446
8	8/16/2018 02:34	10/10/2018 16:53	55.6	3311	110:22	4.6	634
10	8/22/2018 02:11	10/22/2018 00:21	60.9	4385	146:10	6.1	664
12	8/30/2018 02:34	10/6/2018 17:08	37.6	2687	89:34	3.7	339
13	9/11/2018 20:35	10/23/2018 14:34	41.7	3004	100:08	4.2	420
14	10/5/2018 05:46	11/1/2018 16:55	27.5	1977	65:54	2.7	329
16	10/30/2018 14:33	11/21/2018 04:18	21.6	2356	78:32	3.3	206
17	10/31/2018 00:02	11/24/2018 04:31	24.2	8707	290:14	12.1	497
18	10/31/2018 09:58	11/23/2018 18:41	23.4	3879	129:18	5.4	145
19	11/1/2018 02:11	11/27/2018 14:20	26.5	2513	83:46	3.5	253
20	11/5/2018 14:04	11/22/2018 19:21	17.2	2479	82:38	3.4	300
21	11/6/2018 03:43	11/11/2018 09:29	5.2	1257	41:54	1.7	46
22	11/7/2018 14:04	11/27/2018 04:55	19.3	2333	77:46	3.2	145
23	11/22/2018 08:10	12/3/2018 00:25	10.7	3075	102:30	4.3	174
	TOTAL		**529.4**	**57311**	**1910:22**	**79.6**	**5559**

3.3 Sperm whale detections

Sperm whales were detected across 11 drifts throughout the California current using the restricted definition for an acoustic event (clicks must be received at angles greater than 20° declination relative to horizontal) (Figure 12). Sperm whale acoustic encounters were detected in 1736 two-minute files, and often occurred across several consecutive hours (Table 4).

3.4 NBHF detections

NBHF clicks were detected in 136 two-minute files across 11 drifts throughout the California Current (Figure 13). To investigate the variation in NBHF click types, the mean center frequency at -3dB was calculated for all clicks within each encounter. Considering the expected distribution of NBHF species along with the distribution of center frequencies in the study area, five general categories of NBHF clicks emerged, including: "<110 kHz", "114-124 kHz", "125-129 kHz", 130-139 kHz", and "140+ kHz" (Figure 9). There were only one or two click types detected on most drifts; however, all NBHF click types, except for "<110 kHz", occurred on drift 7 (Figure 14).

Table 4. Total number of detections for each species and signal type in two-minute recording files for the full CCES DASBR dataset. The proportion of detections reflects the number of detections for each species relative to the total number of detections for all species (n=3,176).

Species Code	Scientific Name	Common Name	Total Detections	Proportion of detections
BW	*Ziphiid* whale	Unidentified beaked whale	9	0.2%
?BW	NA	Possible beaked whale	90	2.8%
ZC	*Ziphius cavirostris*	Cuvier's beaked whale	925	29.1%
BB	*Berardius bairdii*	Baird's beaked whale	31	1.0%
MS	*Mesoplodon stejnegeri*	Stejneger's beaked whale	41	1.3%
BW43	BW43	43 kHz peak frequency (possibly Perrin's beaked whale)	136	4.3%
BW37V	BW37V	37 kHz valley frequency (possibly Hubbs' beaked whale)	66	2.1%
BWC	BWC	Cross Seamount beaked whale (possibly gingko-toothed beaked whale)	6	0.2%
PM	*Physeter macrocephalus*	Sperm whale	1736	54.7%
NBHF	NBHF	Narrow band high frequency	136	4.3%

Table 5. Confusion matrix of initial and final classifications of two-minute files containing confirmed or possible beaked whale echolocation clicks. Initial classifications were based on a single analyst's review; final classifications were achieved by a consensus of up to three analysts (see text). Species codes are defined in Table 4.

	Final								
Initial	ZC	BB	MS	BW37V	BW43	BWC	BW70	BW	?BW
ZC	869	0	0	0	0	0	0	0	7
BB	2	12	0	0	0	0	0	0	1
MS	0	0	34	0	0	0	0	0	0
BW37V	0	0	0	53	0	0	0	0	0
BW43	0	0	0	0	114	0	0	0	0
BWC	0	0	0	0	0	6	0	0	0
BW70	0	0	0	0	0	0	0	1	0
BW	20	0	0	0	16	0	0	4	3
?BW	34	19	7	13	6	0	0	5	79

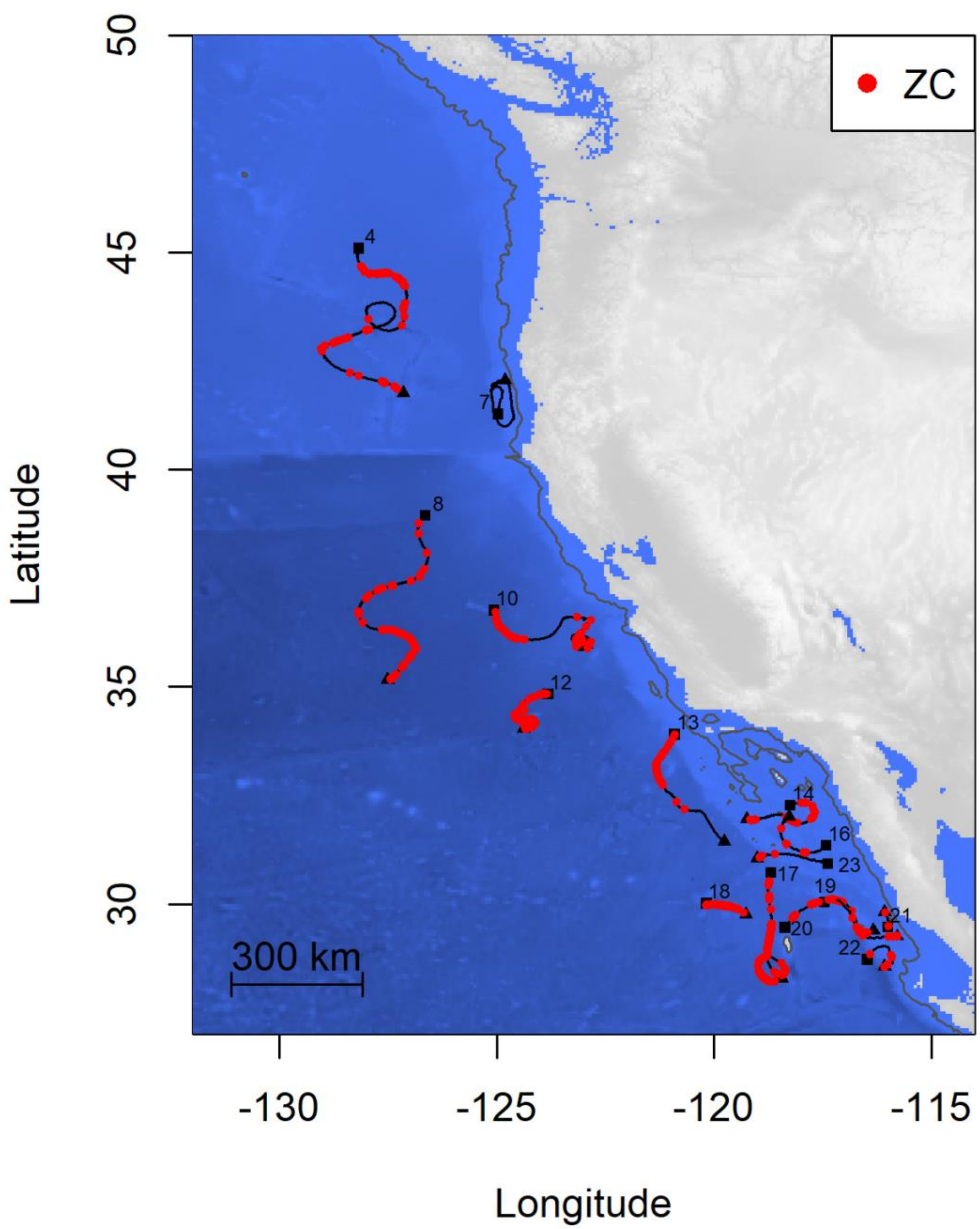

Figure 3. Acoustic detections of Cuvier's beaked whale (ZC) along recovered DASBR drifts. Black squares and triangles show drift origin and recovery locations, respectively. Gray line indicates the 500 m isobath.

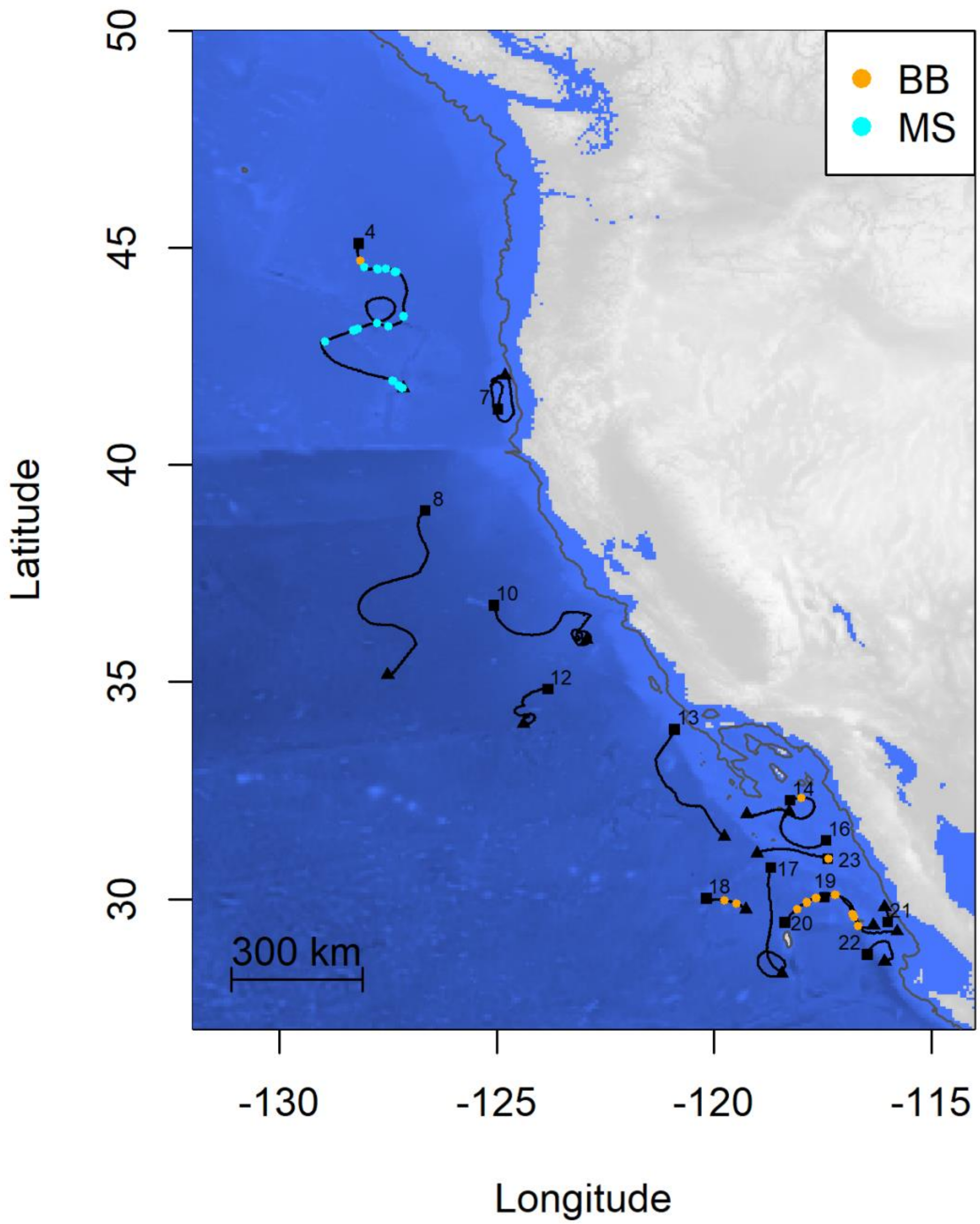

Figure 4. Acoustic detections of Baird's (BB) and Stejneger's (MS) beaked whales along recovered DASBR drifts. Black squares and triangles show drift origin and recovery locations, respectively. Gray line indicates the 500 m isobath.

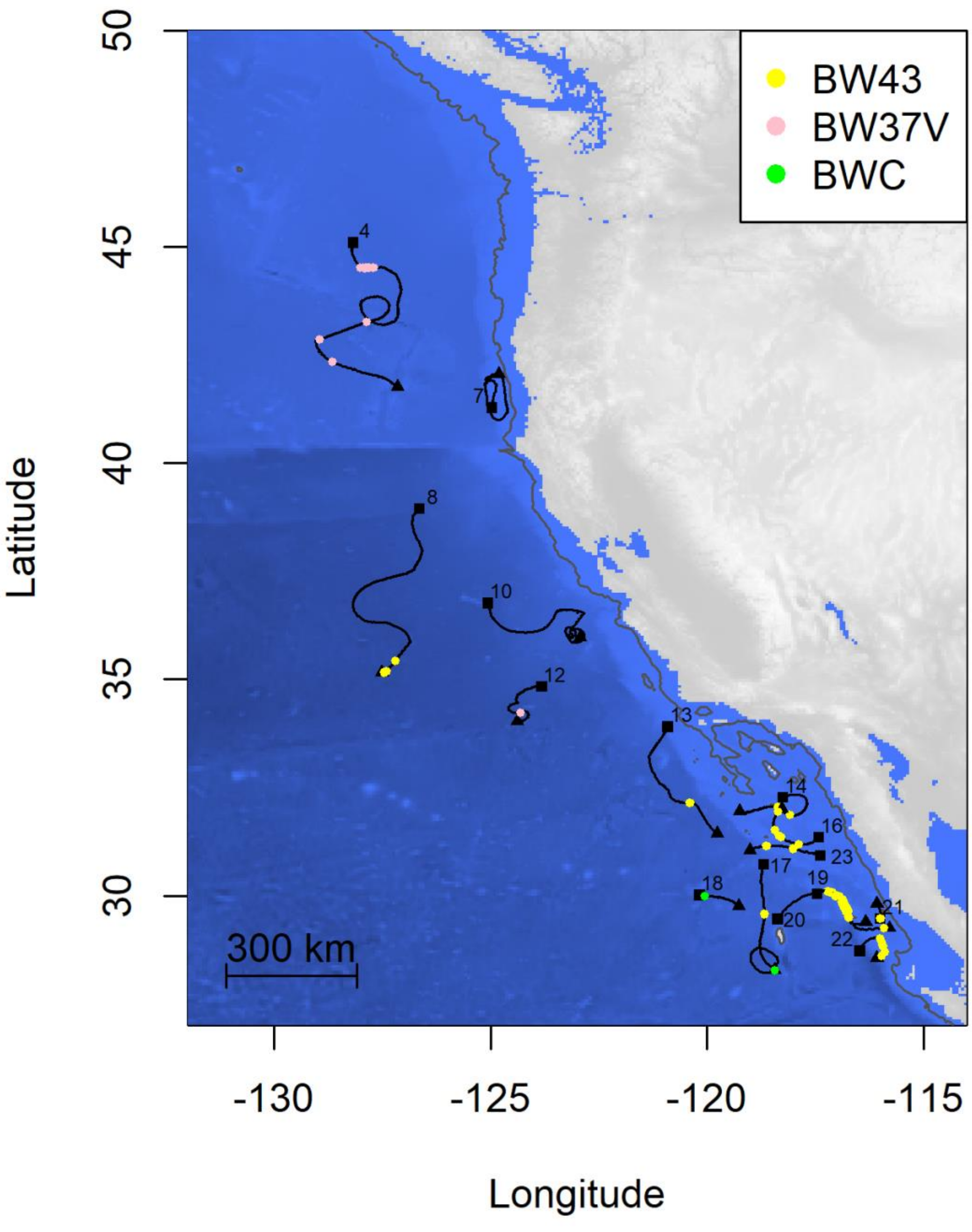

Figure 5. Acoustic detections of BW43, BW37V, and BWC beaked whale signals along recovered DASBR drifts. Black squares and triangles show drift origin and recovery locations, respectively. Gray line indicates the 500 m isobath.

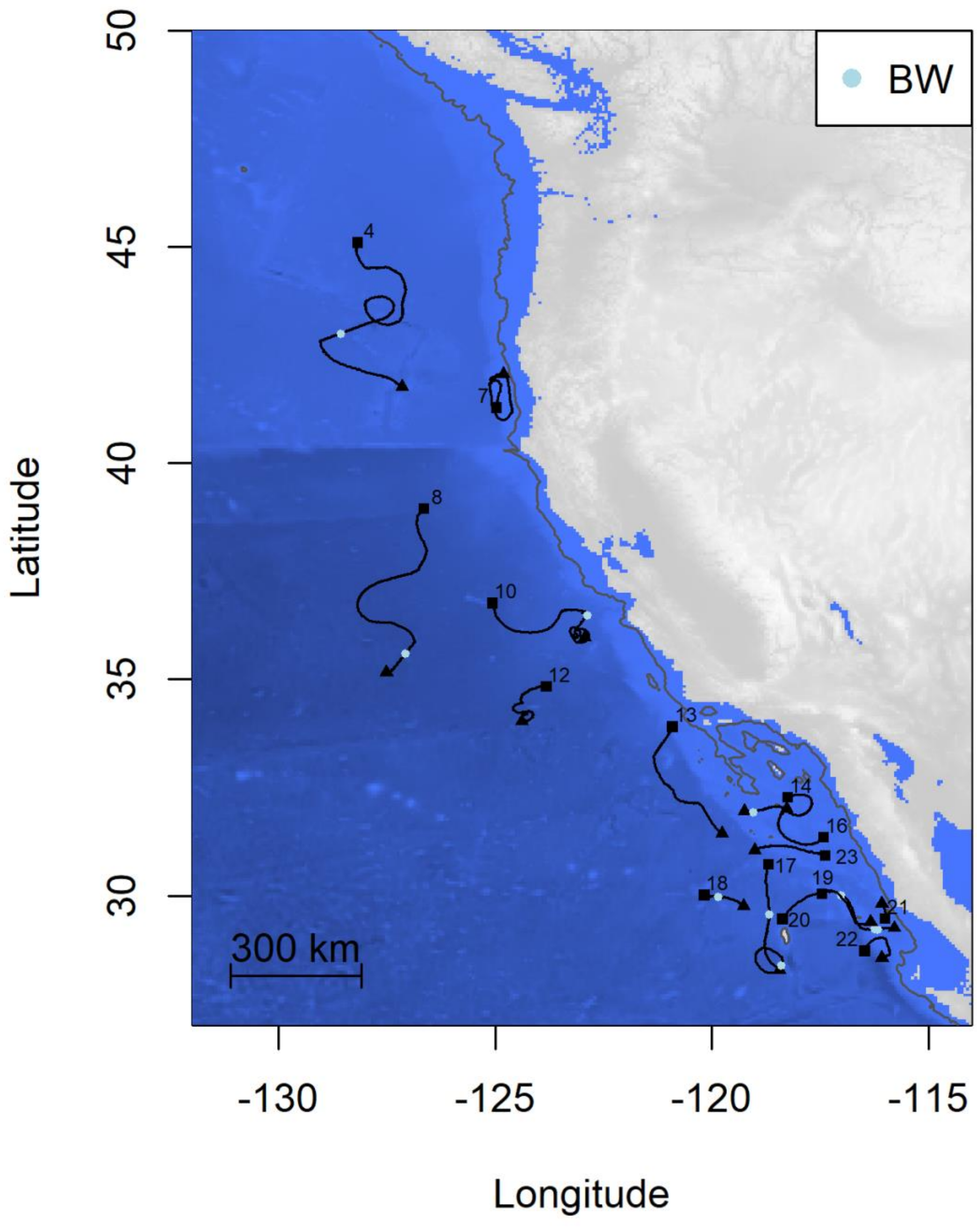

Figure 6. Acoustic detections of unidentified species of beaked whales along recovered DASBR drifts. Black squares and triangles show drift origin and recovery locations, respectively. Gray line indicates the 500 m isobath.

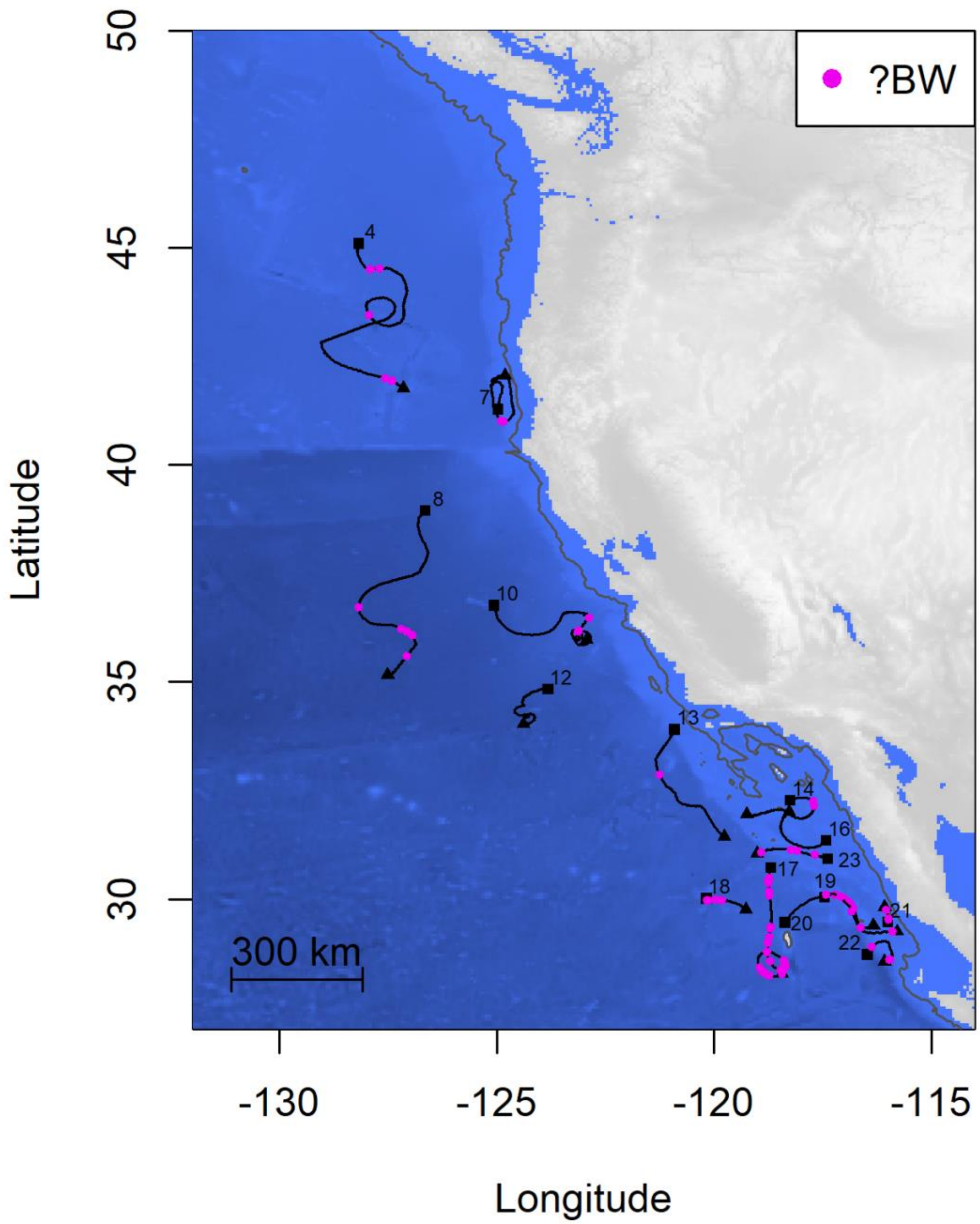

Figure 7. Acoustic detections of possible beaked whale signals along recovered DASBR drifts. Black squares and triangles show drift origin and recovery locations, respectively. Gray line indicates the 500 m isobath.

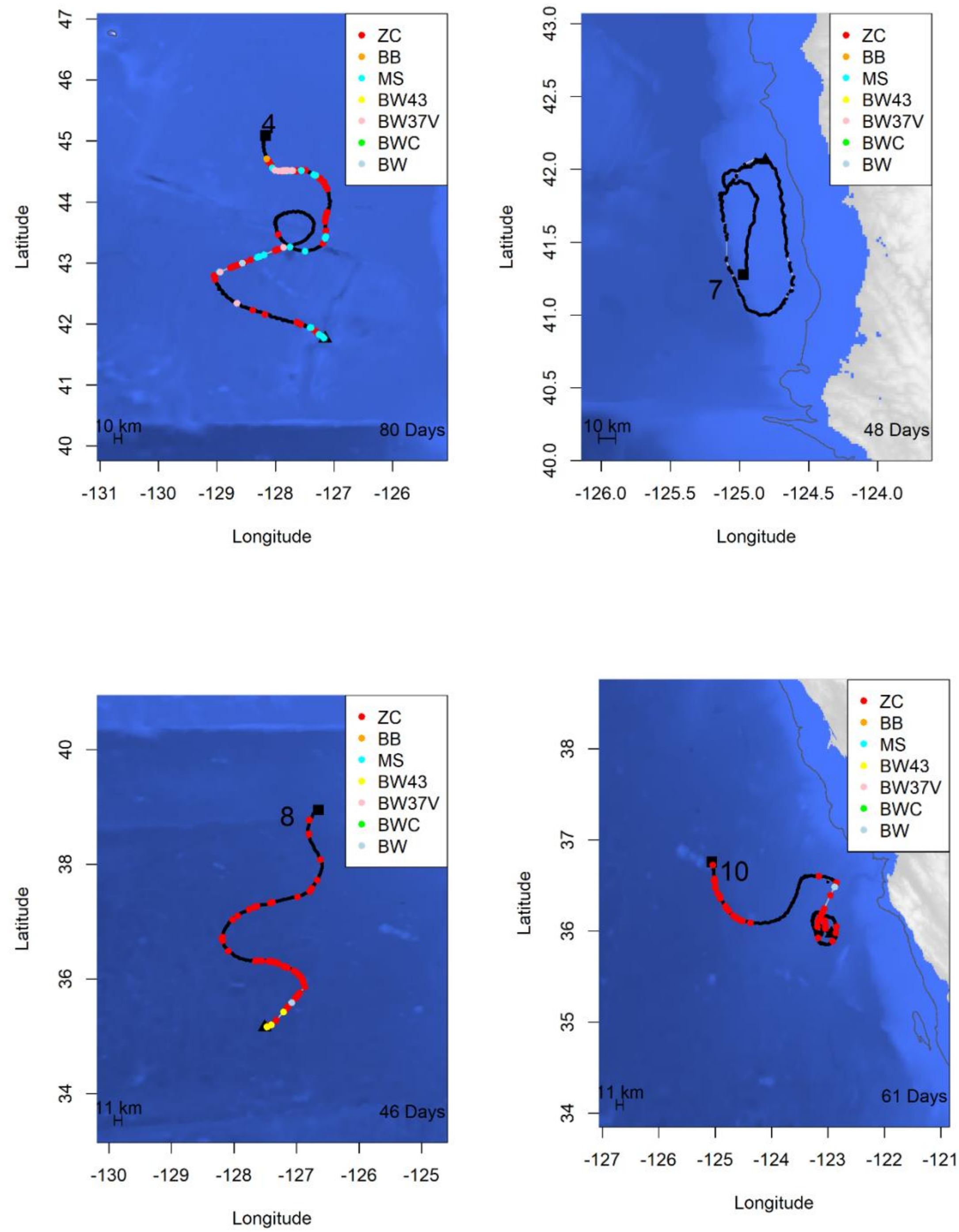

Figure 8. Acoustic detections of distinct beaked whale signals along the track of DASBR drifts 4, 7, 8, and 10. Deployment duration is shown in the lower right corner. Black squares and triangles show drift origin and recovery locations, respectively. Gray line indicates the 500 m isobath. Note: NBHF and Pm detections shown in separate figures.

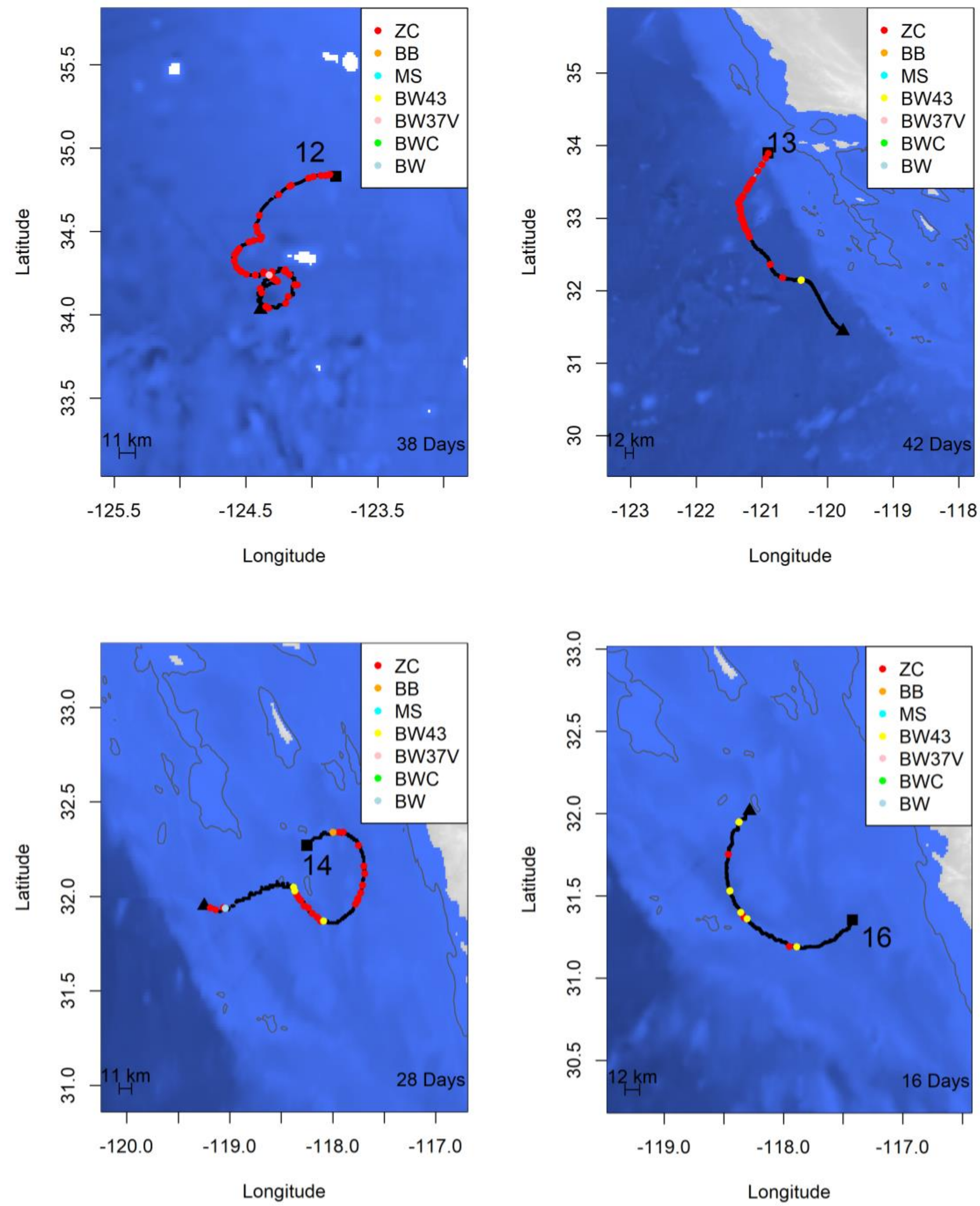

Figure 9. Acoustic detections of distinct beaked whale signals along the track of DASBR drifts 12, 13, 14, and 16. Deployment duration is shown in the lower right corner. Black squares and triangles show drift origin and recovery locations, respectively. Gray line indicates the 500 m isobath. Note: NBHF and Pm detections shown in separate figures

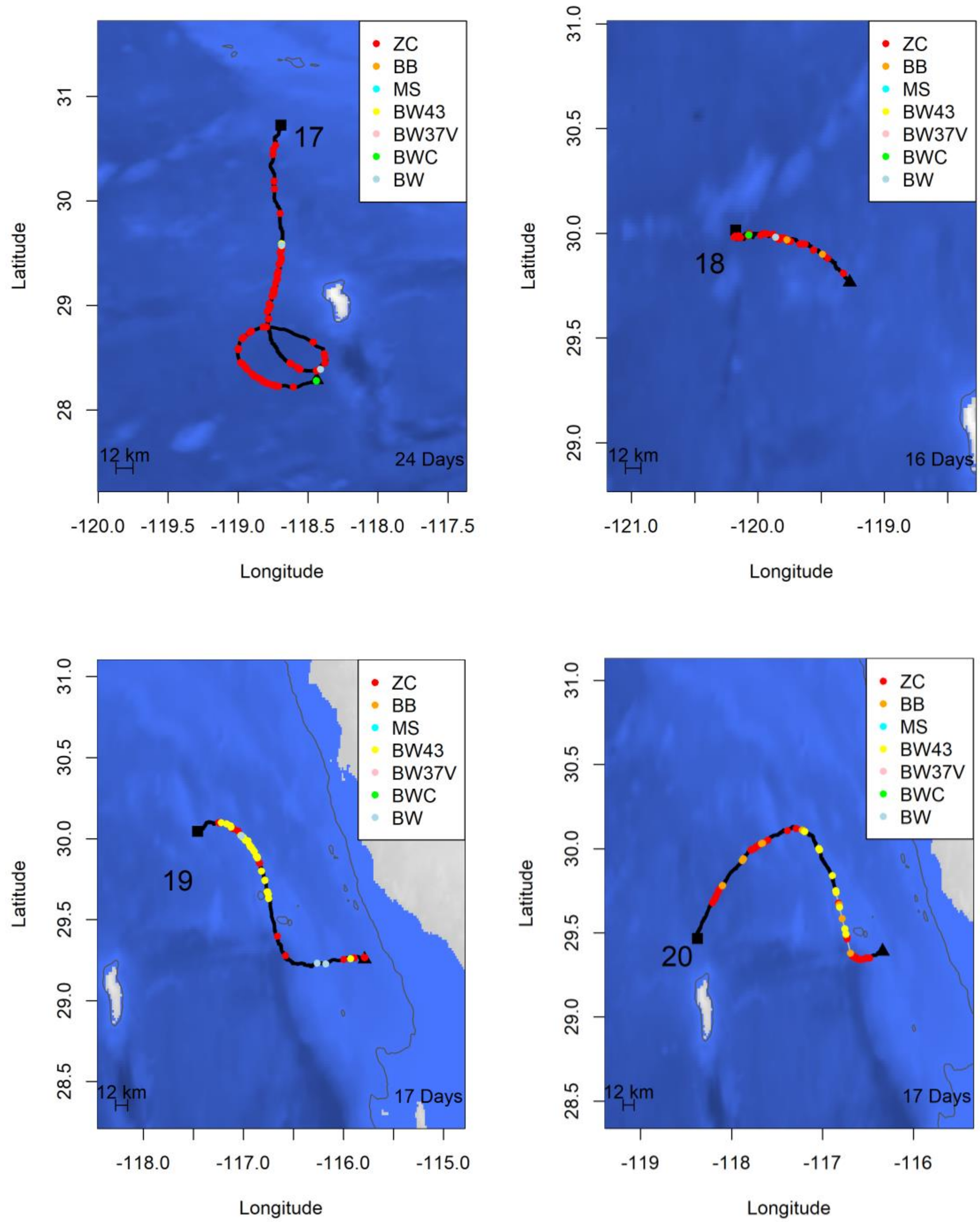

Figure 10. Acoustic detections of distinct beaked whale signals along the track of DASBR drifts 17, 18, 19, and 20. Deployment duration is shown in the lower right corner. Black squares and triangles show drift origin and recovery locations, respectively. Gray line indicates the 500 m isobath. Note: NBHF and Pm detections shown in separate figures.

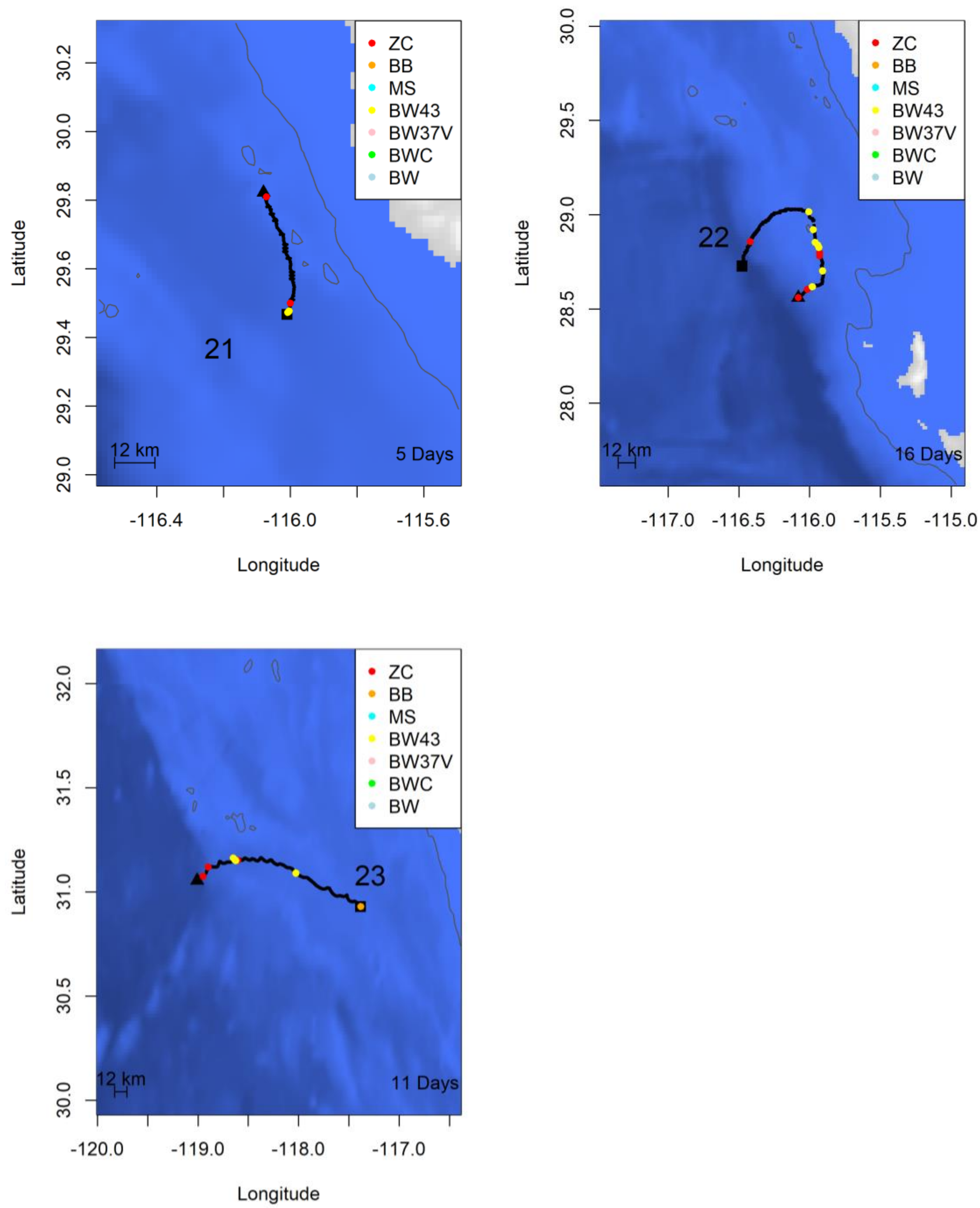

Figure 11. Acoustic detections of distinct beaked whale signals along the track of DASBR drifts 21, 22, and 23. Deployment duration is shown in the lower right corner. Black squares and triangles show drift origin and recovery locations, respectively. Gray line indicates the 500 m isobath. Note: NBHF and Pm detections shown in separate figures.

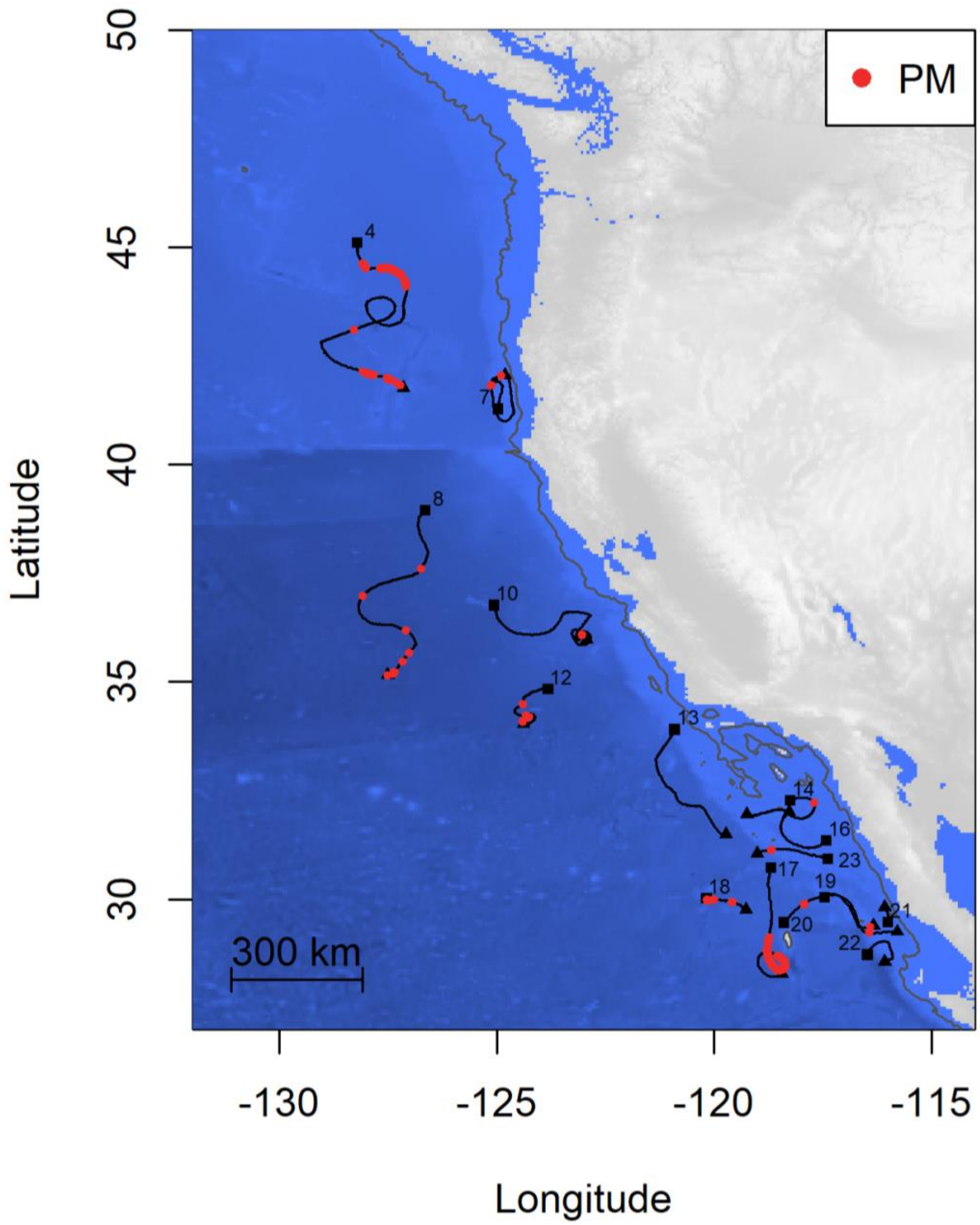

Figure 12. Acoustic detections of sperm whale (PM) echolocation clicks along recovered DASBR drifts. Black squares and triangles show drift origin and recovery locations, respectively. Gray line indicates the 500 m isobath. Sperm whale events are only plotted and included in analysis if the direct-path signal arrived from below the hydrophone array at a declination angle greater than 20° from horizontal.

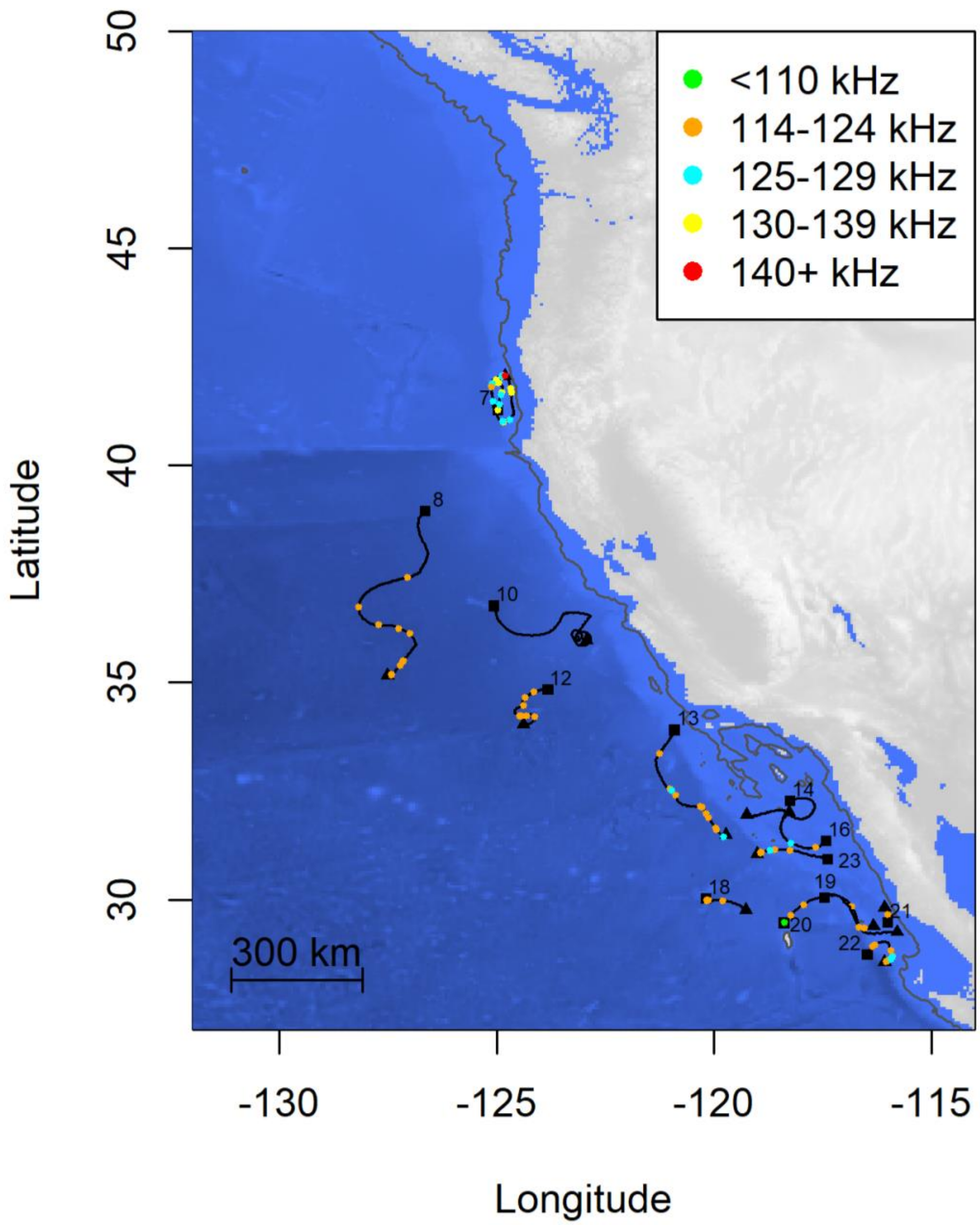

Figure 13. Acoustic detections of NBHF echolocation clicks along recovered DASBR drifts. Black squares and triangles show drift origin and recovery locations, respectively. Acoustic events are color-coded by their mean center frequency

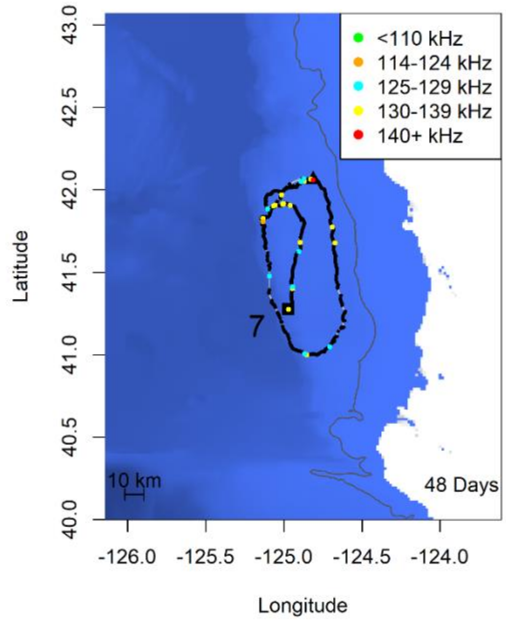

Figure 14. Acoustic detections of distinct NBHF signals along the track of DASBR drift 7. Deployment duration is shown in the lower right corner. Black squares and triangles show drift origin and recovery locations, respectively. Acoustic events are color-coded by their mean center frequency

4 Discussion

The acoustic recordings collected from 15 drifting DASBRs along the US West Coast between Jul 25 and Dec 3, 2018 indicate the presence of 6 distinct beaked whale signals, sperm whales, and multiple types of NBHF signals attributed to harbor and Dall's porpoises, as well as dwarf and pygmy sperm whales. The DASBRs provided an effective means of surveying deep-diving odontocetes, which are otherwise particularly challenging to survey with visual methods. The results of this project provide useful data products to estimate the density of beaked whales throughout the California Current, although additional analyses will be required to similarly estimate the densities of sperm whales and individual NBHF species. Overall, this survey effort and analysis provide further support for the use of drifting buoys to acoustically monitor cetaceans in pelagic environments.

4.1 Beaked whales

The use of the Matched Template Classifier in PAMGuard was particularly helpful to identify beaked whale clicks among detections of delphinid echolocation and noise. There was high agreement among analysts in the classification of species-specific beaked whale signals, which provides confidence in the use of this dataset as a ground-truth to develop more automated routines for beaked whale classification.

Positive sea surface temperature (SST) anomalies during 2018 may have contributed to a northward shift in the range of some cold-temperate species (Stejneger's and BW37V beaked whales), and the first BWC detections in the southern California Current may also have been the result of a northward shift of this warm-temperate to tropical species. Further discussion of the distribution and abundance of each species and unique signal type is discussed below.

4.1.1 Cuvier's beaked whale

Cuvier's beaked whales continue to be the most commonly detected beaked whale throughout the extent of our study area in the California Current between August and December 2018. Cuvier's beaked whales were detected in a greater fraction of the sound files in our study (1.6%) than in the 2016 study (0.8%, Keating et al., 2018). Anomalously warm conditions were present during the 2018 study, particularly in southern California and Baja California (Cheng et al., 2019; Lonhart et al., 2019; Thompson et al., 2019), however the distribution of Cuvier's beaked whales did not seem to appreciably shift compared to previous survey years. Previous DASBR surveys did not cover the area off Baja California, but our study shows that Cuvier's beaked whales are the most common species there too.

4.1.2 Baird's beaked whale

Compared to the 2016 PASCAL survey in which Baird's beaked whale detections were distributed throughout the California Current, in 2018 there were fewer acoustic encounters of Baird's beaked whales occurring over a smaller area. In both surveys, the highest densities of detections in the southern California Current were found on drifts that were closer to the shelf break. This matches the distribution of Baird's beaked whale sightings on previous SWFSC surveys (Figure 10 in Hamilton et al., 2009). After publication of Keating et al., (2018), some of the Baird's beaked whale events were re-classified as unidentified or Cuvier's beaked whales (Barlow, pers. comm.). Near-bottom Cuvier's beaked whales may have been misclassified as Baird's beaked whales in that report because the effect of bottom reflections on signal characteristics was not understood. Prior to any concerted study of Baird's beaked whales from the 2016 PASCAL survey and this survey, a careful review of all Baird's beaked whale detections from both surveys is needed to ensure consistent classification.

Baumann-Pickering et al., (2014) reported Baird's beaked whales as the second most encountered beaked whale species in southern California, which is inconsistent with our observations. Considering the four distinct beaked whale signals that we observed in southern California in 2018, Baird's beaked whale was the third-most encountered species (n=31) after Cuvier's (n=925) and BW43 (n=136), with only BWC signals occurring less frequently. The vast majority of Baird's beaked whale detections (96 of 116) reported from Southern California in Baumann-Pickering et al., (2014) occurred from one location during Mar-May 2009, whereas the CCES 2018 survey occurred during July through December 2018. In addition to dissimilar seasonal coverage, the geographical areas surveyed by PASCAL and CCES predominantly cover offshore areas whereas the Baumann-Pickering et al., (2013) study examined nearshore and island associated areas. The disparate temporal and geographical coverage among these studies may explain the different detection rates of Baird's beaked whales.

4.1.3 Stejneger's beaked whale

In 2018, all detections of Stejneger's beaked whale occurred in the northern California current, which reflects the expected cold-temperate distribution observed in other studies (Mead 1989; Baumann-Pickering et al., 2014; Keating et al., 2018). In 2016, acoustic detections of Stejneger's beaked whale occurred offshore Washington (the northern extent of the study area), to Point Conception in the south (Keating et al., 2018); however, in 2018 detections only occurred in the northern California Current, offshore of Oregon. Sea surface temperature anomalies (relative to 1982-2010 monthly means) in the central and northern California Current may be influencing the distribution of Stejneger's beaked whales, as low SST anomalies were present in August 2016 and high SST anomalies were present in August 2018 (Cheng et al., 2019; Lonhart et al., 2019; Thompson et al., 2019).

4.1.4 BW37V

Detections of the BW37V signal type primarily occurred in the northern, offshore region of the California Current, although one detection occurred offshore of central California (Figure 5). Results from the 2016 PASCAL survey showed a similar distribution of BW37V (referred to as "BW39V" in Keating et al., 2018) acoustic encounters extending from the Oregon-Washington border to Point Conception in the south. The lack of detections in southern California in 2018 may be attributed to anomalously warm summer SST conditions (Thompson et al., 2019). Griffiths et al., (2019) hypothesized that the BW37V signal was produced by Hubb's beaked whales (*Mesoplodon carlhubbsi*), which are considered a cold-temperate species, with a known distribution extending from southern California through Washington along the US west coast (Yamada et al., 2012; Mead, Walker and Houck 1982). The distribution of BW37V encounters from the 2016 and 2018 surveys is consistent with the expected distribution for Hubb's beaked whales.

4.1.5 BW43

A high density area of 'BW43' echolocation clicks was identified offshore of the coast of Baja California, potentially indicating a previously undescribed preferred habitat for the beaked whale that produces the BW43 signal. Results from the 2016 PASCAL survey also indicate a southern distribution for this signal in the California Current, although the BW43 encounters were restricted to further offshore waters in 2016 compared to 2018. Baumann-Pickering et al., (2013) proposed the hypothesis that the BW43 signal type is made by Perrin's beaked whale (*Mesoplodon perrini*). Our observations are generally consistent with this hypothesis but would extend the known range of this species south to approximately 29° N (Pitman et al., 2009; Brownell et al., 2012).

4.1.6 BWC

The BWC signal type was first documented at Cross Seamount near Hawaii (McDonald et al., 2009), resulting in its designation as the "Cross Seamount beaked whale" or "BWC", and it has since been detected throughout the central and western tropical Pacific. However, it has never been detected as far east as the locations included in our study (Baumann-Pickering et al., 2014). Record high sea surface temperatures during summer 2018 in southern California and northern Baja California may have facilitated the influx of this species (Thompson et al., 2019). It is also possible that BWC has historically gone undetected due to infrequent monitoring, and the overall low detectability of the BWC's high frequency, low source level and broad bandwidth echolocation signal (Baumann-Pickering et al., 2013). Although the origin of this signal type remains unknown, Baumann-Pickering et al., (2014) proposed that BWC signals are produced by the gingko-toothed beaked whale (*Mesoplodon gingkodens*). The locations of the BWC encounters in the CCES DASBR datasets support this hypothesis, as they fall within the presumed distribution of gingko-toothed beaked whales (Jefferson et al., 2015) based on the stranding record.

Unlike most other beaked whale species described to date, a strong diel cycle has been documented for the BWC signal (McDonald et al., 2009), with most acoustic activity occurring at nighttime. All BWC detections in the CCES dataset support this nocturnal foraging strategy. It is also believed that the species producing the BWC signal forages at relatively shallow depths compared to most other beaked whale species (Baumann-Pickering et al., 2014), and our observations support this hypothesis as well. The bearing angles were above horizontal, suggesting that the whales were foraging at the depth of the hydrophones (100-150 m depth) and shallower.

4.2 Sperm whales

In contrast to the short duration encounters of beaked whale and NBHF signals, sperm whale acoustic detections were nearly continuous in some areas. Barlow and Taylor (2005) reported that sperm whale clicks can be detected at ranges of 37 km on towed hydrophone arrays. The low self-noise of DASBRs may result in an even greater detection range; however, the local environment (temperature profile, bathymetry, and ambient noise) will also strongly influence the propagation of sperm whale clicks. Given the long range of sperm whale detectability, it is possible that multiple groups of sperm whales were simultaneously detected when the DASBRs drifted through high-density areas. The multi-path arrivals of some sperm whale signals may be useful to estimate the range to the source (Thode 2005), which could in turn be used to distinguish multiple sperm whale groups. Further analytical effort will be needed to distinguish multiple groups and estimate sperm whale detection rates before this data can be used to estimate density.

4.3 NBHF click types

There are four species in the California Current known to produce NBHF signals, including harbor and Dall's porpoises, dwarf and pygmy sperm whales. Although the NBHF signals exhibit many similar spectral and temporal characteristics (narrow bandwidth, high frequency content, long duration), the variation in the mean center frequency of NBHF encounters suggests that center frequency may be a useful feature to distinguish NBHF species (Griffiths et al., *submitted*).

The "140+ kHz" click type occurred in the nearshore section of drift 7 in the northern California Current, corresponding to the only habitat likely suitable for harbor porpoises (depths <200 m). All of the "130-139 kHz" click type detections also occurred on drift 7, although in deeper areas of the drift. The geographic restriction of the "130-139 kHz" encounters to the northern, offshore region of the California Current corresponds with the known distribution of Dall's porpoise. The majority of the "114-124 kHz" encounters occurred in the central and southern California Current. The abundance of detections offshore of the California Current suggest these clicks from *Kogia* spp. The intermediate "125-129 kHz" click type was detected throughout the extent of the study area, and likely represents acoustic encounters from both *Kogia* spp. and Dall's porpoise. Lastly, there were 7 detections of the "<110 kHz" click type, all of which occurred along drift 20 in the southern California Current, near the island of Guadalupe offshore of Baja California. The source of these clicks is still unknown, as the restricted range and unusual spectral features of this click type do not correspond to any click types described for odontocetes in this region.

4.4 DASBR Loss

This survey experienced a much greater DASBR loss rate (7 of 22 deployments) than the 2016 PASCAL survey (which lost none, Keating et al., 2018). Only three DASBRs would have been lost (# 1, 6 and 11) if the deployments in 2018 were as short as in 2016 (less than 24 days), so longer deployments are associated with increased risk of loss. For the two cases when both satellite transmitters stopped at the same time, a ship strike is likely. In the cases when loss was preceded by a long period of very intermittent transmissions, the spar buoy mast may have been entangled in the lines so that transmitters were submerged most of the time. This condition was also seen during the deployment of drift 3 and on several recovered DASBRs. Losses on future DASBR surveys may be reduced by 1) shorter deployments (<30 days), 2) addition of a radar reflector to warn ships thereby reduce the likelihood of hitting DASBRs, and 3) a DASBR re-design that prevents the mast entanglement seen in 2018.

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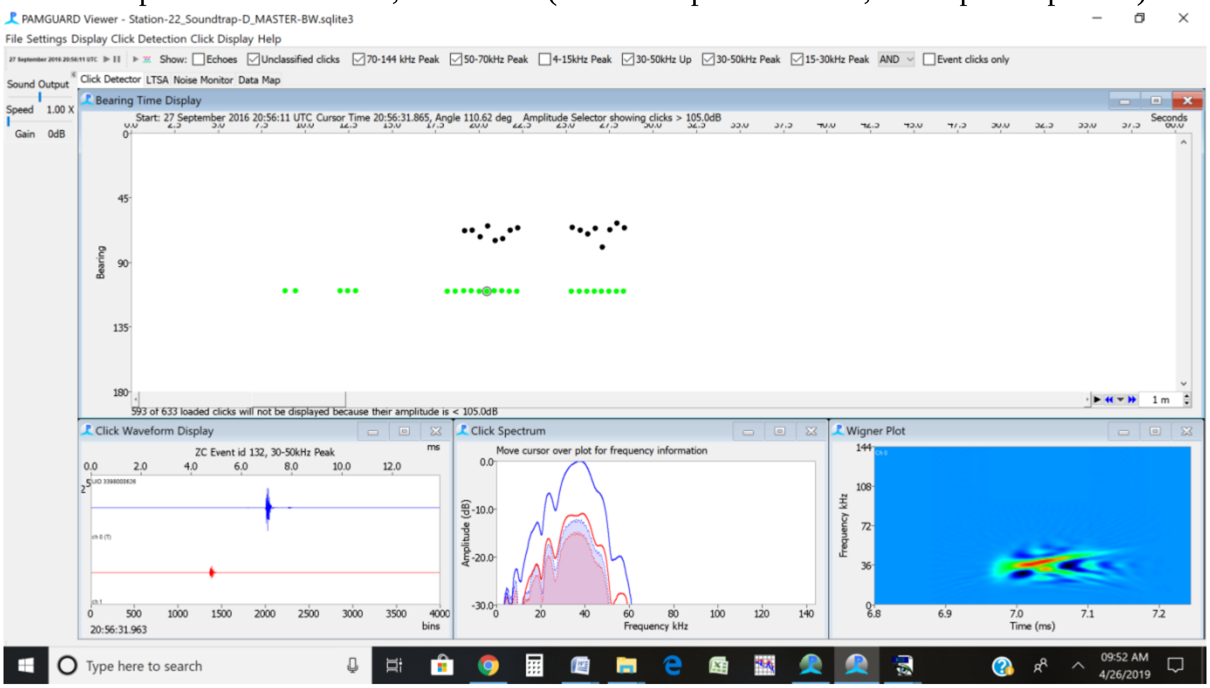
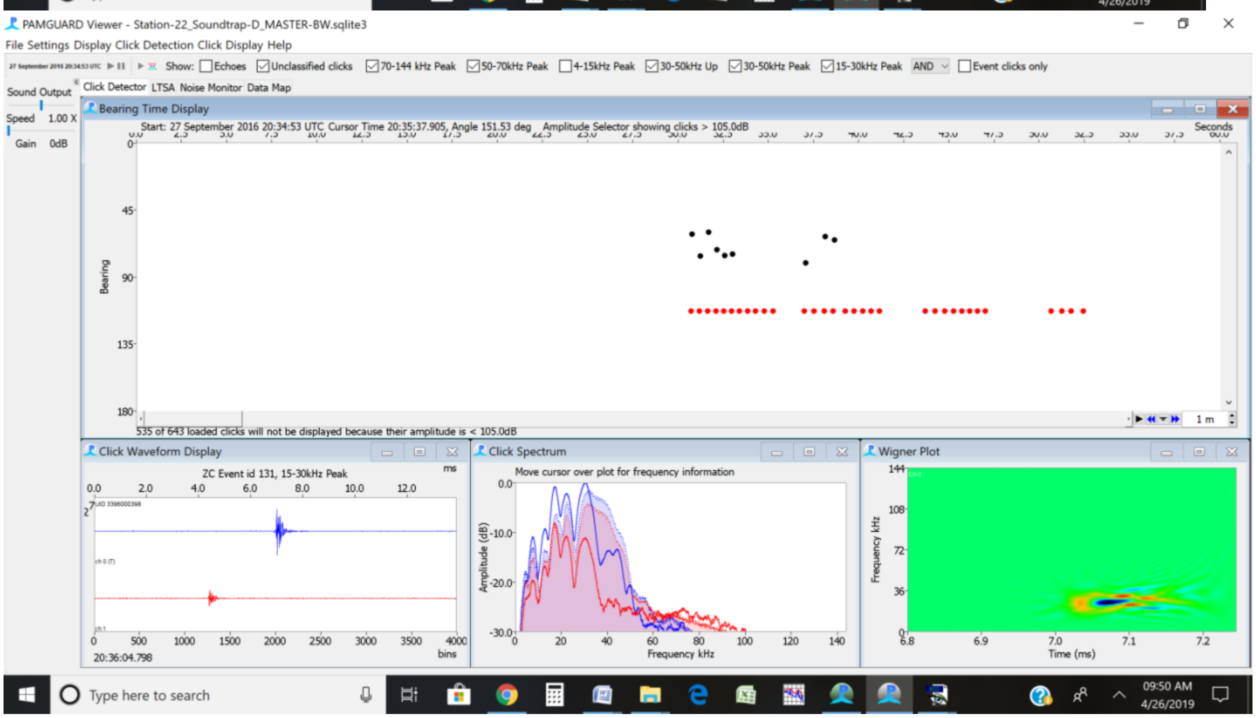
7 Appendix A: Beaked Whale Pulse Species Identification Guide

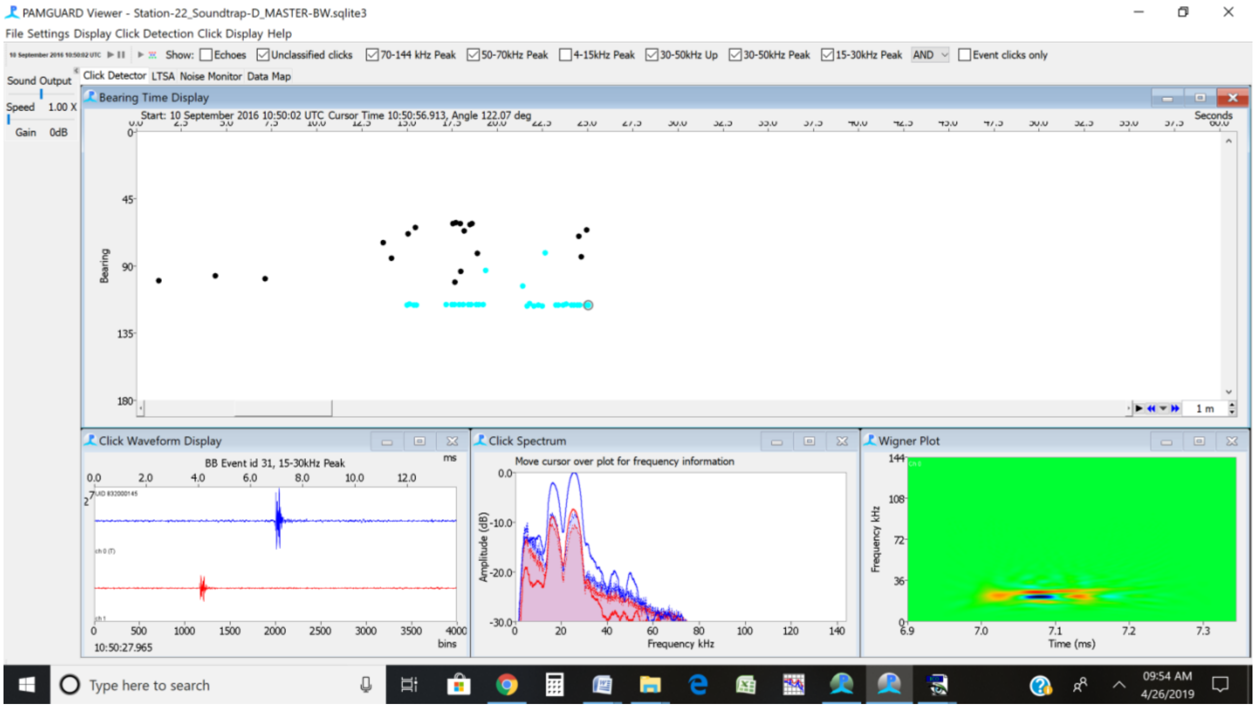
ZC: *Ziphius cavirostris*, Cuvier's beaked whale

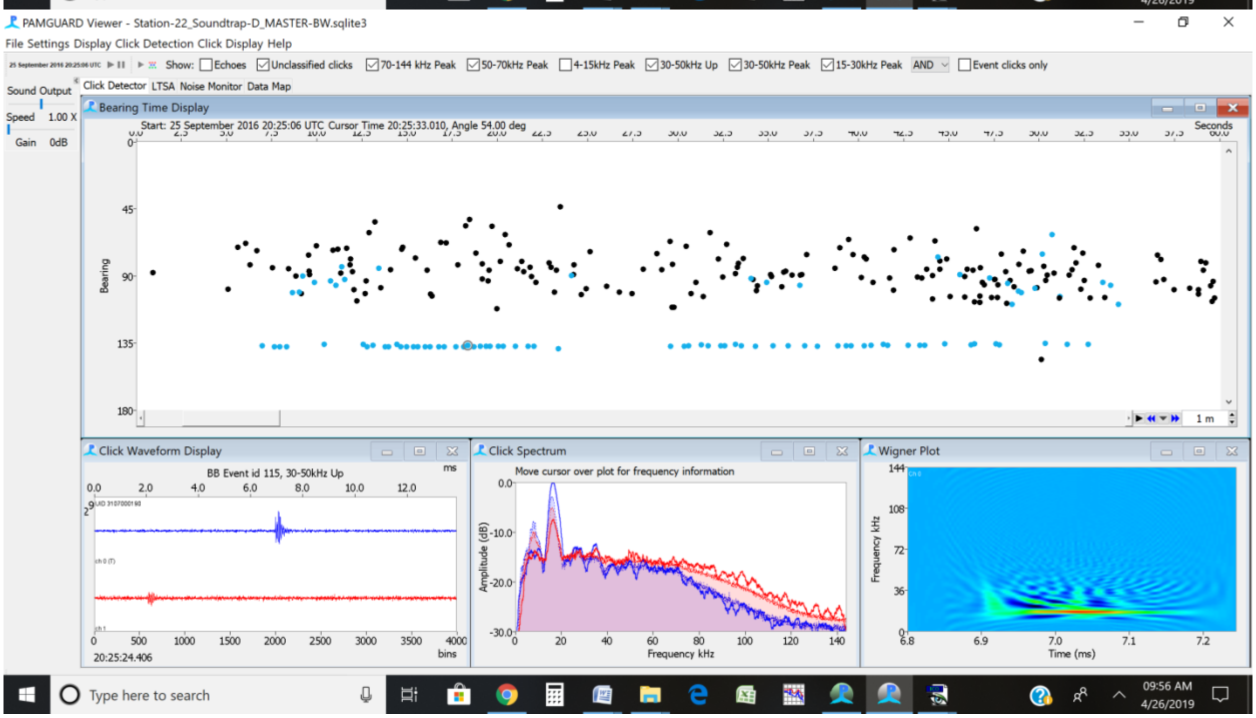
Ziphius template (gray). Strong null at about 27 kHz, with peaks at 32-40 kHz, 22-24 kHz and ~18 kHz. Upsweep usually evident. Wigner plots shows a "kickstand" (downsweep appearing after the upsweep). Sometimes this kickstand can just appear as a dot. At great range, the 18 and 22 kHz peaks may be higher than the 32-40 kHz peak and the Wigner can just show the downsweep. IPI= 0. 3-0. 5 sec, PPS= 2-3. (IPI= inter-pulse interval, PPS= pulses per sec)





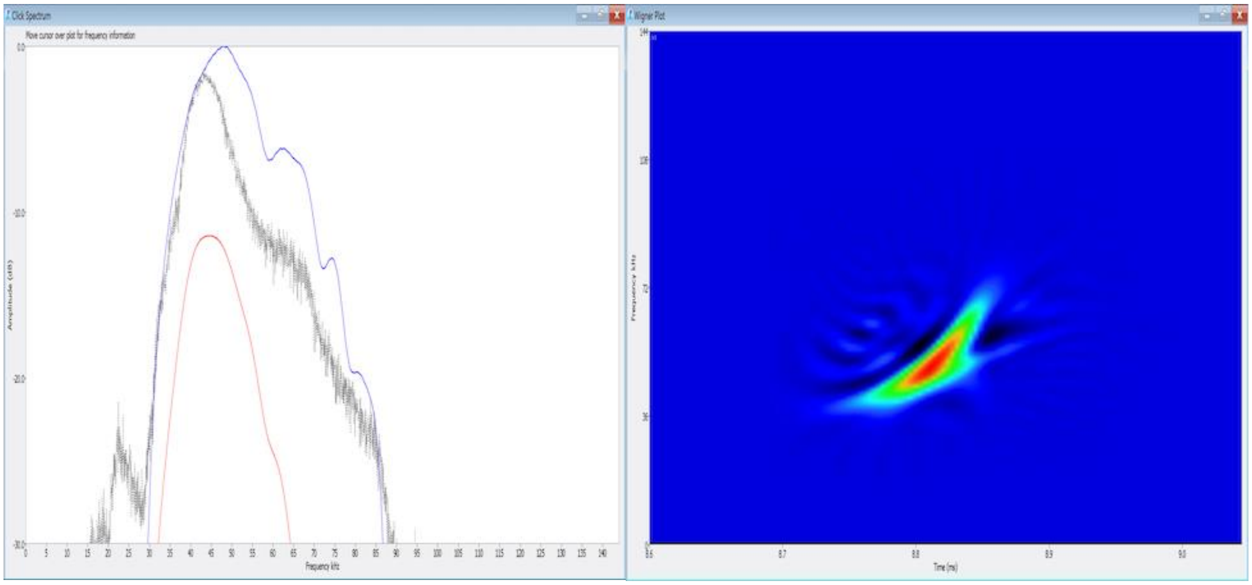
BB: *Berardius bairdii,* Baird's beaked whale. Low frequency click, often with multiple peaks. Upsweep is sometimes present, but pulses will look pretty flat on this scale. Peaks are expected at 15-16 kHz, 25-26 kHz, and, sometimes, 9 kHz and 35-45 kHz. Can produce dolphin-like clicks as well as these longer pulses. Clicks can come from above the hydrophone. IPI= 0. 20-0. 25 sec, PPS= 4-5.



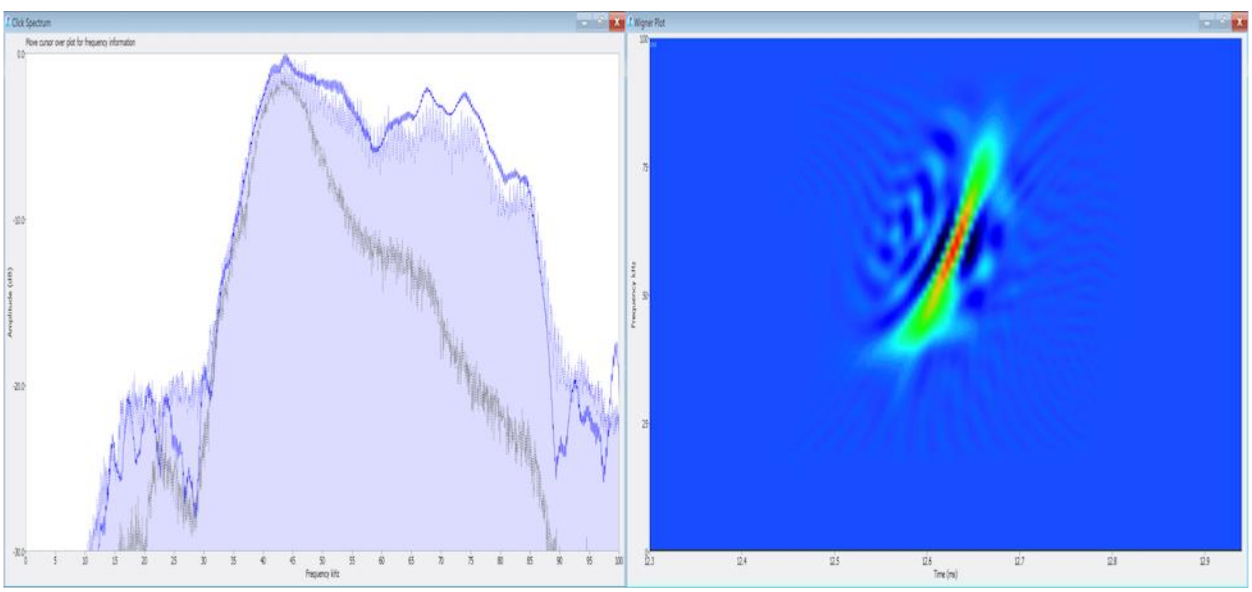


BW43: Possibly Perrin's beaked whale

BW43 (gray template)- Peak frequency at 43 kHz. Some higher peaks may be evident if the animal is close. The left limb declines less steeply than with BW46. Wigner is "crescent moon" shaped and lower limb, if present is strongly upswept. IPI= ~0. 22; PPS= 4-5.

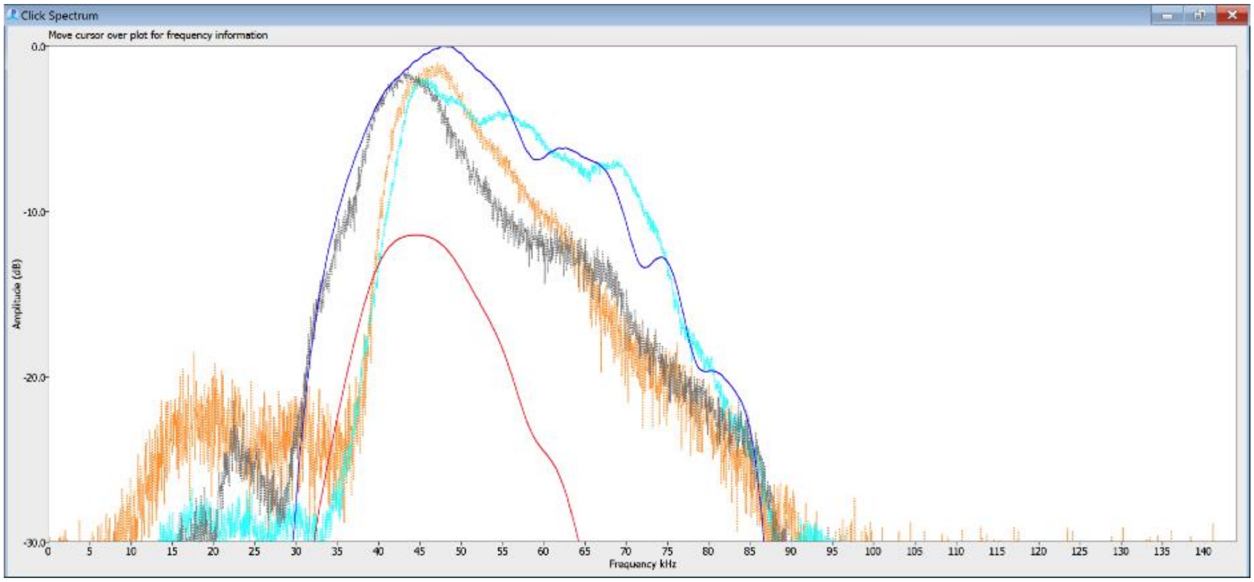


BW43 template (gray) and BW43 click from Baumann and Pickering (blue, pers. comm.). Peak and slope to the left of peak match well. Slope to the right of peak is much broader, perhaps reflecting proximity or hydrophone differences. Differences in Wigner plots are likely due to scaling differences.
[Source: SOCAL41N_DL29_110122_175230. x_0000. wav]

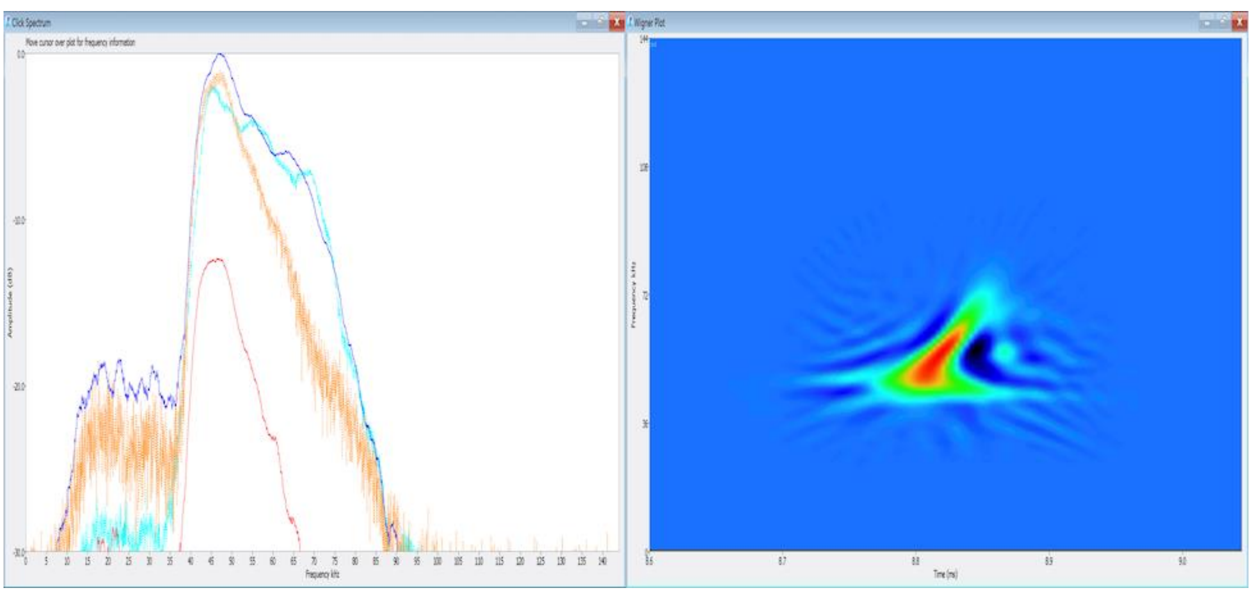


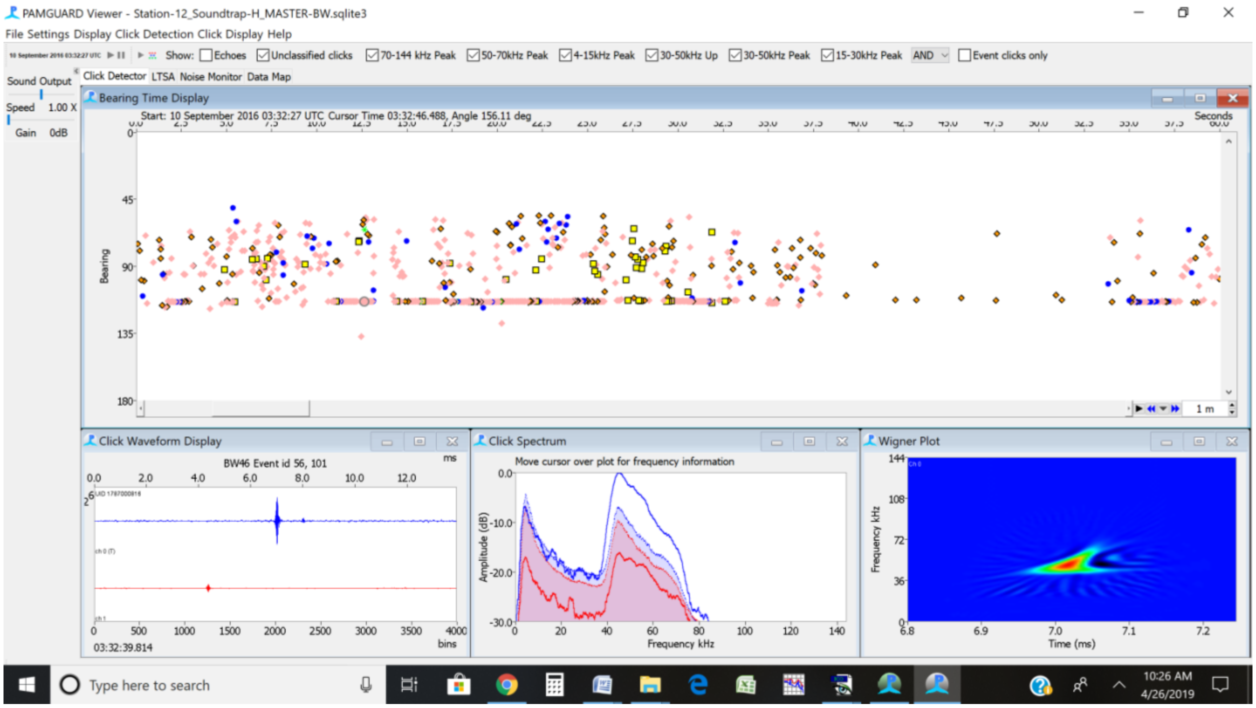
MS: *Mesoplodon stejnegeri,* Stejneger's beaked whale

Peak at about 46kHz (cyan and tan) shown on top of BW43 (gray). Notice how left slope in frequency spectrum declines more steeply than BW43, even when the peaks are similar (dark blue). The right slope is more variable for both types, but is less steep than the left slope. IPI= 0. 09; PPS= 10-11.



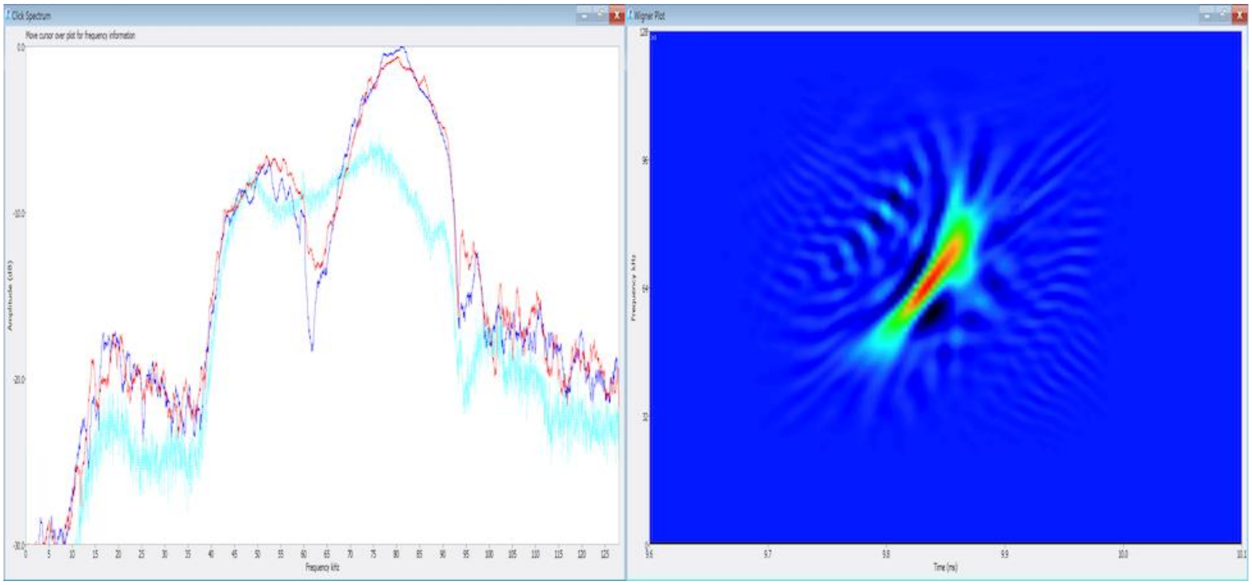
Frequency has very steeply declining slope to the left of peak. Right slope declines less steeply and may show higher peaks. Wigner shows "sorting cap". The lower branch of the Wigner (if present) is nearly horizontal. Peak varies between 44-48 kHz.



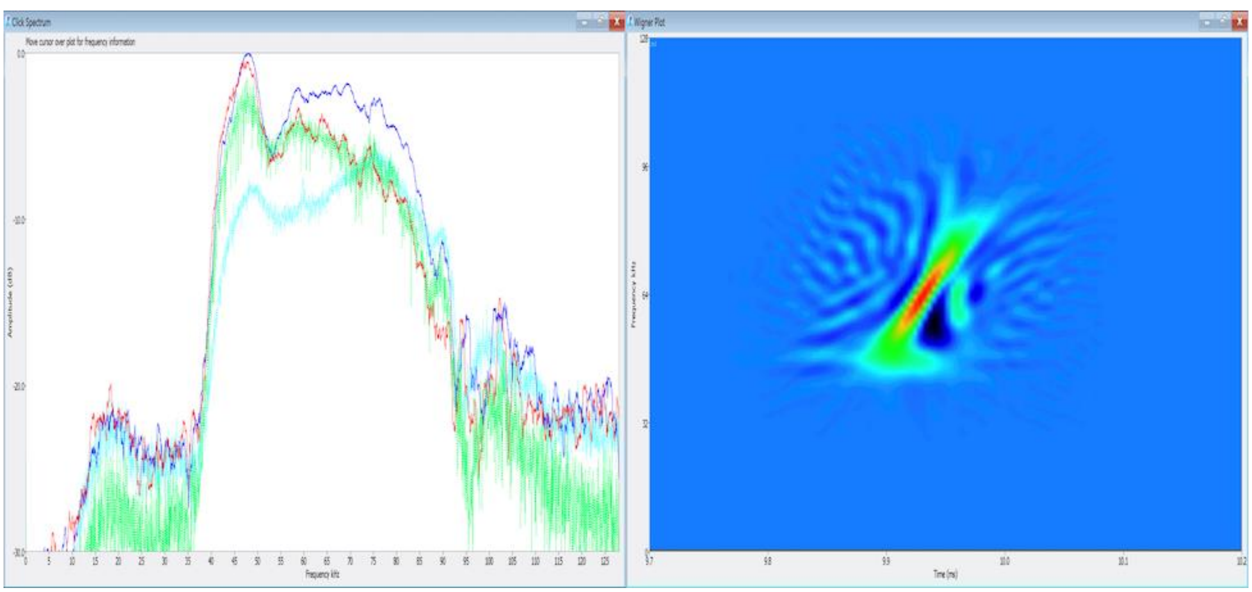


MS: Stejneger’s beaked whale (continued)

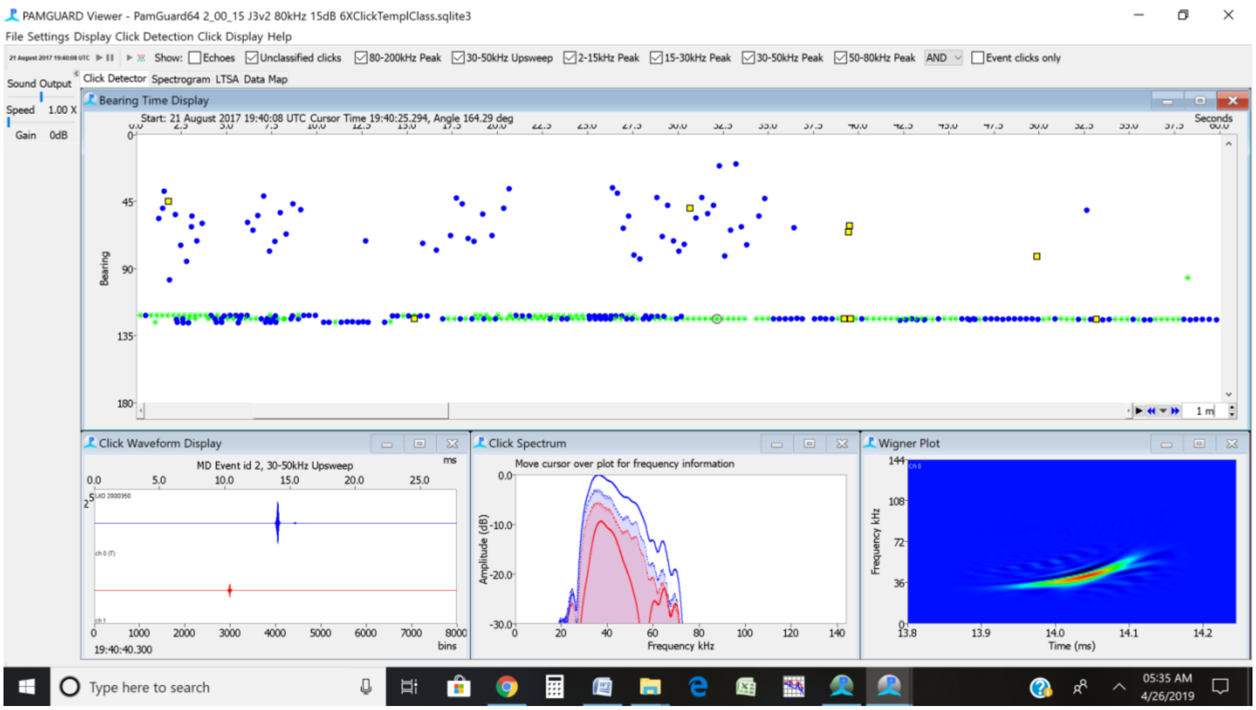
Some pulses show very strong higher peak at about 75 kHz in addition to a distinct lower peak at about 50 kHz. Some signals (presumable closer or more on-axis) show a strong peak at 80 kHz, a second peak at 52 kHz, and a strong null at about 62 kHz. These may appear in the same event as 44-48kHz pulses (see above). No evidence of “sorting hat” in Wigner.



Again two peaks (green, same group as above). In this case, the lower peak is loudest. Inconspicuous “sorting hat” look to wigner.

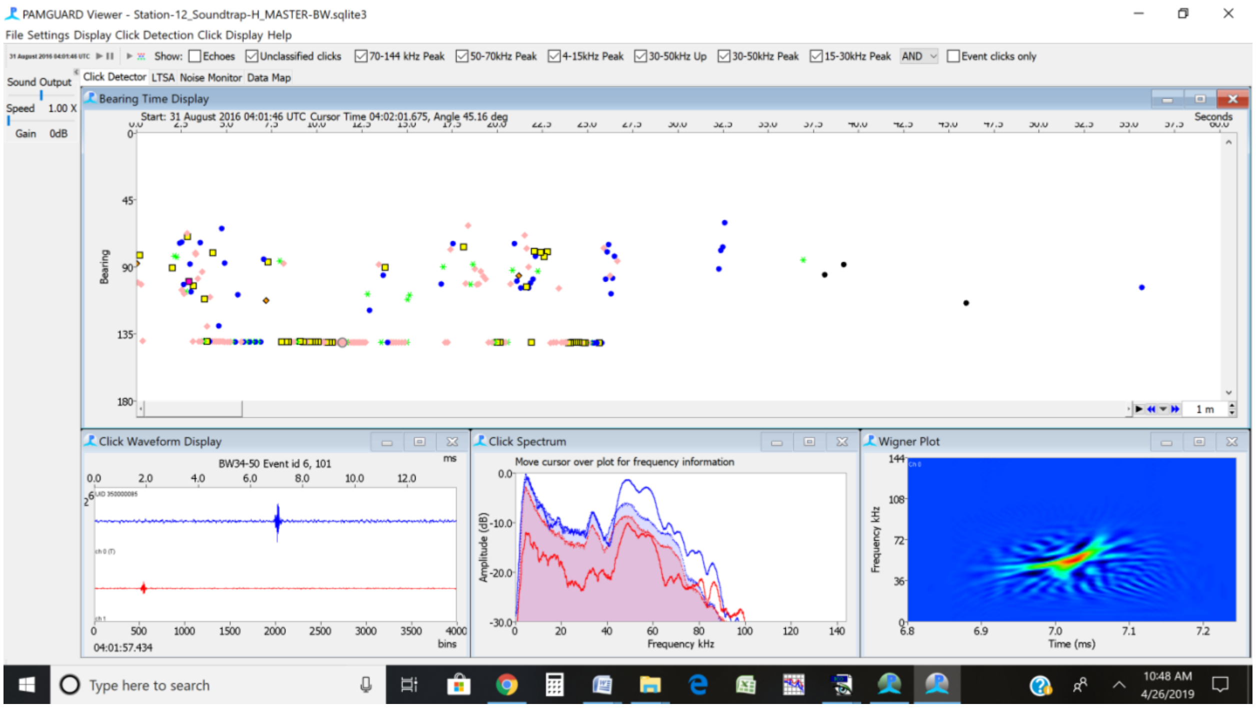


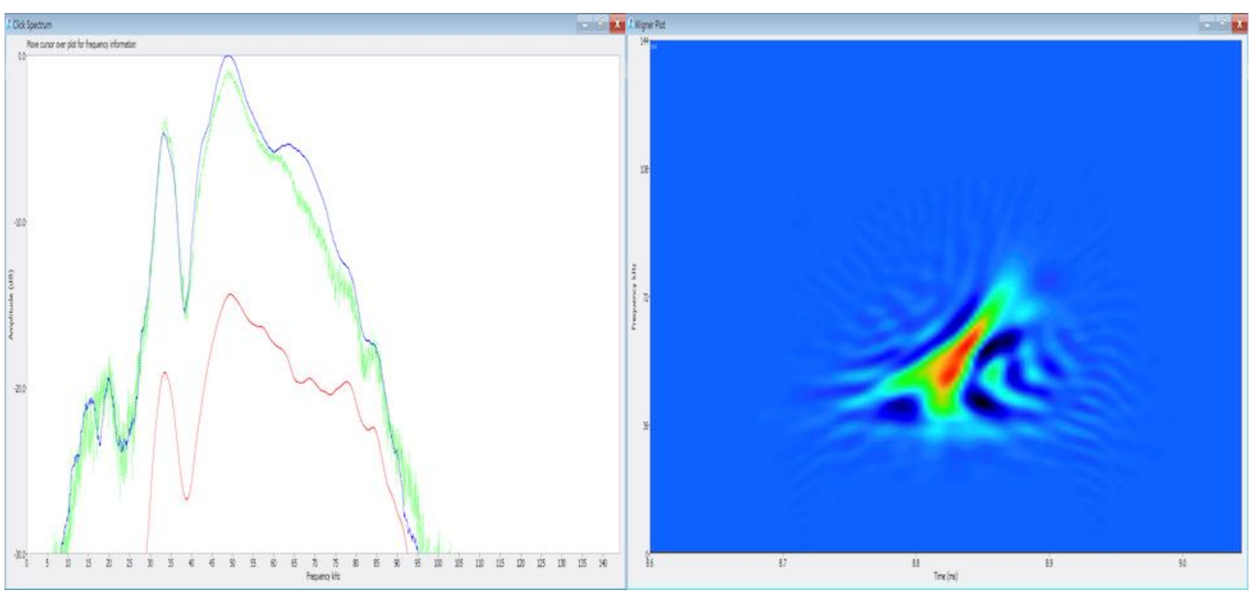
MD: *Mesoplodon densirostris*, Blainville's beaked whale. Peak frequency is ~36kHz (similar to Ziphius) but with a very steep decline in amplitudes at lower frequencies (left of the peak). This very clear one shows a secondary peak at 25 kHz, but that is 20dB below the peak and is not likely to be seen in a lower SNR signal. Wigner plot is slightly concave upward, with no sign of "kickstand". IPI= 0. 25-0. 33; PPS=3-4.



BW37V: Likely Hubb's beaked whale

BW37V template (green) shows two distinct peaks at about 34 kHz and 50 kHz, with a strong null (valley) at 37 kHz. IPI= 0. 125-0. 166; PPS= 6-8.

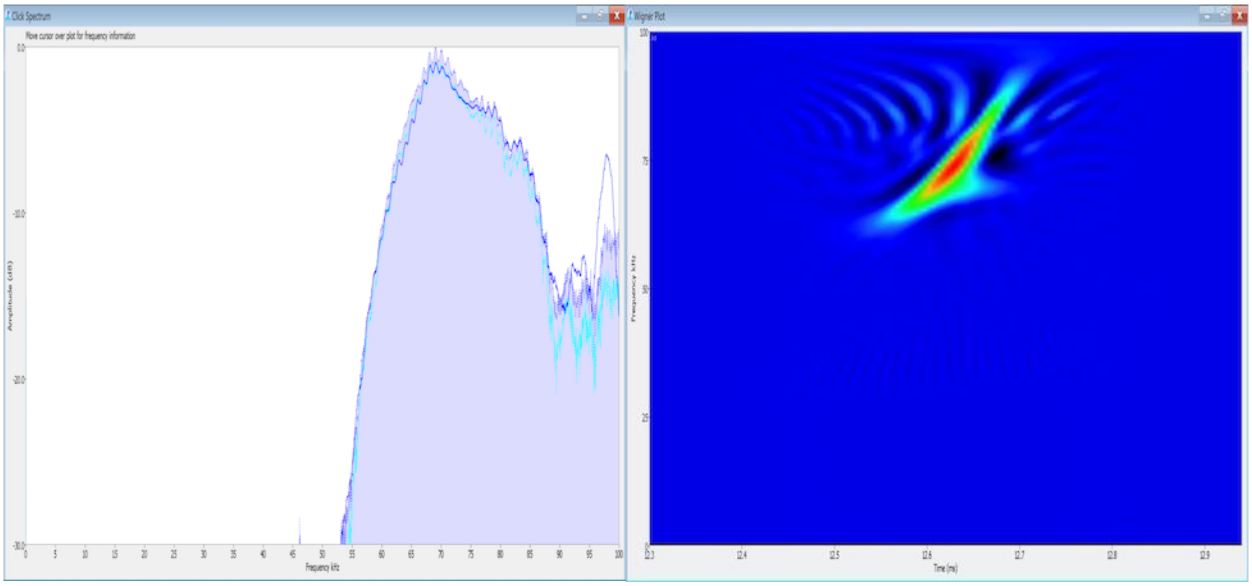




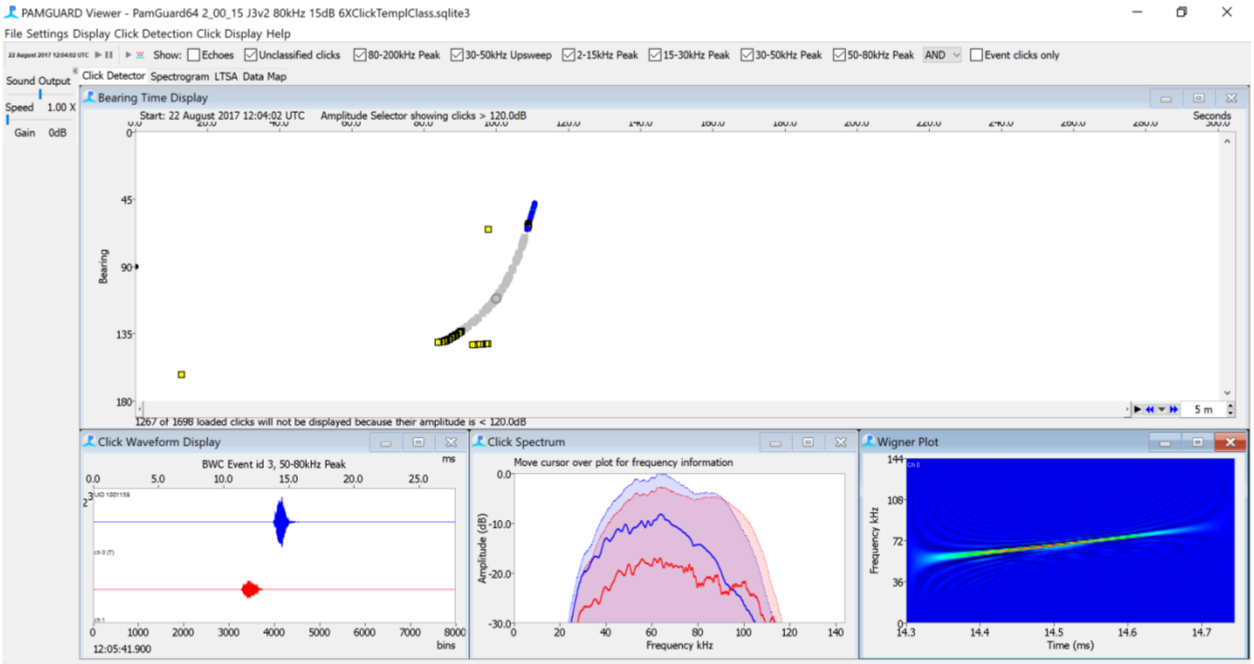
BW70: probably Pygmy beaked whale, *Mesoplodon peruvianus*

BW70 template (cyan) shows a peak at 70 kHz. Slope to the left of the peak is steeper than to the right. Upsweep in the Wigner plot. IPI= 0. 12; PPS= 8.

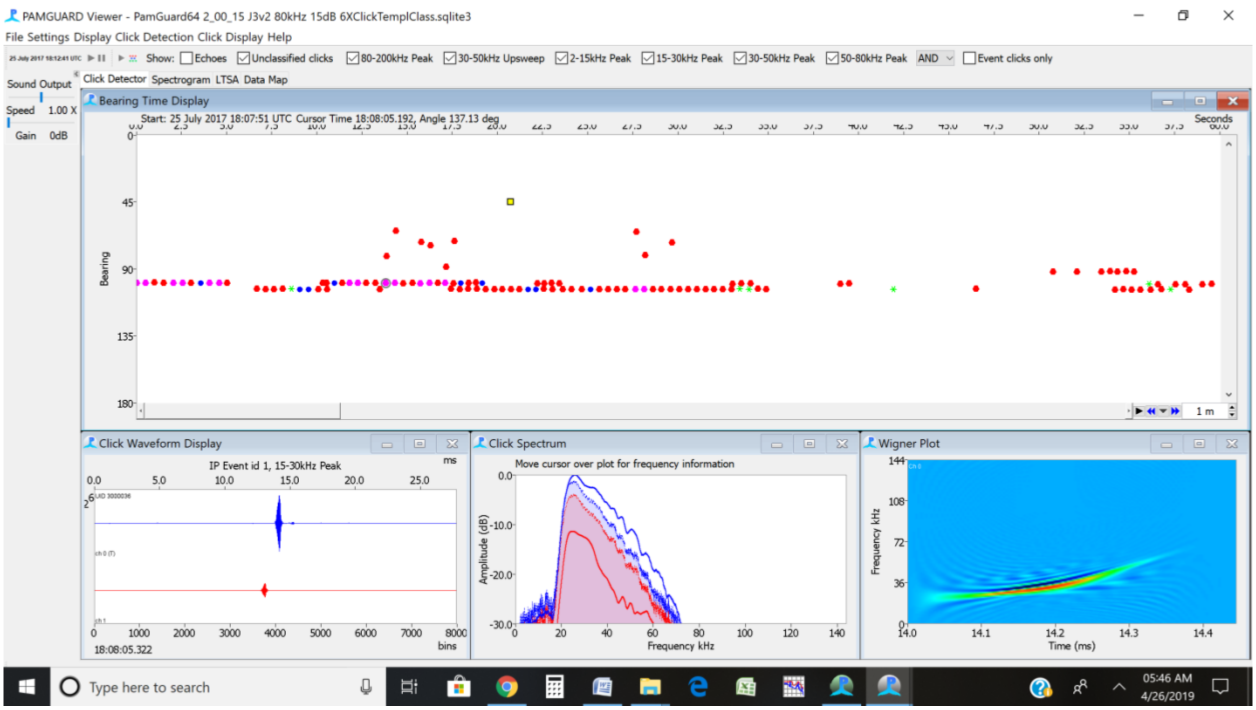
[Source is SIO, Baumann & Pickering pers. comm., GofCA4A4_051217_234230. x_1114. wav]



BWC- Cross Seamount beaked whale. Very long click with very long frequency sweep and a peak frequency of about 60-65 kHz. Signals may come from above the hydrophones. IPI= 0.127; PPS= 8.

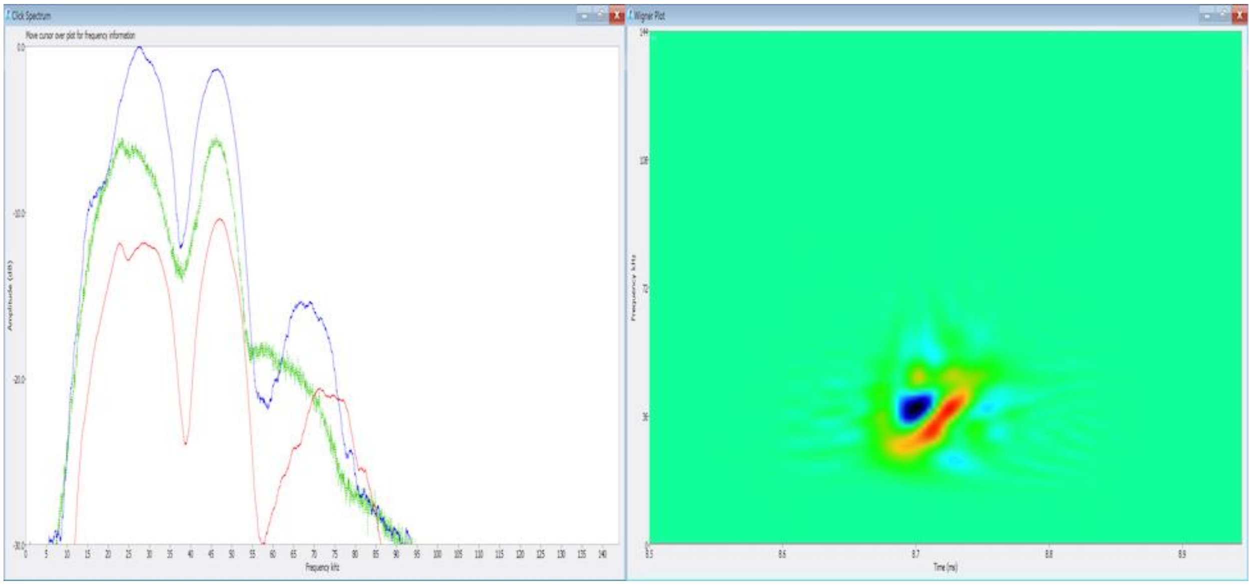


IP: *Indopacetus pacificus*, Longman's beaked whale. Pulses are low-frequency, with peak at ~26 kHz. IPI= 0. 27-0. 40s; PPS= 3-4.

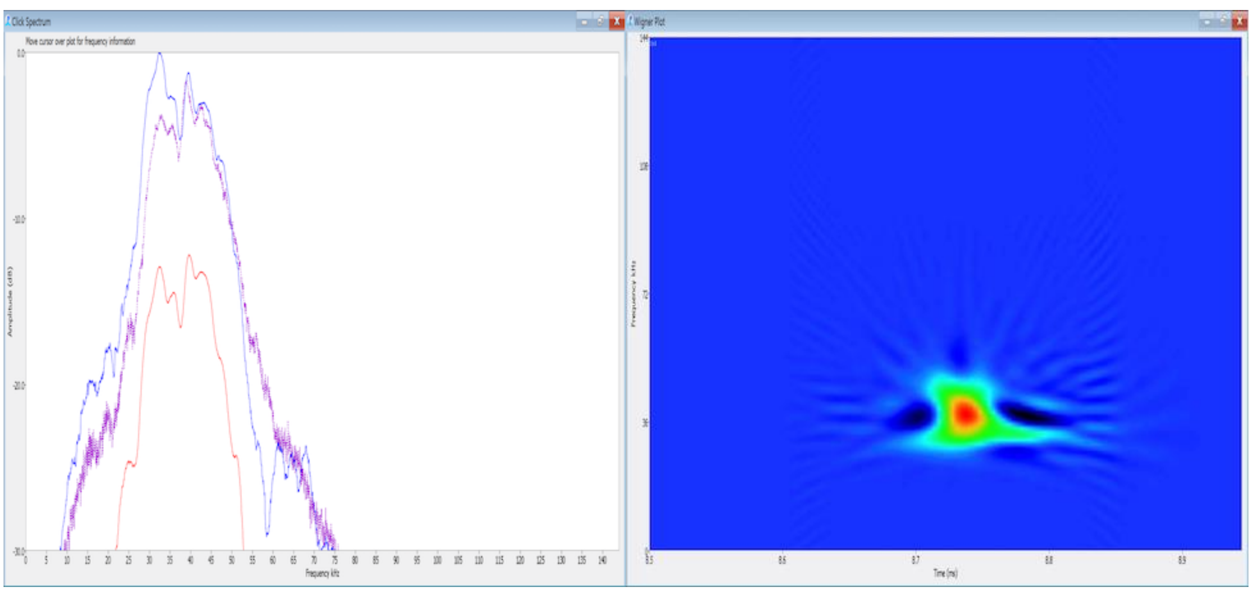


Miscellaneous other signals that looked like beaked whales

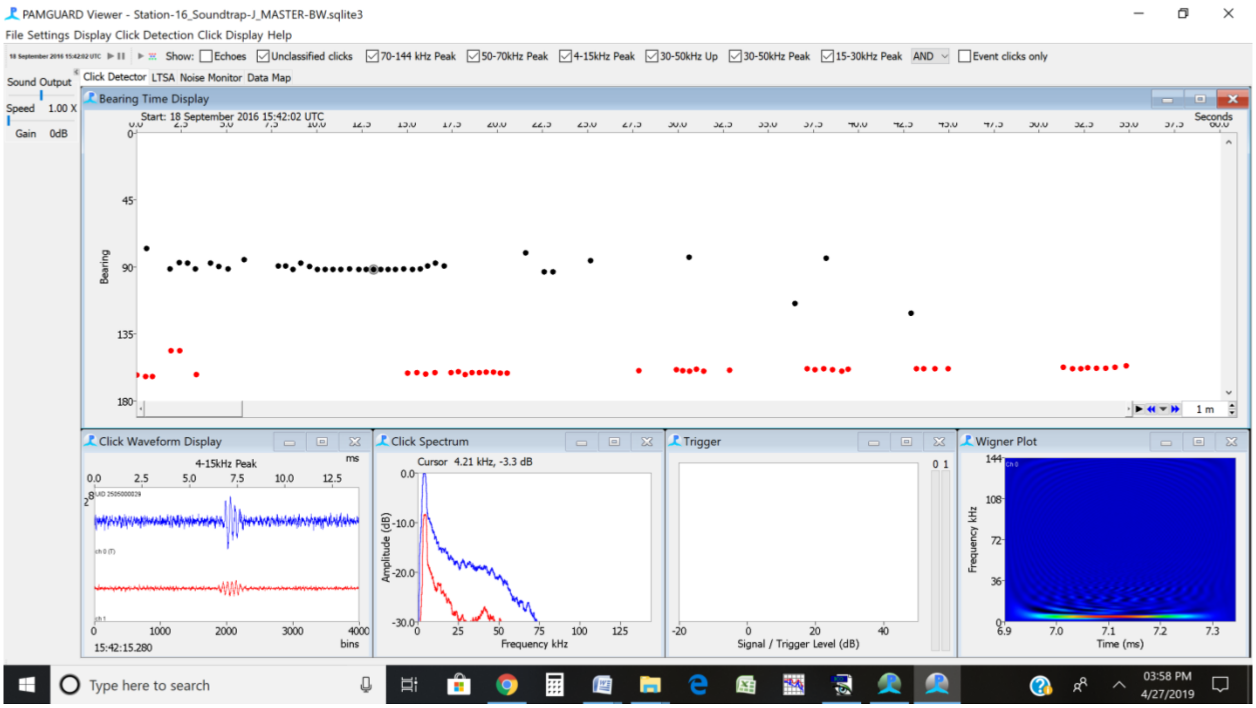
BW26-47 template (dark green). Was above hydrophone. May be alternate part of the beam pattern of a BW46. Wigners were variable and odd looking. Some were almost circular. Need to look for others.



BW38 template (lavender). Maybe M. densirostris, but no evidence of an upsweep and signal was relatively short.



PM: *Physeter macrocephalus*, sperm whale. Low-frequency click, typically < 12 kHz peak. IPI= 0. 4-1. 0, PPS=1-2.



Appendix C: Habitat-based Density Estimates for Cetaceans in the California Current Ecosystem Based on 1991–2018 Survey Data

(Becker et al. 2020, NOAA Technical Memorandum NMFS-SWFSC-638)

This appendix presents the spatial density modeling (SDM) analysis based on visual line transect data collected from all California Current surveys conducted from 1991 through CCES 2018. Outputs include density surface maps for all modeled cetacean species and population size estimates for the survey area.

Habitat-based density estimates for cetaceans in the California Current Ecosystem based on 1991–2018 survey data

Elizabeth A. Becker, Karin A. Forney, David L. Miller, Paul C. Fiedler, Jay Barlow, and Jeff E. Moore

U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
National Marine Fisheries Service
Southwest Fisheries Science Center

NOAA Technical Memorandum NMFS-SWFSC-638

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NOAA Technical Memorandum NMFS

DECEMBER 2020

HABITAT-BASED DENSITY ESTIMATES FOR CETACEANS IN THE CALIFORNIA CURRENT ECOSYSTEM BASED ON 1991-2018 SURVEY DATA

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Introduction

The 2018 California Current Ecosystem Survey (CCES) was conducted between 26 June and 4 December 2018 as a joint project of the Marine Mammal and Turtle Division (MMTD) and the Fisheries Resources Division (FRD) of NOAA's Southwest Fisheries Science Center (SWFSC). One of the primary objectives of this line-transect survey was to collect marine mammal sighting data to support the derivation of cetacean density estimates for the California Current Ecosystem (CCE) study area. Given the heterogeneity of the 2018 survey coverage in the CCE study area (Henry et al. 2020), density estimation required model-based (rather than design-based) analytical approaches for updating population size estimates for US West Coast marine mammal stocks. This report summarizes the results of the cetacean habitat modeling effort.

Habitat models, or species distribution models (SDMs), have been recognized as valuable tools for estimating the density and distribution of cetaceans and assessing potential impacts from a wide range of anthropogenic activities (e.g., Abrahms et al. 2019; Gilles et al. 2011; Goetz et al. 2012; Hammond et al. 2013; Redfern et al. 2013). SDMs for cetaceans have been developed for US West Coast waters from systematic ship survey data collected by SWFSC since 1991 (Barlow et al. 2009; Becker et al. 2010, 2014, 2016, 2018, 2020; Forney 2000; Forney et al. 2012). The most recent models provide spatially-explicit density predictions at a 0.1˚ (approximately 10km x 10km) grid resolution (Becker et al. 2020), and multi-year average density surfaces have been used by the US Navy to assess potential impacts on cetaceans as required by US regulations such as the Marine Mammal Protection Act and Endangered Species Act (U.S. Department of the Navy 2013, 2015, 2017).

The overall goal of this study was to include the 2018 survey data in the previous 1991–2014 modeling dataset in order to improve SMDs for the CCE study area. Specific objectives included:

- Generating multi-year average density surfaces for the Navy and others to use in their long-term (2–7 year) environmental planning efforts; and
- Providing updated abundance and "minimum population size (Nmin)" estimates as defined in the Guidelines for Assessing Marine Mammal Stocks (National Oceanic and Atmospheric Administration 2016).

To develop improved SDMs and to update US West Coast cetacean stock abundance estimates, sighting data from CCES 2018 were combined with previous line-transect survey data collected within the CCE to create a robust modeling database spanning more than 25 years (1991–2018). Habitat models were developed based on previously established methods that allow for the incorporation of segment-specific estimates of detection probability and included dynamic covariates from an ocean model calibrated to the CCE study area (Becker et al. 2016). In addition, recently-developed techniques for deriving more comprehensive estimates of uncertainty in SDM predictions (Miller et al. *In Prep.*) were used to provide variance estimates for the model-based abundance estimates. SDMs were developed for long-beaked common dolphin (*Delphinus delphis bairdii*), short-beaked common dolphin (*Delphinus delphis delphis*), Risso's dolphin (*Grampus griseus*), Pacific white-sided dolphin (*Lagenorhynchus obliquidens*), northern right whale dolphin (*Lissodelphis borealis*), striped dolphin (*Stenella coeruleoalba*), common bottlenose dolphin (*Tursiops truncatus*), Dall's porpoise (*Phocoenoides dalli*), sperm whale (*Physeter macrocephalus*), blue whale (*Balaenoptera musculus*), fin whale (*B. physalus*), humpback whale (*Megaptera novaeangliae*), Baird's beaked whale (*Berardius bairdii*), and a "small beaked whale guild" that included Mesoplodonts (*Mesoplodon* spp.) and Cuvier's beaked whale (*Ziphius cavirostris*). Sample sizes were also sufficient to develop the first model-based density estimates for minke whale (*B. acutorostrata*) in this study area.

The habitat-based models of cetacean density developed in this study represent an improvement over the previous models described by Becker et al. (2020) because they included additional sighting data over the continental shelf and slope that were surveyed more sparsely in previous years, providing better representation of these important habitat regions. In addition, the model-based abundance estimates more accurately account for uncertainty than prior iterations owing to methodological improvements.

Methods

Survey data

Cetacean sighting data used to build the SDMs were collected within waters of the CCE from 1991–2018 (Table 1) using line-transect methods (Buckland et al. 2001). The 1991–1993 surveys covered waters off the state of California while the 1996–2008 and 2014 surveys covered waters off the entire west coast of the United States, with all surveys extending approximately 300 nautical miles offshore (Barlow and Forney 2007). The 2009 survey was a finer-scale survey that focused on waters off central and southern California, as well as the west coast of Baja California (Carretta et al. 2011). The 2018 survey covered waters along the west coasts of southern Canada (Vancouver Island), the west coast of the United States, and Baja California out to a distance of approximately 200 nautical miles offshore (Henry et al. 2020). When combined across years, the surveys provided comprehensive coverage of waters throughout the CCE study area, although the spatial heterogeneity of the 2018 survey is clearly apparent (Figure 1). Only on-effort data collected in Beaufort sea state conditions ≤5 within the study area were used in model development.

The survey protocols were the same for all years (see Barlow 2006; Kinzey et al. 2000) and are briefly summarized here. Each survey used a NOAA research vessel and a team of six experienced visual observers. For each rotation, three observers stationed on the flying bridge of the ship visually searched for and recorded cetacean sightings between 0 and 90 degree to port and starboard using standard line-transect protocols. Port and starboard observers searched with pedestal-mounted 25 × 150 binoculars and a center-stationed third observer searched by eye or with handheld 7 × 50 binoculars. When cetaceans were detected within 3 nautical miles (5.6 km) of the trackline, the sighting was recorded (along with distance and direction from the vessel, from which perpendicular sighting distance was calculated), and the ship would then typically divert from the transect line and go “off-effort” to approach the animals and enable more accurate estimation of group size and species identification. All observers independently provided best, high, and low group size estimates. If the sighting included more than one species, the observers also estimated the percentage of each species in the group. The best estimate from each observer or the best estimate multiplied by the percentage of each species was averaged (i.e., arithmetic mean) to obtain a single group size estimate for each sighting.

Systematic survey effort was conducted along predetermined tracklines at a target survey speed of 18.5 km/hr. During transit between tracklines, transits to or from port, or deviations from pre-determined tracklines for other purposes, the visual observers generally maintained standard data collection protocols. Although such non-systematic effort is generally not used to derive encounter rate for design-based density estimates, it is incorporated into the SDMs as the uneven distribution of effort can be accounted for within the statistical framework (Hedley and Buckland 2004).

Environmental predictor data

To create samples for modeling, continuous portions of on-effort survey tracklines were divided into approximate 5-km segments using methods described by Becker et al. (2010). The total number of species-specific sightings and associated average group size estimates were assigned to each segment and habitat covariates were derived based on the segment’s geographical midpoint. To maintain consistency with the species-specific effective-strip-width estimates derived for this study based on methods described in Barlow et al. (2011a) and used to estimate cetacean densities, sighting data were truncated at a distance of 5.5 km perpendicular to the trackline for the delphinids and large whales, 4.0 km for small whales (Mesoplodonts, minke whale, and Cuvier's beaked whale), and at 3.0 km for Dall's porpoise (Buckland et al. 2001).

Environmental variables from a data-assimilative CCE implementation of the Regional Ocean Modeling System (ROMS), produced by the University of California Santa Cruz Ocean Modeling and Data Assimilation group (Moore et al. 2011), were used as dynamic predictors as they have proven effective in similar SDMs for this study area (Becker et al. 2016, 2018, 2020). Daily averages for each variable at the 0.1 degree (~10 km) horizontal resolution of the ROMS output were used in the models. The suite of potential dynamic predictors included sea surface temperature (SST) and its standard deviation (sd(SST)), calculated for a 3 × 3-pixel box around the modeling segment midpoint, mixed layer depth (MLD, defined by a 0.5˚C deviation from the SST), sea surface height (SSH), and sd(SSH). Water depth (m) was also included as a potential predictor, derived from the ETOPO1 1-arc-min global relief model (Amante and Eakins 2009) and obtained for the midpoint of each transect segment. In addition, distance to the 200-m isobath derived from the geomorphic feature map of the global ocean (Harris et al. 2014) was included in model selection as it represents the edge of the shelf break for much of the U.S. west coast and can be a distinguishing habitat feature for many cetacean species (Becker et al. 2010; Fiedler et al. 1998, 2018). In addition, for those species known to primarily inhabit offshore waters (beaked whales, sperm whale, striped dolphin), distance to the 2,000-m isobath was also included in the list of potential predictor variables, as this depth roughly represents the transition from the continental slope to the continental rise. To differentiate continental shelf, slope, and rise waters, negative values of the distance to isobath terms were used for waters shallower than the 200m or 2,000m isobath. Although the modeling framework applied in our analysis (*mgcv*; see 'Habitat Models' section below) is robust to correlated variables (Wood 2008), distance to the two isobath terms and depth (absolute correlation = 0.75–0.85) were considered separately in the models to avoid any confounding effects.

A spatial term (bivariate spline of longitude and latitude) was also included in the suite of potential predictors because SDMs that explicitly account for geographic effects have exhibited improved explanatory performance as they often account for unmeasured static variables that might be important for driving species distributions (Becker et al. 2018; Cañadas and Hammond 2008; Forney et al. 2015; Hedley and Buckland 2004; Tynan et al. 2005; Williams et al. 2006). The inclusion of a spatial term can result in more robust models but invalidates predictions outside the study area.

A continuous year term was also included as a potential predictor in the models to capture population trends both for species whose abundance has changed substantially during the time period considered in our analyses, and for species for which distribution shifts have resulted in abundance changes over time. For example, increases in population have been documented for both fin whale (Moore and Barlow 2011) and humpback whale (Barlow et al. 2011b), while notable shifts in distribution over the last few decades have resulted in a decline in the number of blue whales (Monnahan et al. 2015), and an increase in the number of short-beaked common dolphins (Barlow 2016; Becker et al. 2018) in the CCE study area. The degrees of freedom for the year term were constrained (i.e., < the maximum of 8 available) in order to capture linear or thresholds in the response curves rather than simply tracking the variable encounter rates over the survey periods. In addition, since environmental covariates are often correlated with time, and year can serve as a proxy for unmeasured habitat variables, the functional forms of all the other dynamic variables were inspected during the modeling process to ensure they remained stable with the addition of the year term.

Correction factors

During CCES 2018, operational requirements necessitated that some of the effort be conducted in passing mode (i.e., when a cetacean/cetacean group is sighted the ship continues on course and is not diverted to the vicinity of the sighting for species identification or group size enumeration). This led to a high proportion of recorded "unidentified large whale" and "*Delphinus* spp." sightings, when observers could not confirm which species of large whale or common dolphin subspecies was present, respectively. Omitting these sightings from the modeling dataset would have resulted in an underestimation of animal density for blue, fin, and humpback whales, as well as both long-and short-beaked common dolphins. To reduce this potential downward bias, species-specific correction factors were applied to account for unidentified animals, using the methods described in Becker et al. (2017) and summarized below.

For both the large whale and common dolphin groups, the correction factor *c* was estimated from the 2018 sighting data according to the simplified formula:

$$c = 1 + \frac{t_{unid}}{t_{tgt} + t_{oth}} \tag{1}$$

where t_{tgt} is the number of individuals identified as the target species, t_{oth} is the number of individuals identified as other species within the broader species group, and t_{unid} is the number of unidentified individuals in that species group. Due to the potential effect of Beaufort sea state on detectability (Barlow et al. 2001, 2011a; Barlow 2015), the correction factors were evaluated to determine if they varied by sea state. If so, separate correction factors were developed by sea state; otherwise a single correction factor was applied. The correction factors were applied to the numbers of animals estimated per segment in the SDMs for the common dolphin and large whale species (see equation 2 below).

The protocol for estimating sperm whale group size changed over the course of the 1991–2018 survey period, with less effort spent estimating group size during the three surveys conducted in the 1990's. Group size estimates for larger sperm whale groups (> 2 animals) are now known to have been underestimated in the earlier surveys, and a correction factor has been estimated to account for this bias (Moore and Barlow 2014). Prior to modeling, this correction factor (2.3x) was applied to the average group size estimates for observed sperm whale group sizes > 2 for the 1991–1996 surveys. No group size corrections were applied to the other species.

Habitat models

Generalized Additive Models (GAM; Wood 2017) were developed in R (v. 3.4.1; R Core Team, 2017) using the package "*mgcv*" (v. 1.8-31; Wood 2011). Methods largely followed those described in Becker et al. (2016) and are summarized here. One of two modeling frameworks was used for each species, depending on its group size characteristics. For the two *Delphinus* species that have very large and variable group sizes (e.g., 1 to 2,000 animals per sighting), separate encounter rate and group size models were developed. Encounter rate models were built using all transect segments, regardless of whether they included sightings, using the number of sightings per segment as the response variable and a Tweedie distribution to account for overdispersion (Miller et al. 2013). Group size models were built using only those segments that included sightings, using the natural log of group size as the response variable, and a Gaussian link function. For the rest of the species, GAMs were fit using the number of individuals of the given species per transect segment as the response variable using all transect segments, and a Tweedie distribution to account for overdispersion. The full suite of potential habitat predictors was offered to both the encounter rate and single response GAMs. A tensor product smooth of latitude and longitude (Wood 2003) was the only predictor variable included in the *Delphinus* group size models.

In all models, restricted maximum likelihood (REML) was used to obtain parameter estimates (Marra and Wood 2011). The shrinkage approach of Marra and Wood (2011) was used to potentially remove terms from each model by modifying the smoothing penalty, allowing the smooth effect to be shrunk to zero. Additionally, to avoid overfitting, an iterative forwards/backwards selection process was used to remove variables that had P-values > 0.05 (Redfern et al. 2017; Roberts et al. 2016). The natural log of the effective area searched (described below) was included as an offset in both the single response and encounter rate models.

Predictions from the final model were incorporated into the standard line-transect equation (Buckland et al. 2001) to estimate density (*D*; number of animals per km^2):

$$D_i = \frac{n_i \cdot s_i \cdot c_i}{A_i} \tag{2}$$

where *i* is the segment, *n* is the number of sightings on segment *i*, *s* is the average group size (i.e., number of a given species present in a group) on segment *i*, *c* is the species-specific correction factor for unidentified common dolphins or large whales (derived in equation 1 and assumed to be 1 for all other species) based on sea state conditions on segment *i*, and *A* is the effective area searched for segment *i*:

$$A_i = 2 \cdot L_i \cdot ESW_i \cdot g(0)_i \tag{3}$$

where L_i is the length of the effort segment *i*, ESW_i is the effective strip half-width, and $g(0)_i$ is the probability of detection on the transect line. Following the methods of Becker et al. (2016), species-specific and segment-specific estimates of both *ESW* and *g(0)* were incorporated into the models based on the recorded detection conditions on that segment and using coefficients estimated specifically for the CCE dataset based on methods of Barlow et al. (2011a) for *ESW* and Barlow (2015) for *g(0)*. For those segments where the average Beaufort sea state was 0 (< 1% of the segments), *g(0)* was assumed to be 1, i.e., that all animals directly on the transect line were detected, for all species except Cuvier's beaked whale (*g(0)* = 0.584) and Mesoplodon *spp*. (*g(0)* = 0.813), which were <1 based on dive behavior (Barlow 2015).

In equation (3) above, the effective area searched is multiplied by two to account for observers searching on both sides of the transect line. During the 2018 survey, coastal fog and other conditions occasionally prohibited visual observations on one side of the ship, so that cetacean sighting data were collected on only one side of the transect line. These portions of reduced effort were systematically recorded in the dataset and the effective area searched was reduced accordingly along these segments, i.e., the constant was changed to a "1" in equation (3) above.

Model performance was evaluated using established metrics, including the percentage of explained deviance, the area under the receiver operating characteristic curve (AUC; Fawcett 2006), the true skill statistic (TSS; Allouche et al. 2006), and visual inspection of predicted and observed distributions during the 1991–2018 cetacean surveys (Barlow et al. 2009; Becker et al. 2010, 2016; Forney et al. 2012). AUC measures the accuracy of predicting observed presences and absences; values range from 0 to 1, where a score > 0.5 indicates better than random skill. TSS accounts for both false negative and false positive errors and ranges from -1 to +1, where +1 indicates perfect agreement and values of zero or less indicate a performance no better than random. To calculate TSS, the sensitivity-specificity sum maximization approach (Liu et al. 2005) was used to obtain thresholds for species presence. In addition, the model-based abundance estimates for the CCE study area based on the sum of individual modeling segment predictions were compared to standard line-transect estimates derived from the same dataset used for modeling in order to assess potential bias in the habitat-based model predictions. The standard line-transect estimates were derived from the 1991–2018 survey data using equations (2) and (3) above, but without the inclusion of habitat predictors (i.e., observed rather than predicted densities).

Spatially-explicit density values for the CCE study area were derived from model predictions on the environmental conditions specific to the 1991–2018 CCE effort periods at a 0.1˚ (approximately 10km x 10km) grid resolution. Model predictions were made on separate environmental conditions for each day encompassing the survey periods, thus taking into account the varying oceanographic conditions during the 1991–2018 cetacean surveys. The separate daily predictions thus provide a dataset from which averages can be derived for any temporal period of interest. In past years, the Navy has used a "multi-year average" of predicted daily cetacean species densities to assess potential impacts on cetaceans as required by U.S. regulations such as the MMPA and ESA (U.S. Department of the Navy 2015, 2017). To ensure that the multi-year average reflects more recent conditions and is based on those survey years that more comprehensively covered the study area, predictions for 1991, 1993, and 2009 were not included in the multi-year average. Further, for the two species with documented population increases in the study area (i.e., fin and humpback whales), the year covariate was set to 2018 to decrease the potential for biased-low density estimates derived from the multi-year average surfaces. The daily predictions were also used to create individual yearly averages for 1996–2018. The prediction grid was clipped to the boundaries of the approximate 1,141,800-km^2 study area to ensure that predictions were not extrapolated outside the region used for model development.

The model-based abundance estimates were calculated as the sum of the individual grid cell abundance estimates, which were derived by multiplying the cell area (in km^2) by the predicted grid cell density, exclusive of any portions of the cells located outside the CCE study area or on land. Area calculations were completed using the R packages *geosphere* and *gpclib* in R (version 2.15.0).

In highly dynamic ecosystems such as the California Current, variation in environmental conditions has been shown to be one of the greatest sources of uncertainty when predicting density as a function of habitat variables, and this source has been used to provide spatially-explicit variance measures for past CCE SDM model predictions (Barlow et al. 2009; Becker et al. 2016, 2018, 2020; Forney et al. 2012). Recently, Miller et al. (*In Prep.*) developed techniques for deriving more comprehensive measures of uncertainty in GAM predictions that, in addition to environmental variability, also account for the uncertainty from the GAM parameters, *ESW*, and *g(0)*. These techniques include generating multiple daily density surfaces taking into account model parameter uncertainty and providing a range of density estimates from which variance can be calculated.

Preliminary analyses in our study, however, revealed that the simulated model parameter draws can – for some species – result in a subset of unrealistic simulated surfaces (i.e., surfaces that infer high densities of a species in habitats where the species is not generally found), so this method was not yet deemed suitable for estimating spatially explicit uncertainty estimates for the pixel-based densities. The method did, however, confirm that environmental variability contributes the most substantial source of uncertainty in the CCE model predictions. Therefore, the methods of Becker et al. (2016, 2018) were applied to estimate spatially-explicit measures of uncertainty based on environmental variability, calculated as pixel-specific standard errors using the set of daily predictions that went into the multi-year average density estimates. The pixel-based variance estimates are thus under-estimated to some degree, but the dominant source of uncertainty (environmental variability) was accounted for.

The methods described in Miller et al. (*In Prep.*) were found to be suitable for estimating uncertainty in the overall model-based abundances for the entire CCE study area, and thus were used to derive variance estimates that included the combined uncertainty from environmental variability, the GAM parameters, and *ESW*. Study area variance was estimated based on the average values of each of the 200 simulations within each year, thereby providing an overall measure of uncertainty associated with the individual yearly average density surfaces for 1996–2018. One additional source of uncertainty in abundance estimates is introduced by *g(0)*, the probability of detecting animals directly on the trackline. The estimates of *g(0)* developed by Barlow (2015) are based on segment-specific Beaufort sea state conditions, but they were not compatible with the Miller et al. (*In Prep*.) methods of incorporating *g(0)*; therefore, this source of uncertainty was handled separately. An overall estimate of uncertainty in *g(0)* was derived using the variance estimates for this parameter weighted by the proportion of survey effort conducted within each of the Beaufort sea state categories and estimated based on 10,000 bootstrap values. Barlow (2015) did not provide *g(0)* estimates for northern right whale dolphin, and the result for Pacific white-sided dolphin was considered an outlier (Barlow 2015), so for both species the *g(0)* estimates for *Delphinus* spp. were used. *Delphinus* spp. was considered a suitable surrogate for Pacific white-sided dolphin since they have similar sighting characteristics. In addition, the *Delphinus* spp. *g(0)* values were similar to the average of all the delphinids and were thus selected as a surrogate for northern right whale dolphin as well. The weighted *g(0)* uncertainty was combined into the study area variance estimates using the delta method (Seber 1982).

For purposes of calculating Potential Biological Removal (PBR) of US West Coast cetacean stocks, the pooled average of the 2014 and 2018 model-predicted study area abundance estimates and associated variance estimates, as well as minimum abundance estimates, were also calculated (National Oceanic and Atmospheric Administration 2016). Abundance estimates were based on the arithmetic mean of the model-predicted estimates for 2014 and 2018. Study area variance was estimated based on the methods described above for individual years but including data specific to 2014 and 2018.

Results

Habitat-based density models were developed for 14 species and one guild (Mesoplodonts and Cuvier's beaked whale) using 92,214 km of on-effort survey data collected between 1991 and 2018 within the CCE study area. The number of sightings within the species-specific truncation distances and available for modeling ranged from 39 to 1,034 (Table 2).

Correction factors for unidentified large whales were applied separately by Beaufort sea state for the 2018 blue, fin, and humpback whale sightings, because the proportion of unidentified whales increased with increasing sea state. For blue and humpback whales, these correction factors were 1.03, 1.04, 1.05, 1.20, and 1.26 for Beaufort sea states 0-1, 2, 3, 4, and 5, respectively, and 1.04, 1.08, 1.10, 1.30, and 1.46 for fin whales. For the common dolphin group, higher multipliers were not associated with higher sea states, so a uniform correction factor of 1.71 was applied across all sea states for the 2018 sightings of both long- and short-beaked common dolphins.

Consistent with past modeling studies in the CCE study area (Becker et al. 2016, 2018, 2020), the most commonly selected predictor variables for the encounter rate models of groups (long- and short-beaked common dolphins) or individuals (all other species) included SST, MLD, and the smooth of latitude and longitude (Table 3). SSH and depth were also selected in many of the models. The group size model for both subspecies of common dolphin included a bivariate spline of longitude and latitude, consistent with other studies that have demonstrated significant spatial variation in group size, particularly for Delphinids (Barlow 2015; Ferguson et al. 2006). The functional forms of the key predictor variables were also consistent with those of SDMs built with subsets of the modeling dataset used for this study (Becker et al. 2016, 2018, 2020; Appendix A).

A year covariate was included in the final fin and humpback whale models, and both captured the documented increasing population trends for these species in the CCE study area (Moore and Barlow 2011; Barlow et al. 2011a; Calambokidis et al. 2017). A year term was also included in the models for short-beaked common dolphin and blue whale, consistent with observed northern shifts in the relative distribution of these two species that have resulted in increasing numbers of short-beaked common dolphins and decreasing numbers of blue whales in the CCE study area (Barlow 2016; Becker et al. 2018; Monnahan et al. 2015). A year term was also included in the SDMs for Risso's, striped, and common bottlenose dolphins, as well as Dall's porpoise (Table 3). The functional forms for the year term in all but the striped dolphin model suggest a decreasing trend in the numbers of these species in the CCE study area during the course of the survey period (Appendix A). For all three species, year represents a significant but very small effect as indicated by the range of values on the y-axis (i.e., relative to the other covariates the y-axis value for year is <1; Figures A3,A7, A8). The functional form of the year term in the striped dolphin model fluctuates throughout the 1991–2018 survey period (Figure A6), consistent with the highly variable abundance estimates for this species for each of the individual survey years (Barlow 2016; Becker et al. 2018).

Deviance explained by the models was variable, ranging from approximately 7% to 57% (Table 3). With the exception of sperm whale, AUC values for all models were greater than 0.7 and the majority were greater than 0.8, indicating that the models did a good job predicting true positives and negatives. The TSS values, which account for both omission and commission errors, were more variable, ranging from 0.18 (sperm whale) to 0.90 (long-beaked common dolphin). All models had observed: predicted density ratios higher than 0.7, with the majority higher than 0.9, indicating that the sum of the segment-based density predictions captured overall abundance in the study area as derived from design-based line-transect methods.

The 1996–2018 multi-year average density surface maps generally captured observed distribution patterns as illustrated by actual sightings during the surveys (Figure 2). For the two species with documented population increases in the study area (i.e., fin and humpback whales), the density estimates were scaled to the 2018 abundance to decrease the potential for biased-low density estimates derived from the multi-year average surfaces (Figures 2l and 2m). The CVs, which were based on the environmental variability of the daily predictions, showed substantial variation among the species, with a few individual pixel values as high as 6.0 (e.g., common bottlenose dolphin and fin whale, Figures 2g and 2l).

The yearly average density surface maps show high annual variability for some species (e.g., short-beaked common dolphin, striped dolphin, Dall's porpoise, blue whale, fin whale) and less so for other species (e.g., minke whale, Baird's beaked whale) (Figure 3). There is almost no variability in the yearly density plots for sperm whale (Figure 3i), due to the overwhelming contribution of the distance to 2,000m isobath term. The pixel-based CVs were generally highest in 2005, suggesting that there was substantial variability in the habitat covariates within this year. For the majority of the species, the yearly sightings match well with the density predictions. However, given the heterogeneity of survey coverage in 2018, sighting data from this survey are not as useful for cross validation since survey coverage needs to be taken into account when assessing the accuracy of the density predictions. For example, the models for both short-beaked common and striped dolphins predict high density in the southwestern portion of the CCE study area in 2018 (Figures 3b and 3f), where there was no survey effort (Figure 1).

The model-based yearly abundance estimates were highly variable for the majority of the species considered here, particularly for those with documented trends due to either changes in abundance or shifts in distribution (i.e., fin, humpback, and blue whales, and short-beaked common dolphin; Table 4). Even for those species for which a year term did not enter the model, substantial variability in the annual model-predicted abundance values were apparent, particularly for the most recent survey years (e.g., long-beaked common dolphin, northern right whale dolphin, Baird's beaked whale). Interestingly, the most stable mean abundance estimates over the 1991–2018 survey period were for sperm whale and the small beaked whale guild (Table 4), the two SMDs that generally had the worst performance metrics among all the species models (Table 3).

Four sources of uncertainty (i.e., environmental variability, GAM parameters, *ESW*, and *g(0))* were combined to provide an overall measure of variance for the model-based study area abundance estimates (Table 4). Uncertainty estimates from the combination of environmental variability, GAM parameters, and ESW estimates ("CV_m (Model)" in Table 4) were variable, ranging from 0.078 for sperm whale to 0.782 for northern right whale dolphin. The final model for sperm whale included only two predictors, of which one was dynamic (Table 3), so the low "Model" CVs are likely due to low parameter variability. Conversely, the final model for northern right whale dolphin included five predictors with large standard error bands around four (Table 3 and Figure A-5), resulting in high variability in the parameter simulations used to derive the variance estimates. Uncertainty due to the Beaufort-weighted g(0) values was quite high for many of the species, particularly Dall's porpoise (CV = 0.518) and minke whale (CV = 0.787). When combined, overall measures of CV for the study area abundance estimates were highly variable among the species, ranging from 0.127 (Risso's dolphin) to 0.799 (minke whale). Similar to the yearly estimates, CVs for the pooled 2014 and 2018 abundance estimates were also variable among species (Table 5).

Discussion and Conclusions

During the last 20 years, subsets of the 1991–2018 SWFSC survey data have been used to model the relationship between habitat predictors and species density, both to improve abundance estimates and to gain valuable insight on spatial and temporal changes in species distributions (Barlow et al. 2009; Becker et al. 2010, 2014, 2016, 2018, 2020; Forney 2000; Forney et al. 2012). With each added year of survey data, the models for most species have become more robust, as increased numbers of sightings collected over a broader range of oceanic conditions have been able to better inform the models. The key functional forms for many of the species have become stable over time, suggesting that at this decadal temporal scale relationships with certain habitat predictors have not changed, despite changing oceanic conditions (e.g., Becker et al. 2018). For example, the functional form of SST in the Dall's porpoise GAM consistently shows a threshold effect at approximately 16°C (Figure A8), apparent in previous GAMs built with only the 1991 and 1996 survey data (Forney 2000). The relationship between SST and fin whale density has also remained constant throughout the 1991 to 2018 period, with the highest densities of whales in waters between about 14°C and 18°C (Figure A12), consistent with GAMs developed with only four years of survey data (1991–2001; Becker et al. 2010). Although high seasonal and interannual variability in cetacean abundance and distribution patterns have been observed and predicted from habitat models developed for the CCE study area (Barlow and Forney 2007; Becker et al. 2014, 2017, 2018; Forney and Barlow 1998; Forney et al. 2012), the multi-year average density plots for the majority of species are broadly similar over the 1991–2018 time period, demonstrating consistency in "average" distribution patterns. These density estimates represent a composite view for the summer/fall survey months (typically July through November) and should not be extrapolated outside of these seasons, given the seasonality of the California Current Ecosystem.

Since a main objective of this study was to produce robust average multi-year density surfaces, a bivariate spline of longitude and latitude was included in the SDMs to increase their explanatory performance (Cañadas and Hammond 2008; Forney et al. 2015; Hedley and Buckland 2004; Tynan et al. 2005; Williams et al. 2006). As Becker et al. (2018) demonstrated, however, for many species the inclusion of a spatial term does not improve a model's novel predictive power, suggesting that these models may not provide the best nowcasts or forecasts.

For Risso's dolphin, sperm whale, and the small beaked whale guild, previous SDMs have not performed well, and there has generally been poor correlation between predicted density patterns and the sighting data used to build the models (Becker et al. 2010, 2020; Forney et al. 2012). Sightings of Risso's dolphins within the CCE study area are concentrated either along the continental shelf (mainly south of 38°N) or in offshore deep waters, with a distinct longitudinal absence between these two areas (Barlow 2016; Barlow and Forney 2007). In the present study, this observed spatial pattern was captured quite well (Figure 2c), likely due to the addition of the CCES 2018 survey data, which contributed an additional 39 sightings to the modeling dataset and provided improved sampling of the continental shelf habitat.

Conversely, models for both sperm whale and the small beaked whale guild showed little to no improvement, with some of the worst model metrics among all species and predicted distribution patterns that match poorly to actual sightings during the surveys (Table 3, Figures 2h, 2n). The addition of the CCES 2018 survey data did not improve either of these models, likely due to the very sparse sampling of offshore waters where both sperm and small beaked whales are typically found. These results also suggest that the current suite of environmental variables offered to the models are not effective proxies for their habitat and prey. Model improvements for these deep-diving species may only be realized by identifying an available proxy that better captures the ecological processes driving their distribution or by using alternative data (e.g., acoustics) for model input.

Unlike previous modeling efforts where a year term was considered only for those species with documented population increases or decreases in the CCE study area, a year term was included in the list of potential predictors for all the SDMs in this study. To ensure that year did not simply track the variable encounter rates over the 1991–2018 survey period, this term was constrained (i.e., the degrees of freedom were reduced) in the GAMs in order to identify a trend or threshold effect. Consistent with past modeling efforts, the year term entered the SDMs for those species with documented increases in population in the study area (fin and humpback whales; Moore and Barlow 2011; Barlow et al. 2011a; Calambokidis et al. 2017) and for those species with documented distribution shifts that have resulted in substantial changes in the number of animals present in the study area (blue whale and short-beaked common dolphin; Barlow 2016; Becker et al. 2018; Monnahan et al. 2015). A year term was also included in the striped dolphin GAM, indicating flucutating numbers of this species in the study area over the survey period (Figure A6). This result is consistent with past studies that suggest that available striped dolphin habitat fluctuates substantially with changing ocean conditions (Barlow 2016; Becker et al. 2018, 2020), and since the range of this species extends continuously from the study area south to waters offshore Mexico (Perrin et al. 1985; Mangels and Gerrodette 1994), there can be a large increase or decrease of animals in the study area in any single year.

A year term was also included in the models for Risso's dolphin, common bottlenose dolphin, and Dall's porpoise, suggesting a decreasing trend in the numbers of these species in the CCE study area during the course of the survey period (Figures A3, A7, A8). A negative year trend indicates that the numbers of these species in the study area has decreased either due to a true change in population or to a distribution shift out of the study area. Boyd et al. (2018) demonstrated that the amount of suitable Dall's porpoise habitat within the CCE study area changed substantially during the 1991–2008 survey period, so perhaps this could be driving the apparent decrease in numbers of this species over time. The yearly density predictions for Dall's porpoise do not appear consistent with a shift in distribution to the north, however, but rather imply a contraction of suitable habitat centered off Oregon and northern California (Figure 3h). Bayesian hierarchical approaches have been used to improve population trend analyses for fin, sperm, and beaked whales in the CCE (Moore and Barlow 2011, 2014, 2017). Similar trend analyses that incorporate the additional 2018 survey data are needed to resolve what is driving the apparent decrease in abundance indicated by the GAMs for Risso's dolphin, common bottlenose dolphin, and Dall's porpoise.

The modeling framework used in the present analysis was largely the same as that used in Becker et al. (2016), but incorporated updated measures of uncertainty in the study area abundance estimates based on a modification of the methods described in Miller et al. (*In Prep.*). This is an improvement from past studies that only accounted for uncertainty due to environmental variability. Uncertainty estimates for the overall study-area abundance estimates based on the combined sources of environmental variability, GAM parameters, and *ESW* were generally lower for species with high sighting numbers and lower variability in encounter rates such as short-beaked common dolphin, Dall's porpoise, and blue, fin, and humpback whales (Table 4). Uncertainty due to the Beaufort-weighted *g(0)* values was quite high for many of the species, and served to increase uncertainty in the overall study area abundance estimates. This is not surprising given the nontrivial uncertainty estimates associated with the Beaufort-specific *g(0)* values calculated by Barlow (2015) and used in this study. Similar to past studies, the pixel-based variance estimates presented here account for uncertainty due to environmental variability and are thus under-estimated to some degree. Methods to derive spatially-explicit variance measures that also account for uncertainty in the GAM parameters, *ESW*, and *g(0)* are currently in development (Miller et al. *In Prep*.).

For all species, abundance estimates derived from the habitat-based models are more stable than previous design-based estimates for each of the 1996–2014 survey years (Barlow 2016). Design-based estimates are based on the realized encounter rates within each year, and are thus subject to high variation due to sampling error and patchiness in both the environment and animal distribution. This generally results in highly variable single year abundance estimates that often appear inconsistent with long-term trends in animal abundance (Moore and Barlow 2014). Conversely, habitat models establish relationships between environmental predictors and species density based on the full, multi-year dataset, and yearly abundance estimates derived from the models are based on the temporally-specific environmental conditions throughout the study area, thus serving to smooth across the annual variation in observed encounter rates along transect lines. This results in less variability in model-based abundance estimates between years, as much of the remaining variance is largely attributed to environmental variability rather than to low single year sample size (Barlow et al. 2009; Forney et al. 2012). The most variable yearly design-based estimates are thus typically for those species with the highest variation in encounter rates (Barlow 2016), and these tend to differ most from the more stable model-based estimates (e.g., common bottlenose dolphin, Table 4).

GAMs are able to effectively deal with spatial heterogeneity of survey coverage within the statistical framework (Hedley and Buckland 2004), and thus the CCES 2018 survey contributed valuable data to the CCE modeling dataset and allowed for population size updates for many of the US West Coast cetacean stocks. Offshore waters were undersampled, however, and SDMs for species that primarily inhabit these regions did not improve with the addition of the CCES 2018 data (i.e., sperm whale, beaked whales). One of the greatest strengths of the SWFSC dataset is the broad, consistent survey coverage of the CCE study area over multiple years, which has supported novel analyses and methodological improvements in SDM development. For example, the SWFSC CCE dataset has supported the evaluation of different modeling approaches, different sampling scales, different interpolation methods, and different sources of habitat data (Barlow et al. 2009; Becker et al. 2010, 2016, 2020; Forney et al. 2012; Redfern et al. 2008). This extensive dataset has also supported studies evaluating the predictive ability of SDMs to provide nowcasts, forecasts, and across-season predictions (Becker et al. 2012, 2014, 2018), as well as allow for robust trend analyses (Moore and Barlow 2011, 2014, 2017). While systematic regional surveys or those that cover only portions of the CCE study area provide valuable data, routine survey coverage of the full study area is required to maintain and increase the utility of this unique dataset.

As additional data are collected on future surveys, model improvements are expected to continue, both from increased sample sizes and ideally from surveys conducted in more anomalous conditions that will allow for an even broader range of habitat conditions to be represented. Model improvements are also expected from the availability of additional habitat variables that are more relevant to the cetaceans than the proxy variables used here. Improvements to ocean model products may in turn produce more robust cetacean SDMs, particularly if the ocean model outputs can be produced at finer spatial resolutions. Continued methodological improvements are also expected, with active research aimed at developing robust methods for combining data from different sources, e.g., visual line-transect, passive acoustics, tagging data, etc. For those species that exhibit substantial distribution shifts in and out of the CCE study area, e.g., striped dolphin, long-beaked common dolphin, and Dall's porpoise (Becker et al 2018; Boyd et al. 2018; Carretta et al. 2011), SDMs that incorporate survey data that better sample the broader distribution range of these species should provide greater insight into observed abundance changes within the study area. SDMs that incorporate data from portions of the CCES 2018 survey that covered waters along the west coasts of southern Canada and Baja California will help in this regard, and SDMs for waters off Baja California are currently in development.

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Tables

Table 1. Cetacean and ecosystem assessment surveys and effort conducted within the California Current Ecosystem study area during 1991–2018. CA/OR/WA = California/Oregon/Washington, CenCA = central California, SoCA = southern California, Baja = Baja California. DSJ = *David Starr Jordan.*

Cruise numbers	Period	Research vessel	Region
1426	Jul-Nov 1991	*McArthur*	California
1508/1509	Jul-Nov 1993	*McArthur/DSJ*	California
1604/1605	Jul-Nov 1996	*McArthur/DSJ*	CA/OR/WA
1617/1619	Jul-Dec 2001	*McArthur/DSJ*	CA/OR/WA
1627/1628	June-Dec 2005	*McArthur II/DSJ*	CA/OR/WA
1642	Jul-Nov 2008	*McArthur II*	CA/OR/WA
1635	Sept-Dec 2009	*McArthur II*	CenCA/SoCAL/Baja
1647	Aug-Dec 2014	*Ocean Starr**	CA/OR/WA
2017	June-Dec 2018	*Reuben Lasker*	Canada/CA/OR/WA/Baja

*Previously the *David Starr Jordan*

Table 2. Number of sightings and average group size (Avg. GS) of cetacean species observed in the California Current Ecosystem study area during the 1991–2018 shipboard surveys for which habitat-based density models were developed. All sightings were made while on systematic and non-systematic effort in Beaufort sea states ≤5 within the species-specific truncation distances (see text for details).

Common name	Taxonomic name	No. of sightings	Avg. GS
Long-beaked common dolphin	*Delphinus delphis bairdii*	160	291.82
Short-beaked common dolphin	*Delphinus delphis delphis*	1,034	155.73
Risso’s dolphin	*Grampus griseus*	249	18.57
Pacific white-sided dolphin	*Lagenorhynchus obliquidens*	296	54.70
Northern right whale dolphin	*Lissodelphis borealis*	147	45.31
Striped dolphin	*Stenella coeruleoalba*	153	39.38
Common bottlenose dolphin	*Tursiops truncatus*	66	14.48
Dall’s porpoise	*Phocoenoides dalli*	678	3.72
Sperm whale	*Physeter macrocephalus*	105	6.67
Minke whale	*Balaenoptera acutostrata*	49	1.13
Blue whale	*Balaenoptera musculus*	316	1.66
Fin whale	*Balaenoptera physalus*	558	2.06
Humpback whale	*Megaptera novaeangliae*	967	1.70
Baird’s beaked whale	*Berardius bairdii*	39	7.46
Small beaked whale guild	*Mesoplodon spp. & Ziphius cavirostris*	92	2.12

Table 3. Summary of the final models built with the 1991–2018 survey data. Variables are listed in the order of their significance and are as follows: SST = sea surface temperature, SSTsd = standard deviation of SST, MLD = mixed layer depth, SSH = sea surface height, SSHsd = standard deviation of SSH, depth = bathymetric depth, shelf= distance to shelf, d2000=distance to the 2,000m isobath, LON = longitude, and LAT = latitude. Separate encounter rate (ER) and group size (GS) models were built for long- and short-beaked common dolphins due to large and variable group sizes. All single response and encounter rate models were corrected for effort with an offset for the effective area searched (see text for details). Performance metrics included the percentage of explained deviance (Expl. Dev.), the area under the receiver operating characteristic curve (AUC), the true skill statistic (TSS), and the ratio of observed to predicted density for the study area (Obs:Pred).

Species	Predictor variables	Expl.Dev.	AUC	TSS	Obs:Pred
Long-beaked common dolphin					
	ER: LON:LAT + SST + SSHsd + SSH	52.50	0.98	0.90	0.95
	GS: LON:LAT	6.55			
Short-beaked common dolphin					
	ER: LON:LAT + year + SST + SSH + MLD	17.00	0.77	0.40	0.95
	GS: LON:LAT	11.10			
Risso's dolphin					
	LON:LAT + SST + MLD + year + SSTsd	22.40	0.76	0.41	0.87
Pacific white-sided dophin					
	LON:LAT + shelf + SST + SSH + MLD	51.70	0.87	0.62	0.86
Northern right whale dolphin					
	LON:LAT + SST + depth + MLD + SSTsd	44.40	0.83	0.51	0.92
Striped dolphin					
	depth + LON:LAT + SST + year + MLD	33.20	0.76	0.41	0.72
Common bottlenose dolphin					
	LON:LAT + MLD + SSTsd + SST + year	51.20	0.92	0.74	0.94
Dall's porpoise					
	LON:LAT + SSH + year + SST + SSHsd + SSTsd	32.20	0.89	0.63	0.95
Sperm whale					
	d2000 + MLD	13.30	0.61	0.17	0.91
Minke whale					
	shelf + SST + LON:LAT	7.73	0.85	0.59	1.00
Blue whale					
	LON:LAT + year + SSH + depth + SST + MLD	23.90	0.78	0.42	0.94
Fin whale					
	LON:LAT + SST + SSH + year + MLD + depth	22.40	0.75	0.39	0.88
Humpback whale					
	LON:LAT + year + depth + SST + MLD	57.40	0.94	0.75	0.98
Baird's beaked whale					
	LON:LAT + depth + MLD + SSH	46.00	0.90	0.65	0.96
Small beaked whale guild					
	shelf + MLD + SST + LON:LAT	8.19	0.73	0.39	0.97

Table 4. Annual model-predicted mean estimates of abundance, density (animals km^{-2}), and corresponding coefficient of variation (CV) within the CCE study area. Annual estimates are predicted from the full model using the habitat characteristics in that year. CV_m (Model) represents the combined uncertainty from three sources: GAM parameters, ESW, and environmental variability. CV_{Tot} is the total CV from CV_m (Model) and CV_{g0} derived using the Delta method (see text for details). Log-normal 95% confidence intervals (Low and High 95% CIs) apply to abundance estimates. Also shown is the 20th percentile for the abundance estimate, corresponding to the "minimum population size (Nmin)" as defined in the Guidelines for Assessing Marine Mammal Stocks, and calculated as the log-normal 20th percentile of the mean abundance estimate using standard formulae.

	Year					
	1996	**2001**	**2005**	**2008**	**2014**	**2018**
Long-beaked common dolphin						
Abundance	57,623	53,044	52,356	58,624	58,794	83,379
Density	0.0506	0.0465	0.0459	0.0514	0.0516	0.0732
CV_m (Model)	0.151	0.128	0.146	0.087	0.101	0.140
CV_{g0}	0.165	0.165	0.165	0.165	0.165	0.165
CV_{Tot}	0.224	0.209	0.220	0.187	0.193	0.216
Low 95% CI	37,370	35,381	34,170	40,799	40,380	54,823
High 95% CI	88,851	79,524	80,221	84,236	85,605	126,809
Nmin	47,841	44,574	43,587	50,170	50,031	69,636
Short-beaked common dolphin						
Abundance	328,134	391,356	394,610	433,628	880,425	1,056,308
Density	0.2879	0.3434	0.3462	0.3804	0.7724	0.9267
CV_m (Model)	0.145	0.196	0.139	0.163	0.090	0.125
CV_{g0}	0.165	0.165	0.165	0.165	0.165	0.165
CV_{Tot}	0.220	0.256	0.216	0.232	0.188	0.207
Low 95% CI	214,423	238,750	259,781	276,866	611,073	707,020
High 95% CI	502,146	641,507	599,417	679,148	1,268,504	1,578,155
Nmin	273,320	316,497	329,739	357,612	752,592	888,971
Risso's dolphin						
Abundance	15,761	15,462	12,044	11,657	8,153	8,977
Density	0.0138	0.0136	0.0106	0.0102	0.0072	0.0079
CV_m (Model)	0.116	0.087	0.123	0.128	0.189	0.190
CV_{g0}	0.093	0.093	0.093	0.093	0.093	0.093
CV_{Tot}	0.149	0.127	0.154	0.158	0.211	0.212
Low 95% CI	11,796	12,059	8,918	8,565	5,419	5,957
High 95% CI	21,060	19,826	16,265	15,865	12,265	13,528
Nmin	13,916	13,896	10,586	10,211	6,841	7,527
Pacific white-sided dolphin						
Abundance	37,147	38,533	39,008	37,369	28,901	34,999
Density	0.0326	0.0338	0.0342	0.0328	0.0254	0.0307
CV_m (Model)	0.230	0.235	0.506	0.323	0.292	0.149
CV_{g0}	0.165	0.165	0.165	0.165	0.165	0.165

CV_{Tot}	0.283	0.287	0.532	0.363	0.335	0.222
Low 95% CI	21,558	22,194	14,657	18,761	15,240	22,756
High 95% CI	64,010	66,900	103,814	74,432	54,807	53,829
Nmin	29,404	30,402	25,617	27,794	21,954	29,090
Northern right whale dolphin						
Abundance	33,893	39,697	27,370	42,767	18,031	29,285
Density	0.0297	0.0348	0.0240	0.0375	0.0158	0.0257
CV_m (Model)	0.706	0.782	0.445	0.661	0.534	0.698
CV_{g0}	0.165	0.165	0.165	0.165	0.165	0.165
CV_{Tot}	0.725	0.798	0.475	0.681	0.559	0.717
Low 95% CI	9,481	10,012	11,314	12,750	6,489	8,284
High 95% CI	121,158	157,397	66,211	143,454	50,099	103,521
Nmin	19,608	21,966	18,727	25,428	11,624	17,024
Striped dolphin						
Abundance	17,758	26,215	47,974	46,563	70,107	29,988
Density	0.0156	0.0230	0.0421	0.0409	0.0615	0.0263
CV_m (Model)	0.293	0.193	0.357	0.317	0.324	0.282
CV_{g0}	0.098	0.098	0.098	0.098	0.098	0.098
CV_{Tot}	0.309	0.216	0.370	0.332	0.338	0.299
Low 95% CI	9,826	17,235	23,765	24,714	36,762	16,913
High 95% CI	32,093	39,875	96,843	87,727	133,696	53,170
Nmin	13,772	21,893	35,478	35,470	53,128	23,448
Common bottlenose dolphin						
Abundance	6,198	5,408	3,855	3,493	5,908	3,477
Density	0.0054	0.0047	0.0034	0.0031	0.0052	0.0031
CV_m (Model)	0.504	0.357	0.503	0.508	0.510	0.647
CV_{g0}	0.256	0.256	0.256	0.256	0.256	0.256
CV_{Tot}	0.565	0.439	0.564	0.569	0.571	0.696
Low 95% CI	2,208	2,374	1,375	1,237	2,087	1,015
High 95% CI	17,398	12,320	10,806	9,861	16,726	11,915
Nmin	3,978	3,797	2,476	2,237	3,778	2,048
Dall's porpoise						
Abundance	49,811	44,418	36,373	34,654	21,219	16,498
Density	0.0437	0.0390	0.0319	0.0304	0.0186	0.0145
CV_m (Model)	0.244	0.166	0.178	0.152	0.199	0.319
CV_{g0}	0.518	0.518	0.518	0.518	0.518	0.518
CV_{Tot}	0.573	0.544	0.548	0.540	0.555	0.608
Low 95% CI	17,541	16,376	13,328	12,861	7,686	5,493
High 95% CI	141,452	120,481	99,264	93,374	58,580	49,554
Nmin	31,813	28,933	23,630	22,637	13,717	10,286
Sperm whale						
Abundance	2,783	2,896	2,691	2,869	2,656	2,606
Density	0.0024	0.0025	0.0024	0.0025	0.0023	0.0023
CV_m (Model)	0.078	0.109	0.111	0.090	0.186	0.135

CV_{g0}	0.285	0.285	0.285	0.285	0.285	0.285
CV_{Tot}	0.295	0.305	0.306	0.299	0.340	0.315
Low 95% CI	1,578	1,614	1,497	1,617	1,388	1,425
High 95% CI	4,907	5,197	4,836	5,090	5,082	4,765
Nmin	2,181	2,253	2,092	2,243	2,010	2,011
Minke whale						
Abundance	847	812	819	804	1,062	915
Density	0.0007	0.0007	0.0007	0.0007	0.0009	0.0008
CV_m (Model)	0.139	0.110	0.110	0.113	0.109	0.085
CV_{g0}	0.787	0.787	0.787	0.787	0.787	0.787
CV_{Tot}	0.799	0.795	0.795	0.795	0.795	0.792
Low 95% CI	214	206	208	204	270	233
High 95% CI	3,358	3,200	3,227	3,170	4,184	3,590
Nmin	469	451	454	446	589	509
Blue whale						
Abundance	1,946	1,657	1,042	919	1,077	670
Density	0.0017	0.0015	0.0009	0.0008	0.0009	0.0006
CV_m (Model)	0.224	0.139	0.149	0.227	0.273	0.299
CV_{g0}	0.309	0.309	0.309	0.309	0.309	0.309
CV_{Tot}	0.382	0.339	0.343	0.383	0.412	0.430
Low 95% CI	945	868	542	445	495	299
High 95% CI	4,009	3,162	2,004	1,899	2,342	1,502
Nmin	1,427	1,255	787	673	771	474
Fin whale						
Abundance	3,804	5,733	7,319	7,606	10,139	11,065
Density	0.0033	0.0050	0.0064	0.0067	0.0089	0.0097
CV_m (Model)	0.200	0.212	0.250	0.303	0.175	0.333
CV_{g0}	0.230	0.230	0.230	0.230	0.230	0.230
CV_{Tot}	0.305	0.313	0.340	0.381	0.289	0.405
Low 95% CI	2,120	3,149	3,828	3,699	5,817	5,156
High 95% CI	6,826	10,439	13,994	15,640	17,672	23,747
Nmin	2,959	4,432	5,540	5,580	7,986	7,970
Humpback whale						
Abundance	1,181	1,364	1,575	1,727	2,178	4,784
Density	0.0010	0.0012	0.0014	0.0015	0.0019	0.0042
CV_m (Model)	0.147	0.081	0.113	0.175	0.271	0.118
CV_{g0}	0.283	0.283	0.283	0.283	0.283	0.283
CV_{Tot}	0.319	0.294	0.305	0.333	0.392	0.307
Low 95% CI	642	775	878	915	1,038	2,658
High 95% CI	2,173	2,400	2,824	3,259	4,568	8,609
Nmin	909	1,070	1,226	1,315	1,584	3,717
Baird’s beaked whale						
Abundance	739	730	590	681	977	1,363
Density	0.0006	0.0006	0.0005	0.0006	0.0009	0.0012

CV_m (Model)	0.458	0.434	0.628	0.521	0.423	0.422
CV_{g0}	0.326	0.326	0.326	0.326	0.326	0.326
CV_{Tot}	0.562	0.543	0.708	0.615	0.534	0.533
Low 95% CI	265	270	169	225	366	511
High 95% CI	2,064	1,976	2,057	2,065	2,608	3,634
Nmin	475	476	345	423	641	894
Small beaked whale guild						
Abundance	4,979	5,701	4,399	5,088	4,670	4,989
Density	0.0044	0.0050	0.0039	0.0045	0.0041	0.0044
CV_m (Model)	0.153	0.113	0.213	0.201	0.188	0.211
CV_{g0}	0.438	0.438	0.438	0.438	0.438	0.438
CV_{Tot}	0.464	0.452	0.487	0.482	0.477	0.486
Low 95% CI	2,096	2,447	1,781	2,078	1,924	2,023
High 95% CI	11,830	13,281	10,866	12,461	11,336	12,306
Nmin	3,433	3,964	2,983	3,463	3,191	3,385

Table 5. Arithmetic mean of the model-predicted 2014 and 2018 estimates of abundance and density (animals km^{-2}) within the CCE study area. The corresponding coefficient of variation (CV_{Tot}) is the total CV from four sources: environmental variability, GAM parameters, ESW, and *g(0)* (see text for details). Log-normal 95% confidence intervals (Low and High 95% CIs) apply to abundance estimates. Also shown is the 20th percentile for the abundance estimate, corresponding to the "minimum population size (Nmin)" as defined in the Guidelines for Assessing Marine Mammal Stocks, and calculated as the log-normal 20th percentile of the mean abundance estimate using standard formulae.

Species	Abundance	Density	CV_{Tot}	Low 95% CI	High 95% CI	Nmin
Long-beaked common dolphin						
	71,087	0.0624	0.190	49,156	102,803	60,669
Short-beaked common dolphin						
	968,367	0.8496	0.192	667,050	1,405,792	825,082
Risso's dolphin						
	8,565	0.0075	0.209	5,713	12,841	7,197
Pacific white-sided dolphin						
	31,950	0.0280	0.249	19,769	51,636	25,996
Northern right whale dolphin						
	23,658	0.0208	0.612	7,836	71,428	14,717
Striped dolphin						
	50,048	0.0439	0.314	27,454	91,237	38,668
Common bottlenose dolphin						
	4,693	0.0041	0.407	2,177	10,117	3,374
Dall's porpoise						
	18,859	0.0165	0.562	6,750	52,693	12,129
Sperm whale						
	2,631	0.0023	0.324	1,415	4,891	2,016
Minke whale						
	986	0.0009	0.793	251	3,874	548
Blue whale						
	874	0.0008	0.396	414	1,845	634
Fin whale						
	10,602	0.0093	0.328	5,670	19,824	8,103
Humpback whale						
	3,481	0.0031	0.320	1,888	6,417	2,677
Baird's beaked whale						
	1,170	0.0010	0.501	463	2,956	786
Small beaked whale guild						
	4,830	0.0042	0.481	1,976	11,804	3,290

Figures

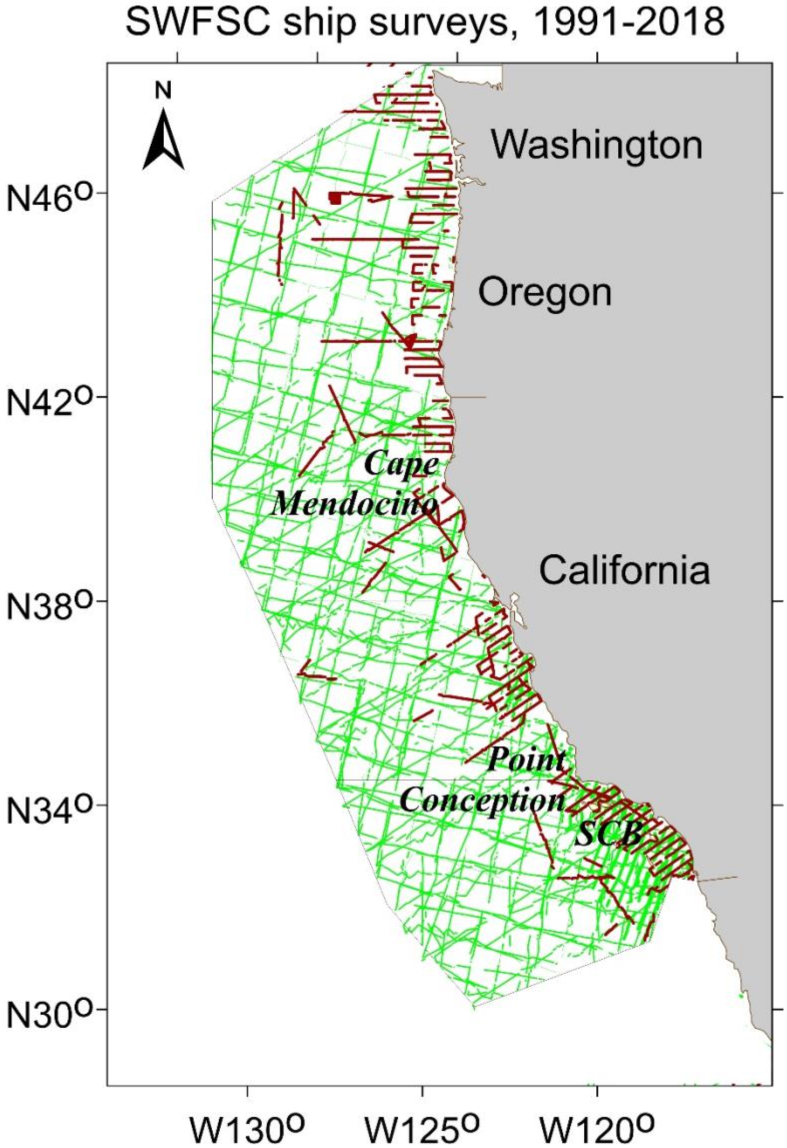


Figure 1. Completed transects for the Southwest Fisheries Science Center systematic ship surveys conducted between 1991 and 2018 in the California Current Ecosystem study area. The lines (green = 1991–2014 surveys, red=2018 survey) show on-effort transect coverage in Beaufort sea states of 0-5.

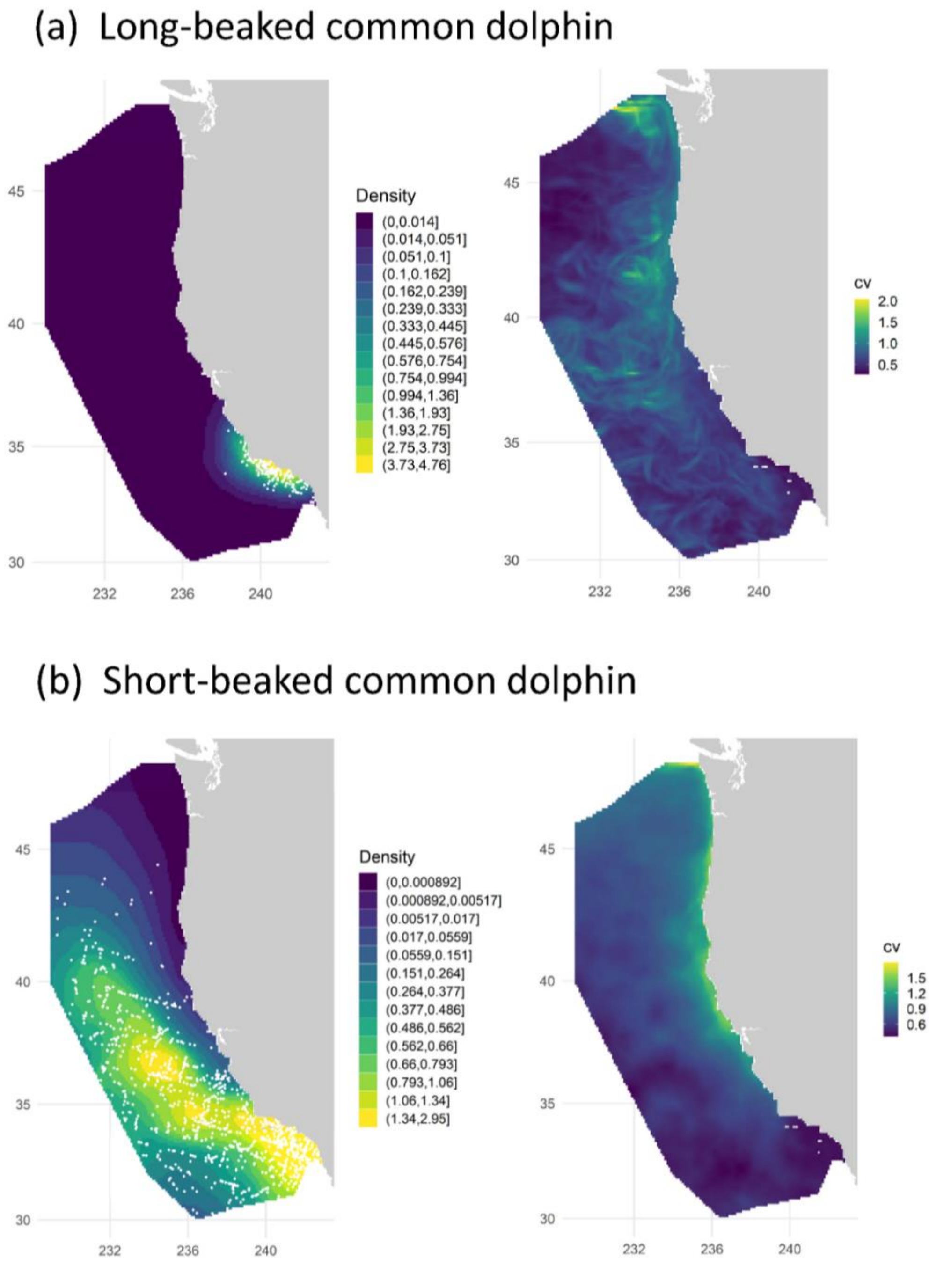


Figure 2a-b. Predicted mean density (animals km^{-2}) and associated coefficients of variation (CV) from the 1991–2018 habitat-based density models for (a) long-beaked common dolphin, and (b) short-beaked common dolphin. Panels show the multi-year average density based on predicted daily cetacean species densities covering the 1996-2018 survey periods (summer/fall). Predictions are shown for the study area (1,141,800 km^{2}). White dots in the average plots show actual sighting locations from the SWFSC 1996-2018 summer/fall ship surveys for the respective species.

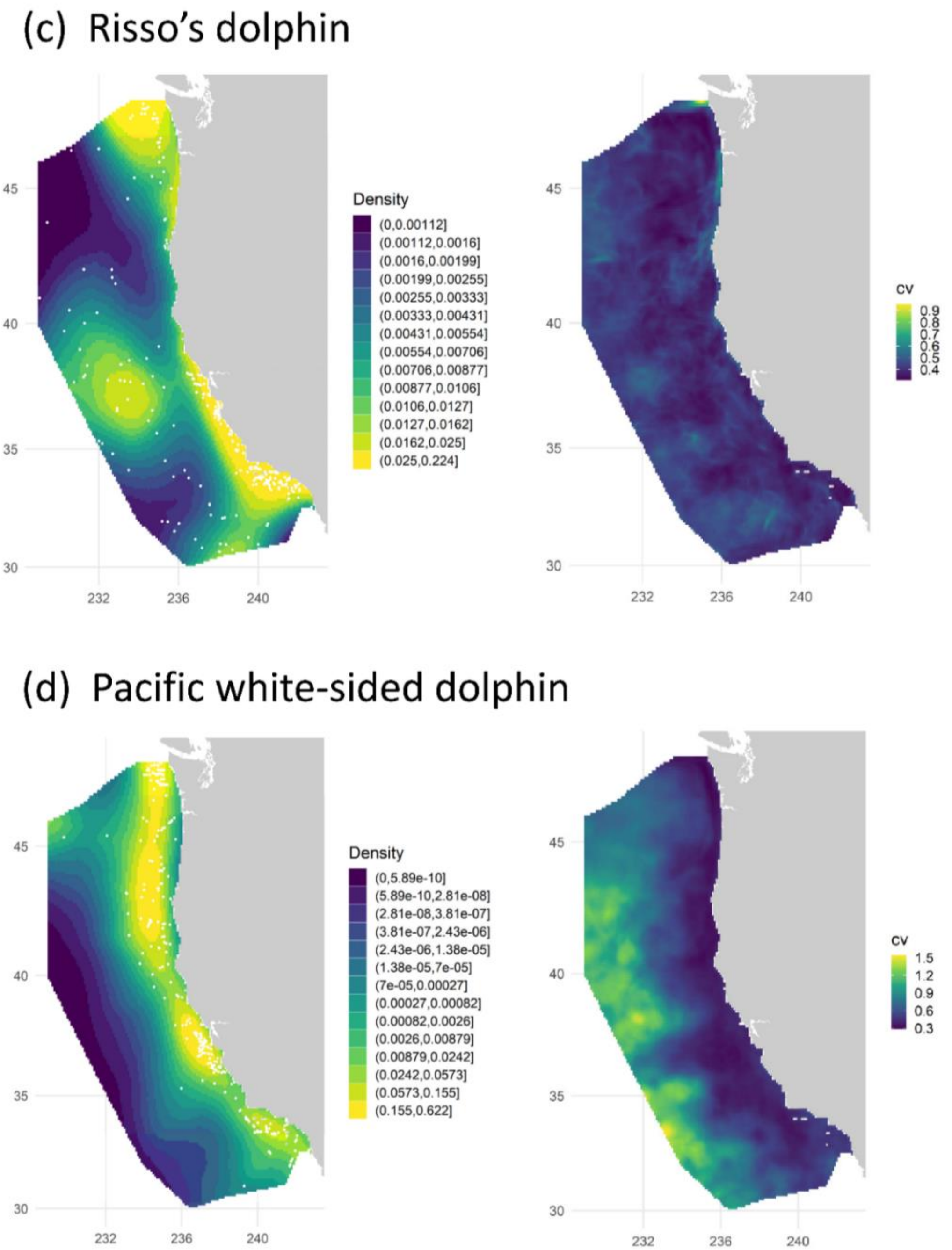


Figure 2c-d. Predicted mean density (animals km^{-2}) and associated coefficients of variation (CV) from the 1991–2018 habitat-based density models for (c) Risso's dolphin, and (d) Pacific white-sided dolphin. Panels show the multi-year average density based on predicted daily cetacean species densities covering the 1996-2018 survey periods (summer/fall). Predictions are shown for the study area (1,141,800 km^2). White dots in the average plots show actual sighting locations from the SWFSC 1996-2018 summer/fall ship surveys for the respective species.

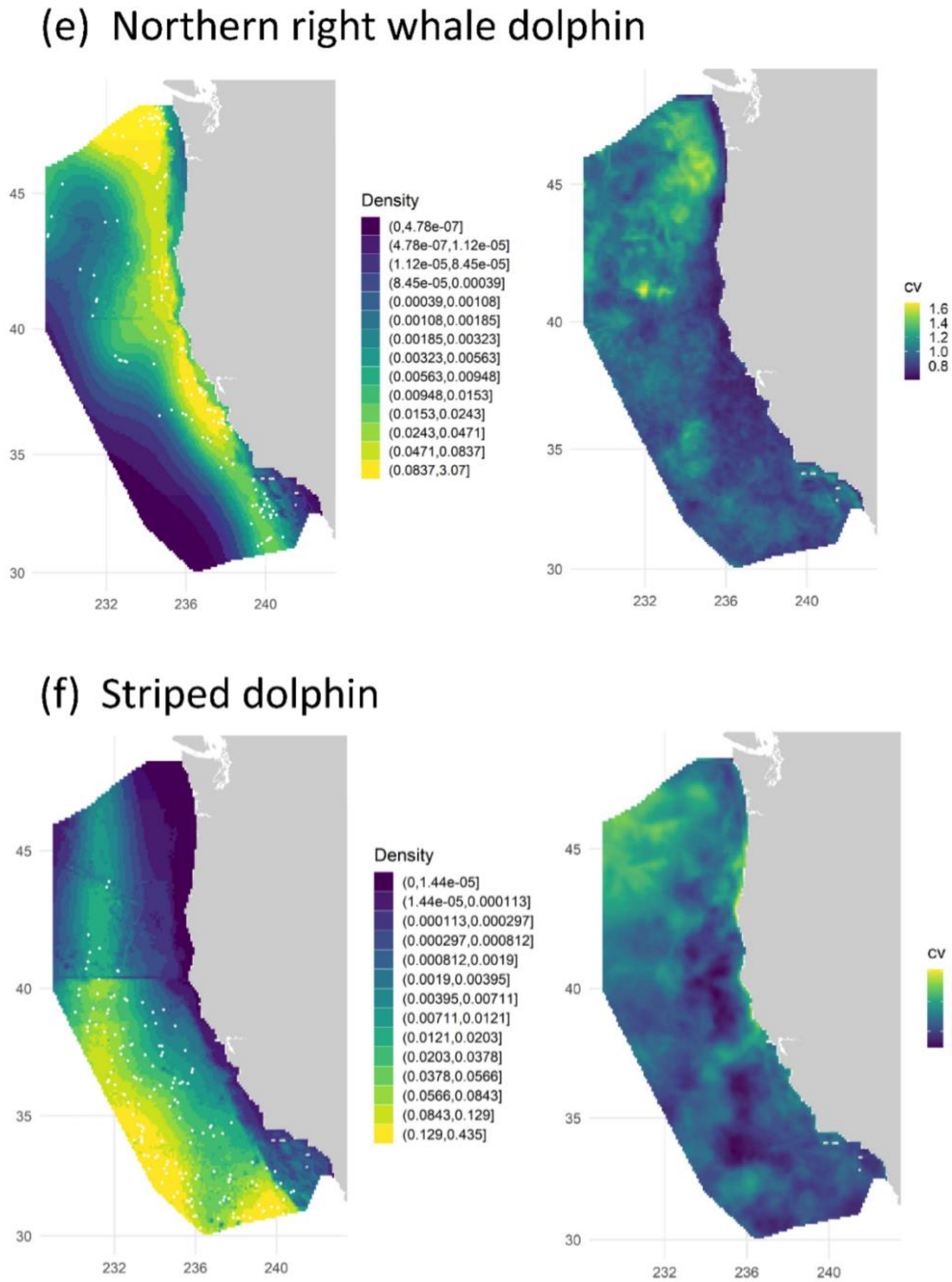
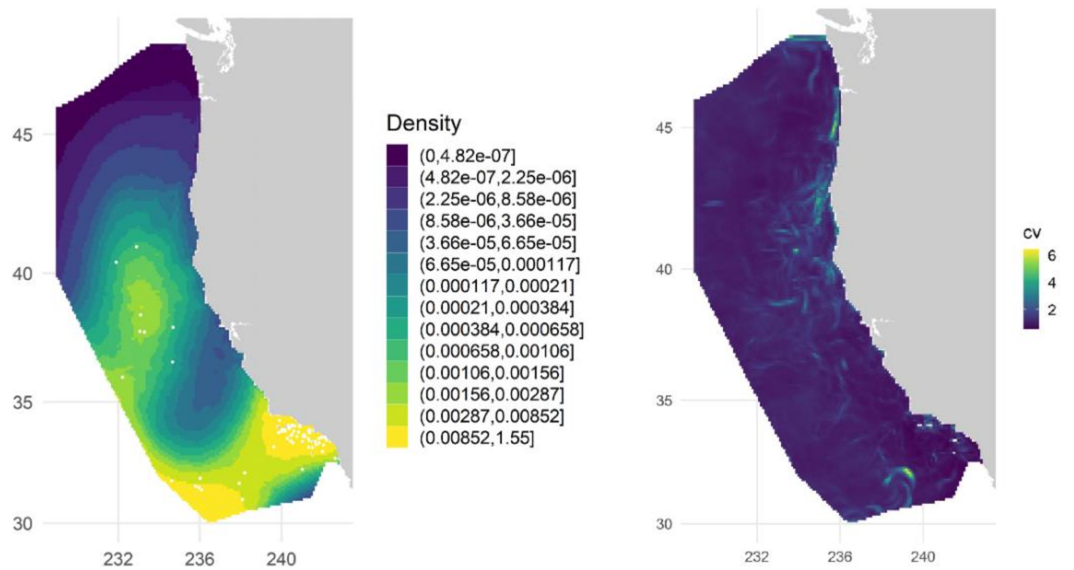


Figure 2e-f. Predicted mean density (animals km^{-2}) and associated coefficients of variation (CV) from the 1991–2018 habitat-based density models for (e) northern right whale dolphin, and (f) striped dolphin. Panels show the multi-year average density based on predicted daily cetacean species densities covering the 1996-2018 survey periods (summer/fall). Predictions are shown for the study area (1,141,800 km^2). White dots in the average plots show actual sighting locations from the SWFSC 1996-2018 summer/fall ship surveys for the respective species.

(g) Common bottlenose dolphin



(h) Dall's porpoise

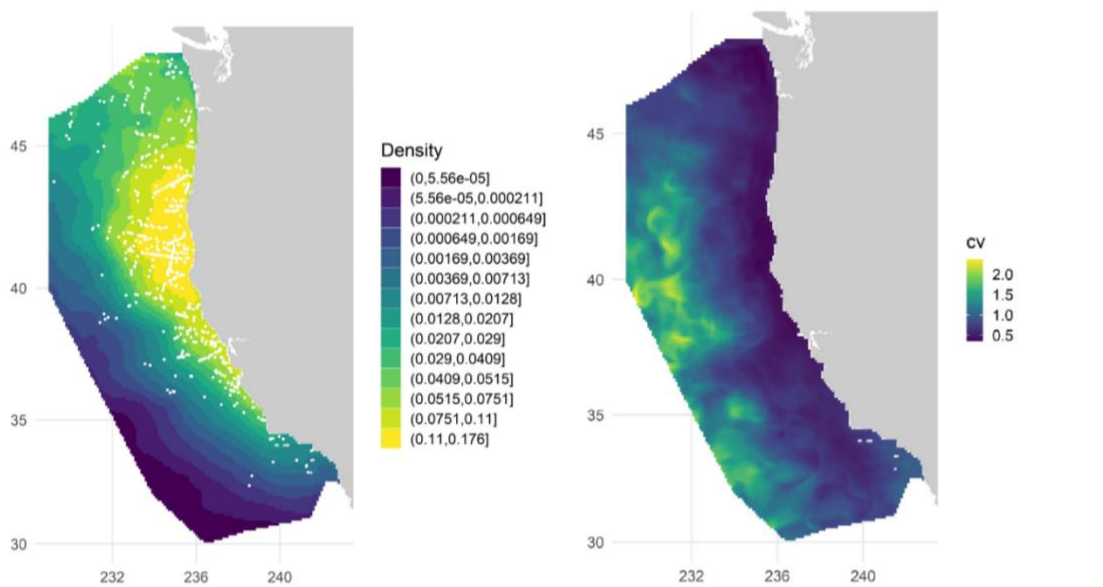
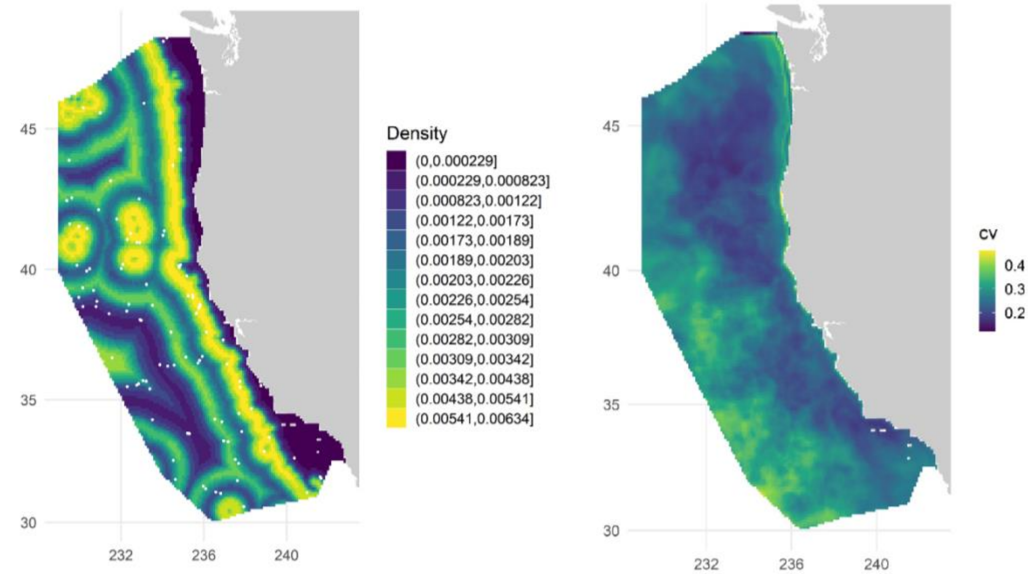


Figure 2g-h. Predicted mean density (animals km^{-2}) and associated coefficients of variation (CV) from the 1991–2018 habitat-based density models for (g) common bottlenose dolphin, and (h) Dall's porpoise. Panels show the multi-year average density based on predicted daily cetacean species densities covering the 1996-2018 survey periods (summer/fall). Predictions are shown for the study area (1,141,800 km^2). White dots in the average plots show actual sighting locations from the SWFSC 1996-2018 summer/fall ship surveys for the respective species.

(i) Sperm whale



(j) Minke whale

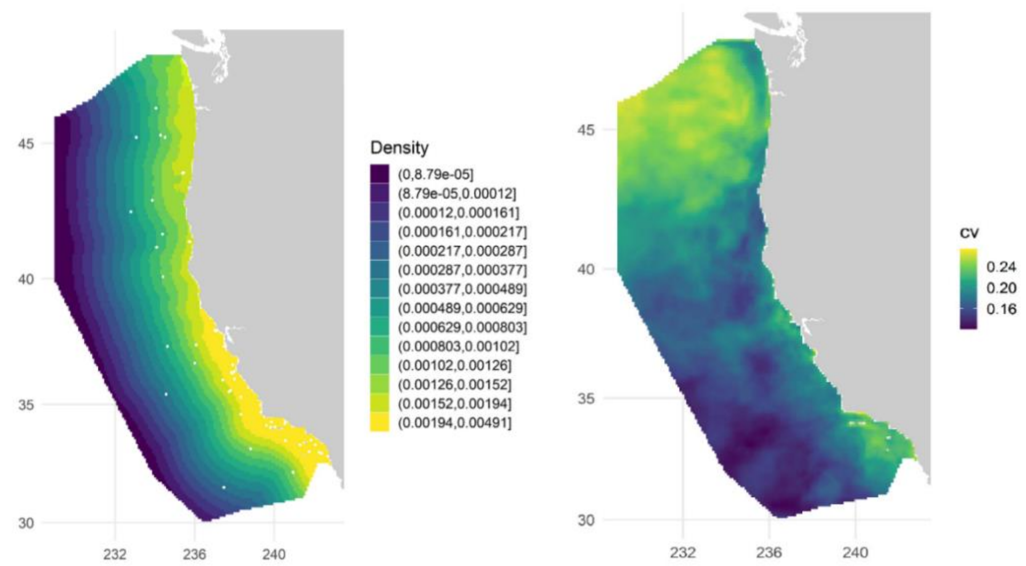


Figure 2i-j. Predicted mean density (animals km^{-2}) and associated coefficients of variation (CV) from the 1991–2018 habitat-based density models for (i) sperm whale, and (j) minke whale. Panels show the multi-year average density based on predicted daily cetacean species densities covering the 1996-2018 survey periods (summer/fall). Predictions are shown for the study area (1,141,800 km^2). White dots in the average plots show actual sighting locations from the SWFSC 1996-2018 summer/fall ship surveys for the respective species.

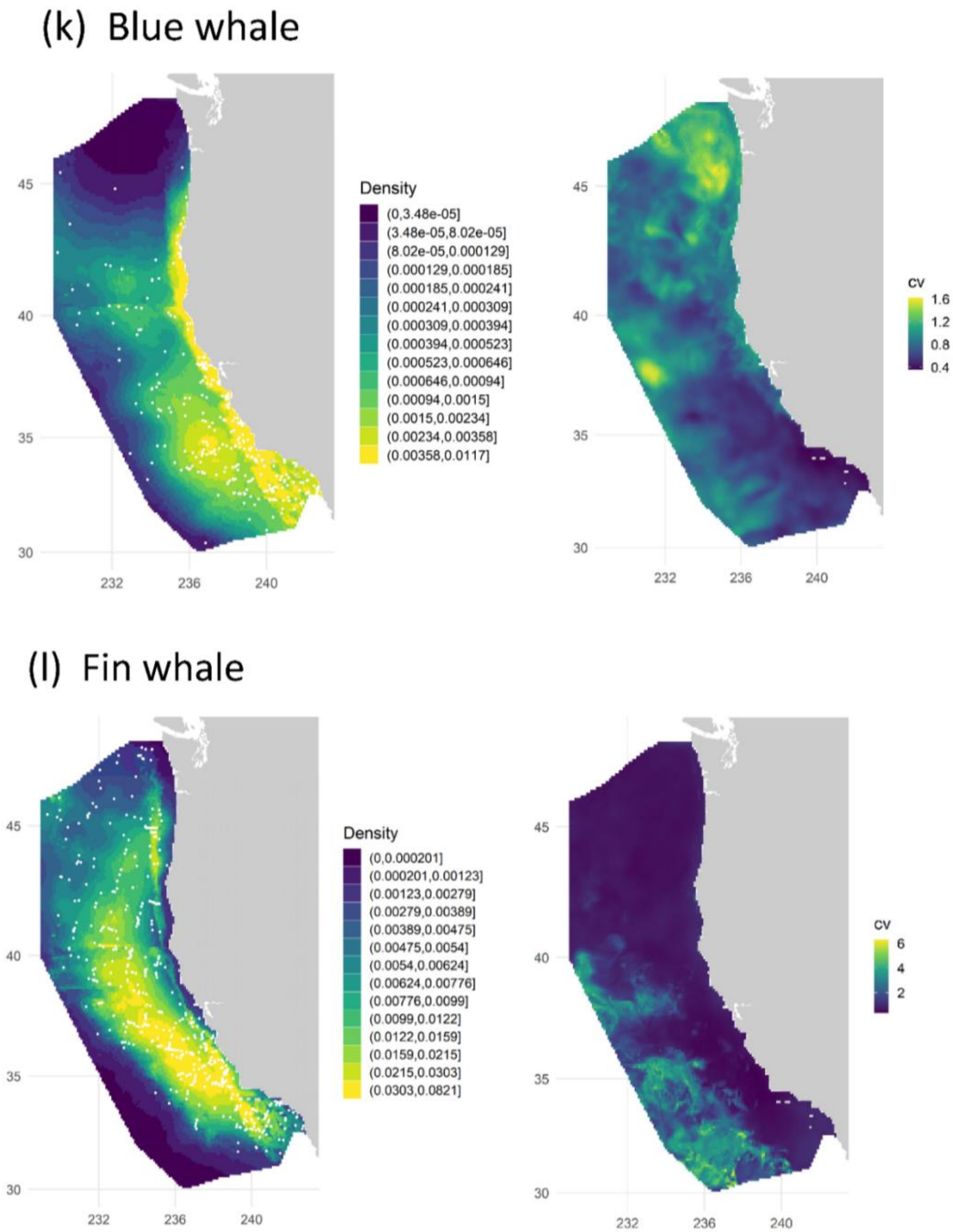


Figure 2k-l. Predicted mean density (animals km^{-2}) and associated coefficients of variation (CV) from the 1991–2018 habitat-based density models for (k) blue whale, and (l) fin whale. Panels show the multi-year average density based on predicted daily cetacean species densities covering the 1996-2018 survey periods (summer/fall). Predictions are shown for the study area (1,141,800 km^2). White dots in the average plots show actual sighting locations from the SWFSC 1996-2018 summer/fall ship surveys for the respective species.

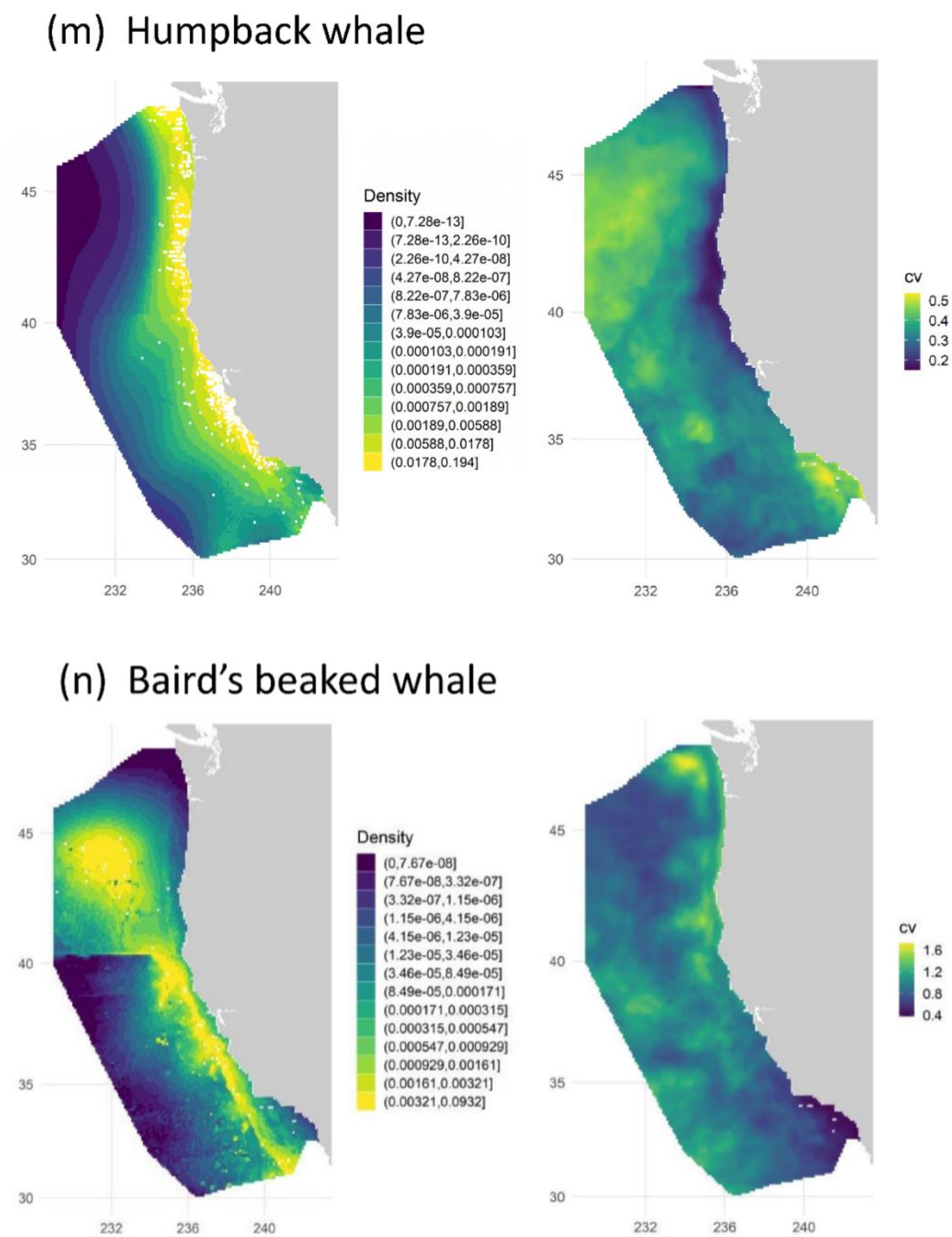


Figure 2m-n. Predicted mean density (animals km^{-2}) and associated coefficients of variation (CV) from the 1991–2018 habitat-based density models for (m) humpback whale, and (n) Baird's beaked whale. Panels show the multi-year average density based on predicted daily cetacean species densities covering the 1996-2018 survey periods (summer/fall). Predictions are shown for the study area (1,141,800 km^2). White dots in the average plots show actual sighting locations from the SWFSC 1996-2018 summer/fall ship surveys for the respective species.

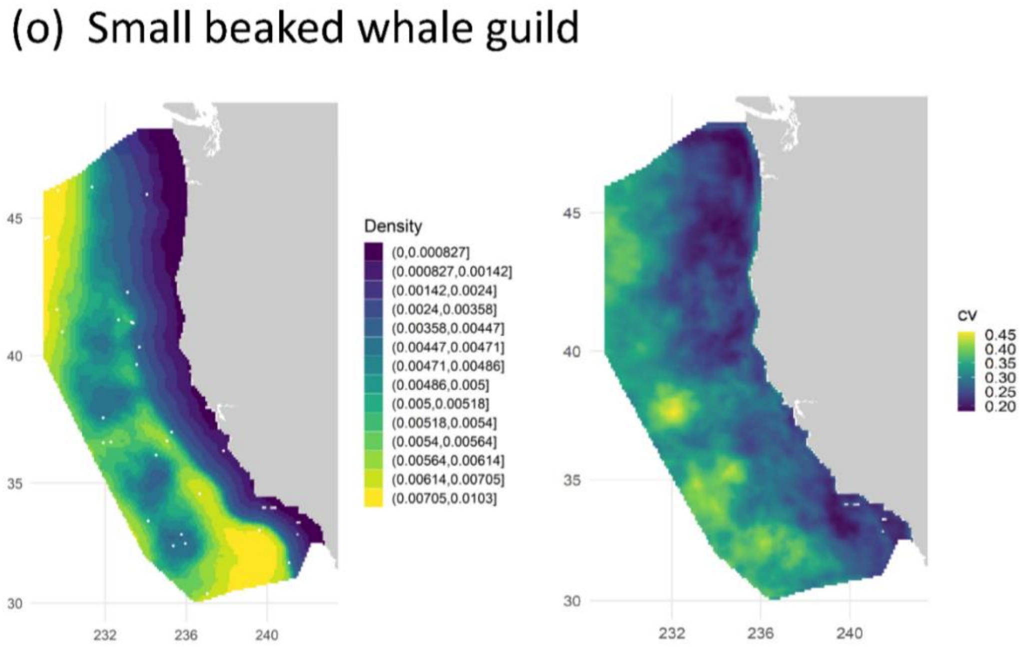


Figure 2o. Predicted mean density (animals km^{-2}) and associated coefficients of variation (CV) from the 1991–2018 habitat-based density models for (o) small beaked whale guild. Panels show the multi-year average density based on predicted daily cetacean species densities covering the 1996-2018 survey periods (summer/fall). Predictions are shown for the study area (1,141,800 km^2). White dots in the average plots show actual sighting locations from the SWFSC 1996-2018 summer/fall ship surveys for the respective species.

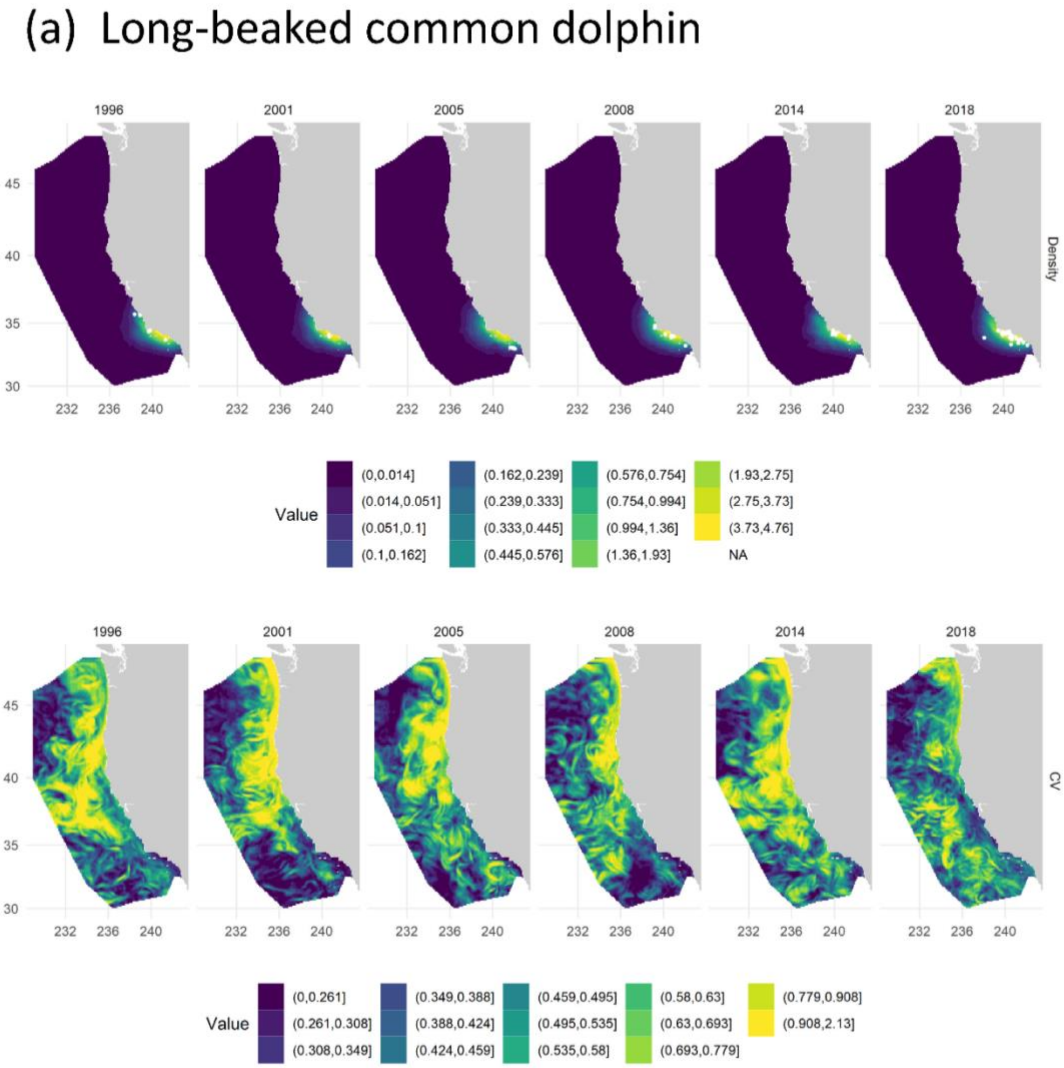


Figure 3a. Predicted annual (1996-2018) mean density (animals km^{-2}) and associated coefficients of variation (CV) from the 1991–2018 habitat-based density models for long-beaked common dolphin. Panels show the yearly average density based on predicted daily long-beaked common dolphin densities covering the 1996-2018 survey periods (summer/fall). Predictions are shown for the study area (1,141,800 km^2). White dots in the average plots show actual sighting locations from the respective SWFSC summer/fall ship surveys.

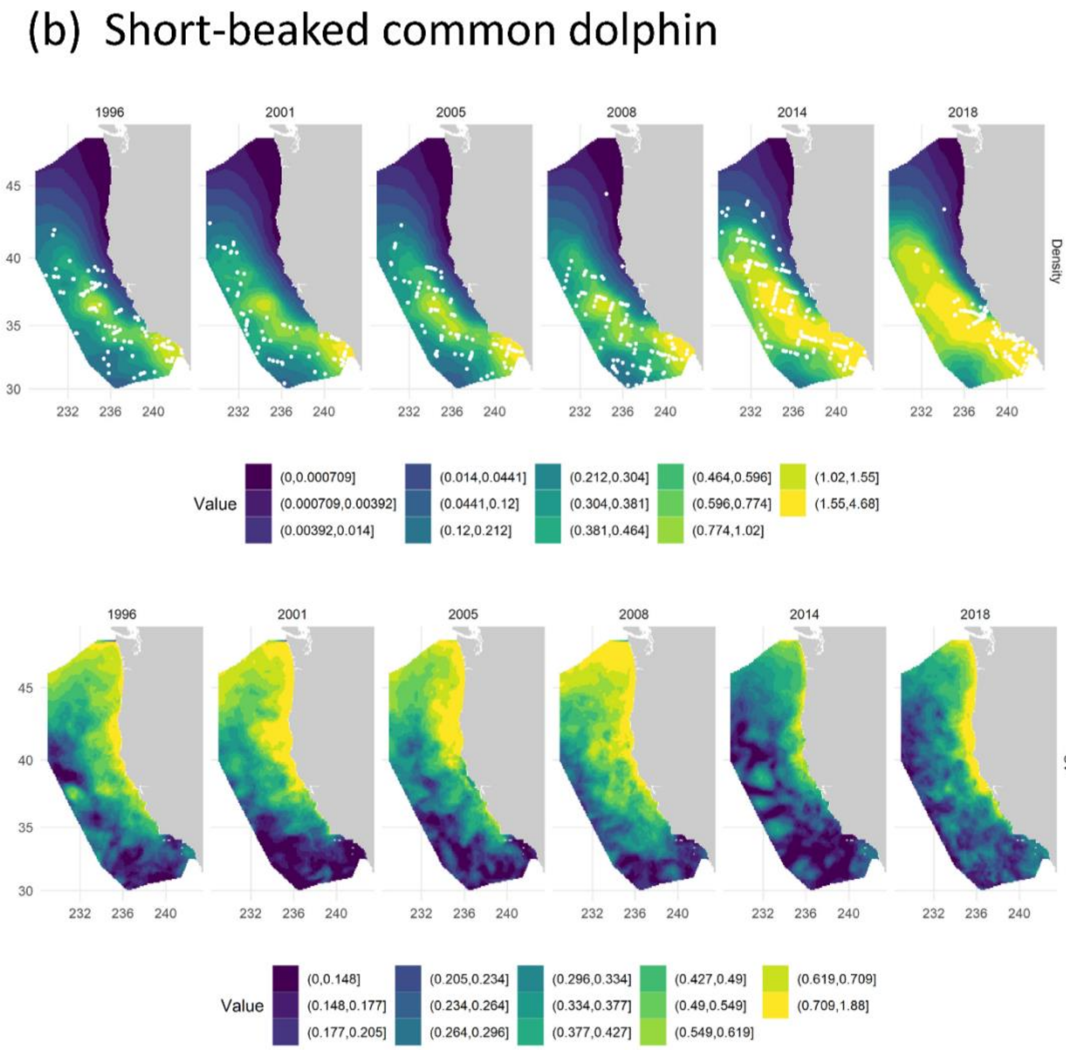


Figure 3b. Predicted annual (1996-2018) mean density (animals km^{-2}) and associated coefficients of variation (CV) from the 1991–2018 habitat-based density models for short-beaked common dolphin. Panels show the yearly average density based on predicted daily short-beaked common dolphin densities covering the 1996-2018 survey periods (summer/fall). Predictions are shown for the study area (1,141,800 km^2). White dots in the average plots show actual sighting locations from the respective SWFSC summer/fall ship surveys.

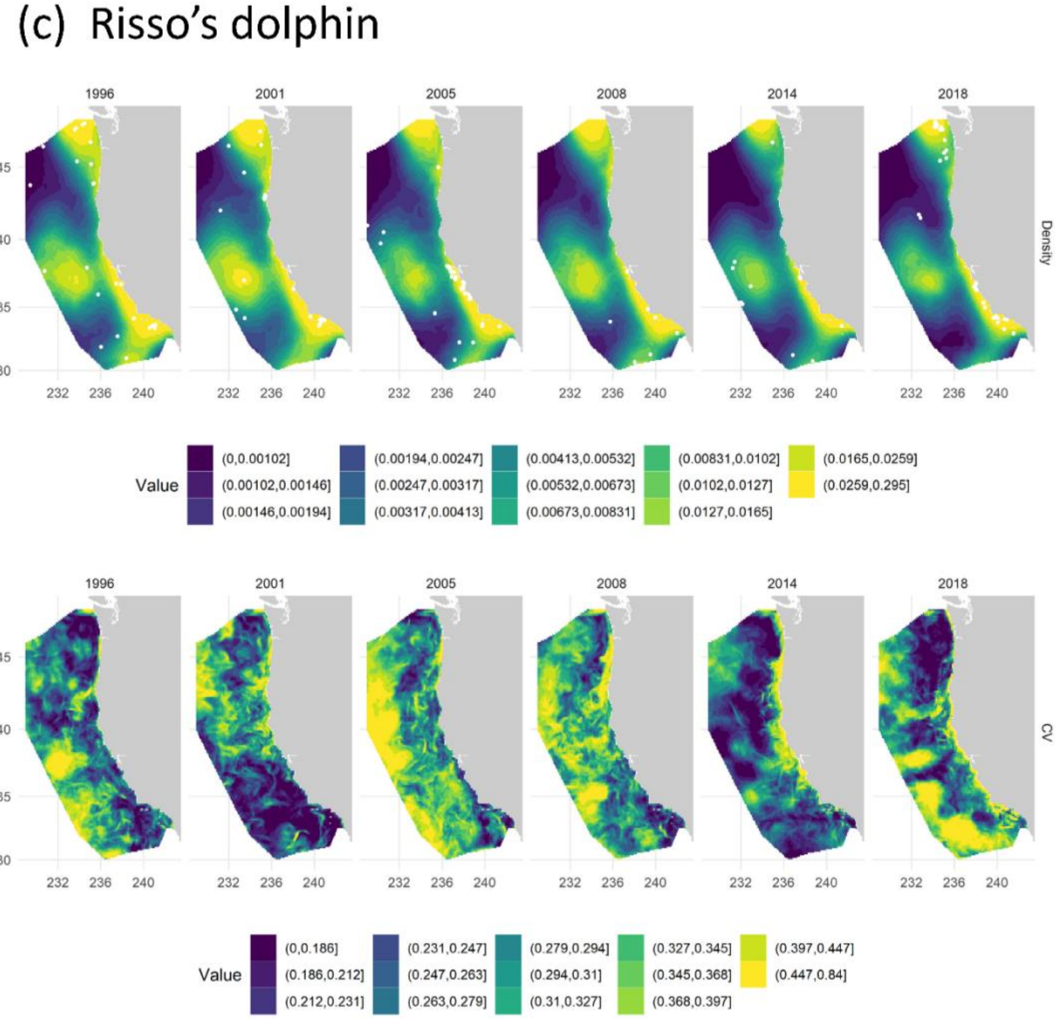


Figure 3c. Predicted annual (1996-2018) mean density (animals km^{-2}) and associated coefficients of variation (CV) from the 1991–2018 habitat-based density models for Risso's dolphin. Panels show the yearly average density based on predicted daily Risso's dolphin densities covering the 1996-2018 survey periods (summer/fall). Predictions are shown for the study area (1,141,800 km^2). White dots in the average plots show actual sighting locations from the respective SWFSC summer/fall ship surveys.

(d) Pacific white-sided dolphin

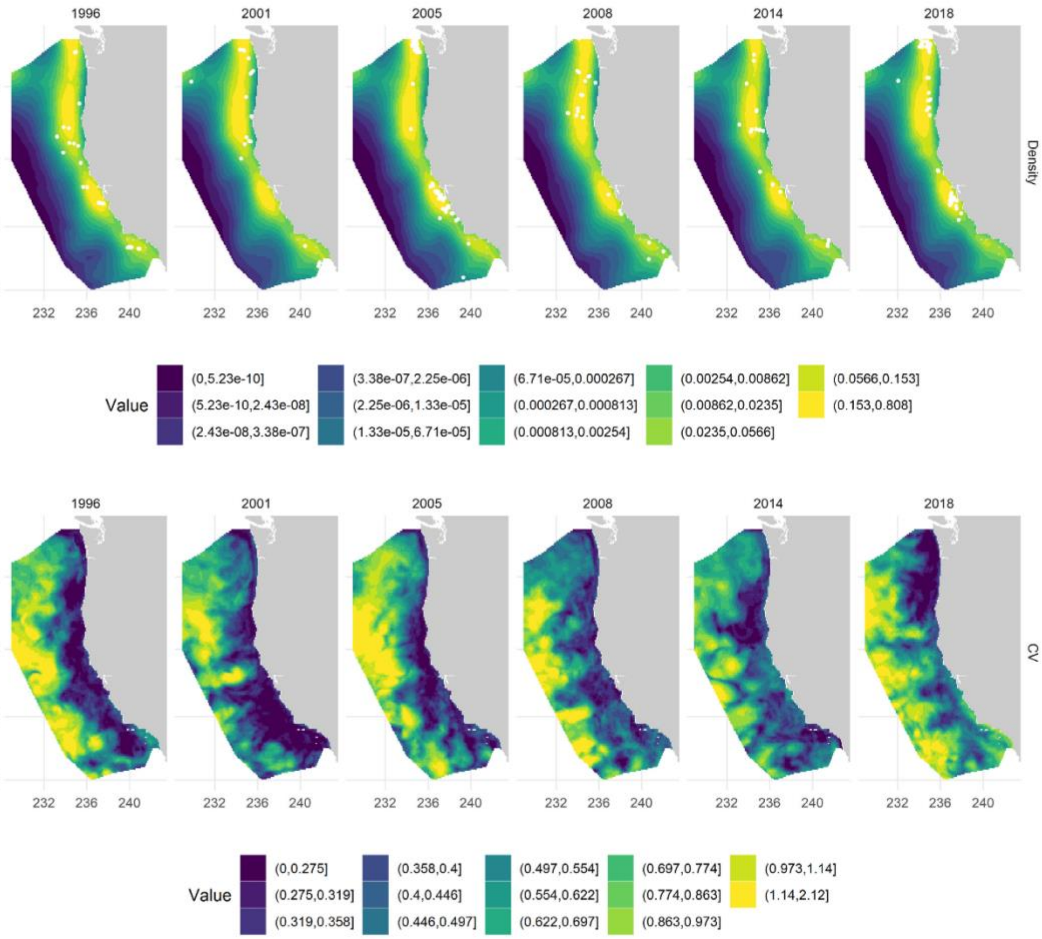


Figure 3d. Predicted annual (1996-2018) mean density (animals km^{-2}) and associated coefficients of variation (CV) from the 1991–2018 habitat-based density models for Pacific white-sided dolphin. Panels show the yearly average density based on predicted daily Pacific white-sided dolphin densities covering the 1996-2018 survey periods (summer/fall). Predictions are shown for the study area (1,141,800 km^2). White dots in the average plots show actual sighting locations from the respective SWFSC summer/fall ship surveys.

(e) Northern right whale dolphin

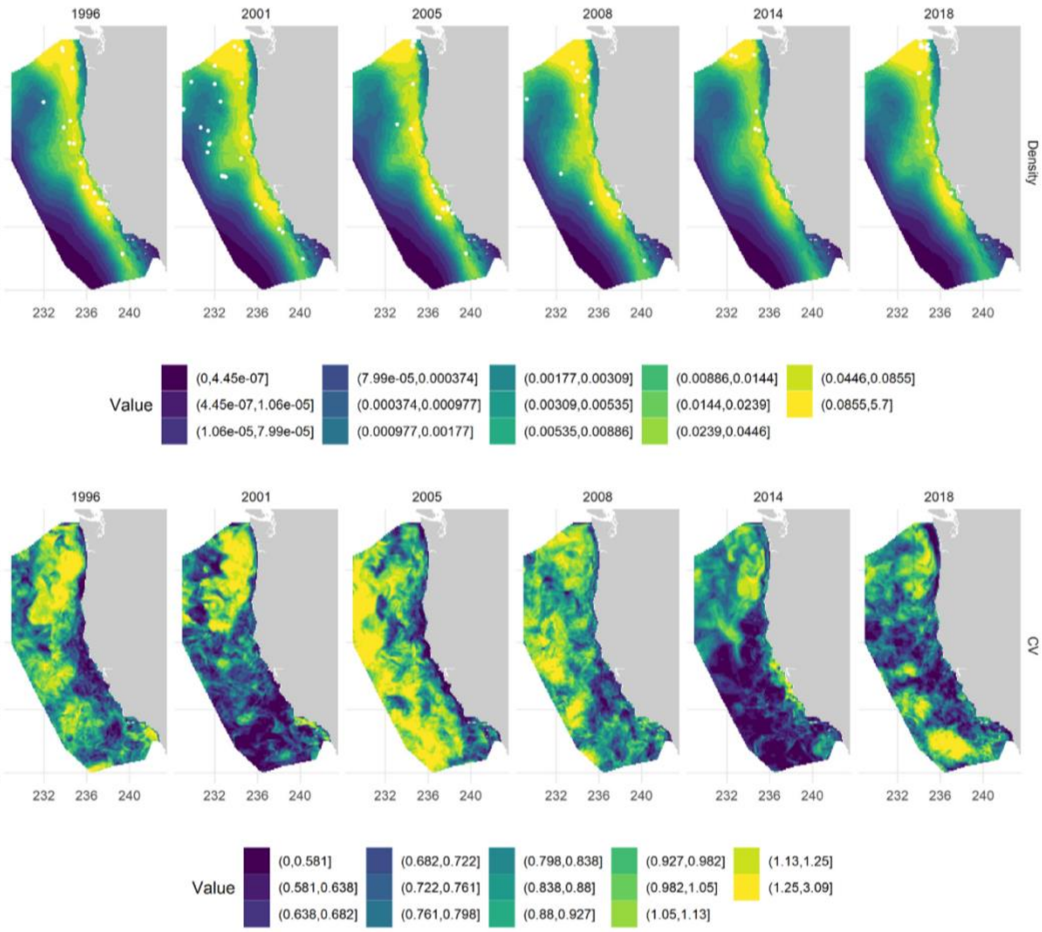


Figure 3e. Predicted annual (1996-2018) mean density (animals km^{-2}) and associated coefficients of variation (CV) from the 1991–2018 habitat-based density models for northern right whale dolphin. Panels show the yearly average density based on predicted daily northern right whale dolphin densities covering the 1996-2018 survey periods (summer/fall). Predictions are shown for the study area (1,141,800 km^2). White dots in the average plots show actual sighting locations from the respective SWFSC summer/fall ship surveys.

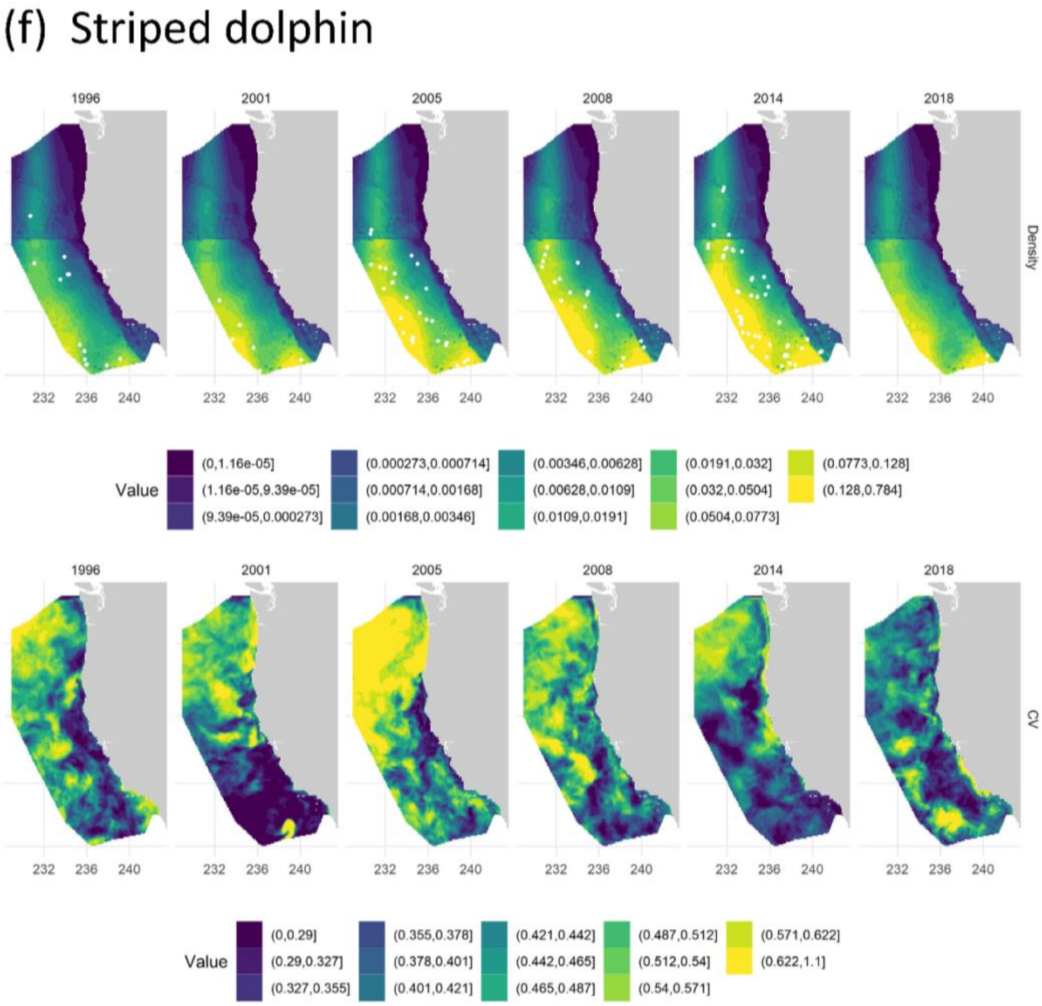


Figure 3f. Predicted annual (1996-2018) mean density (animals km^{-2}) and associated coefficients of variation (CV) from the 1991–2018 habitat-based density models for striped dolphin. Panels show the yearly average density based on predicted daily striped dolphin densities covering the 1996-2018 survey periods (summer/fall). Predictions are shown for the study area (1,141,800 km^{2}). White dots in the average plots show actual sighting locations from the respective SWFSC summer/fall ship surveys.

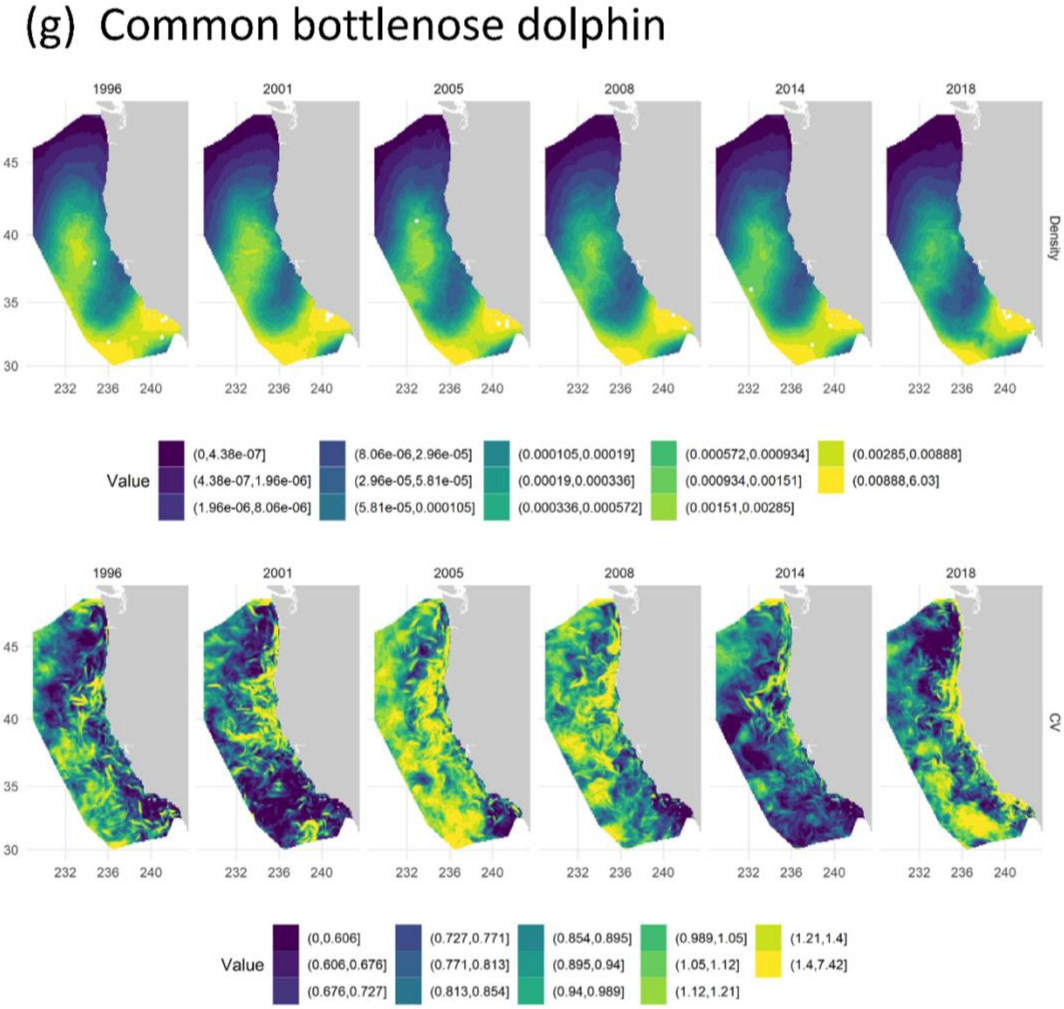


Figure 3g. Predicted annual (1996-2018) mean density (animals km^{-2}) and associated coefficients of variation (CV) from the 1991–2018 habitat-based density models for common bottlenose dolphin. Panels show the yearly average density based on predicted daily common bottlenose dolphin densities covering the 1996-2018 survey periods (summer/fall). Predictions are shown for the study area (1,141,800 km^2). White dots in the average plots show actual sighting locations from the respective SWFSC summer/fall ship surveys.

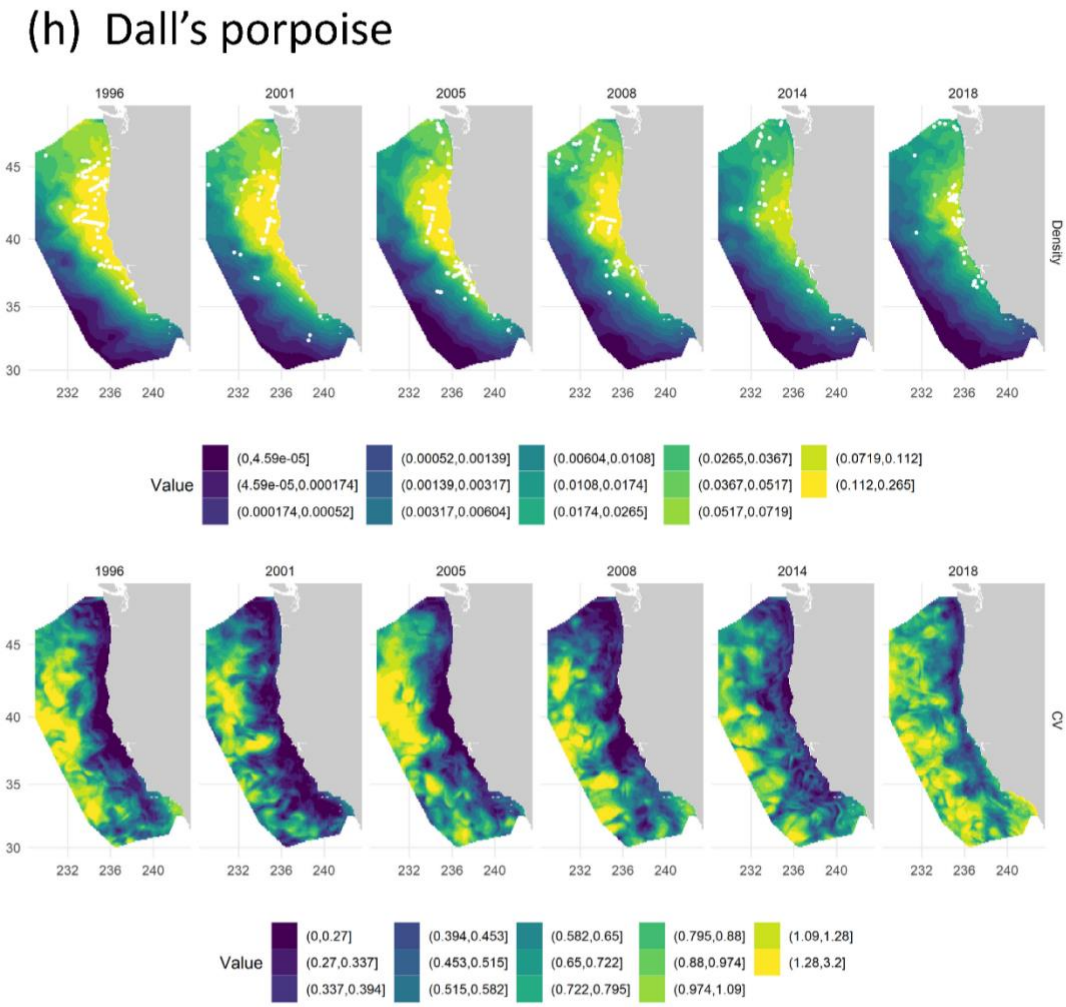


Figure 3h. Predicted annual (1996-2018) mean density (animals km^{-2}) and associated coefficients of variation (CV) from the 1991–2018 habitat-based density models for Dall's porpoise. Panels show the yearly average density based on predicted daily Dall's porpoise densities covering the 1996-2018 survey periods (summer/fall). Predictions are shown for the study area (1,141,800 km^2). White dots in the average plots show actual sighting locations from the respective SWFSC summer/fall ship surveys.

(i) Sperm whale

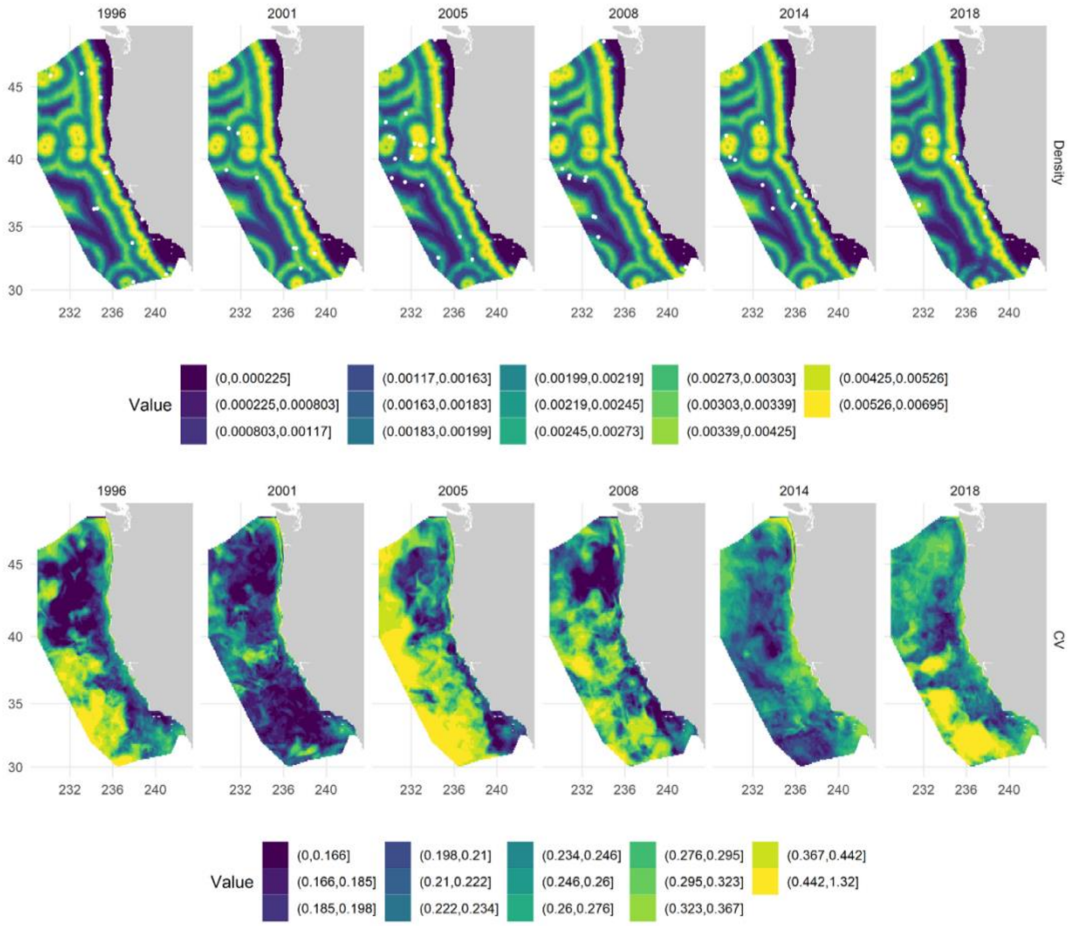


Figure 3i. Predicted annual (1996-2018) mean density (animals km^{-2}) and associated coefficients of variation (CV) from the 1991–2018 habitat-based density models for sperm whale. Panels show the yearly average density based on predicted daily sperm whale densities covering the 1996-2018 survey periods (summer/fall). Predictions are shown for the study area (1,141,800 km^2). White dots in the average plots show actual sighting locations from the respective SWFSC summer/fall ship surveys.

(j) Minke whale

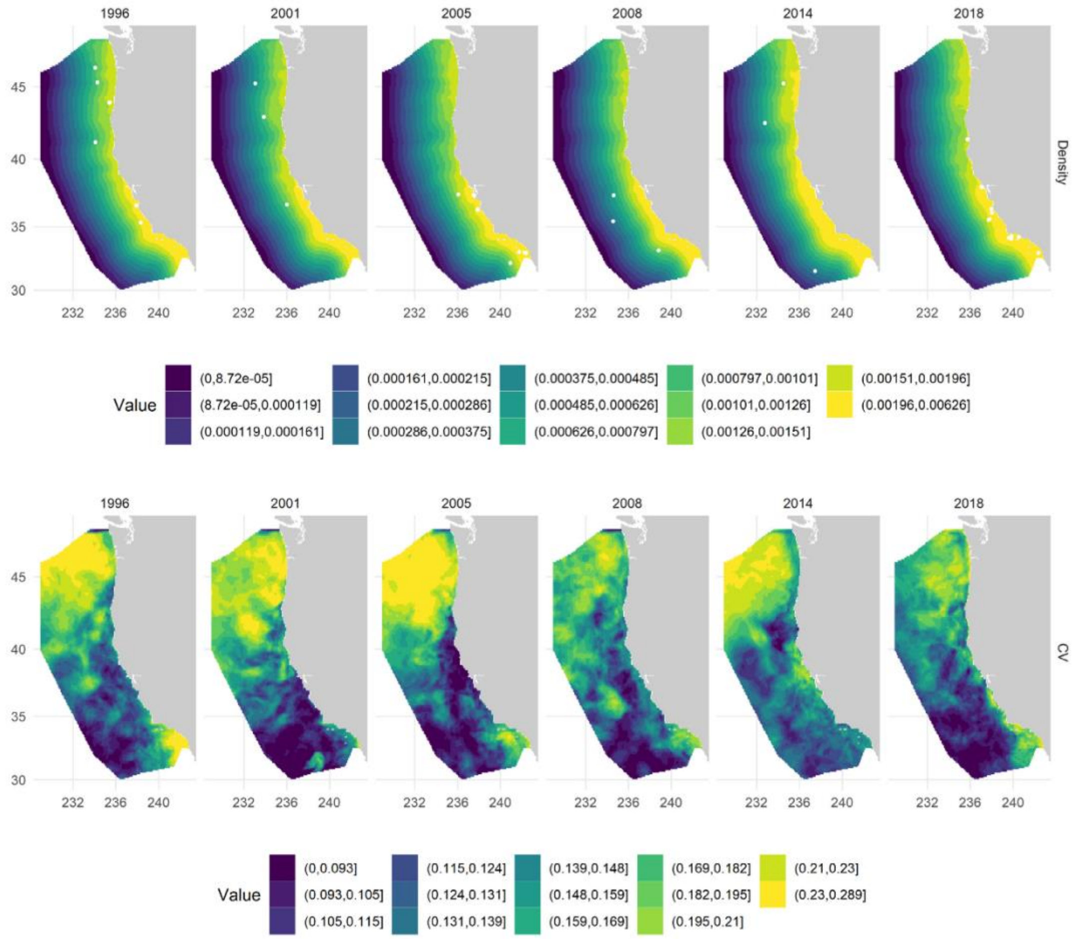


Figure 3j. Predicted annual (1996-2018) mean density (animals km^{-2}) and associated coefficients of variation (CV) from the 1991–2018 habitat-based density models for minke whale. Panels show the yearly average density based on predicted daily minke whale densities covering the 1996-2018 survey periods (summer/fall). Predictions are shown for the study area (1,141,800 km^{2}). White dots in the average plots show actual sighting locations from the respective SWFSC summer/fall ship surveys.

(k) Blue whale

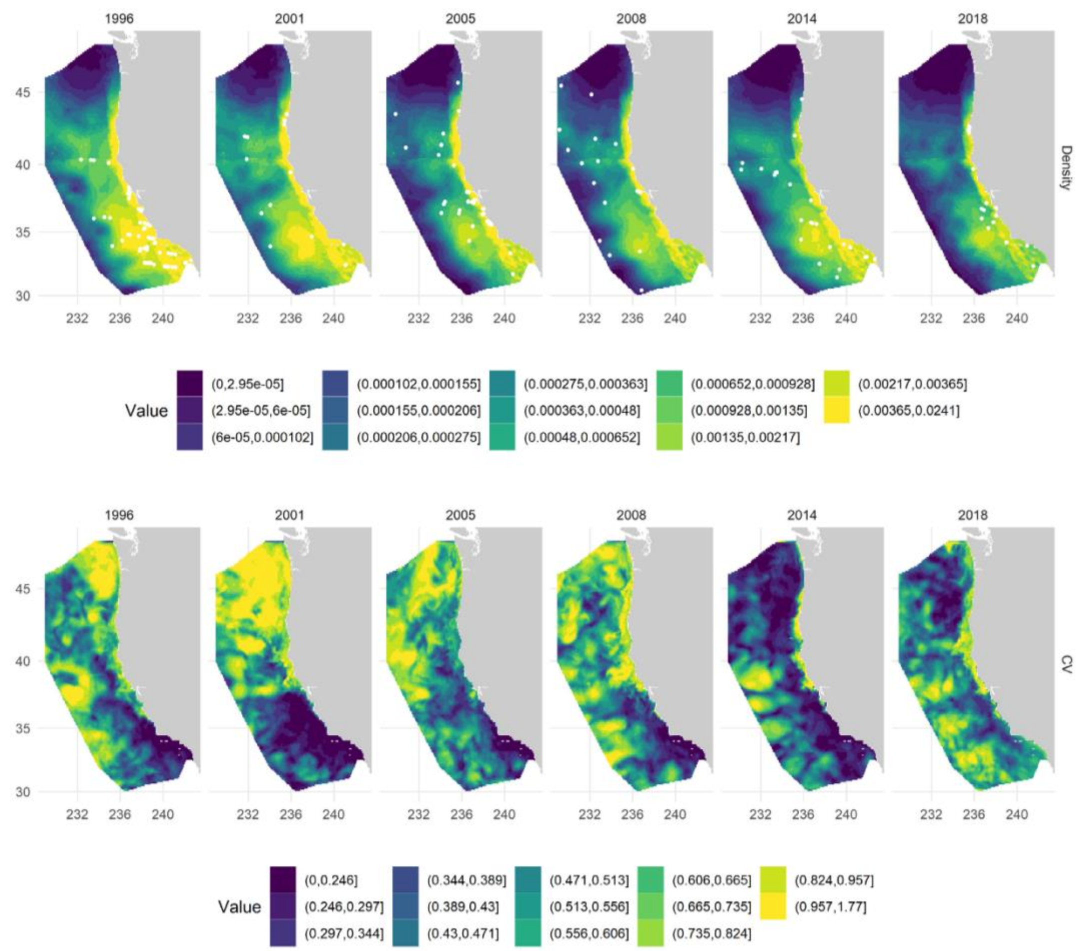


Figure 3k. Predicted annual (1996-2018) mean density (animals km^{-2}) and associated coefficients of variation (CV) from the 1991–2018 habitat-based density models for blue whale. Panels show the yearly average density based on predicted blue whale densities covering the 1996-2018 survey periods (summer/fall). Predictions are shown for the study area (1,141,800 km^2). White dots in the average plots show actual sighting locations from the respective SWFSC summer/fall ship surveys.

(l) Fin whale

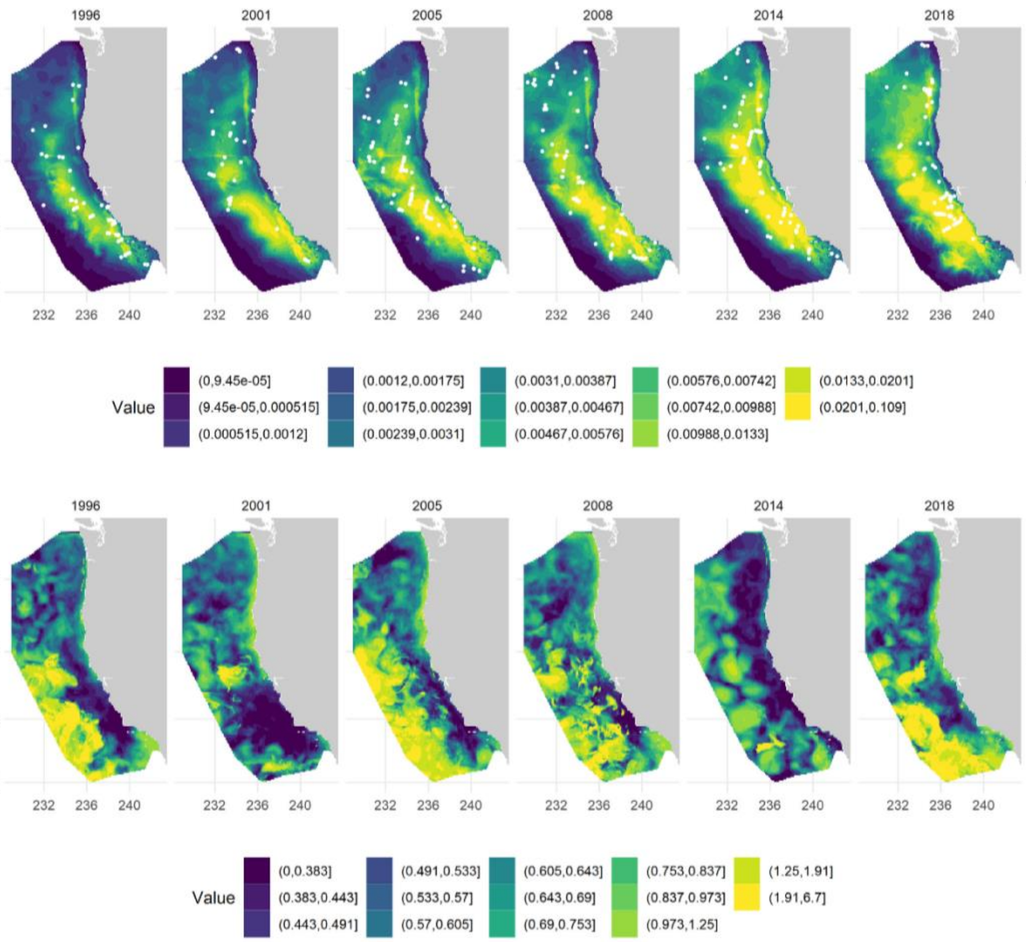


Figure 3l. Predicted annual (1996-2018) mean density (animals km^{-2}) and associated coefficients of variation (CV) from the 1991–2018 habitat-based density models for fin whale. Panels show the yearly average density based on predicted fin whale densities covering the 1996-2018 survey periods (summer/fall). Predictions are shown for the study area (1,141,800 km^{2}). White dots in the average plots show actual sighting locations from the respective SWFSC summer/fall ship surveys.

(m) Humpback whale

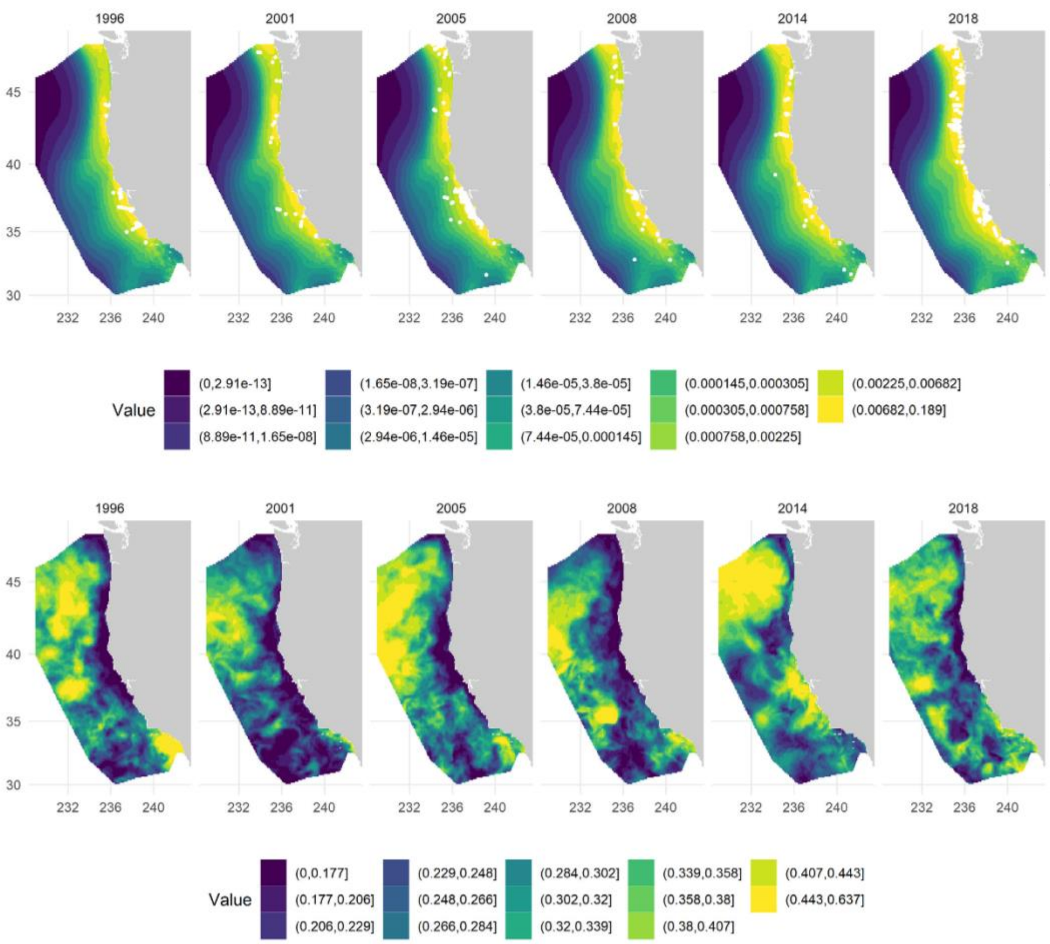


Figure 3m. Predicted annual (1996-2018) mean density (animals km^{-2}) and associated coefficients of variation (CV) from the 1991–2018 habitat-based density models for humpback whale. Panels show the yearly average density based on predicted humpback whale densities covering the 1996-2018 survey periods (summer/fall). Predictions are shown for the study area (1,141,800 km^{2}). White dots in the average plots show actual sighting locations from the respective SWFSC summer/fall ship surveys.

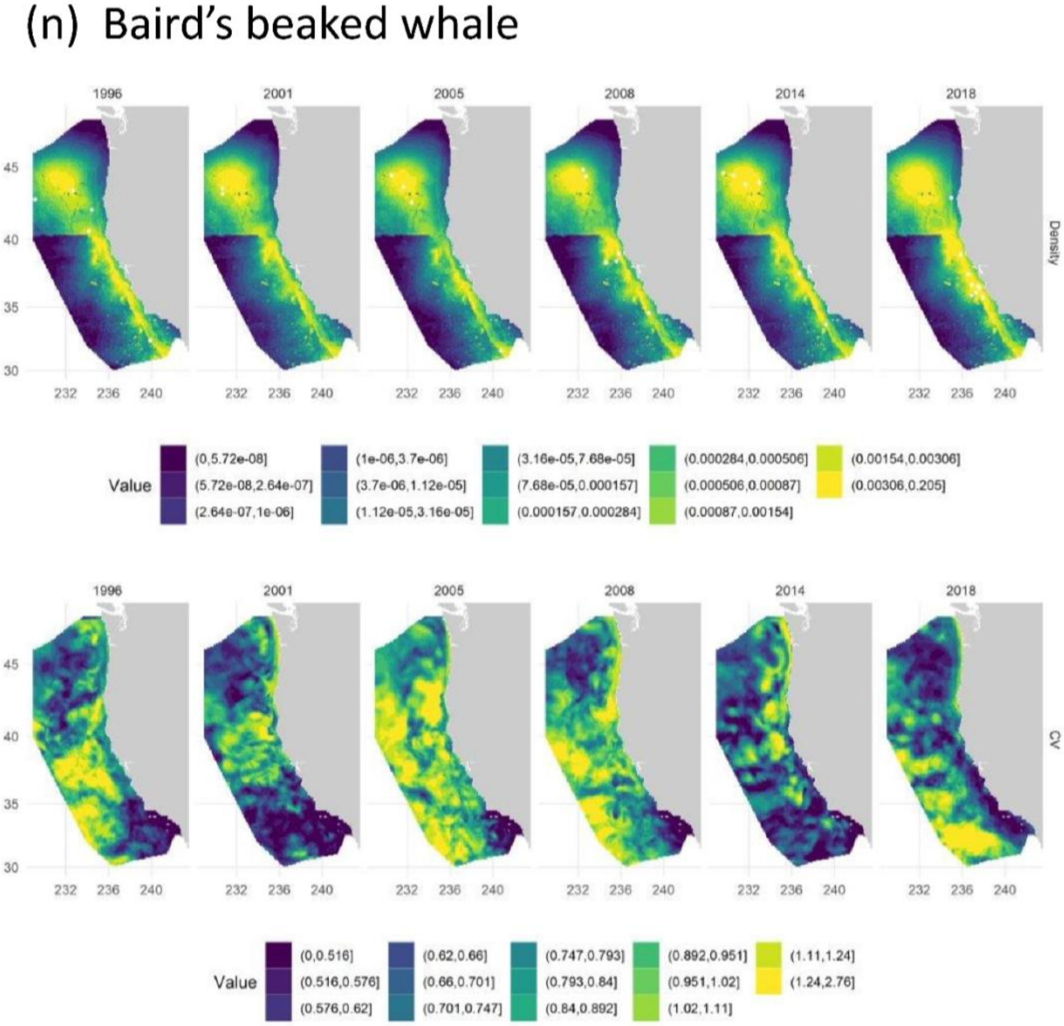


Figure 3n. Predicted annual (1996-2018) mean density (animals km^{-2}) and associated coefficients of variation (CV) from the 1991–2018 habitat-based density models for Baird's beaked whale. Panels show the yearly average density based on predicted Baird's beaked whale densities covering the 1996-2018 survey periods (summer/fall). Predictions are shown for the study area (1,141,800 km^{2}). White dots in the average plots show actual sighting locations from the respective SWFSC summer/fall ship surveys.

(o) Small beaked whale guild

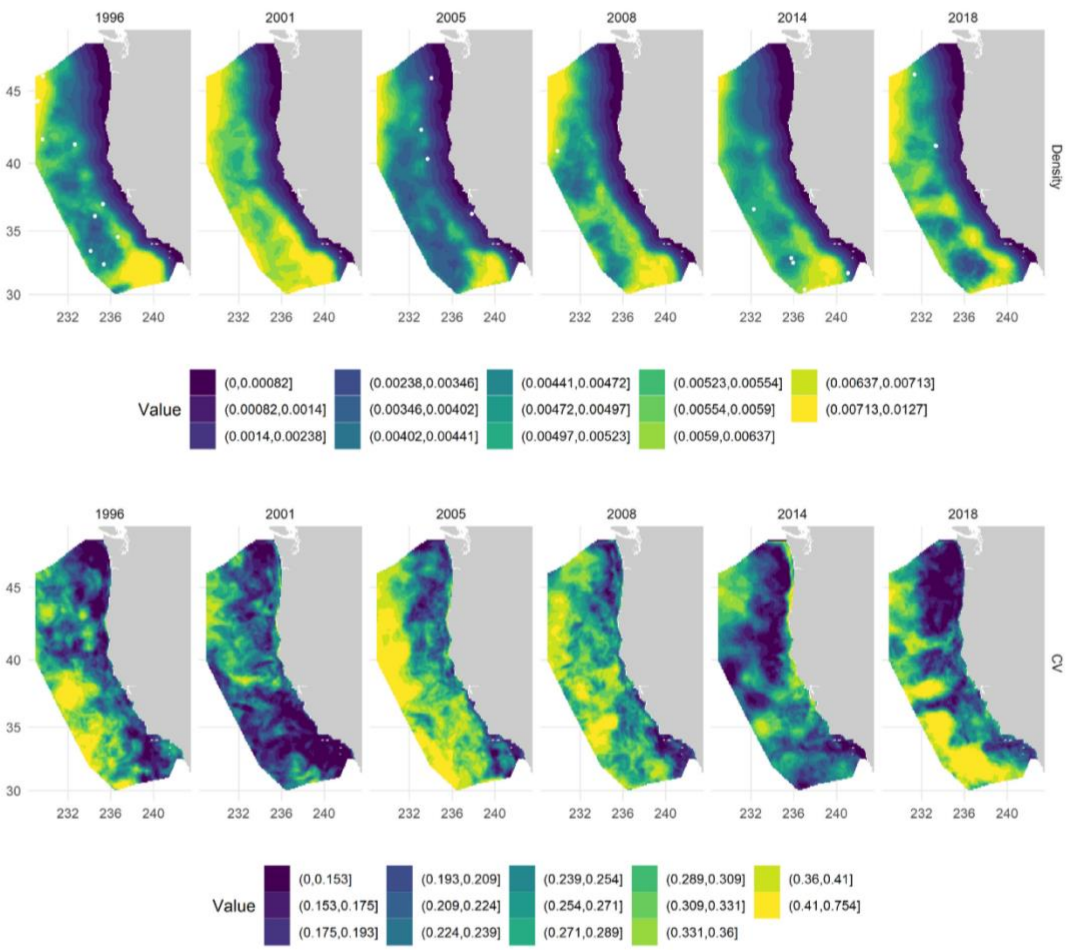


Figure 3o. Predicted annual (1996-2018) mean density (animals km^{-2}) and associated coefficients of variation (CV) from the 1991–2018 habitat-based density models for the small beaked whale guild (Mesoplodonts and Cuvier's beaked whale). Panels show the yearly average density based on predicted small beaked whale guild densities covering the 1996-2018 survey periods (summer/fall). Predictions are shown for the study area (1,141,800 km^2). White dots in the average plots show actual sighting locations from the respective SWFSC summer/fall ship surveys.

Appendix A: SDM functional plots

Final SDM response curves for (1) long-beaked common dolphin, (2) short-beaked common dolphin, (3) Risso's dolphin, (4), Pacific white-sided dolphin, (5) northern right whale dolphin, (6) striped dolphin, (7) common bottlenose dolphin, (8) sperm whale, (9) minke whale, (10) blue whale, (11) fin whale, (12) humpback whale, (13) Baird's beaked whale, and (14) the small beaked whale guild (*Mesoplondon* spp. and Cuvier's beaked whale). The suite of environmental and geographic covariates included: SST = sea surface temperature, sdSST = standard deviation of SST, MLD = mixed layer depth, SSH = sea surface height, sdSSH = standard deviation of SSH, depth = bathymetric depth, dShelf = distance to the 200m isobath, d2000 = distance to the 2,000m isobath, mlat = latitude, mlon = longitude, and yearCoVar = year. Models were constructed with both linear terms and smoothing splines. Degrees of freedom for single variables are shown in the parentheses on the y-axis. Variables for the interaction terms are shown on the x- and y-axes. For single variables the y-axes represent the term's (linear or spline) function. Zero on the y-axes corresponds to no effect of the predictor variable on the estimated response variable. Scaling of y-axis varies among predictor variables to emphasize model fit. The shading reflects 2x standard error bands (i.e., 95% confidence interval); tick marks ('rug plot') above the X axis show data values. For the interaction terms, yellow indicates higher prediction densities and red lower predicted densities.

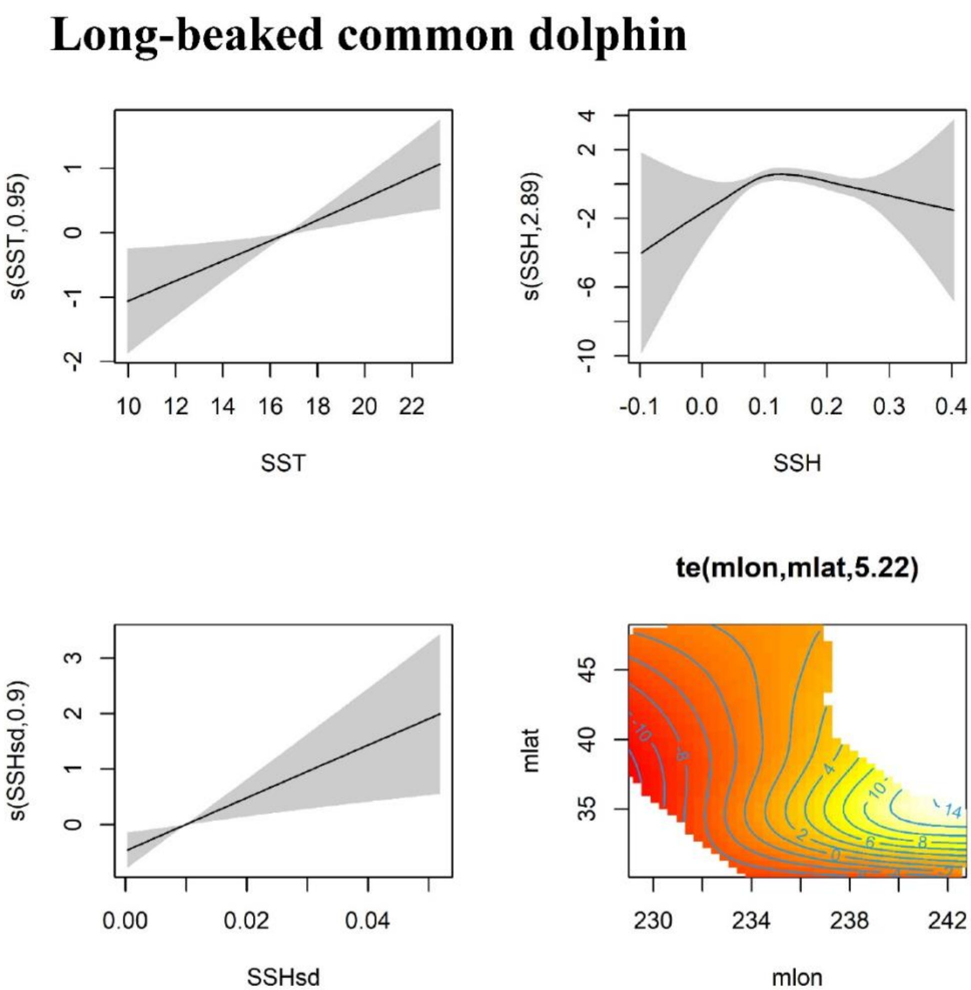


Figure A 1. Functional plot for long-beaked common dolphin (*Delphinus delphis bairdii*) encounter rate model.

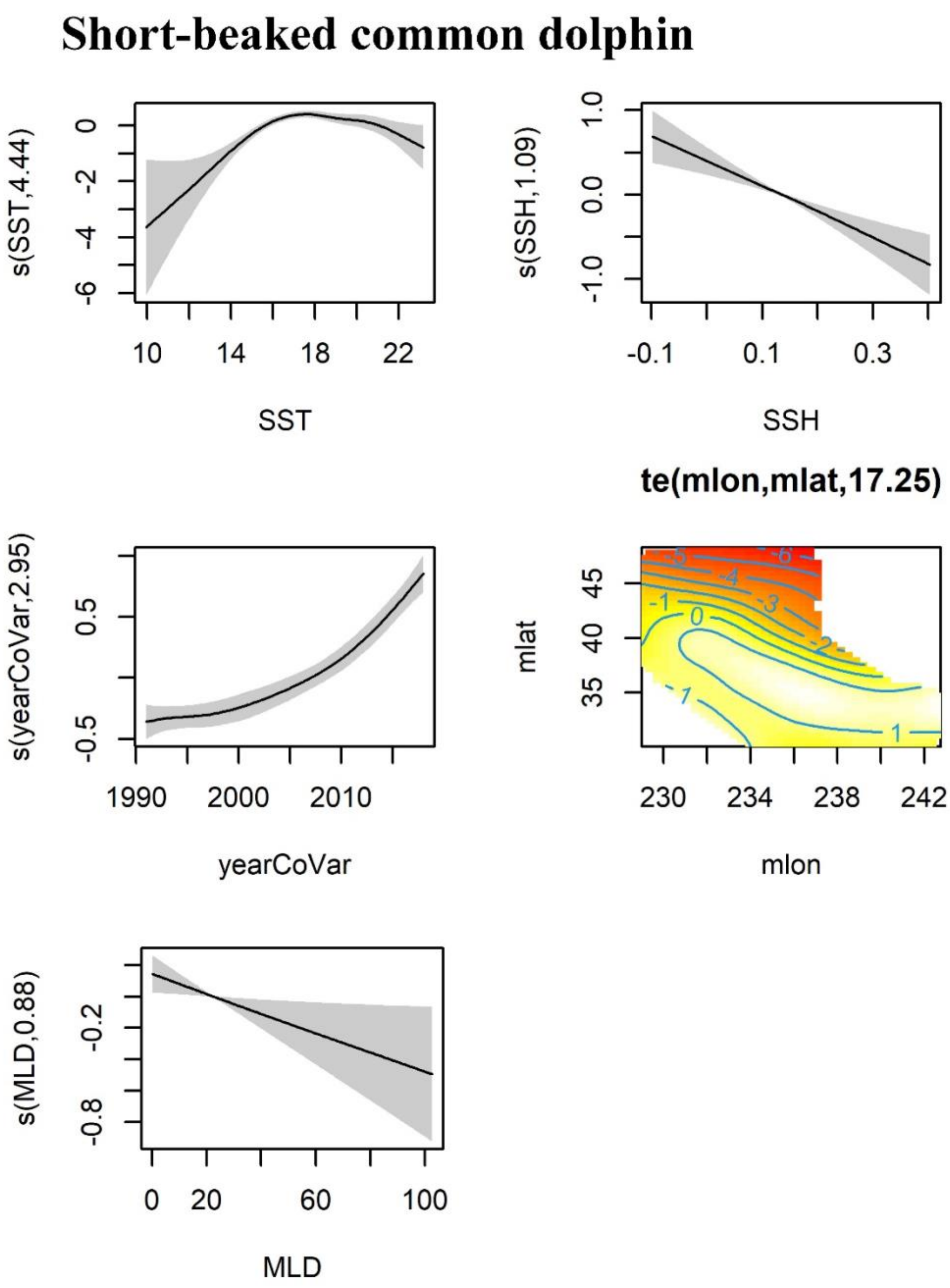


Figure A 2. Functional plot for short-beaked common dolphin (*Delphinus delphis delphis*) encounter rate model.

Risso's dolphin

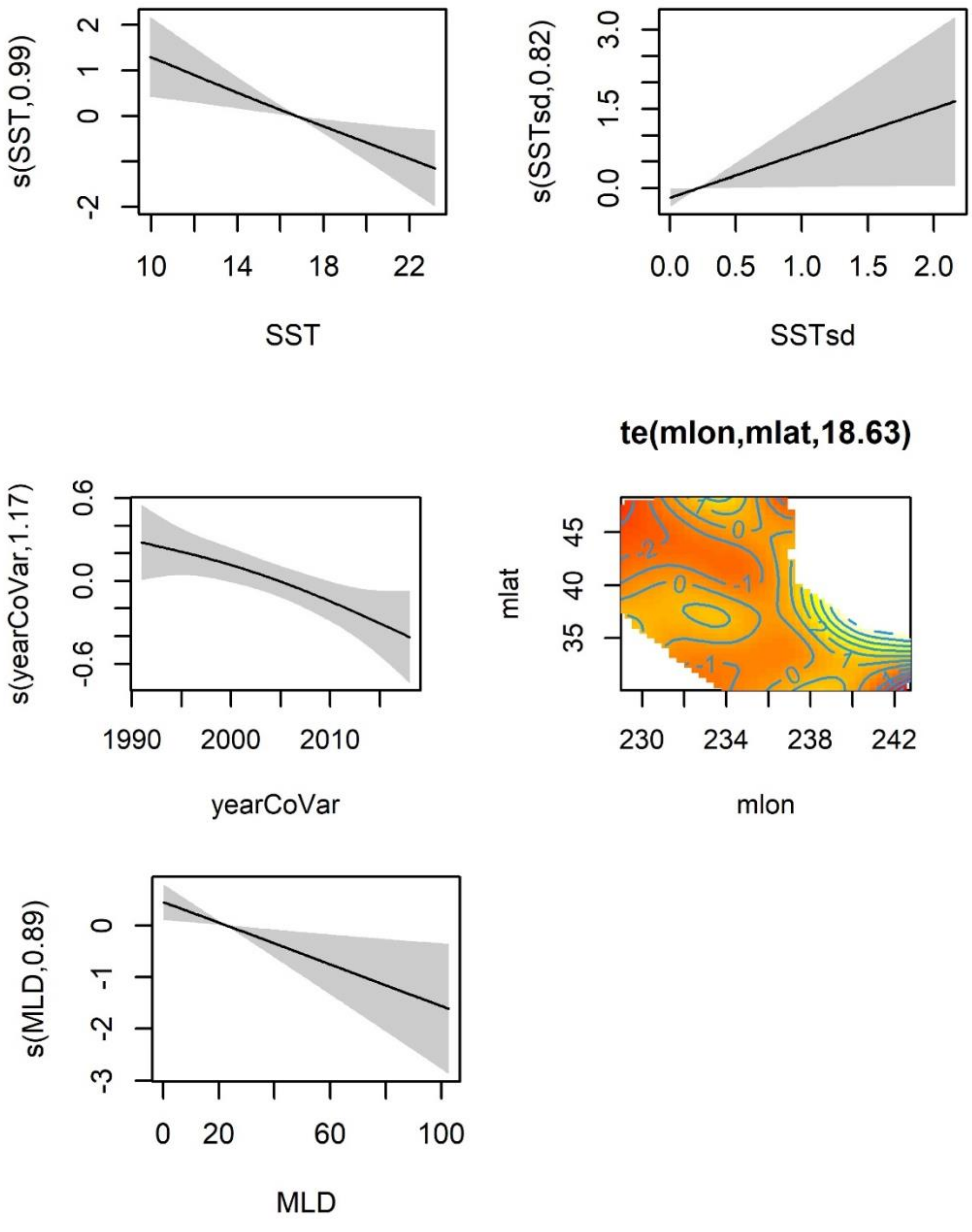


Figure A 3. Functional plot for Risso's dolphin (*Grampus griseus*) model.

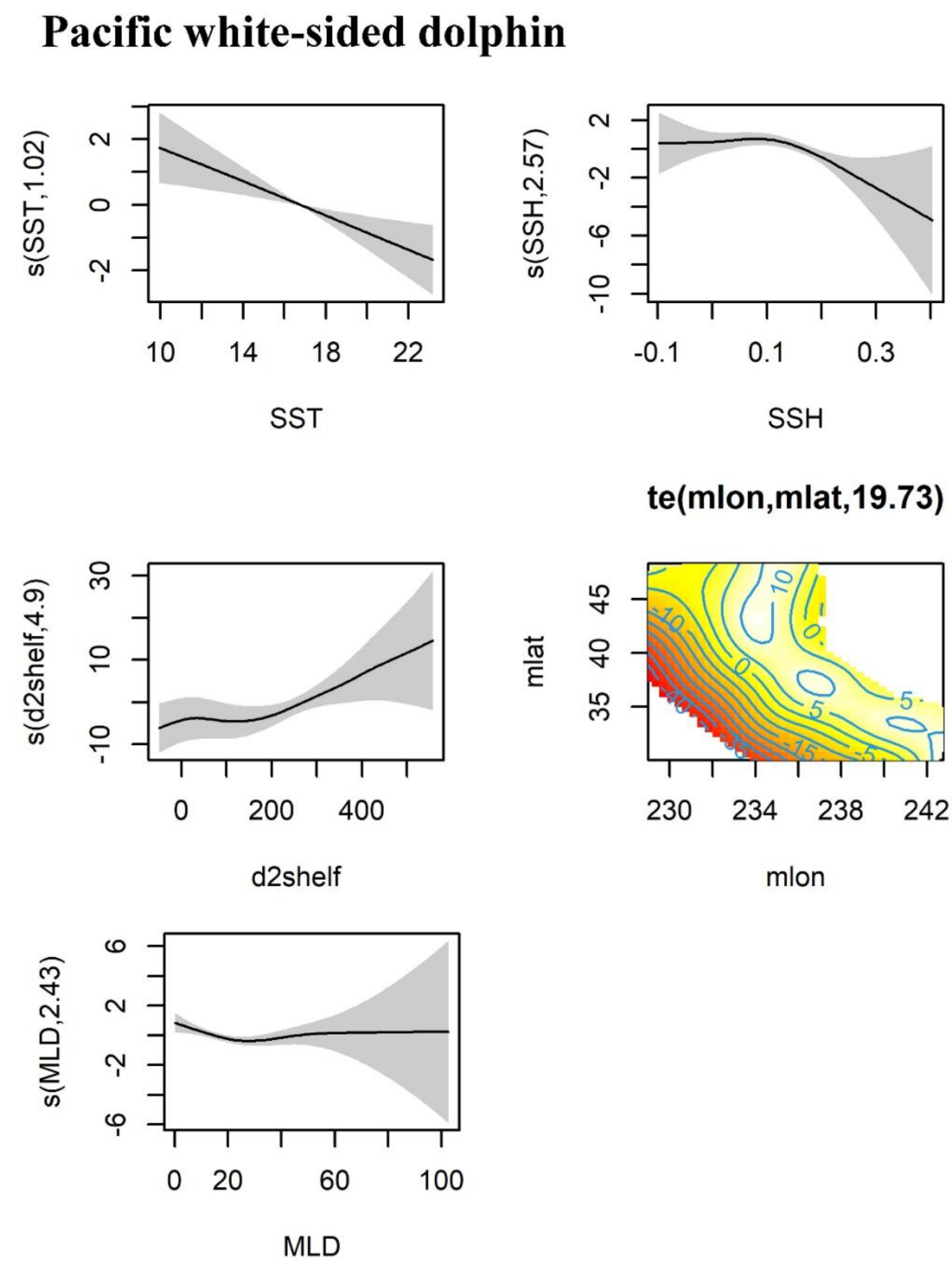


Figure A 4. Functional plot for Pacific white-sided dolphin (*Lagenorhynchus obliquidens*) model.

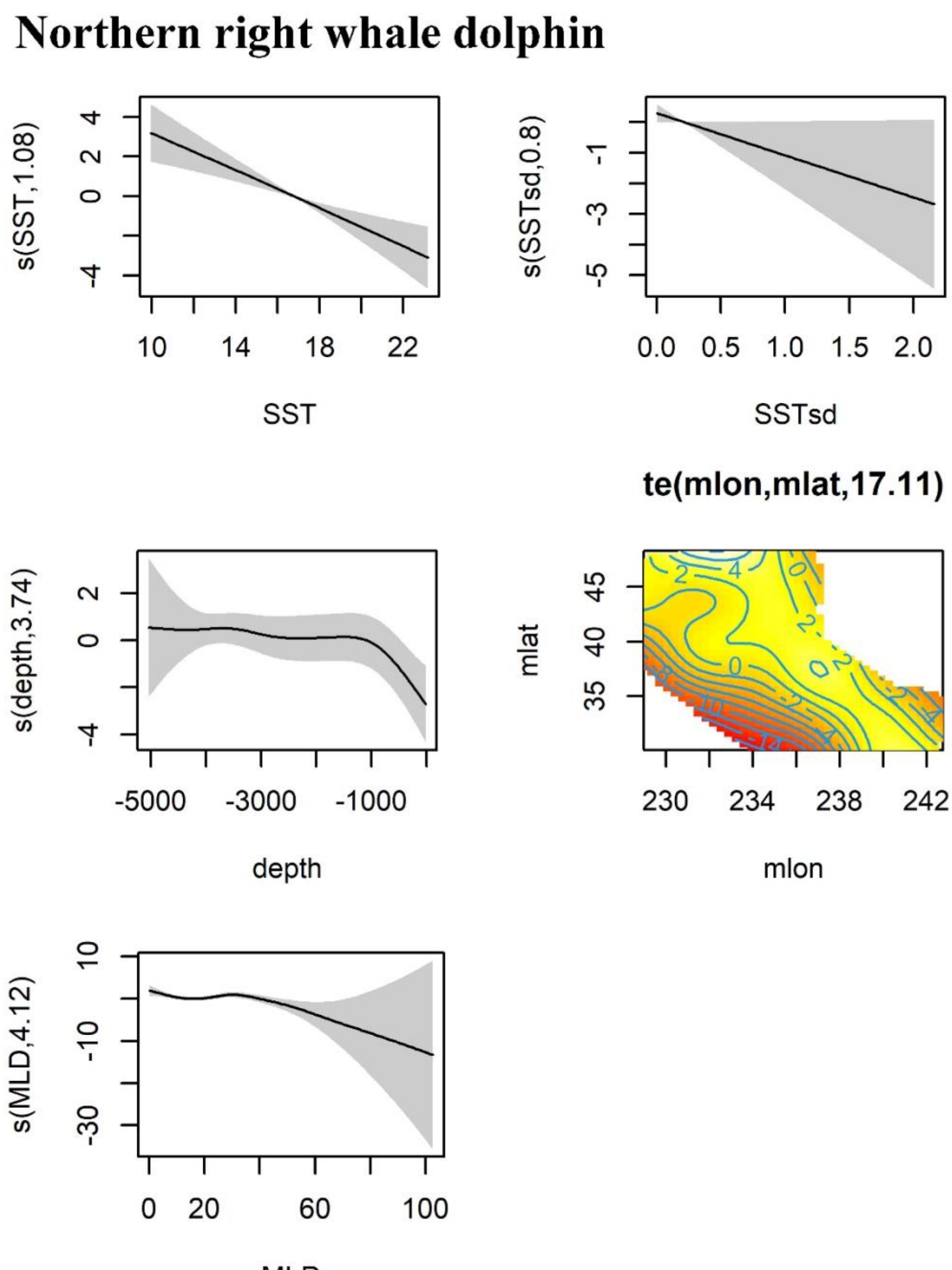


Figure A 5. Functional plot for northern right whale dolphin (*Lissodelphis borealis*) model.

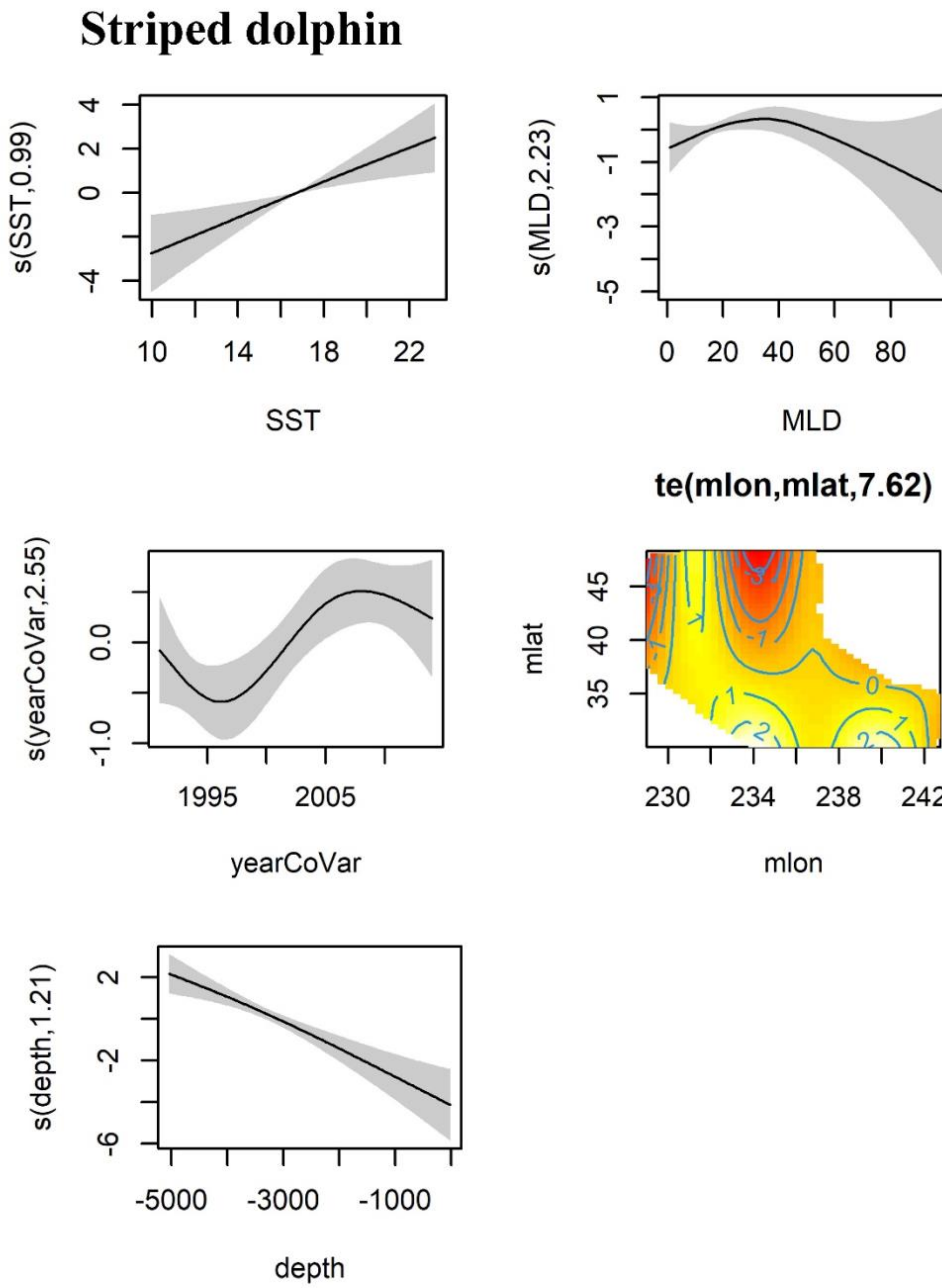


Figure A 6. Functional plot for striped dolphin (*Stenella coeruleoalba*) model.

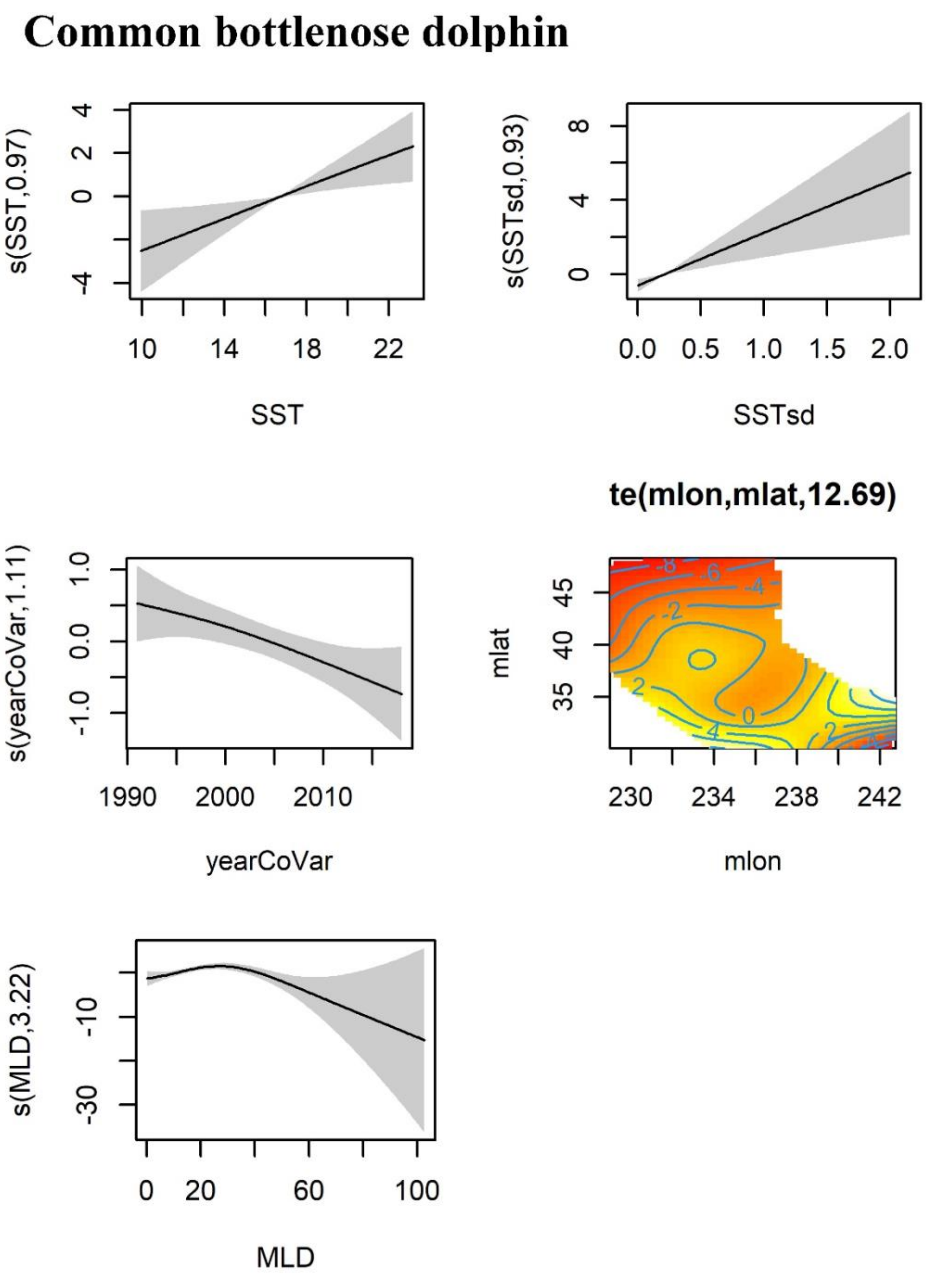


Figure A 7. Functional plot for common bottlenose dolphin (*Tursiops truncatus*) model.

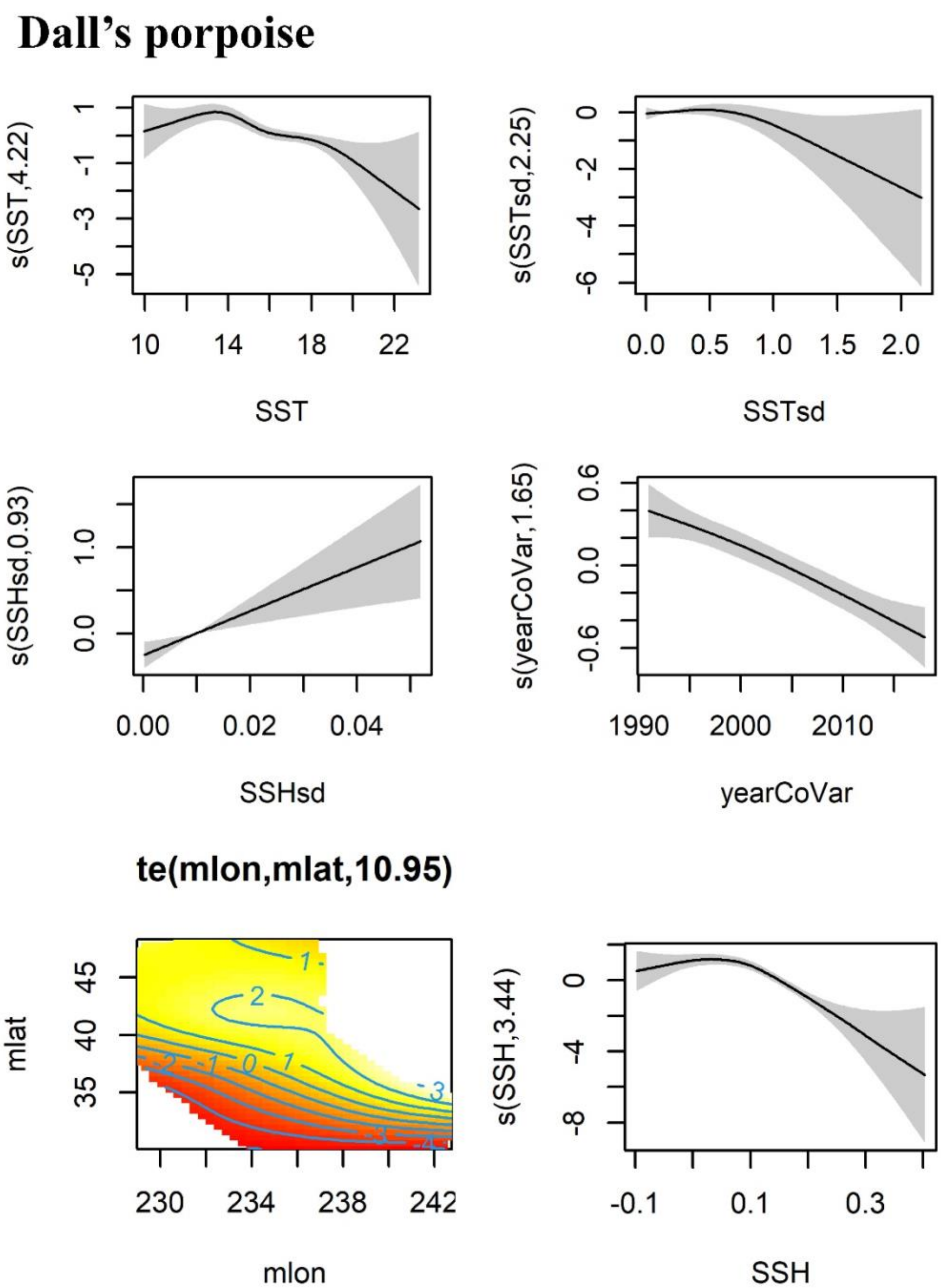


Figure A 8. Functional plot for Dall's porpoise (*Phocoenoides dalli*) model.

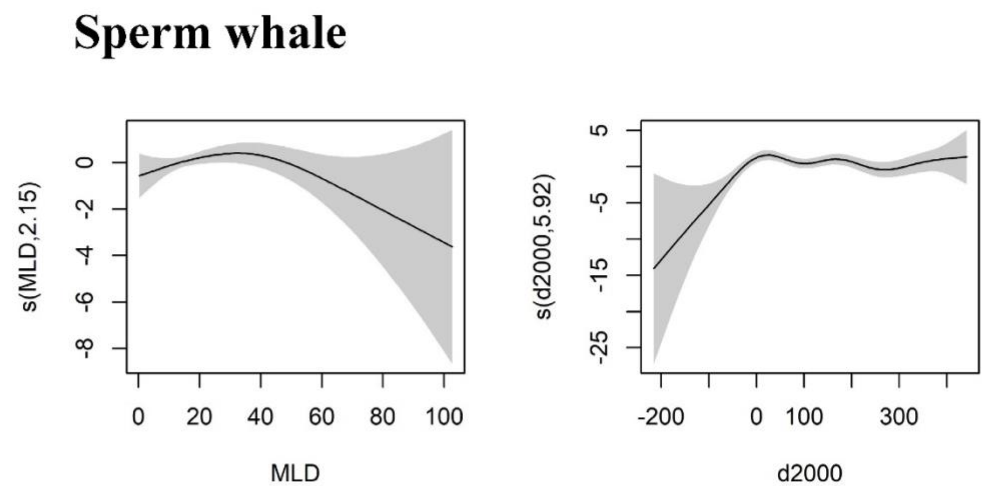


Figure A 9. Functional plot for sperm whale (*Physeter macrocephalus*) model.

Minke whale

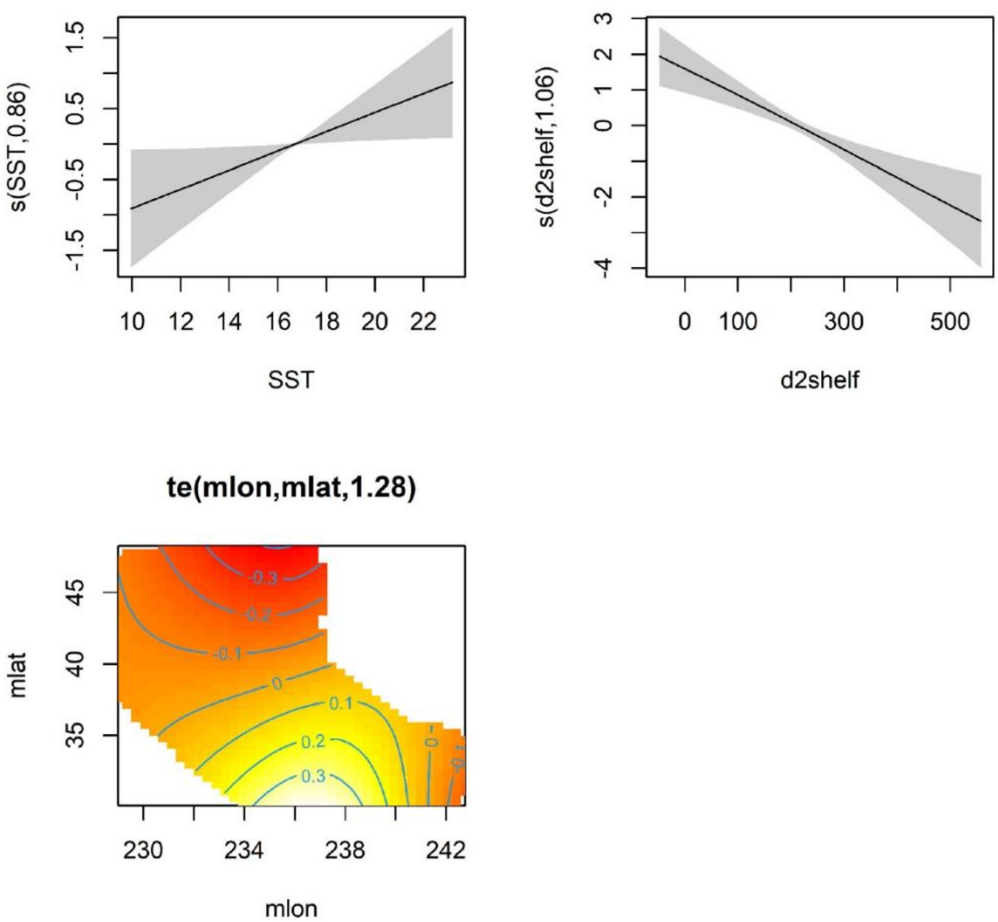


Figure A 10. Functional plot for minke whale (*Balaenoptera acutorostrata*) model.

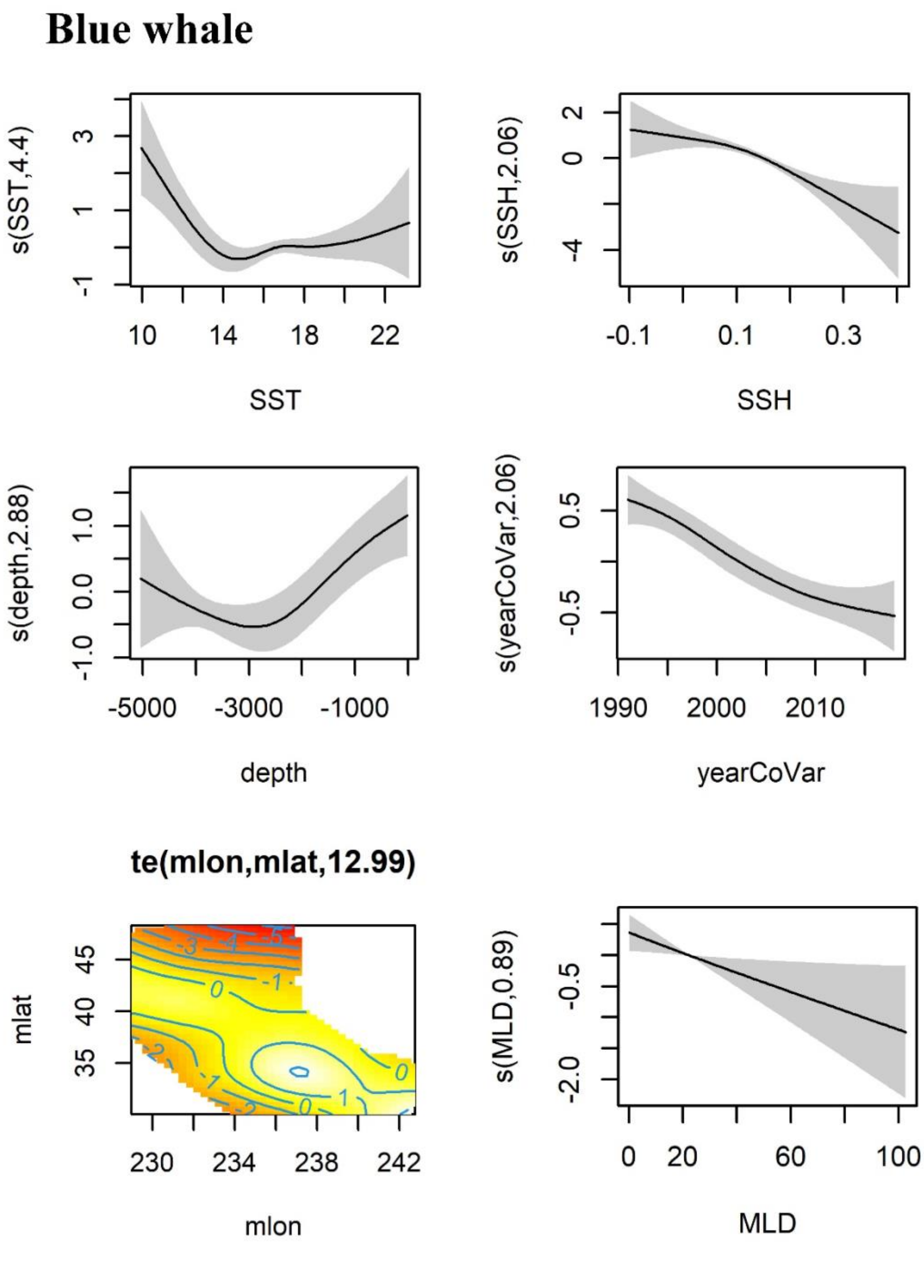


Figure A 11. Functional plot for blue whale (*Balaenoptera musculus*) model.

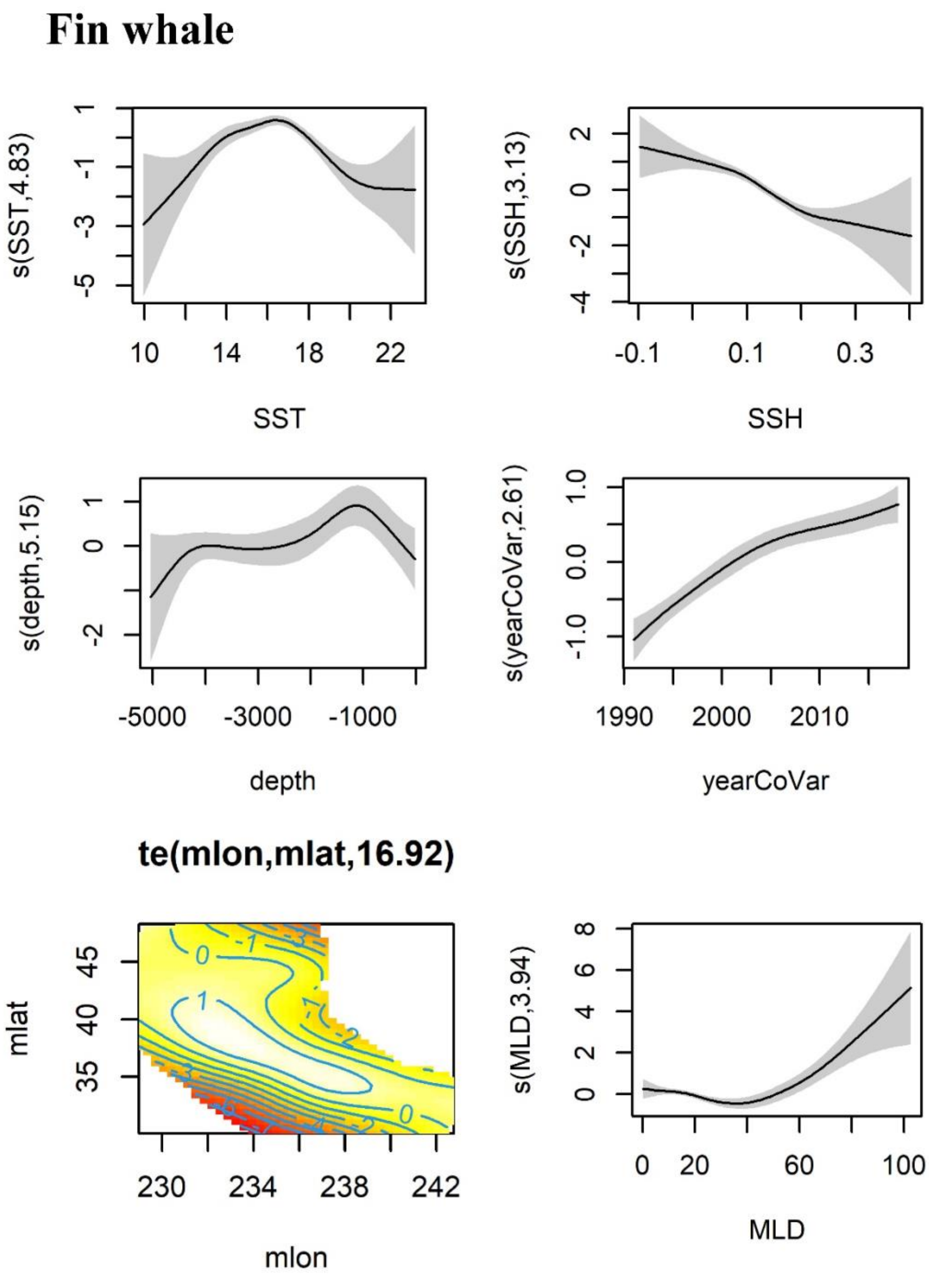


Figure A 12. Functional plot for fin whale (*Balaenoptera physalus*) model.

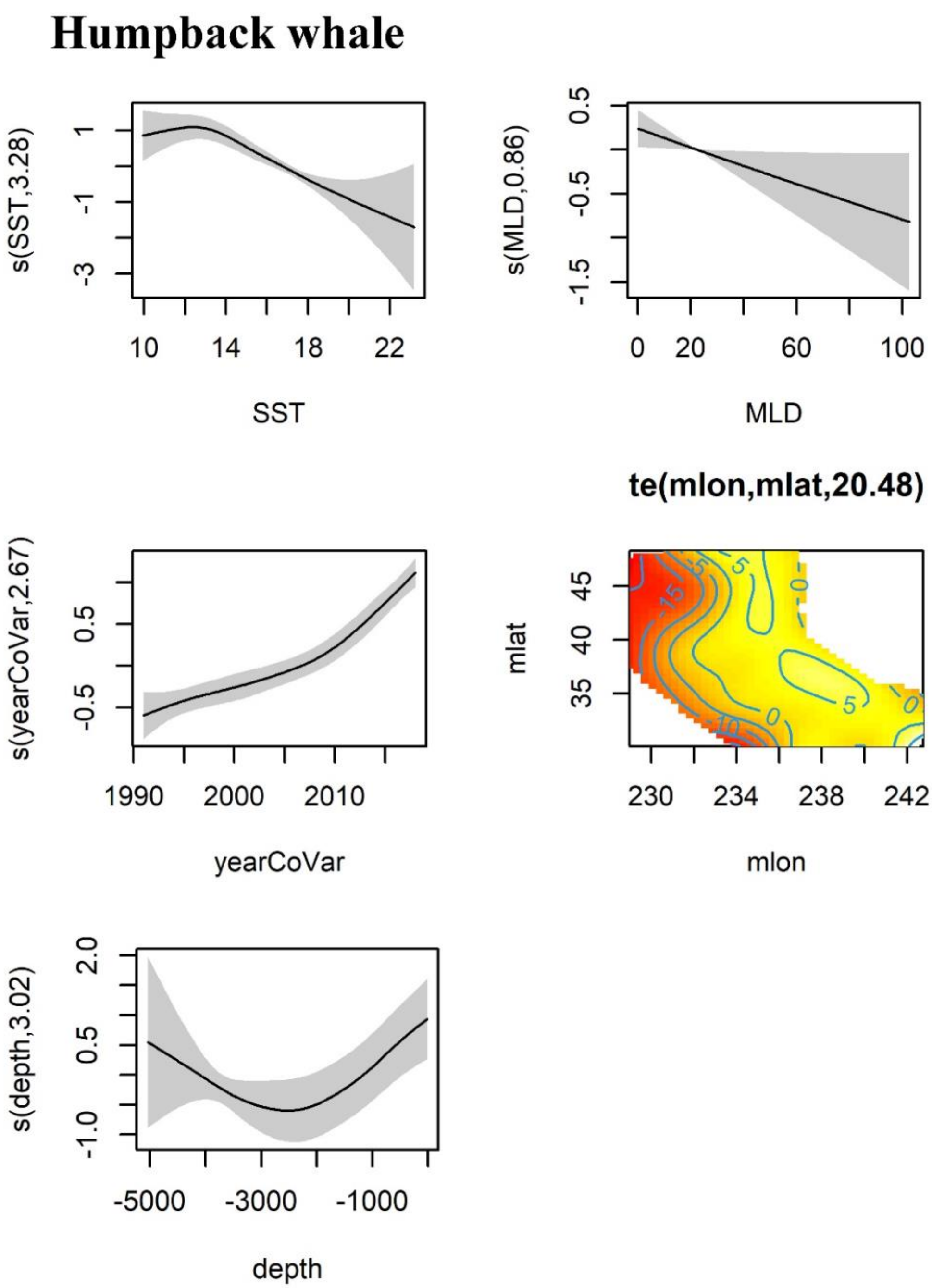


Figure A 13. Functional plot for fin whale (*Megaptera novaeangliae*) model.

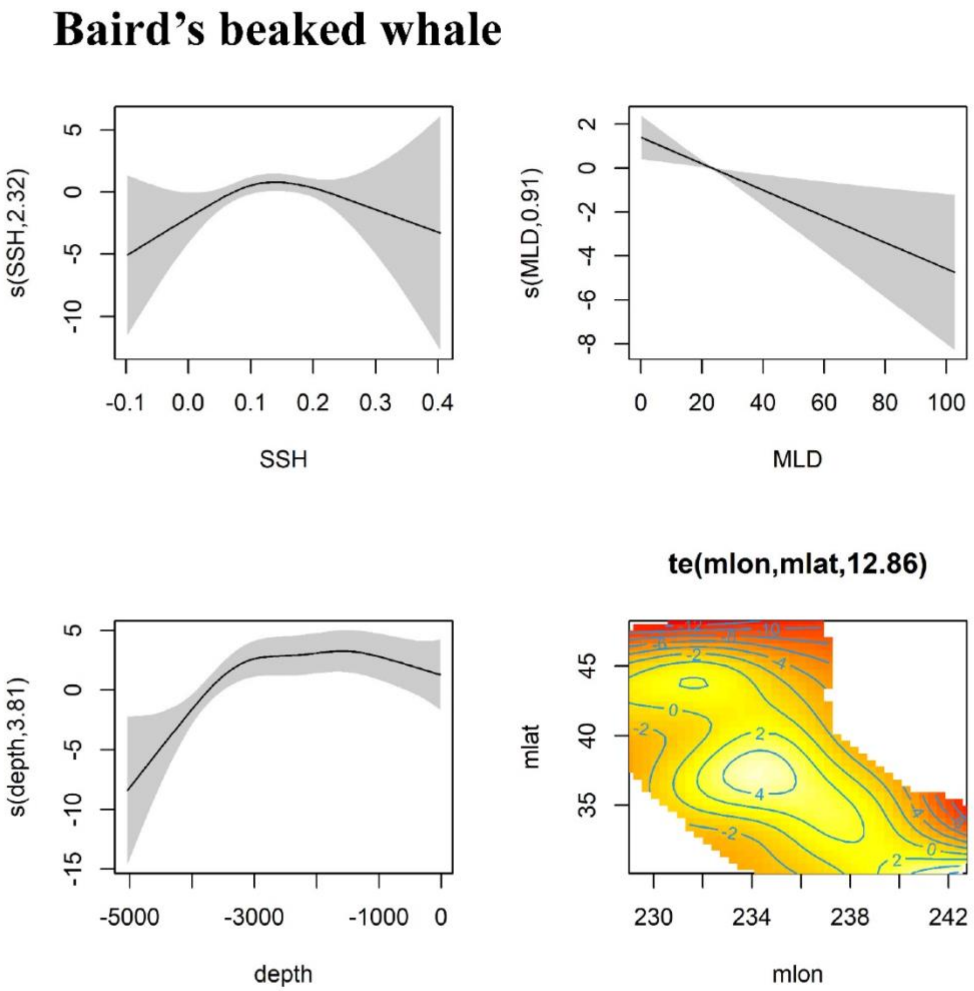


Figure A 14. Functional plot for Baird's beaked whale (*Berardius bairdii*) model.

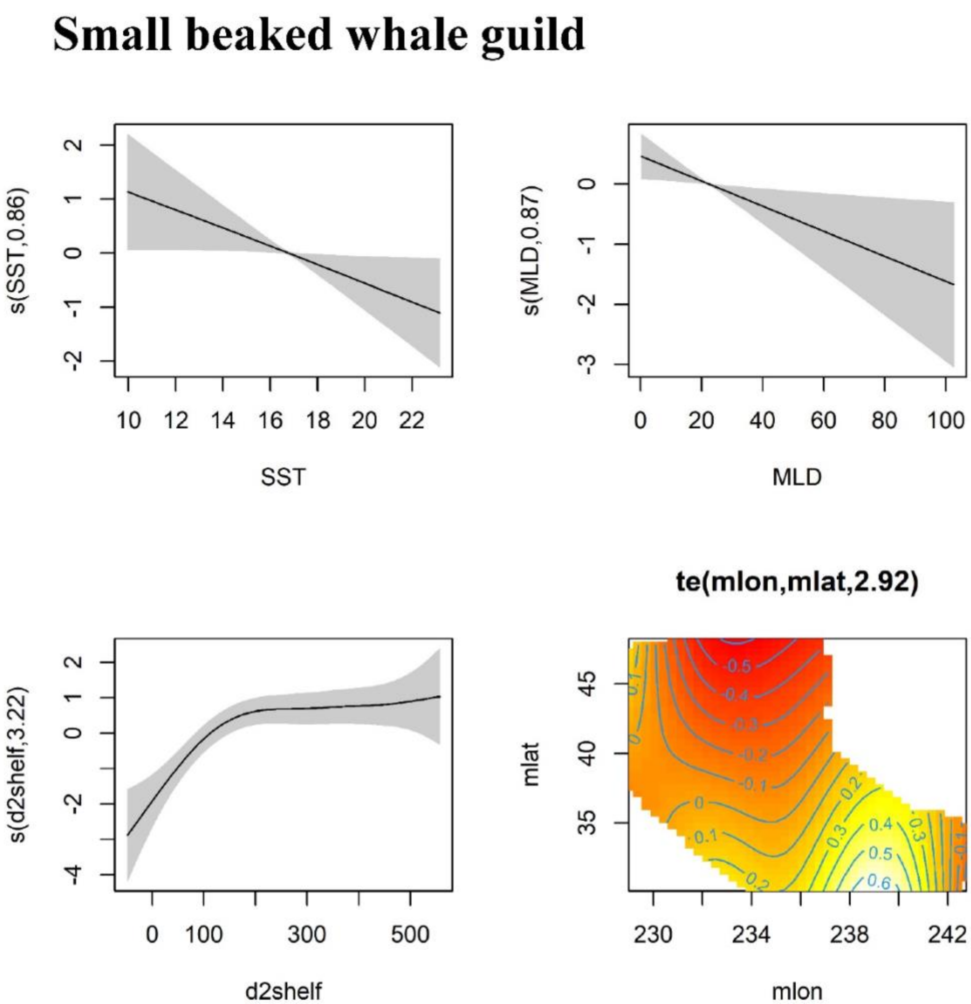


Figure A 15. Functional plot for the small beaked whale guild (*Mesoplondon spp. & Ziphius cavirostris*) model.

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