Submitted in support of the U.S. Navy's 2018 Annual Marine Species Monitoring Report for the Pacific

Final Report

Baleen Whale Tagging in Support of Marine Mammal Monitoring Across Multiple Navy Training Areas Covering the Years 2014, 2015, 2016, and 2017

Submitted to:

Naval Facilities Engineering Command Southwest
for Commander, U.S. Pacific Fleet
under Contract No. N62470-15-D-8006-17F4016
issued to HDR, Inc.

Prepared by

Bruce R. Mate, Daniel M. Palacios, C. Scott Baker,
Barbara A. Lagerquist, Ladd M. Irvine, Tomas Follett,
Debbie Steel, Craig E. Hayslip, and Martha H. Winsor

Oregon State University Marine Mammal Institute
Hatfield Marine Science Center
2030 SE Marine Science Drive
Newport, OR 97365

Submitted by:

HDR
San Diego, CA

October 2018

Suggested Citation:

Mate, B.R., D.M. Palacios, C.S. Baker, B.A. Lagerquist, L.M. Irvine, T. Follett, D. Steel, C.E. Hayslip, and M.H. Winsor. 2018. *Baleen Whale Tagging in Support of Marine Mammal Monitoring Across Multiple Navy Training Areas Covering the Years 2014, 2015, 2016, and 2017.* Final Report. Prepared for Commander, U.S. Pacific Fleet. Submitted to Naval Facilities Engineering Command Southwest under Contract No. N62470-15-8006-17F4016 issued to HDR, Inc., San Diego, California. October 2018.

Photo Credit(s):

A blue whale (*Balaenoptera musculus*) raises its flukes at the start of a foraging dive in Southern California, 2016. Photograph taken by Craig Hayslip under National Marine Fisheries Service Permit 14856 issued to Dr. Bruce Mate.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
10-2018

2. REPORT TYPE
Monitoring report

3. DATES COVERED *(From - To)*
2014 - 2018

4. TITLE AND SUBTITLE
BALEEN WHALE TAGGING IN SUPPORT OF MARINE MAMMAL MONITORING ACROSS MULTIPLE NAVY TRAINING AREAS COVERING THE YEARS 2014, 2015, 2016, AND 2017

5a. CONTRACT NUMBER
N62470-15-D-8006

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Bruce R. Mate
Daniel M. Palacios
C. Scott Baker
Barbara A. Lagerquist
Ladd M. Irvine
Tomas Follett
Debbie Steel
Craig E. Hayslip
Martha H. Winsor

5d. PROJECT NUMBER
F4016

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Oregon State University, Newport, OR

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Commander, U.S. Pacific Fleet, 250 Makalapa Dr., Pearl Harbor, HI

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSORING/MONITORING AGENCY REPORT NUMBER

12. DISTRIBUTION AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT
OSU conducted a 4-year (2014-2017) tagging and tracking study on eastern North Pacific blue whales and fin whales to determine their movement patterns, occurrence, and residence times within U.S. Navy training and testing areas, as well as NMFS-identified BIAs. Tracking periods ranged from 0.6 to 283.8 d. Blue whale locations ranged from the northern tip of Vancouver Island, British Columbia, to very close to the equator, while fin whales were from Haida Gwaii, British Columbia, to the northern coast of Baja California, Mexico. Interannual differences existed for both species, in sizes of home ranges (HRs) and core areas (CAs), in latitudinal extent of movements, in total distance traveled, and in whales’ use of Navy training ranges and NMFS-identified BIAs for blue whales. Blue whales had locations in SOCAL, PT MUGU, and the SOAR in all 4 years. Locations in the NWTT occurred in 3 years (2014-2016), and in W237 of the NWTT in 2014 only. Blue whales were not found in GOA in any year. PT MUGU was the most heavily used Navy training range by blue whales for the combined 4 years of study in terms of total numbers of whales having locations there, residence time, and overlapping HRs and CAs. SOCAL also was used by a high number of blue whales and was the most heavily used range in terms of whale numbers and percentage of locations in 2014. SOAR was used by 18 of 90 tracked whales over the 4 years, with very low residence times in this small range (averaging less than 1 d). NWTT was used by a small number of blue whales (9 of 90) over the 4-year study, but those that were located there spent an average of 23.4 d in the area, resulting in more extensive overlap of HRs and CAs within this range than within SOCAL. An equal proportion (17%) of tracked blue whales was located in NWTT in both 2014 and 2016. Only one of 90 tracked blue whales had

locations in W237 of NWTT, spending 19.5 d in the area in 2014. Seasonality in the Navy training ranges was similar between tagging years, with locations occurring predominantly in the summer-fall (July-November in SOCAL and PT MUGU, July-September in SOAR, August-November in NWTT, and September-November in W237). There were additional locations in SOCAL, PT MUGU, and SOAR in spring (March-April) for 2 blue whales migrating north from wintering areas, in 2015 and 2017. Of the 6 blue whale BIAs that overlap Navy training ranges, the Santa Barbara Channel and San Miguel Island BIA appeared to be the most important to blue whales, in terms of number of whales using the area, time spent there, and number of overlapping CAs within the area. This area likely offers an optimal foraging habitat for blue whales off the U.S. West Coast, especially during strong upwelling years. There were differences in BIA use between years, however, with the San Diego and the Santa Monica Bay to Long Beach BIAs being the most heavily used in 2014, whereas the Santa Barbara Channel and San Miguel Island and the Point Conception/Arguello BIAs being the most heavily used in 2015-2017. The remaining two BIAs, San Nicolas Island and Tanner-Cortes Banks, were used only minimally by blue whales in all 4 years. The timing of blue whale occurrence in BIAs was similar between years – summer and fall (July to November). The single fin whale tagged in 2017 did not spend time in any Navy training ranges. For fin whales tagged in 2014–2016, locations occurred in the PT MUGU and NWTT in all 3 years, but locations in SOCAL and SOAR occurred only in 2014 and 2015, and in W237 during 2015 and 2016 only. The GOA had no fin whale locations in any of the 4 years. PT MUGU was the most heavily used Navy training range for fin whales in 2014-2016, in terms of number of whales having locations there as well as HRs and CAs occurring there. SOCAL was the second most heavily used training range in terms of number of fin whales as well as HR and CA overlap in 2014, but NWTT was the second most heavily used range in 2015. Two fin whales were tracked in SOAR in both 2014 and 2015 but none had locations there in 2016. No fin whales tagged in 2016 had locations in SOCAL, and only one fin whale crossed through NWTT in 2016. Two whales had locations in W237 of NWTT in 2015, and one in 2016, but the latter only passed through the area briefly on its way farther north. Fin whale use of SOAR, NWTT, and W237 occurred primarily in late summer and fall, whereas fin whales could be found in PT MUGU during summer–winter, and in SOCAL during all seasons. In general, tagged fin whales fed across broad areas, in contrast to DM-tagged blue whales, which tended to feed in localized areas. As with blue whales, only male fin whales made long, clock-wise circuits of southern California waters with little feeding, while female tracks were generally more clustered and reported more feeding behavior, suggesting that there may be a reproductive or courtship aspect that influences the behavior of male whales of both species while using southern California waters in late summer.Blue whales occurred in areas with an average depth of 1,260.3 m, average distance to the continental shelf break of 32.7 km, and average distance to the nearest shoreline of 63.3 km. From a biogeographic perspective, most of the SSSM locations occurred in the CCAL and in the PNEC, with a small proportion occurring in adjacent provinces (including the PQED and GUCA). The track from the single fin whale tag deployed in 2017 was restricted, covering approximately 2 ° longitude (124-122°W) and 1 degree of latitude (36.9–37.9°N) off the coast of central California between Santa Cruz and San Francisco. The area where this fin whale occurred had an average SST of 16.5°C, average CHL of 2.3 mg m-3, average depth of 470.7 m, average distance to the continental shelf break of 6.6 km, and average distance to the nearest shoreline of 34.6 km. The geographic extent covered by the 28 fin whales tracked in the four years of this study was smaller than that of the blue whales, but it also displayed marked inter-annual variability (10-16 ° longitude and 12-22 ° latitude). Fin whales were only present in 2 of the 8 biogeographic provinces of the eastern North Pacific considered here, CCAL andALSK. Also, while blue whales migrated in late fall and winter from CCAL to lower-latitude provinces (PNEC, GUCA, PQED), fin whales moved northward and remained in CCAL or visited ALSK (reaching Haida Gwaii and Hecate Strait off British Columbia).

15. SUBJECT TERMS

Monitoring, marine mammals, baleen whales, tagging, biopsy, genetics, Southern California Range Complex, Northwest Training Range Complex

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT** UU	**18. NUMBER OF PAGES** 155	**19a. NAME OF RESPONSIBLE PERSON** Department of the Navy
a. REPORT Unclassified	**b. ABSTRACT** Unclassified	**c. THIS PAGE** Unclassified			**19b. TELEPONE NUMBER (*Include area code)*** 808-471-6391

Executive Summary

Oregon State University (OSU) conducted a four-year (2014, 2015, 2016, and 2017) tagging and tracking study on eastern North Pacific blue whales (*Balaenoptera musculus*) and fin whales (*Balaenoptera physalus*) to determine their movement patterns, occurrence, and residence times within United States (U.S.) Navy training and testing areas, as well as Biologically Important Areas (BIAs), along the U.S. West Coast. This work was performed in support of the Navy's efforts to meet regulatory requirements for monitoring under the Endangered Species Act and the Marine Mammal Protection Act. Tagging occurred off the coast of southern and central California in the months from July to September. Three types of Argos (satellite-monitored) tags were used: Location-Only (LO) tags, providing long-term tracking information; Dive-Monitoring (DM) tags, providing intermediate- to long-duration tracking and dive behavior (duration, depth, number of feeding lunges per dive); and pop-off Advanced Dive Behavior (ADB) tags, providing intermediate-duration, fine-scale dive profile information upon tag recovery and Global Positioning System-quality locations. This report presents detailed results from the 2017 tagging, as well as interannual comparisons for both blue and fin whales between 2014, 2015, 2016, and 2017. Detailed results from the 2014–2016 tagging years can be found in OSU's previously submitted project reports (Mate et al. 2015, 2016, 2017a). While both ADB and DM tags provided dive behavior data, the scales and resolutions of the data provided by these tags were not directly comparable, and the ADB technology, which included tag release and recovery, ceased production and was superseded by the longer-term implantable DM tags in 2016. Therefore, this report focuses on the DM tag data collected in 2016 and 2017, while detailed results from ADB tags, which guided the development of the DM tags, can also be found in previous project reports (Mate et al. 2015, 2016, 2017a).

Twenty-four blue whales (20 LO tags, 4 ADB tags) and six fin whales (3 LO, 3 ADB) were tagged in 2014. Twenty-two blue whales (18 LO, 4 ADB), and 11 fin whales (9 LO, 2 ADB) were tagged in 2015. Nineteen blue whales (11 LO tags, 8 DM tags) and 14 fin whales (5 LO tags, 9 DM tags) were tagged in 2016. Twenty-seven blue whales (13 LO tags, 14 DM tags) and one fin whale (1 LO tag) were tagged in 2017. In addition, one blue-fin whale hybrid (1 LO) and one Bryde's whale (*Balaenoptera edeni brydei*; 1 LO) were tagged in 2015 as part of this project; the tracking details of which are presented in Mate et al. (2016 and 2017a). Locations were received from all but four tags (two blue whales [1 LO tag and 1 DM tag] and two fin whales [1 LO tag and 1 DM tag]), with tracking periods ranging from 0.6 to 283.8 days (d). Average tracking duration for non-ADB tags was 73.4 d (standard deviation = 58.4 d) for blue whales and 55.4 d (standard deviation = 52.9 d) for fin whales, for the four years combined. Average tracking duration for ADB tags was 23.0 d (standard deviation = 4.5 d) for blue whales and 12.3 d (standard deviation = 4.4 d) for fin whales, for 2014 and 2015 combined (the two years in which these tags were used). Most tags were deployed in southern California and a smaller number were deployed off central California.

Both blue and fin whales were widespread in their tracked distributions, with locations over the four years extending from the northern tip of Vancouver Island, British Columbia, to very close to the equator for blue whales; and from Haida Gwaii, British Columbia, to the northern coast of

Baja California, Mexico, for fin whales. Differences existed between years, however, for both species, in sizes of home ranges (HRs) and core areas (CAs), in latitudinal extent of movements, in total distance traveled, and in whales' use of Navy training ranges and National Marine Fisheries Service-identified Biologically Important Areas (BIAs) for blue whales. Blue whales were distributed farther north, traveled significantly longer distances, and had significantly larger HRs and CAs in 2014 than in the other three years. Only one fin whale was tagged in 2017, remaining in central California for the duration of its 42-d tracking period; this whale was not included in interannual comparisons. Fin whales were distributed farther north in 2015 and 2016 than in 2014 but had significantly larger HRs and CAs in 2015 than either 2014 or 2016. Distances traveled by fin whales were significantly longer in 2015 than in 2016 but were of intermediate lengths in 2014. These differences were likely in response to dramatic changes in environmental conditions across the years of this study.

Blue whales had locations in the Southern California Range Complex (SOCAL), the Point Mugu Range Complex (PT MUGU), and the Southern California Anti-submarine warfare Offshore Range subarea (SOAR) in all four tagging years, likely due to the proximity of deployment locations to these ranges (and thus also likely in relation to food resources). Locations in the Northwest Training and Testing Study Area (NWTT) occurred in three years (2014 to 2016), and in Warning Area 237 (W237) of the NWTT in 2014 only. Blue whales were not found in the Gulf of Alaska training range in any year. PT MUGU was the most heavily used Navy training range by blue whales for the combined four years of study in terms of total numbers of whales having locations there (76 of 90 tracked whales), residence time (overall mean of 28.8 d), and overlapping HRs and CAs. SOCAL was also used by a high number of blue whales (51 of 90 tracked whales, overall mean of 7.8 d) and was the most heavily used range in terms of whale numbers and percentage of locations in 2014. SOAR was used by 18 of 90 tracked whales over the four years, with very low residence times in this small range (averaging less than 1 d). NWTT was used by a small number of blue whales (9 of 90) over the four-year study, but those that were located there spent an average of 23.4 d in the area, resulting in more extensive overlap of HRs and CAs within this range than within SOCAL. An equal proportion (17 percent) of tracked blue whales was located in NWTT in both 2014 and 2016. Only one of 90 tracked blue whales had locations in W237 of NWTT, spending 19.5 d in the area in 2014. Seasonality in the Navy training ranges was similar between tagging years, with locations occurring predominantly in the summer and fall (July through November in SOCAL and PT MUGU, July through September in SOAR, August through November in NWTT, and September through November in W237). There were additional locations in SOCAL, PT MUGU, and SOAR in spring (March and April) for two blue whales migrating north from wintering areas, in 2015 and 2017.

Of the six blue whale BIAs that overlap Navy training ranges, the Santa Barbara Channel and San Miguel Island BIA appeared to be the most important area to blue whales, in terms of number of whales using the area, time spent there (with a maximum residency of 63.3 d), and number of overlapping CAs within the area. This was likely in part because of the proximity of deployment locations to this BIA, although being located downstream of the strong wind-driven upwelling and elevated biological productivity generated at Point Conception, and combined with the shelf breaks, island slopes, and nearby seamounts that characterize the west end of the Channel Islands, the Santa Barbara Channel and San Miguel Island BIA likely offers an optimal foraging habitat for blue whales off the U.S. West Coast, especially during strong upwelling years. There were differences in BIA use between years, however, with the San Diego and the Santa Monica Bay to Long Beach BIAs being the most heavily used in 2014, whereas the Santa Barbara Channel and San Miguel Island and the Point Conception/Arguello BIAs being the most heavily used in 2015, 2016, and 2017. The remaining two BIAs, San Nicolas Island and Tanner-Cortes Banks, were used only minimally by blue whales in all four years, with residencies ranging from <0.1 to 1.7 d for Tanner-Cortes Bank, and 0.1 to 0.3 d for San Nicolas Island. The timing of blue whale occurrence in BIAs was similar between years, taking place in summer and fall (July to November).

The single fin whale tagged in 2017 did not spend time in any Navy training ranges. For fin whales tagged in 2014–2016, locations occurred in the PT MUGU and Northwest Training Range Complex ranges in all three years, but locations in SOCAL and SOAR occurred only in 2014 and 2015, and in W237 during 2015 and 2016 only. The Gulf of Alaska training range had no fin whale locations in any of the four years. PT MUGU was the most heavily used Navy training range for fin whales in 2014–2016, in terms of number of whales having locations there as well as HRs and CAs occurring there. SOCAL was the second most heavily used training range in terms of number of fin whales as well as HR and CA overlap in 2014, but NWTT was the second most heavily used range in 2015. Two fin whales were tracked in SOAR in both 2014 and 2015 but none had locations there in 2016. No fin whales tagged in 2016 had locations in SOCAL, and only one fin whale crossed through NWTT in 2016. Two whales had locations in W237 of NWTT in 2015, and one in 2016, but the latter only passed through the area briefly on its way farther north. Fin whale use of SOAR, NWTT, and W237 occurred primarily in late summer and fall, whereas fin whales could be found in PT MUGU during summer, fall, and winter, and in SOCAL during all seasons.

DM tags in 2017 summarized a median of 41.8 percent of the blue whales’ dive behavior during tracking (range = 16.4–62.3 percent) and provided data for a median of 2,291 dives (range = 93–5,943). Maximum dive depths were highly variable within and across individuals with most dives occurring to depths < 200 meters (m). However, all tagged whales made dives exceeding 300 m at various times. A diel pattern of more lunges and deeper dives during the day was recorded in 2017 and closely matched with data from previous years. Daytime dive depths for DM-tagged blue whales were deepest near San Miguel Island off southern California, while areas to the north had shallower daytime dive depths. This may be related to regional differences in prey species composition, or each region’s bathymetry, topography, and physical oceanographic structure. Feeding lunges most commonly occurred during dives associated with locations classified as area-restricted searching (ARS), as obtained from a Bayesian switching state-space model (SSSM) of the tracking data, while the fewest lunges occurred during dives associated with locations classified as transiting. As hoped, this pattern suggests that the behavior classification from the SSSM is a useful general indicator of foraging for whales tracked with tags that did not report dive or feeding data.

Spatial distribution of foraging effort for blue whales in California waters in 2017 was generally similar to that of 2016, with most foraging occurring in a broad, highly productive area near San Miguel Island (where most of the blue whales were tagged) and north to the area off San Francisco. Little feeding occurred south of the Channel Islands. However, tagged whales fed in the area south of San Clemente Island and near San Diego in all years except 2016. Across all years, only male whales were documented feeding in the offshore waters south of the Channel Islands, while both male and female whales fed in the nearshore waters from San Diego north to Point Mugu. No differentiation in spatial distribution of foraging by sex was apparent for the areas near San Miguel Island north to the waters off San Francisco. This suggests that if there are impacts from anthropogenic activity, they may affect different segments of the population depending on where they occur off southern California. However, the limited occupancy and amount of feeding effort in those waters also suggests that fewer individuals would be impacted (if there are such impacts) compared to an area farther north near San Miguel Island or off central California. This evidence argues for further research into sex-based differences in occupancy patterns in southern California waters using a controlled sampling design or numerical modeling approaches.

The single fin whale tracked in 2017 was tagged with a LO tag, so no dive information was available for this year. In 2016, DM tags were deployed on nine fin whales, staying attached for a median of 28.7 d and providing summaries for a median of 1,670 dives per whale. DM-tagged fin whales in 2016 recorded consistent feeding effort across their central California tracking range, except one whale that traveled north to the Hecate Strait, British Columbia, and fed there for the remainder of its tracking period. In general, tagged fin whales fed across broad areas, in contrast to DM-tagged blue whales, which tended to feed in localized areas. As with blue whales, only male fin whales made long, clock-wise circuits of southern California waters with little feeding, while female tracks were generally more clustered and reported more feeding behavior, suggesting that there may be a reproductive or courtship aspect that influences the behavior of male whales of both species while using southern California waters in late summer.

This project also sought to identify ecological relationships that help explain the spatial and temporal movement patterns by tracked blue and fin whales in the eastern North Pacific from satellite-determined and bathymetric measurements. For this purpose, we applied a Bayesian SSSM to regularize the tracks and improve location estimates. The SSSM also provided a behavioral classification for each location (transiting or ARS), and we interpreted ARS behavior as foraging activity. We then used the SSSM data to put whale distribution in a biogeographic context and to characterize the influence of oceanographic and climatic events on the distribution and movement behavior of the tracked whales over the four years of the project. The large-scale climatic context was provided by three independent indices with well-known linkages to changes in marine ecosystem productivity in the Pacific Ocean: the Oceanic Niño Index, the Pacific Decadal Oscillation (PDO) index, and the North Pacific Gyre Oscillation (NPGO) index.

For blue whales tagged in 2017, the SSSMs generated 25 regularized tracks, which covered approximately 31 degrees of longitude (124.8–94.1°W) and 30 degrees of latitude (9.2–39.2°N). Of 1,664 SSSM locations, 900 (54.1 percent) were classified as ARS, 569 (34.2 percent) were classified as uncertain, and 195 (11.7 percent) were classified as transiting. Average satellite-determined sea surface temperature (SST) where blue whales occurred in 2017 was 18.4 degrees Celsius (°C), and average chlorophyll-*a* concentration (CHL) was 1.4 milligrams per cubic meter [mg m^{-3}]. Blue whales occurred in areas with an average depth of 1,260.3 m, average distance to the continental shelf break of 32.7 kilometers (km), and average distance to the nearest shoreline of 63.3 km.

Comparing all four years of the project, the 85 blue whales with SSSM tracks covered a large but inter-annually variable geographic extent (20 to 44 degrees of longitude and 26 to 44 degrees of latitude). From a biogeographic perspective, most of the SSSM locations occurred in the California Current Province (CCAL) (73.1 to 99.3 percent) and in the North Pacific Equatorial Countercurrent Province (PNEC) (0.7 to 26.7 percent), with a small proportion occurring in adjacent provinces (including the Pacific Equatorial Divergence Province, PQED [2.6 percent], and the Gulf of California Province, GUCA ([0.8 to 2.2 percent]).

The proportion of SSSM locations classified as ARS in CCAL (the only province consistently occupied by both species in all years) during the summer–fall months (July to November), was lower in 2014 and 2015 (11.2 and 18.4 percent of locations, respectively), while it was very high in 2016 and 2017 (51 and 54.1 percent, respectively). In ARS, blue whales covered larger distances between location pairs in 2014 and 2015 (mean pairwise distance between SSSM locations [PWDIST] = 58.3 and 44.1 km, respectively), and substantially smaller distances in 2016 and 2017 (mean PWDIST = 21.6 and 30.5 km, respectively). Examination of oceanographic conditions indicated that the little ARS activity in 2014 and 2015 occurred in the warmest SST recorded by blue whales during the study (mean = 22.9 and 19.1°C, respectively), compared to the more predominant ARS activity that was recorded in cooler waters in 2016 and 2017 (mean = 16.3 and 18.0°C, respectively). Correspondingly, CHL values where ARS activity took place in 2014 and 2015 were low (mean = 0.7 mg m^{-3} in both years) compared to the more elevated values in 2016 and 2017 (mean = 1.7 and 1.5 mg m^{-3}, respectively). During 2016, ARS activity took place in shallower waters (mean = 640.1 m), in the vicinity of the shelf break (mean = 13.3 km), and closer to shore (mean = 33.5 km) than in the other years of the project.

These inter-annual differences were likely in response to the strongly anomalous oceanographic conditions that occurred during the first three years of the project, including: (a) warm SST anomalies associated with the marine heat wave of 2013–2015, (b) warm SST anomalies associated with the 2015–2016 El Niño event, and (c) cold SST anomalies associated with the 2016–2017 La Niña event. Although no major oceanographic perturbations were reported in 2017, strongly negative NPGO sea-surface height anomalies were persistent in the latter half of 2017, concomitant with cold Oceanic Niño Index SST anomalies. Dramatic biotic changes were documented across the food web and throughout the study area in 2014 to 2017 in response to these events, and they likely had an impact on the abundance, distribution, species composition, and nutritional value of the euphausiids upon which blue whales foraged.

The track from the single fin whale tag deployed in 2017 was restricted, covering approximately 2 degrees of longitude (124–122°W) and 1 degree of latitude (36.9–37.9°N) off the coast of central California between Santa Cruz and San Francisco. Of 40 SSSM locations in this track, 37 (92.5 percent) were classified as ARS, 3 (7.5 percent) were classified as uncertain, and none were classified as transiting. The area where this fin whale occurred had an average SST of 16.5°C, average CHL of 2.3 mg m^{-3}, average depth of 470.7 m, average distance to the continental shelf break of 6.6 km, and average distance to the nearest shoreline of 34.6 km.

The geographic extent covered by the 28 fin whales tracked in the four years of this study was smaller than that of the blue whales, but it also displayed marked inter-annual variability (10 to 16 degrees of longitude and 12 to 22 degrees of latitude). Fin whales were only present in two of the eight biogeographic provinces of the eastern North Pacific considered here, CCAL (90 to 100 percent) and Alaska Downwelling Coastal Province (ALSK; 0 to 10 percent). Also, while blue whales migrated in late fall and winter from CCAL to lower-latitude provinces (PNEC, GUCA, PQED), fin whales moved northward and remained in CCAL or visited ALSK (reaching Haida Gwaii and Hecate Strait off British Columbia).

For the first three years of the project (which were more appropriately comparable because of sample size considerations), the proportion of fin whale SSSM locations classified as ARS in CCAL during the summer-fall months was lowest (11.2 percent of locations) in 2015, intermediate (18.8 percent) in 2014, and highest (34.9 percent) in 2016. Correspondingly, while in ARS average PWDIST was highest in 2015 (59.0 km) and lower in 2014 and 2016 (49.6 and 38.3 km, respectively). Examination of oceanographic conditions indicated that the very low ARS activity in 2015 (during El Niño) occurred in the warmest SST recorded during the study (mean = 18.5°C), compared to the higher ARS activity that was recorded in cooler waters in 2014 (mean = 16.7°C) and especially in 2016 (mean = 15.2°C). Correspondingly, CHL values where ARS activity took place in 2015 were the lowest recorded (mean = 0.5 mg m^{-3}) compared to the more elevated values in 2014 or 2016 (mean = 1.1 and 1.9 mg m^{-3}, respectively). During 2015, ARS activity took place in deeper waters (mean = 2,465.3 m) and farther away from the shelf break and the shore (mean = 61.9 km and 84.9 km, respectively) than in 2014 or 2016.

Together, these results suggest that the anomalous warm-water events of 2014 and 2015 had different impacts on blue and fin whales. During the 2014 heat wave, blue whale foraging effort was lowest, while during the 2015–2016 El Niño fin whale foraging effort appeared worse. Strong upwelling pulses occurred at several coastal locations in spring-summer 2015 that supported high biological productivity at these sites and, being found closer to shore, blue whales may have benefited in the otherwise unfavorable conditions prevalent farther offshore as the El Niño event unfolded. In 2016 (during La Niña), both species had high levels of ARS as they foraged in habitats with the coolest SST and highest CHL recorded during the study. Foraging effort during 2017 was similarly high for both species and occurred in cool and productive conditions (although for fin whales this was based on only one track).

Thus, despite partial geographic and environmental overlap, blue and fin whales have distinct ecological optima that likely are reflections of different prey resource utilization in much of their range. With the 2014 shift to a warm Pacific Decadal Oscillation phase (and a negative NPGO phase), in the next decade we might expect blue and fin whale range and movement patterns in CCAL to change, given that the euphausiid and pelagic schooling fish prey they forage upon respond strongly to decadal variability. Indeed, the tracking data from this project are consistent with a northward range contraction for blue whales and an expansion for fin whales. The four years of this study have provided invaluable information towards a better understanding of how these species respond to climatic variability.

Tissue samples collected from the tagged blue and fin whales in 2014, 2015, 2016, and 2017 were used for "deoxyribonucleic acid (DNA) profiling," including sex identification, sequencing of mitochondrial DNA (mtDNA) control region haplotypes, and genotyping of up to 17 microsatellite loci. The DNA profiles were used to confirm species identification and individual identity and to investigate population structure using published information on mtDNA haplotype frequencies or unpublished referenced databases developed through collaborative agreements.

For all years combined, the 62 samples of blue whales were represented by unique multi-locus genotypes with an average probability of identity of 6.0×10^{-16} (i.e., there was a very low probability of a match by chance). Of the 62 individuals, 24 were females and 38 were males. Of the 14 mtDNA haplotypes resolved in the tagged blue whales from 2014 to 2017, 10 matched to the 16 haplotypes represented in a reference database from the eastern North Pacific ($n = 76$ individuals), resulting in a total of 20 haplotypes for this stock (a 25 percent increase). There was no evidence of differences in haplotype frequencies of the tagged blue whales in comparison to the reference database from the eastern North Pacific. Although this comparison provided reasonable confidence that the two samples do not represent distinct stocks, we cannot discount the potential for more subtle spatial heterogeneity or fine-scale population structure in this geographic region. Our analysis of stock structure was also limited by the absence of samples from other putative stocks in the North Pacific, particularly the Central or Western North Pacific stocks.

A biopsy sample was not collected from the single fin whale tagged in 2017. Of the 20 samples collected from whales and identified in the field to be fin whales between 2014 and 2016, one was subsequently confirmed to be a Bryde's whale (*Balaenoptera edeni brydei*) and one was found to be a blue-fin whale hybrid. In collaboration with researchers from Cascadia Research Collective, we used the DNA profile of the hybrid to confirm a match with a previously reported hybrid individual, first sampled off California on 22 September 2004, providing an 11-year record of genotype recapture.

All of the 18 tagged fin whales were represented by unique multi-locus genotypes, with an average probability of identity of 8.8×10^{-21} (i.e., there was a very low probability of a match by chance). Of the 18 individuals, 10 were females and 8 were males. To investigate population structure, we compared the mtDNA haplotype frequencies of the 18 tagged fin whales to a reference dataset of 397 samples (subdivided into seven *a priori* population strata). Despite the small sample sizes for these comparisons, the haplotype frequencies of the tagged fin whales from all years showed significant differences from several of the other strata, including California/Oregon/Washington and the Gulf of California, but not the Southern California Bight. However, the location of tagging/sampling of fin whales shifted to the north in 2016. Sample sizes were not sufficient for an analysis of any differences because of this change in location.

This page intentionally left blank.

Table of Contents

Figures

Tables

Acronyms and Abbreviations

°C	degree(s) Celsius
ADB	Advanced Dive Behavior
ALSK	Alaska Downwelling Coastal Province
ARS	area-restricted searching
ASPECT	compass direction of the bottom slope (data variable)
BIA	Biologically Important Area
bp	base pair
CA	core area
CAMR	Central American Coastal Province
CCAL	California Current Province
CHL	chlorophyll-*a* (data variable)
cm	centimeter(s)
d	day(s)
DEPTH	water depth (data variable)
DISTSHELF	distance from the 200-meter isobath/shelf break (data variable)
DISTSHORE	distance from shore (data variable)
DM	Dive-Monitoring
DNA	deoxyribonucleic acid
EEZ	Exclusive Economic Zone
g	gram(s)
GUCA	Gulf of California Province
h	hour(s)
HR	home range
ID	identification
IQR	inter-quartile range
km	kilometer(s)
km^2	square kilometer(s)
LC	location class
LO	Location-Only
LSD	least significant difference
m	meter(s)
$mg\ m^{-3}$	milligrams per cubic meter
min	minute(s)

mm	millimeter(s)
mtDNA	mitochondrial deoxyribonucleic acid
Navy	U.S. Navy
NMFS	National Marine Fisheries Service
NOAA	National Oceanic and Atmospheric Administration
NPGO	North Pacific Gyre Oscillation
NPPF	North Pacific Transition Zone Province
NPTG	North Pacific Tropical Gyre Province
NWTT	Northwest Training and Testing Study Area
ONI	Oceanic Niño Index
OSU	Oregon State University (Marine Mammal Institute)
PCR	polymerase chain reaction
PDO	Pacific Decadal Oscillation
photo-ID	photo-identification
PNEC	North Pacific Equatorial Countercurrent Province
PQED	Pacific Equatorial Divergence Province
PSGEP	Pacific Subarctic Gyre East Province
PT MUGU	Point Mugu Range Complex
PWDIST	pairwise distance between SSSM locations (data variable)
R/V	research vessel
s	second(s)
SD	standard deviation
SE	standard error
SLOPE	bottom slope (data variable)
SOAR	Southern California Anti-submarine warfare Offshore Range subarea
SOCAL	Southern California Range Complex
SSSM	switching state-space model
SST	sea-surface temperature (data variable)
SWS	saltwater conductivity switch
U.S.	United States
W237	Warning Area 237

1. Introduction

Whales of several species in the eastern North Pacific Ocean, including blue (*Balaenoptera musculus*) and fin (*Balaenoptera physalus*) whales, arrive in the productive California Current ecosystem off the West Coast of the United States (U.S.) in summer and fall months (Larkman and Veit 1998, Burtenshaw et al. 2004, Oleson et al. 2007, Dransfield et al. 2014, Irvine et al. 2014, Fleming et al. 2016) to forage on the seasonally abundant aggregations of euphausiids and schooling fish, their primary prey (Schoenherr 1991, Fiedler et al. 1998, Croll et al. 2005, Fleming et al. 2016). In winter and spring, blue whales migrate to the Costa Rica Dome region off Central America and to the Gulf of California in Mexico (Bailey et al. 2009) to breed and calve in low latitudes. In contrast, fin whales do not appear to migrate to low latitudes, remaining year-round in the California Current System (Scales et al. 2017).

In 2017, Oregon State University (OSU) conducted a fourth year of tagging operations in support of the U.S. Navy's (Navy) marine mammal monitoring in five areas along the U.S. West Coast: (1) the Southern California Range Complex (SOCAL), which is a portion of the Hawaii-Southern California Training and Testing Study Area, (2) the Point Mugu Range Complex (PT MUGU), (3) the Southern California Anti-submarine warfare Offshore Range subarea (SOAR), (4) the Northwest Training and Testing Study Area (NWTT), and (5) Warning Area 237 (W237) within the NWTT. The focus of these studies is to address key science objectives the Navy has committed to complete as part of regulatory requirements promulgated from the National Marine Fisheries Service (NMFS). In particular, this multi-year project was designed to address the following questions:

1. What are the movement patterns, occurrence, and residence times of blue and fin whales within Navy training and testing areas along the U.S. West Coast as compared to other areas visited by tagged whales outside of Navy training and testing areas?
2. What are the residency time/occupancy patterns of blue whales within NMFS-designated Biologically Important Areas (BIAs) for this species along the U.S. West Coast? (i.e., the areas identified by Calambokidis et al. [2015] and referenced in the Navy's Letter of Authorization and Environmental Impact Statement)
3. Are there bathymetric, annual oceanographic conditions (e.g., sea surface temperature, frontal zones, etc.), and/or climatic and ocean variations (e.g., global warming, North Pacific Gyre Oscillation [NPGO], Pacific Decadal Oscillation [PDO], El Niño/La Niña events, etc.) that can help explain blue and fin whale affinity for any identified areas of high residency along the U.S. West Coast?

In order to address these questions, the project's specific objectives for 2017 were as follows:

A. Determine blue and fin whale distribution and habitat use through deployment of long-term Location-Only (LO) satellite tags to refine understanding of short- and long-term movement patterns and, most importantly, to generate metrics for defining residency times, home ranges (HRs) and core areas (CAs), area-restricted searches (ARS), and migratory timing.

B. Determine blue and fin whale behavior changes over time, by individual and between individuals, over the course of several weeks to several months by deploying intermediate-duration Dive-Monitoring (DM) tags. This new technology incorporates depth and tri-axial accelerometer sensors into the traditional LO-tag design, enabling us to obtain a relative measure of foraging effort and its changes over time via satellite, without the need to recover the tags.

C. Identify ecological relationships that help explain/predict spatial and temporal movement patterns from bathymetric and satellite-determined measurements like sea surface temperature (SST), frontal zones, phytoplankton chlorophyll-*a* (CHL) concentration, salinity, or current information derived from altimetry.

D. Conduct genetic analyses from tissue samples of tagged blue and fin whales to integrate with the tracking results and further expand their interpretation. These analyses include determination of sex, mitochondrial haplotypic composition, nuclear microsatellite locus composition, individual identification, population structure, and interspecific introgressive hybridization.

This Final Report presents detailed analyses of the 2017 blue and fin whale tracking results, including deployment specifics and tracking information through 31 December 2017, when the last tag stopped transmitting, as well as inter-annual comparisons of tracking results between 2014, 2015, 2016, and 2017. It includes maps of whale tracks, HRs, and CAs of highest use for all four years of the study, as well as a characterization of the seasonality and extent of use of Navy training ranges by blue and fin whales, and BIA use by blue whales, for all four years. This report also includes analyses of the dive characteristic data obtained from the DM tags used in 2016 and 2017, and a comparison of these results with those from Advanced Dive Behavior (ADB) tags used in 2014 and 2015. It further provides a characterization of the whale tracking data in the context of environmental conditions and a comparison between the four years. Finally, the report provides the results of genetic analysis of biopsy samples from all four years, including sex determination, individual identification, species and stock identification, as well as results from the photo-identification (photo-ID) of tagged and untagged whales, which can provide valuable information on sighting histories, life-history parameters, and wound healing.

2. Methods

2.1 Field Efforts

Blue and fin whale tagging efforts in 2017 took place off the southern and central coast of California (where they are found in summer and fall), during a 31-day (d) cruise aboard the OSU research vessel (R/V) *Pacific Storm*. The 26-meter (m) *Pacific Storm* served as a home base and support vessel for the research crew, as well as an additional platform from which to search for whales and conduct visual observations. The cruise took place from 5 July to 5 August 2017, departing from Santa Barbara (in southern California) and returning to Half Moon Bay (in central California). There was one crew change on 19 July 2017 in Santa Barbara. Tagging efforts were conducted on 15 d. Aerial observations to locate whales were conducted on 4 d between 1 and 21 July 2017 from a Cessna 206. Tagging began off southern California, but switched to central California after three weeks (and 27 blue whale taggings), due to a scarcity of fin whales in southern California.

All tagging efforts were conducted from a 6.7-m rigid-hulled inflatable boat launched with a crane from the back deck of the R/V *Pacific Storm*. The tagging crew consisted of a tagger, biopsy darter, photographer, data recorder, and boat driver. Identification (ID) photographs were taken of all tagged whales for comparison with existing ID catalogs for blue (maintained by Cascadia Research Collective, Olympia, Washington) and fin whales (maintained by Marine Ecology and Telemetry Research, Seabeck, Washington). Candidate whales for tagging were selected based on visual observation of body condition. No whales were tagged that appeared emaciated or that were extensively covered by external parasites. Satellite tags were deployed using an Air Rocket Transmitter System, an air-powered applicator (Heide-Jørgesen et al. 2001), following the methods described in Mate et al. (2007). Tags were deployed from distances of 1.5 to 3.5 m with 92 to 95 pounds of force per square inch in the applicator’s 70-cubic centimeter pressure chamber.

2.2 Satellite Tags

Two types of fully implantable, non-recoverable, Argos-based tags were used in 2017: Wildlife Computers Smart Positioning or Temperature Transmitting Tag, version 6 (SPOT6; referred to hereafter as Location-Only or LO tags) and Telonics RDW-665 (hereafter referred to as Dive-Monitoring or DM tags). Both tag types followed the same design, which was composed of a main body, a penetrating tip, and an anchoring system (**Figures 1 and 2**). The main body consisted of a stainless steel cylinder (2.0 centimeters [cm] in diameter × 20.7 cm in length for the LO tag, and 1.9 cm in diameter × 20.7 cm in length for the DM tag) that housed a certified Argos transmitter and a 6-volt lithium battery pack. A flexible whip antenna (15.8 cm long) and a saltwater conductivity switch (SWS; 2.2 cm long), both constructed of single-strand nitinol (1.27 millimeter [mm] in diameter), were mounted on the distal endcap of this cylinder, while a penetrating tip was screwed onto the other end. The distal endcap had two perpendicular stops (0.83 cm thick for the LO tag and 0.63 cm thick for the DM tag) extending approximately 1.5 cm laterally to prevent tags from embedding too deeply on deployment or from migrating inward after deployment. The penetrating tip consisted of a Delrin® nose cone, into which was pressed a ferrule shaft with four double-edged blades. The anchoring system consisted of two rows of

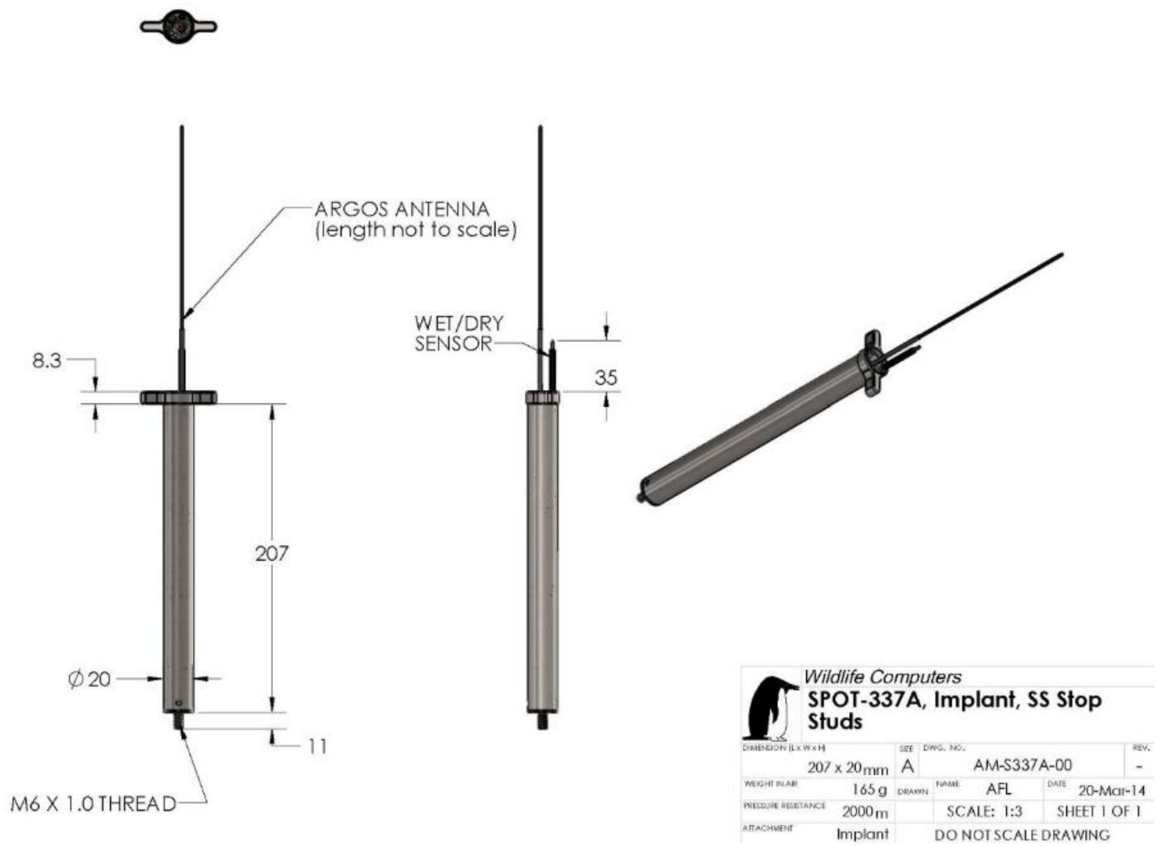

Figure 1. Schematic diagram of the Wildlife Computers SPOT6 (also known as SPOT-337A) LO tag, showing the main body and the distal endcap with the antenna and saltwater conductivity switch. The penetrating tip and anchoring system are depicted in Figure 2.

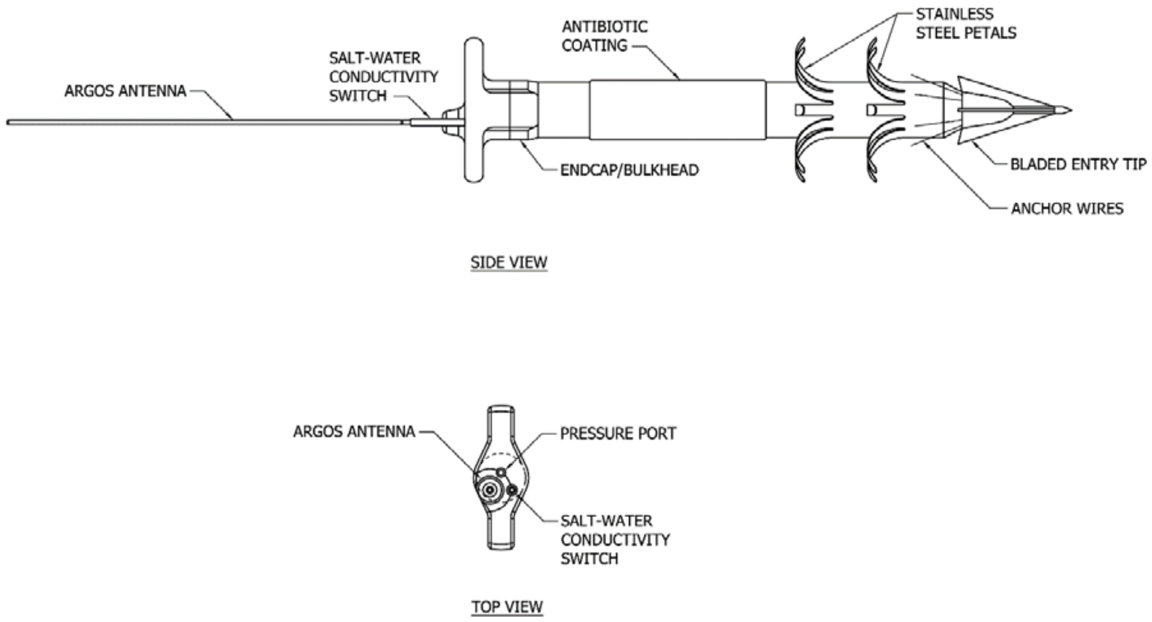

Figure 2. Schematic diagram of the Telonics RDW-665 DM tag showing the main body, the distal endcap with the antenna and saltwater conductivity switch endcap, as well as the penetrating tip and anchoring system.

outwardly curved metal strips (each strip was 3.2 cm long × 0.6 cm wide) mounted on the main body at the nose cone (proximal) end. Twenty-two of the tags (13 LO and 9 DM) also had eight stainless steel wires (3.5 cm long, 0.9 mm gauge) mounted behind the blades on the penetrating tip for added anchorage, but these wires are no longer used in our current tags. Total tag weight was 200 grams (g) for the LO tags and 228 g for the DM tags.

Tag cylinders were partially coated with a long-dispersant polymer matrix (Resomer® or Eudragit®) in which a broad-spectrum antibiotic (gentamicin sulfate) was mixed to allow for a continual release of antibiotic into the tag site for an extended period of time to reduce the chances of infection (Mate et al. 2007). These tags were designed to be almost completely implantable (except for the perpendicular stops, antenna and saltwater switch), and were ultimately shed from the whale due to hydrodynamic drag and the natural migration of foreign objects out of the tissue (Mate et al. 2007). The operational duration of these tags was almost always limited by issues related to retention on the whale rather than by battery life. To date, the mean duration of the fully implantable tags deployed by OSU on blue whales has been 92 d (standard deviation [SD] = 84 d, median = 67 d, n = 188), with a maximum duration of 514 d (OSU, unpublished data). The mean duration of fully implantable tags deployed by OSU on fin whales is 86 d (SD = 94 d, median = 55 d, n = 43), with a maximum duration of 394 d (OSU, unpublished data).

2.2.1 LO Tag Programming

In addition to providing transmissions for location calculation, the LO tag reported the percentage of time in user-specified temperature ranges (which is not analyzed for this report, as the temperature sensor is internal to the tag and its primary use is for monitoring the tag's status rather than as an environmental sampler). LO tags were programmed to transmit at least 10 s apart only when out of the water during four 1-hour (h) periods per day, coinciding with times when satellites were most likely to be overhead. With such a duty cycle, the life expectancy of a tag's battery was estimated at over one year.

2.2.2 DM Tag Programming

The DM tag generated Argos locations similar to the LO tag and also incorporated a pressure sensor and tri-axial accelerometers, so it was able to record dive depth, duration, body orientation and motion while attached to a whale. During deployment, tags recorded: dive depth every 5 seconds (s) with 2 m vertical resolution up to a maximum of 511 m; dive duration at 1 s resolution up to a maximum of 4,095 s using the tag's SWS; and accelerometer readings were recorded every 0.25 s.

Feeding behavior activity was derived from the motion data for "selected dives" ([i.e., dives > 2 minutes [min] in duration and 10 m in depth), as follows. For every selected dive, the magnitude of the acceleration vector (*A*) was calculated as in Simon et al. (2012):

$$A = \sqrt{ax^2 + ay^2 + az^2}$$

Where *ax*, *ay*, and *az* are the *x*, *y*, and *z* components of the acceleration vector relative to the Earth's gravitational field.

The rate of change in this acceleration vector, or Jerk (Simon et al. 2012), was then calculated as:

$$\text{Jerk} = A_{(t+1)} - A_{(t)}$$

Feeding lunges are associated with a peak followed by a minimum in Jerk (Allen et al. 2016), so we identified feeding lunges as instances when the Jerk value exceeded 1.5 (or 3.0 for Tag #832) SD above the mean, followed by a value less than 1/2 of the mean (or less than the mean for Tag #832) within 30 s after the Jerk peak. The mean Jerk value was continually updated following each selected dive and therefore represented a "grand mean" across all dives. Acceleration data recorded in the first 5 s or final 5 s of a selected dive were not used in these calculations to eliminate spurious peaks from strong fluking at the start or end of a dive. Lunges for each selected dive were then counted if they occurred more than 35 s from the previous lunge.

Argos messages for DM tags consisted of the start date and time of each selected dive, dive duration, maximum depth, and number of lunges for four to six consecutive selected dives, depending on data compression. The tag maintains an Argos message buffer that holds up to 10 messages in the tag's memory. When enough selected dives are recorded to create a new message, it is added to the buffer. If there are already 10 messages in the buffer, the oldest message is discarded to make space for the new message. Every time the tag transmits, it randomly selects one of the messages for transmission from the buffer and every third transmission is a utility message, containing the tag's current temperature and voltage. The current Jerk mean and SD values were included in the utility message for diagnostic purposes and to monitor for any potential drift in the feeding lunge detection criteria over time. DM tags were programmed to transmit only when out of the water during six 1 h periods every day until 1 September 2017, when they started transmitting for six 1 h periods every other day to prolong battery life. The transmission periods were chosen to coincide with times when satellites were most likely to be overhead. With such a transmission schedule, the life expectancy of the DM tag's battery was approximately 100 to 160 d.

2.3 Tracking Analyses

2.3.1 Argos Track Editing

Tag transmissions were processed by Service Argos using the Kalman filter to calculate locations during polar-orbiting satellite passes (Collecte Localisation Satellites 2015). Service Argos assigns a quality to each location, depending, among other things, on the number and temporal distribution of transmissions received for each satellite pass (of varying duration from horizon to horizon, Collecte Localisation Satellites 2015). The accuracy associated with each Argos satellite location was reported as one of six possible location classes (LCs) ranging from less than 200 m (LC = 3) to greater than 5 kilometers (km) (LC = B) (Vincent et al. 2002).

Before generating a complete Argos track, OSU implemented a sequential data editing protocol on the received Argos locations from each tag to retain the best locations. First, locations occurring on land were excluded. Then, locations of class Z were removed from analyses because of the unbounded errors (or sometimes invalid locations) associated with them. The remaining locations were further filtered by LC, as follows. Lower-quality LCs (LC = 0, A, or B) were not used if they were received within 20 min of higher-quality locations (LC = 1, 2, or 3). Finally, speeds between remaining locations were computed, and if a speed between two locations exceeded 12 km per hour, one of the two locations was removed, with the location resulting in a shorter overall track length being retained. These edited Argos tracks were used for analyses involving calculation of distance from shore and occurrence in Navy areas and BIAs (see **Sections 2.4** and **2.5**).

2.3.2 Track Regularization and Behavioral Annotation with State-Space Models

Several of the analyses covered by this report, such as home range, historical comparisons, dive behavior, and ecological relationships (see **Sections 2.6** through 2**.9**), further required that track locations be spaced at regular intervals and have a behavioral mode annotation. For these purposes, the raw Argos locations (i.e., prior to applying the sequential data editing protocol described in **Section 2.3.1**) were used largely unedited (except for the removal of Z-class locations) as input into a Bayesian switching state-space model (SSSM) (Jonsen et al. 2005) in the software package R v. 2.12.1 and WinBUGS v. 1.4.3. The model provided a regularized track with one estimated location per day, after accounting for Argos satellite location errors (based on Vincent et al. 2002) and movement dynamics of the animals (for tracks with locations on at least 3 d). The SSSM model ran two Markov chain Monte Carlo simulations each for 30,000 iterations, with the first 10,000 iterations being discarded as a burn-in, and the remaining iterations being thinned, removing every fifth one to reduce autocorrelation (Bailey et al. 2009). Included in the model was the classification of locations into two behavioral modes based on mean turning angles and autocorrelation in speed and direction: "transiting" (mode 1) and "area-restricted searching" (ARS; mode 2). Although only two behavioral modes were modeled, the means of the Markov chain Monte Carlo samples provided a continuous behavioral state value from 1 to 2 (Bailey et al. 2009). As in Bailey et al. (2009) and Irvine et al. (2014), we chose behavioral state values greater than 1.75 to represent ARS locations and values lower than 1.25 to represent transiting. Locations with behavioral state values in between were considered "uncertain."

2.4 Calculation of Distance from Shore

The closest point on land was determined for each filtered Argos location using the NEAR toolbox function in ESRI® ArcMap v.10.3. The geodesic distance was then computed between each point and its corresponding whale location using the WGS 1984 ellipsoid parameters in ESRI® ArcMap v.10.3.

2.5 Occurrence in Navy Areas and BIAs

The number of filtered locations occurring inside versus outside Navy areas were computed for each whale track, with the percentage of locations inside reported as a proportion of the total number of locations obtained for each whale. Numbers of blue whale locations and corresponding percentages were also computed for areas that were identified in Calambokidis et al. (2015) as Biologically Important Areas (hereafter referred to as BIAs) for blue whale feeding areas. Four of the nine BIAs (Calambokidis et al. 2015) overlapped completely or partially with the SOCAL area: Santa Monica Bay to Long Beach, San Nicolas Island, Tanner-

Cortes[1] Bank, and San Diego (using the same nomenclature for BIAs as in Calambokidis et al. [2015]). Two blue whale BIAs overlapped with the PT MUGU area: Santa Barbara Channel and San Miguel BIA and Point Conception/Arguello BIA. The other three blue whale BIAs (Calambokidis et al. 2015) did not overlap Navy areas and were not considered in this report.

To compute estimates of residence time inside Navy areas and overlapping BIAs, interpolated locations were derived at 10 min intervals between filtered Argos locations, assuming a linear track and a constant speed. These interpolated locations provided evenly spaced time segments from which reasonable estimates of residence times could be generated, especially within the smaller Navy areas and BIAs. Residence time was calculated as the sum of all 10-min segments from the interpolated tracks that were completely within each area of interest. The amount of time spent inside these areas was expressed as the number of days as well as the proportion (percentage) of the total track duration. The number of edited Argos locations inside these areas was also reported, as well as the proportion (percentage) of the total number of edited Argos locations per track.

2.6 Home Range Analysis

Kernel HRs were created for the portion of each SSSM track inside the U.S. Exclusive Economic Zone (EEZ; ocean waters extending out to 200 nautical miles of the U.S. coastline) using the least-squares cross-validation bandwidth selection method (Worton 1995, Powell 2000, Irvine et al. 2014). Only those portions of tracks within the EEZ were considered for this analysis to allow comparison with historical home range analysis for blue whales conducted by Irvine et al. (2014). Kernel analysis was implemented using the "adehabitatHR" package (Calenge 2006) in R v. 2.12.1. The 90 percent (HR) and 50 percent (CA) isopleths were produced for each track with 30 or more estimated locations (Seaman et al. 1999) and all portions that overlapped land were removed. The areas of each whale's HR and CA were then calculated in ESRI® ArcMap v.10.0.

2.7 Inter-annual Comparisons

Comparisons between the four tagging years were conducted for tracking duration and total distance traveled for each whale, as well as HR and CA size using the STATGRAPHICS® Centurion XVI v.16.1.03 software package. Analysis of variance (ANOVA) was used to test whether the yearly means were equal, and if not (ANOVA $p < 0.05$), multiple range tests using the Fisher's least significant difference (LSD) procedure to compute 95 percent confidence limits around each mean allowed determination of which means were significantly different from one another. ANOVAs (and Fisher's LSD) were also used for yearly comparisons in time spent by whales in Navy training ranges and BIAs (for blue whales), and for mean distances to shore in Navy training ranges.

2.8 Dive Behavior Analysis

The goal of this analysis was to better understand the diving and feeding behavior of tagged whales over their tracking duration using DM tags and examine how they changed temporally

---

[1] We use the spelling of Cortes Bank as shown on navigational charts, rather than the spelling used in Calambokidis et al. (2015) to refer to this BIA ("Cortez Bank").

and spatially. The percentage of the tracking duration summarized by reported dives from the tags was calculated as the sum of all received dive durations plus the sum of all received post-dive intervals (i.e., the time between the end of one selected dive and the start of the next one). We only calculated post-dive intervals for dives reported within the same transmission because we could not be sure dives were sequential from one transmission to the next (e.g., if there was a 15 min time difference between the end of the last dive in one received transmission and the start of the first dive of the next received transmission, it is possible the whale made no selected dives during that time, or made a series of short-duration selected dives that were packaged into a transmission that was not received). Each reported dive was assigned a location along the track by linear interpolation, using the proportional time difference between the start of each dive and the two temporally closest Argos locations (i.e., before and after the start of the dive) to determine where on the line the dive should fall. Positions were separately assigned to dives using SSSM-derived locations in order to test how well the ARS behavioral-state classification corresponded to feeding.

Summary plots showing dive duration, maximum dive depth, and number of feeding lunges by tag over time and versus time of day were generated for each individual and for all tags combined to visualize temporal trends in the dive data. Due to the large number of plots generated, only the plots aggregating all tag data are presented to illustrate the trends that are described in the results. The number of feeding lunges for each whale was then mapped onto a 0.25-degree hexagonal grid so that each grid cell showed the total number of lunges that occurred within that cell for one whale. The number of lunges in each cell was then divided by the sum of the dive durations for all dives occurring in the cell (i.e., the total time spent diving in that cell) to get the number of lunges per hour reported for each grid cell. This process was repeated for each DM-tagged whale, then the value of each grid cell was averaged across all whales of a species and relativized so that all values fell from 0 to 1. The result shows the spatial distribution of where higher feeding effort occurred (i.e., higher lunges/h) after accounting for day-to-day differences in the number of dives both within and between whales. Cells that averaged data from a greater number of whales are more likely to be representative of the overall behavior occurring in that cell so the gridded map of dive durations is presented with a corresponding gridded map showing the number of DM-tagged whales that occupied each grid cell. This map indicates where DM-tagged whales were more likely to be found and/or spend time. A similar gridded analysis was conducted using the average dive duration and daytime maximum dive depths recorded in each grid cell to examine spatial differences across whales.

DM tags occasionally reported abnormally long-duration (anomalous) dives lasting up to the maximum possible value recorded by the tag (4,095 s or 68.3 min)[2]. ADB-tagged blue whales rarely made dives > 25 min in duration and never exceeded 30 min (Mate et al. 2017a), so all DM dives > 30 min in duration were removed. Such instances were limited to 60 dives across all tags (out of 23,770 total dives, <0.3 percent).

---

[2] Diagnostic information on this problem is unfortunately limited. However, the most likely explanation is related to the tag's SWS, which detects when the tag breaks the surface of the water, allowing it to set the start and end times of a dive. Abnormally long dives may have been the result of plankton growth on the tag, causing an underwater reading of the SWS even at the surface, or whale behavior/posture that kept a tag underwater despite the whale being at the surface.

2.9 Ecological Relationships

In order to provide an environmental context to the tracking data collected in 2017, we annotated each SSSM location with relevant variables from remotely sensed measurements acquired by oceanographic satellites and from digital elevation models of the seafloor. The oceanographic variables extracted included: SST and phytoplankton CHL. These products are available through the web service Environmental Research Division Data Access Program, hosted by the National Oceanic and Atmospheric Administration (NOAA) NMFS/Southwest Fisheries Science Center (http://coastwatch.pfeg.noaa.gov/erddap/index.html) (see **Table 1**). Variables describing the seafloor relief were depth (DEPTH), slope (SLOPE, or depth gradient), aspect (ASPECT, the directional facing of the slope), and distance to the 200 m isobath (or distance to the shelf break, DISTSHELF). Finally, the distance to the nearest shoreline (DISTSHORE, using the Great Circle distance WGS84 ellipsoid method) was also computed for each SSSM location (**Table 1**).

Table 1. List of environmental data products and variables on the ERDDAP server accessed through the R package xtractomatic v. 3.4.1. Columns include variable name (and abbreviation), measurement unit, data set or parameter (dtypename) required by xtractomatic,

Variable	Unit	dtypename	Sensor/Product	Temporal resolution	Spatial resolution
Sea surface temperature (SST)	°C	jplMURSST41SST*	Multi-scale Ultra-high Resolution (MUR) SST Analysis fv04.1	1 d	0.01 deg (1.11 km)
Chlorophyll-*a* concentration (CHL)	mg m^{-3}	mbchla8day**	Moderate Resolution Imaging Spectroradiometer (MODIS) on Aqua satellite	8 d†	0.025 deg (2.78 km)
Depth (DEPTH)	m	ETOPO180	ETOPO1 global relief model of Earth's surface	NA	0.0167 deg (1.85 km)
Slope (SLOPE)‡	m km^{-1}	ETOPO180	ETOPO1	NA	0.0167 deg (1.85 km)
Aspect (ASPECT)‡	degrees	ETOPO180	ETOPO1	NA	0.0167 deg (1.85 km)
Distance to 200 m isobath (DISTSHELF)‡	km	ETOPO180	ETOPO1	NA	0.0167 deg (1.85 km)
Distance to shore (DISTSHORE)§	km	cntry_06.shp	ESRI World Countries 2006	NA	50 m

*jplMURSST41SST is available from 1 June 2002 to present.

**mbchla8day is available from 29 December 2005 to present.

†Although this variable covers 8 d periods, it is computed as a running composite, such that it provides a value for every day.

‡The variables SLOPE, ASPECT, and DISTSHELF were not available on ERDDAP. They were derived from a DEPTH extract covering the entire study area.

§The variable DISTSHORE was not obtained from ERDDAP. It was computed from the World Countries 2006 shoreline available in ArcGIS.

The annotation process was automated using the R package xtractomatic v. 3.4.1 (Mendelssohn 2018), a collection of functions that permit client-side access to the data sets served by the Environmental Research Division Data Access Program. The xtractomatic functions permit the use of a box of arbitrary size to extract the underlying data around each location. In order to account for the uncertainty in the location estimation by the SSSM, we obtained the median value for the environmental observations closest in time and space to each location occurring within a box defined by the 95 percent credible limits in longitude and in latitude, respectively. The number of observations used in this computation was dependent not only on the extent of the credible limits around each SSSM location, but also on the spatial resolution of the environmental products used, which varied from 1.11 km (for SST) to 4.63 km (for CHL) (**Table 1**). In addition to reflecting the uncertainty in location estimation, this approach had the benefit of minimizing the number of locations with missing environmental values due to cloud cover in some of the products had we simply obtained the single pixel value nearest to a location.

To reduce the bias introduced by SSSM locations with large estimation uncertainty, we excluded locations with 95 percent credible limits exceeding 1 degree in longitude and/or in latitude from further analyses. We also excluded SSSM locations that were estimated on land. Finally, for each track we computed the Great Circle distance (WGS84 ellipsoid method, in km) between pairs of SSSM locations (pairwise distance [PWDIST]) as metric of the local scale of movement of the tagged whales under a variety of environmental conditions. In this way, we generated fully annotated SSSM tracks with behavioral mode, pairwise distance, and a suite of environmental variables at each estimated location for ecological characterization.

We analyzed the annotated SSSM tracks in a biogeographic context by using the regional framework developed by Longhurst (1998, 2006). Although there are a number of alternative biogeographic frameworks available (as discussed in our annual report for 2014 [Mate et al. 2015]), we chose Longhurst's regionalization for its objective and consistent approach based on physiognomic and ecological considerations. The study area comprised eight biogeographic provinces: the Alaska Downwelling Coastal Province (ALSK), Pacific Subarctic Gyre-East Province (PSGEP), North Pacific Transition Zone Province (NPPF), North Pacific Tropical Gyre Province (NPTG), California Current Province (CCAL), North Pacific Equatorial Countercurrent Province (PNEC), Pacific Equatorial Divergence Province (PQED), and Central American Coastal Province (CAMR). We obtained the digital boundaries (polygons) for the Longhurst provinces as shapefiles from the Gazetteer of marine regions (Claus et al. 2014) available in the Marine Regions web site (http://marineregions.org/; Marine Regions Geographic Identifier, MRGID: 22538). As described in our annual report for 2014 (Mate et al. 2015), we modified the boundaries of two of these provinces to better reflect whale distribution, as follows. First, the jagged offshore edge of the CCAL boundary was replaced by a straight line to avoid interrupting some of the whale tracks that occurred near it. Second, because few locations occurred in CAMR outside of the Gulf of California (which Longhurst considered part of CAMR), we created a new province designation for the Gulf of California (GUCA), where whales did occur, by slightly altering the boundaries of CCAL and PNEC, and did not further consider the rest of CAMR as a separate province in this study.

The regional biogeography of the tagged whales was assessed across the four years of this project (2014, 2015, 2016, and 2017) by calculating the number and percentage of SSSM locations occurring within each province. A breakdown of the proportion of SSSM locations by behavioral mode was only reported for CCAL because this was the only province consistently occupied by both species in all years. For the same reason, summary statistics for the associated environmental variables were reported only for CCAL, and were further limited to the summer–fall months (July to November). Within CCAL, we broadly interpreted ARS behavior as foraging activity. Inter-annual differences in ecological relationships in CCAL were additionally assessed using graphical methods (i.e., maps and violin plots [Hintze and Nelson 1998]).

For the long-term environmental context, we used three independent indices of climate variability with well-known linkages to changes in marine ecosystem productivity in the Pacific Ocean: the Oceanic Niño Index (ONI), the PDO index, and the NPGO index. Time-series plots of these climate indices were presented for the five-year period January 2013–December 2017.

The ONI quantifies inter-annual fluctuations in SST in the eastern equatorial Pacific and is considered the official indicator of El Niño and La Niña events by NOAA (Barnston 2015). It is computed as the three-month running mean of SST anomalies in the Niño 3.4 region (5°N-5°S, 120-170°W), based on centered 30-year base periods updated every five years. El Niño/La Niña events are declared when a threshold anomaly of ±0.5 degrees Celsius (°C) is met for a minimum of five consecutive overlapping seasons. The three-month running mean (i.e., monthly scale) ONI indices were downloaded from NOAA's National Weather Service/Climate Prediction Center (http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears.shtml).

The PDO quantifies mid-latitude fluctuations in SST contrasting the eastern and western parts of the North Pacific basin and persisting for 20 to 30 years (i.e., "warm" and "cool phases") (Mantua et al. 1997, Zhang et al. 1997). Standardized values of the PDO index correspond to the leading principal component of monthly SST anomalies in the North Pacific Ocean (poleward of 20°N), after removal of the monthly mean global average SST anomalies, to separate this pattern of variability from any global warming signal that may be present in the data. The monthly PDO values were downloaded from the University of Washington's Joint Institute for the Study of the Atmosphere and Ocean PDO web page (http://research.jisao.washington.edu/pdo).

The NPGO quantifies deviations in sea surface height varying at similar time scales as the PDO. However, the NPGO is derived as the second principal component of monthly sea surface height, and its spatial pattern is most strongly manifested in the central North Pacific as contrast between the North Pacific Gyre and the Subarctic Gyre (which co-varies with the California Current) (Di Lorenzo et al. 2008). The NPGO pattern is similar to the second principal component of SST anomalies (also known as the "Victoria Mode"), and therefore it is mechanistically unrelated to the PDO. While the PDO tracks fluctuations in temperature observations across the North Pacific basin, the NPGO tends to track fluctuations in salinity, nutrients and chlorophyll-*a* observations, especially in the two North Pacific gyres and in the California Current (Di Lorenzo et al. 2008). The monthly NPGO values were downloaded from the Georgia Institute of Technology's Ocean Climate and Ecosystem Science NPGO web page (http://www.oces.us/npgo/).

2.10 Genetics

2.10.1 DNA Extraction and mtDNA Sequencing

Total genomic deoxyribonucleic acid (DNA) was extracted from skin tissue following standard proteinase K digestion and phenol/chloroform methods (Sambrook et al. 1989) as modified for small samples by Baker et al. (1994). An approximate 800-base-pair (bp) fragment of the mitochondrial deoxyribonucleic acid (mtDNA) control region was amplified with the forward primer M13Dlp1.5 and reverse primer Dlp8G (Dalebout et al. 2004) under standard conditions (Sremba et al. 2012). Control region sequences were edited and trimmed to a 410 bp consensus region in Sequencher vs4.6. Unique haplotypes were then aligned with previously published haplotypes downloaded from GenBank® and from samples collected during previous tagging efforts. Published datasets include LeDuc et al. (2007), Attard et al. (2015), Torres et al. (2017) and Sremba et al. (2012) for blue whales; and Archer et al. (2013) for fin whales. New haplotypes were confirmed by reverse sequencing from a new polymerase chain reaction (PCR) product following recommendations by Morin et al. (2010).

2.10.2 Microsatellite Genotypes

Up to 17 microsatellite loci were also amplified for each sample using previously published conditions (LeDuc et al. 2007, Sremba et al. 2012). These included the following loci: EV14, EV21, EV37, EV94, EV96, EV104 (Valsecchi and Amos 1996); GATA28, GATA417, GATA98 (Palsbøll et al. 1997); rw31, rw4-10, rw48 (Waldick et al. 1999); GT211, GT23, GT575 (Bérubé et al. 2000); 464/465 (Schlötterer et al. 1991); and DlrFCB17 (Buchanan et al. 1996). Microsatellite loci were amplified individually in 10-microliter reactions and co-loaded in four sets for automated sizing on an ABI3730xl (Applied Biosystems™). Microsatellite alleles were sized and binned using Genemapper vs4.0 (Applied Biosystems™) and all peaks were visually inspected.

2.10.3 Sex Determination

Sex was identified by multiplex PCR using primers P1-5EZ and P2-3EZ to amplify a 443 to 445 bp region on the X chromosome (Aasen and Medrano 1990) and primers Y53-3C and Y53-3D to amplify a 224 bp region on the Y chromosome (Gilson et al. 1998).

2.10.4 Individual Identification

Individual whales were identified from the multi-locus genotypes using CERVUS v. 3.0.3 (Marshall et al. 1998). Mismatches of up to three loci were allowed as a precaution against false exclusion due to allelic dropout and other genotyping errors (Waits and Leberg 2000, Waits et al. 2001). Electropherograms from mismatching loci were reviewed and corrected or repeated. A final "DNA profile" for each sample included up to 17 microsatellite genotypes, sex, and mtDNA control region sequence or haplotype.

2.10.5 Species and Stock Identification

Species identity from field observations was confirmed by submitting mtDNA sequences to the web-based program *DNA-surveillance* (Ross et al. 2003) and by Basic Local Alignment Search Tool search of GenBank®. If species identification from mtDNA did not agree with the field observations, we used the Bayesian clustering program STRUCTURE v. 2.3.1 to assess the potential for hybrid ancestry (Falush et al. 2003). In this method, individuals are assigned probabilistically to species or population units using allele frequencies of the multi-locus genotypes.

Stock identity of the tagged blue and fin whales was investigated by developing a reference database of published mtDNA sequences and by initiating collaboration with other holders of unpublished data. The mtDNA haplotypes of the tagged whales were compared to the relevant reference databases using standard indices of differentiation (e.g., F_{ST}) and tested using the permutation procedure available in the program Arlequin (Excoffier and Lischer 2010).

For blue whales, we considered differences of the tagged whales in relationship to a reference database of mtDNA haplotypes from unpublished results of samples from the eastern North Pacific and published reports of samples representing populations or subspecies in the Southern Hemisphere as described by Donovan (1991). To our knowledge, no samples are currently available to represent the proposed Western North Pacific stock of blue whales, as described from vocalizations by Stafford et al. (2001) and Stafford (2003) and further characterized by Monnahan et al. (2014).

For analysis of fin whale stock structure, we initiated collaboration with F.I. (Eric) Archer of the NMFS/Southwest Fisheries Science Center, providing access to a large reference database of mtDNA haplotypes from fin whales in the North Pacific and elsewhere (Archer et al. 2013). For this, we considered differences of the tagged whales in relationship to seven *a priori* population strata: Gulf of California, Southern California Bight, California/Oregon/Washington, Gulf of Alaska, Central Pacific, Bering Sea, and Hawaii.

At present, it is not possible to include nuclear microsatellite loci in the comprehensive stock analyses of blue and fin whales because of differences in loci used by other investigators and the difficulties of standardizing allele sizes across laboratories (Morin et al. 2010).

2.11 Photo-identification

Photographs of the whales' right/left sides with dorsal fins were taken during field efforts for ID purposes, as well as to document tag placement, wound condition, and to identify previously tagged whales to examine wound healing. Besides tagged whales, photographs were taken of all other whales seen while tagging for ID purposes and to examine for tag wounds or scars. Each individual whale that had a recognizable dorsal fin and lateral surface was compared to our existing OSU photo catalog to determine if it had previously been identified. If not in the catalog, it was given a unique ID number and the best ID photographs were added.

Once this process is completed, our photo-IDs will be submitted to other researchers to compare with their photo-ID catalogs to determine if there are matches that can show us the sighting histories of tagged whales. Blue whale photographs will be submitted to Cascadia Research Collective (Olympia, Washington) and fin whale photographs will be submitted to Marine Ecology and Telemetry Research (Seabeck, Washington).

3. Results

3.1 Blue Whale

3.1.1 Body Condition Assessment and Tagging Rates

In 2017, 27 blue whales were tagged during approaches to 308 whales (9 percent; **Table 2**). This is similar to the tagging rates in 2015 and 2016 (6 percent for both years), but less than the rate in 2014 (12 percent). Twenty-nine percent of blue whales approached were in poor body condition and were not considered candidates for tagging (**Table 2**). The proportion of blue whales approached in 2014 to 2016 that were in poor body condition ranged from 7 to 36 percent (**Table 2**).

Table 2. Approach details for tagging efforts in California and Oregon, 2014–2017.

Species	# Whales Approached	# Whales Tagged	# Whales in Poor Body Condition	% Whales in Poor Body Condition	Average Time in Tagging Vessel (h/d)
Southern California Deployments – 2014 – 22 Days of Tagging Effort (42-day cruise)					
blue	204	24	15	7	8.11
fin	108	6	0	0	
Southern California Deployments – 2015 – 15 Days of Tagging Effort (30-day cruise)					
blue	392	22	90	23	8.68
fin	110	13	0	0	
Bryde's	5	1	0	0	
minke	2	0	0	0	
Southern and Central California Deployments – 2016 – 13 Days of Tagging Effort (30-day cruise)					
blue	295	19	105	36	9.87
fin	160	14	3	2	
Southern and Central California Deployments – 2017 – 15 Days of Tagging Effort (31-day cruise)					
blue	308	27	89	29	8.57
fin	12	1	0	0	

KEY: # = number.

3.1.2 Behavioral Responses to Tagging

Four of the 27 tagged blue whales exhibited short-term startle responses to the tagging/biopsy process. One of these responses consisted of a brief period of rapid swimming after tagging. The other three responses consisted of low-level "tail flicks." A tail flick is defined here as a swift or abrupt movement of the tail flukes dorso-ventrally (up and down). The level of response follows definitions described in Weinrich et al. (1992), Hooker et al. (2001), and Baumgartner et al. (2015), with "low-level" referring to behavior modifications that are not overtly forceful, with no prolonged evidence of behavioral disturbance.

3.1.3 Wound Healing

Four blue whales tagged in 2017 were photographed 1 d after tagging, with three of these showing slight swelling at the tag site and one showing some bleeding (**Table 3**). Additionally, two blue whales tagged in 2017 were resighted by whale-watching operators in Monterey Bay. One whale was resighted from 52 to 56 d after it was tagged. There was an extensive tissue response around the tag, which was still transmitting. The wound was reported to NMFS on 6 September 2017, at which time it was determined that the wound did not constitute a serious injury and did not require an Incident Report. The whale was otherwise in good condition and its behavior did not differ from other whales seen at the same time. The other whale was resighted 65 days after tagging with the tag still attached and transmitting. This whale was in good condition, with no swelling or scarring around the tag site, but the skin was slightly discolored just forward of the tag. One blue whale tagged in 2014, one tagged in 2015, and one tagged in 2016 were resighted during our tagging efforts in 2017. In addition, one blue-fin whale hybrid tagged in 2015 was also resighted on two different days. See **Table 3** for tag site and body condition for whales tagged in previous seasons.

3.1.4 Tracking Analysis – 2017

The 27 tags deployed on blue whales (between 7 July and 2 August 2017) consisted of 13 LO tags and 14 DM tags. An additional DM tag was launched from the tag applicator, but did not properly deploy and was lost. Most of the tags (26) were deployed on blue whales off southern California, in the Santa Barbara Channel or west of San Miguel Island. One tag was deployed off the central California coast, near the continental shelf edge between Half Moon Bay and Pigeon Point. All 27 tags on blue whales provided locations, with tracking durations ranging from 1.9 to 158.8 d (**Table 4**). Tracking durations for LO tags averaged 80.7 d (SD = 40.6 d). DM tags averaged 49.2 d (SD = 53.2 d). The last transmission was received on 31 December 2017 (for Tag #10831).

Six of the 14 DM tags transmitted for periods of less than 7 d, much shorter than DM tags deployed in the past on blue (mean = 73.2 d) and fin whales (mean = 38.6 d) (Mate et al. 2017a), prompting us to send the remaining, un-deployed tags of this type back to the manufacturer (Telonics) for assessment. Telonics discovered minute amounts of water inside the tags (presumably from pre-field pressure testing), which were attributed to failure in the O-ring seals of the antenna and SWS. This failure was due in part to the pressure transducer occupying a large portion of the endcap, creating tight tolerances to fit the antenna and SWS. These tolerances were such that extremely small variations in O-ring diameter (within specifications) were enough to slightly contact the endcap walls as the antenna or SWS was inserted, and damage the O-ring, resulting in leakage. The leakage of saltwater into the tag was so slight that it took varying lengths of time (up to 7 d after deployment) to result in tag failure. This was why it was undetected during our pressure testing before deployment. This led to a new endcap design as well as new testing procedures by Telonics for each individual endcap before tags are assembled. Despite these failures, eight of the 14 deployed DM tags provided tracking periods ranging from 24.8 to 158.8 d (mean = 83.7 d), which was nearly identical to the LO tags applied during 2017 (mean = 80.7 d).

Table 3. Resightings and tag site descriptions for blue whales satellite-tagged off southern and central California, 2014–2017. Wound size estimates are approximate.

Species/ Tag#	Tagging Date	Resighting Dates	# Days Post-Tagging	Tag Present/ Tag Transmitting	Body Condition	Tag Site Condition
Blue/10833	9/11/14	7/25/17	1048	No/No	Good	Slight swelling around tag site, ~3 cm high, extending out radially ~25 cm.
Blue-Fin Hybrid/10831	7/6/15	7/13/17 7/18/17	738 743	No/No	Somewhat skinny – slight depression along lateral flank beneath midline	No visible swelling, but tag site could not be distinguished from other small wound sites caused by ectoparasites and cookie cutter shark bites.
Blue/838	7/7/15	7/10/17	734	No/No	Good	Circular depression around tag site, ~8 cm diameter, 2 cm depth, moderate scarring below tag site, consisting of a raised area (~25 × 8 cm) with pale gray skin discoloration. No swelling.
Blue/5701	7/14/16	7/25/17	376	No/No	Good	Slight swelling around tag site, ~2 cm high, extending out radially ~15 cm.
Blue/832	7/7/17	7/8/17	1	Yes/Yes	Good	Blood extending from tag site downward ~15 cm. No swelling.
Blue/5803	7/25/17	7/26/17	1	Yes/Yes	Good	Very slight swelling around tag site, ~1 cm high, extending out radially ~5 cm.
Blue/5910	7/25/17	7/26/17	1	Yes/Yes	Good	Very slight swelling around tag site, ~1 cm high, extending up toward midline ~13 cm.
Blue/5921	7/25/17	7/26/17	1	Yes/Yes	Good	Slight swelling around tag site, ~1 cm high, extending forward of the tag site ~15 cm.
Blue/835	7/10/17	8/31/17-9/4/17	52-56	Yes/Yes	Good	Extensive tissue response around tag site, ~ 12 × 18 cm
Blue/10831	7/25/17	9/28/17	65	Yes/Yes	Good	Slight discoloration near tag site

KEY: cm = centimeter; # = number.

Table 4. Deployment and performance data for satellite-monitored radio tags deployed on blue whales in southern and central California, 2017. In the Sex column, U = unknown sex, in cases when no biopsy sample was collected. See Section 2.3.1 for location filtering method.

Tag #	Sex	Tag Type	Deployment Date	Last Location	# Days Tracked	# Filtered Locations	Total Distance (km)
Blue Whales							
826	M	LO	10-Jul-17	5-Nov-17	117.9	378	7,793
835	F	LO	10-Jul-17	30-Sep-17	81.5	303	4,437
841	M	LO	10-Jul-17	8-Dec-17	150.3	437	8,302
845	F	LO	16-Jul-17	23-Nov-17	129.3	428	7,615
847	U	LO	13-Jul-17	12-Oct-17	90.3	287	3,958
4176	F	LO	16-Jul-17	25-Sep-17	70.3	263	4,828
5648	M	LO	16-Jul-17	18-Aug-17	32.3	137	1,306
5670	M	LO	16-Jul-17	15-Aug-17	29.3	104	1,332
5679	U	LO	16-Jul-17	22-Aug-17	36.7	142	1,733
5803	M	LO	25-Jul-17	19-Sep-17	55.3	158	2,485
5910	F	LO	25-Jul-17	24-Oct-17	91.0	237	8,245
5921	M	LO	25-Jul-17	5-Sep-17	41.3	158	2,046
10826	M	LO	25-Jul-17	26-Nov-17	123.2	408	6,482
Mean		**LO**			**80.7**	**265**	**4,659**
Median		**LO**			**81.5**	**263**	**4,437**
825	U	DM	26-Jul-17	29-Jul-17	3.2	11	157
827	M	DM	26-Jul-17	1-Dec-17	127.6	322	5,634
831	F	DM	26-Jul-17	9-Sep-17	45.0	230	2,717
832	U	DM	7-Jul-17	9-Jul-17	1.9	10	131
836	M	DM	25-Jul-17	27-Jul-17	1.9	14	100
1385	U	DM	13-Jul-17	21-Oct-17	100.1	416	3,607
1386	U	DM	2-Aug-17	5-Aug-17	2.7	9	57
5736	M	DM	13-Jul-17	16-Jul-17	2.9	9	119
5800	M	DM	16-Jul-17	23-Jul-17	6.9	44	295

Tag #	Sex	Tag Type	Deployment Date	Last Location	# Days Tracked	# Filtered Locations	Total Distance (km)
Blue Whales (continued)							
5840	U	DM	16-Jul-17	21-Oct-17	97.0	370	4,339
10830	U	DM	24-Jul-17	18-Aug-17	24.8	142	1,065
10831	U	DM	25-Jul-17	31-Dec-17	158.7	489	6,574
10840	M	DM	25-Jul-17	3-Oct-17	70.3	290	4,476
23031	M	DM	25-Jul-17	9-Sep-17	46.2	251	2,948
Mean		DM			49.2	186	2,301
Median		**DM**			**34.9**	**186**	**1,891**
Fin Whale							
2082	U	LO	2-Aug-17	14-Sep-17	42.3	111	1,089

KEY: DM = Telonics RDW-665 Dive-Monitoring tag; F = Female; km = kilometer(s); LO = Wildlife Computers SPOT6 Location-Only tag, M = Male; # = number.

Locations of blue whales tagged off southern California ranged over 31 degrees of latitude, from the Costa Rica Dome, off Central America, to Point Arena, California (**Figure 3**). Most of the blue whale locations were over continental slope waters, with concentrations west of San Miguel Island and at the western edge of the Santa Barbara Channel, off San Francisco, and off Monterey Bay. Ten whales left California waters during their tracking periods. Two of these whales traveled briefly to northern Baja California, Mexico, off Ensenada (one in mid-August, Tag #5921; and one in mid-September, Tag #845) before heading back to California, and one other whale (Tag #826) traveled briefly to Vizcaíno Bay, midway down Baja California, in mid-August before heading back to California. Seven other whales migrated south along the Baja California coast. One of these whales (Tag #10840) reached Vizcaíno Bay on the central coast of Baja California by mid-September and remained in that area for 10 d before its tag stopped transmitting. Five whales reached the waters southwest of Magdalena Bay near the southern end of Baja California; one in early September (Tag #23031), one in mid-September (Tag #841), one in mid-October (Tag #827), and two in mid-November (Tag #s 10826 and 10831). Time spent in this area for four of these whales ranged from 7 to 88 d. The seventh whale (Tag #5910) reached the Costa Rica Dome, off Central America, in mid-October, and was tracked moving southwest through the area for 2 d before its tag stopped transmitting. The single blue whale tagged off central California (Tag #1386) remained in an area near the continental shelf edge off Año Nuevo Point for its entire 2.7-d tracking period.

3.1.4.1 USE OF NAVY TRAINING AREAS BY TAGGED BLUE WHALES

The most heavily used Navy training area for tagged blue whales in 2017 was PT MUGU, where all but two tags were applied, with 26 of the 27 tracked whales having from 26 to 100 percent of their total locations there (**Table 5, Figure 4**). This represented from 24 to 100 percent of their total tracking periods or 1 to 96 d in PT MUGU. Distances to shore in PT MUGU averaged 49 km (SD = 21.7 km, maximum = 233 km; **Table 6**). Fourteen blue whales had between 1 and 43 percent of their total locations within SOCAL, representing between 1 and 44 percent of their total tracking periods (1 to 30 d; **Table 5**, **Figure 5**). Distances to shore in SOCAL averaged 97 km (SD = 31.2 km, maximum = 236 km; **Table 6**). Seven blue whales had between <1 and 2 percent of their total locations within SOAR, representing between <1 and 2 percent of their total tracking periods (0.2 to 1.0 d; **Table 5, Figure 6**). Distances to shore in SOAR averaged 36 km (SD = 12.4 km, maximum = 56 km; **Table 6**).None of the blue whales tagged in 2017 were tracked within NWTT, W237, or the Gulf of Alaska Temporary Maritime Activities Area. Blue whale locations occurred in PT MUGU and SOCAL during five months (July through November), and in SOAR during three months (July through September).

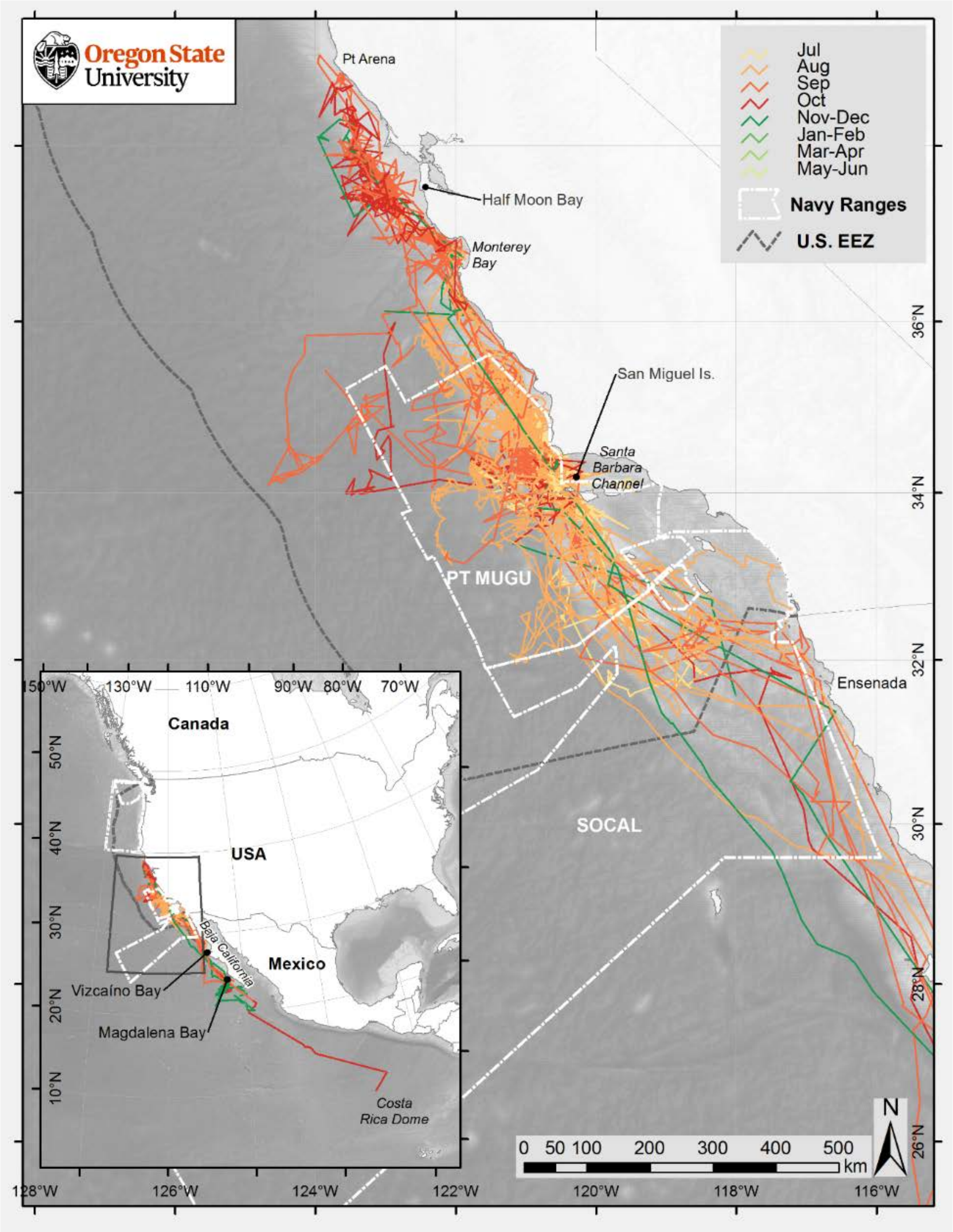

Figure 3. Satellite-monitored tracks for blue whales tagged off southern and central California in July 2017 (13 LO tags, 14 DM tags).

Table 5. Percentage of filtered locations and time spent inside Navy training ranges for blue whales tagged off southern and central California, 2017. See Section 2.3.1 for location filtering method.

Tag #	Tag Type	Total		SOCAL			PT MUGU			SOAR			NWTRC			W237		
		# Locs	# Days	% Locs	% Days	# Days	% Locs	% Days	# Days	% Locs	% Days	# Days	% Locs	% Days	# Days	% Locs	% Days	# Days
826	LO	378	118.0	17	15	18.1	55	57	67.6	<1	<1	1	0	0	0	0	0	0
835	LO	303	81.5	0	0	0	53	53	42.8	0	0	0	0	0	0	0	0	0
841	LO	437	150.3	1	2	3.0	26	24	36.2	0	0	0	0	0	0	0	0	0
845	LO	428	129.4	1	1	1.6	36	34	44.6	0	0	0	0	0	0	0	0	0
847	LO	287	94.5	7	8	7.6	85	84	79.3	<1	<1	0.6	0	0	0	0	0	0
4176	LO	263	70.3	3	6	4.3	81	79	55.9	<1	<1	0.2	0	0	0	0	0	0
5648	LO	137	32.3	0	0	0	92	94	30.2	0	0	0	0	0	0	0	0	0
5670	LO	104	29.3	0	0	0	99	100	29.3	0	0	0	0	0	0	0	0	0
5679	LO	142	36.7	43	44	16.0	57	56	20.6	0	0	0	0	0	0	0	0	0
5803	LO	158	55.3	1	1	0.6	80	78	43.4	0	0	0	0	0	0	0	0	0
5910	LO	237	112.8	5	3	3.5	46	28	31.4	0	0	0	0	0	0	0	0	0
5921	LO	158	41.3	12	15	6.1	81	83	34.3	2	2	0.7	0	0	0	0	0	0
10826	LO	408	123.2	6	6	7.9	82	78	96.5	<1	<1	0.6	0	0	0	0	0	0
825	DM	11	3.2	0	0	0	91	95	3.0	0	0	0	0	0	0	0	0	0
827	DM	322	127.5	31	24	30.3	38	34	43.5	0	0	0	0	0	0	0	0	0
831	DM	230	45.0	0	0	0	57	52	23.5	0	0	0	0	0	0	0	0	0
832	DM	10	1.9	0	0	0	60	32	0.6	0	0	0	0	0	0	0	0	0
836	DM	14	2.0	0	0	0	100	99	1.9	0	0	0	0	0	0	0	0	0
1385	DM	416	100.1	0	0	0	56	44	43.6	0	0	0	0	0	0	0	0	0
1386	DM	9	2.8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5736	DM	9	2.9	0	0	0	78	48	1.4	0	0	0	0	0	0	0	0	0
5800	DM	44	6.9	0	0	0	100	100	6.9	0	0	0	0	0	0	0	0	0
5840	DM	370	98.5	0	0	0	52	35	34.5	0	0	0	0	0	0	0	0	0
10830	DM	142	24.8	0	0	0	98	97	24.1	0	0	0	0	0	0	0	0	0
10831	DM	489	158.8	1	2	3.5	47	26	41.6	0	0	0	0	0	0	0	0	0
10840	DM	290	70.3	23	32	22.7	66	48	33.5	2	<1	0.5	0	0	0	0	0	0
23031	DM	251	46.2	36	36	16.6	51	41	19.1	<1	10	0.6	0	0	0	0	0	0
Mean+		**224**	**65.4**	**14**	**14**	**10.1**	**68**	**62**	**34.2**	**<1**	**<1**	**0.6**	**-**	**-**	**-**			
Median+		**237**	**55.3**	**7**	**7**	**6.9**	**63**	**54**	**33.9**	**<1**	**<1**	**0.6**	**-**	**-**	**-**			

KEY: DM = Telonics RDW-665 Dive-Monitoring tag; LO = Wildlife Computers SPOT6 Location-Only tag; Locs = Locations; # = number; + Summary statistics do not include zero values in their calculation.

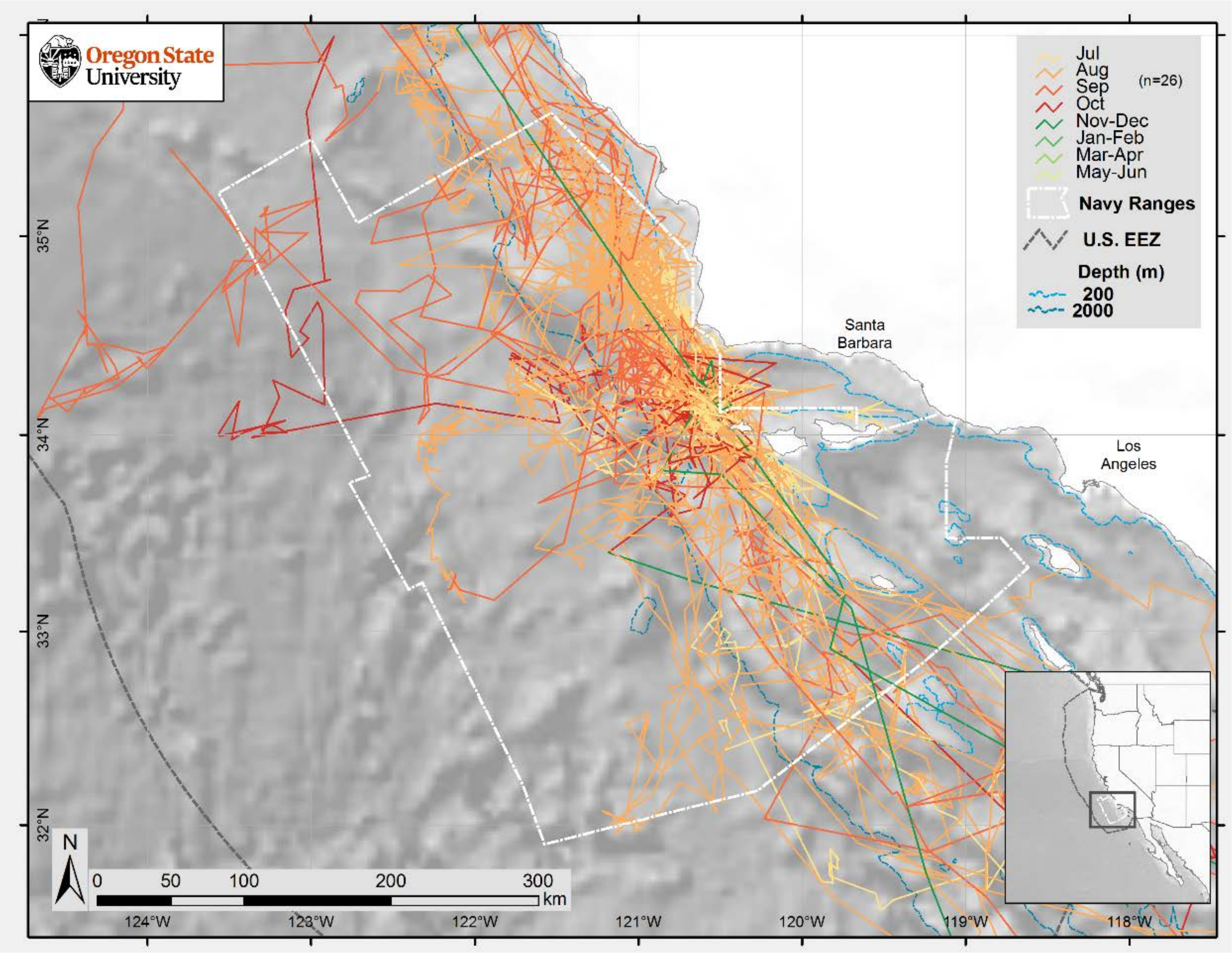

Figure 4. Satellite-monitored tracks in PT MUGU for blue whales tagged off southern California in July 2017 (13 LO tags, 13 DM tags). The light and dark blue bathymetric contours correspond to the 200 and 1,000 m isobaths, respectively.

Table 6. Geodesic distances to nearest point on shore in Navy training ranges for blue whales tagged off southern and central California, 2017 (including mean, median, and maximum distance to shore for each whale). The number of locations includes filtered locations (see Section 2.3.1 for filtering method) plus deployment location (when the deployment location occurred within a Navy range).

Tag #	Tag Type	SOCAL				PT MUGU				SOAR				NWTT				W237			
		n	Mean	Median	Max	n	Mean	Median	Max	n	Mean	Median	Max	n	Mean	Median	Max	n	Mean	Median	Max
825	DM	0	-	-	-	14	38	41	52	0	-	-	-	0	-	-	-	0	-	-	-
826	LO	82	110	109	207	281	92	89	216	1	34	34	34	0	-	-	-	0	-	-	-
827	DM	121	103	102	171	153	66	38	233	0	-	-	-	0	-	-	-	0	-	-	-
831	DM	0	-	-	-	168	32	33	73	0	-	-	-	0	-	-	-	0	-	-	-
832	DM	0	-	-	-	7	5	4	8	0	-	-	-	0	-	-	-	0	-	-	-
835	LO	0	-	-	-	227	37	35	88	0	-	-	-	0	-	-	-	0	-	-	-
836	DM	0	-	-	-	17	38	38	50	0	-	-	-	0	-	-	-	0	-	-	-
841	LO	8	132	141	173	147	31	32	130	0	-	-	-	0	-	-	-	0	-	-	-
845	LO	7	171	206	209	229	55	36	198	0	-	-	-	0	-	-	-	0	-	-	-
847	LO	24	75	64	188	347	49	39	153	2	27	27	28	0	-	-	-	0	-	-	-
1385	DM	0	-	-	-	302	60	55	130	0	-	-	-	0	-	-	-	0	-	-	-
4176	DM	10	56	59	75	304	66	65	177	1	54	54	54	0	-	-	-	0	-	-	-
5648	LO	0	-	-	-	153	35	34	87	0	-	-	-	0	-	-	-	0	-	-	-
5670	LO	0	-	-	-	139	55	47	117	0	-	-	-	0	-	-	-	0	-	-	-
5679	LO	79	105	109	155	108	74	56	144	0	-	-	-	0	-	-	-	0	-	-	-
5736	LO	0	-	-	-	9	28	31	36	0	-	-	-	0	-	-	-	0	-	-	-
5800	DM	0	-	-	-	57	33	32	56	0	-	-	-	0	-	-	-	0	-	-	-
5803	DM	3	114	111	135	164	38	33	153	0	-	-	-	0	-	-	-	0	-	-	-
5840	LO	0	-	-	-	253	30	28	88	0	-	-	-	0	-	-	-	0	-	-	-
5910	DM	16	116	120	166	163	51	39	143	0	-	-	-	0	-	-	-	0	-	-	-
5921	LO	18	73	71	113	174	37	32	114	3	28	31	32	0	-	-	-	0	-	-	-
10826	LO	31	83	63	182	485	39	37	104	2	28	28	28	0	-	-	-	0	-	-	-
10830	LO	0	-	-	-	167	58	58	105	0	-	-	-	0	-	-	-	0	-	-	-
10831	DM	5	96	98	104	295	92	55	202	0	-	-	-	0	-	-	-	0	-	-	-
10840	DM	90	57	57	124	246	48	35	130	5	26	27	29	0	-	-	-	0	-	-	-
23031	DM	110	73	51	236	153	93	61	231	2	53	53	56	0	-	-	-	0	-	-	-
Mean		**43**	**97**	**97**	**160**	**183**	**49**	**42**	**124**	**2**	**36**	**36**	**37**		-	-	-			-	-
Median		**21**	**99**	**100**	**168**	**166**	**44**	**38**	**123**	**2**	**28**	**31**	**32**		-	-	-			-	-

KEY: DM = Telonics RDW-665 Dive-Monitoring tag; LO = Wildlife Computers SPOT6 Location-Only; n = number of locations

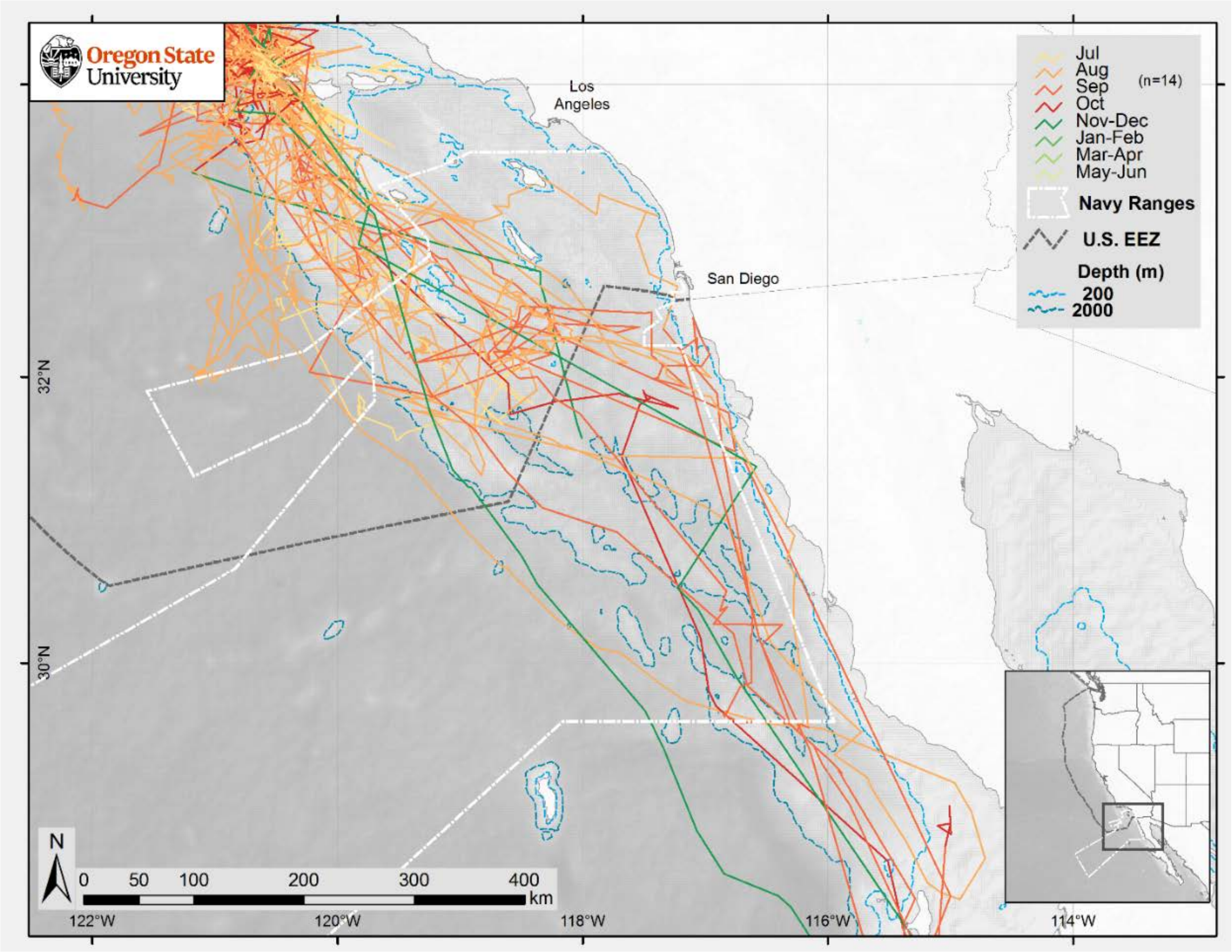

Figure 5. Satellite-monitored tracks in SOCAL for blue whales tagged off southern California in July 2017 (10 LO tags, 4 DM tags). The light and dark blue bathymetric contours correspond to the 200 and 1,000 m isobaths, respectively.

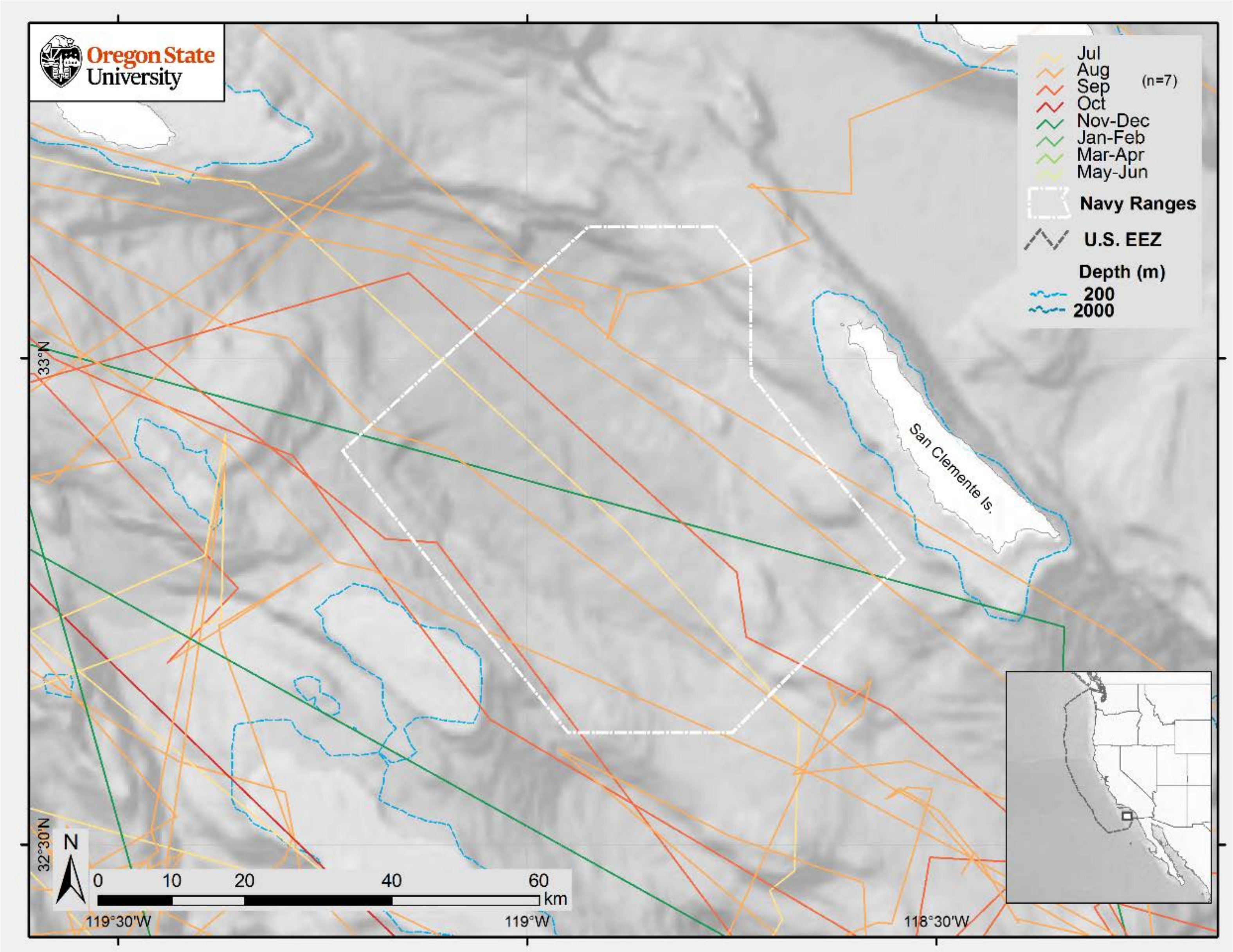

Figure 6. Satellite-monitored tracks in SOAR for blue whales tagged off southern California in July 2017 (5 LO tags, 2 DM tags). The light and dark blue bathymetric contours correspond to the 200 and 1,000 m isobaths, respectively.

3.1.4.2 USE OF BIAs BY TAGGED BLUE WHALES

The amount of time spent in BIAs by tagged blue whales ranged from <1 to 90 percent of their total tracking periods (**Table 7**). The two most heavily used BIAs (of the six overlapping Navy training ranges), in terms of number of whales having locations there, were the Santa Barbara Channel and San Miguel BIA and the Point Conception/Arguello BIA (**Figures 7 and 8**). Twenty-six blue whales were tracked in the Santa Barbara Channel and San Miguel BIA, having 5 to 91 percent of their locations there. This represented 3 to 90 percent of their total tracking time, or <1 to 42 d. Sixteen blue whales had locations in the Point Conception/Arguello BIA, spending <1 to 18 percent of their total time there, or <1 to 9 d. For 14 of these 16 whales, this represented <1 to 12 percent of their total number of locations. The tracks of the remaining two whales crossed the Point Conception/Arguello BIA (1 to 2 percent of their total tracks, or 1 d for each whale), but neither whale had locations there. Blue whale locations occurred in these former two BIAs over five months (July through November). Two blue whales had locations within the Tanner-Cortes Bank BIA and the tracks of another two whales crossed this same area, representing <1 and 1 percent of the total number of locations and <1 and 1 percent of the tracking periods (<1 and 1 d) for the former whales, and <1 percent of the tracking periods (<1 d) for both of the latter whales (**Figure 9**). Blue whale locations/tracks occurred in the Tanner-Cortes Bank BIA in August and November. One blue whale had <1 percent of its locations in the San Nicolas Island BIA (**Figure 10**), representing <1 percent of its total tracking period (<1 d). One other blue whale had <1 percent of its locations in the San Diego BIA, representing <1 percent of its total tracking period, or <1 d (**Figure 11**). Blue whale locations occurred in the San Nicolas Island and the San Diego BIAs in August. None of the blue whales tagged in 2016 were tracked within the Santa Monica to Long Beach BIA.

3.1.4.3 HOME RANGE ANALYSIS

Twenty blue whales provided enough locations to calculate HRs and CAs within waters of the U.S. EEZ (**Table 8, Figures 12 and 13**). HR sizes ranged from 2,136 to 110,458 square kilometers (km^2) (mean = 28,360.0 km^2; SD = 24,143.3 km^2) and extended from the southern edge of the U.S. EEZ, west of Ensenada, Mexico, to Point Arena, California. The densest location of HRs occurred at the west end of the Santa Barbara Channel in southern California, where HRs overlapped for up to 20 whales (of 22 tagged there). CAs ranged in size from 394 to 31,097 km^2 (mean = 5,796.2 km^2, SD = 6,593.8 km^2), extending from the California/Mexico border to Point Arena, and averaged 20 percent of the HR values. The area of highest use, with overlapping CAs for up to 19 blue whales, was at the west end of San Miguel Island in the Channel Islands. There was a significant relationship between the number of SSSM locations (equivalent to number of days, at 1 SSSM location/d) used in the analysis and the size of HRs (linear regression of log-transformed variables, $p = 0.02$), but not between number of locations and CAs (linear regression of log-transformed variables, $p = 0.09$). Despite the relationship between number of locations and HRs, we used a 30 d cutoff as the minimum number of days from which to calculate HRs to maintain consistency with analyses from previous years.

Table 7. Percentage of filtered locations and time spent inside the Biologically Important Areas (BIAs) for blue whales tagged off southern and central California, 2017. See Section 2.3.1 for location filtering method.

Tag #	Tag Type	Total		Santa Monica Bay			San Diego			San Nicolas			Tanner Cortes			Santa Barbara			Point Conception		
		# Locs	# Days	% Locs	% of Days	# Days	% Locs	% of Days	# Days	% Locs	% of Days	# Days	% Locs	% of Days	# Days	% Locs	% of Days	# Days	% Locs	% of Days	# Days
826	LO	378	118.0	0	0	0	0	0	0	0	0	0	0	0	0	7	7	8.5	<1	<1	0.3
835	LO	303	81.5	0	0	0	0	0	0	0	0	0	0	0	0	19	18	14.3	0	0	0
841	LO	437	150.3	0	0	0	0	0	0	0	0	0	0	0	0	19	16	24.0	<1	1	0.8
845	LO	428	129.4	0	0	0	0	0	0	0	0	0	0	0	0	10	9	11.3	7	7	8.8
847	LO	287	94.5	0	0	0	0	0	0	0	0	0	0	0	0	44	39	37.1	1	2	1.5
4176	LO	263	70.3	0	0	0	0	0	0	0	0	0	0	0	0	13	10	7.1	3	3	2.0
5648	LO	137	32.3	0	0	0	0	0	0	0	0	0	0	0	0	65	62	20.2	7	7	2.2
5670	LO	104	29.3	0	0	0	0	0	0	0	0	0	0	0	0	23	17	5.0	13	18	5.4
5679	LO	142	36.7	0	0	0	0	0	0	0	0	0	<1	<1	0.2	27	21	7.7	<1	2	0.7
5803	LO	158	55.3	0	0	0	0	0	0	0	0	0	0	0	0	22	16	9.1	<1	1	0.7
5910	LO	237	112.8	0	0	0	0	0	0	0	0	0	0	0	0	5	3	3.4	0	0	0
5921	LO	158	41.3	0	0	0	0	0	0	0	0	0	0	0	0	53	56	23.1	6	4	1.7
10826	LO	408	123.2	0	0	0	0	0	0	<1	<1	0.2	<1	<1	0.02	36	34	42.0	2	2	2.4
825	DM	11	3.2	0	0	0	0	0	0	0	0	0	0	0	0	18	41	1.3	0	0	0
827	DM	322	127.5	0	0	0	0	0	0	0	0	0	<1	1	1.3	7	4	5.4	2	2	2.7
831	DM	230	45.0	0	0	0	0	0	0	0	0	0	0	0	0	37	31	13.9	7	5	2.5
832	DM	10	1.9	0	0	0	0	0	0	0	0	0	0	0	0	30	7	0.1	0	0	0
836	DM	14	2.0	0	0	0	0	0	0	0	0	0	0	0	0	86	84	1.7	0	0	0
1385	DM	416	100.1	0	0	0	0	0	0	0	0	0	0	0	0	24	18	18.2	2	2	2.3
1386	DM	9	2.8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5736	DM	9	2.9	0	0	0	0	0	0	0	0	0	0	0	0	78	82	2.4	0	0	0
5800	DM	44	6.9	0	0	0	0	0	0	0	0	0	0	0	0	91	90	6.2	0	0	0
5840	DM	370	98.5	0	0	0	0	0	0	0	0	0	0	0	0	7	3	3.4	0	0	0
10830	DM	142	24.8	0	0	0	0	0	0	0	0	0	0	0	0	33	28	6.9	0	0	0
10831	DM	489	158.8	0	0	0	0	0	0	0	0	0	<1	<1	0.3	16	7	11.2	9	5	7.3
10840	DM	290	70.3	0	0	0	<1	<1	0.3	0	0	0	0	0	0	27	19	13.6	6	3	2.0
23031	DM	251	46.2	0	0	0	0	0	0	0	0	0	0	0	0	19	13	6.2	0	0	0
Mean+		**224**	**65.4**	**-**	**-**	**-**	<1	<1	0.3	<1	<1	0.2	**<1**	**<1**	**0.5**	**31**	**28**	**11.7**	**4**	**4**	**2.7**
Median+		**237**	**55.3**	**-**	**-**	**-**	<1	<1	0.3	<1	<1	0.2	**<1**	**<1**	**0.2**	**24**	**18**	**8.1**	**3**	**3**	**2.1**

KEY: DM = Telonics RDW-665 Dive-Monitoring tag; LO = Wildlife Computers SPOT6 Location-Only tag; Locs = Locations; # = number; + Summary statistics do not include zero values in their calculation.

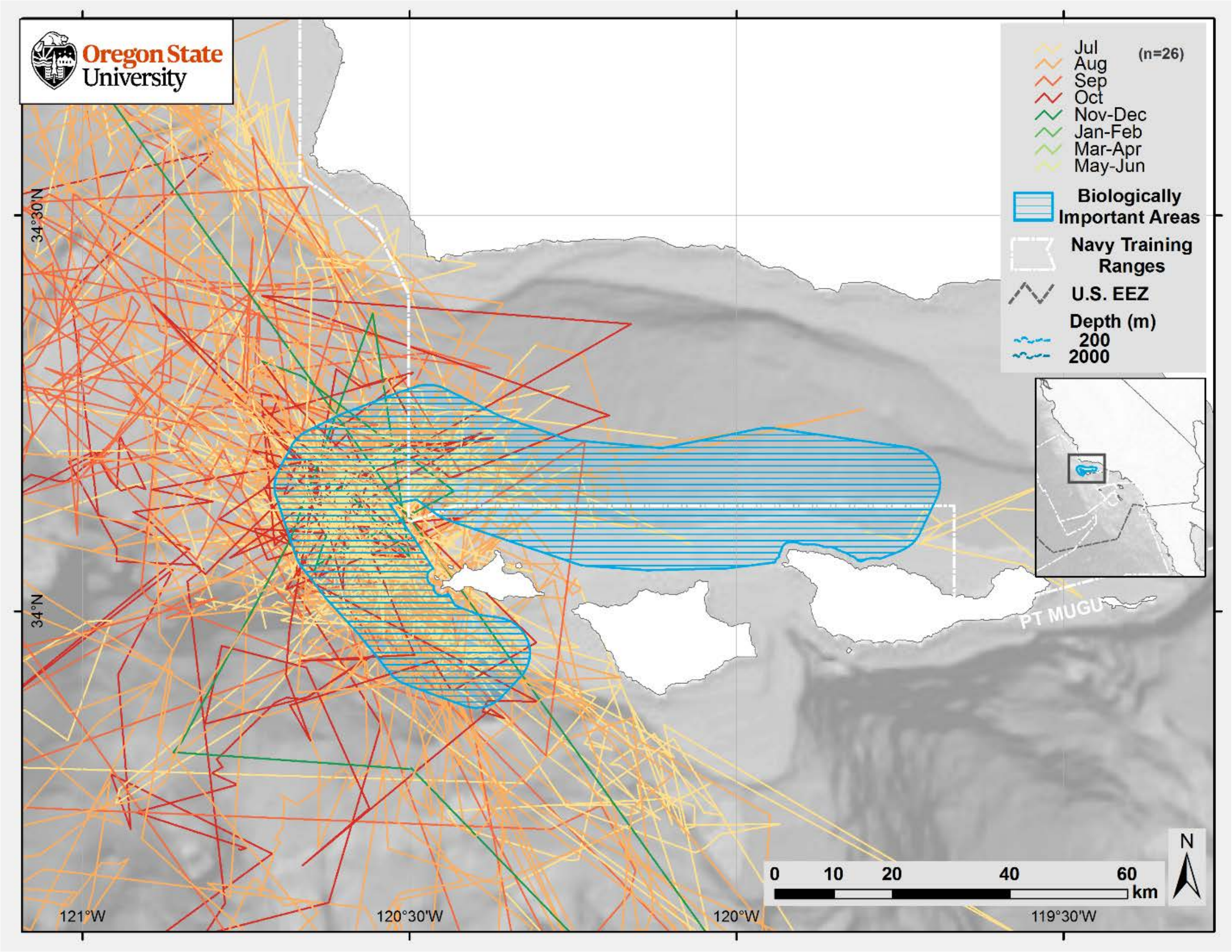

Figure 7. Satellite-monitored tracks in the Santa Barbara Channel and San Miguel BIA for blue whales tagged off southern California in July 2017 (13 LO tags, 13 DM tags).

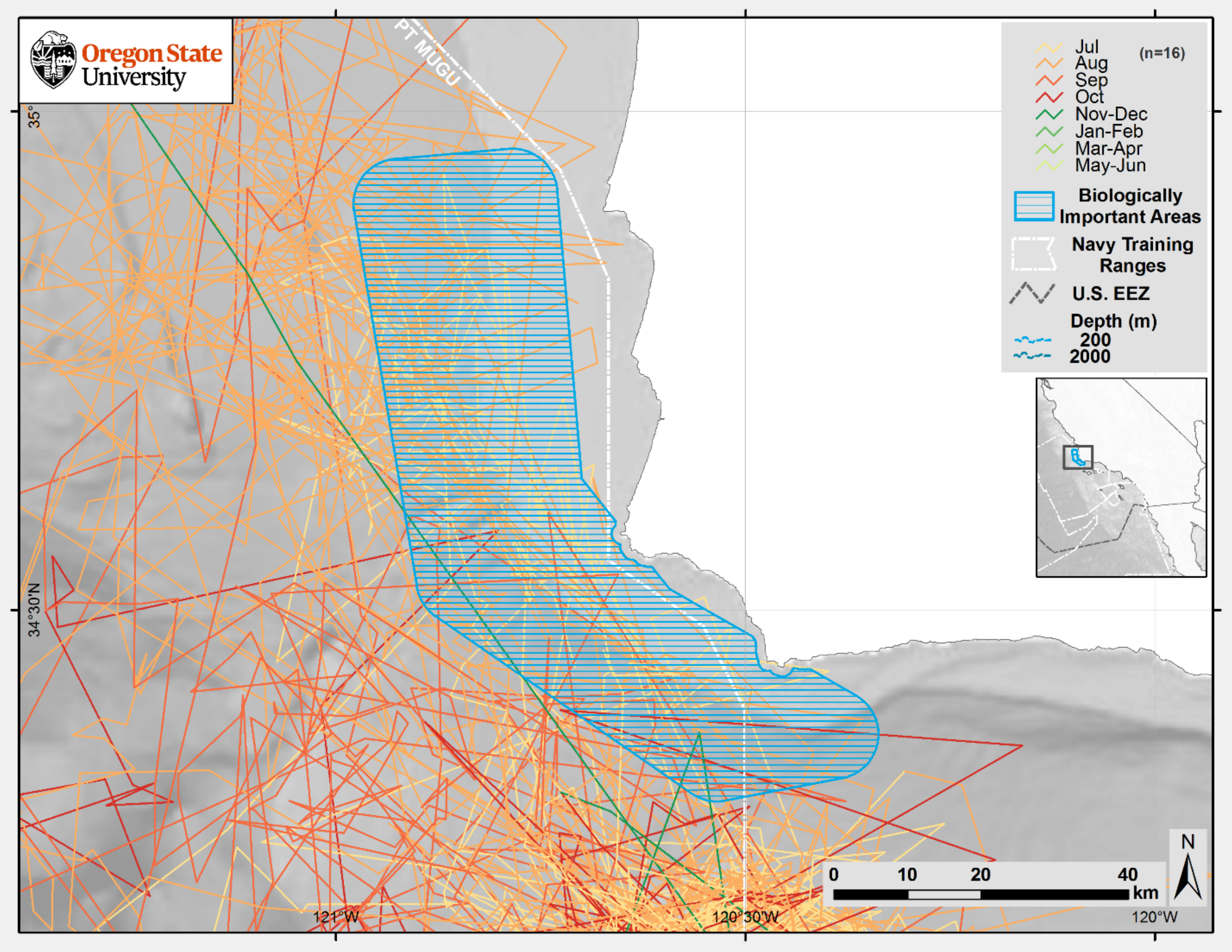

Figure 8. Satellite-monitored tracks in the Point Conception/Arguello BIA for blue whales tagged off southern California in July 2017 (11 LO tags, 5 DM tags).

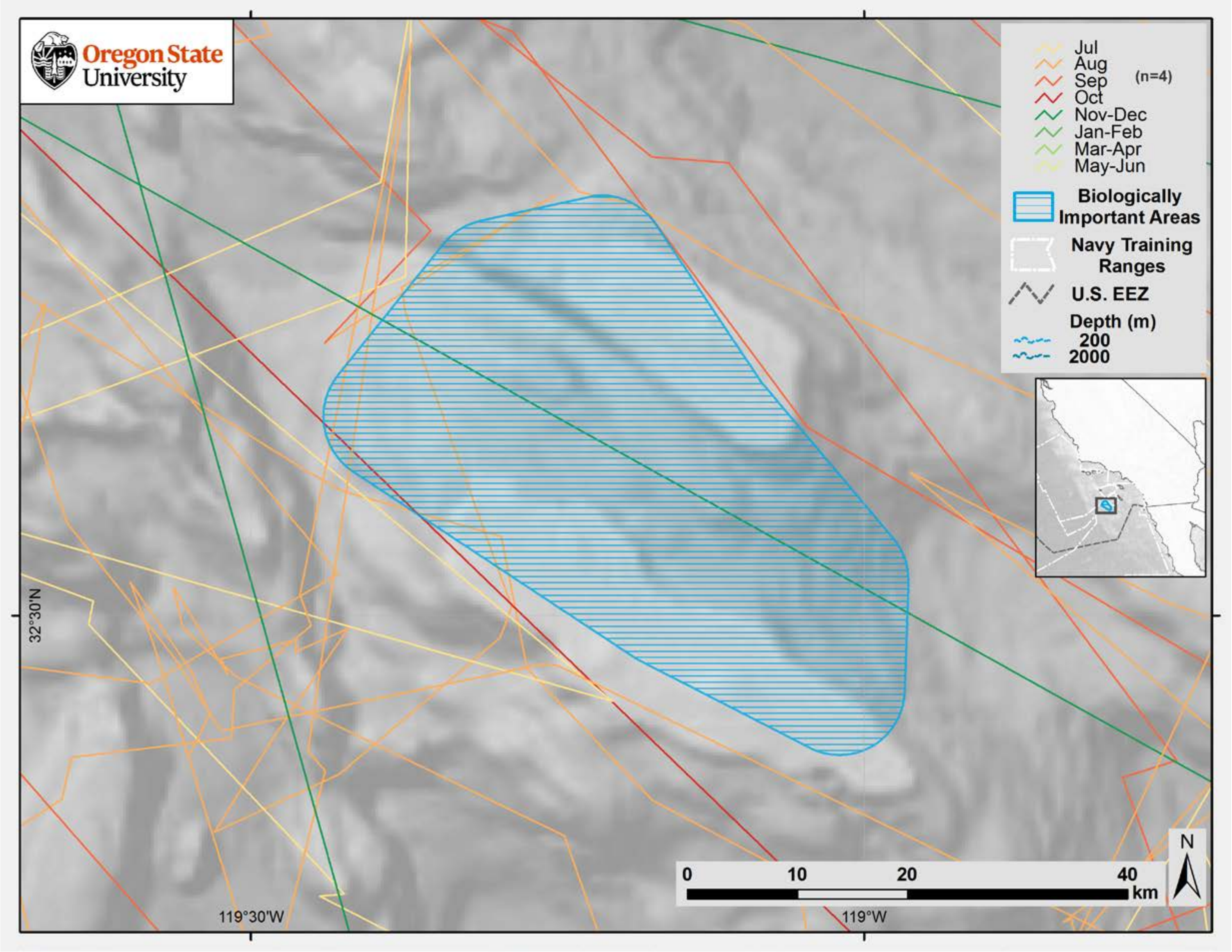

Figure 9. Satellite-monitored tracks in the Tanner-Cortes Bank BIA for blue whales tagged off southern California in July 2017 (2 LO tags, 2 DM tags).

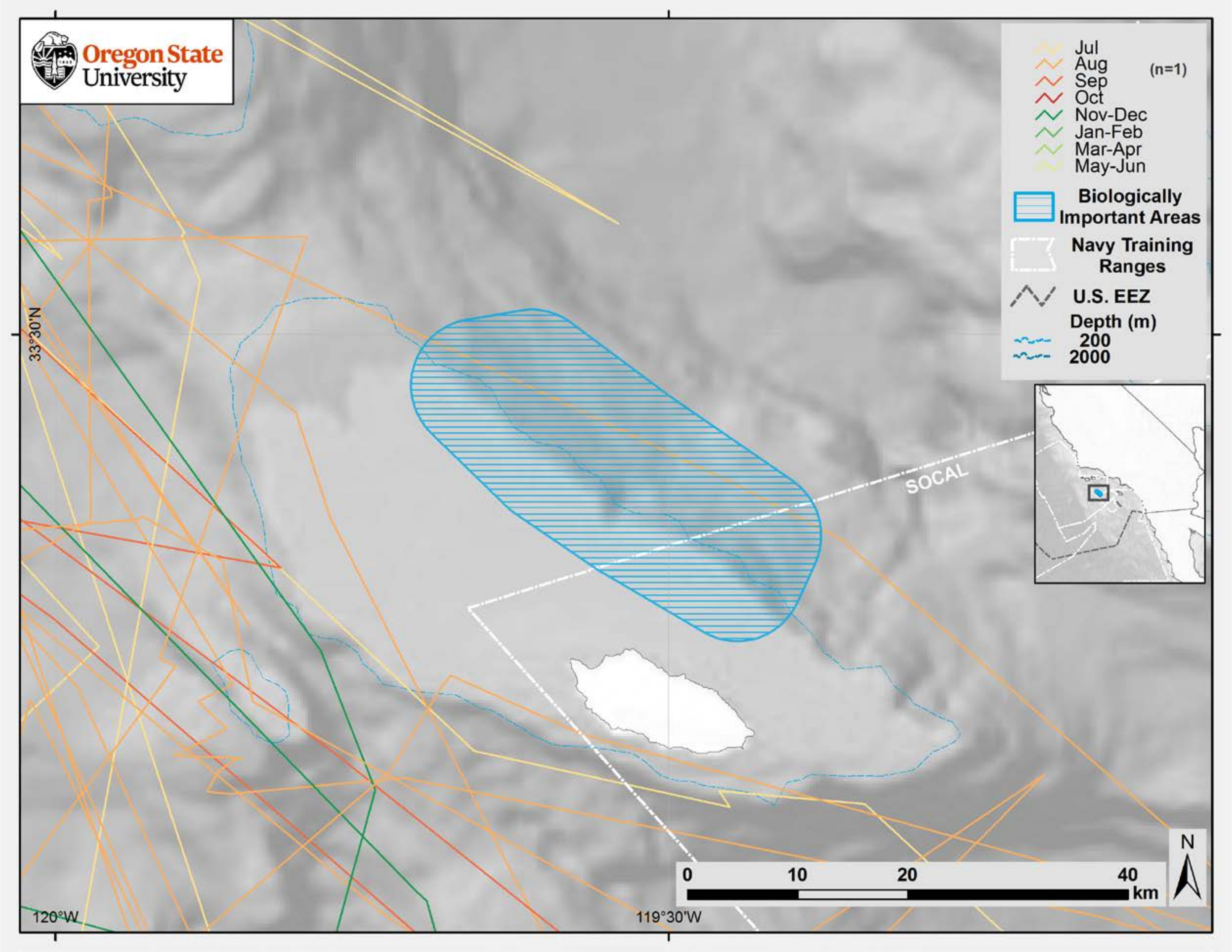

Figure 10. Satellite-monitored tracks in the San Nicolas Island BIA for blue whales tagged off southern California in July 2017 (1 LO tag).

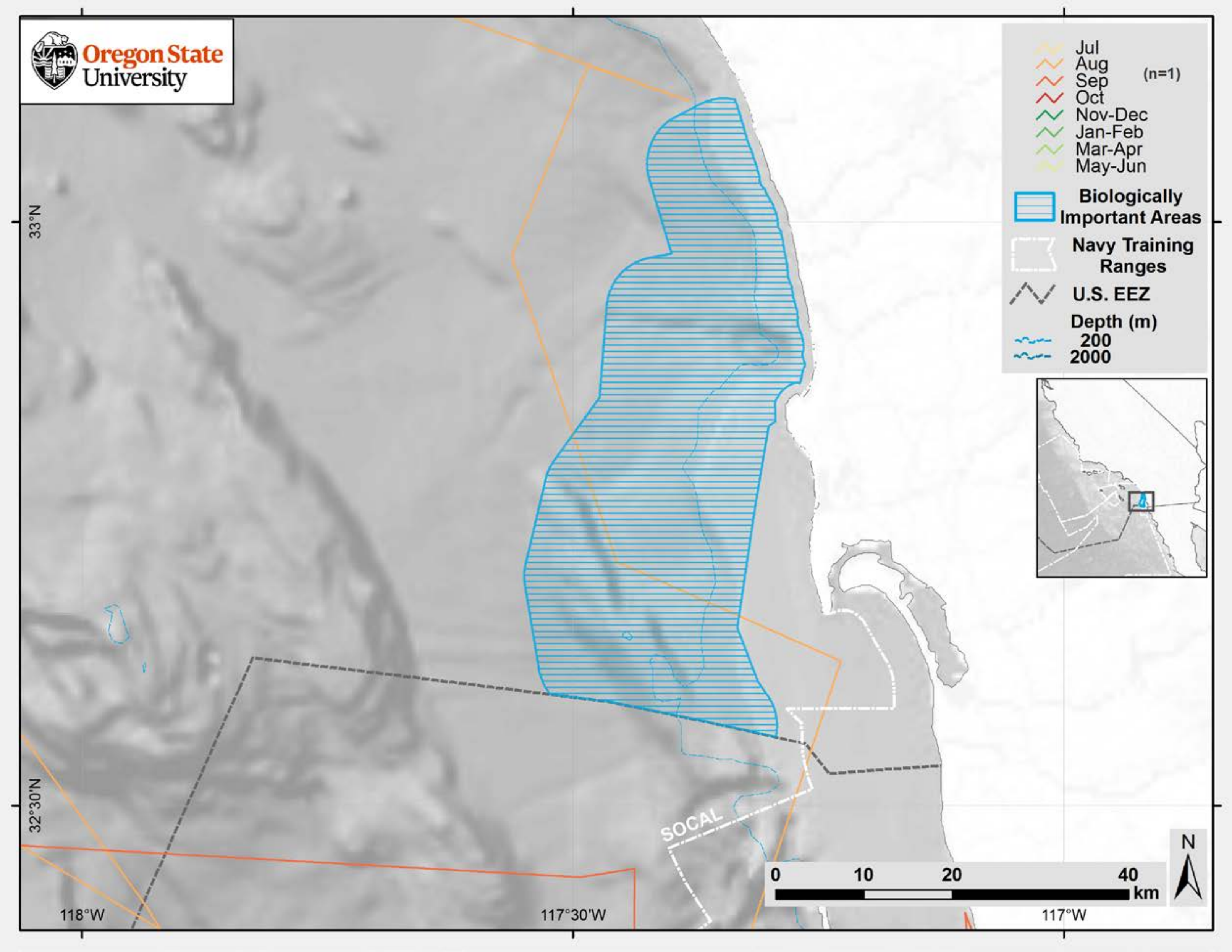

Figure 11. Satellite-monitored tracks in the San Diego BIA for blue whales tagged off southern California in July 2017 (1 DM tag).

Table 8. Sizes of HRs and CAs of use calculated from state-space modeled (SSM) locations within the EEZ for blue and fin whales tagged off southern and central California, 2017. In the Sex column, Unknown sex whales are cases where no biopsy sample was collected. SSM locations were calculated at 1 per day and only tags that had 30 or more locations were included.

Tag #	# SSM Locations	Sex	HR Size (km^2)	CA Size (km^2)
Blue Whales				
826	108	Male	110,458	31,097
827	75	Male	41,958	8,279
831	46	Female	20,110	3,390
835	82	Female	34,934	6,856
841	48	Male	7,629	1,512
845	130	Female	49,408	9,070
847	90	Unknown	9,283	1,222
1385	101	Unknown	33,545	5,634
4176	60	Female	36,092	9,245
5648	33	Male	2,136	394
5670	30	Male	16,885	5,909
5679	37	Unknown	13,233	2,964
5803	56	Male	33,763	5,163
5840	98	Unknown	29,641	7,248
5910	59	Female	47,205	6,514
5921	41	Male	7,313	979
10826	107	Male	6,018	885
10831	107	Unknown	34,500	3,334
10840	38	Male	13,204	1,894
23031	34	Male	19,884	4,335
Mean			**28,360**	**5,796**
Fin Whale				
2082	43	Unknown	5,263	1,553

Key: km^2 = square kilometer(s); # = number.

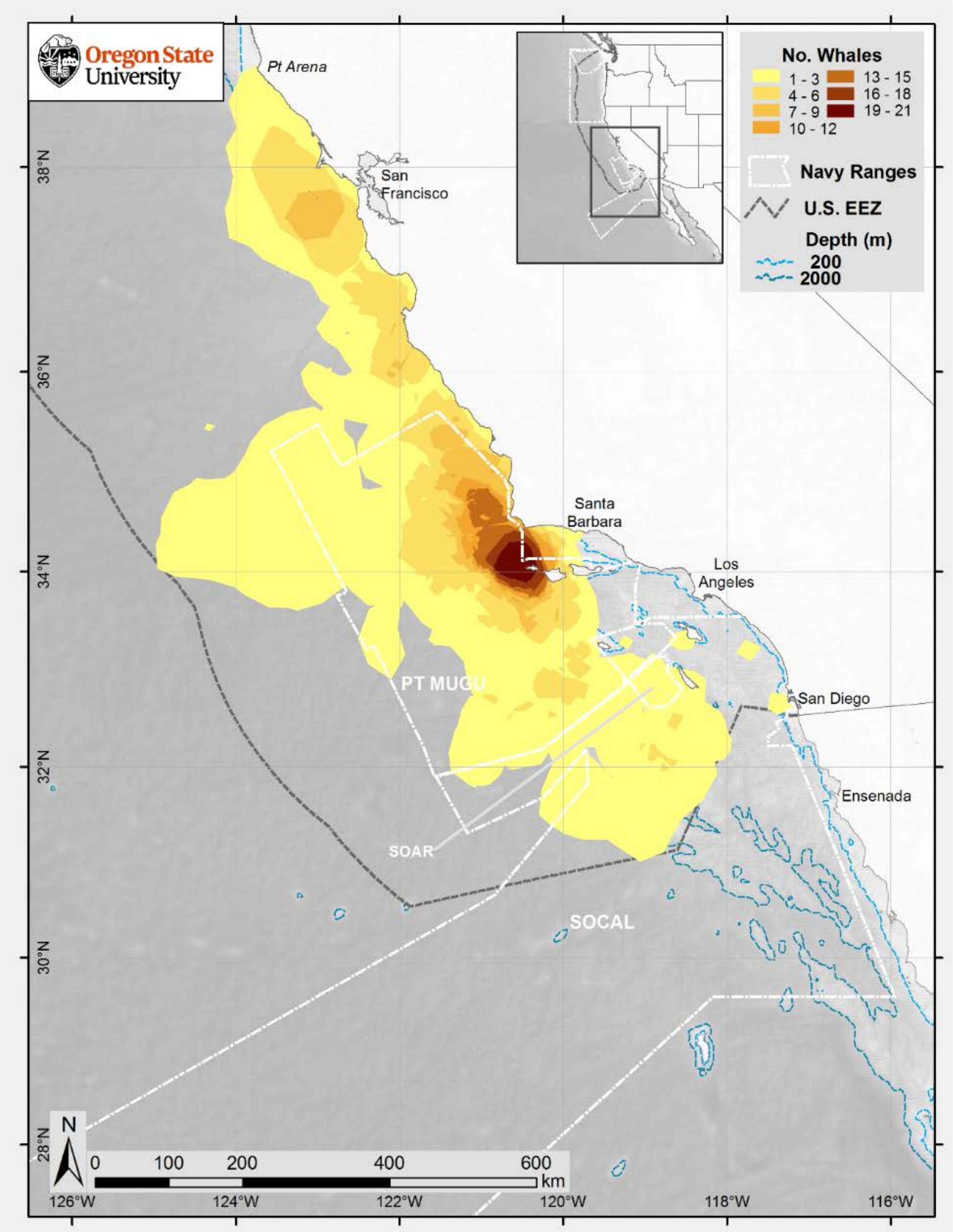

Figure 12. HRs in the U.S. EEZ for 20 blue whales tagged off southern and central California in 2017. Shading represents the number of individual whales with overlapping HRs. The light and dark blue bathymetric contours correspond to the 200 and 1,000 m isobaths, respectively.

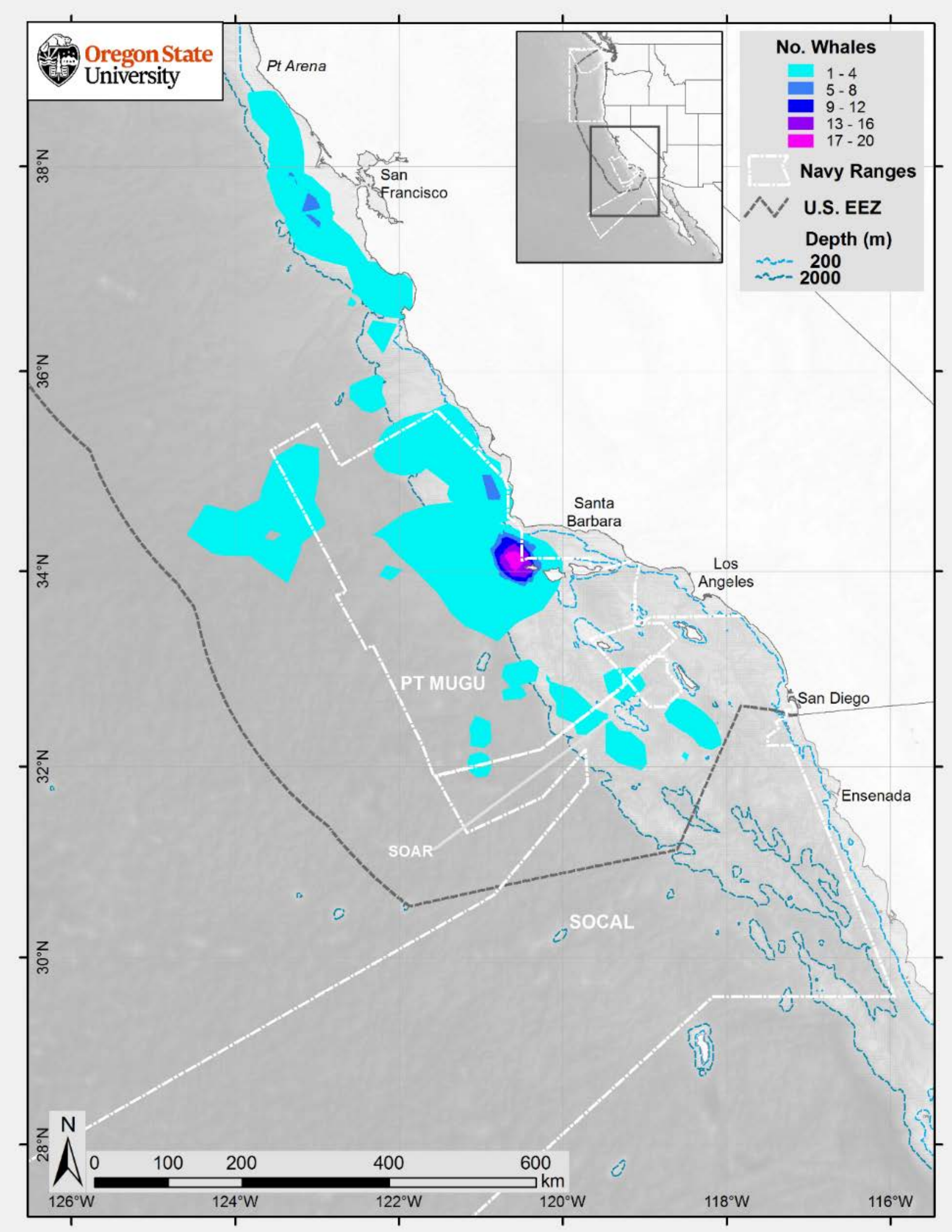

Figure 13. CAs in the U.S. EEZ for 20 blue whales tagged off southern and central California in 2017. Shading represents the number of individual whales with overlapping CAs. The light and dark blue bathymetric contours correspond to the 200 and 1,000 m isobaths, respectively.

3.1.5 Tracking Analysis – Inter-annual Comparison

Tracking durations of non-ADB tags deployed on blue whales did not vary significantly among years (2014–2017; ANOVA, $p = 0.53$; **Table 9**). Tracking durations were not compared for ADB tags (deployed in limited numbers in 2014 and 2015), as ADB tags were designed to come off a whale approximately 3 to 4 weeks after tagging (Mate et al. 2017b) and thus had much shorter tracking durations than non-ADB tags. The average tracking duration for all non-ADB tags on blue whales in these four years was 73.4 d (SD = 58.4 d, median = 61.7, n = 81).

The latitudinal range, or the difference between the latitudes of the northernmost and southernmost locations for all blue whales in a given tagging year, was virtually the same in 2014 and 2015 (44 degrees), and much larger than in 2016 (26 degrees; **Figure 14**). The locations of these northernmost and southernmost extents were not similar, however, between 2014-tagged and 2015-tagged blue whales. For 2014-tagged whales, locations were spread out between the northern tip of Vancouver Island, British Columbia (50.55°N), and the Costa Rica Dome off Central America (6.76°N). For 2015-tagged blue whales, the locations ranged between the central Oregon coast (43.70°N) and the equator (0.14°N). For 2016-tagged blue whales, the northernmost location was in a similar location off central Oregon as that for 2015-tagged blue whales (44.04°N), but the southernmost location only extended to the west coast of mainland Mexico (17.62°N). Locations of blue whales tagged off California in 2017 ranged over 31 degrees of latitude, from the Costa Rica Dome, off Central America (8.11°N), to Point Arena, California (**Figure 14**), with the northernmost location being farther south than in the previous three years.

Sixty-three percent of the blue whales tagged with LO tags in 2014 (12 of 19) migrated south of the California/Mexico border, with three of these whales reaching the Costa Rica Dome, their suspected migratory destination. Thirty-nine percent of the blue whales tagged with LO tags in 2015 (7 of 18) migrated south of the border, with two whales reaching typical winter migratory destinations; one at the Costa Rica Dome and one in the northern Gulf of California. A third whale in 2015 was last located at the equator, approximately 4,200 km west of Ecuador, much farther south than previously documented. Only 22 percent of the blue whales tagged with LO and DM tags in 2016 (4 of 18) migrated south of the border, with three reaching migratory destinations in the Gulf of California (two in the northern Gulf and one in the central Gulf). Twenty-six percent of blue whales tagged with LO and DM tags in 2017 (7 of 27) migrated south of the border, with one reaching the Costa Rica Dome.

There was a positive relationship between tracking duration and total distance traveled by blue whales tagged with fully implantable tags (linear regression using log-transformed variables, $p < 0.0001$). After accounting for this relationship, distance traveled was found to be significantly different between years (general linear model of log-transformed variables, $p = 0.0004$), with 2014 having the longest distances, 2016 having the shortest, and 2015 and 2017 having similar, intermediate distances (**Table 9**).

Table 9. Mean (and SE) tracking duration, total distance traveled, home range, and core area for blue whales tracked with LO and DM satellite tags off southern and central California, 2014–2017.

	Tracking Duration (d)			**Total Distance (km)+**			**Home Range (km^2)**			**Core Area (km^2)**		
	n	**Mean**	**SE**	**n**	**Mean**	**SE**	**n**	**Mean**	**SE**	**n**	**Mean**	**SE**
2014	18	66.7	16.6	18	2,698.2	1.1	5	145,302.0	25,191.0	5	32,639.2	5,775.9
2015	18	88.8	13.7	18	2,105.9	1.1	17	48,604.9	9,689.4	17	10,625.3	2,393.7
2016	18	78.2	14.0	18	1,684.9	1.1	14	25,611.0	8,381.3	14	6,305.9	2,373.4
2017	27	64.4	9.5	27	2,150.7	1.1	20	28,359.9	5,398.6	20	5,796.2	1,474.4
Mean		**74.5**			**2,159.9**			**61,969.4**			**13,841.6**	

KEY: d = days; km = kilometers; km^2 = square kilometers, n = sample size; SE = standard error; +Total distance is back-calculated from log values used in analysis.

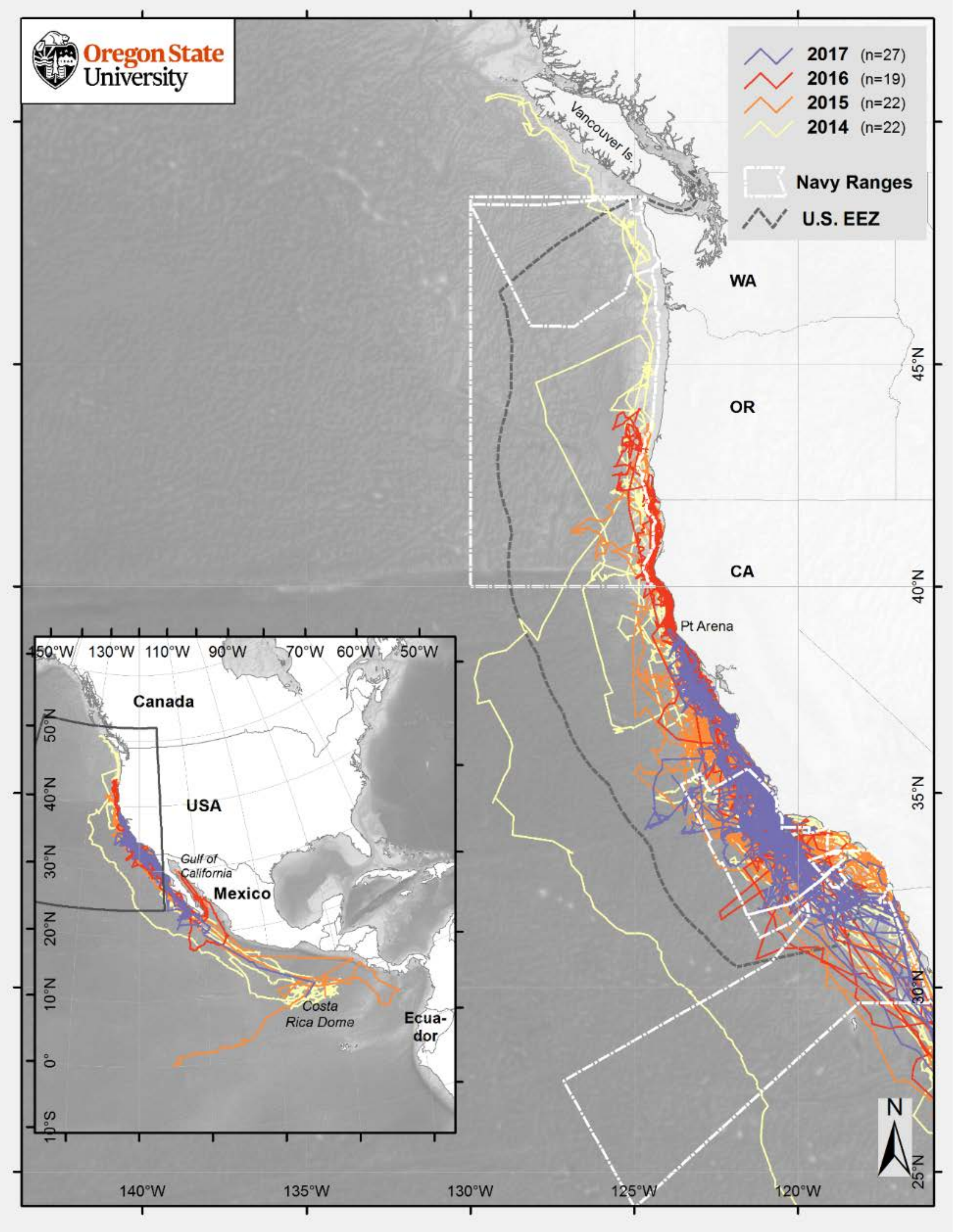

Figure 14. Satellite-monitored tracks for blue whales tagged off southern and central California during July and/or August, 2014 to 2017, with different tagging years being shown in different colors. Tracks show northern- and southern-most destinations.

3.1.5.1 USE OF NAVY TRAINING AREAS BY TAGGED BLUE WHALES

SOCAL was the most heavily used Navy training range for blue whales in 2014 (78 percent of all transmitting tags had locations/tracks there), followed by the PT MUGU range (61 percent of tracked whales; **Table 10**, **Figures 15 and 16**). In 2015, 2016, and 2017 PT MUGU was the most heavily used range (100, 78, and 96 percent of tracked whales for 2015, 2016, and 2017, respectively), followed by SOCAL (64, 28, and 52 percent for 2015, 2016, and 2017, respectively; **Table 10**, **Figures 15 and 16**). SOAR was used by blue whales in all four years, ranging from a low of 4 percent of whales in 2014 to a high of 36 percent in 2015 (**Table 10, Figure 17**). The NWTT range was used by 17 percent of tracked blue whales in both 2014 and 2016, 9 percent of tracked whales in 2015, and 0 percent in 2017 (**Table 10**, **Figure 18**). Only one blue whale had locations/tracks in W237 in 2014 (**Table 10**, **Figure 19**).

For blue whales using SOCAL, number of days spent in the range did not vary significantly between the four tagging years (ANOVA, $p = 0.36$), with whales spending an overall average of 7.8 d there (standard error [SE] = 0.8 d; **Table 10**). For whales using the PT MUGU range, number of days spent there was significantly different in 2014 (mean = 7.8 d, SE = 1.6 d) than in either 2015 (mean = 32.3 d, SE = 4.2 d), 2016 (mean = 34.2 d, SE = 9.2 d), or 2017 (mean = 34.2 d, SE = 4.6 d; ANOVA using log-transformation, $p = 0.002$, Fisher's LSD; **Table 10**). Mean number of days spent in SOAR was quite low, ranging from 0.4 to 0.6 d for all four years. Sample sizes were not large enough in SOAR to test for differences between years (**Table 10**). Mean number of days spent in the NWTT area ranged from 18.2 to 28.9 for 2014 to 2016, but sample sizes were not large enough to test for differences between years (**Table 10**). No blue whales spent time in the NWTT area in 2017. The one blue whale with locations in W237 (in 2014) spent 19.5 d there (**Table 10**).

Seasonality in the Navy training ranges was similar between tagging years, with locations occurring predominantly in the summer and fall (July through November in SOCAL and PT MUGU, July through September in SOAR, August through November in NWTT, September through November (2014) in W237. There were also December locations in PT MUGU in 2016. In the case of two blue whales that were tracked returning to U.S. waters after migrating south for the winter (Tag #10827, a whale of unknown sex tagged in southern California in 2014; Tag #10825, a male tagged in central California in 2016) additional locations occurred in SOCAL in March and June, in PT MUGU in March and April, and in SOAR in March.

Distances to shore for tagged blue whales did not differ significantly between tagging years in PT MUGU or SOCAL (ANOVA test of means, $p = 0.09$ for SOCAL, Kruskal-Wallis test of medians, $p = 0.73$ for PT MUGU). Sample sizes were too small to test for distance to shore differences between years in SOAR, NWTT or W237. Overall, mean distances to shore across all years ranged from 36 km in SOAR to 82 km in SOCAL (**Table 11**).

Table 10. Mean (and SE) number of days spent inside Navy training ranges for blue whales tagged off southern and central California, 2014–2017.

Year (# Whales Tracked)	**# Days**														
	SOCAL			**PT MUGU**			**SOAR**			**NWTT**			**W237**		
	n	**Mean**	**SE**	**n**	**Mean**	**SE**	**n**	**Mean**	**SE**	**n**	**Mean**	**SE**	**n**	**Mean**	**SE**
2014 (23)	18	6.3	1.1	14	7.8	1.6	1	0.6	-	4	28.9	11.0	1	19.5	-
2015 (22)	14	7.3	1.0	22	32.3	4.2	8	0.4	0.1	2	20.4	19.9	0	-	-
2016 (18)	5	8.3	2.1	14	34.2	9.2	2	0.4	0.0	3	18.2	17.1	0	-	-
2017 (27)	14	10.1	2.4	26	34.2	4.6	7	0.6	0.1	0	-	-	0	-	-
Mean (90)	**51**	**7.8**	**0.8**	**76**	**28.8**	**2.8**	**18**	**0.5**	**0.0**	**9**	**23.4**	**7.7**	**-**	**-**	**-**

KEY: n = number of whales having locations in that particular Navy training range; SE = standard error; # = number.

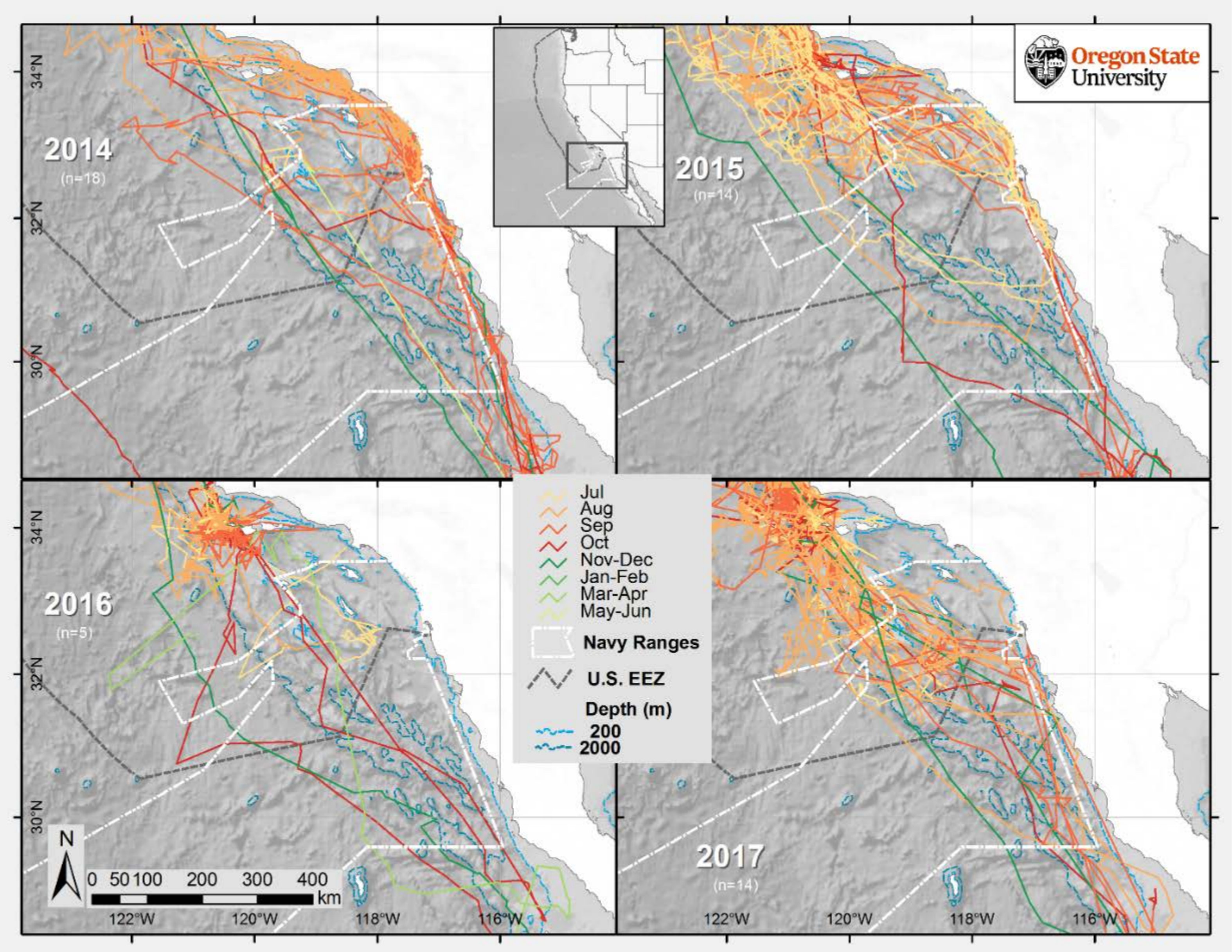

Figure 15. Satellite-monitored tracks of blue whales in the SOCAL range, by tagging year (2014–2017). The light and dark blue bathymetric contours correspond to the 200 and 1,000 m isobaths, respectively.

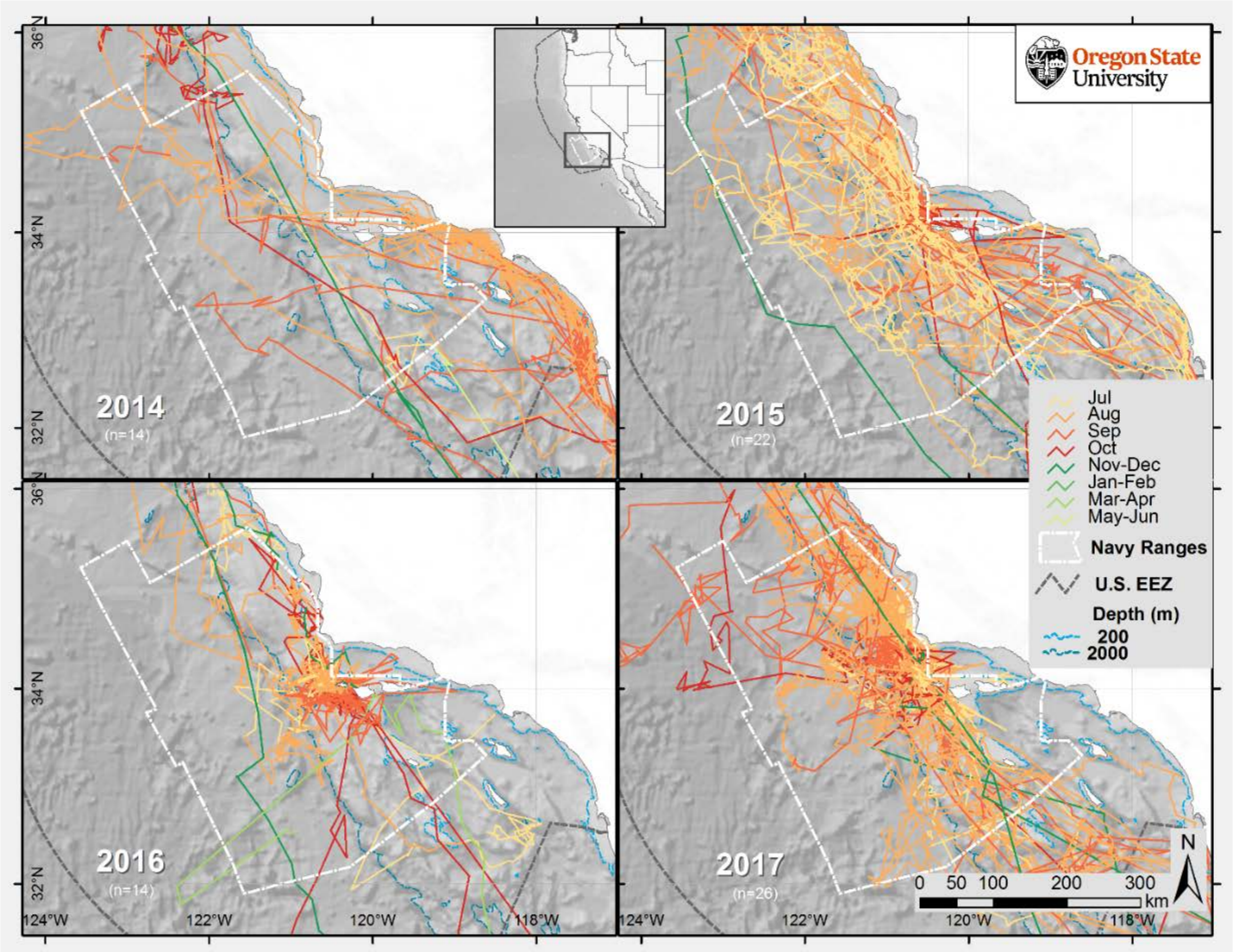

Figure 16. Satellite-monitored tracks of blue whales in the PT MUGU range, by tagging year (2014–2017). The light and dark blue bathymetric contours correspond to the 200 and 1,000 m isobaths, respectively.

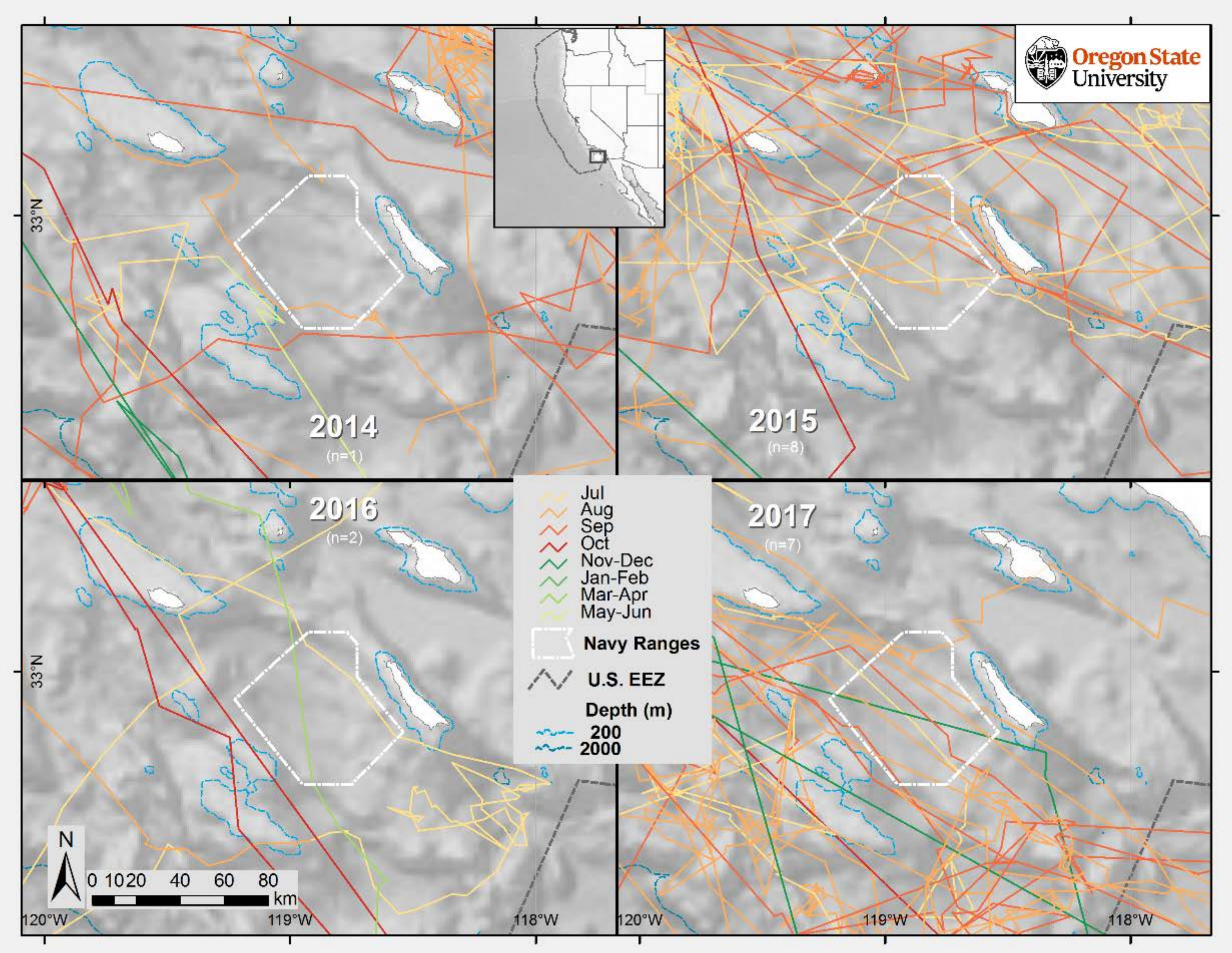

Figure 17. Satellite-monitored tracks of blue whales in the SOAR range, by tagging year (2014–2017). The light and dark blue bathymetric contours correspond to the 200 and 1,000 m isobaths, respectively.

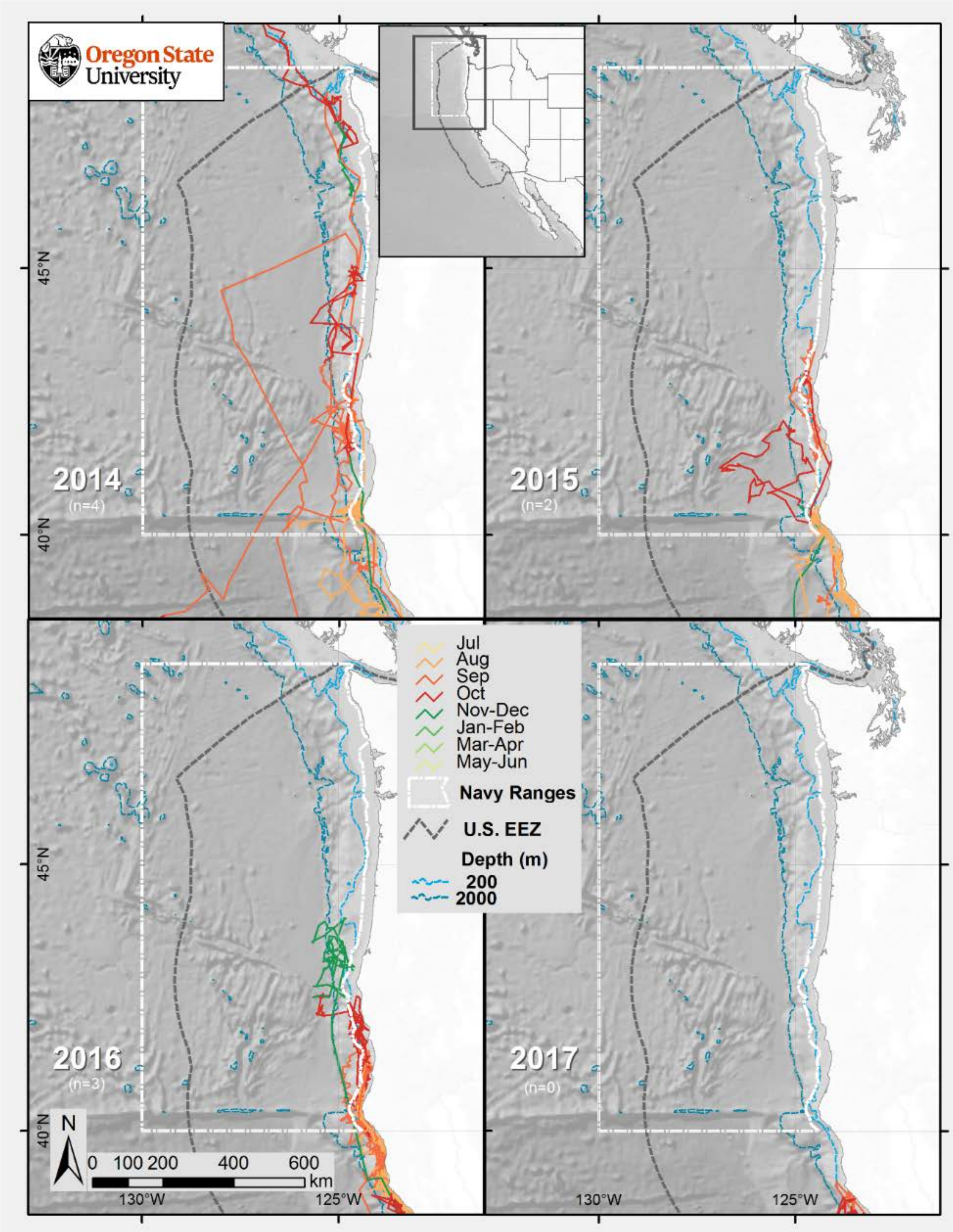

Figure 18. Satellite-monitored tracks of blue whales in the NWTT range, by tagging year (2014–2017). The light and dark blue bathymetric contours correspond to the 200 and 1,000 m isobaths, respectively.

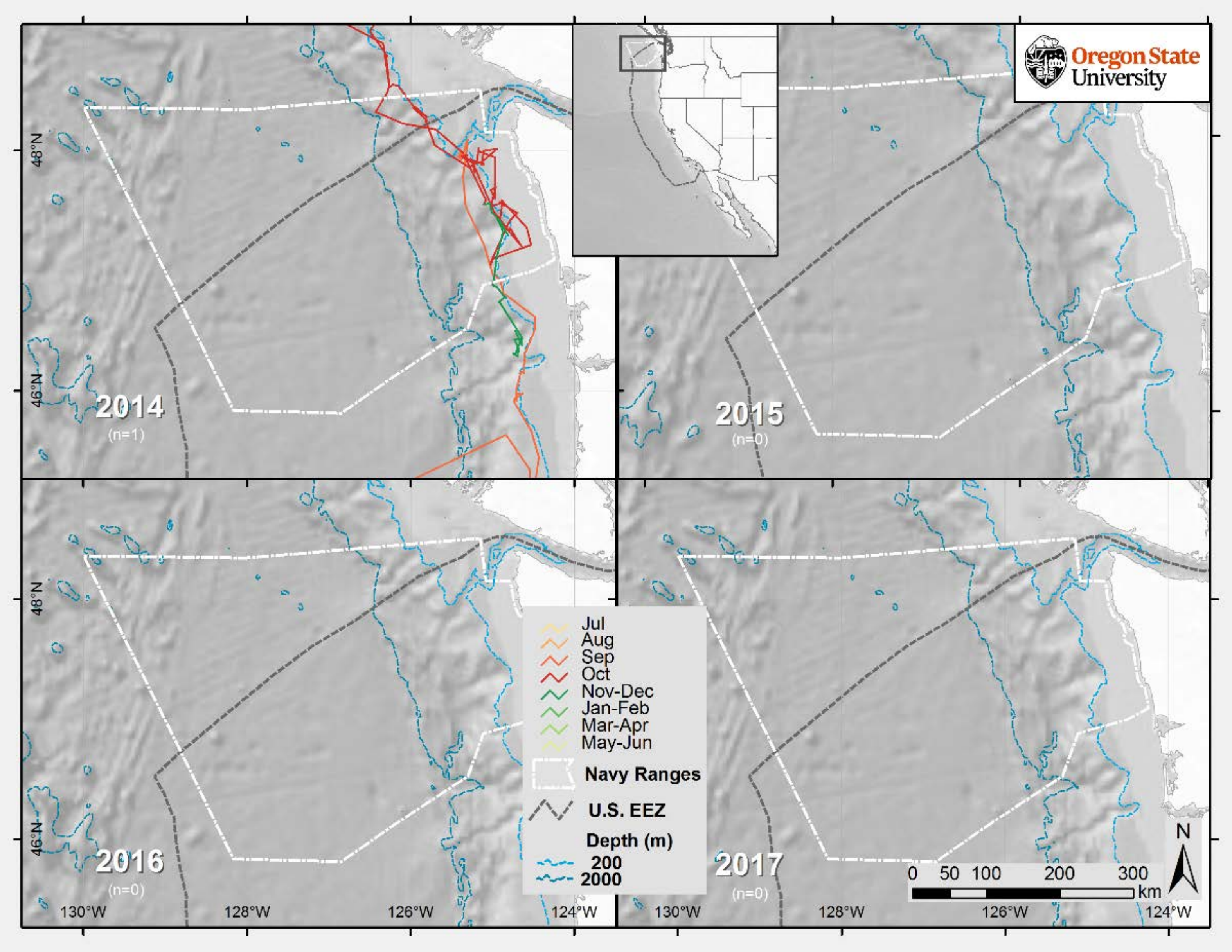

Figure 19. Satellite-monitored tracks of blue whales in W237 of the NWTT range, by tagging year (2014–2017). The light and dark blue bathymetric contours correspond to the 200 and 1,000 m isobaths, respectively.

Table 11. Mean geodesic distances to nearest point on shore in Navy training ranges for blue whales tagged off southern and central California, 2014–2017 (including mean, median, and maximum distances to shore).

Year	SOCAL				PT MUGU				SOAR				NWTT				W237			
	n	Mean	Median	Max	n	Mean	Median	Max	n	Mean	Median	Max	n	Mean	Median	Max	n	Mean	Median	Max
2014	18	57	25	359	14	55	34	145	1	41	41	41	4	66	55	108	1	49	49	49
2015	14	57	40	187	22	57	55	155	8	30	33	39	2	52	52	75	0	-	-	-
2016	5	114	114	186	14	52	34	112	2	35	35	48	2	44	44	54	0	-	-	-
2017	14	98	100	171	26	49	44	93	7	36	28	54	0	-	-	-	0	-	-	-
Mean		**81.5**	**69.8**	**225.8**		**53.2**	**41.8**	**126.2**		**35.5**	**36.3**	**45.5**		**54.0**	**50.3**	**79.0**		**-**	**-**	**-**
Median		**77.5**	**70**	**186.5**		**53.5**	**39**	**128.5**		**35.5**	**34.0**	**44.5**		**52.0**	**52.0**	**75.0**		**-**	**-**	**-**

KEY: n = number of whales having locations in that particular Navy training range.

3.1.5.2 USE OF BIAs BY TAGGED BLUE WHALES

Only the Santa Barbara Channel and San Miguel BIA and the Point Conception/Arguello BIA had large enough sample sizes to allow statistical comparisons among all four tagging years (**Table 12, Figures 20 and 21**). Time spent by blue whales in the Santa Barbara Channel and San Miguel BIA was significantly different between 2014 and the other three years (ANOVA using log transformation, $p = 0.001$, Fisher's LSD), with number of days being lowest for 2014 (mean = 0.6 d, SE = 0.2 d, n = 4), compared to 2015 (mean = 11.0 d, SE = 2.6 d, n = 21), 2016 (mean = 23.3 d, SE = 7.2 d, n = 10), and 2017 (mean = 11.7 d, SE = 2.1 d, n = 26). Time spent in the Point Conception/Arguello BIA did not vary significantly between the four tagging years (overall mean = 2.1 d, SE = 0.4 d, n = 43; ANOVA $p = 0.44$). The Santa Monica Bay to Long Beach BIA and the San Diego BIA were used by more blue whales in 2014 than any other year, yet time spent in these BIAs was quite short, even in 2014 (less than 2 d; **Figures 22 and 23**). Four or fewer whales had locations in the San Nicolas Island (**Figure 24**) or Tanner-Cortes Bank (**Figure 25**) BIAs in any year, and time spent in these BIAs was also quite short (less than 2 d).

Blue whale seasonality in BIAs was similar between tagging years, occurring in August, September, and October in all four years. Blue whale locations/tracks also occurred in BIAs in July in 2015 through 2017, when tag deployments occurred one month earlier (in July) than in 2014 (in August/September). Blue whale locations also occurred in the Santa Barbara Channel and San Miguel and Point Conception/Arguello BIAs in November in 2016 and 2017.

3.1.5.3 HOME RANGE ANALYSIS

HRs (90 percent kernel isopleths) and CAs (50 percent kernel isopleths) for blue whales were significantly different between 2014 and the other three years (ANOVA, $p < 0.0001$, Fisher's LSD; **Table 9; Figures 26 and 27**), with mean sizes of HRs and CAs being much larger for whales tagged in 2014 than in either 2015, 2016, or 2017. Areas of highest use (where CAs overlapped for the most number of whales) were off Point Dume in southern California in 2014, but off the west end of San Miguel Island in the Channel Islands in 2015, 2016, and 2017, and just north of Point Arena in northern California in 2016 (**Figures 26 and 27**).

To investigate potential geographic separation of blue whales occurring off the coast of California, we visually compared the tracks of blue whales tagged off central and northern California (from Point Arguello to the California/Oregon border, referred to hereafter as "central") with those of blue whales tagged off southern California (south of Point Arguello; **Figure 28**) during the four years of this study (2014 to 2017), and with those of previously tagged blue whales by OSU in these two areas from 1994 to 2008 (which were initially presented in our 2014 report and again in our 2016 report; Mate et al. 2015, Mate et al. 2017a). All combined, just over three times as many blue whales were tagged off southern California (n = 159) than off central California (n = 49). The latitudinal spread in blue whale locations was slightly greater for whales tagged in southern California (53 degrees) than for those tagged in central California (43 degrees), as was maximum distance to shore (approximately 2,800 km and 2,200 km for southern and central California whales, respectively). Summer-fall feeding season movements and winter destinations were similar between the two groups, however. With a few exceptions, the range of locations for blue whales tagged in both central and southern California covered the entire coast of California and into central Oregon. The northern extreme for whales tagged

Table 12. Mean (and SE) number of days spent inside the Biologically Important Areas (BIAs) for blue whales tagged off southern and central California, 2014–2017.

Year (# tracked)	Santa Monica Bay			San Diego			San Nicolas			Tanner Cortes			Santa Barbara			Pt. Conception		
	# Days																	
	n	**Mean**	**SE**	**n**	**Mean**	**SE**	**n**	**Mean**	**SE**	**n**	**Mean**	**SE**	**n**	**Mean**	**SE**	**n**	**Mean**	**SE**
2014 (23)	10	1.8	0.6	14	1.5	0.3	1	0.3	-	1	1.7	-	4	0.6	0.2	4	0.3	0.04
2015 (22)	3	1.0	0.8	9	1.0	0.4	3	0.2	0.1	4	0.5	0.3	21	11.0	2.6	16	1.9	0.8
2016 (18)	1	0.1	-	0	-	-	1	0.3	-	2	0.4	0.4	10	23.3	7.2	7	2.4	0.9
2017 (27)	0	-	-	1	0.3	-	1	0.2	-	4	0.5	0.3	26	11.7	2.1	16	2.7	0.6
Mean (90)	**14**	**1.6**	**0.4**	**24**	**1.2**	**0.2**	**6**	**0.2**	**0.1**	**11**	**0.6**	**0.2**	**61**	**12.6**	**1.8**	**43**	**2.1**	**0.4**

KEY: n = number of whales having locations in that particular BIA; SE = standard error; # = number.

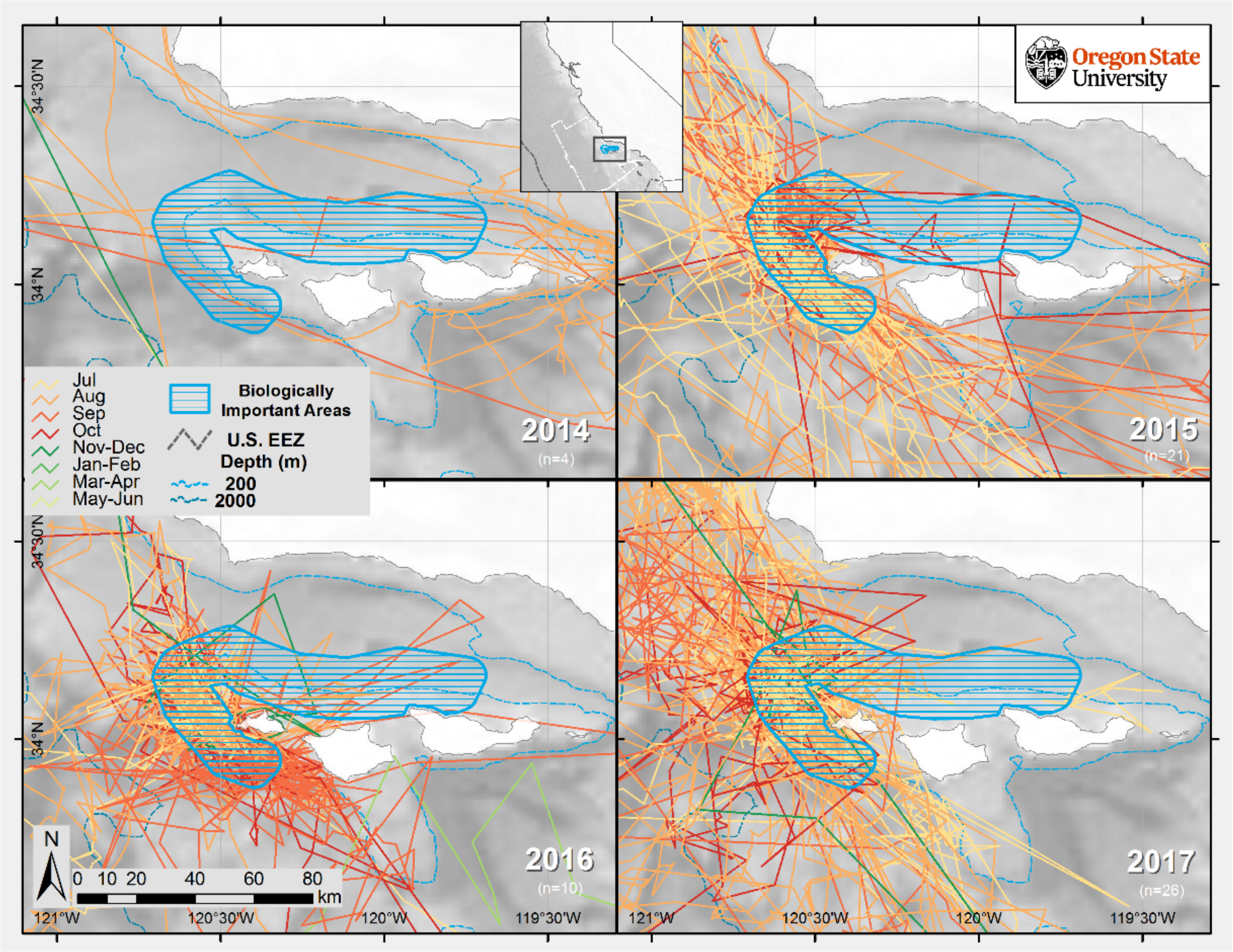

Figure 20. Satellite-monitored tracks of blue whales in the Santa Barbara Channel and San Miguel BIA (partially located in the PT MUGU range), by tagging year (2014–2017). The light and dark blue bathymetric contours correspond to the 200 and 1,000 m isobaths, respectively.

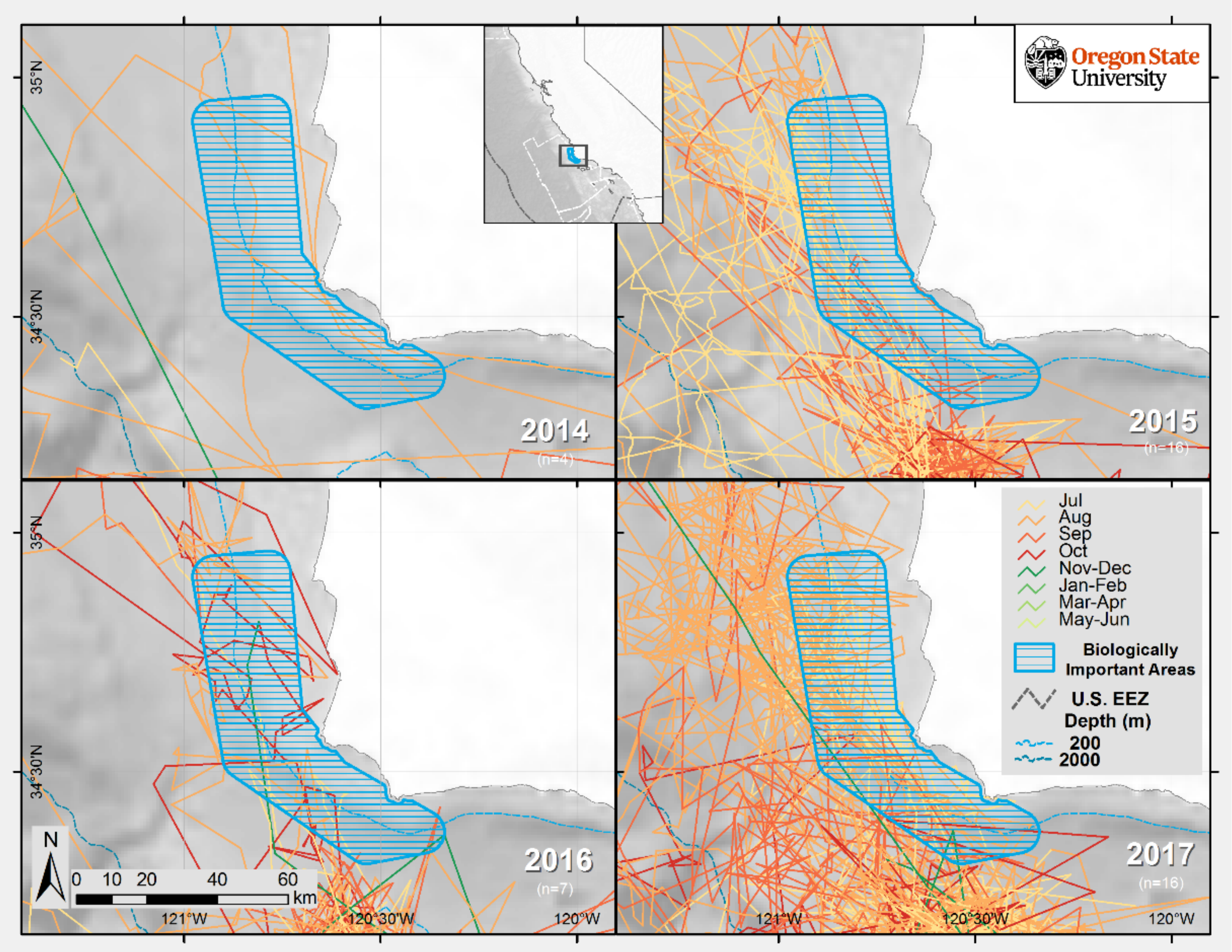

Figure 21. Satellite-monitored tracks of blue whales in the Point Conception/Arguello BIA (partially located in the PT MUGU range), by tagging year (2014–2017). The light and dark blue bathymetric contours correspond to the 200 and 1,000 m isobaths, respectively.

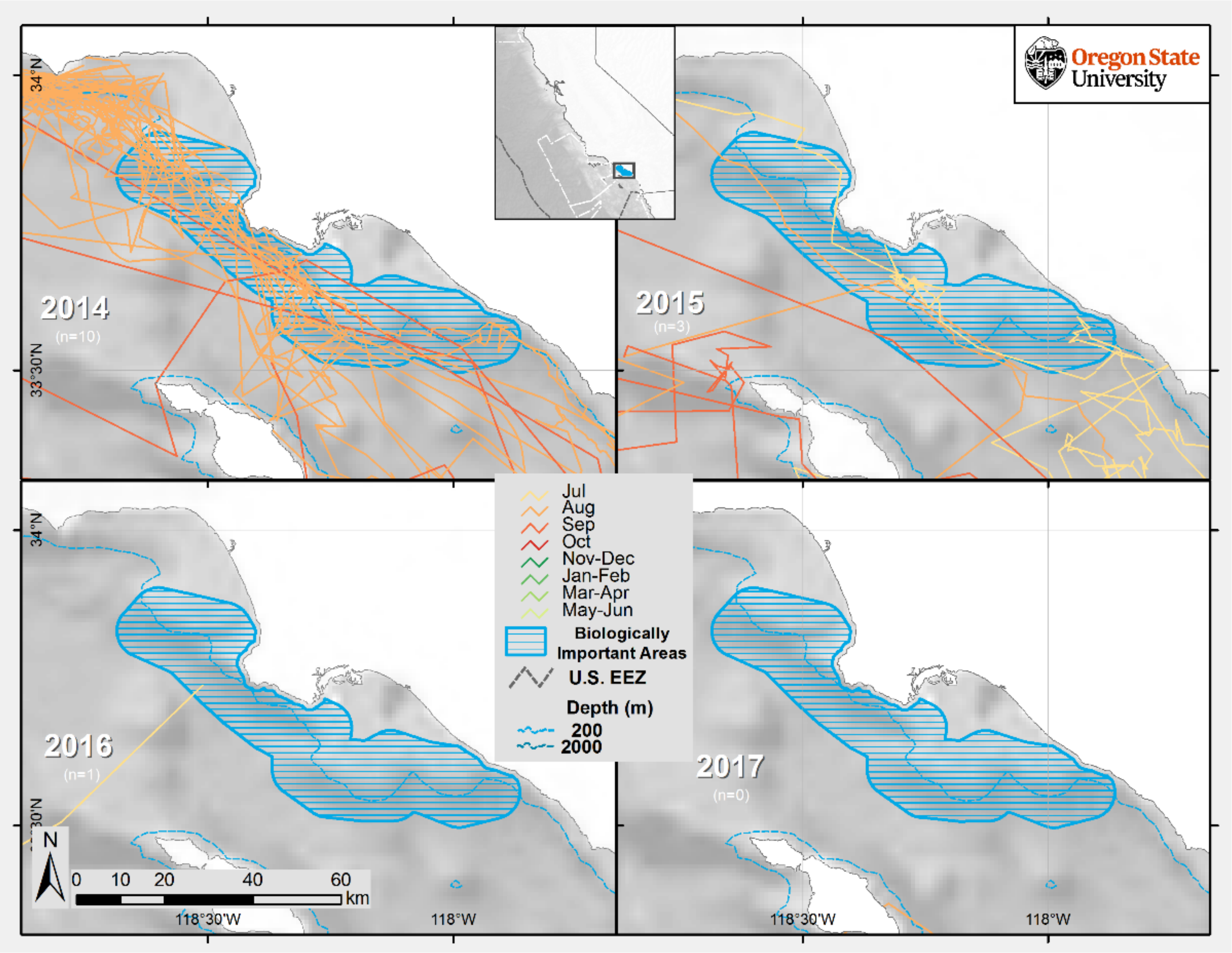

Figure 22. Satellite-monitored tracks of blue whales in the Santa Monica Bay to Long Beach BIA (partially located in the SOCAL range), by tagging year (2014–2017). The light and dark blue bathymetric contours correspond to the 200 and 1,000 m isobaths, respectively.

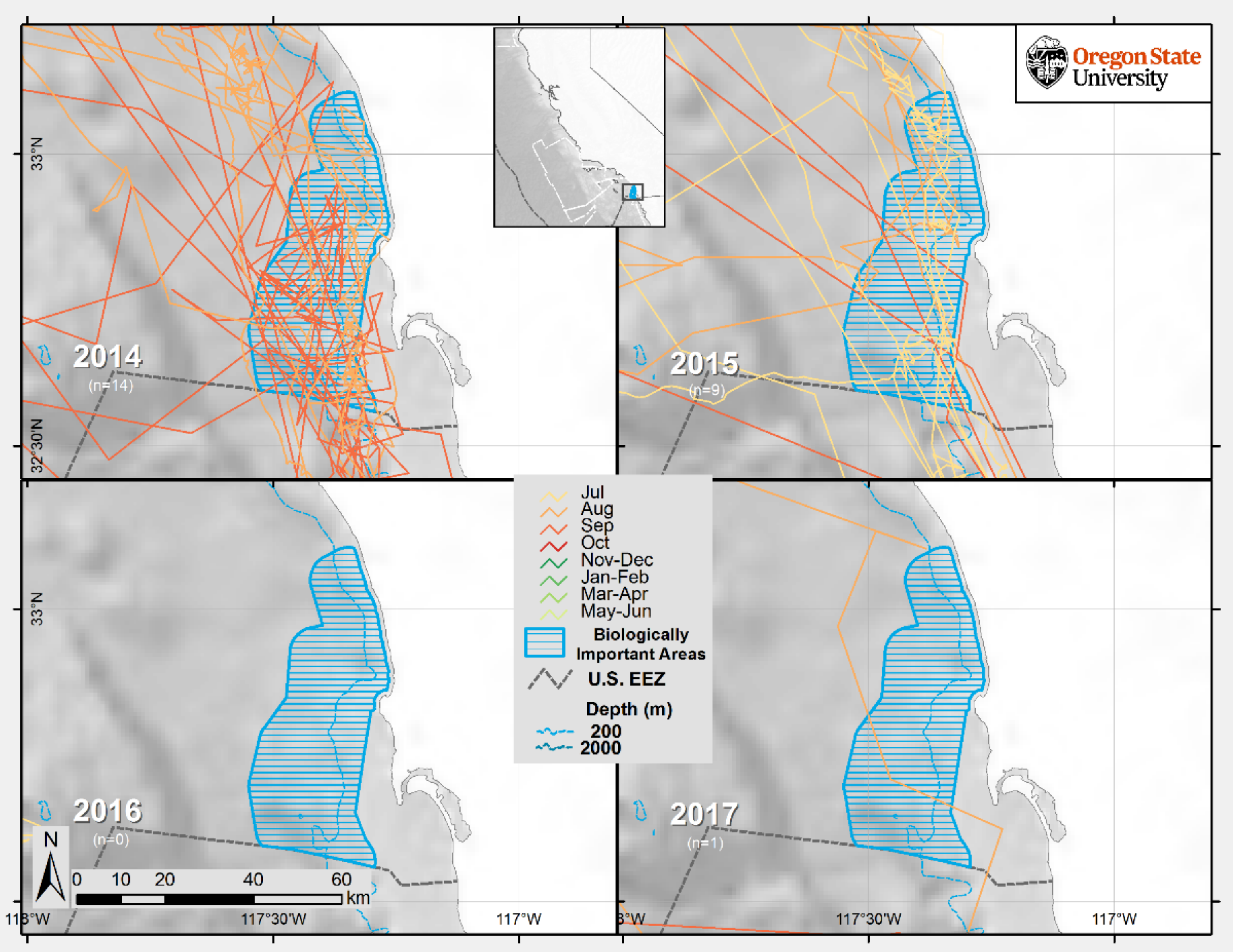

Figure 23. Satellite-monitored tracks of blue whales in the San Diego BIA (located in the SOCAL range), by tagging year (2014–2017). No blue whales tagged in 2016 were tracked in the San Diego BIA. The light and dark blue bathymetric contours correspond to the 200 and 1,000 m isobaths, respectively.

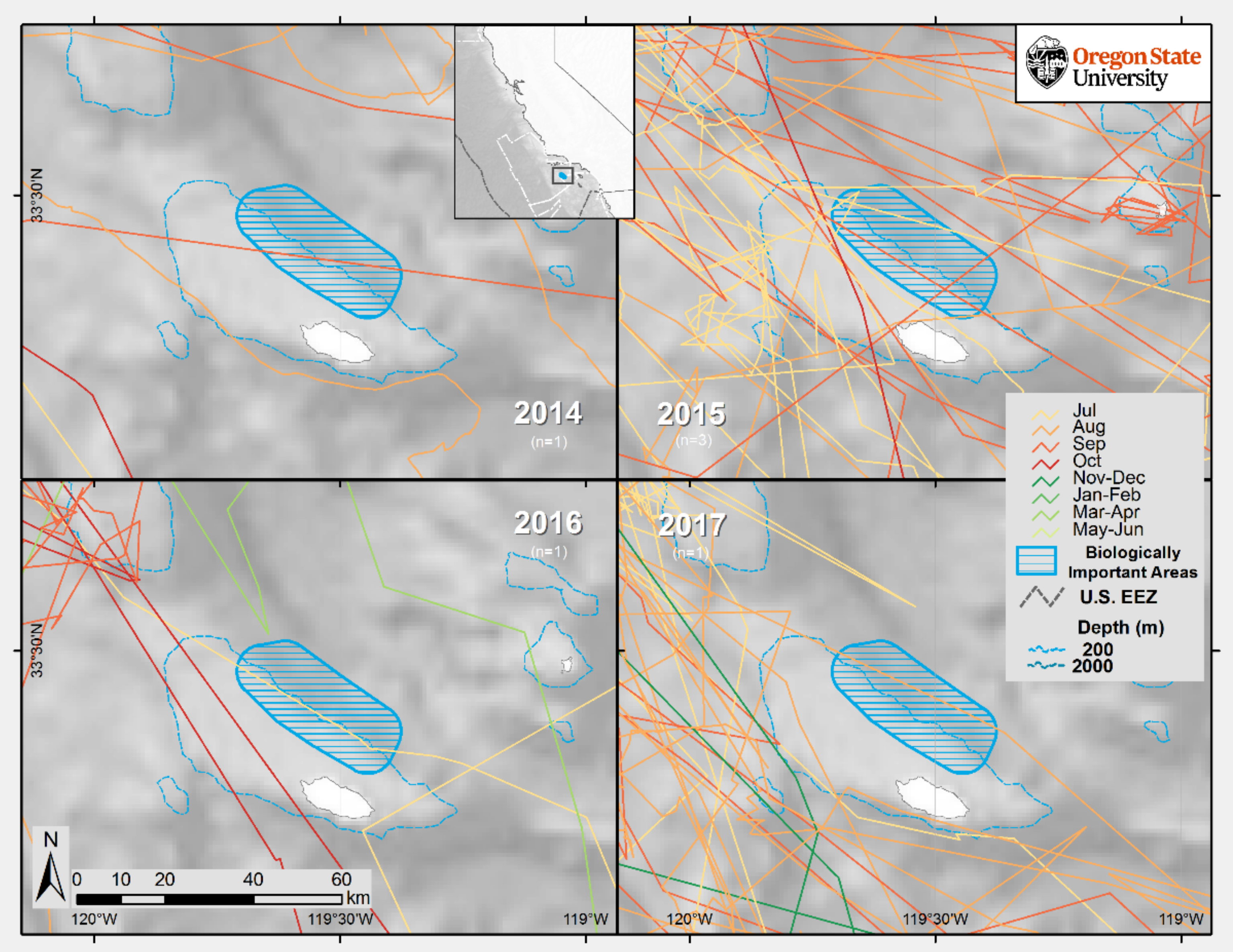

Figure 24. Satellite-monitored tracks of blue whales in the San Nicolas Island BIA (located in the PT MUGU range and partially in the SOCAL range), by year (2014–2017). The light and dark blue bathymetric contours correspond to the 200 and 1,000 m isobaths, respectively.

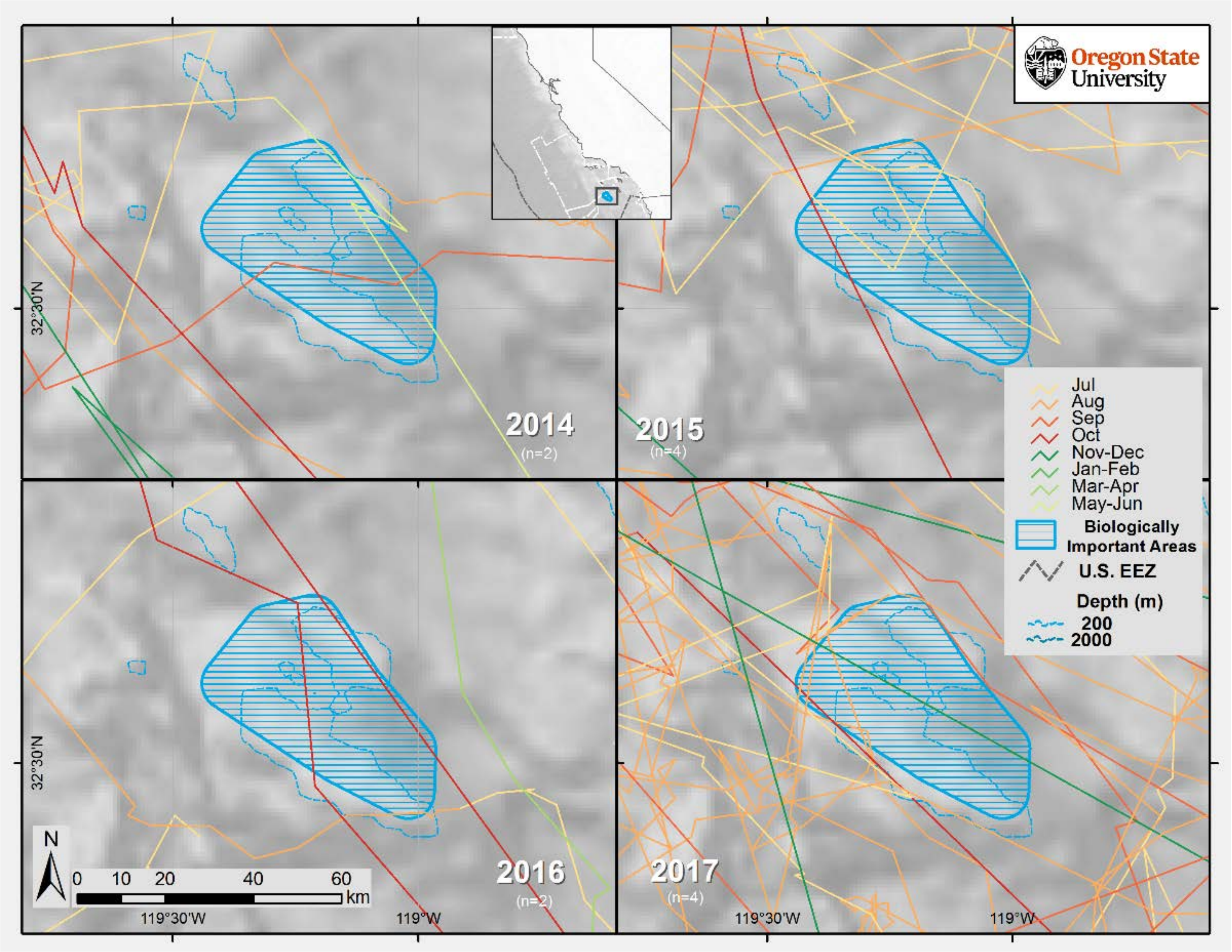

Figure 25. Satellite-monitored tracks of blue whales in the Tanner-Cortes Bank BIA (located in the SOCAL range), by tagging year (2014–2017). The light and dark blue bathymetric contours correspond to the 200 and 1,000 m isobaths, respectively.

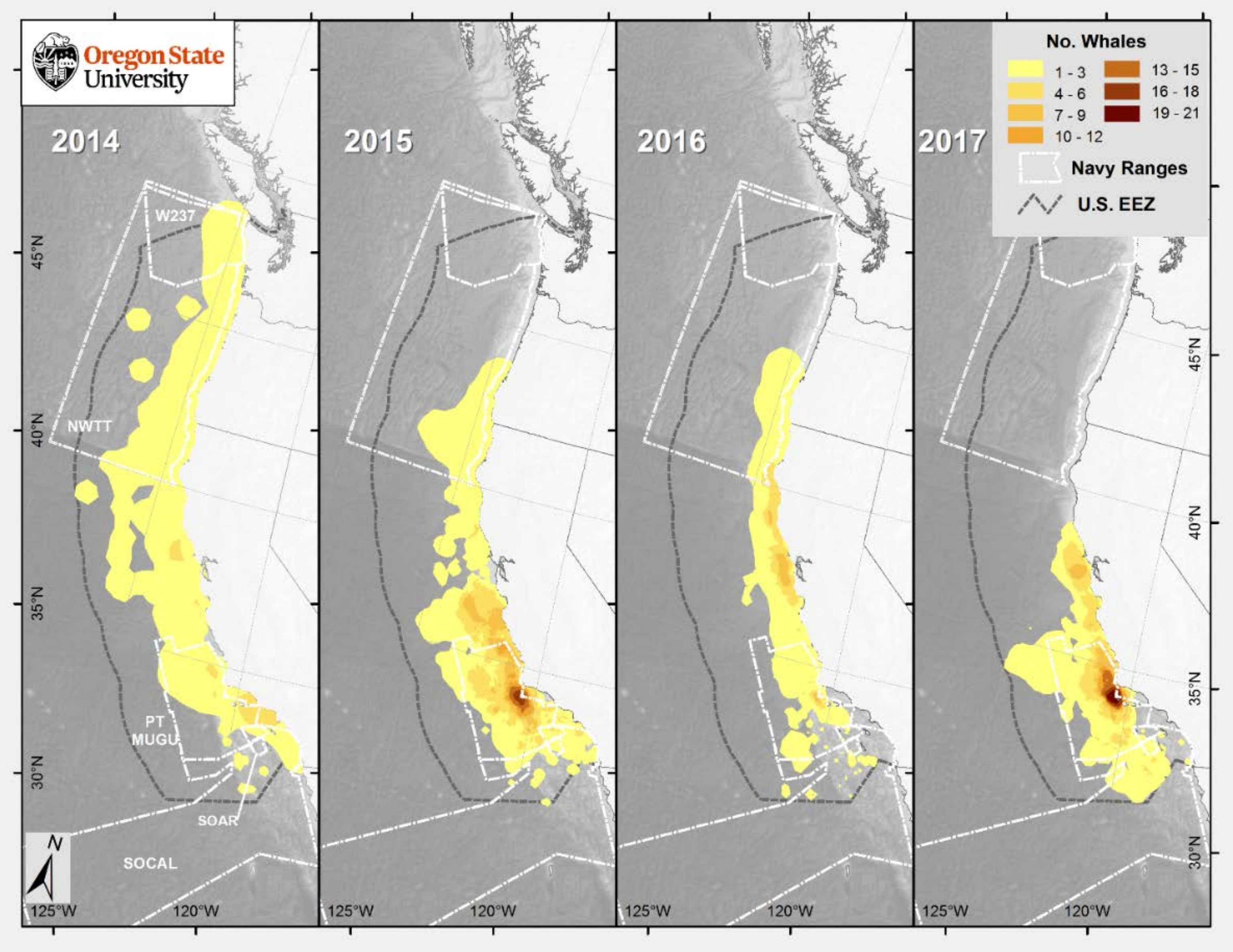

Figure 26. HRs in the U.S. EEZ for blue whales tagged off southern California in 2014 (5 whales), off southern California in 2015 (17 whales), off southern and central California in 2016 (14 whales), and off southern California in 2017 (20 whales). Shading represents the number of individual whales with overlapping HRs.

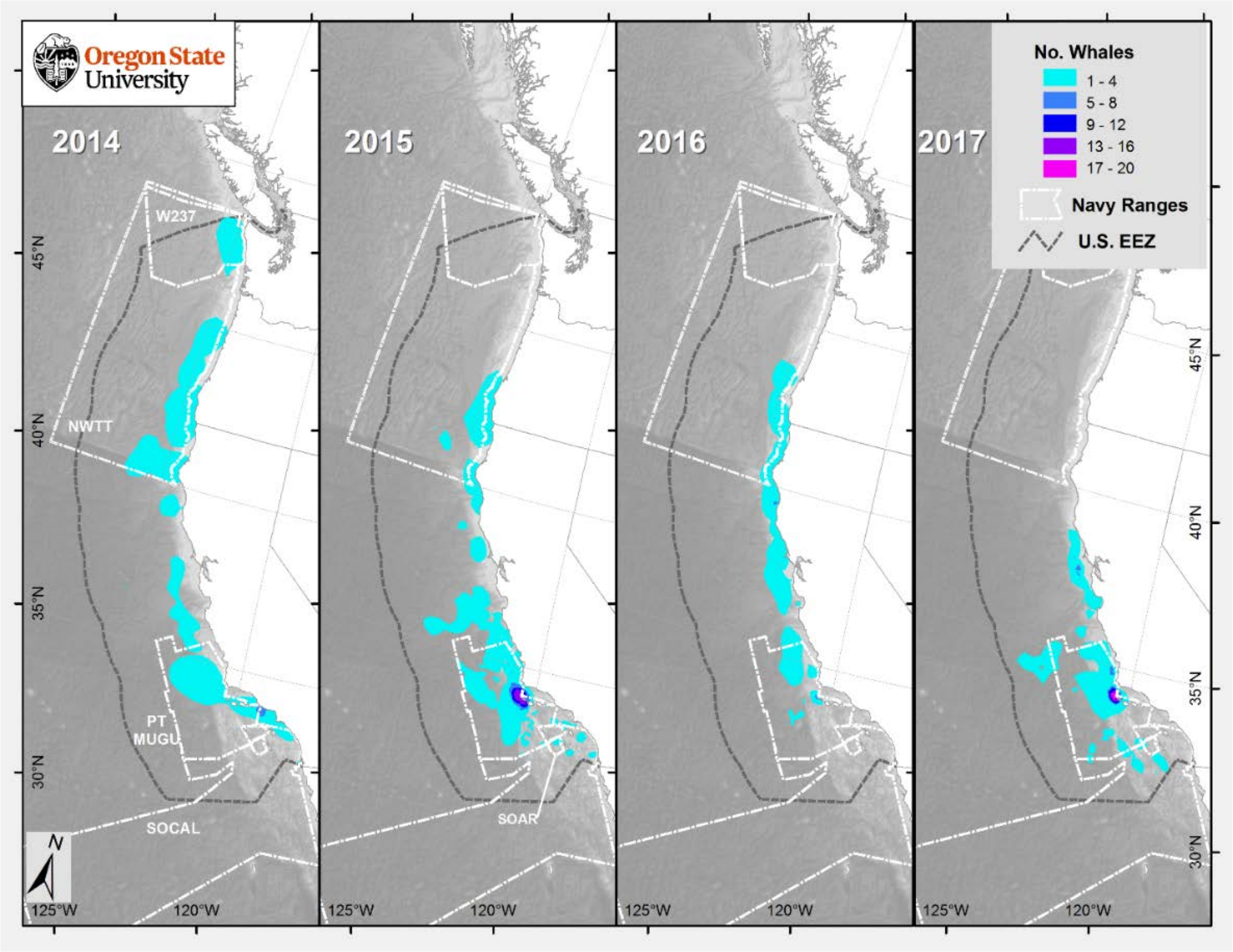

Figure 27. CAs in the U.S. EEZ for blue whales tagged off southern California in 2014 (5 whales), off southern California in 2015 (17 whales), off southern and central California in 2016 (14 whales), and off southern California in 2017 (20 whales). Shading represents the number of individual whales with overlapping CAs.

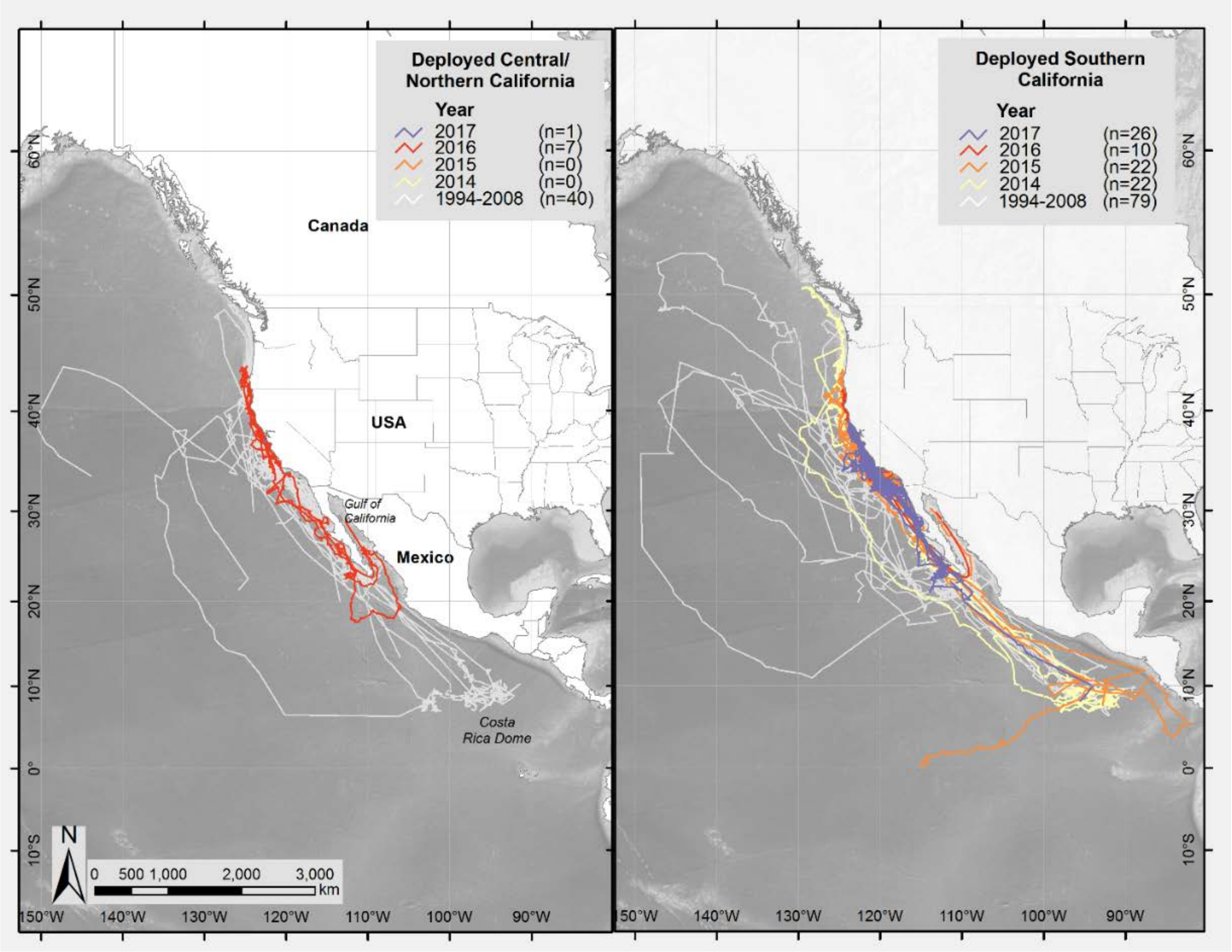

Figure 28. Satellite-monitored tracks of blue whales tagged by OSU off central and northern California (left panel) and southern California (right panel) between 1994 and 2017.

in southern California was west of Haida Gwaii, British Columbia, and west of Vancouver Island, British Columbia, for whales tagged in central California. Blue whales tagged in both locations had similar winter migratory destinations, with both southern and central whales migrating to the Costa Rica Dome as well as to the Gulf of California. The blue whale that traveled to the equator was one that was tagged off southern California in 2015.

3.1.6 Dive Behavior Analysis – 2017

Five of the DM tags that malfunctioned due to a saltwater leak (Tag #s 825, 832, 836, 5736, 5800) did not transmit any dive data (see **Section 3.1.1**), so they were excluded from further analyses. The remaining DM tags provided a median of 2,291 dive summaries (range = 93–5943; **Table 13**). The reported dives summarized a median of 41.8 percent of the tracking duration (range = 16.4 to 62.3 percent). Maximum dive depths were highly variable within and across individuals with most dives occurring to depths < 200 m. However, all tagged whales made dives exceeding 300 m at various times (**Figure 29**). One dive to 429 m was recorded, but the duration of that dive was only 4.2 min and the tag was the shortest-lived of all tags providing data (Tag #1386, lasting just 2.7 d), so the result should be treated with caution. Both dive depths and number of feeding lunges showed a strong diel pattern with deeper dives and more feeding lunges occurring during the daytime (**Figure 30**). While within-individual variability was more consistent, dive durations were also variable across individuals, generally ranging from 5 to 15 min in duration with occasional dives lasting over 20 min (**Figure 31**) and longer duration dives occurring during the daytime (**Figure 32**). Feeding lunges most commonly occurred during dives classified as ARS using the SSSM locations, with the fewest lunges occurring during dives classified as transiting (**Figure 33**).

Table 13.Summary of Dive-Monitoring tag deployments on blue whales off southern and central California during July-August 2017. Note this table does not include five tags (Tag #s 825, 832, 836, 5736, 5800) as no dive information was received from those tags (see Section 3.1.1).

PTT	Summary Period (d)	# Dives	% Track Summarized	Median Dives Per Day	Min Dives Per Day	Max Dives Per Day
827	120.9	2291	16.4	18	2	67
831	38.7	1724	35.7	42	6	113
1385	80.3	4656	43.4	50	1	122
1386	1.5	93	51.3	NA*	4	83
5840	82.0	5943	47.7	73.5	6	140
10830	15.2	314	41.8	21	7	32
10831	151.3	4354	26.8	29	2	86
10840	61.8	2635	36.4	37	3	109
23031	38.8	1760	62.3	41	10	84
median	61.8	2291.0	41.8	37.0	4.0	86.0

KEY: # = number; * = too few days for a median

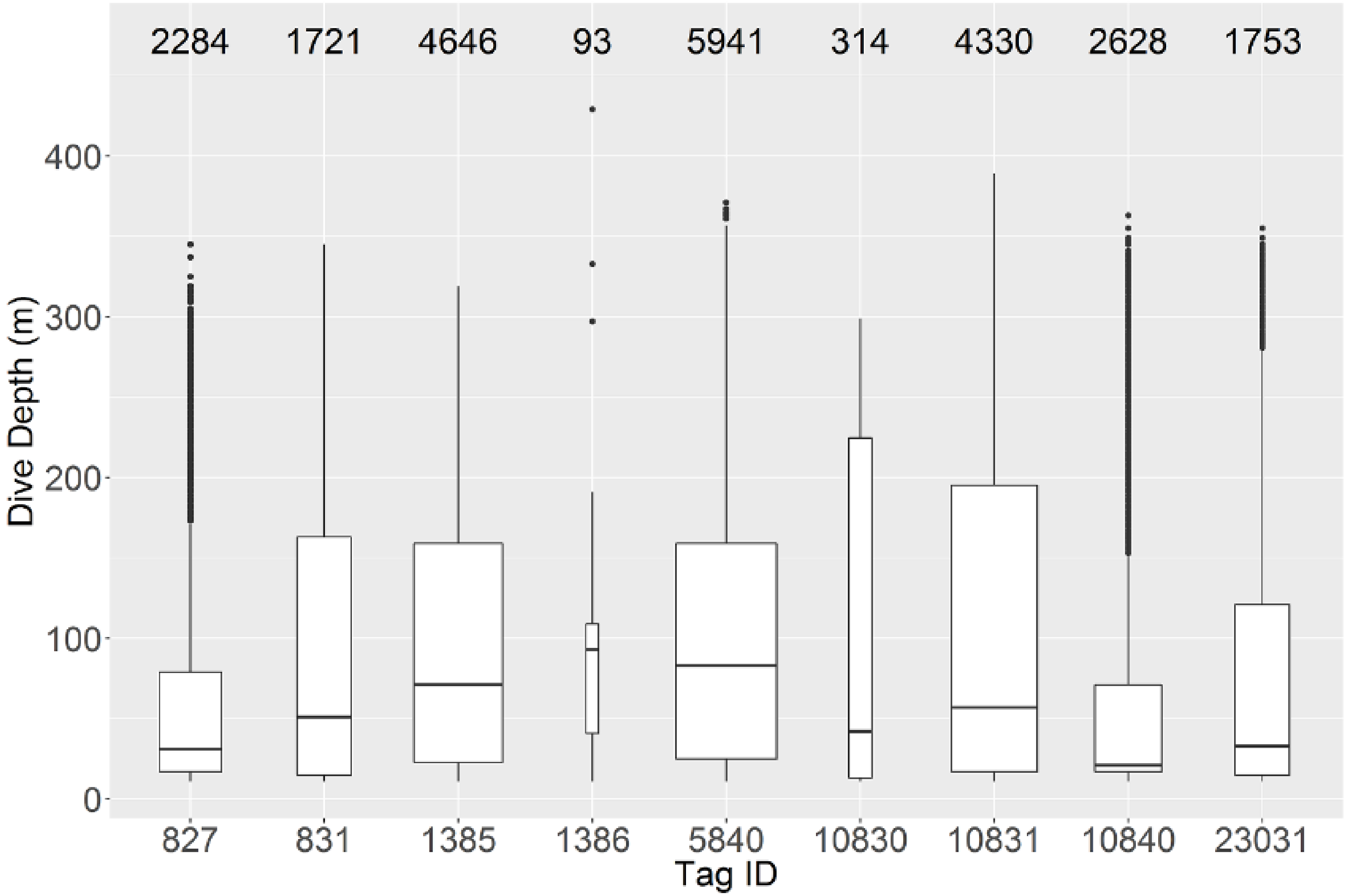

Figure 29. Dive depth of DM tagged blue whales tagged off central and southern California during summer 2017. The bottom and top horizontal lines of the boxes represent the first and third quartiles of the data, respectively, with the centerline representing the median. The upper vertical line, or upper whisker, extends from the third quartile to the largest value no further than 1.5 times the inter-quartile range (IQR, distance between the first and third quartiles) from the third quartile. The lower vertical line, or lower whisker, extends from the first quartile to the smallest value at most 1.5 times IQR from the first quartile. Points represent outliers, or values beyond the end of the whiskers. Box widths are related to the number of dives made by each tagged whale, which are listed at the top of the figure.

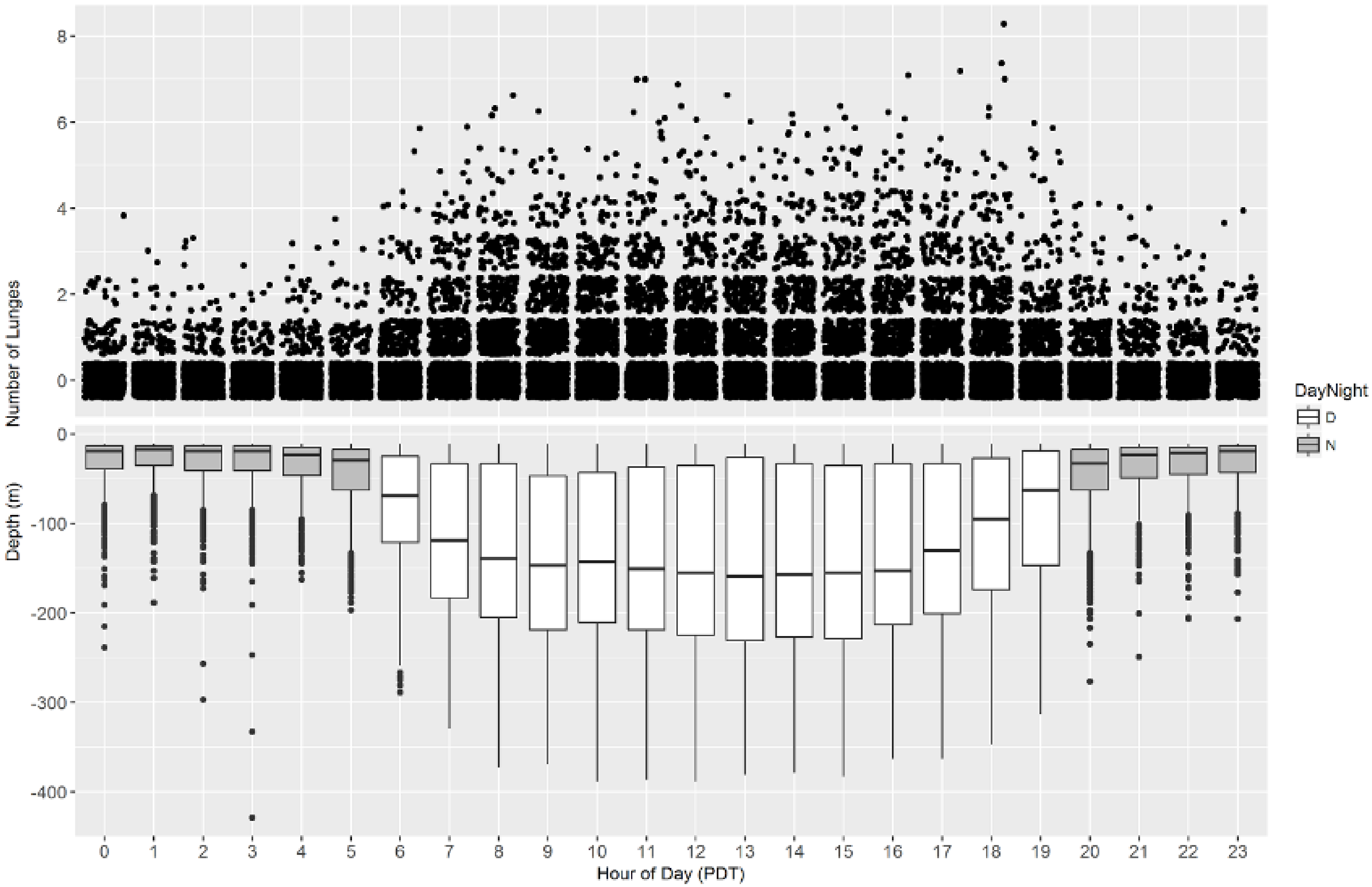

Figure 30. Number of lunges per dive (upper panel) and maximum dive depth (lower panel) of DM-tagged blue whales tracked off central and southern California during summer/fall 2017 (n = 9). Data are presented by hour of day to better visualize diel variability and the data in the top panel are jittered to avoid over plotting. The bottom and top horizontal lines of the boxes in the bottom panel represent the first and third quartiles of the data, respectively, with the centerline representing the median. The upper vertical line, or upper whisker, extends from the third quartile to the largest value no further than 1.5 times the IQR from the third quartile. The lower vertical line, or lower whisker, extends from the first quartile to the smallest value at most 1.5 times IQR from the first quartile. Points represent outliers, or values beyond the end of the whiskers.

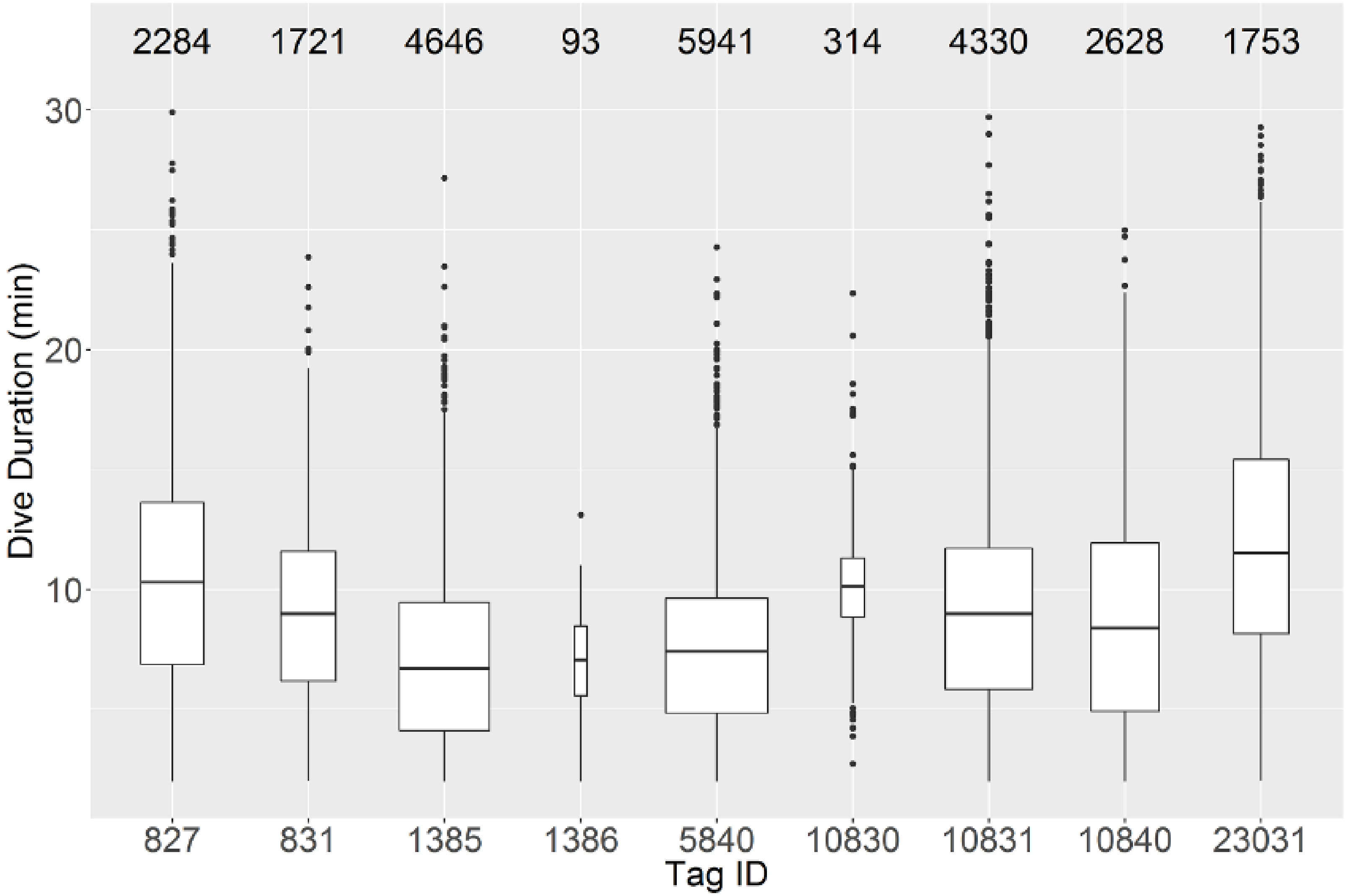

Figure 31. Dive duration of DM tagged blue whales tagged off central and southern California during summer 2017. The bottom and top horizontal lines of the boxes represent the first and third quartiles of the data, respectively, with the centerline representing the median. The upper vertical line, or upper whisker, extends from the third quartile to the largest value no further than 1.5 times the IQR from the third quartile. The lower vertical line, or lower whisker, extends from the first quartile to the smallest value at most 1.5 times IQR from the first quartile. Points represent outliers, or values beyond the end of the whiskers. Box widths are related to the number of dives made by each tagged whale, which are listed at the top of the figure.

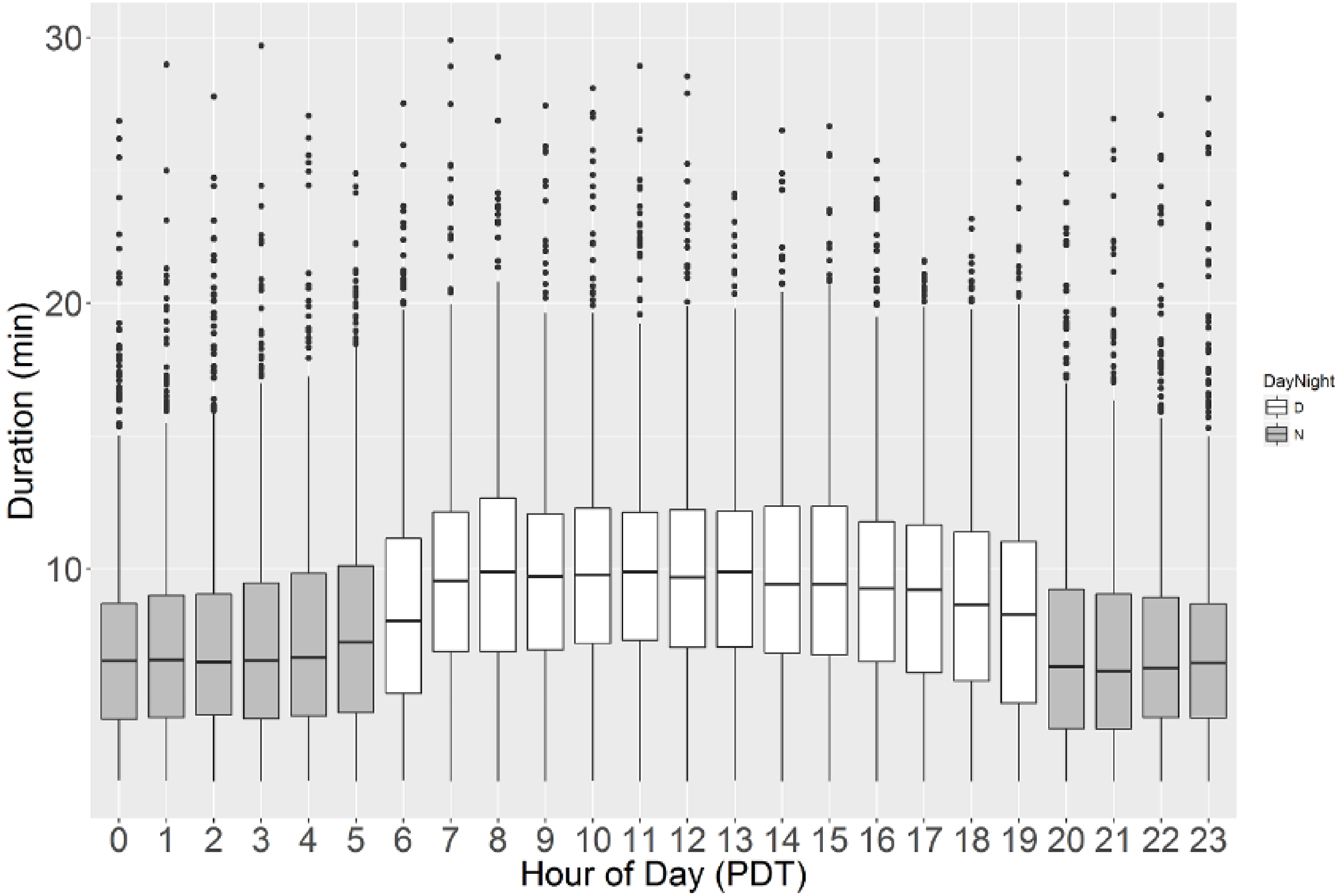

Figure 32. Dive duration of DM-tagged blue whales tracked off central and southern California during summer/fall 2017 (n = 9). Data are presented by hour of day to better visualize diel variability. The bottom and top horizontal lines of the boxes represent the first and third quartiles of the data, respectively, with the centerline representing the median. The upper vertical line, or upper whisker, extends from the third quartile to the largest value no further than 1.5 times the IQR from the third quartile. The lower vertical line, or lower whisker, extends from the first quartile to the smallest value at most 1.5 times IQR from the first quartile. Points represent outliers, or values beyond the end of the whiskers.

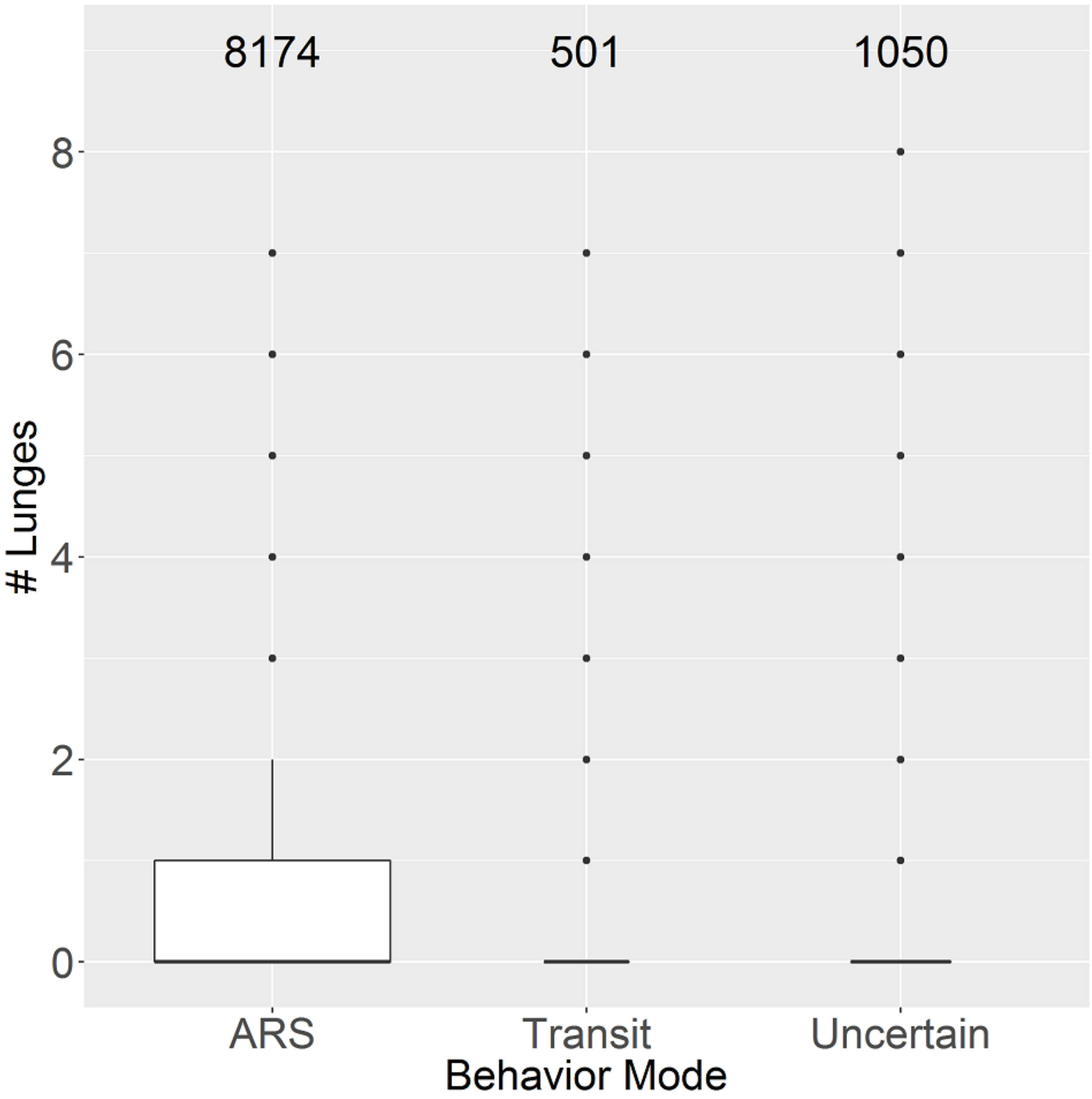

Figure 33. Number of feeding lunges recorded by DM-tagged blue whales tagged off southern and central California during summer 2017 presented by SSSM-derived behavior state. Text at the top of each behavior mode is the total number of lunges recorded during dives assigned to each behavior mode. The bottom and top horizontal lines of the boxes represent the first and third quartiles of the data, respectively, with the centerline representing the median. The upper vertical line, or upper whisker, extends from the third quartile to the largest value no further than 1.5 times IQR from the third quartile. The lower vertical line, or lower whisker, extends from the first quartile to the smallest value at most 1.5 times IQR from the first quartile. Points represent outliers, or values beyond the end of the whiskers. Box widths are related to the number of dives made by each tagged whale, which are listed at the top of the figure.

The spatial distribution of feeding effort was variable with tagged whales feeding extensively around the tagging area near San Miguel Island and extending offshore to the west (**Figure 34**). Little feeding was recorded south of the tagging area, despite the area being visited by multiple tagged whales, although it did occur to the southeast in an area south of San Clemente Island and near San Diego. Multiple whales traveled north and foraged extensively off central California. Maximum dive depths were deepest near the Channel Islands with shallower dives occurring off central California and in the rest of the Southern California Bight. Dive durations were generally shortest off central California with longer duration dives occurring in the Bight.

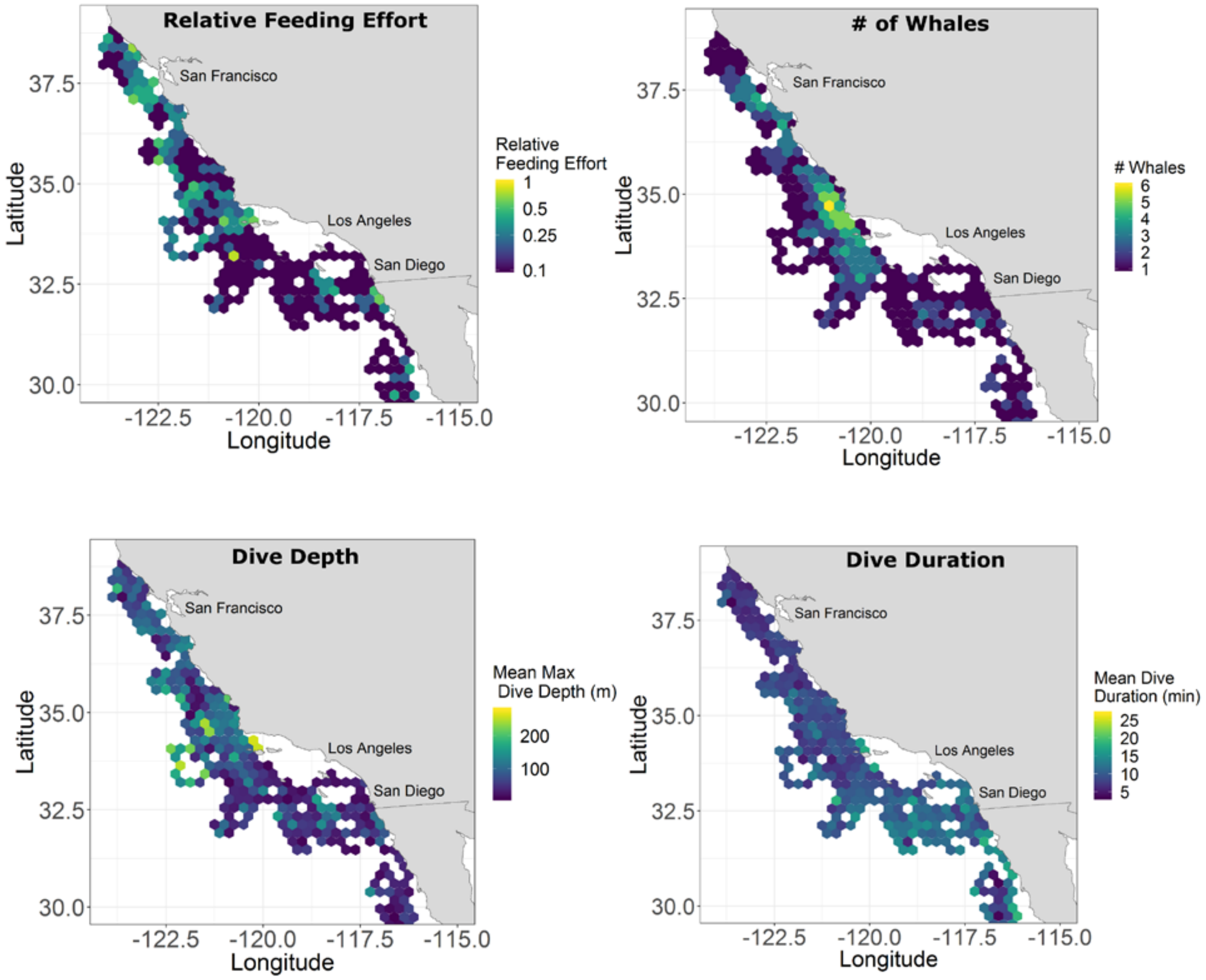

Figure 34. A series of 0.25-degree hexagonal grids generated from DM-tagged blue whales tagged off central and southern California during summer 2017. Grids show the amount of feeding effort that occurred in each grid cell based on the number of lunges recorded by the tags (top left); the mean maximum dive depth in each grid cell (bottom left); the mean dive duration in each grid cell (bottom right); and the number of DM-tagged blue whales occupying each grid cell (top right).

3.1.7 Dive Behavior Analysis – Inter-annual Comparison

Direct comparisons between 2016 and 2017 DM tagging results are difficult due to differences in lunge-detection programming. Blue whale dive behavior characteristics were generally similar across years with a strong diel trend in both the dive depth and number of lunges. However, daytime maximum dive depths reported for 2017 were substantially deeper than those from 2016 (125 to 150 m versus 50 to 75 m, respectively) or ADB tagged whales from 2014 and 2015 (50 to 75 m; Mate et al. 2017a). Spatial distribution of dive depths was similar across years with deeper dives occurring near San Miguel Island and generally shallower dives occurring off central California. Spatial distribution of foraging effort in 2017 was generally similar to that of 2016, with most foraging occurring in a broad area near San Miguel Island and north to the area off San Francisco (**Figure 35**). Little feeding occurred south of the Channel Islands in 2016 and one whale occupied that area without recording any feeding effort. ADB tags recorded blue whale feeding in similar parts of southern California waters during 2014 and 2015, including the areas south of San Clemente and near San Diego (Mate et al. 2017a). Across all years, whales feeding offshore south and west of San Clemente Island were male, while whales feeding near San Diego were both male and female. Feeding also occurred extensively along the coast from Point Mugu south to San Diego in 2014–2015. However, the area from Point Mugu to Los Angeles was essentially unoccupied by tagged whales in 2016 and 2017. Feeding (and occupancy in general) was more limited north of Point Conception for ADB-tagged whales in 2014 and 2015.

3.1.8 Ecological Relationships – 2017

The SSSMs generated regularized daily locations for 25 blue whale tags in 2017, resulting in 1,749 estimated locations, of which 11 occurred on land and 40 had unacceptable estimation uncertainty (**Table 14**). The geographic extent of these tracks covered approximately 31 degrees of longitude (124.8–94.1°W) and 30 degrees of latitude (9.2–39.2°N) (**Figure 36**). Most of the 1,698 accepted locations occurred in CCAL (99.3 percent), followed by PNEC (0.7 percent). The ALSK, NPPF, NPTG, GUCA, and PQED provinces were not occupied in 2017 (**Table 14** and **Figure 36**).

The behavioral classification for each location for all tracks is shown in the map in **Figure 36**. The number and proportion of locations classified by behavioral mode in CCAL is reported in **Table 15**. Of 1,664 SSSM locations, 900 (54.1 percent) were classified as ARS, 569 (34.2 percent) were classified as uncertain, and 195 (11.7 percent) were classified as transiting (**Table 15**). Within CCAL, and for the summer-fall months, average PWDIST was 36.7 km (**Table 16, Figure 37**).

Details of the environmental variables examined are provided in **Table 1**. Summary statistics for these variables obtained for the SSSM locations are reported for CCAL only (**Tables 16 and 17**), as this was the only biogeographic province consistently occupied by both species and in all years (calculations reported are based on values measured closest in space and time to each whale SSSM location, per the temporal and spatial resolution of each product listed in **Table 1**). In 2017, average SST was 18.5°C, and average CHL was 1.4 milligrams per cubic meter [mg m^{-3}] (**Table 16**). The values at each location for these environmental variables are shown as maps in **Figures 38 and 39**.

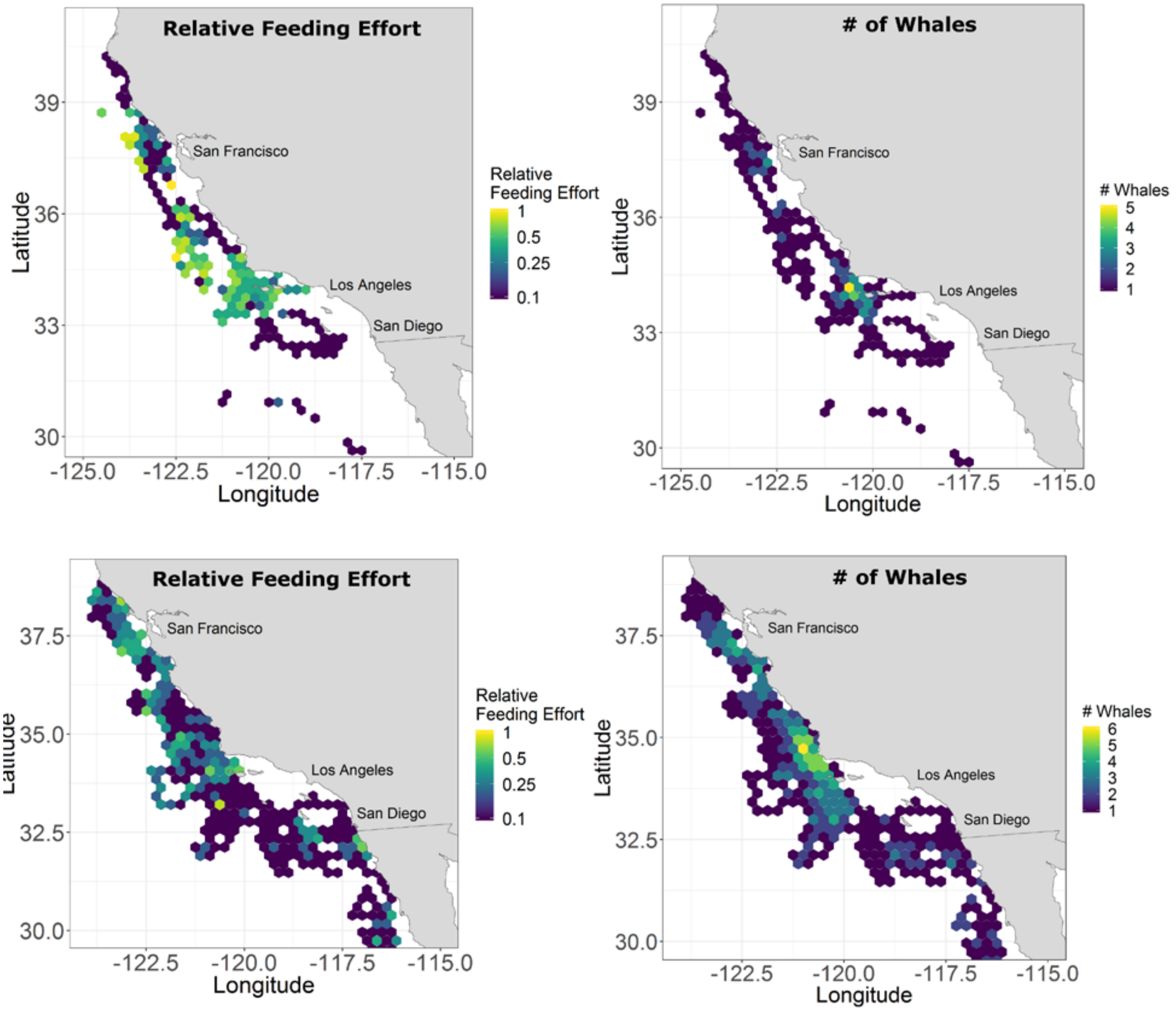

Figure 35. A series of 0.25-degree hexagonal grids generated from DM-tagged blue whales tagged off central and southern California during summer 2016 (top panels) and 2017 (bottom panels). Grids show the amount of feeding effort that occurred in each grid cell based on the number of lunges recorded by the tags (left) and the number of DM-tagged blue whales occupying each grid cell (right).

Table 14. Number (and percentage) of accepted SSSM locations (locs) inside each province for blue whales in each year of the project. Also provided are the number of locations that fell on land and the number of locations excluded from the analyses because their high estimation uncertainty. Unclassified locations correspond to the end-of-track locations, which do not receive a behavioral mode classification by the SSSM. This number can be lower than the number of tracks because of the exclusion of locations on land and those with high estimation uncertainty. The number of SSSM tracks is indicated (n) and can be lower than the number of tracked whales (See Section 2.3.2).

	2014 (n = 20)*	**2015 (n = 22)***	**2016 (n = 18)**	**2017 (n = 25)**
Longitudinal range	**39 degrees (129.8–90.8°W)**	**43.6 degrees (126.8–83.2°W)**	**20 degrees (125.7–106°W)**	**31 degrees (124.8–94.1°W)**
Latitudinal range	**43.6 degrees (6.9–50.5°N)**	**43.6 degrees (0.1–43.7°N)**	**26 degrees (17.6–43.9°N)**	**30 degrees (9.2–39.2°N)**
Province				
ALSK	1 (0.1%)	NA	NA	NA
CCAL	841 (73.1%)	1,425 (89.8%)	1,146 (95.3%)	1,686 (99.3%)
GUCA	NA	13 (0.8%)	27 (2.2%)	NA
NPPF	1 (0.1%)	NA	NA	NA
NPTG	1 (0.1%)	NA	NA	NA
PNEC	307 (26.7%)	107 (6.7%)	30 (2.5%)	12 (0.7%)
PQED	NA	41 (2.6%)	NA	NA
Accepted locs	1,151 (100%)	1,586 (100%)	1,203 (100%)	1,698 (100%)
Unclassified locs	16	18	17	22
Excluded locs	18	101	15	40
Land locs	14	28	7	11
Total locs	1,183	1,715	1,225	1,749

KEY: n = number; * = number of SSSM tracks includes those from ADB tags (4 in 2014, 4 in 2015).

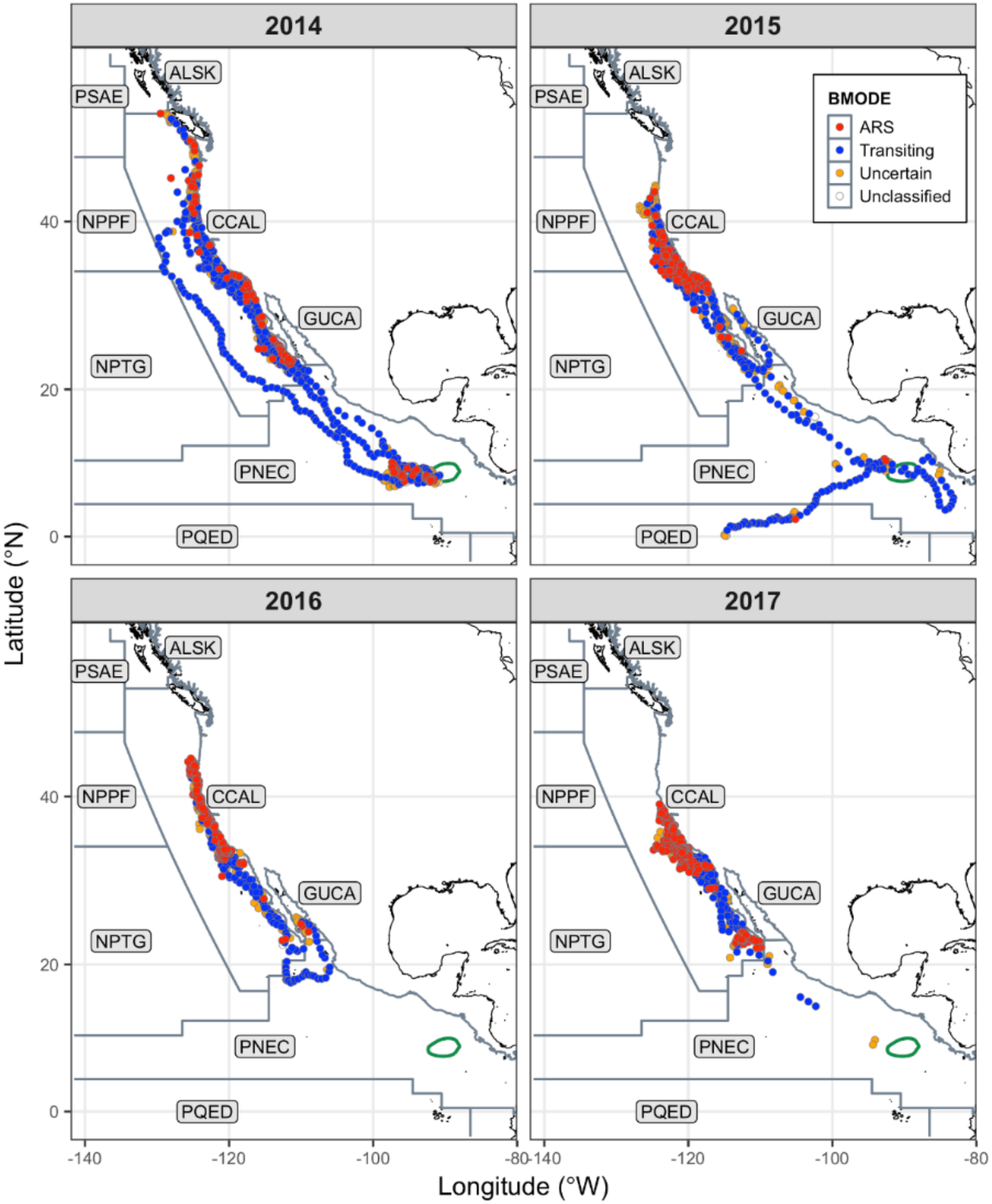

Figure 36. Accepted SSSM locations for blue whales colored by behavioral mode for each year in the study. The eight biogeographic provinces identified by Longhurst (1998, 2006) in the eastern North Pacific are outlined and labeled. The green, oval-shaped contour in PNEC outlines the position of the CRD, as determined by the mean location of the depth of the 20°C isotherm (from Fiedler 2002, Fiedler et al. 2017).

Table 15. Number of classified SSSM locations (and percentage) in CCAL for each behavioral mode for blue whales in each year of the project. The number of SSSM tracks is indicated (n).

Behavioral mode	2014 (n = 20)	2015 (n = 22)	2016 (n = 18)	2017 (n = 25)
Transiting	383 (46.3%)	321 (22.8%)	113 (10%)	195 (11.7%)
Uncertain	352 (42.5%)	830 (58.9%)	440 (39%)	569 (34.2%)
ARS	93 (11.2%)	259 (18.4%)	576 (51%)	900 (54.1%)
Classified locs	828 (100%)	1,410 (100%)	1,129 (100%)	1,664 (100%)

Table 16. Summary statistics (mean and standard deviation [SD]) for the PWDIST and the remotely sensed variables obtained for each SSSM location for blue whales in CCAL in July-November for each year of the project. The total number of locations (N Total) and the number of locations with valid matching environmental values (n) are given for each species and year. SSSM locations falling on land, those with high estimation uncertainty, and those with unclassified behavioral mode have been excluded.

Year	N Total	PWDIST (km)			SST (°C)			CHL (mg m^{-3})		
		n	Mean	SD	n	Mean	SD	n	Mean	SD
2014	828	803	55.68	42.04	767	21.22	4.53	815	0.82	2.50
2015	1,410	1,371	42.83	37.27	1,347	19.71	2.81	1,391	0.75	1.45
2016	1,129	1,073	25.38	24.54	1,091	15.77	2.27	942	2.11	3.14
2017	1,664	1,625	36.74	35.51	1,650	18.43	3.01	1,514	1.37	2.25

Table 17. Summary statistics (mean and standard deviation [SD]) for the seafloor relief variables obtained for each SSSM location for blue whales in CCAL in July–November for each year of the project. The total number of locations (N Total) and the number of locations with valid matching environmental values (n) are given for each species and year. SSSM locations falling on land, those with high estimation uncertainty, and those with unclassified behavioral mode have been excluded.

Year	N Total	DEPTH (m)			DISTSHELF (km)			DISTSHORE (km)			SLOPE (m km^{-1})			ASPECT (deg)		
		n	Mean	SD	n	Mean	SD	n	Mean	SD	n	Mean	SD	n	Mean	SD
2014	828	814	1,674.87	1,489.20	814	58.75	100.31	814	88.11	113.53	814	46.92	47.06	814	208.81	76.37
2015	1,410	1,384	1,476.48	1,370.23	1,384	37.73	45.61	1,384	61.81	49.43	1,384	45.60	43.28	1,384	220.86	72.09
2016	1,129	1,082	710.11	1,013.28	1,091	16.48	25.82	1,087	36.05	31.71	1,090	39.66	46.40	1,088	234.33	61.91
2017	1,664	1,648	1,260.29	1,254.01	1,650	32.67	46.16	1,650	63.27	54.57	1,650	48.54	48.76	1,650	219.36	77.15

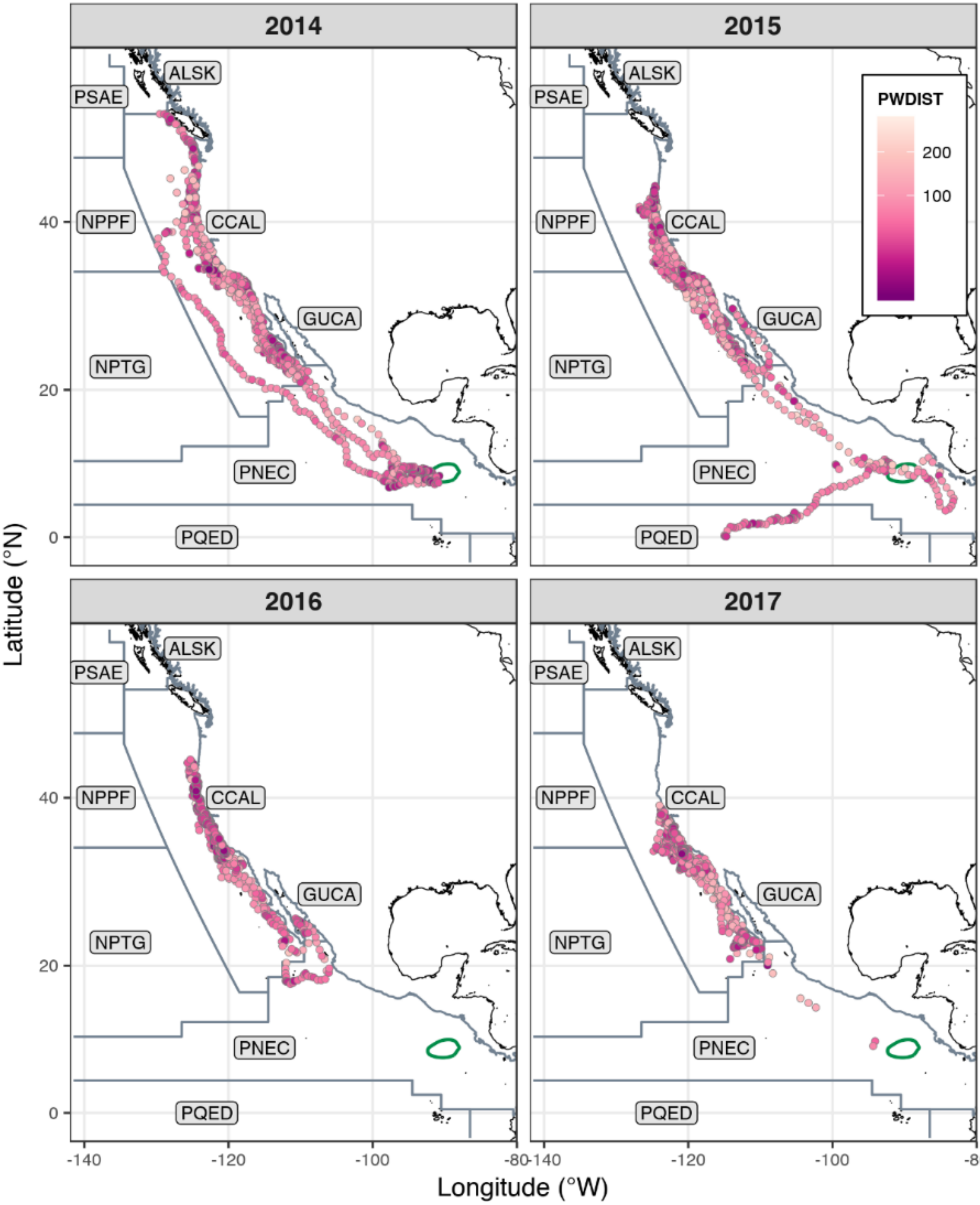

Figure 37. Map representation of PWDIST (km) between blue whale SSSM locations for each year in the study. The eight biogeographic provinces identified by Longhurst (1998, 2006) in the eastern North Pacific are outlined and labeled. The green, oval-shaped contour in PNEC outlines the position of the Costa Rica Dome (CRD), as determined by the mean location of the depth of the 20°C isotherm (from Fiedler 2002, Fiedler et al. 2017). Note the square-root-transformed color scale for enhanced visualization.

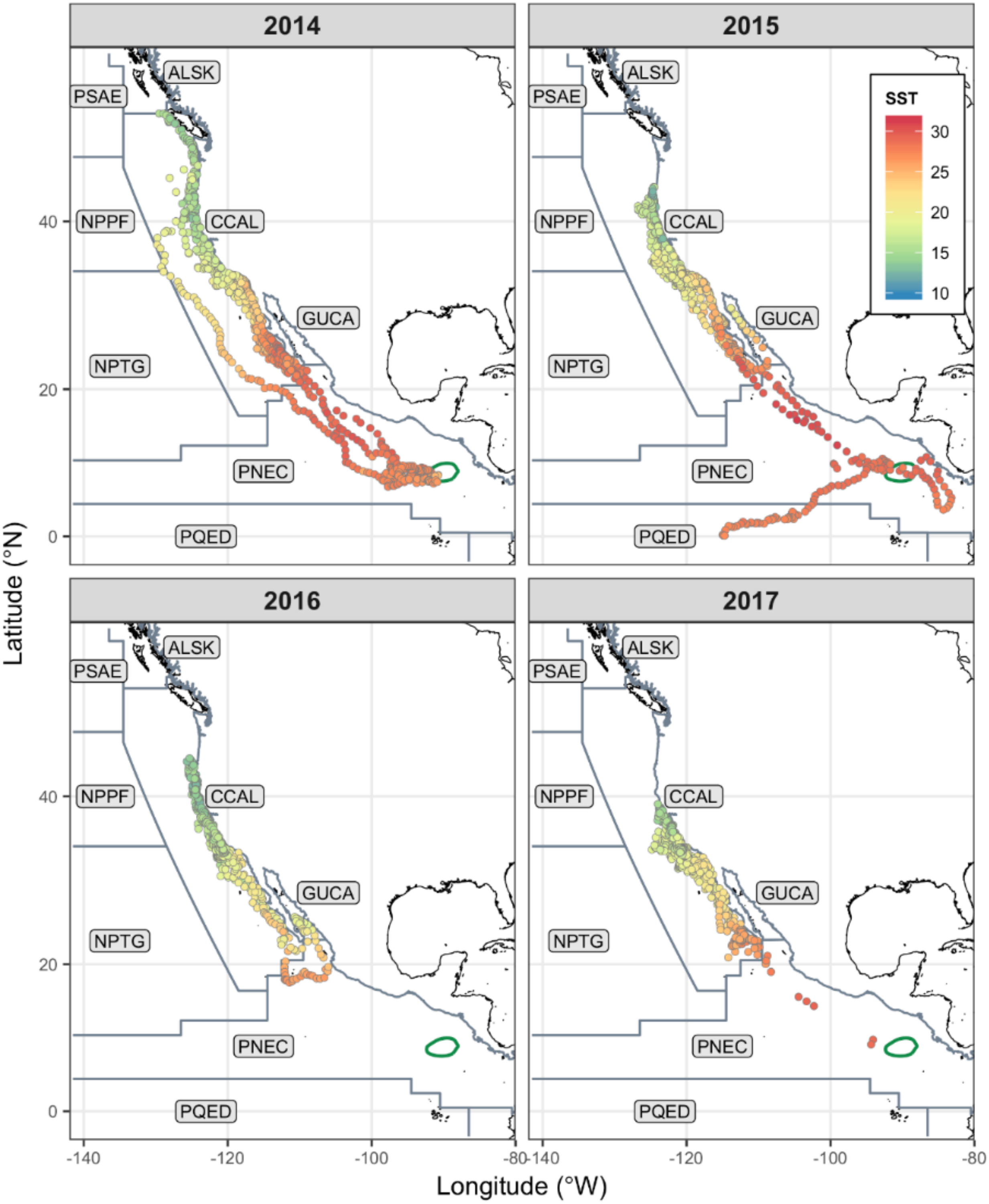

Figure 38. Map representation of sea surface temperature (SST, °C) values obtained from satellite remote sensing around each blue whale location for each year in the study. The eight biogeographic provinces identified by Longhurst (1998, 2006) in the eastern North Pacific are outlined and labeled. The green, oval-shaped contour in PNEC outlines the position of the CRD, as determined by the mean location of the depth of the 20°C isotherm (from Fiedler 2002, Fiedler et al. 2017).

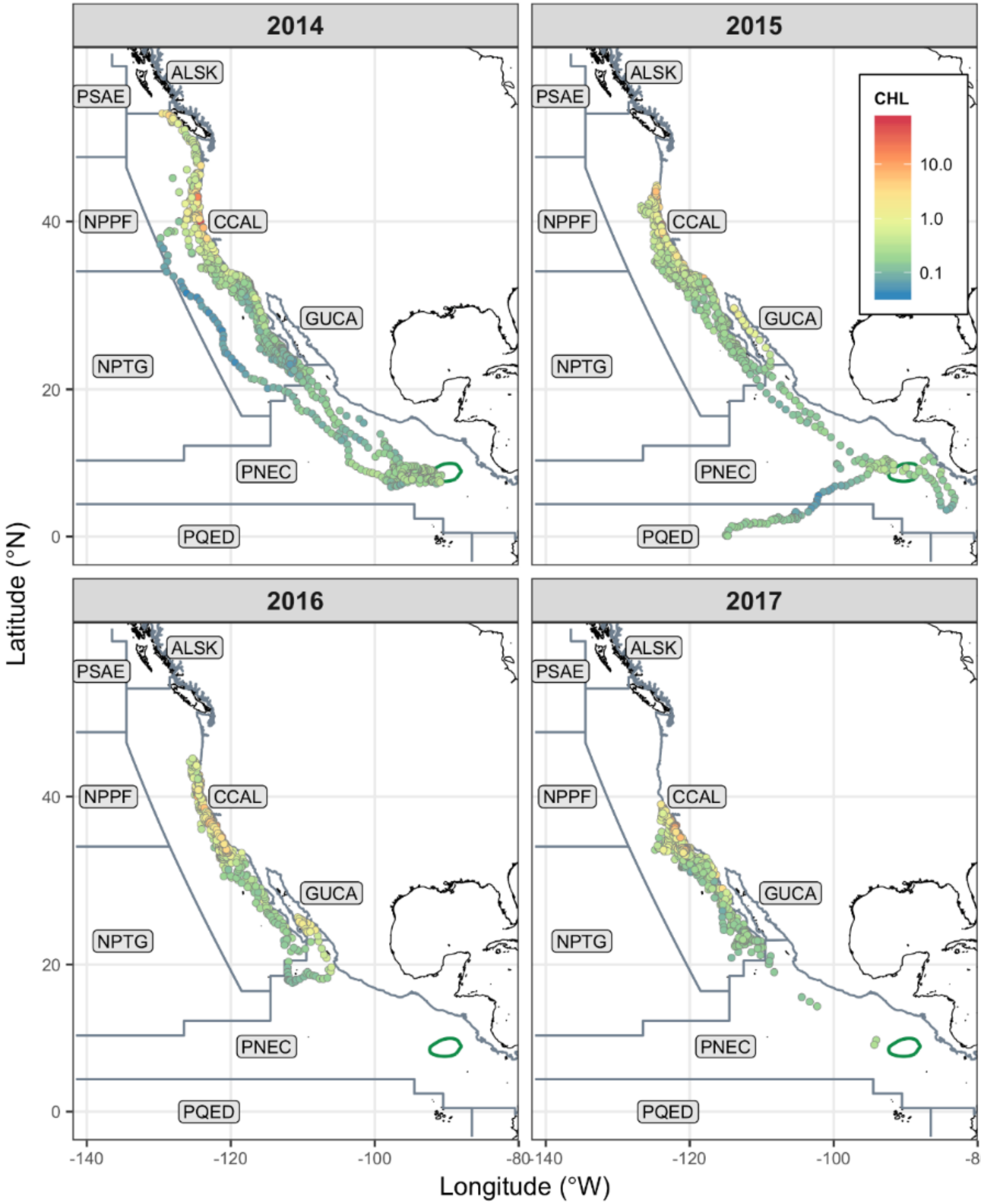

Figure 39. Map representation of chlorophyll-a concentration (CHL, mg m^{-3}) values obtained from satellite remote sensing around each blue whale location for each year in the study. The eight biogeographic provinces identified by Longhurst (1998, 2006) in the eastern North Pacific are outlined and labeled. The green, oval-shaped contour in PNEC outlines the position of the CRD, as determined by the mean location of the depth of the 20°C isotherm (from Fiedler 2002, Fiedler et al. 2017). Note the log-transformed color scale for enhanced visualization.

In terms of seafloor characteristics, in 2017 blue whales occurred in areas with an average DEPTH of 1,273.5 m, average DISTSHELF of 33.5 km, and average DISTSHORE of 64.2 km. The average SLOPE in these areas was 48.4 m km^{-1} and faced toward the southwest (average ASPECT = 218.9°) (**Table 17**). The values at each location for these seafloor relief variables are shown as maps in **Figures 40** through **44**.

3.1.9 Ecological Relationships – Inter-annual Comparison

The numbers of tracked blue whales in each of the four years were comparable (n = 20 in 2014, n = 22 in 2015, n = 18 in 2016, and n = 25 in 2017; **Table 14**). The longitudinal range of these tracks was similar in 2014 and 2015 (39 and 43.6 degrees, respectively), but it was approximately half as much in 2016 (20 degrees), as animals did not migrate to the eastern tropical Pacific in winter. Correspondingly, the latitudinal range was the same (43.6 degrees) in 2014 and 2015, but only 26 degrees in 2016. In 2017, these ranges were intermediate (31 degrees in longitude by 30 degrees in latitude; **Table 14** and **Figure 36**). In 2014, the northernmost extent in summer-fall range was farthest to the north (50.5°N), while in 2015 and 2016 animals only ranged to 43.7°N and 43.9°N, respectively. In 2017 the northernmost extent was found even farther to the south (39.2°N). During this season, animals also reached their westernmost (offshore) extent in 2014 (129.8°W), while in 2015, 2016, and 2017 they remained closer to the North American continent (126.8°W, 125.7°W, and 124.8°W, respectively). During the winter migration to the eastern tropical Pacific, animals ranged farthest to the east and south in 2015, reaching the equator (0.1°N), while in 2016 they only migrated as far south as the mouth of the Gulf of California (17.6°N; **Table 14** and **Figure 36**).

Blue whales were present in seven of the eight biogeographic provinces of the eastern North Pacific considered here, although they primarily occupied CCAL in summer-fall and PNEC in winter-spring (**Table 14**). However, their pattern of occurrence was different between the four years. Occupation of CCAL was lowest in 2014 (73.1 percent of locations), intermediate in 2015 (89.8 percent), and highest in 2016 and 2017 (95.3 and 99.3 percent, respectively). Conversely, occupation of PNEC was highest in 2014 (26.7 percent), intermediate in 2015 (6.7 percent), and lowest in 2016 and 2017 (2.5 and 0.7 percent). In 2015, blue whales additionally occurred in PQED (2.6 percent), and in 2015 and 2016 they also were present in GUCA (0.8 and 2.2 percent, respectively). The ALSK, NPPF, and NPTG provinces were occupied to a small extent (0.1 percent) and only in 2014 (**Table 14** and **Figure 36**).

The behavioral classification in CCAL was based on 828 SSSM locations in 2014, 1,410 locations in 2015, 1,129 locations in 2016, and 1,664 locations in 2017. The proportion of locations classified as ARS was lower in 2014 and 2015 (11.2 and 18.4 percent of locations, respectively), while it was high in 2016 and 2017 (51 and 54.1 percent, respectively). The proportion of locations classified as transiting was highest (46.3 percent) in 2014, intermediate in 2015 (22.8 percent), and lowest in 2016 and 2017 (10 and 11.7 percent, respectively). Locations considered uncertain made up the remainder (42.5 percent in 2014, 58.9 percent in 2015, 39 percent in 2016, and 34.2 percent in 2017; **Table 15**). Within CCAL, and for the summer-fall months, average PWDIST was highest in 2014 and 2015 (55.7 and 42.8 km, respectively) and lowest in 2016 and 2017 (25.4 and 36.7 km, respectively; **Table 16, Figure 37**).

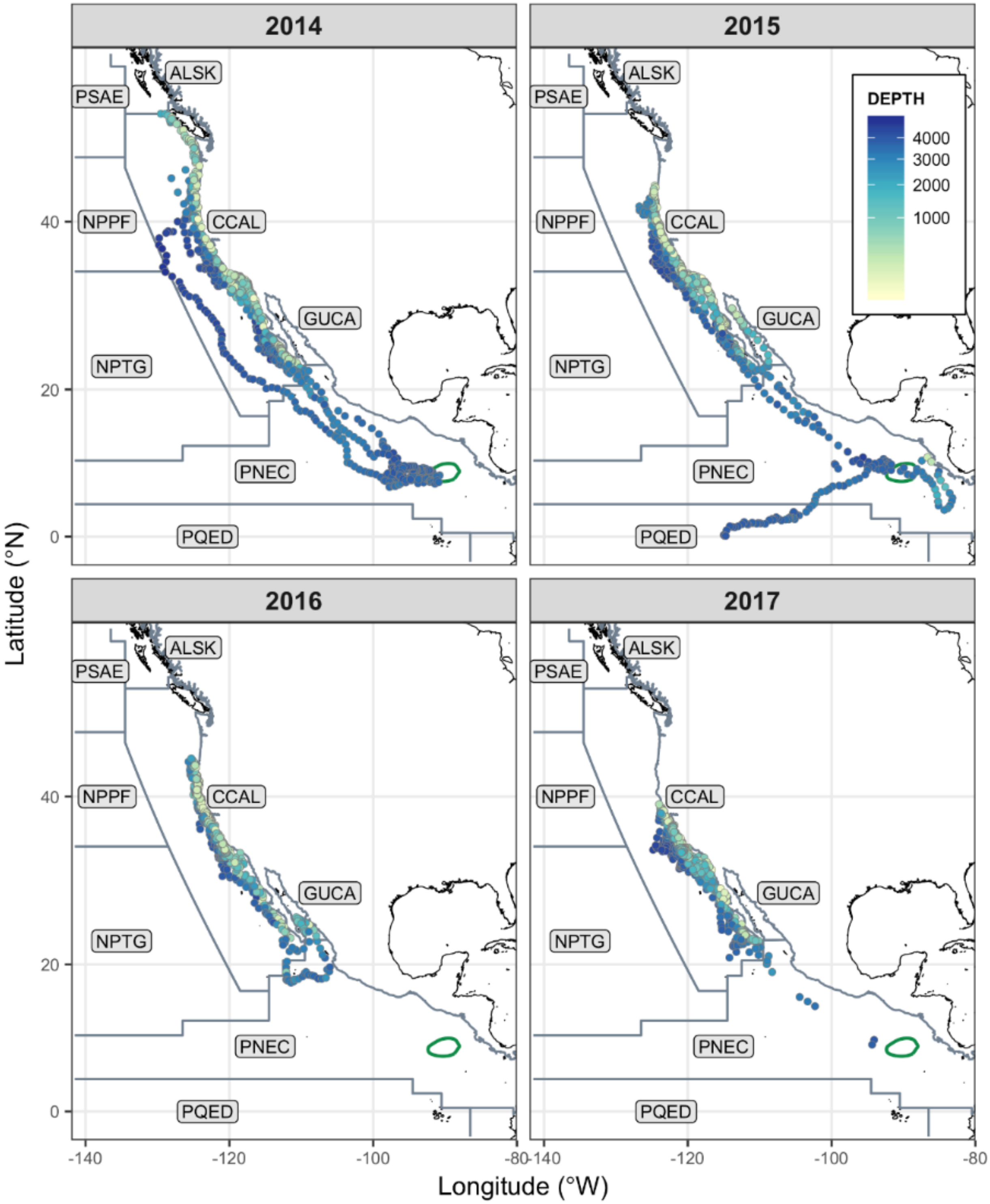

Figure 40. Map representation of seafloor depth (DEPTH, m) values obtained from ETOPO1 around each blue whale location for each year in the study. The eight biogeographic provinces identified by Longhurst (1998, 2006) in the eastern North Pacific are outlined and labeled. The green, oval-shaped contour in PNEC outlines the position of the CRD, as determined by the mean location of the depth of the 20°C isotherm (from Fiedler 2002, Fiedler et al. 2017). Note the square-root-transformed color scale for enhanced visualization.

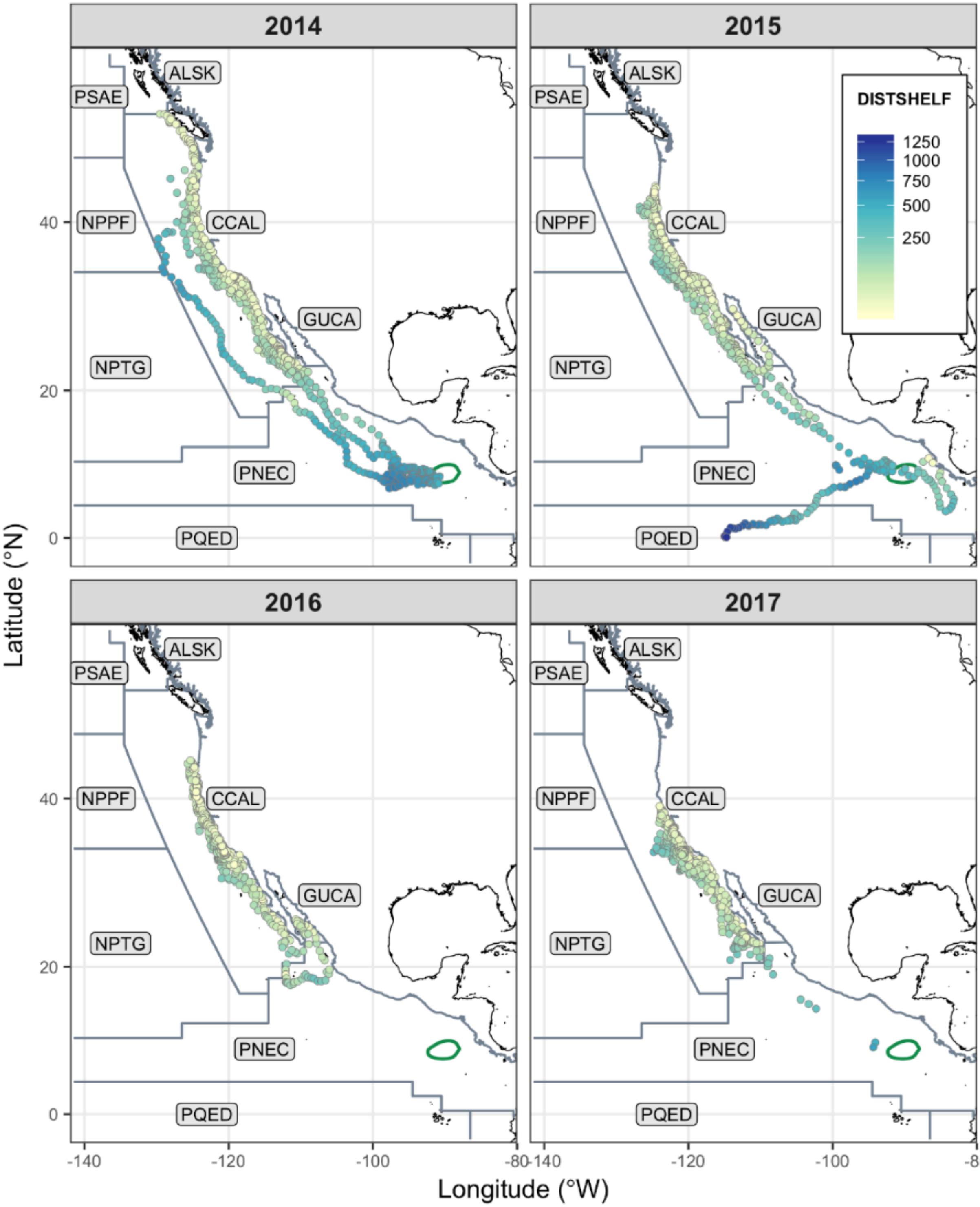

Figure 41. Map representation of distance to the 200-m isobath (DISTSHELF, km) values obtained from ETOPO1 around each blue whale location for each year in the study. The eight biogeographic provinces identified by Longhurst (1998, 2006) in the eastern North Pacific are outlined and labeled. The green, oval-shaped contour in PNEC outlines the position of the CRD, as determined by the mean location of the depth of the 20°C isotherm (from Fiedler 2002, Fiedler et al. 2017). Note the square-root-transformed color scale for enhanced visualization.

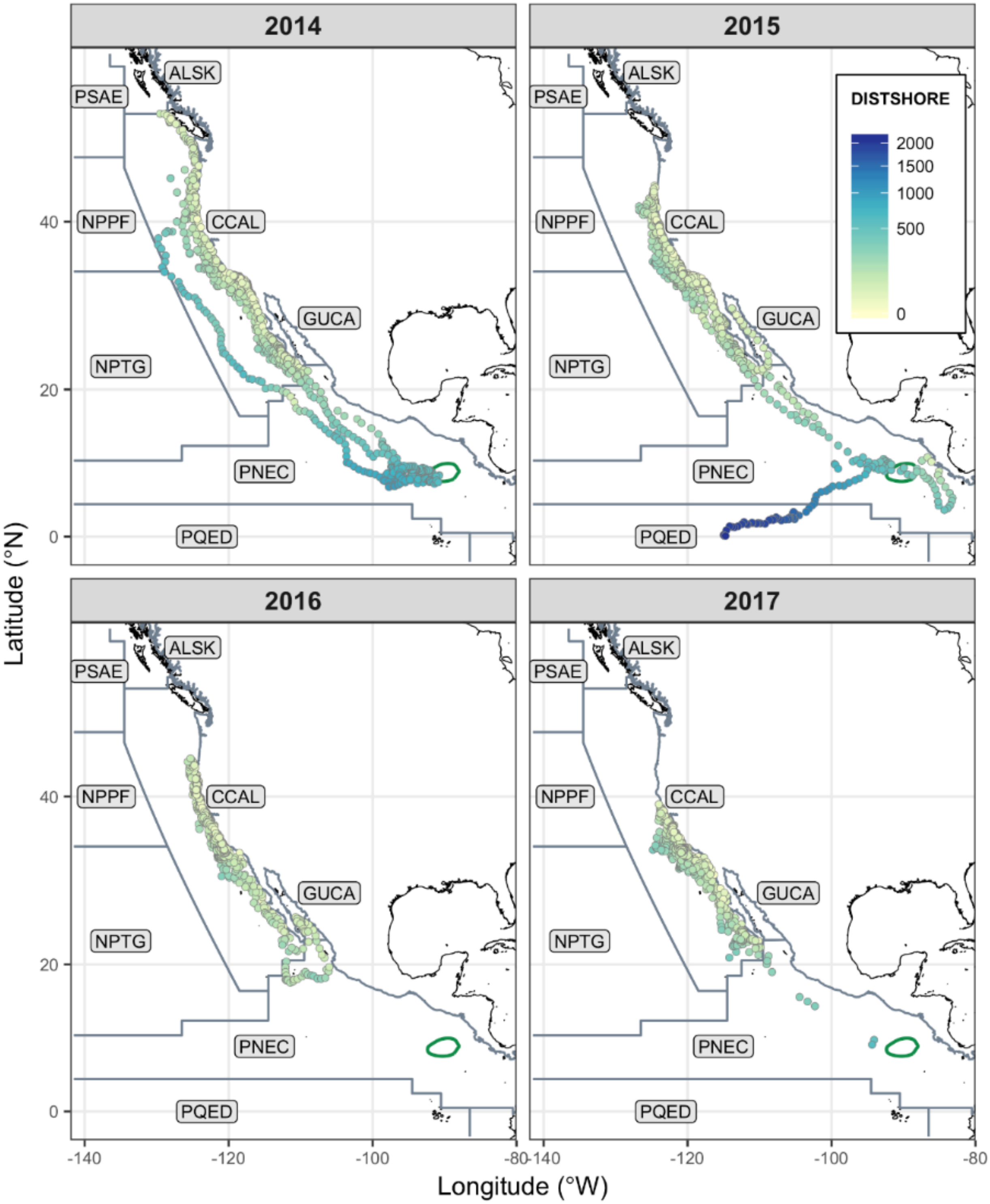

Figure 42. Map representation of distance to the shoreline (DISTSHORE, km) values obtained from cntry_06.shp around each blue whale location for each year in the study. The eight biogeographic provinces identified by Longhurst (1998, 2006) in the eastern North Pacific are outlined and labeled. The green, oval-shaped contour in PNEC outlines the position of the CRD, as determined by the mean location of the depth of the 20°C isotherm (from Fiedler 2002, Fiedler et al. 2017). Note the square-root-transformed color scale for enhanced visualization.

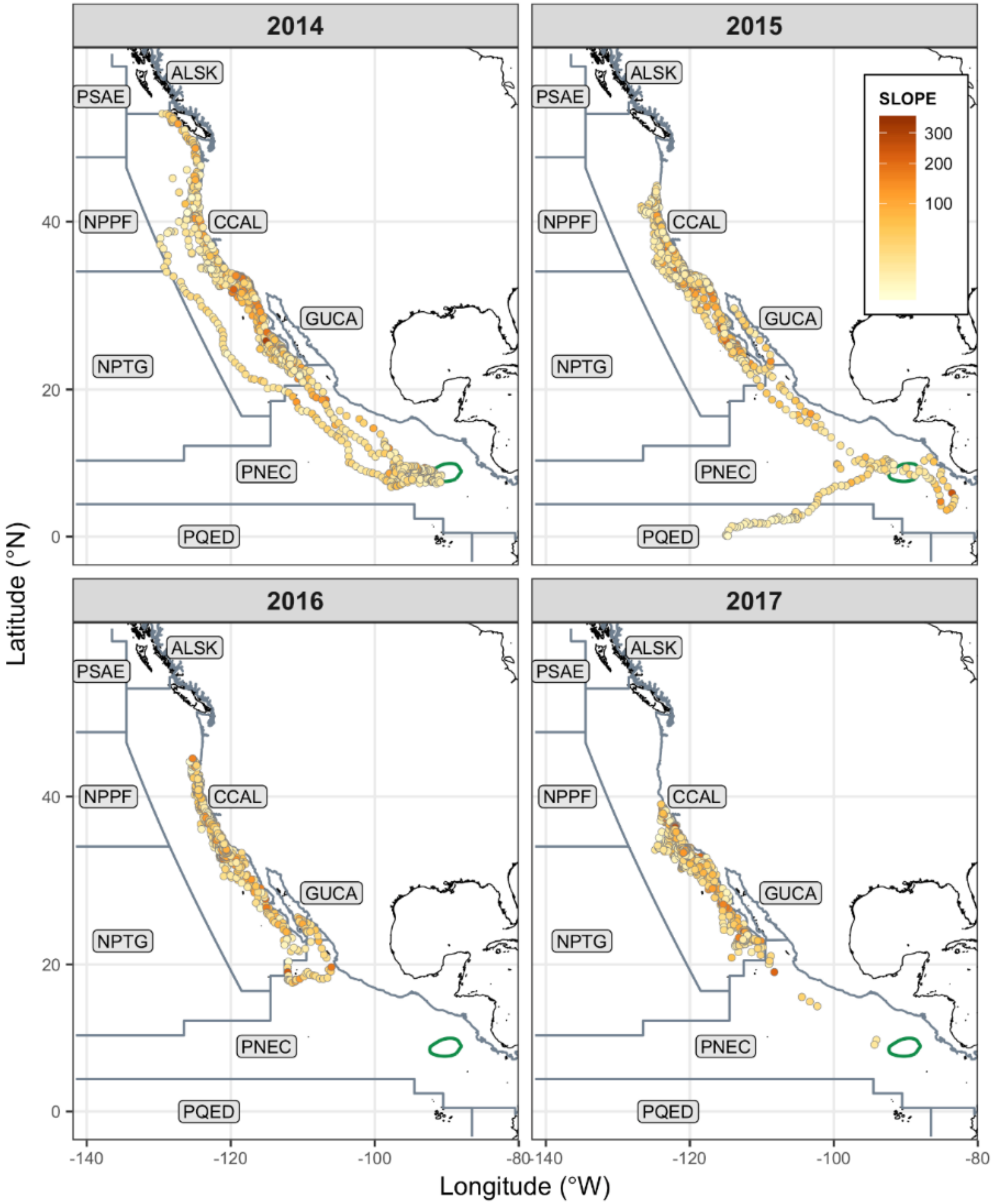

Figure 43. Map representation of seafloor slope (SLOPE, m km^{-1}) values obtained from ETOPO1 around each blue whale location for each year in the study. The eight biogeographic provinces identified by Longhurst (1998, 2006) in the eastern North Pacific are outlined and labeled. The green, oval-shaped contour in PNEC outlines the position of the CRD, as determined by the mean location of the depth of the 20°C isotherm (from Fiedler 2002, Fiedler et al. 2017). Note the square-root-transformed color scale for enhanced visualization.

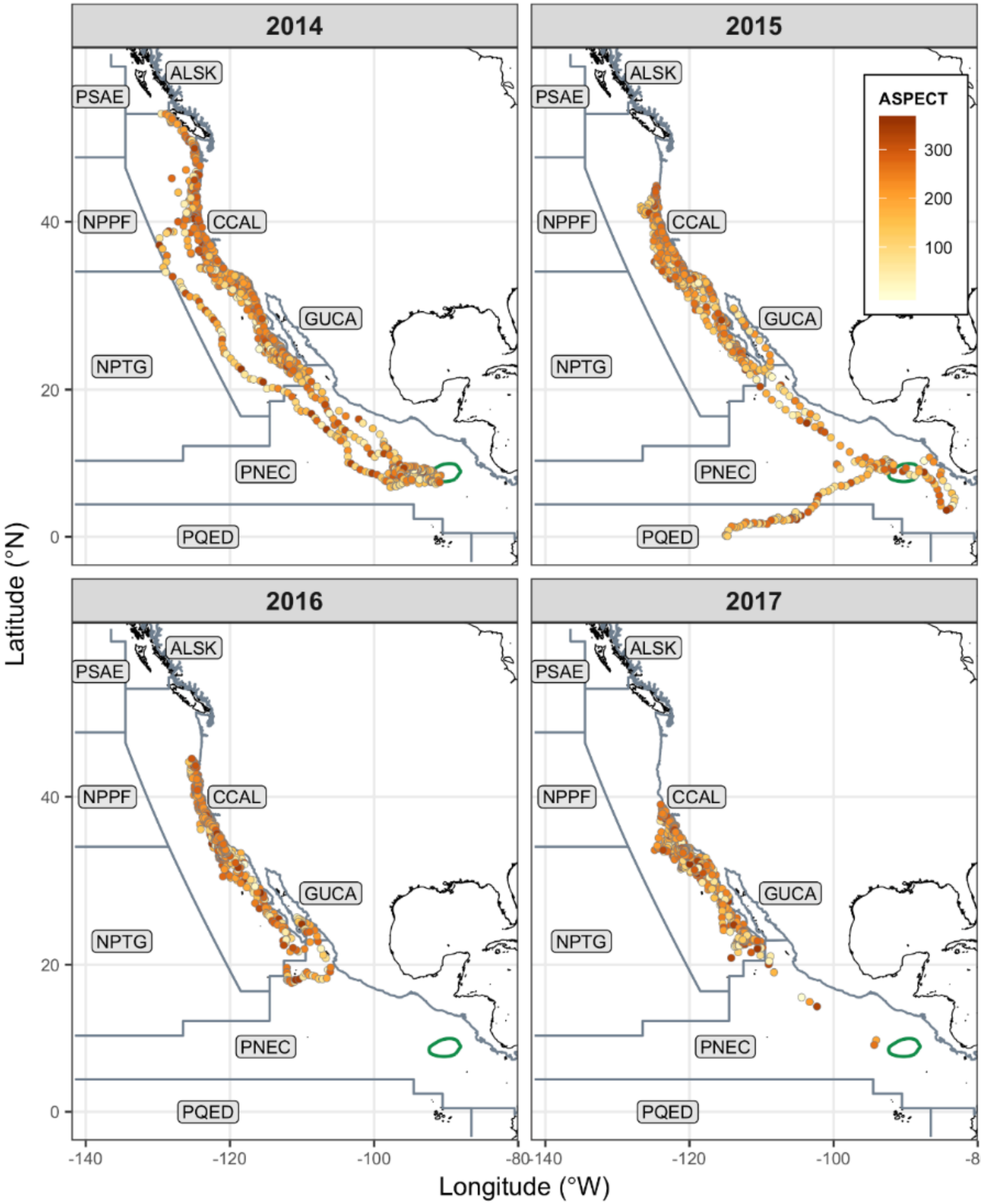

Figure 44. Map representation of seafloor slope aspect (ASPECT, °) values obtained from ETOPO1 around each blue whale location for each year in the study. The eight biogeographic provinces identified by Longhurst (1998, 2006) in the eastern North Pacific are outlined and labeled. The green, oval-shaped contour in PNEC outlines the position of the CRD, as determined by the mean location of the depth of the 20°C isotherm (from Fiedler 2002, Fiedler et al. 2017).

In terms of oceanographic characteristics in CCAL, average SST was warmest in 2014 and 2015 (21.2 and 19.7°C, respectively), and coolest in 2016 and 2017 (15.7 and 18.4°C, respectively). Average CHL was low in 2014 and 2015 (0.8 mg m^{-3} in both years) and higher in 2016 and 2017 (2.1 and 1.4 mg m^{-3}, respectively; **Table 16**). The values at each location for these environmental variables are shown on maps in **Figures 38 and 39.**

While in ARS, blue whales covered larger distances between location pairs in 2014 and 2015 (mean PWDIST = 58.3 and 44.1 km, respectively), and substantially smaller distances in 2016 and 2017 (mean PWDIST = 21.6 and 30.5 km, respectively; **Figure 45**). The little ARS activity in 2014 and 2015 occurred in the warmest SST recorded by blue whales during the study (mean = 22.9 and 19.1°C, respectively), compared to the more predominant ARS activity that was recorded in cooler waters in 2016 and 2017 (mean = 16.3 and 18.0°C, respectively; **Figure 46**). Correspondingly, CHL values where ARS activity took place in 2014 and 2015 were low (mean = 0.7 mg m^{-3} in both years) compared to the more elevated values in 2016 and 2017 (mean = 1.7 and 1.5 mg m^{-3}, respectively; **Figure 47**).

In terms of seafloor characteristics in CCAL, blue whales occurred in areas with average DEPTH that became shallower in the first three years of the project (1,684.6 m in 2014, 1,482.8 m in 2015, and 759 m in 2016), and then became deeper in the final year (1,273.5 m in 2017). This same trend was apparent in the other seafloor relief variables (average DISTSHELF: 59.2 km in 2014, 37.7 km in 2015, 18.1 km in 2016, and 33.5 km in 2017; average DISTSHORE: 88.6 km in 2014, 62.1 km in 2015, 38.4 km in 2016, and 64.2 km in 2017; average SLOPE: 46.7 m km^{-1} in 2014, 45.7 m km^{-1} in 2015, 39.8 m km^{-1} in 2016, and 48.4 m km^{-1} in 2017; and average ASPECT: 208.5° in 2014, 220.9° in 2015, 233.10° in 2016, and 218.9° in 2017; **Table 17**). The values at each location for these seafloor relief variables are shown on the maps in **Figures 40** through **44**, and their distributional properties are shown in the violin plots of **Figures 48** through **52**. During 2016, ARS activity took place in shallower waters (mean = 640.1 m), in the vicinity of the shelf break (mean = 13.3 km), and closer to shore (mean = 33.5 km) than in the other years of the project (**Figures 48** through **50**).

Time series of monthly values of the ONI for the 5-year period January 2013–December 2017 are presented in **Figure 53**. Based on the ±0.5°C threshold anomaly for ONI, one El Niño event (2015–2016) and one La Niña event (2016–2017) occurred in this period (**Figure 53**). Although only the period 2015–2016 was officially recognized as an El Niño, weaker warm anomalies occurred in the Niño 3.4 region (the region defined by the box 5°N-5°S, 120-170°W that is used by NOAA to derive the ONI anomalies) in every month between October 2014 and May 2016 (**Figure 53**). This period was followed by a continuous series of cold anomalies starting in July 2016 and lasting through January 2017, associated with the La Niña event of 2016–2017. Weak warm anomalies were then recorded between March and July 2017, followed by increasing cold anomalies between August and the end of 2017 (**Figure 53**).

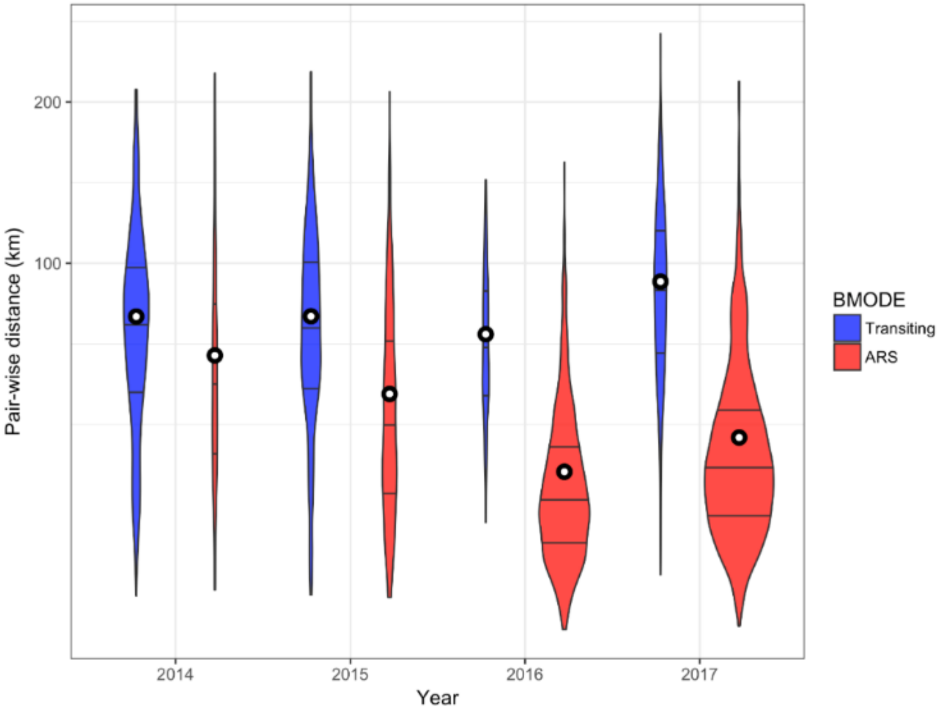

Figure 45. Paired violin plots of (km) in CCAL between blue whale SSSM locations classified as transiting and ARS for each year in the study. Horizontal lines inside each violin indicate the quartiles of the data distribution and white circle with black outline indicates the mean. Note the square-root-transformed y-axis for enhanced visualization.

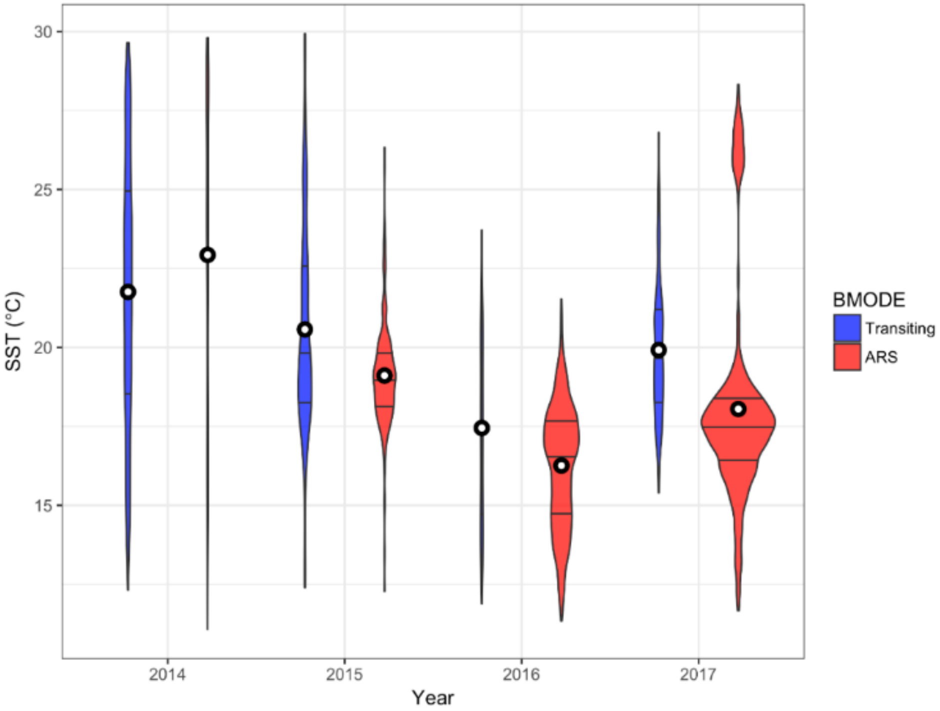

Figure 46. Paired violin plots of sea surface temperature (SST, °C) values in CCAL for blue whale SSSM locations classified as transiting and ARS for each year in the study. Horizontal lines inside each violin indicate the quartiles of the data distribution and white circle with black outline indicates the mean.

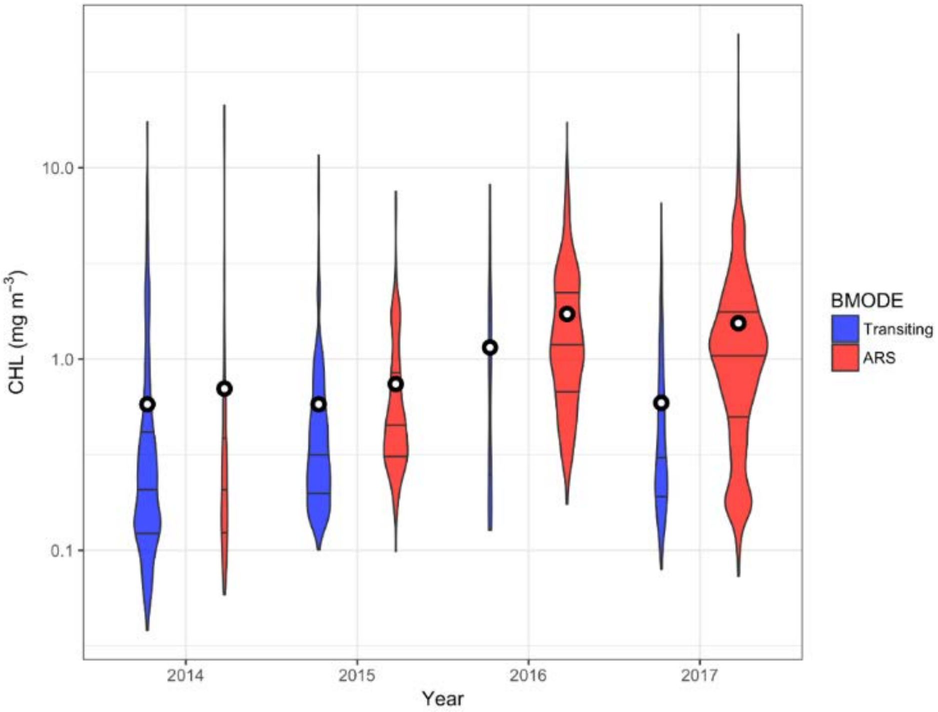

Figure 47. Paired violin plots of chlorophyll-a concentration (CHL, mg m^{-3}) values in CCAL for blue whale SSSM locations classified as transiting and ARS for each year in the study. Horizontal lines inside each violin indicate the quartiles of the data distribution and white circle with black outline indicates the mean. Note the log-transformed y-axis for enhanced visualization.

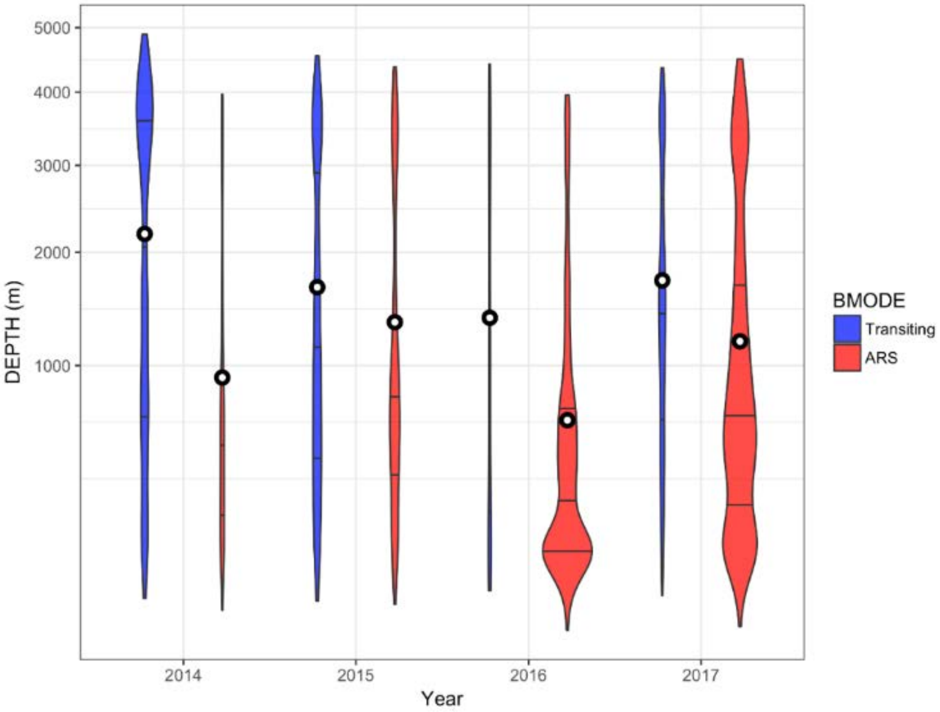

Figure 48. Paired violin plots of seafloor depth (DEPTH, m) values in CCAL for blue whale SSSM locations classified as transiting and ARS for each year in the study. Horizontal lines inside each violin indicate the quartiles of the data distribution and white circle with black outline indicates the mean. Note the square-root-transformed y-axis for enhanced visualization.

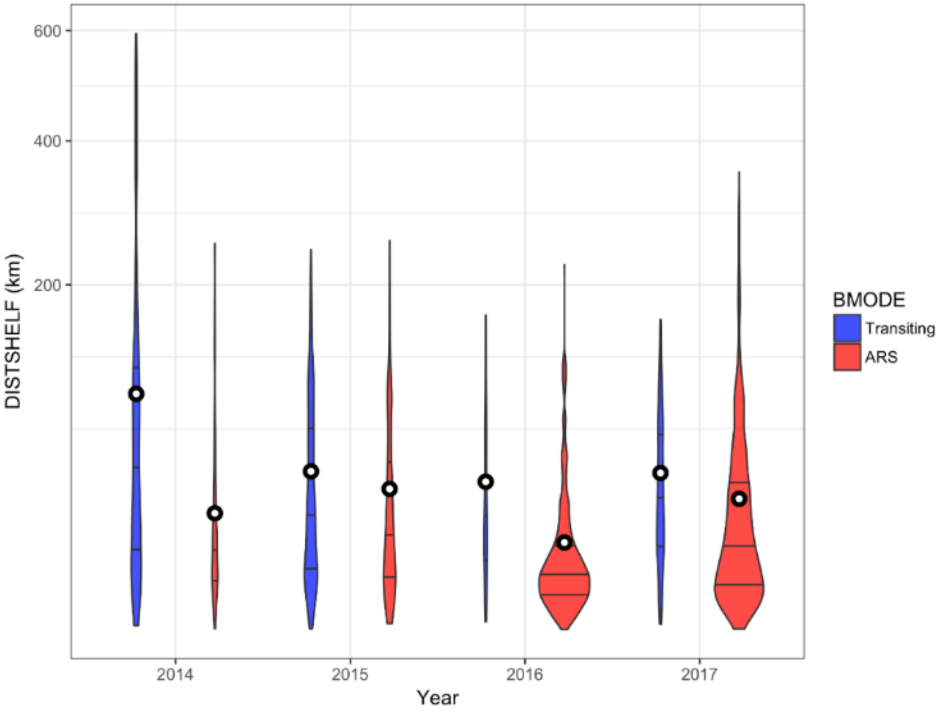

Figure 49. Paired violin plots of distance to the 200-m isobath (DISTSHELF, km) values in CCAL for blue whale SSSM locations classified as transiting and ARS for each year in the study. Horizontal lines inside each violin indicate the quartiles of the data distribution and white circle with black outline indicates the mean. Note the square-root-transformed y-axis for enhanced visualization.

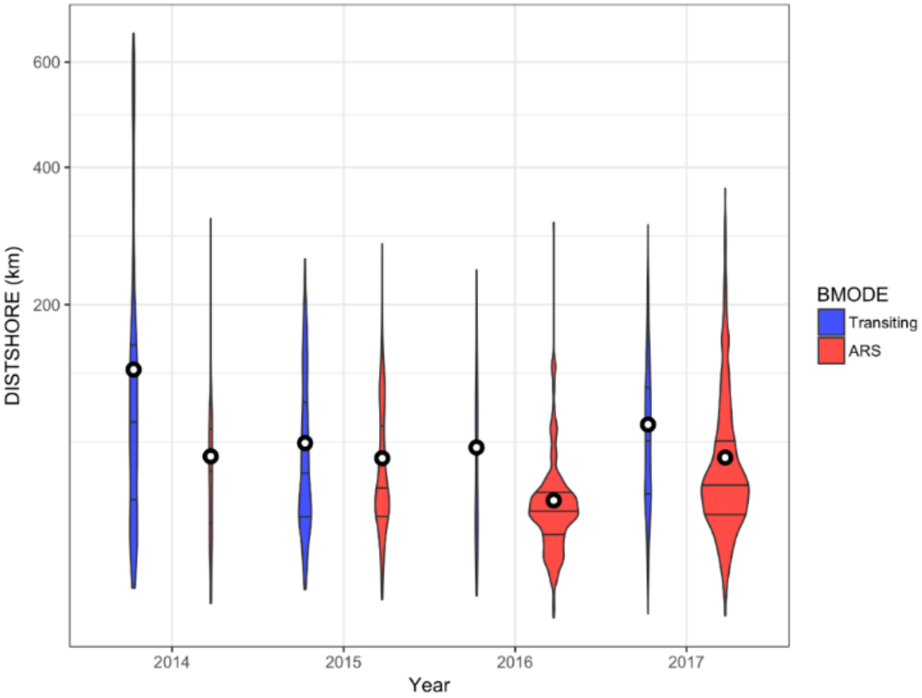

Figure 50. Paired violin plots of distance to the shoreline (DISTSHORE, km) values in CCAL for blue whale SSSM locations classified as transiting and ARS for each year in the study. Horizontal lines inside each violin indicate the quartiles of the data distribution and white circle with black outline indicates the mean. Note the square-root-transformed y-axis for enhanced visualization.

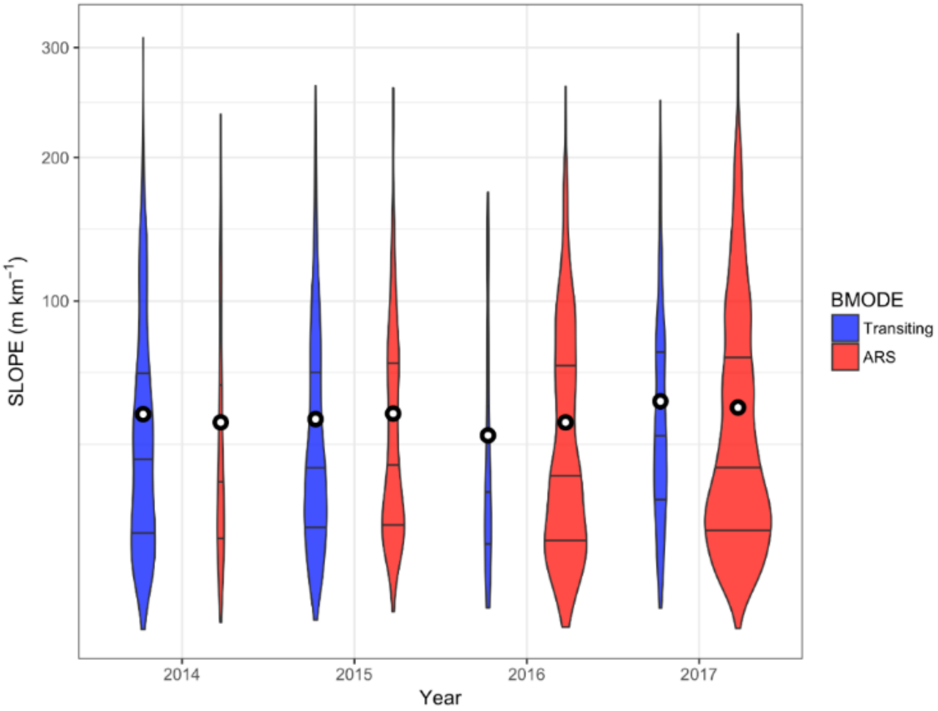

Figure 51. Paired violin plots of seafloor slope (SLOPE, m km^{-1}) values in CCAL for blue whale SSSM locations classified as transiting and ARS for each year in the study. Horizontal lines inside each violin indicate the quartiles of the data distribution and white circle with black outline indicates the mean. Note the square-root-transformed y-axis for enhanced visualization.

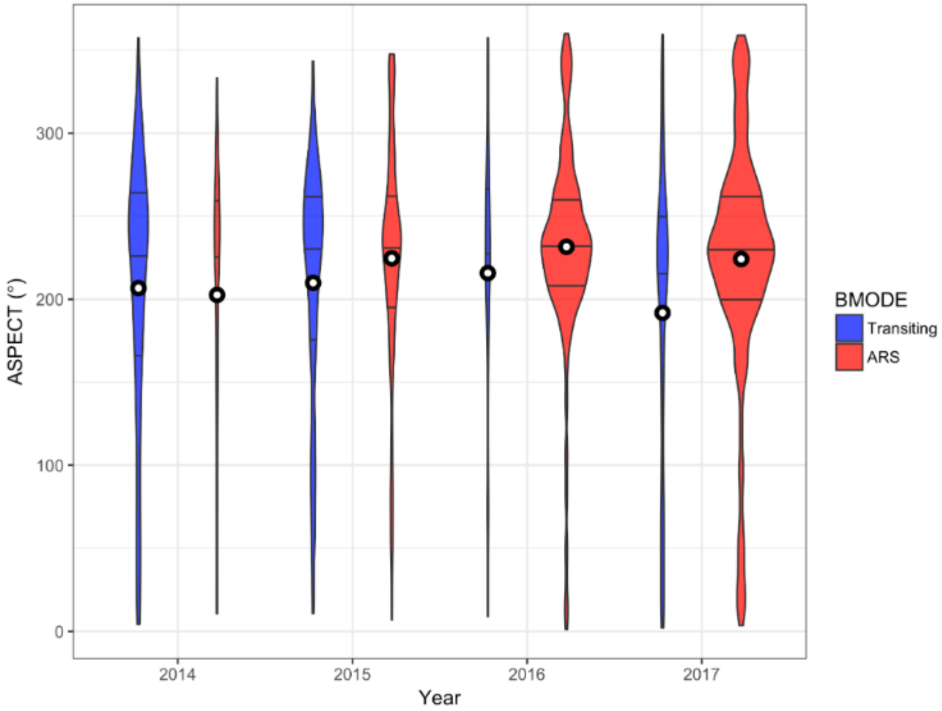

Figure 52. Paired violin plots of seafloor slope aspect (ASPECT, °) values in CCAL for blue whale SSSM locations classified as transiting and ARS for each year in the study. Horizontal lines inside each violin indicate the quartiles of the data distribution and white circle with black outline indicates the mean.

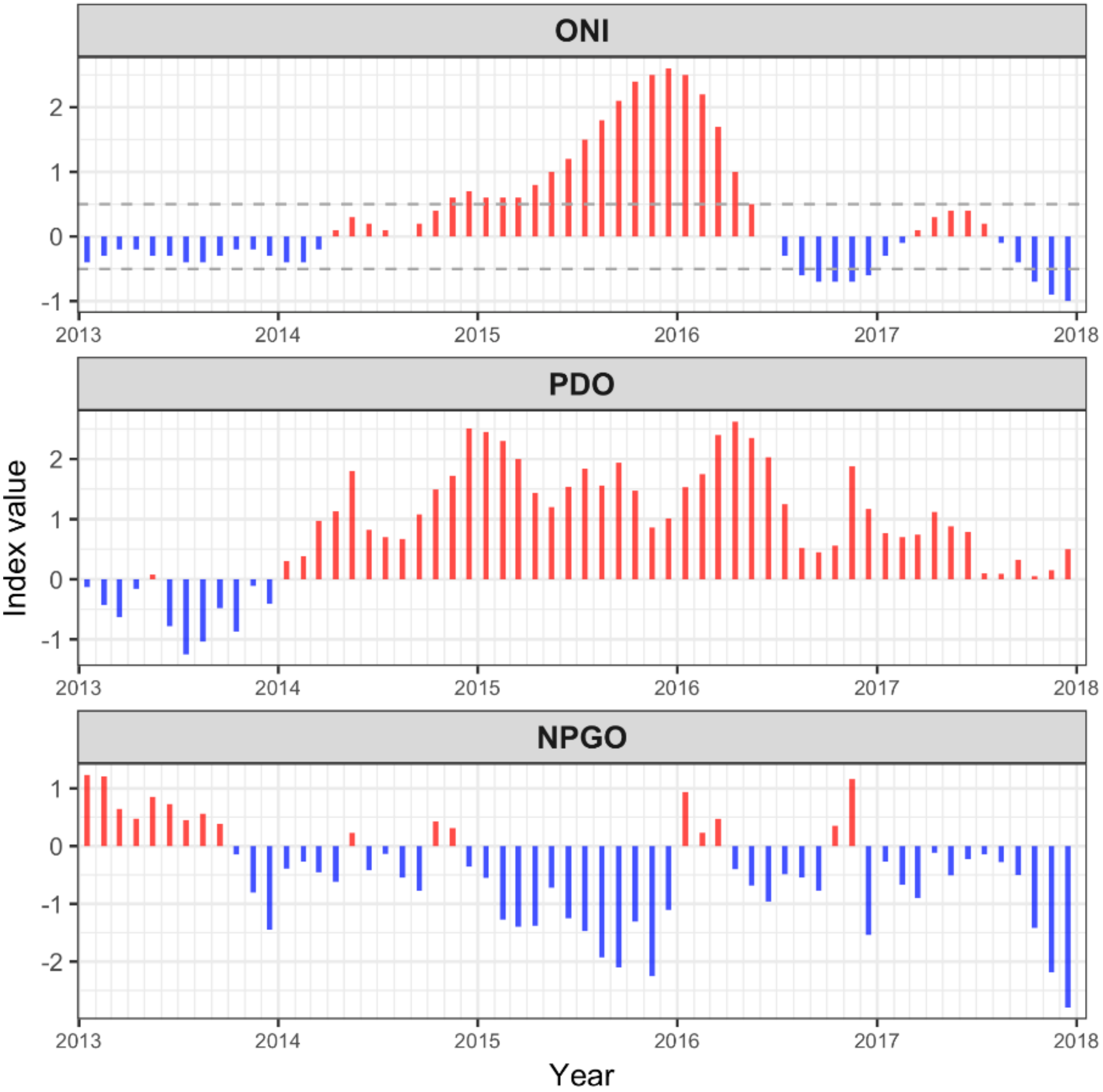

Figure 53. Time series of monthly values of the Oceanic Niño Index (ONI; top panel), the PDO (middle panel), and the North Pacific Gyre Oscillation (NPGO; bottom panel) for the period January 2013–December 2017. NOAA declares an El Niño/La Niña event in the Niño 3.4 region when a threshold ONI anomaly of ±0.5°C (horizontal dashed lines in top panel) is met for a minimum of five consecutive overlapping seasons.

Monthly values of the PDO and the NPGO are also presented in **Figure 53.** The PDO indicated that a transition from a cool phase to a warm phase occurred in January 2014. This PDO warm phase persisted through December 2017, although the monthly anomalies were weaker between July and December 2017 (**Figure 53**). The NPGO had a generally similar behavior to the PDO (although of opposite sign) over the 5-year period January 2013 to December 2017, with a shift from positive to negative sea-surface height anomalies in October 2013 (three months ahead of the PDO) that persisted through December 2017 with only a few departures. The strongest negative NPGO sea-surface height anomalies occurred in late 2016 and late 2017 (**Figure 53**).

Thus, the period of this study (2014 to 2017) was characterized by a decadal "warm regime" driven by the combined effects of persistent positive PDO SST anomalies and negative NPGO sea-surface height anomalies—both conducive to reduced biological productivity—and punctuated by the far-reaching equatorial ONI SST anomalies associated with the inter-annual events of 2015–2016 (El Niño) and 2016–2017 (La Niña).

3.1.10 Genetics and Species Identification

In 2017, skin biopsy samples were collected from 19 of the tagged whales, considered to be blue whales based on field observations (**Figure 54**). All samples provided DNA profiles sufficient for subsequent analyses. An additional 43 skin biopsy samples were collected from tagged whales in 2014–2016, also providing DNA profiles sufficient for subsequent analyses (Mate et al. 2017a).

The mtDNA sequences of the 62 samples resolved 14 haplotypes for a consensus region of 410 bp in length. Based on submission to *DNA-surveillance* and a Basic Local Alignment Search Tool search of GenBank®, all of the mtDNA haplotypes were consistent with field identification of blue whales.

3.1.10.1 SEX DETERMINATION

The 62 blue whale samples represented 24 females and 38 males.

3.1.10.2 INDIVIDUAL IDENTIFICATION

All 62 samples were represented by unique multi-locus genotypes and the probability of identity for the 17 loci was very low, 6.0×10^{-16} (i.e., there was a very low probability of a match by chance). Consequently, we are confident that the 62 unique multi-locus genotypes represented 62 individuals (i.e., there were no replicate samples among the blue whales tagged in 2014–2017). This was consistent with sex and mtDNA haplotypes, as provided in the full DNA profile.

The DNA profiles of the 62 blue whales tagged in 2014–2017 were compared to a reference database of blue whales sampled previously in the eastern North Pacific by OSU or made available through a collaborative agreement with Cascadia Research (Mate et al. 2017a). Although the quality of the DNA profiles for the archived samples was variable, there were 76 individuals with genotypes sufficient for individual identification and most of these included mtDNA haplotypes and sex. None of these was a match to any of the 62 blue whales tagged and biopsied in 2014–2017.

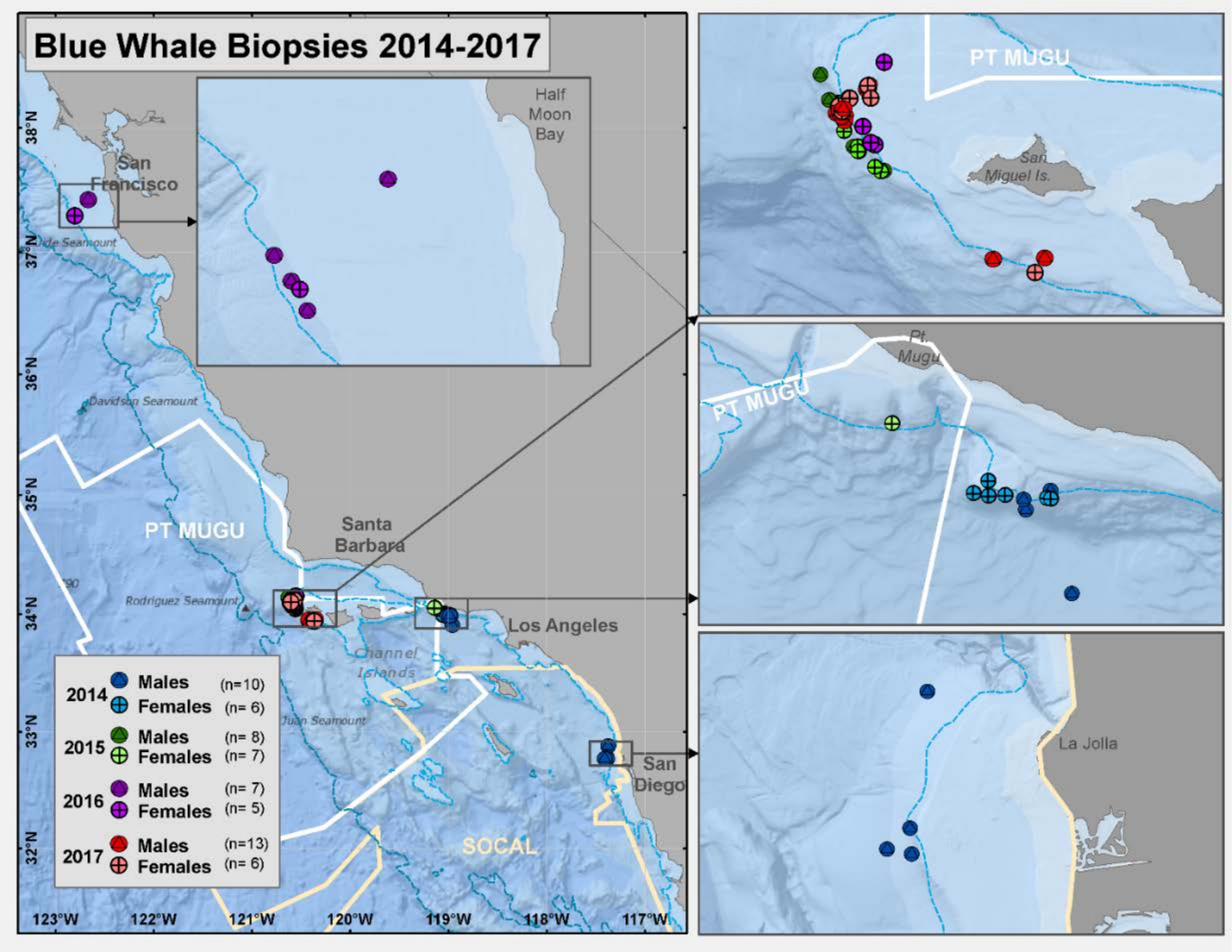

Figure 54. The locations of biopsy sample collections from blue whales tagged in California from 2014 to 2017. The light and dark blue bathymetric contours correspond to the 200- and 1,000-m isobaths, respectively.

3.1.10.3 STOCK IDENTIFICATION

A review of published literature and datasets on GenBank® provided information on identity and frequencies of mtDNA haplotypes from blue whales representing several populations or subspecies (**Table 18**): the eastern South Pacific (Chile), Australia and New Zealand, and the Antarctic. The total of 327 samples represented 74 mtDNA haplotypes based on sequence variation in the first 410 bp of the control region. Unpublished information on the identity and frequencies of mtDNA haplotypes in the eastern North Pacific was also available for samples of blue whales archived at OSU or made available through collaboration with Cascadia Research, as archived with the Southwest Fisheries Science Center (see above). Of the 76 individuals with partial or complete DNA profiles, there were 64 individuals with mtDNA haplotypes. These 64 individuals from the eastern North Pacific represented 16 haplotypes based on the consensus length of 410 bp.

Table 18. The frequency and identity of 20 mtDNA haplotypes for blue whales in the eastern North Pacific, including 14 from the 2014–2017 tagging, and the sharing of these haplotypes with other populations or subspecies of blue whales.

mtDNA haplotype	GenBank code	Antarctic	Australia/ New Zealand	Eastern South Pacific	Eastern North Pacific	2014–17 Tagged Whales
haplotype d	EU093921	4	38	1	4	1
haplotype dd	EU093947			4		1
haplotype e	EU093922		6		1	4
haplotype p				21		1
haplotype q	EU093934			20	8	7
haplotype r	EU093935	2	1	19	25	29
haplotype t	EU093937			15	1	
BMCH01	JX035887			2	2	4
NPBW05(Bmu15CA007)	JQ717165					1
NPBW06(Bmu07CA001)	JQ717166				5	6
NPBW10(Bmu15CA004)	JQ717170					1
NPBW13(Bmu07Ca016)	JQ717173				3	
NPBW15(Bmu06Ca005)	JQ717175				3	2
NPBW16(Bmu07Ca002)	JQ717176				2	2
NPBW18(Bmu06CA002)	JQ717178				4	1
Hap53(Bmu07Ca004)	KP187717				1	
Bmu07Ca006	MH614324				1	
Bmu08Ca002	MH614325				1	
Bmu51118	MH614326				2	
Bmu24035	MH614327				1	2
Unshared haplotypes (66)		178 (50)	14 (8)	38 (9)		
Total individuals		**184**	**51**	**113**	**64**	**62**

Of the 14 haplotypes resolved among the 62 biopsied blue whales from 2014 to 2017, 10 matched to the 16 haplotypes represented in reference database from the eastern North Pacific, resulting in a total of 20 haplotypes for this stock. Of these 20 haplotypes, eight were also shared with one or more of the other stocks or subspecies, including two shared with the Antarctic subspecies. In total, the sample from the 2014–2017 tagging and the reference databases represented 86 haplotypes, 66 of which were not shared with the eastern North Pacific.

The test of differentiation showed no significant differences in haplotype frequencies between the 18 females and 25 males ($p = 0.108$) or between the 2017 tagged whales and the previous three years ($p = 0.385$). The combined sample of 62 tagged whales showed no significant differences from the reference dataset representing the eastern North Pacific (**Table 19**). This is consistent with the available information suggesting a single stock of blue whales in the eastern North Pacific (Lang and LeDuc 2015). There was, however, significant differentiation between the 2014–2017 tagged whales and the other populations or subspecies of blue whales, despite the sharing of some haplotypes. The differentiation with the eastern North Pacific was most pronounced for the Antarctic and Australian/New Zealand stocks or subspecies and least pronounced for the eastern South Pacific, perhaps indicating recent or ongoing genetic exchange across the equator (Torres-Florez et al. 2015).

Table 19. Pairwise tests of differentiation (FST) for mtDNA haplotype frequencies of the tagged blues whales and available reference datasets representing the eastern North Pacific and other populations or subspecies of blue whales.

Strata 1	n 1	Strata 2	n 2	F_{ST}	p value
Antarctic	184	SoCal tagging	43	**0.124**	< 0.001
Australia/New Zealand	51	SoCal tagging	43	**0.316**	< 0.001
Eastern South Pacific	113	SoCal tagging	43	**0.090**	<0.001
Eastern North Pacific	64	SoCal tagging	43	0.000	0.572

3.1.11 Photo-ID

A total of 12,844 photographs of blue whales was taken during the field efforts in 2017, from which 184 individual whales were identified. Fourteen of these IDs represented resightings of blue whales photographed in 2014, 2015, or 2016 (389 individuals), resulting in a resight rate of 3.2 percent. Photo-IDs were obtained of 22 of 28 tagged blue whales in 2017, with both left- and right-side photographs of 8 of these, 12 with right-side photographs only, and 2 with left-side photographs only. Six whales did not have photographs that included the dorsal fin to make a proper ID. Fluke photographs also were obtained for one of the tagged blue whales.

3.2 Fin Whale

3.2.1 Body Condition Assessment and Tagging Rates

In 2017, one fin whale was tagged during approaches to 12 whales (8 percent, **Table 2**). This is similar to the tagging rates in 2014 (6 percent) and 2016 (9 percent), but less than the rate in 2015 (12 percent). No fin whales were observed to be in poor body condition in 2017, nor were any in 2014 or 2015 (**Table 2**). Two percent of fin whales approached in 2016 were in poor body condition and were not considered candidates for tagging.

3.2.2 Behavioral Responses to Tagging

The fin whale tagged in 2017 did not respond to the tagging process.

3.2.3 Wound Healing

The 2017-tagged fin whale was not resighted during subsequent days for wound assessment. No fin whales tagged in the three previous seasons (2014, 2015, and 2016) were resighted in 2017.

3.2.4 Tracking Analysis—2017

One LO tag was deployed on a fin whale off the central California coast on 2 August 2017 and was tracked for 42.3 days (**Table 4**). It spent the first three weeks of its tracking period between Santa Cruz and Half Moon Bay, primarily over the continental shelf edge and slope waters (**Figure 55**). In late August the fin whale moved north to an area off San Francisco, over continental slope waters, for the remaining three weeks of its tracking period.

3.2.4.1 USE OF NAVY TRAINING AREAS BY TAGGED FIN WHALES

There were no locations in Navy training areas for the one fin whale tagged in 2017.

3.2.4.2 HOME RANGE ANALYSIS

The HR for the tagged fin whale was 5,263.0 km^2 in size and extended from Monterey Bay to Point Reyes, California (**Table 20**, **Figure 56**). There were two CA isopleths totaling 1,553.5 km^2, with one centered around the Farallon Islands and the other stretching along the continental shelf edge between Santa Cruz and Half Moon Bay (**Table 20**, **Figure 56**).

3.2.5 Tracking Analysis – Inter-annual Comparison

As only one fin whale was tagged in 2017, that year was not included in inter-annual comparisons. Tracking durations for fully implantable tags on fin whales did not vary significantly between years ANOVA, $p = 0.10$), and after adding the duration for the fin whale tagged in 2017, average tracking duration for all years combined was 55.4 d (SD = 52.9 d, median = 38.2 d, n = 25; **Table 20**). As with blue whales, there was no difference in tracking durations between LO and DM tags in 2016 (ANOVA, $p = 0.53$), so these two tag types were combined in analyses.

After accounting for a positive relationship between tracking duration and distance traveled (linear regression using log-transformed variables, $p < 0.0001$), distance traveled by fin whales was found to be significantly different between 2015 and 2016 (general linear model of log-transformed variables, $p = 0.02$), with 2015 having the longest distances traveled (2,240 km), and 2016 having the shortest (1,467 km; **Table 20**). Distances traveled by fin whales in 2014 were of intermediate length (1,912 km) and did not differ significantly from 2015 or 2016.

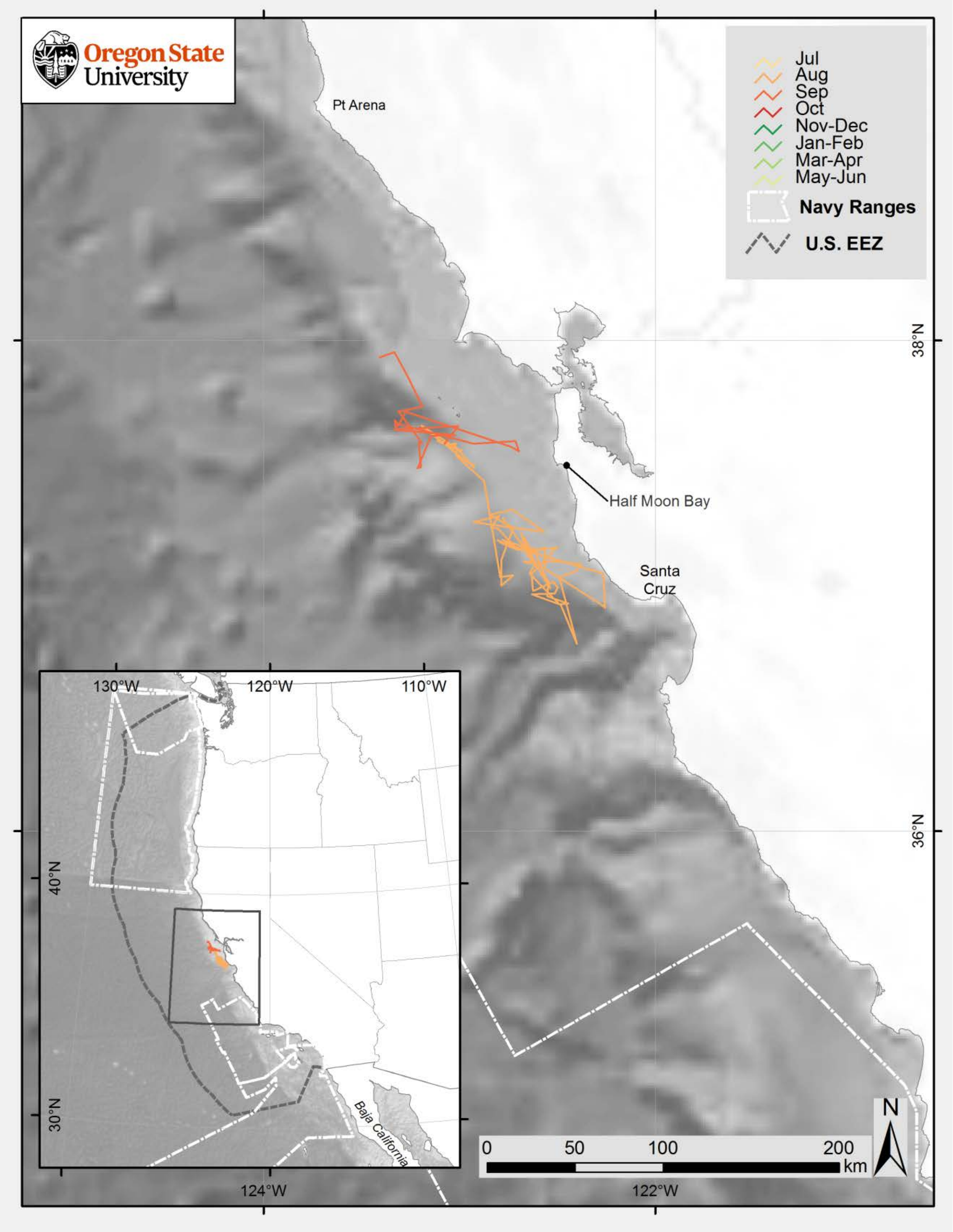

Figure 55. Satellite-monitored tracks for a fin whale tagged off central California in August 2017 (LO tag).

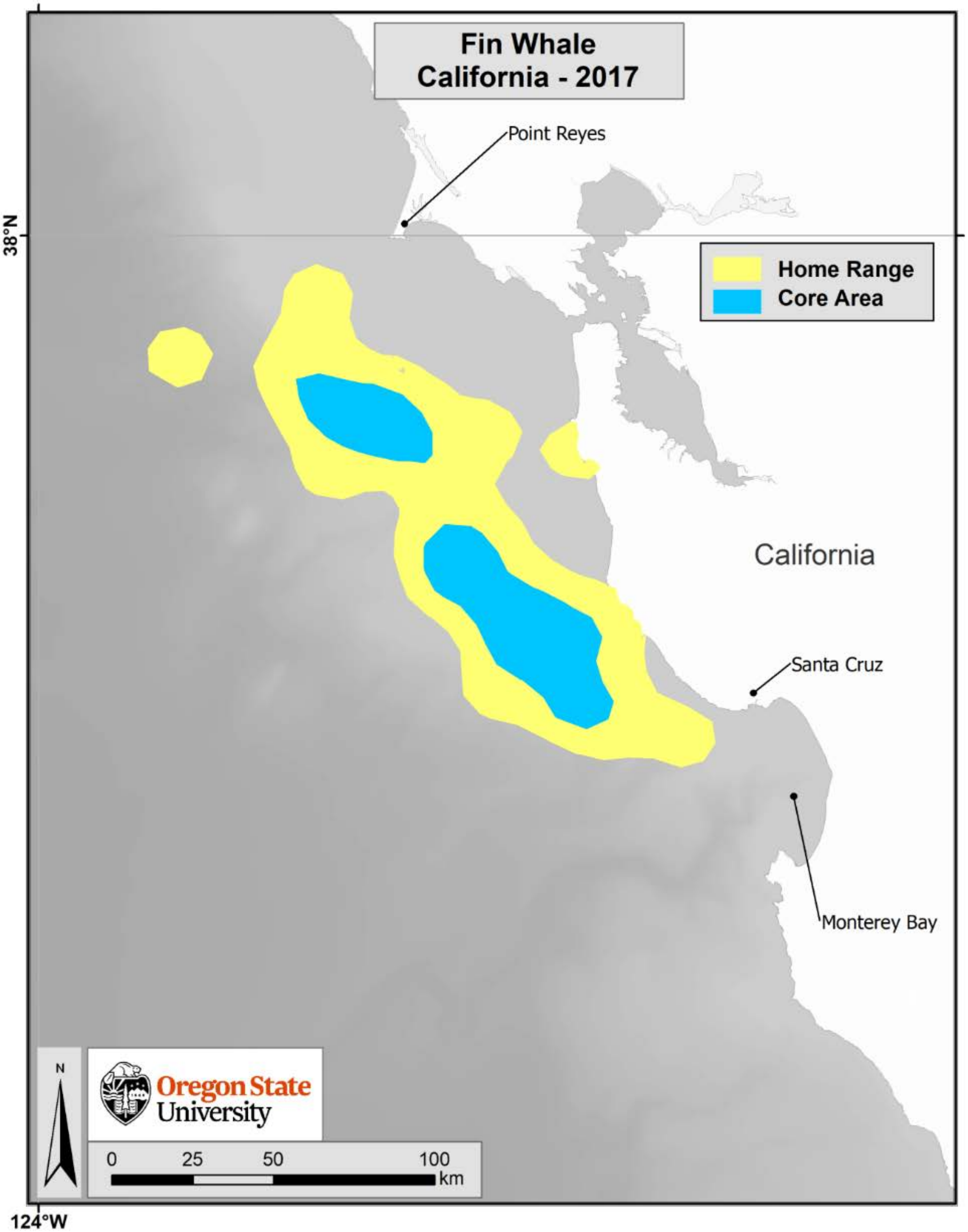

Figure 56. HR and CA in the U.S. EEZ of a fin whale tagged in central California in August 2017.

Table 20. Mean (and SE) tracking duration, total distance traveled, home range, and core area for fin whales tracked with LO and DM satellite tags off southern and central California, 2014–2017.

	Tracking Duration (d)			**Total Distance (km)$^+$**			**Home Range (km^2)**			**Core Area (km^2)**		
	n	**Mean**	**SE**	**n**	**Mean**	**SE**	**n**	**Mean**	**SE**	**n**	**Mean**	**SE**
2014	3	90.8	27.1	3	1,911.9	1.2	3	64,515.5	8,634.9	3	11,580.0	642.6
2015	8	77.1	27.1	8	2,239.8	1.1	5	177,545.0	32,821.7	5	34,278.4	8,427.5
2016	13	34.8	7.3	13	1,466.5	1.1	5	34,025.0	11,832.8	5	10,278.2	3,717.4
2017	1	42.3	-	1	1,089^{++}	-	1	5,263.0	-	1	1,553.5	-
Mean		**61.2**			**1,872.7**			**70,337.1**			**14,422.5**	

KEY: d = days; km = kilometers; km^2 = square kilometers, n = sample size; SE = standard error. $^+$Total distance is back-calculated from log values used in analysis. $^{++}$ Total distance in 2017 was not used in interannual comparison, so this value is not a back-calculated log value.

The latitudinal range, or the difference between the latitudes of the northern-most and southern-most locations for all fin whales in a given tagging year, was similar in 2015 and 2016 (22 degrees in 2015 and 20 degrees in 2016), and larger than in 2014 (12 degrees; **Figure 57**). Fin whales ranged as far north as Haida Gwaii off the coast of British Columbia in 2015 and 2016, and just south of Cape Blanco on the southern Oregon coast in 2014. Southern extents were similar in 2014 and 2015, approximately halfway down the coast of Baja California Norte, but only ranged as far south as west of San Nicolas Island, California, in 2016. The latitudinal range of the fin whale tagged in 2017 was much more compressed, at just over 1 degree, from Monterey Bay to Point Reyes on the central California coast.

None of the fin whales tagged from 2014 to 2017 engaged in a typical baleen whale migration to a sub-tropical/tropical wintering ground. One of six fin whales tagged in 2014 traveled back and forth repeatedly between southern California and the west coast of Baja California Norte from late October to late December, and was last located off San Diego, California, on 24 December 2014. Three of 10 fin whales tagged in 2015 also traveled briefly to the west coast of Baja California Norte before coming back into southern California waters (two in August and one in December). None of the fin whales tagged in 2016, nor the fin whale tagged in 2017, crossed south into Mexican waters.

3.2.5.1 USE OF NAVY TRAINING AREAS BY TAGGED FIN WHALES

The 2017 fin whale did not spend time in any Navy training ranges. PT MUGU was the most heavily used Navy training range for fin whales in the other three tagging years (100 percent of all transmitting tags had locations there in both 2014 and 2015, and 23 percent had locations there in 2016; **Table 21**, **Figure 58**). SOCAL was used by 67 percent of tracked fin whales in 2014 and by 40 percent in 2015, but no fin whale locations occurred there in 2016 (**Table 21**, **Figure 59**). Two fin whales were tracked in SOAR in both 2014 and 2015 (33 and 20 percent of tracked whales, respectively), but none had locations there in 2016 (**Table 21**, **Figure 60**). One fin whale in each of 2014 (17 percent of tracked whales) and 2016 (8 percent of tracked whales) had locations in NWTT, whereas four fin whales (40 percent of tracked whales) had locations in NWTT in 2015 (**Table 21**, **Figure 61**). Two fin whales (20 percent) had locations within W237 in 2015; one fin whale (8 percent) had locations in W237 in 2016; no fin whales occurred in W237 in 2014 (**Table 21**, **Figure 62**).

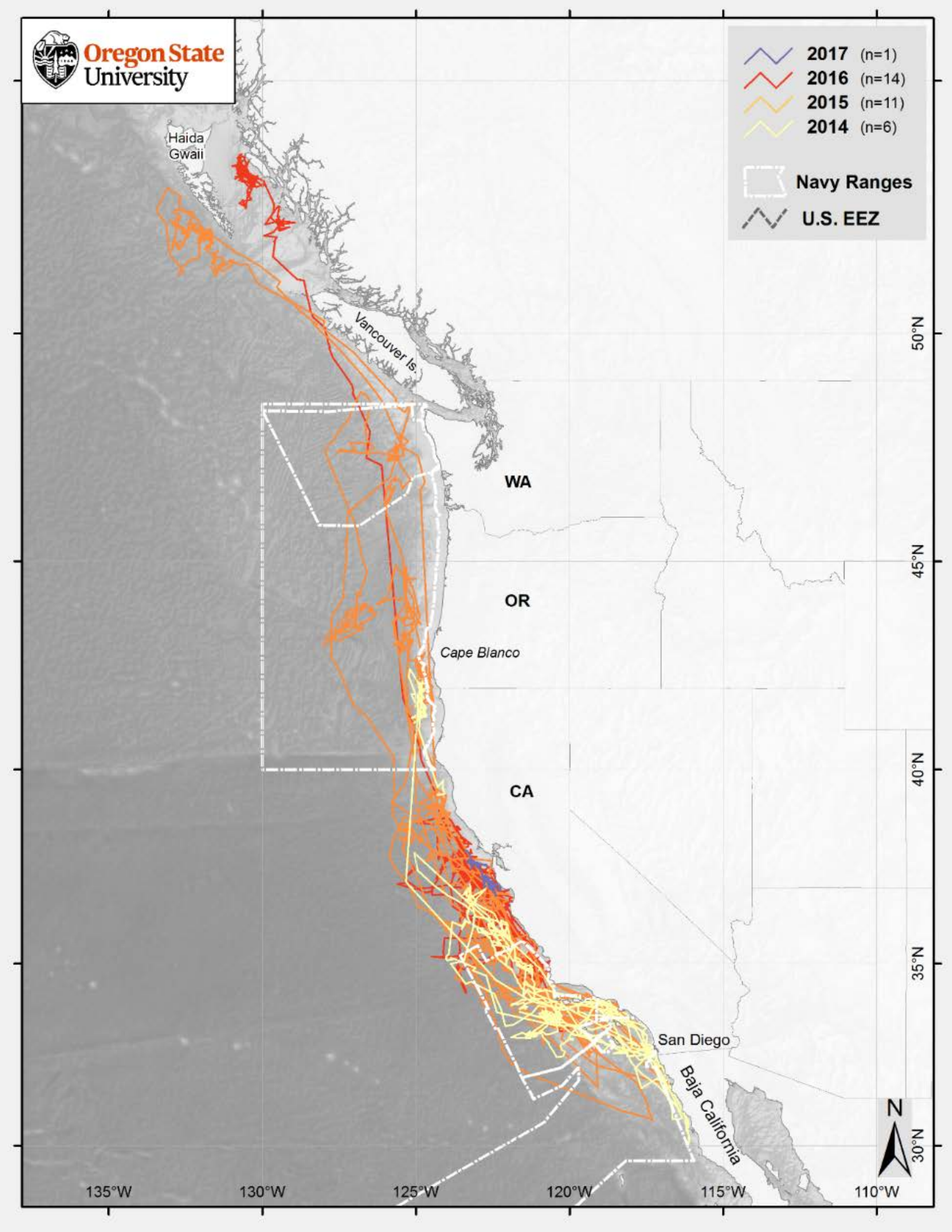

Figure 57. Satellite-monitored tracks for fin whales tagged off southern and central California during July and/or August, 2014 to 2017.

Table 21. Mean (and SE) number of days spent inside Navy training ranges for fin whales tagged off California, 2014–2016. There were no locations in Navy training ranges for the fin whale tagged off central California in 2017.

Year (# Whales Tracked)	# Days														
	SOCAL			PT MUGU			SOAR			NWTT			W237		
	n	Mean	SE	n	Mean	SE	n	Mean	SE	n	Mean	SE	n	Mean	SE
2014 (6)	4	14.2	10.4	6	17.8	9.2	2	1.3	1.3	1	35.7	-	0	-	-
2015 (10)	4	11.5	4.5	10	17.3	3.0	2	0.3	0.1	4	34.4	9.6	2	13.7	8.6
2016 (13)	0	-	-	3	17.9	13.4	0	-	-	1	6.1	-	1	1.7	-
All Years (29)	**8**	**12.9**	**5.3**	**19**	**17.6**	**3.6**	**4**	**0.8**	**0.6**	**6**	**29.9**	**7.7**	**3**	**9.7**	**6.4**

KEY: n = number of whales having locations in that particular Navy training range; SE = standard error; # = number.

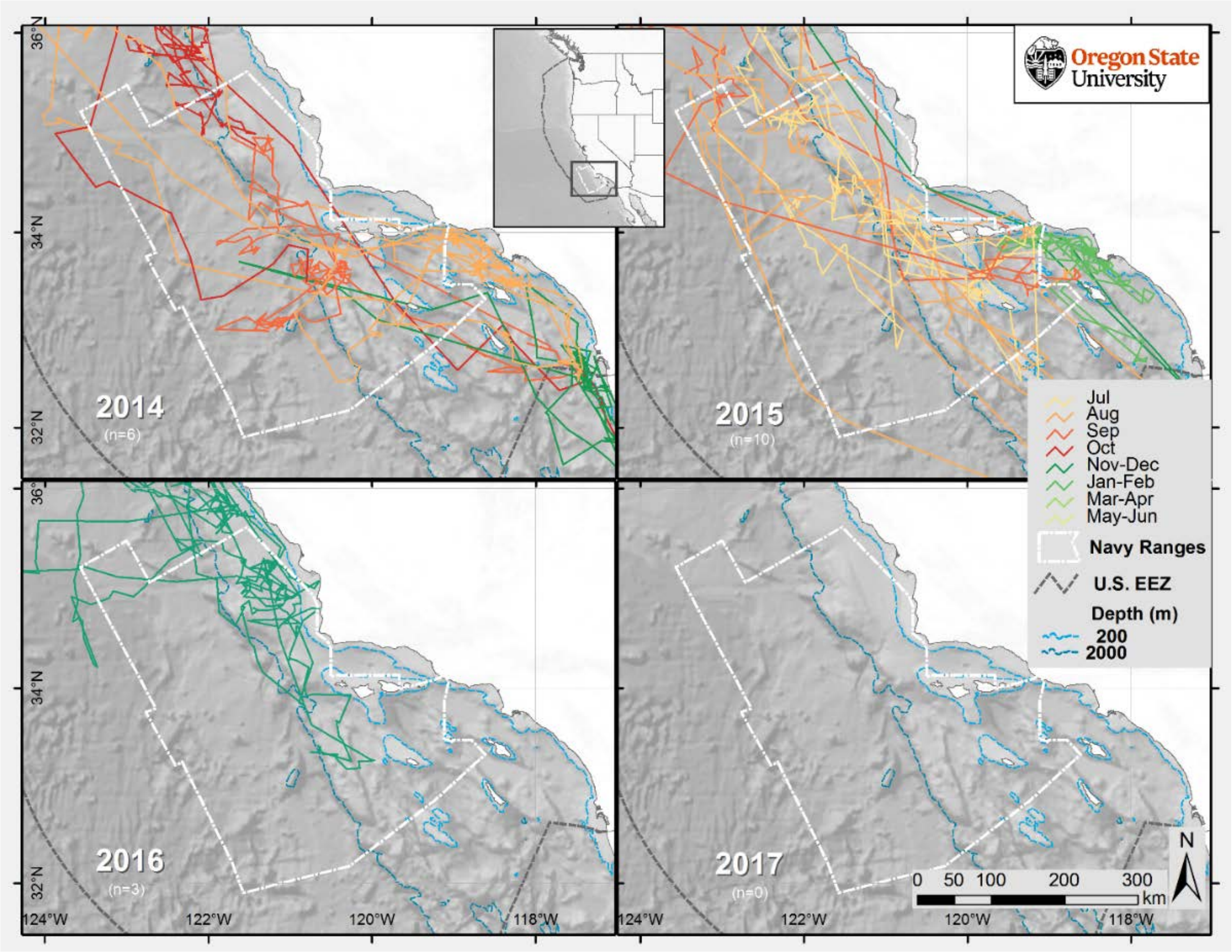

Figure 58. Satellite-monitored tracks of fin whales in the PT MUGU range, by tagging year (2014–2017). The 2017 fin whale was not tracked in the PT MUGU range. The light and dark blue bathymetric contours correspond to the 200 and 1,000 m isobaths, respectively.

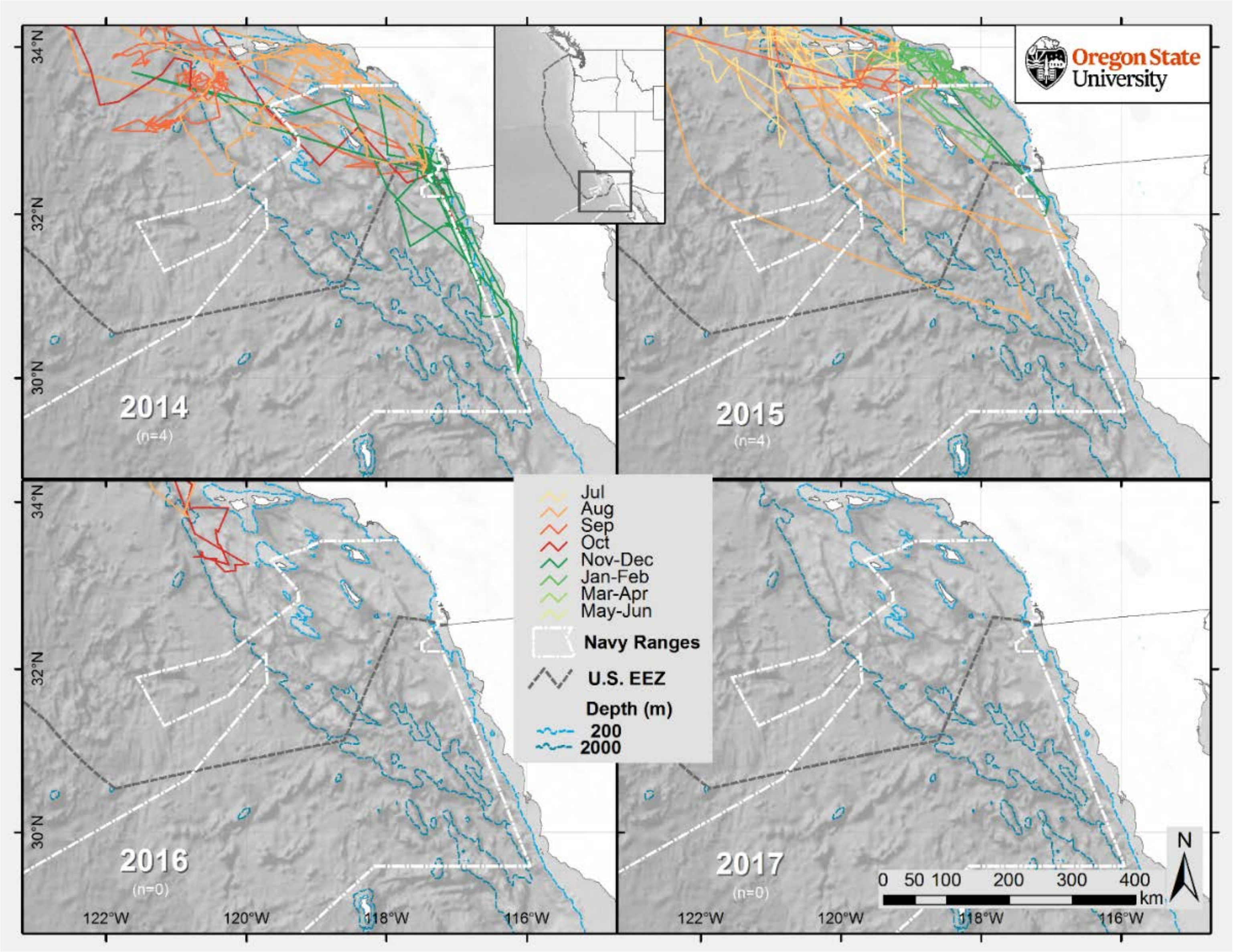

Figure 59. Satellite-monitored tracks of fin whales in the SOCAL range, by tagging year (2014–2017). No fin whales tagged in 2016 and 2017 were tracked in the SOCAL range. The light and dark blue bathymetric contours correspond to the 200 and 1,000 m isobaths, respectively.

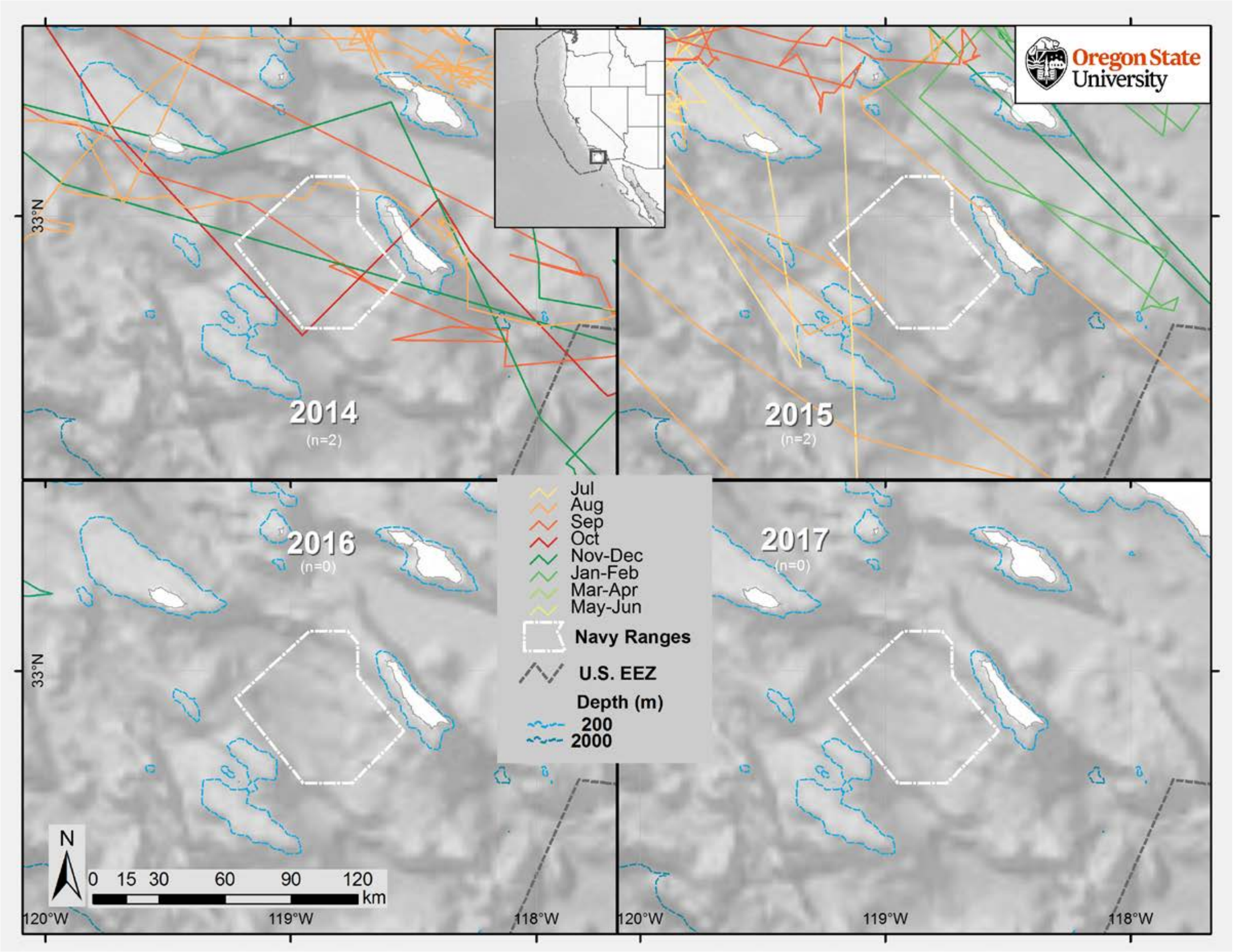

Figure 60. Satellite-monitored tracks of fin whales in the SOAR range, by tagging year (2014–2017). No fin whales tagged in 2016 and 2017 were tracked in the SOAR range. The light and dark blue bathymetric contours correspond to the 200 and 1,000 m isobaths, respectively.

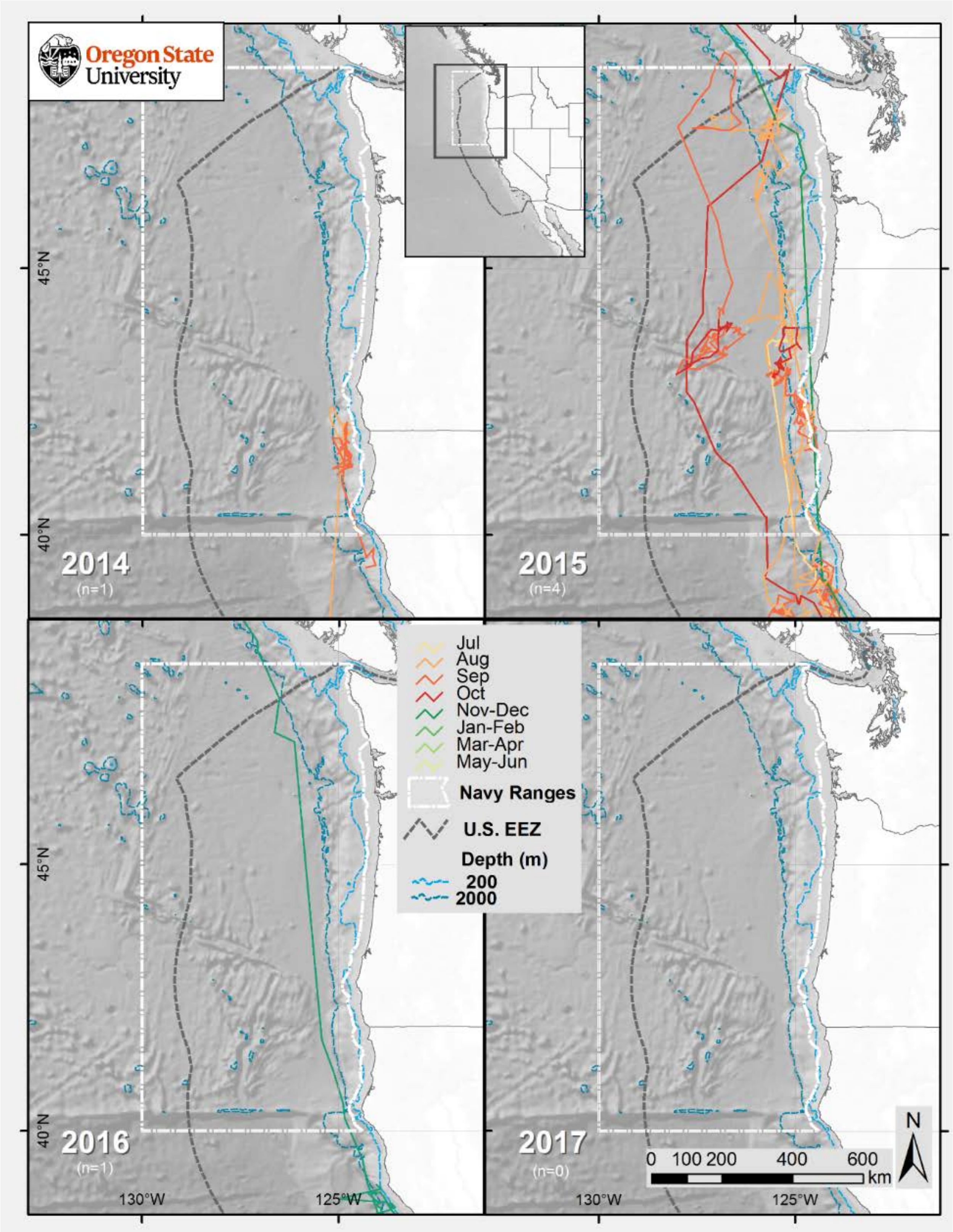

Figure 61 Satellite-monitored tracks of fin whales in the NWTT range, by tagging year (2014–2017). The 2017 fin whale was not tracked in the NWTT range. The light and dark blue bathymetric contours correspond to the 200 and 1,000 m isobaths, respectively.

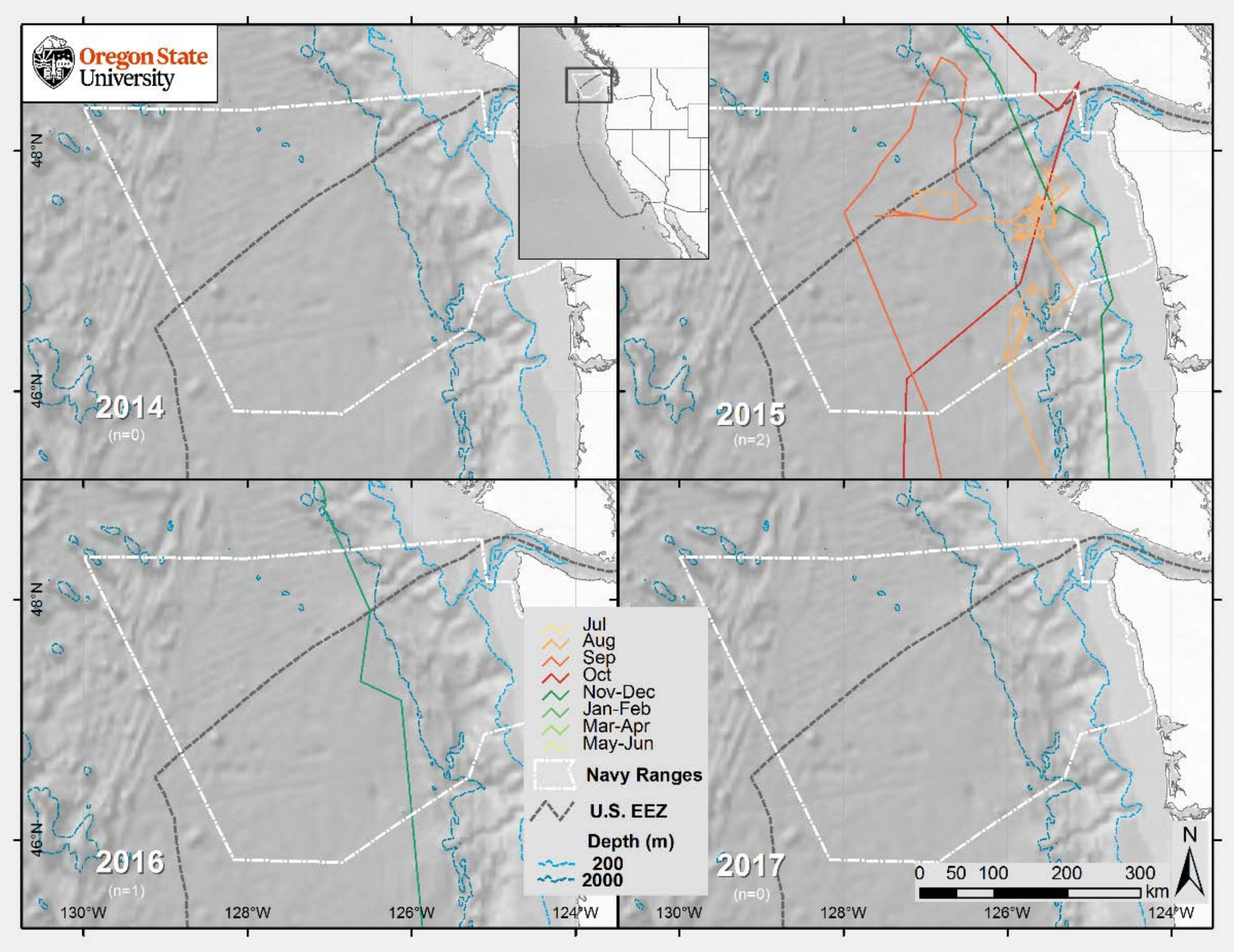

Figure 62. Satellite-monitored tracks of fin whales in W237 of the NWTT range, by tagging year (2014–2017). No fin whales tagged in 2014 and 2017 were tracked in W237. The light and dark blue bathymetric contours correspond to the 200 and 1,000 m isobaths, respectively.

For fin whales using PT MUGU, the number of days spent in the range did not vary significantly between years (ANOVA, $p = 0.998$), with whales spending an overall average of 17.6 d there (SE = 3.6 d; **Table 21**). The number of days fin whales spent in SOCAL did not vary significantly between 2014 and 2015 (ANOVA, $p = 0.82$), averaging 12.9 d (SE = 5.3 d) for both years combined. The mean number of days spent in SOAR ranged from 0.3 to 1.3 d for 2014 and 2015, but sample sizes were not large enough to test for differences between years (**Table 21**). Mean number of days spent in the NWTT area ranged from 6.1 to 35.7 d for the three tagging years, but sample sizes were also not large enough to test for differences between years (**Table 21**). The one fin whale that occurred in W237 in 2016 spent 1.7 d there. In 2015, two fin whales spent 5.1 and 22.3 d, respectively, in W237. Fin whales tagged in 2015 occurred in most Navy training ranges in more months than those tagged in either 2014 or 2016. In 2015, fin whale locations occurred in SOCAL in seven months (July, August, September, December, January, February, and March), in PT MUGU in five months (July, August, September, December, and January), in NWTT in five months (July, August, September, October, and December), and in W237 in four months (August, September, October, and December). In 2014, fin whales occurred in SOCAL during five months (August through December), in PT MUGU during four months (August through November), and in NWTT during two months (August and September). In 2016, fin whales were located in PT MUGU during three months (August through October), and in NWTT and W237 during only one month (August). Fin whales were located in SOAR during August in 2015, but during two months in 2014 (August and September). Mean distances to shore for tagged fin whales did not vary significantly between 2014, 2015, and 2016 in PT MUGU (ANOVA, $p = 0.49$) but did vary between 2014 and 2015 in SOCAL (ANOVA, p = 0.048, Fisher's LSD; **Table 22**). Sample sizes in the other training ranges were insufficient for yearly comparisons in distance to shore.

3.2.5.2 HOME RANGE ANALYSIS

HRs and CAs for fin whales were significantly different between 2015 and 2014/2016 (ANOVA $ps \leq 0.03$ Fisher's LSD; **Table 20, Figures 63 and 64**), with mean sizes of HRs and CAs being much larger for whales tagged in 2015 than in either 2014 or 2016. Fin whale HRs covered the entire West Coast of the contiguous U.S. in 2015. In contrast, HRs extended from the California/Mexico border to southern Oregon in 2014, and primarily along the central coast of California, from San Nicolas Island to Point Arena, in 2016. The HR of the fin whale tagged in 2017 was even more compressed along the central California coast. Multiple areas of highest use (where CAs overlapped for up to five whales) ranged from the southern California Bight to Coos Bay, Oregon, in 2015. Areas of highest use were more concentrated in other years, occurring from southwest of San Miguel Island in southern California to Point Sur in central California in 2014 (two whales with overlapping CAs), and only off Half Moon Bay in central California in 2016 (five whales with overlapping CAs). The CA for the fin whale tagged in 2017 was also confined to central California, centered off Pigeon Point and the Farallon Islands.

3.2.6 Dive Behavior Analysis – 2017

The single fin whale tracked in 2017 was tagged with a LO tag, so no dive information was available for this year.

Table 22. Geodesic distances to nearest point on shore in Navy training ranges for fin whales tagged off southern and central California, 2014–2016 (including mean, median, and maximum distance to shore). There were no locations in Navy training ranges for the fin whale tagged off central California in 2017.

Year	SOCAL				PT MUGU				SOAR				NWTT				W237			
	n	**Mean**	**Median**	**Max**	**n**	**Mean**	**Median**	**Max**	**n**	**Mean**	**Median**	**Max**	**n**	**Mean**	**Median**	**Max**	**n**	**Mean**	**Median**	**Max**
2014	4	18	18	28	6	62	64	96	2	30	30	32	1	56	56	56	0	-	-	-
2015	4	61	59	102	10	67	62	122	1	51	51	51	4	119	125	168	2	107	107	122
2016	0	-	-	-	3	94	52	181	0	-	-	-	1	108	108	108	1	140	140	140
Mean		**39.5**	**38.5**	**65.0**		**74.3**	**59.3**	**133.0**		**40.5**	**40.5**	**41.5**		**94.3**	**96.3**	**110.7**		**123.5**	**123.5**	**131.0**
Median		**39.5**	**38.5**	**65.0**		**67.0**	**62.0**	**122.0**		**40.5**	**40.5**	**41.5**		**108.0**	**108.0**	**108.0**		**123.5**	**123.5**	**131.0**

KEY: n = number of whales having locations in that particular training range.

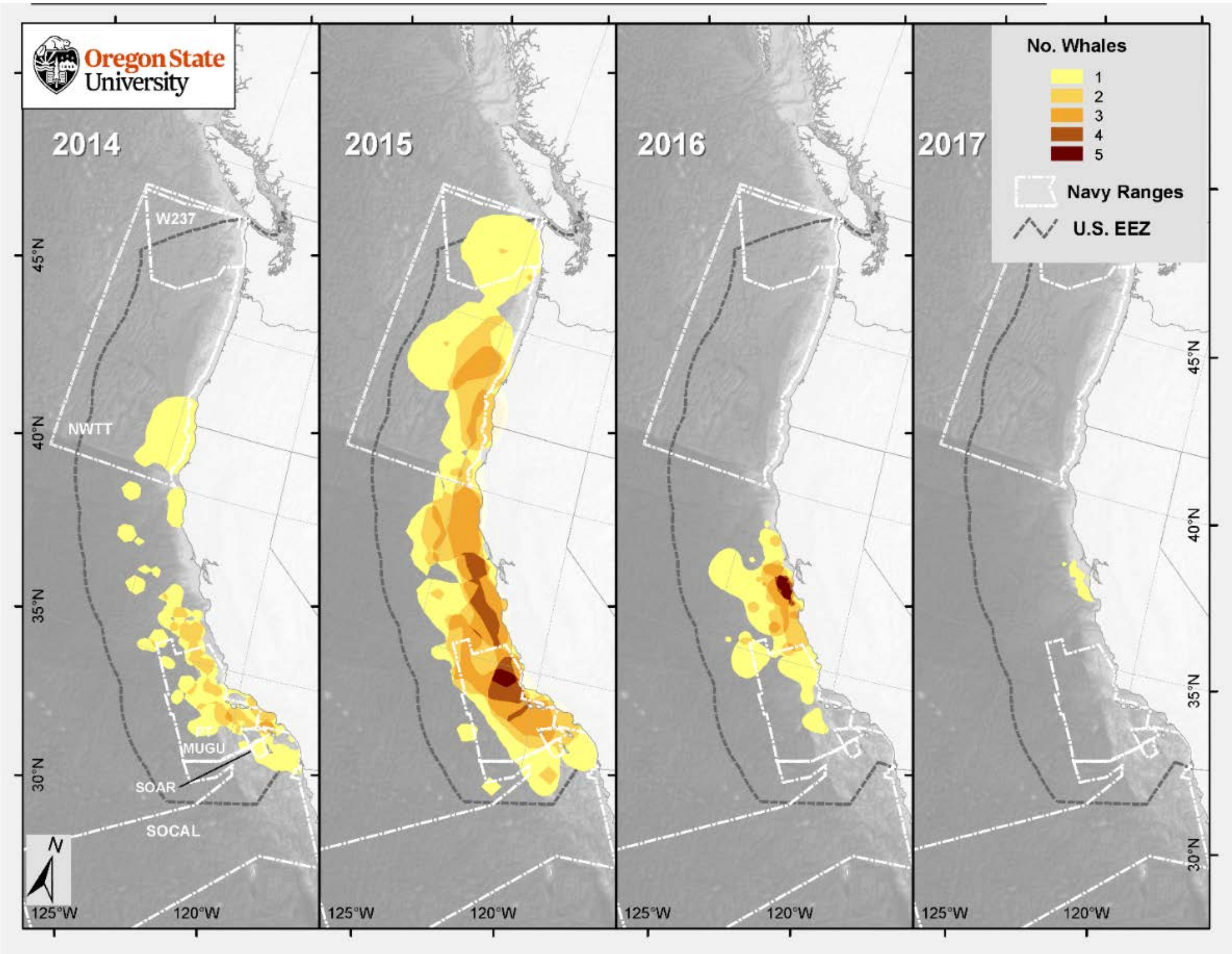

Figure 63. HRs in the U.S. EEZ for fin whales tagged off southern California in 2014 (3 whales), off southern California in 2015 (5 whales), off central California in 2016 (5 whales), and off central California in 2017 (1 whale). Shading represents the number of individual whales with overlapping HRs.

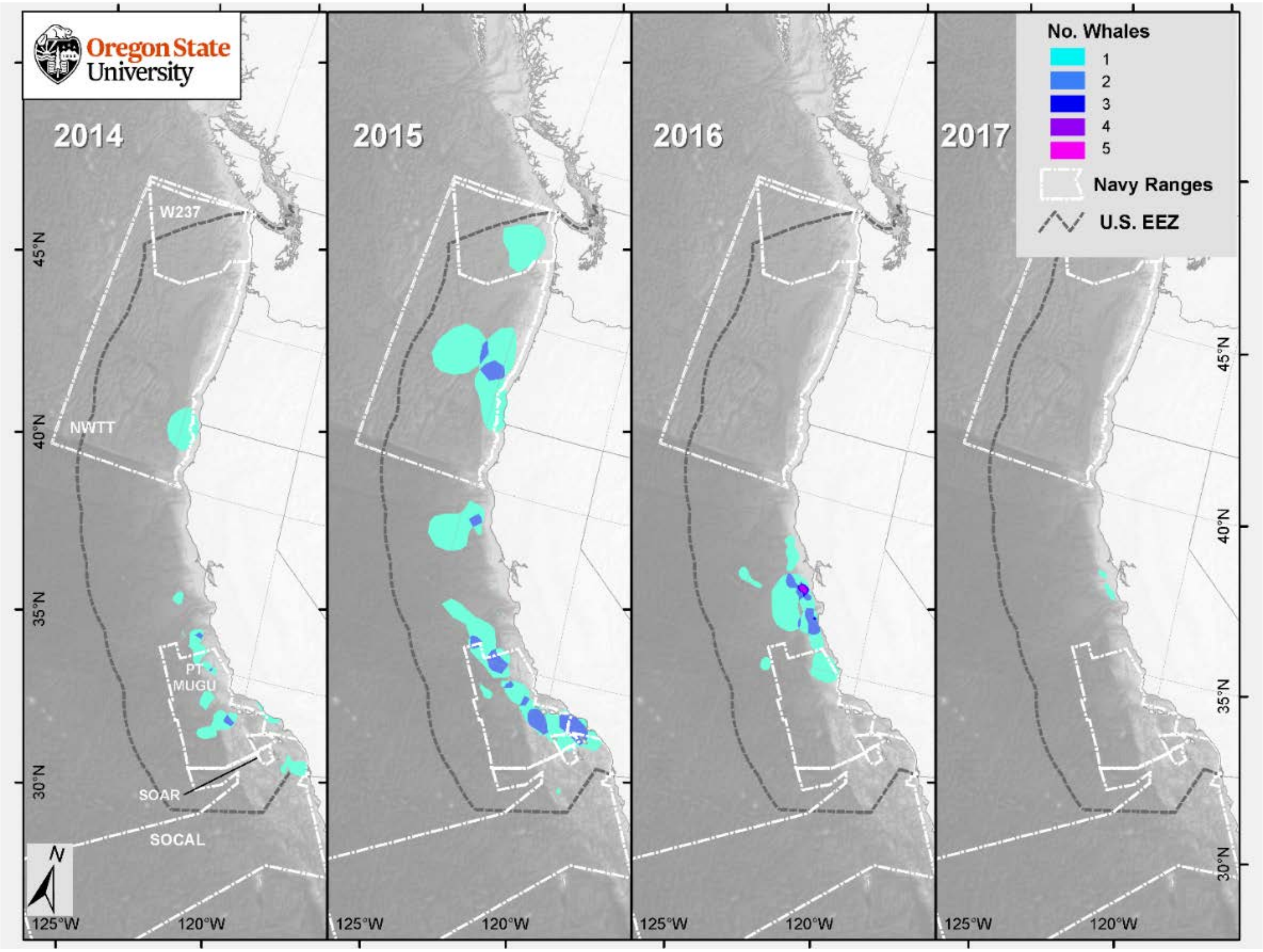

Figure 64. CAs in the U.S. EEZ for fin whales tagged off southern California in 2014 (3 whales), off southern California in 2015 (5 whales), off central California in 2016 (5 whales), and off central California in 2017 (1 whale). Shading represents the number of individual whales with overlapping CAs.

3.2.7 Dive Behavior Analysis—Inter-annual Comparison

A detailed inter-annual comparison for ADB-tagged fin whales in 2014 and 2015 can be found in the project reports from previous years (Mate et al. 2015, 2016, 2017a). As no DM tags were deployed on fin whales in 2017, no inter-annual comparison was possible. The dive data from the DM tags deployed in 2016 are fully described in last year's annual report (Mate et al. 2017a); a brief summary is presented here.

In 2016, DM tags were deployed on nine fin whales off central California. Although one tag provided no transmissions, the others stayed attached for a median of 28.7 d and provided summaries for a median of 1,670 dives per whale and a median of 125 Argos locations. DM-tagged fin whales generally occupied the waters over the continental slope from Monterey Bay to Point Arena, with the exception of one whale that traveled north to an area east of Haida Gwaii, British Columbia, and remained there for 39 d until its tag stopped transmitting.

Dive depths reported by the eight DM tags that transmitted in 2016 showed a diel trend, with fewer lunges and shallower dives occurring at night (mean = 2.6 lunges versus 4.6 lunges and mean = 33 m depth versus 87 m depth), although there were not always large differences. Daytime dive depths were highly variable within and across individuals with most dives limited to 150 m or less in depth. The spatial distribution of dive depths was generally consistent across the study area, with slightly shallower average maximum dive depths occurring off Monterey Bay, California. Feeding effort was also generally consistent across southern and central California, with slightly increased effort off Monterey Bay and Point Arena. Feeding effort was highest off British Columbia, especially in the Hecate Strait.

3.2.8 Ecological Relationships—2017

The track from the single fin whale tag deployed in 2017 generated 43 estimated daily SSSM locations, of which 2 occurred on land and none had unacceptable estimation uncertainty (**Table 23**). The geographic extent of this track covered approximately 2 degrees of longitude (124–122°W) and 1 degree of latitude (36.9–37.9°N; **Figure 65**). All of the 41 accepted locations occurred in CCAL (100 percent). The ALSK, NPPF, NPTG, GUCA, PNEC and PQED provinces were not visited by this 2017 fin whale (**Table 23** and **Figure 65**).

The behavioral classifications for each location of this track are shown on the map in **Figure 65**. The number and proportion of locations classified by behavioral mode in CCAL is reported in **Table 24**. Of 40 SSSM locations, 37 (92.5 percent) were classified as ARS, 3 (7.5 percent) were classified as uncertain, and none were classified as transiting (**Table 24**). Within CCAL, and for the summer-fall months, average PWDIST was 23.2 km (**Table 25, Figure 66**).

Details of the environmental variables examined are provided in **Table 1**. Summary statistics for these variables obtained for the SSSM locations were reported in CCAL only (**Tables 25 and 26**), as this was the only biogeographic province consistently occupied in all years. In 2017, average SST was 16.5°C, and average CHL was 2.3 mg m^{-3} (**Table 25**). The values at each location for these environmental variables are shown on the maps in **Figures 67** and **68**.

In terms of seafloor characteristics, the single fin whale tracked in 2017 occurred in areas with an average DEPTH of 470.7 m, average DISTSHELF of 6.6 km, and average DISTSHORE of 34.6 km. The average SLOPE in these areas was 80.2 m km^{-1} and faced toward the southwest (average ASPECT = 217°) (**Table 26**). The values at each location for these seafloor relief variables are shown on the maps in **Figures 69** through **73**.

Table 23. Number (and percentage) of accepted SSSM locations (locs) inside each province for fin whales in each year of the project. Also provided are the number of locations that fell on land and the number of locations excluded from the analyses because their high estimation uncertainty. Unclassified locations correspond to the end-of-track locations, which do not receive a behavioral mode classification by the SSSM. This number can be lower than the number of tracks because of the exclusion of locations on land and those with high estimation uncertainty. The number of SSSM tracks is indicated (n) and can be lower than the number of tracked whales (See Section 2.3.2).

	2014 (n = 5)	**2015 (n = 10)**	**2016 (n = 12)**	**2017 (n = 1)**
Longitudinal range	**9.7 degrees (125.8–116.1°W)**	**16.1 degrees (133.1–117.0°W)**	**10.9 degrees (130.9–120°W)**	**2 degrees (124–122°W)**
Latitudinal range	**12.2 degrees (30.1–42.3°N)**	**21.8 degrees (30.8–52.6°N)**	**20 degrees (33.2–53.5°N)**	**1 degree (36.9–37.9°N)**
Province				
ALSK	NA	51 (10.3%)	40 (10.2%)	NA
CCAL	261 (100%)	446 (89.7%)	353 (89.8%)	41 (100%)
GUCA	NA	NA	NA	NA
NPPF	NA	NA	NA	NA
NPTG	NA	NA	NA	NA
PNEC	NA	NA	NA	NA
PQED	NA	NA	NA	NA
Accepted locs	261 (100%)	497 (100%)	393 (100%)	41 (100%)
Unclassified locs	5	7	10	1
Excluded locs	12	56	54	0
Land locs	29	11	11	2
Total locs	302	564	458	43

KEY: n = number; * = number of SSSM tracks includes those from ADB tags (3 in 2014, 2 in 2015).

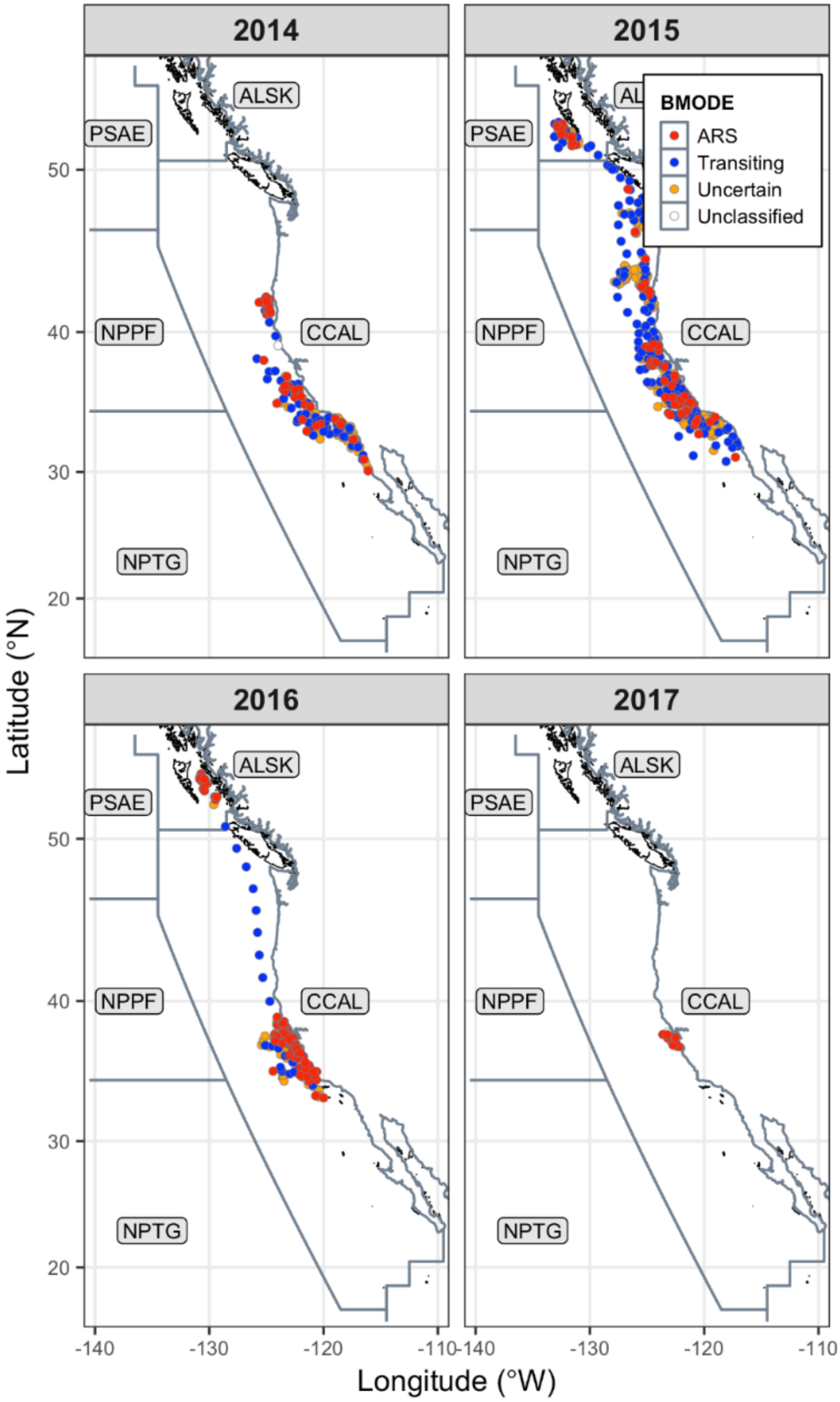

Figure 65. Accepted SSSM locations for fin whales colored by behavioral mode for each year in the study. Five of the Longhurst (1998, 2006) biogeographic provinces in the eastern North Pacific occupied by tagged fin whales are outlined and labeled.

Table 24. Number of classified SSSM locations (and percentage) in CCAL for each behavioral mode for fin whales in each year of the project. The number of SSSM tracks is indicated (n).

Behavioral Mode	2014 (n = 5)	2015 (n = 10)	2016 (n = 12)	2017 (n = 1)
Transiting	50 (19.5%)	157 (35.8%)	33 (9.6%)	NA
Uncertain	158 (61.7%)	230 (52.4%)	191 (55.5%)	3 (7.5%)
ARS	48 (18.8%)	52 (11.8%)	120 (34.9%)	37 (92.5%)
Classified locs	256 (100%)	439 (100%)	344 (100%)	40 (100%)

Table 25. Summary statistics (mean and standard deviation [SD]) for the PWDIST and the remotely sensed variables obtained for each SSSM location for fin whales in CCAL in July–November for each year of the project. The total number of locations (N Total) and the number of locations with valid matching environmental values (n) are given for each species and year. SSSM locations falling on land, those with high estimation uncertainty, and those with unclassified behavioral mode have been excluded.

		PWDIST (km)			SST (°C)			CHL (mg m^{-3})		
Year	**N Total**	**n**	**Mean**	**SD**	**n**	**Mean**	**SD**	**n**	**Mean**	**SD**
2014	256	230	49.63	44.25	226	18.81	2.36	232	0.59	0.73
2015	439	409	58.97	53.13	413	17.96	1.94	418	0.64	0.66
2016	344	332	38.27	35.14	344	15.40	1.08	244	1.47	4.25
2017	40	39	23.24	25.72	40	16.53	0.78	36	2.32	4.30

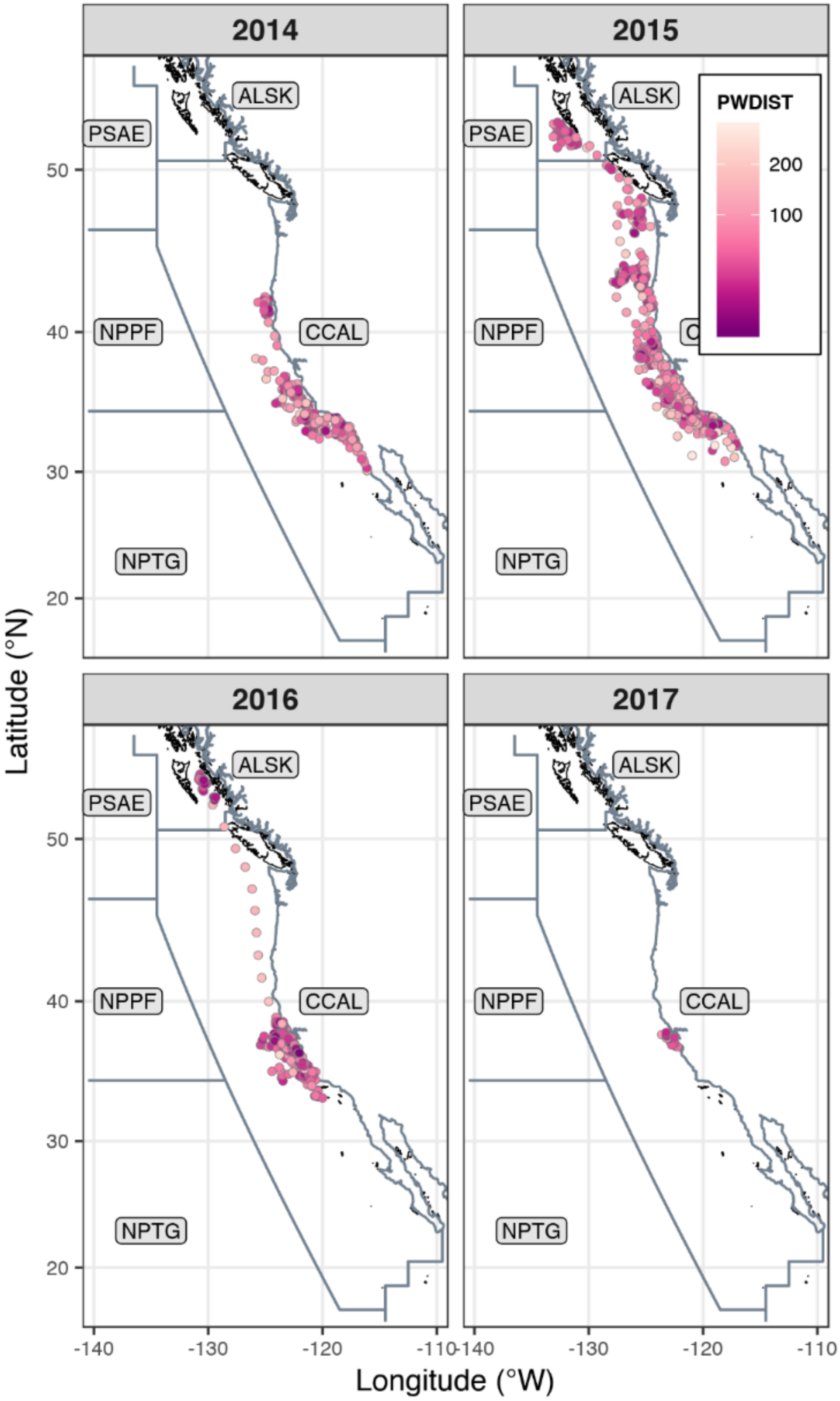

Figure 66. Map representation of PWDIST (km) between fin whale SSSM locations for each year in the study. Five of the Longhurst (1998, 2006) biogeographic provinces in the eastern North Pacific occupied by tagged fin whales are outlined and labeled. Note the square-root-transformed color scale for enhanced visualization.

Table 26. Summary statistics (mean and standard deviation [SD]) for the seafloor relief variables obtained for each SSSM location for fin whales in CCAL in July-November for each year of the project. The total number of locations (N Total) and the number of locations with valid matching environmental values (n) are given for each species and year. SSSM locations falling on land, those with high estimation uncertainty, and those with unclassified behavioral mode have been excluded.

		DEPTH (m)			DISTSHELF (km)			DISTSHORE (km)			SLOPE (m km^{-1})			ASPECT (deg)		
Year	**N Total**	**n**	**Mean**	**SD**	**n**	**Mean**	**SD**	**n**	**Mean**	**SD**	**n**	**Mean**	**SD**	**n**	**Mean**	**SD**
2014	256	233	1,789.61	1,264.50	233	48.48	44.93	233	66.15	47.87	233	49.46	51.82	233	212.31	67.97
2015	439	418	2,208.31	1,278.65	418	64.49	59.45	418	93.03	63.87	418	41.22	42.09	418	223.30	66.79
2016	344	343	1,479.91	1,289.77	344	35.37	44.26	344	60.87	46.23	344	47.59	49.78	344	232.00	52.11
2017	40	39	470.72	588.12	40	6.59	7.21	40	34.63	14.75	40	80.20	87.44	40	217.02	32.55

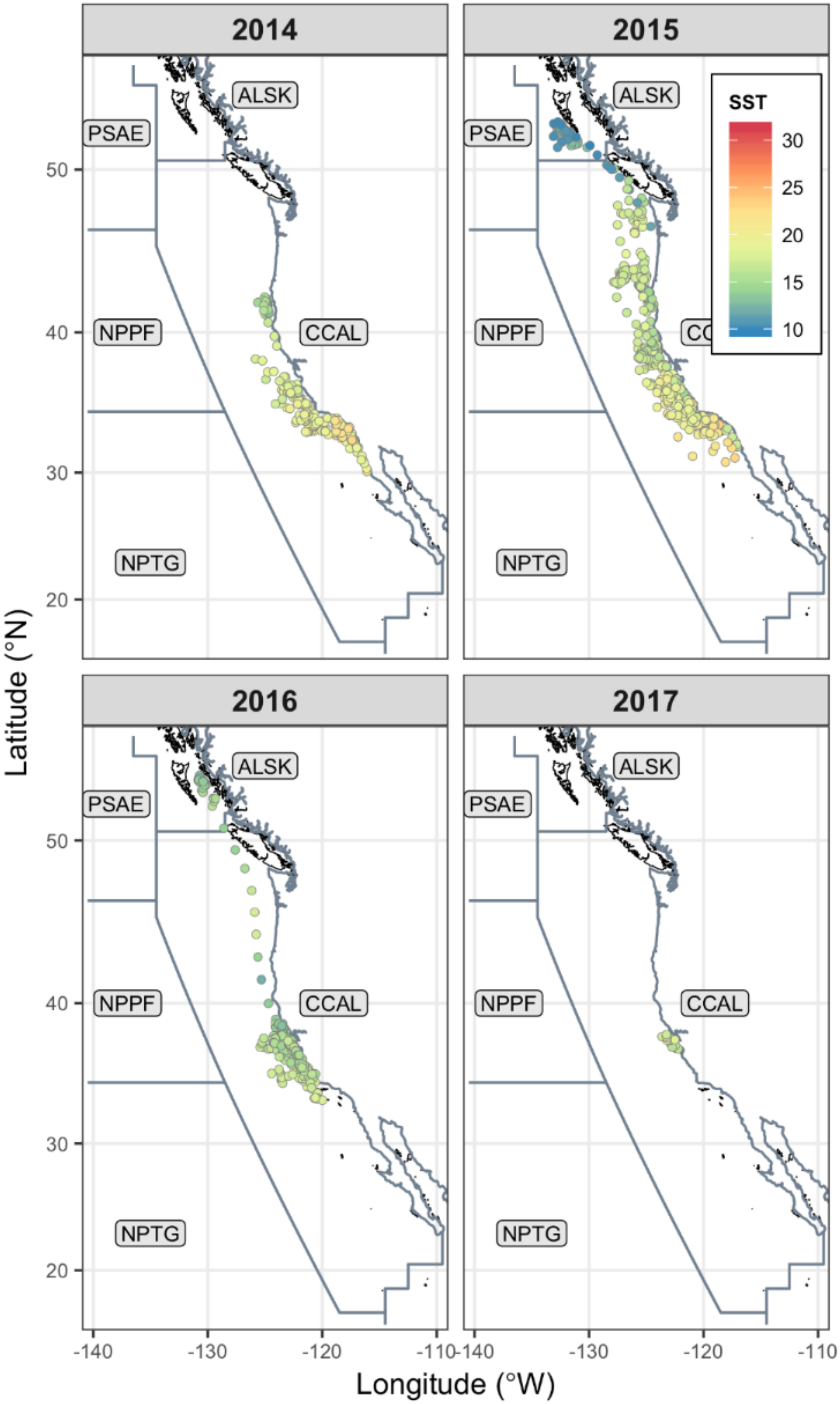

Figure 67. Map representation of sea surface temperature (SST, °C) values obtained from satellite remote sensing around each fin whale location for each year in the study. Five of the Longhurst (1998, 2006) biogeographic provinces in the eastern North Pacific occupied by tagged fin whales are outlined and labeled.

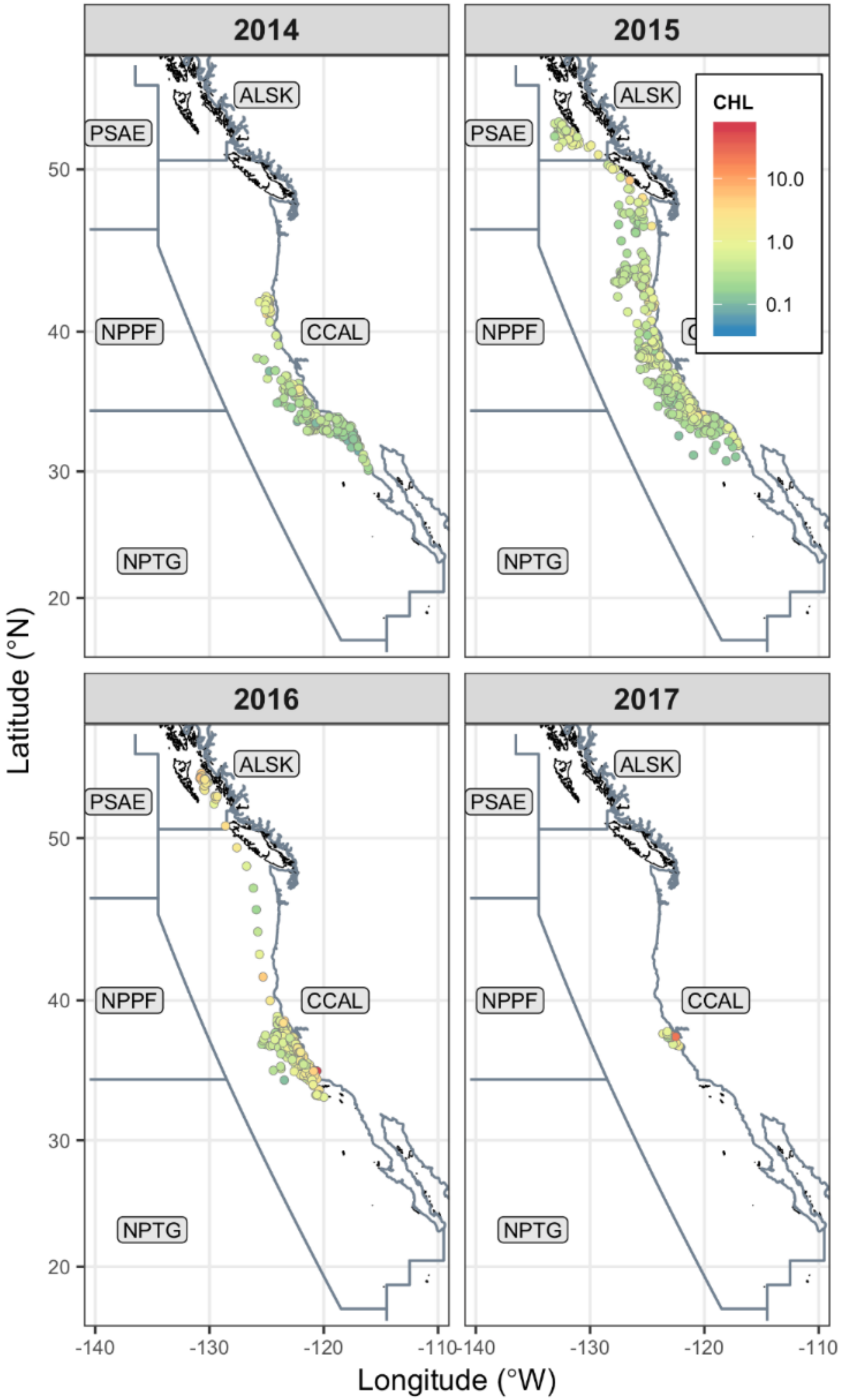

Figure 68. Map representation of chlorophyll-a concentration (CHL, mg m^{-3}) values obtained from satellite remote sensing around each fin whale location for each year in the study. Five of the Longhurst (1998, 2006) biogeographic provinces in the eastern North Pacific occupied by tagged fin whales are outlined and labeled. Note the log-transformed color scale for enhanced visualization.

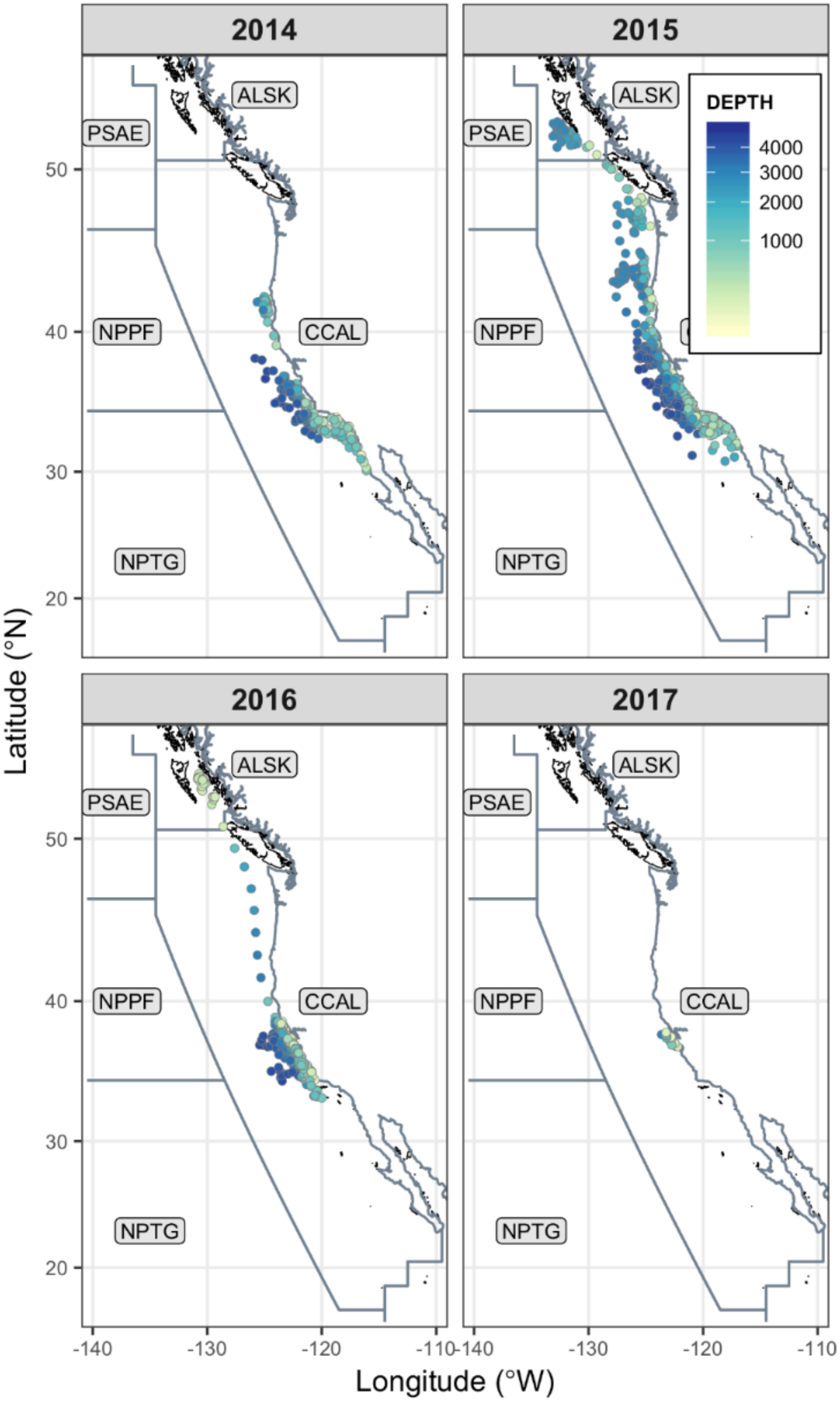

Figure 69. Map representation of seafloor depth (DEPTH, m) values obtained from ETOPO1 around each fin whale location for each year in the study. Five of the Longhurst (1998, 2006) biogeographic provinces in the eastern North Pacific occupied by tagged fin whales are outlined and labeled. Note the square-root-transformed color scale for enhanced visualization.

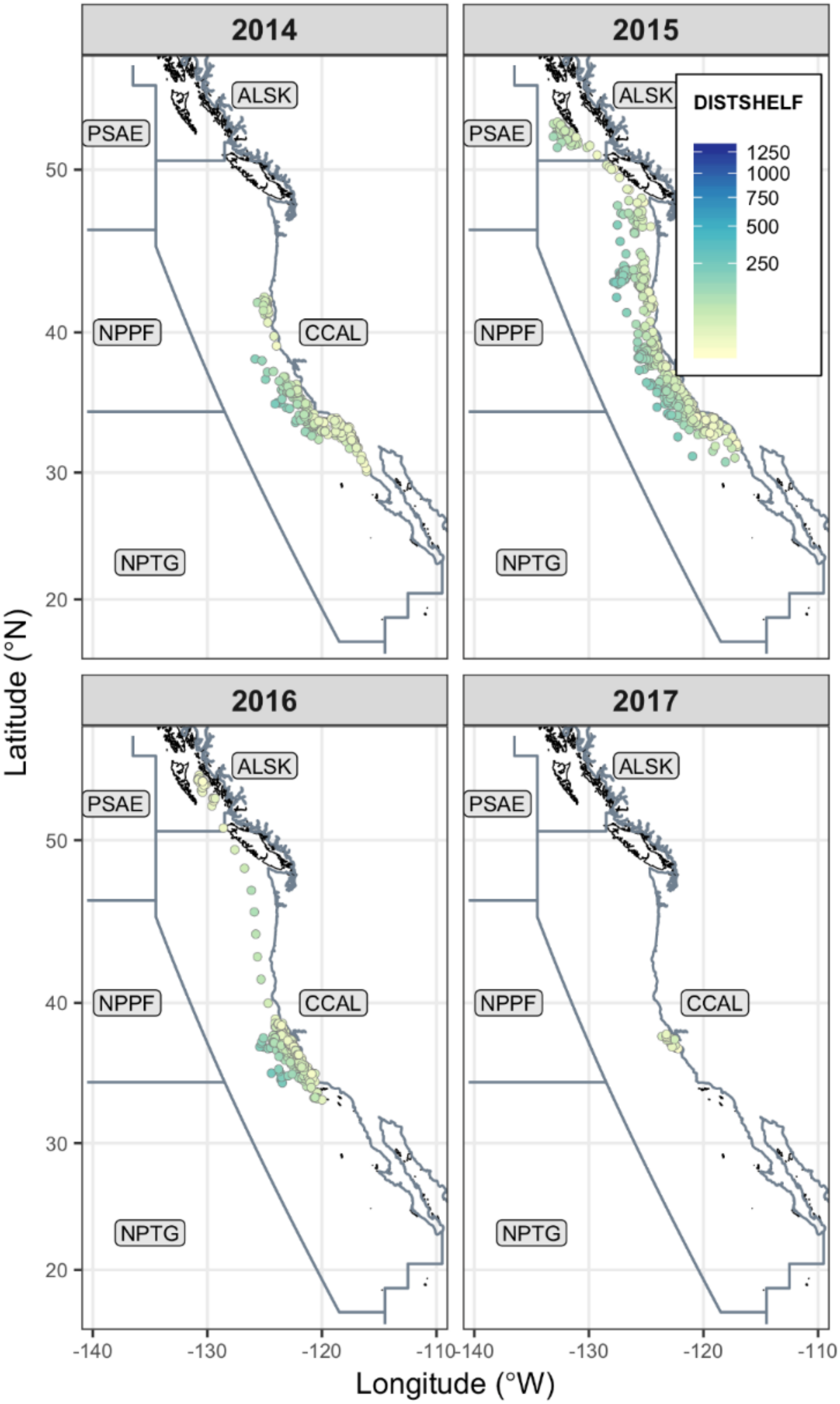

Figure 70. Map representation of distance to the 200-m isobath (DISTSHELF, km) values obtained from ETOPO1 around each fin whale location for each year in the study. Five of the Longhurst (1998, 2006) biogeographic provinces in the eastern North Pacific occupied by tagged fin whales are outlined and labeled. Note the square-root-transformed color scale for enhanced visualization.

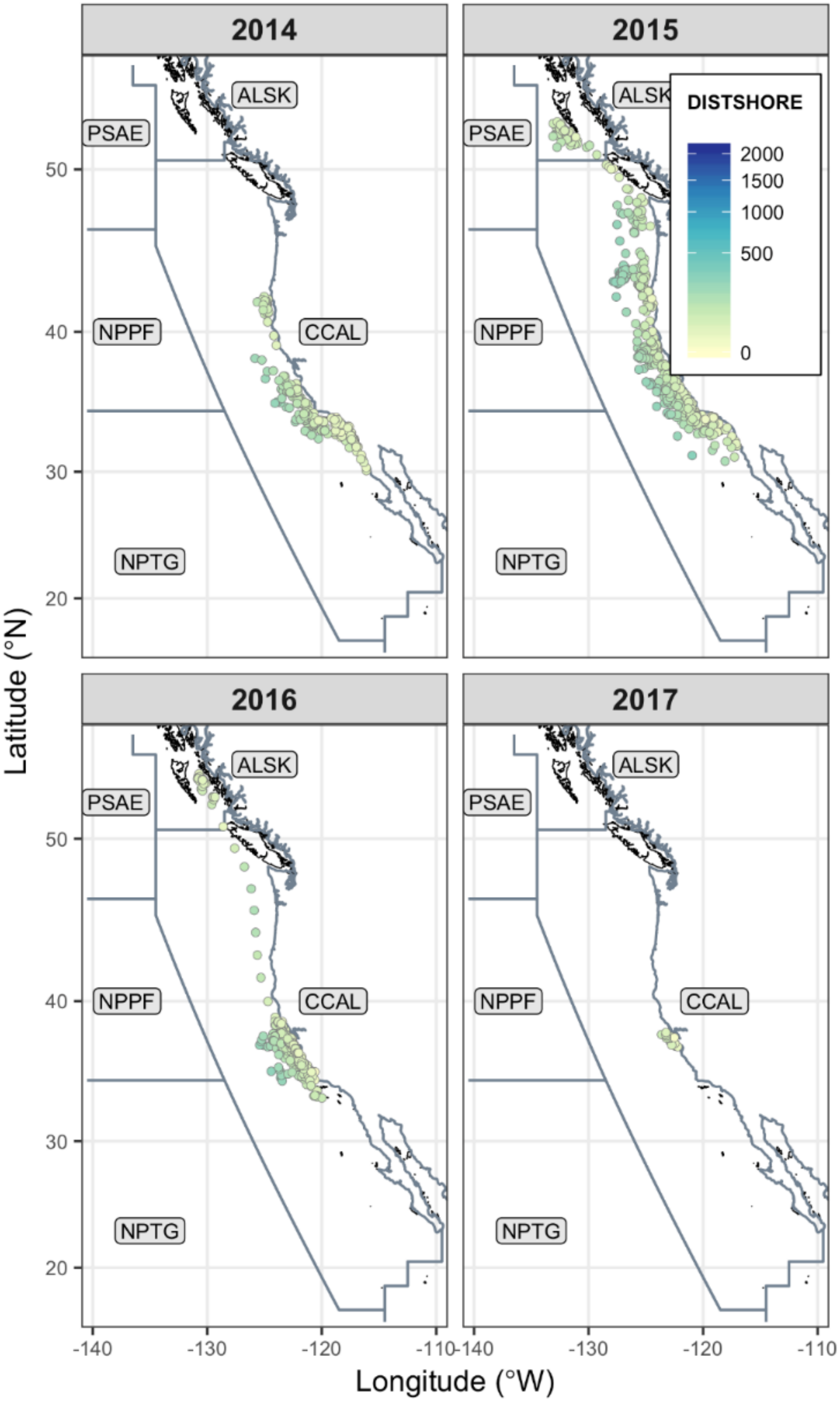

Figure 71. Map representation of distance to the shoreline (DISTSHORE, km) values obtained from cntry_06.shp around each fin whale location for each year in the study. Five of the Longhurst (1998, 2006) biogeographic provinces in the eastern North Pacific occupied by tagged fin whales are outlined and labeled. Note the square-root-transformed color scale for enhanced visualization.

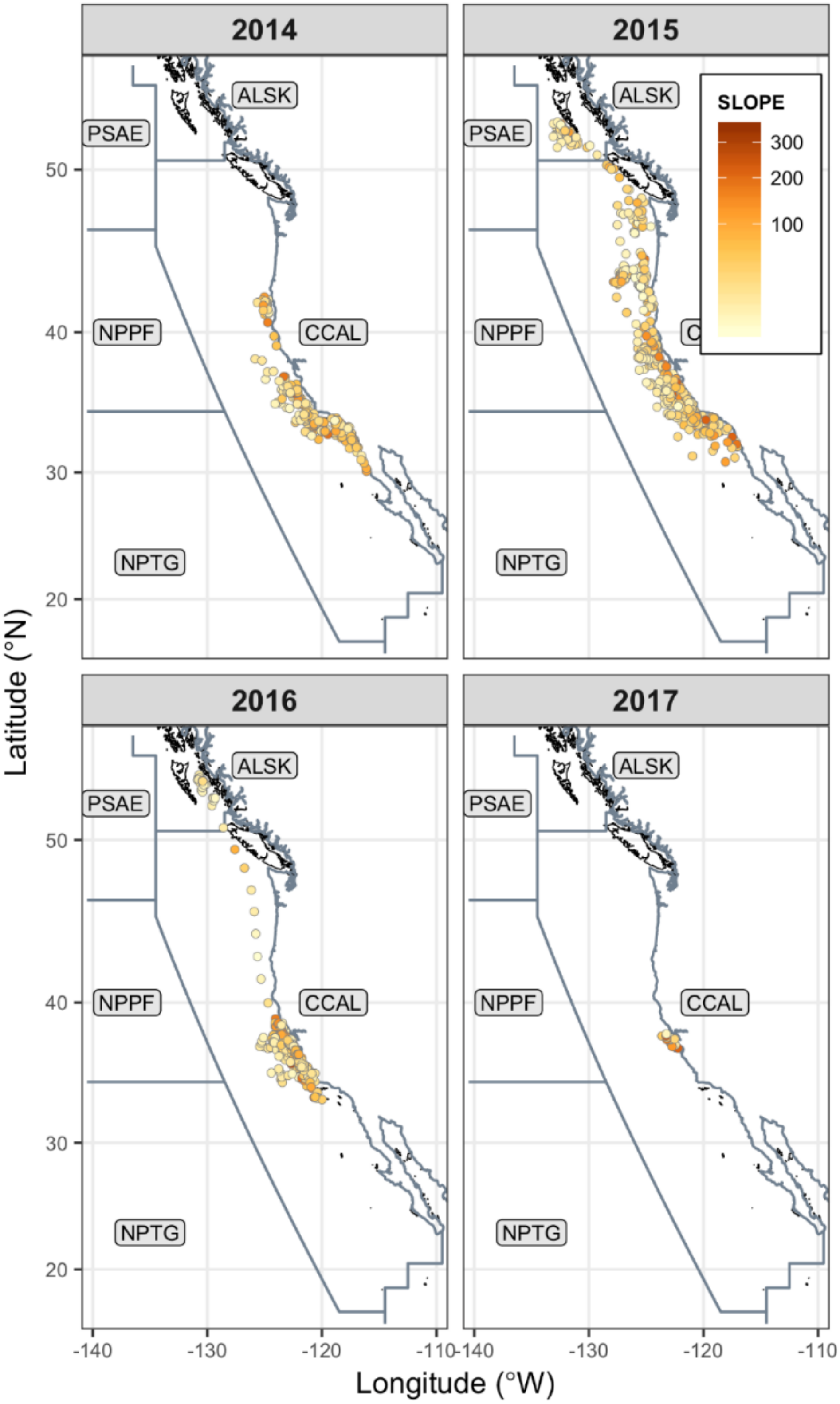

Figure 72. Map representation of seafloor slope (SLOPE, m km^{-1}) values obtained from ETOPO1 around each fin whale location for each year in the study. Five of the Longhurst (1998, 2006) biogeographic provinces in the eastern North Pacific occupied by tagged fin whales are outlined and labeled. Note the square-root-transformed color scale for enhanced visualization.

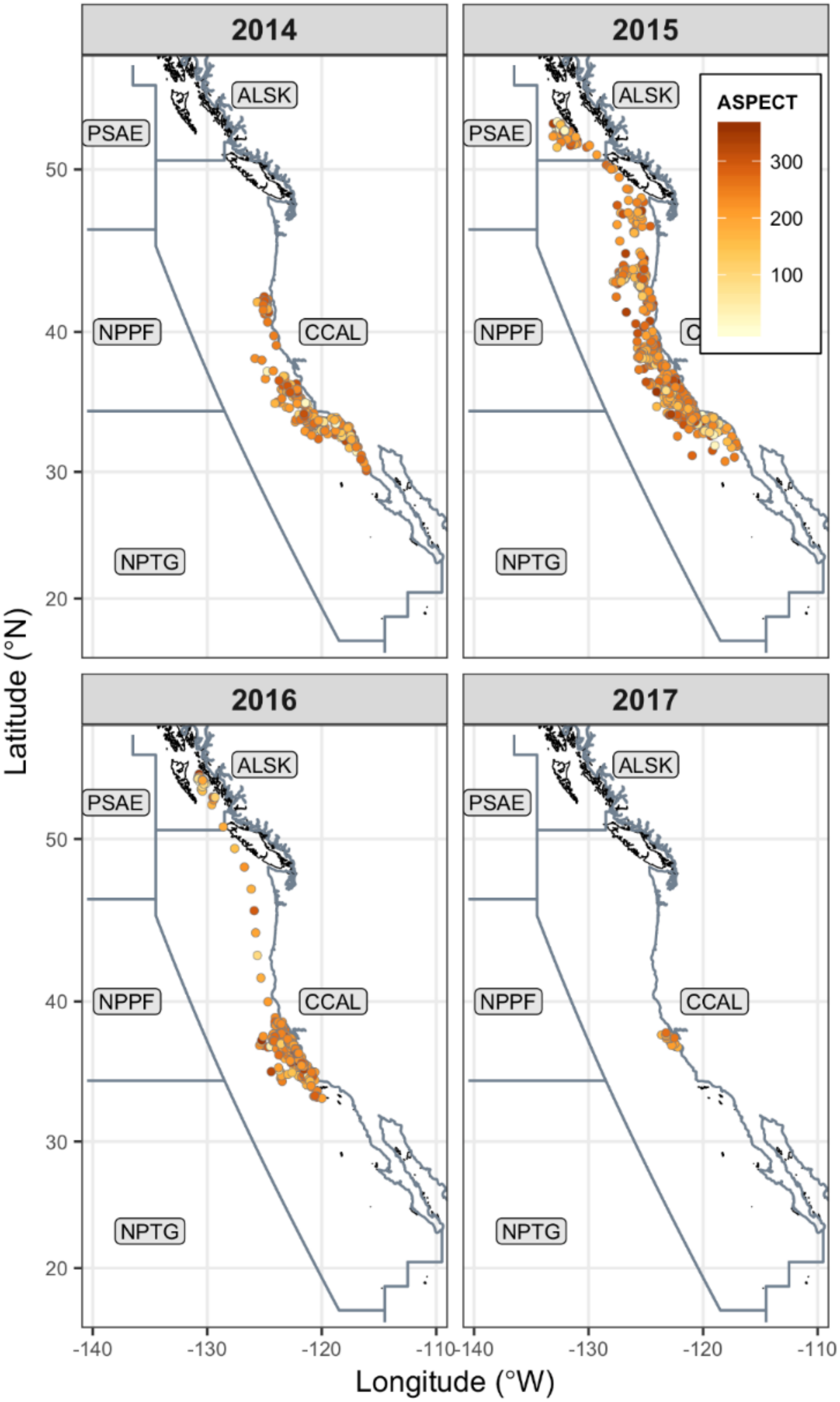

Figure 73. Map representation of seafloor slope aspect (ASPECT, °) values obtained from ETOPO1 around each fin whale location for each year in the study. Five of the Longhurst (1998, 2006) biogeographic provinces in the eastern North Pacific occupied by tagged fin whales are outlined and labeled.

3.2.9 Ecological Relationships—Inter-annual Comparison

The numbers of tracked fin whales across the four years of the study were smaller and more variable than for blue whales (n = 5 in 2014[3], n = 10 in 2015[4], n = 12 in 2016, and n = 1 in 2017, for a total of 28; **Table 23**). Because the movements of the single fin whale tracked in 2017 for 43 days were confined to a small area off central California between Santa Cruz and San Francisco (**Figure 65**), it did not cover a representative extent of the study area to justify a balanced comparison with the previous three years of tracking. Therefore, we limited our inter-annual comparisons for fin whales to the period 2014–2016 (similar to what was presented in our annual report for 2016; Mate et al. 2017a).

The longitudinal range of the fin whale tracks in the first three years of the project was smallest in 2014 and 2016 (9.7 and 10.9 degrees, respectively), and it was greatest in 2015 (16.1 degrees). The latitudinal range was restricted and shifted to the south in 2014 (12.2 degrees; 30.1–42.3°N), while in 2015 and 2016 it was larger (21.8 and 20 degrees, respectively) and shifted to the north, reaching Haida Gwaii and Hecate Strait off British Columbia (**Table 23** and **Figure 65**).

In contrast to blue whales, fin whales were only present in two of the eight biogeographic provinces of the eastern North Pacific considered here, CCAL and ALSK (**Table 23**). Their proportional occupation of these provinces was virtually identical in 2015 and 2016 (CCAL: 89.7 and 89.8 percent of locations, respectively; ALSK: 10.3 and 10.2 percent, respectively), while in 2014 they were restricted to CCAL (**Table 23** and **Figure 65**).

The behavioral classification in CCAL was based on 256 SSSM locations in 2014, 439 locations in 2015, and 344 locations in 2016. The proportion of locations classified as ARS was lowest (11.2 percent of locations) in 2015, intermediate (18.8 percent) in 2014, and highest (34.9 percent) in 2016. The proportion of locations classified as transiting was highest (35.8 percent) in 2015, intermediate in 2014 (19.5 percent), and lowest in 2016 (9.6 percent). Locations considered uncertain made up the remainder (61.7 percent in 2014, 52.4 percent in 2015, and 55.5 percent in 2016; **Table 24**). Within CCAL, and for the summer-fall months, average PWDIST was highest in 2015 (59.0 km) and lower in 2014 and 2016 (49.6 and 38.3 km, respectively; **Table 25, Figure 66**).

In terms of oceanographic characteristics in CCAL, average SST was warmest in 2014 and 2015 (18.8 and 17.6°C, respectively), and coolest in 2016 (15.4°C). Average CHL was low in 2014 and 2015 (approximately 0.6 mg m^{-3} in both years) and higher in 2016 (1.5 mg m^{-3}; **Table 25**). The values at each location for these environmental variables are shown on the maps in **Figures 67** and **68.**

---

[3] This includes SSSM tracks from 3 ADB tags in 2014.
[4] This includes SSSM tracks from 2 ADB tags in 2015.

While in ARS, fin whales covered larger distances between location pairs in 2015 (mean PWDIST = 76.0 km), and substantially smaller distances in 2014 and 2016 (mean PWDIST = 46.8 and 35.5 km, respectively; **Figure 74**). Examination of oceanographic conditions only for SSSM locations where ARS was recorded revealed that the little ARS activity in 2015 occurred in the warmest SST recorded during the study (mean = 18.5°C), compared to the higher ARS activity that was recorded in cooler waters in 2014 (mean = 16.7°C) and especially in 2016 (mean = 15.2°C; **Figure 75**). Correspondingly, CHL values where ARS activity took place in 2015 were the lowest in the three years (mean = 0.5 mg m^{-3}) compared to the more elevated values in 2014 or 2016 (mean = 1.1 and 1.9 mg m^{-3}, respectively; **Figure 76**).

In terms of seafloor characteristics in CCAL, in 2015 fin whales occurred in areas that on average were deeper (DEPTH = 2,145.7 m), occurred farther away from the shelf break (DISTSHELF = 62.1 km) and the shore (DISTSHORE = 90.3 km), and had gentler slopes (SLOPE = 42.9 m km^{-1}) than in 2014 (DEPTH = 1,696.4 m, DISTSHELF = 45.1 km, DISTSHORE = 62.5 km, SLOPE = 50.1 m km^{-1}) or 2016 (DEPTH = 1,492.3 m, DISTSHELF = 35.4 km, DISTSHORE = 60.9 km, SLOPE = 47.6 m km^{-1}). Finally, the average ASPECT of the slope generally faced toward the southwest in all three years, without marked variability (212.1° in 2014, 223.7° in 2015, and 232.0° in 2016; **Table 26**). The values at each location for these seafloor relief variables are shown on the maps in **Figures 69 through 73**, and their distributional properties are shown in the violin plots of **Figures 77 through 81**. During 2015, ARS activity took place in deeper waters (mean = 2,465.3 m) and farther away from the shelf break and the shore (mean = 61.9 km and 84.9 km, respectively) than in 2014 or 2016 (**Figures 77 through 79**).

An examination of the state of the ONI, PDO, and NPGO (**Figure 53**) during the four years of this study was presented in **Section 3.1.9** concerning blue whales. These results apply equally to fin whales, and the reader is referred to that section for the climatic context.

3.2.10 Genetics and Species Identification

A biopsy sample was not collected from the fin whale tagged in 2017; therefore, there are no genetics results to report for 2017.

3.2.11 Photo-ID

A total of 522 photos of fin whales was taken during the 2017 cruise, resulting in IDs for 6 individuals. No fin whales identified in the three previous seasons were resighted in 2017. Photo-IDs were obtained for the single tagged fin whale for the left side only.

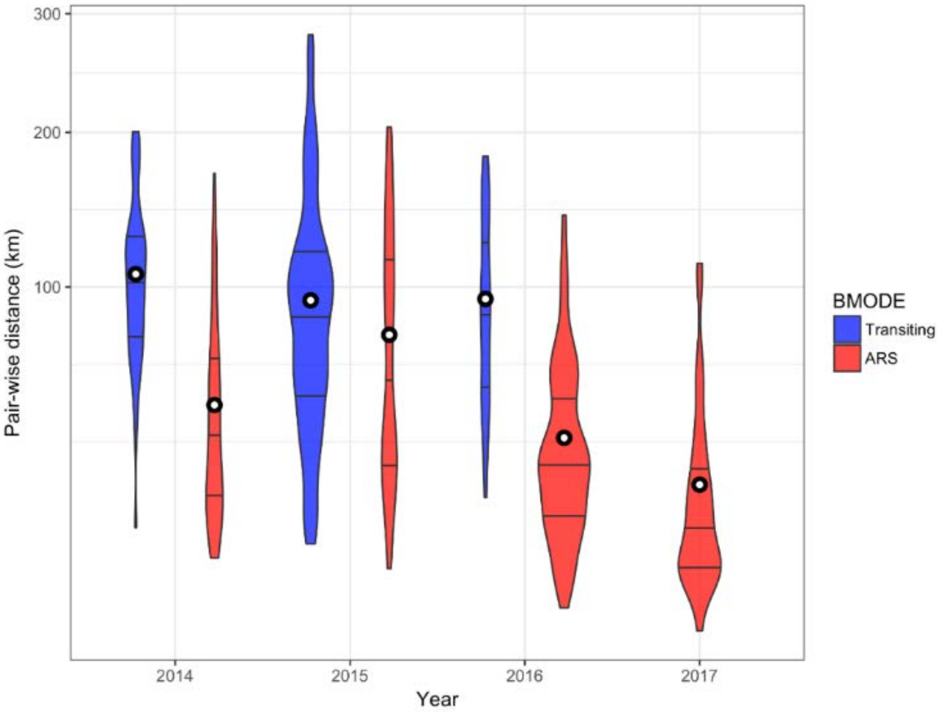

Figure 74. Paired violin plots of PWDIST (km) in CCAL between fin whale SSSM locations classified as transiting and ARS for each year in the study. Horizontal lines inside each violin indicate the quartiles of the data distribution and white circle with black outline indicates the mean. Note the square-root-transformed y-axis for enhanced visualization.

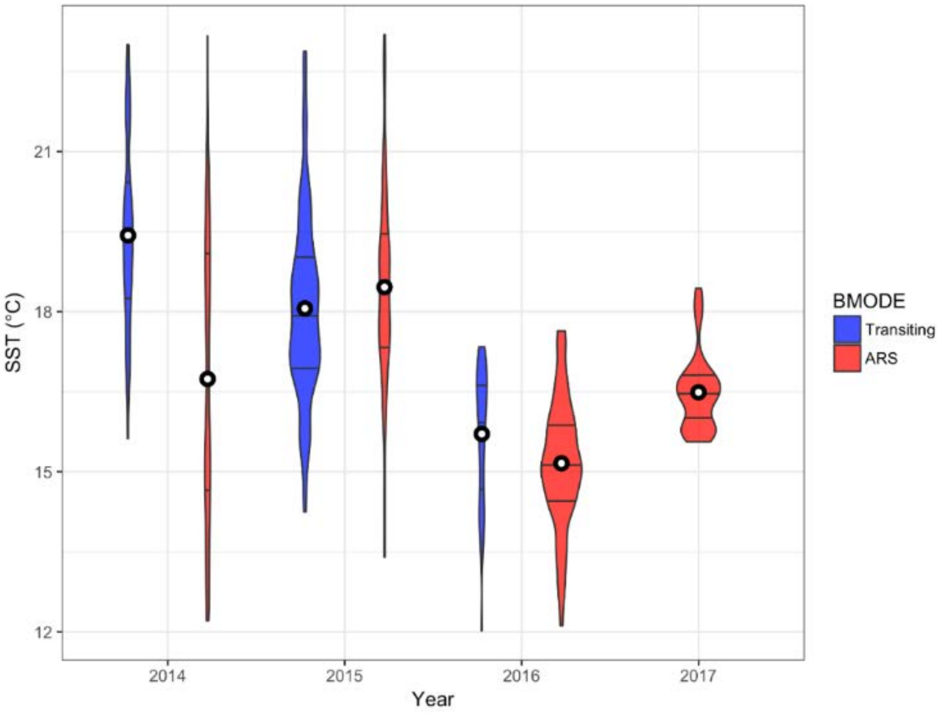

Figure 75. Paired violin plots of sea surface temperature (SST, °C) values in CCAL for fin whale SSSM locations classified as transiting and ARS for each year in the study. Horizontal lines inside each violin indicate the quartiles of the data distribution and white circle with black outline indicates the mean.

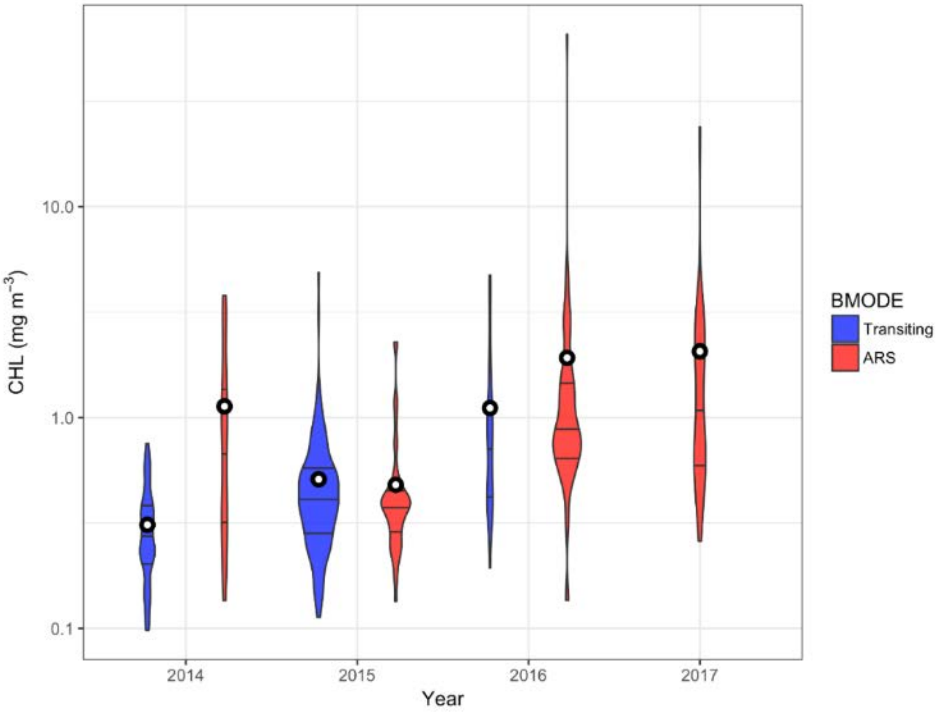

Figure 76. Paired violin plots of chlorophyll-a concentration (CHL, mg m^{-3}) values in CCAL for fin whale SSSM locations classified as transiting and ARS for each year in the study. Horizontal lines inside each violin indicate the quartiles of the data distribution and white circle with black outline indicates the mean. Note the log-transformed y-axis for enhanced visualization.

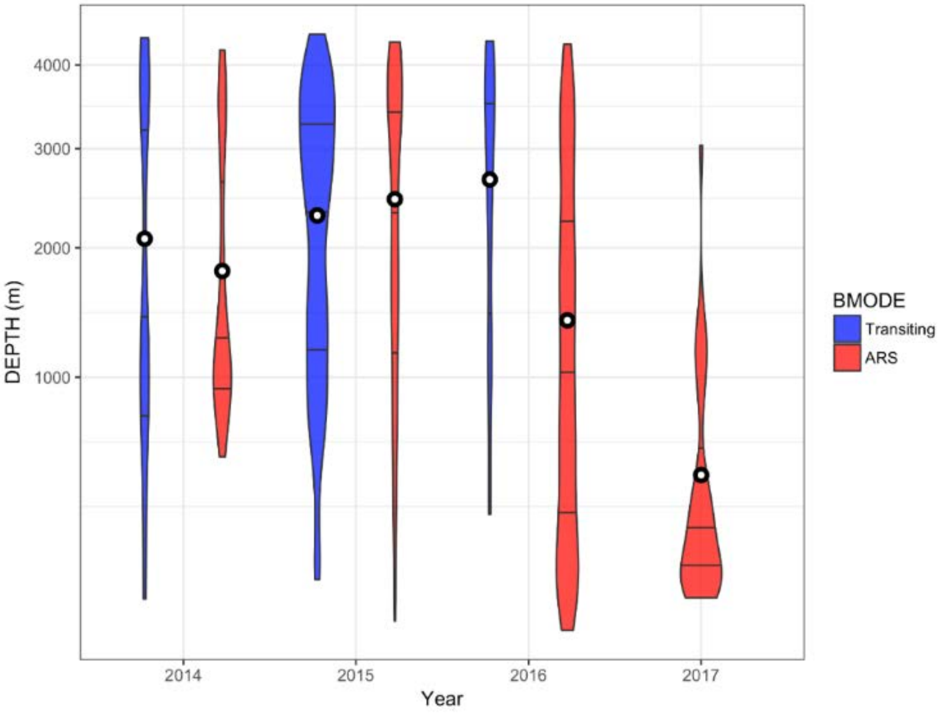

Figure 77. Paired violin plots of seafloor depth (DEPTH, m) values in CCAL for fin whale SSSM locations classified as transiting and ARS for each year in the study. Horizontal lines inside each violin indicate the quartiles of the data distribution and white circle with black outline indicates the mean. Note the square-root-transformed y-axis for enhanced visualization.

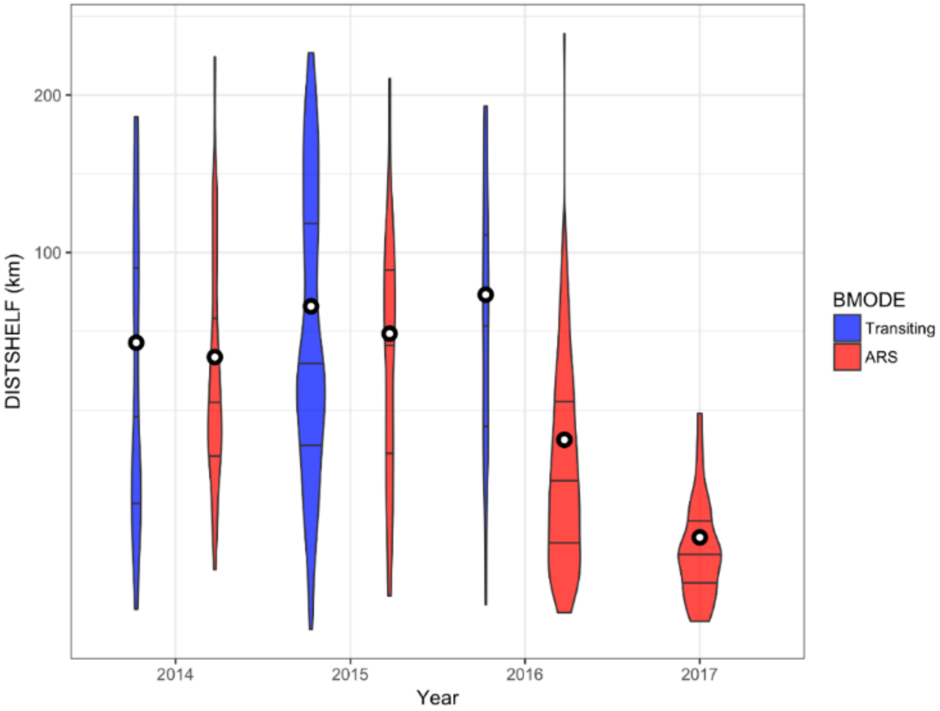

Figure 78. Paired violin plots of distance to the 200-m isobath (DISTSHELF, km) values in CCAL for fin whale SSSM locations classified as transiting and ARS for each year in the study. Horizontal lines inside each violin indicate the quartiles of the data distribution and white circle with black outline indicates the mean. Note the square-root-transformed y-axis for enhanced visualization.

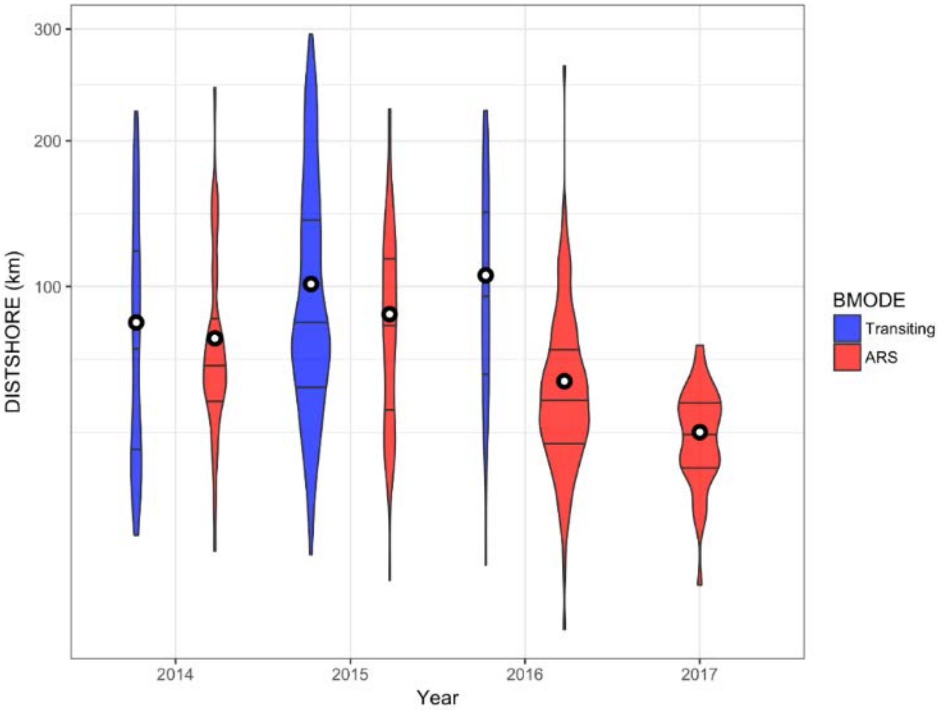

Figure 79. Paired violin plots of distance to the shoreline (DISTSHORE, km) values in CCAL for fin whale SSSM locations classified as transiting and ARS for each year in the study. Horizontal lines inside each violin indicate the quartiles of the data distribution and white circle with black outline indicates the mean. Note the square-root-transformed y-axis for enhanced visualization.

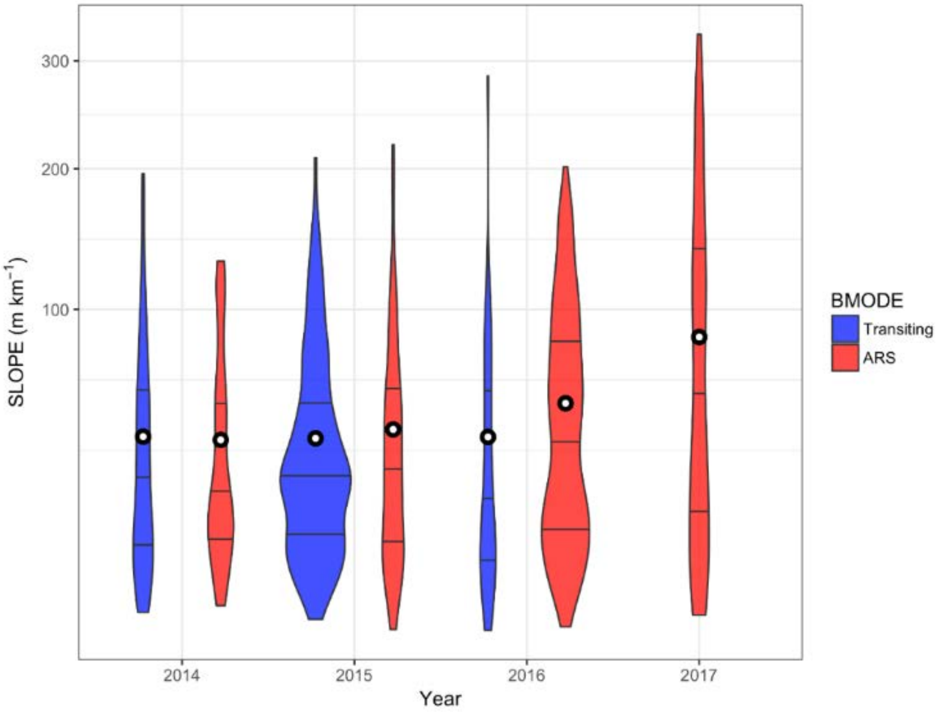

Figure 80. Paired violin plots of seafloor slope (SLOPE, m km^{-1}) values in CCAL for fin whale SSSM locations classified as transiting and ARS for each year in the study. Horizontal lines inside each violin indicate the quartiles of the data distribution and white circle with black outline indicates the mean. Note the square-root-transformed y-axis for enhanced visualization.

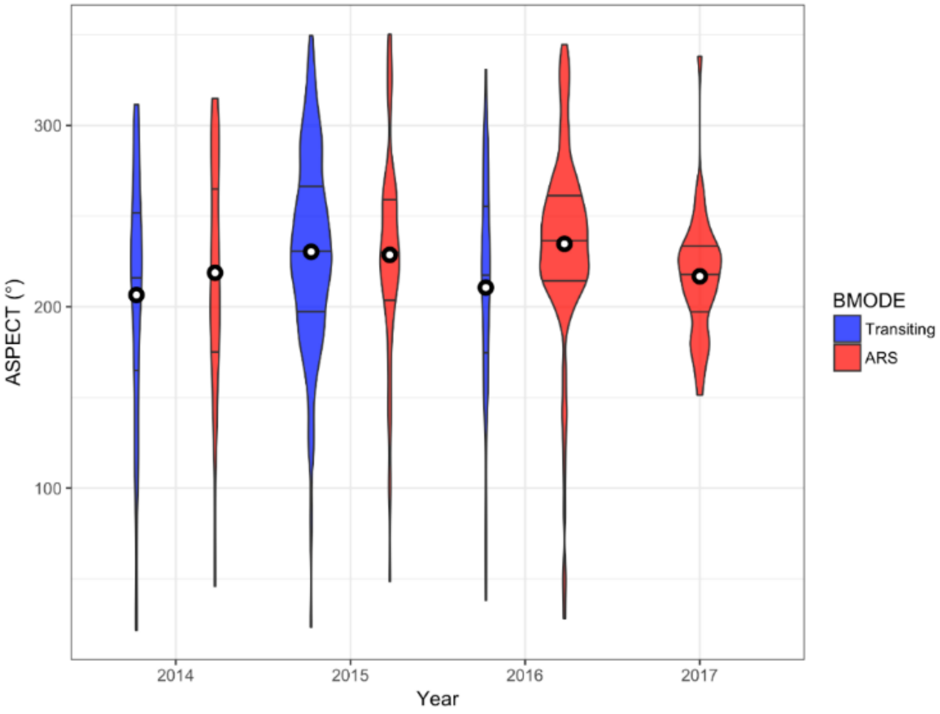

Figure 81. Paired violin plots of seafloor slope aspect (ASPECT, °) values in CCAL for fin whale SSSM locations classified as transiting and ARS for each year in the study. Horizontal lines inside each violin indicate the quartiles of the data distribution and white circle with black outline indicates the mean.

4. Discussion

This report details the results of four years of satellite telemetry studies on blue and fin whales tagged in southern and central California waters. The resulting tracks and dive behavior data provide valuable information regarding the timing, distribution, and behavior of these species with a focus in Navy training ranges in the eastern Pacific and NMFS-identified BIAs for blue whales, as well as an examination of baleen whale movements in relation to oceanographic conditions through their range. The biopsy samples collected provided sex determination for tagged whales and individual identifications, as well as stock structure information. Similarly, the photographs collected provided valuable information about tag wound healing, individual identification, and resighting histories.

As in the previous three years, blue whales were more numerous and easier to approach than fin whales in 2017, with the result that only one tag was applied to a fin whale in 2017, compared to 27 blue whales. Mean tracking duration for the four years combined was longer for blue whales (73.4 d) than for fin whales (55.4 d), but not significantly so (ANOVA, $p = 0.17$).

4.1 Blue Whale

4.1.1 Tracking Analysis

The tracking results from blue whales tagged in 2017 continue to expand our knowledge of the long-term movements, distribution, and dive behavior of these whales in the eastern North Pacific, supplementing information from past years on blue whale occurrence and use of Navy training and testing ranges. As in previous years, most of the blue whale locations in 2017 were within the distribution of blue whales described in previous studies (Calambokidis et al. 2009, 2015, Bailey et al. 2009, Irvine et al. 2014).

Twenty-six blue whales were tagged in southern California in 2017, compared to only one in central California, the latter of which was tracked for less than 3 d. Thus, intra-annual comparisons in movement patterns and habitat use between whales tagged in the two areas were not possible for 2017, as they were for blue whales tagged in 2016. Spatial separation of tracking data in 2016, as well as the photo-ID results from that year, suggested the possibility of distinct groups of blue whales in southern versus central California (Mate et al. 2017a). The tracking data from blue whales tagged in 2017 appears to refute this idea of distinct groups, as 31 percent of the whales tagged in southern California (8 of 26) traveled north of Point Sur, central California, during their tracking periods. A distinction between southern and central California blue whales was also not borne out in the tracking results of all blue whales tagged by OSU from 1994 to 2016 (Mate et al. 2017a), which showed that overall feeding area distribution and migratory destinations were similar between whales tagged in southern and central California. The differences noted between the two tagging groups in 2016 may have been the result of increased productivity in both locations, allowing blue whales to remain in more localized areas, rather than some intrinsic variability between the groups leading to feeding area separation.

Differences also existed between the four tagging years in this study (2014 through 2017), in latitudinal range of blue whales, in total distances traveled, and in sizes and locations of home ranges and core areas. The significantly longer distances traveled and larger home ranges and core areas in 2014 than in either 2015, 2016, or 2017 were likely the result of poorer productivity in the California Current System in 2014 (during the 2013–2015 heat wave; Leising et al. 2015, McClatchie et al. 2016), likely requiring blue whales to range farther to find food. Unlike humpback whales, which have been shown to switch their dominant prey type (from euphausiids to fish or vice versa) in response to changing oceanographic conditions and prey availability (Fleming et al. 2016), blue whales are almost completely stenophagous (euphausiid-eating). They likely need to travel in search of other locations or species of euphausiids in times of low prey abundance (Hazen et al. 2012), rather than switching to a different prey type. Fleming et al. (2016) noted that blue whales were distributed more widely throughout the California Current System and farther north in 2004 to 2006, when there was a delay in seasonal summer upwelling (compared to other years) and poor euphausiid recruitment in nearshore feeding areas. Calambokidis et al. (2009) also pointed to changes in oceanographic conditions and inadequate feeding conditions in California to explain recent shifts in blue whale habitat to include areas off British Columbia and Alaska. Burtenshaw et al. (2004) reported increased calling duration of vocalizing blue whales off Washington and Vancouver Island in 1998 and 1999 than in other years of their study, and suggested this was due to increased prey availability or increased northern movements by whales. The authors suggested that El Niño conditions during 1997/1998 decreased prey availability in southern California, while the northern regions remained productive. The northern extent of blue whale locations in this study in 2014 was off the northern tip of Vancouver Island, compared to central Oregon for both 2015 and 2016, and central California for 2017, when upwelling conditions were more prevalent (Leising et al. 2015, McClatchie et al. 2016, NWS 2018, NOAA 2018). A progressively worsened body condition as a result of consecutive low-productivity years may also have resulted less stamina for longer distance movements to the north in subsequent years.

PT MUGU was the most heavily used Navy training range by blue whales for the four years of study combined, both in terms of total numbers of whales having locations there (76 of 90 tracked whales) and in residence time (overall mean of 28.8 d). This is not surprising, as most of the whales were tagged there and this range encompasses one of the main hotspots of blue whale occurrence in California (the western end of the Santa Barbara Channel), as identified by overlapping core areas for tagged blue whales in this study and in Irvine et al. (2014). SOCAL was also used by a high number of blue whales in this study (51 of 90 tracked whales), and was the most heavily used range in 2014. Differences in blue whale use of Navy training ranges between different tagging years was likely driven by differing oceanographic conditions. In 2014, blue whales used inshore, more southern waters of the Southern California Bight when there was a collapse of the typical upwelling at Point Conception (Leising et al. 2015). The NWTT area was used by a small number of blue whales (9 of 90) over the three-year study, but those that were located there spent an average of 23.4 d in the area, resulting in more extensive overlap of HRs and CAs with this range than with SOCAL. In both 2014 and 2016, 17 percent of tracked blue whales spent time in NWTT, which suggests that the area is not just used by blue whales in times of reduced productivity. Only one of 90 tracked blue whales had locations in W237 of the NWTT, however, spending 19.5 d in the area in 2014. W237 may only be used by a small number of blue whales and only in times of reduced productivity, as whales range farther north in search of food. While the numbers of tagged blue whales occurring in the NWTT and W237 are not high, the lengthy residencies highlight the importance of both of these areas as northern feeding habitat for some blue whales.

Blue whale locations occurred in PT MUGU from July to December, in SOCAL from July to November, in SOAR from July to September, in NWTT from August to December, and in W237 from September to November. The predominance of summer and fall locations of tagged blue whales in Navy training ranges off the U.S. West Coast reflects the seasonality typical of most baleen whales, in which individuals migrate poleward to feeding areas in the summer and fall. Two blue whales in this study were tracked returning to U.S. waters after migrating south for the winter, and provided additional locations in SOCAL in March and June, in PT MUGU in March and April, and in SOAR in March. These results indicate that springtime use of Navy ranges, and southern ranges in particular, may be common, whereas winter occurrence in the ranges is rare.

As with the Navy training ranges, there were also striking differences in blue whale use of BIAs between 2014 and the other three tagging years. The San Diego and the Santa Monica Bay to Long Beach BIAs were the most heavily used in 2014, whereas the Santa Barbara Channel and San Miguel Island and the Point Conception/Arguello BIAs were the most heavily used in 2015, 2016, and 2017. This preference for the more southeasterly and coastal BIAs in 2014 coincided with the decrease of upwelling mentioned above around Point Conception that year (Leising et al. 2015). Despite these inter-annual differences, overall, the Santa Barbara Channel and San Miguel Island BIA appears to be the most important BIA to blue whales of the six that overlap Navy training ranges, in terms of number of whales using the area, time spent there (with a maximum residency of 63.3 d), and number of overlapping core areas. The southward wind-driven upwelling from Point Conception, shelf breaks, island slopes, and nearby seamounts at the west end of the Channel Islands support dense aggregations of euphausiids as a result of increased turbulence, mixing, and surface nutrients, thus contributing to the importance of this area for blue whales (Fiedler et al. 1998, Burtenshaw et al. 2004). The remaining two BIAs, San Nicolas Island and Tanner-Cortes Banks, were used only minimally by blue whales in 2017, as was the case in the other three years, suggesting that these areas are of much less importance to blue whales than the other BIAs. Most tracking results are from summer and fall, however, and perhaps these latter BIAs see more blue whale use in the spring. Calambokidis et al. (2015) report that the primary months of occurrence for blue whales in San Nicolas Island and Tanner-Cortes Banks begins in June, before any of our tagging took place. It is also important to note that our tracking data span only four years, whereas BIA identification was based on 25 years of sighting data, during which time the PDO experienced both cool and warm phases. As noted in Section 4.1.3, shifts in blue whale occurrence have been reported to coincide with the PDO cycle (Calambokidis et al. 2009), and as our tracking data were obtained during only a warm phase of the PDO, differences between our data and the data used in BIA identification are to be expected. Tagging more blue whales, earlier in the year, and perhaps south of the U.S. border would refine our understanding of blue whale use of these more southerly BIAs. Our tracking data also suggest that some BIAs could be extended further offshore (such as the Santa Barbara and Point Conception BIAs) or that additional BIAs may be appropriate, such as between Point Buchon and Monterey Bay, and off Cape Mendocino and the California/Oregon border.

4.1.2 Dive Behavior Analysis

DM tags were able to document blue whale diving and feeding behavior over extended time periods by transmitting dive data that summarized a mean of 42 percent of the tracking period. The percentage of the track summarized by the transmitted data was shortest for the longest duration tags, likely due to the change in transmission protocol from every day to every other day after 1 September 2017. A larger percentage of the tracking period could be summarized by increasing the number of transmit days, but that would reduce the functional life of the tag, so research priorities should be carefully considered when deciding on desired level of data recovery for future research.

The diel pattern of more lunges and deeper dives reported during the day by DM tags matches closely with what was documented by ADB tags deployed in 2014–2015. This suggests that the number of lunges detected by DM tags in 2017 is a reasonable approximation of the feeding effort that occurred during the tracking period. Daytime dive depths were over two times deeper in 2017 compared to previous years. This may suggest that prey was located deeper in the water column in 2017, or it may be the result of a disproportionately large number of non-feeding dives being reported in 2016 due to the shorter attachment durations.

Similar to DM tags deployed in 2016, 2017 tag data indicated there were regional differences in the spatial distribution of daytime dive depths at which DM-tagged whales were feeding. Daytime dive depths for DM-tagged blue whales were deepest at the high-feeding-effort area near San Miguel Island off southern California. High-feeding-effort areas to the north coincided with shallower daytime dive depths. This may be related to regional differences in prey species composition, or represent a difference in the daytime behavior of prey species that is related to each region's topography and physical oceanographic structure.

DM-tagged whales were tracked across an extensive portion of southern and central California waters; however, foraging effort predominantly occurred from the tagging area to central California. This is known to be a highly productive region where blue whales regularly occur (Fiedler et al. 1998, Santora et al. 2011, Mate et al. 2017a). Feeding effort in those areas was broadly distributed in both 2016 and 2017 suggesting that prey may have been dispersed, forcing the whales to move continuously, rather than remaining in one localized area. The two most dominant euphausiid species off the U.S. West Coast are *Thysanoessa spinifera*, typically found nearshore and out to the shelf edge, and *Euphausia pacifica*, which is typically found in waters deeper than 200 m (Brinton 1962) although they both occur in some nearshore areas like Monterey Bay and the west end of the Channel Islands (Croll et al. 1998, 2005, Fiedler et al. 1998). Blue whales are known to feed on both species (Croll et al. 1998, 2005, Fiedler et al. 1998) and there is evidence they selectively target the larger *T. spinifera* when both are available (Fiedler et al. 1998, Nickels et al. 2018). The difference in tagged whales remaining in consistently productive places like the tagging areas, versus feeding offshore may therefore be related to the euphausiid composition in each region. The tagging areas likely offer both *T. spinifera* and *E. pacifica*, while the whales feeding farther offshore are likely finding lower species variety and/or density.

In 2016 DM tags were deployed in both southern and central California with little interchange between the two areas. In 2017 multiple whales fed extensively off central California despite only one short-lived DM tag being deployed there. The movement of more tagged whales from southern to central California in 2017 compared to 2016 may be due to inter-annual differences in prey concentration in these two areas or to the whales' body condition. The longer attachment durations of 2017 tags may have also allowed for a more comprehensive view of the whale's movements.

In contrast to other areas, foraging effort recorded to the south of the tagging area was limited despite extensive occupancy of the area. This suggests that feeding opportunities were highly localized and of limited duration (for a specific example see **Figure 82**; also Mate et al. 2017a). The apparent spatial segregation of male and female blue whales in southern California waters, first noted in Mate et al. (2017a), was further re-enforced by the 2017 results as only male whales were recorded feeding in the waters south and west of San Clemente Island. The results across all years suggest that whales of both sexes feed in the nearshore waters of southern California, but the offshore waters appear to be used predominantly by males. While feeding does occur in these offshore areas, it is sporadic and of short duration. The behavioral difference between sexes would suggest that it is related somehow to reproduction, but more research is needed to understand the mechanism that may be driving such behavior.

4.1.3 Ecological Relationships

The 85 SSSM blue whale tracks analyzed in the four years of this study (2014, 2015, 2016, and 2017) covered a large but inter-annually variable geographic extent (20 to 44 degrees of longitude and 26 to 44 degrees of latitude), with a presence in seven of the eight biogeographic provinces of the eastern North Pacific considered here. No tagged blue whales were tracked to the (PSGEP) during this study, although one blue whale was tracked there by OSU in 2007 (as presented in our annual report for 2014; Mate et al. 2015). Conversely, during this study one blue whale was tracked to ALSK (2014) and one to PQED (2015–2016) for the first time. It should be kept in mind, however, that the pattern of occupation of the biogeographic provinces reported here may not directly reflect that of the entire eastern North Pacific blue whale population due to biases arising from the province where the animals were tagged (CCAL) as well as from the typical duration of the tracking period. Tagging in a different region and migration phase might have resulted in a different biogeographic pattern.

These large-scale shifts within the range likely are in response to the strongly anomalous oceanographic conditions that occurred during the first three years of the project, including: (a) warm SST anomalies associated with the marine heat wave of 2013–2015 (Bond et al. 2015, Leising et al. 2015, Di Lorenzo and Mantua 2016, McClatchie et al. 2016), (b) warm SST anomalies associated with the 2015–2016 El Niño event (Jacox et al. 2016, Levine and McPhaden 2016, Wells et al. 2017), and (c) cold SST anomalies associated with the 2016–2017 La Niña event (Wells et al. 2017). Further, although no major oceanographic perturbations were reported in 2017 (http://origin.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ONI_v5.php), strongly negative NPGO sea-surface height anomalies were persistent in the latter half of 2017, concomitant with cold ONI SST anomalies, possibly being the cause of the "warm in the north, cold in the south" pattern observed in the California Current ecosystem that was reported by Wells et al. (2017).

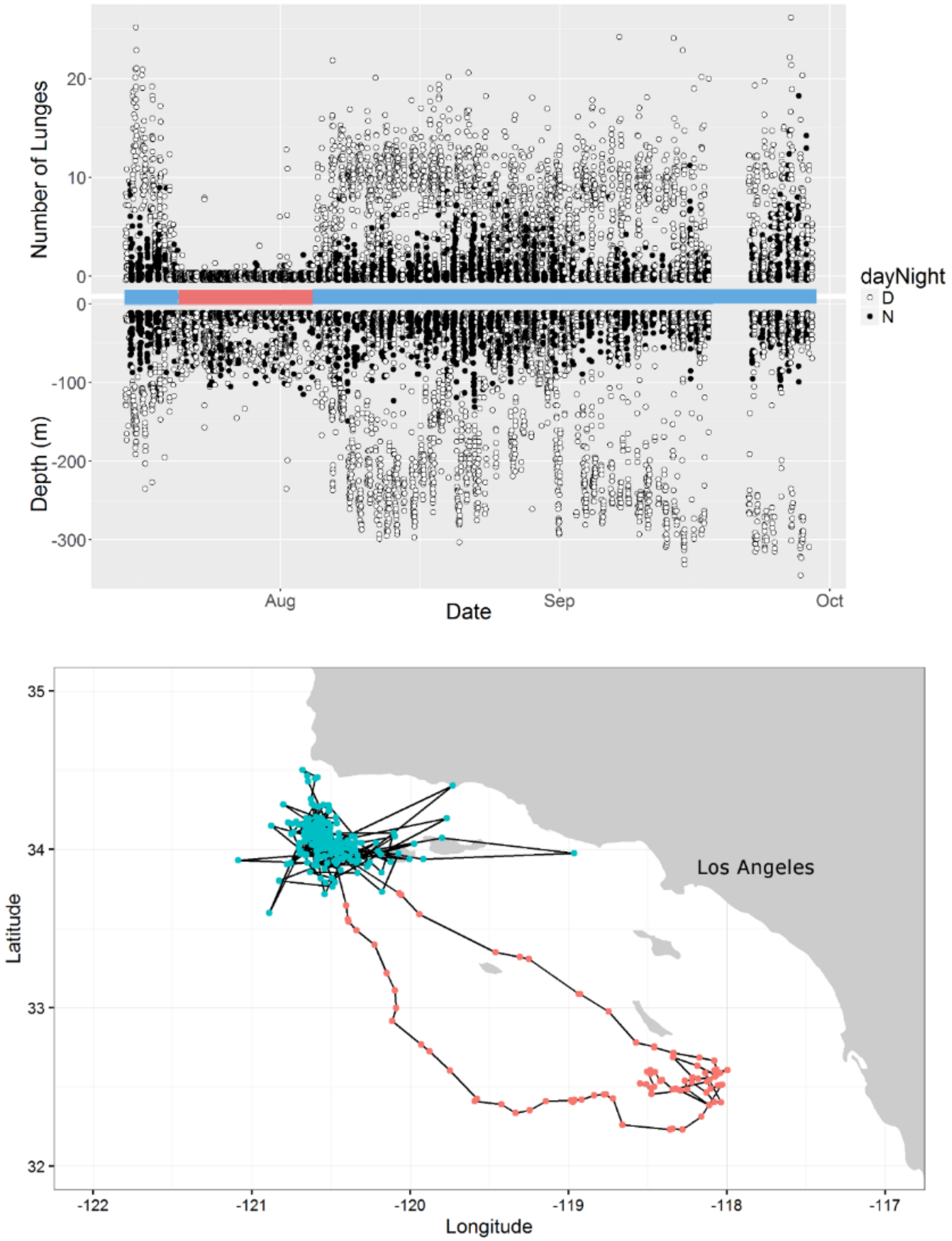

Figure 82. The number of lunges per dive (top, upper panel) and maximum depth of dives (bottom, upper panel) made by a DM-tagged blue whale (Tag #5790; a male) off southern California showing a strong diel trend of deeper dives with more lunges during the daytime. The colored bar in the upper panel corresponds to the color of portions of the whale's track shown in the bottom panel. The greatly reduced number of lunges in late July–early August coincides with the whale moving to an area south of San Clemente Island before returning to the tagging area off San Miguel Island. This figure is reproduced from last year's annual report (Mate et al. 2017a) and the tag was programmed differently than those in the current report.

Specifically, within CCAL, the province with highest occupation during summer and fall (73 to 99 percent), inter-annual differences were observed in blue whale behavior and in several of the environmental variables examined in this study that reflected these anomalous oceanographic conditions. These trends are consistent with documented biotic changes in the California Current in response to the anomalies that occurred during the study period, which likely had an impact on the abundance, distribution, species composition, and nutritional value of the euphausiids upon which blue whales foraged. The 2013–2015 heat wave led to unprecedented and lasting alterations to the ecosystem due to the widespread cessation of upwelling (Leising et al. 2015, Cavole et al. 2016, Du et al. 2016, McCabe et al. 2016, McClatchie et al. 2016, Auth et al. 2018, Daly et al. 2017, Gómez-Ocampo et al. 2017), and to greatly reduced blue whale foraging success in 2014. In contrast, the 2015–2016 El Niño, while being one of the strongest on record (at least in terms of the magnitude of the ONI SST anomalies in the Niño 3.4 region), reportedly only had modest biotic effects in the CCAL ecosystem (Leising et al. 2015, Jacox et al. 2016, McClatchie et al. 2016, Wells et al. 2017). Strong upwelling pulses at several coastal locations in spring–summer 2015 were responsible for maintaining an overall moderate productivity at this time (Leising et al. 2015, Jacox et al. 2016), such that during the 2015 tracking period environmental conditions were slightly improved and blue whale foraging success was slightly higher than in 2014. The cold anomalous conditions of the 2016 La Niña, which returned in the latter part of 2017, were conducive to elevated biological productivity, especially south of Cape Mendocino (Wells et al. 2017), and blue whale foraging success was greatest.

The background to these inter-annual changes was a warm phase of the PDO that started in January 2014 and that continued through the end of 2017. These PDO phase or "regime" shifts occur every 20 to 30 years (Mantua et al. 1997, Zhang et al. 1997, Mantua and Hare 2002), and in the California Current ecosystem they are accompanied by profound and widespread changes in community structure and function, from phytoplankton to top predators (e.g., Brinton and Townsend 2003, Peterson and Keister 2003, Ainley and Hyrenbach 2010, Keister et al. 2011, Koslow et al. 2013, Du et al. 2015, Messié and Chavez 2017). For blue whales, Calambokidis et al. (2009) documented an apparent correlation between range expansions and contractions and PDO cool and warm phases, respectively. The results of our four-year project are consistent with this interpretation, as the northernmost latitudinal extent of the distribution of tracked blue whales retracted each year from 51°N in 2014 to 44°N in 2015 and 2016, to 39°N (south of Cape Mendocino) in 2017. It may be that during warm PDO phases the northern part of the California Current ecosystem becomes unfavorable for forage species, especially if the NPGO is in a negative (i.e., low-productivity) phase. Consideration of alternative climate indices specifically developed for the California Current ecosystem (Sydeman et al. 2014, Frischknecht et al. 2015, Ohman et al. 2017) may provide enhanced support for this interpretation.

Blue whales may rely on intrinsic and extrinsic signals to respond to these environmental and biotic changes. For example, poor feeding success in the coastal upwelling ecosystem of the California Current in one year may affect how far north a whale ventures in the following year(s), as it may not have acquired sufficient energy to make extended forays into regions of more unpredictable resources in subsequent years. Alternatively, it may be that the whales' movements are a more direct reflection of local prey composition and availability along the coast in a given year. During El Niño events, lower-quality tropical forage species invade the

California Current System from the south, displacing the local high-quality species. Analogously, during warm PDO phases, species from the north are found in more southern latitudes, such that the transition to a more subarctic (and comparatively lower-quality) biological community occurs farther south along the western coast of North America, and whales from this population avoid venturing farther to the north. The opposite patterns of whale occupation would occur in response to La Niña events and cool PDO phases with the expansion of the productive habitat to the south and to the north, respectively.

Finally, we note that while blue whales generally had distinct preferences for all the environmental and seafloor relief variables we examined, several of the variables showed no noticeable differences between years. Such was the case for seafloor slope (SLOPE) and slope aspect (ASPECT). Because inter-annual differences were noticeable for the related variables depth (DEPTH) and distance to the shoreline (DISTSHORE), this suggests that slope and aspect have a limited range of variability throughout CCAL, making them less useful as habitat predictors in the face of changing environmental conditions. In this regard, the scales of sea surface temperature (SST) and chlorophyll-*a* concentration (CHL) variability were most closely matched to the scale of blue whale movement in CCAL in the four years of the project (as determined by the daily SSSM locations). Further, while conceptually the pairwise distance between SSSM locations (PWDIST) is implicit in the estimation of behavioral mode (as the classification of transiting and ARS modes is based on the pattern of speed and turning angle between location pairs), PWDIST provided an ecologically meaningful metric of the scale of whale movement (and hence possibly of the scales of foraging and prey patchiness) under a variety of environmental conditions.

4.1.4 Genetics

The genetic analyses to date have provided new information on the diversity of mtDNA haplotypes for blue whales in the eastern North Pacific, as well as the sex and individual identity of tagged individuals. The "DNA profiles" (i.e., microsatellite genotypes, mtDNA haplotypes, and sex) of 62 tagged whales have been reconciled with those available from archived samples with OSU and with a subset of available samples from the Cascadia Research Collective. This provides a catalogue or "DNA register" of more than 120 individual blue whales, most of which have associated information from tagging or photo-ID.

There were no significant differences in mtDNA haplotype frequencies between the tagged blue whales from 2014 to 2017 and the reference database for the eastern North Pacific. Although this comparison provided reasonable confidence that the two samples do not represent distinct stocks, we cannot discount the potential for more subtle spatial heterogeneity or fine-scale population structure in this geographic region. Our analysis of stock structure was also limited by the absence of samples from other putative stocks in the North Pacific, particularly the Western North Pacific stock (Monnahan et al. 2014). Without more representative sampling, it is difficult to construct analyses for alternate stock structure hypotheses.

Although we confirmed differentiation of the eastern North Pacific blue whales from other populations or subspecies in the Southern Hemisphere, there was considerable sharing of mtDNA haplotypes, particularly with the eastern South Pacific. The sharing of common haplotypes at high frequencies is evidence of recent divergence or ongoing genetic exchange between the hemispheres. The documented migration of a female blue whale from the Chilean feeding ground to the Galapagos Islands, just south of the equator (Torres-Florez et al. 2015), also suggests the potential for genetic exchange by individual movement or by male-mediated "gametic exchange" (although the probability is likely limited by out-of-phase seasonal use of the area between the two populations). This possibility could be tested further by collaboration on developing a standardized set of nuclear markers (e.g., microsatellites or Single Nucleotide Polymorphisms) for further comparison of the two populations.

4.1.5 Concluding Thoughts (Integration of Tagging, Ecological, and Genetic Information)

The 85 SSSM blue whale tracks analyzed in the four years of this study (2014, 2015, 2016, and 2017) add to the collection of 104 blue whale tracks that OSU had previously obtained in the eastern North Pacific between 1994 and 2008 (Bailey et al. 2009, Irvine et al. 2014, Mate et al. 2015). Combined, these data sets now span more than two decades and present a unique opportunity for a more complete examination of blue whale responses to inter-annual and decadal variability. Over this time period, the PDO went from a warm phase (years prior to 1999) to a cool phase (1999–2013) and back to a warm phase (2014–present). Multiple El Niño (1994–1995, 1997–1998, 2002–2003, 2009–2010, 2015–2016) and La Niña (1995–1996, 1998–1999, 1999–2000, 2007–2008, 2010–2011, 2011–2012, 2016–2017) events occurred during this period (Fisher et al. 2015), and other anomalous events that disrupted North Pacific ecosystems were recorded (a subarctic intrusion in 2002 [Murphree et al. 2003]; delayed upwelling in 2005 [Schwing et al. 2006]; and collapsed upwelling in 2009 [Bjorkstedt et al. 2010, Melin et al. 2010]).

In addition, the collection of biopsy samples and identification photographs in southern and central California during the four years of this study present opportunities for further integration with external genetic collections and photo-ID catalogs. An integration of these datasets would be a valuable resource for future estimates of abundance by genotype capture-recapture (Carroll et al. 2013) and further investigation of population structure (similar to that now available for humpback whales in the North Pacific [Baker et al. 2013]), including looking into fine-scale genetic structure of blue whales in the North Pacific (Costa-Urrutia et al. 2013). Finally, analysis of stable isotopes and pregnancy determination on the biopsy samples collected through this project would yield further insight into their seasonal movement patterns (Busquets-Vass et al. 2017), reproductive condition (Clark et al. 2016), and inter-annual/decadal responses to climate variability (Fleming et al. 2016).

Because the 2014–2017 taggings during this study included a variety of oceanographic circumstances indicative of lower-than-normal productivity, it would be valuable to see additional tagging occur during future years with more usual productivity to determine the duration of the observed effects that appear to have compressed the range of blue whales, perhaps as a result of reduced fitness. A better knowledge for the Navy to address year-to-year variability would be useful as a fact-based explanatory factor affecting whale use of Naval training areas.

4.2 Fin Whale

4.2.1 Tracking Analysis

As with the blue whales, the tracking data obtained from fin whales in 2017 add to our sample sizes from the previous three years, providing a richer data set of information on long-term movements and dive behavior of fin whales in the eastern North Pacific, as well as increasing our understanding of occurrence and use of Navy training and testing ranges. Few fin whales were encountered in California in 2017, either in southern or central California, and only one whale was tagged off the central California coast. The resulting fin whale locations from the 2017 tagging matched sightings and some fin whale tracks off central California from other studies (Falcone et al. 2011, Calambokidis et al. 2015, Scales et al. 2017).

The overall latitudinal range of tagged fin whales in 2016 was similar to that in 2015, with the northern-most extent being off the islands of Haida Gwaii, British Columbia, in both years. This was much farther north than for fin whales tagged in 2014, for which the northernmost location was off Cape Blanco in southern Oregon. Inter-annual differences in oceanographic conditions affecting prey distribution may have been a contributing factor in these patterns, but another important contributor is the different sample sizes between years, with twice as many fin whales being tagged in both 2015 and 2016 than in 2014. In 2017, when only one fin whale was tagged, the latitudinal range was the most compressed, with this whale remaining between Monterey Bay and Point Reyes for its entire 42-d tracking period. Despite similar northern extremes in 2015 and 2016, distances traveled by fin whales were significantly different between 2015 and 2016, with the former being longer than the latter. Significant differences between years also existed in the size of fin whale home ranges and core areas, with 2015 have the largest areas. Larger home ranges and core areas and longer distances traveled in 2015 than in 2014 is the opposite pattern that was found for blue whales in those two years. This is not surprising, however, as fin whales have a broader foraging niche than blue whales, capable of prey-switching between euphausiids and small pelagic fish (Calambokidis et al. 2015, Scales et al. 2017), so they quite likely respond differently than blue whales during times of low productivity. The constriction of home ranges and core areas for fin whales off central California in 2016 and 2017 and shorter distances traveled suggest even better oceanographic conditions in that area in those years, perhaps with higher concentrations of prey that were more localized and persistent, allowing fin whales to forage well in smaller areas.

There were no locations in Navy training ranges for the fin whale tagged in 2017. PT MUGU was the most heavily used Navy training range for fin whales in all other tagging years, in terms of number of whales having locations there as well as home ranges and core areas occurring there (more than half of them were also tagged there). SOCAL was the second most heavily used training range in terms of number of fin whales as well as home range and core area overlap in 2014, but NWTT was the second most heavily used range in 2015. No fin whales tagged in 2016 had locations in SOCAL or SOAR, and only one fin whale crossed through NWTT in 2016. Two whales had locations in W237 in 2015, and one in 2016, but the latter only passed through the area briefly on its way farther north. PT MUGU, SOCAL, and SOAR encompass some of the areas of highest density for fin whales identified previously by visual surveys and habitat-based density models (Falcone et al. 2011, Calambokidis et al. 2015), as well as previous tagging studies (Scales et al. 2017). NWTT also encompasses areas with high predicted density for fin whales (Becker et al. 2016) and while numbers of fin whales in this study using this range and W237 were low, time spent there was high for some whales (maximum of 57.4 d for NWTT and 22.3 d for W237) and much higher than in other ranges in 2014 and 2015. As with blue whales, these northern ranges appeared to be important feeding habitat for some fin whales in some years. Schorr et al. (2013) noted an increase in fin whale sightings off the Washington coast since 2009 and reported extended residencies of fin whales in the NWTT and W237.

Fin whale use of NWTT and W237 occurred primarily in late summer and fall, whereas fin whales could be found in PT MUGU in summer, fall, and winter, and in SOCAL in all seasons. The occurrence of fin whale locations in SOCAL in January, February, and March, as well as in the summer and fall support the evidence of previous studies that fin whales have a year-round presence off southern California (Caretta et al. 1995, Forney and Barlow 1998, Širović et al. 2013, 2015, Scales et al. 2017). Scales et al. (2017) report that North Pacific fin whales do not engage in a standard baleen whale migration, a finding that is further confirmed here by the fact that fin whales tracked in this study did not engage in a typical unidirectional migration south of California in winter.

The fin whale tracking results in this study refute the idea of regional subpopulations of fin whales in the eastern North Pacific (Falcone et al. 2011), with little movement between regions. Even with the shorter distances traveled by fin whales in 2016, two of the animals visited more than one of the regions delineated by Falcone et al. (2011), one having locations in three regions—1) northern California, 2) Oregon and Washington, and 3) British Columbia and Southeast Alaska—and one having locations in two regions—northern California and southern California. Nine of the 12 fin whales tracked with fully implantable tags in 2014 and 2015 (all tagged within the Southern California Bight) visited more than one region, and most of these whales spent time in three or more regions. In addition, these inter-regional movements occurred within the same year and in many cases involved movements back and forth between the regions, contrary to photo-ID studies, for which few whales were seen in more than one region and none were seen in different regions in the same year (Falcone et al. 2011). An extreme example of inter-regional movement is provided by a fin whale tagged by OSU in 2006, that traveled from its tagging location off southern California to Haida Gwaii, out to the Gulf of Alaska, south on an offshore route to 18ºN, north again to Haida Gwaii, and ultimately returning to southern California during its 316 d tracking period (**Figure 83**). Note that the entire loop from British Columbia to 18ºN and back to British Columbia was well offshore and did not involve any apparent ARS behavior that would be typical of either feeding or reproductive activity. Further, from a navigation standpoint, it transited through a very similar location off the shore of Washington State during these southward and northward excursions. Scales et al. (2017) also proposed the idea of a distinct subpopulation of fin whales in the Southern California Bight based on their satellite tracking of fin whales from 2008 to 2014, but acknowledge that some regional seasonality exists in movements, with habitat suitability and fin whale presence increasing in central California in summer and fall.

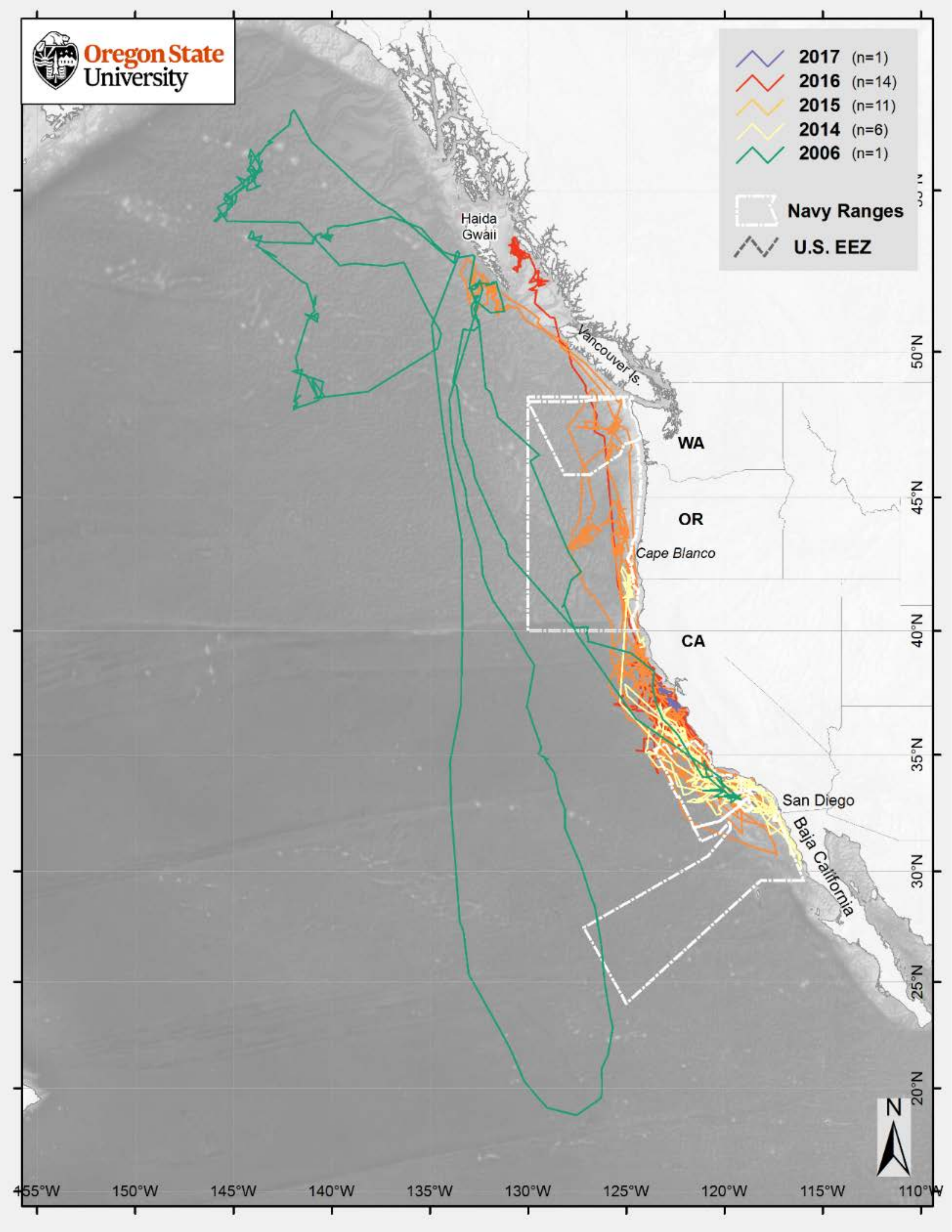

Figure 83. Satellite-monitored tracks for fin whales tagged off southern and central California during summer 2006, and 2014–2017.

BIAs have not yet been identified for fin whales due to the poor agreement between predicted high-density areas from habitat-based density models and sighting concentrations, poor knowledge of population structure, and the offshore distribution of the species compared to the primarily coastal effort of sighting surveys (Calambokidis et al. 2015). The tracking data presented here align well with some areas of predicted high density (Calambokidis et al. 2015), such as off Point Buchon and central California (Monterey Bay to San Francisco) but also with areas of concentration identified from sighting surveys, such as in the Southern California Bight (including inshore waters near Palos Verdes) and off the coast of Washington State. These latter areas as well as perhaps areas off the coast of Oregon and British Columbia deserve consideration in future BIA discussions.

4.2.2 Dive Behavior Analysis

DM tags offered the ability to document fin whale diving and feeding behavior over substantially longer time periods than were previously possible (e.g., with suction-cup tags or with ADB tags), allowing for better insight into where and how much feeding occurs. No data were available for discussion of fin whale dive behavior in 2017, but feeding effort in 2016 was generally uniform at a moderate level across the U.S. West Coast, with small patches of limited effort far offshore (as was described in last year's annual report [Mate et al. 2017a]). The highest feeding effort was recorded by a whale that traveled to the Hecate Strait and fed there for 39 d. This was surprising, especially as the tagged whales visited highly productive regions like the Gulf of the Farallones, Monterey Bay, and the western Santa Barbara Channel, without generating elevated feeding effort in any of them. As prey distribution and abundance are primary drivers of baleen whale distribution over broad scales, this would indicate that fin whales were able to find sufficient prey throughout the study area and/or preferentially did not limit themselves to feeding for an extended period of time in one area (with the exception of the whale that fed extensively in the Hecate Strait off British Columbia). Daytime dive depths reported by the rest of the DM-tagged fin whales in 2016 also was similar across the study area, suggesting the whales were feeding on similar prey throughout the areas used off the U.S. West Coast.

The generally consistent feeding effort recorded by DM-tagged fin whales across their central California tracking range in 2016 was in contrast to DM-tagged blue whales, which were more likely to feed in localized areas. As with blue whales, however, only male fin whales made long, clock-wise circuits of southern California waters with little feeding, while female tracks were more clustered and reported more feeding behavior. The behavioral difference between sexes would suggest it is somehow related to reproduction but more research is needed to understand the mechanism that may be driving such behavior.

4.2.3 Ecological Relationships

The geographic extent covered by the 28 fin whales tracked in the four years of this study (2014, 2015, 2016, and 2017) was smaller than that of the blue whales, but it also displayed marked interannual variability (10 to 16 degrees of longitude and 12 to 22 degrees of latitude; not including the single fin whale tagged in 2017 that had a very restricted range). Also, while blue whales migrated in late fall and winter from CCAL to lower-latitude provinces (PNEC, GUCA, PQED), fin whales moved northward and remained in CCAL or visited ALSK.

Inter-annual differences in fin whale behavior in CCAL during the first three years of the project (which were more appropriately compared from a sample size perspective) suggested very low foraging success in 2015 (11 percent ARS activity), relative to the other two years (19 percent in 2014 and 35 percent in 2016). In contrast, blue whale foraging success in 2015 (during El Niño) was higher than in 2014 (during the heat wave). Examination of PWDIST, SST, and CHL values where ARS activity occurred provided clues for this interspecific difference in foraging success during the two years; while in 2015 blue whales covered smaller distances between ARS location pairs and foraged in areas with lower SST and similar CHL levels than in 2014, fin whales covered significantly larger distances and occurred in areas with the highest SST and lowest CHL recorded during the study. In contrast, in 2016 (during La Niña), both species foraged in habitats with the coolest SST and highest CHL recorded during the study, and both had high levels of ARS as well as the smallest distances between ARS locations pairs (mean PWDIST = 21.6 km for blue whales and 35.5 km for fin whales).

Together, these results suggest that the anomalous warm events of 2014 and 2015 had different impacts on blue and fin whales. Being found farther offshore in most of CCAL, fin whales appeared to have fared worse (based on the relative proportions of ARS and transiting activity) than blue whales during the 2015-2016 El Niño event. Strong upwelling pulses occurred at several coastal locations in spring-summer 2015 that supported high biological productivity at these sites (Leising et al. 2015, Jacox et al. 2016) and, being found closer to shore, blue whales may have benefited from this supply in the otherwise unfavorable conditions prevalent farther offshore.

These environmental relationships suggest that while in CCAL (but outside of southern California, where they overlap spatially and may share the same prey resources), blue whales rely on the high but episodic productivity of coastal upwelling ecosystems, while fin whales may be more reliant on offshore upwelling processes that are more susceptible to disruption from climatic events (Chavez et al. 2011). Thus, despite partial spatial and environmental overlap, fin and blue whales have distinct niche breadths and ecological optima that likely reflect different prey resource utilization in much of their range (cf. Fossette et al. 2017, Scales et al. 2017). In the North Pacific, the diet of fin whales includes both euphausiids and pelagic schooling fish (Tershy and Wiley 1992, Aguilar 2009), while blue whales only feed on euphausiids (Fiedler et al. 1998, Croll et al. 2005).

As with blue whales, the 2014 shift to a warm PDO phase (and a negative NPGO phase), suggests we might expect fin whale range and movement patterns in CCAL to change during the next decade, possibly in the opposite direction as the pelagic schooling fish abundance and composition strongly respond to decadal variability, with numerically dominant species like sardines and anchovies respectively alternating during warm and cool phases (Chavez et al. 2003, 2011, Rykaczewski and Checkley 2008). Indeed, in the first three years of this project the northernmost latitudinal extent of the distribution of tracked fin whales expanded from 42.3°N in 2014 to 52.6°N in 2015 and to 53.5°N in 2016, into the Haida Gwaii and Hecate Strait off British Columbia, in the ALSK province.

Finally, the discussion presented in **Section 4.1.3** regarding the usefulness of several of the environmental variables considered in this study as ecological predictors for blue whales applies equally to fin whales.

4.2.4 Genetics

The genetic analyses to-date identified the hybrid origin of one of the tagged whales (Tag #2015_10831; **Figure 84**; also Mate et al. 2016 and 2017a) and, through a collaborative relationship with Cascadia Research Collective, documented a previous biopsy sampling of this individual (a male) in 2004 during photo-ID surveys conducted under NMFS/Southwest Fisheries Science Center funding (Steiger et al. 2009). The genetic analyses also confirmed identification of a Bryde's whale (**Figure 85**; also Mate et al. 2016 and 2017a), initially identified in the field as a fin whale. Initial analysis indicates that this individual represented the '*brydei'* subspecies or type, as described by Yoshida and Kato (1999).

The analysis of fin whale stock structure was limited by the small number of samples from tagged whales but benefitted from comparison to a large reference database of mtDNA haplotypes from throughout the eastern and central North Pacific. Other limitations include the absence of sex identification and compatible nuclear genetic markers in the reference database (e.g., microsatellites were used for tagging and single nucleotide polymorphisms for only a subset of the reference database (Archer et al. 2013). There is also unexplored potential for an influence of seasonal migration on the geographical strata used for the comparisons of population structure. With these caveats, however, the observed differences in mtDNA haplotypes among the *a priori* strata are strong evidence of spatial heterogeneity in the genetic structure of this species in the eastern and central North Pacific. In particular, the haplotype frequencies of the tagged whales from 2014–2015 showed the greatest similarity to the reference dataset from the Southern California Bight, despite the documented movement of these individuals northward along the coast into the California/Oregon/Washington stratum. The 2016 samples, however, were sampled farther north and differed in haplotype frequency from those collected in 2014-2015. Surprisingly, the 2016 samples also showed a weak but significant differentiation from several of the geographic strata despite the small sample sizes.

4.2.5 Concluding Thoughts (Integration of Tagging, Ecological, and Genetic Information)

The fin whale tracking data collected over the four years of this study have provided a wealth of new information about this poorly known species. Although the species shares a substantial part of its range with the blue whale in the California Current, the environmental data indicate that it has a distinct ecology, with particular responses to strongly contrasting environmental conditions and climatic fluctuations that we are just beginning to understand. This highlights the importance of continued monitoring of this enigmatic species.

There would be considerable benefit to further integration of information from the available reference biopsy samples of fin whales, including microsatellite genotyping and sex for individual identification and population assignment procedures. Alternate hypotheses for population structure are also likely to benefit from further integration of genetic identity with seasonal movement, as revealed by satellite tagging, and perhaps differences in vocalizations as evidence of breeding stocks (Širović et al. 2013). Additionally, pregnancy tests and stable isotopic analysis of the biopsy samples collected would further help answer these questions (Clark et al. 2016, Busquets-Vass et al. 2017).

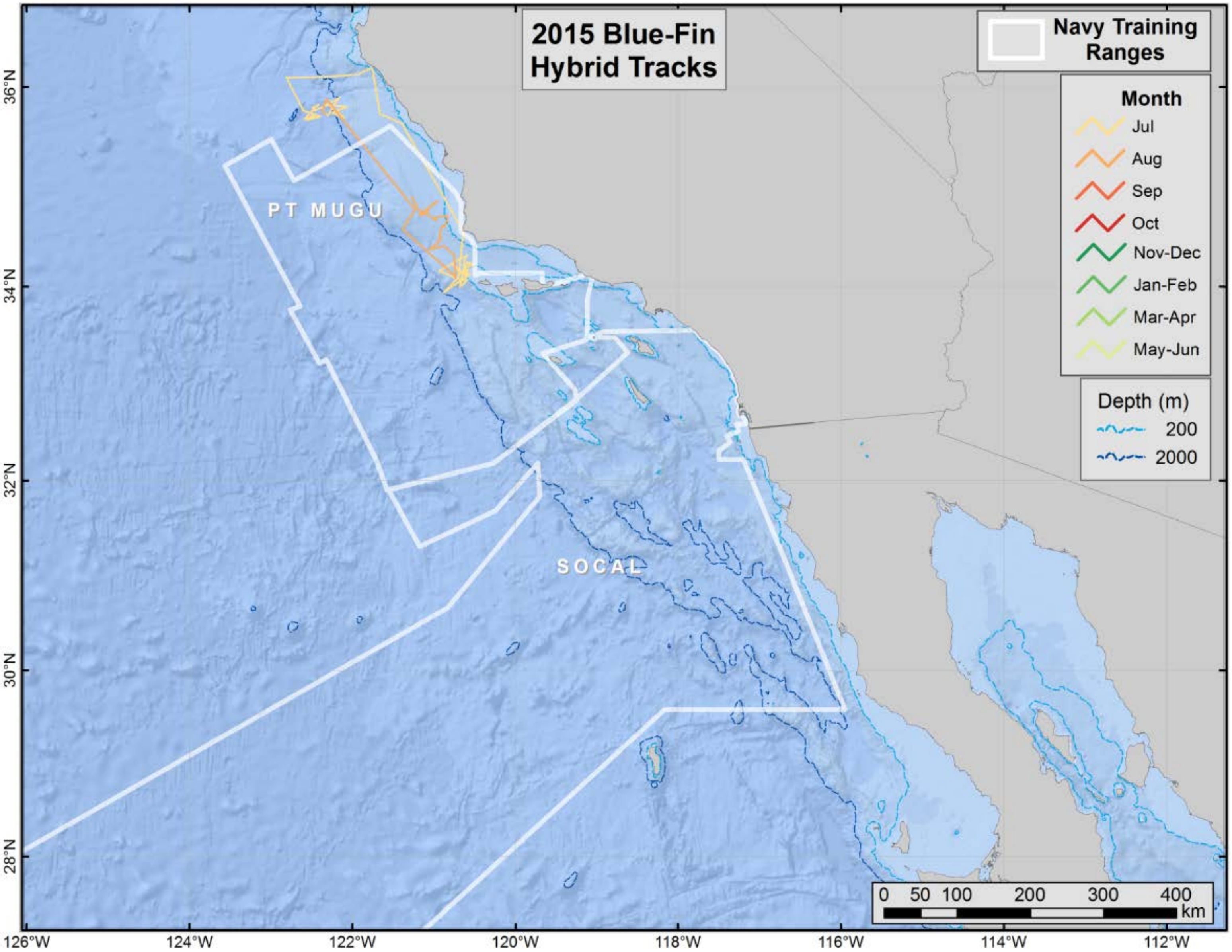

Figure 84. Satellite-monitored track for a blue/fin hybrid whale tagged with an LO tag off southern California in July 2015 (from Mate et al. 2016). The light and dark blue bathymetric contours correspond to the 200 and 1,000 m isobaths, respectively.

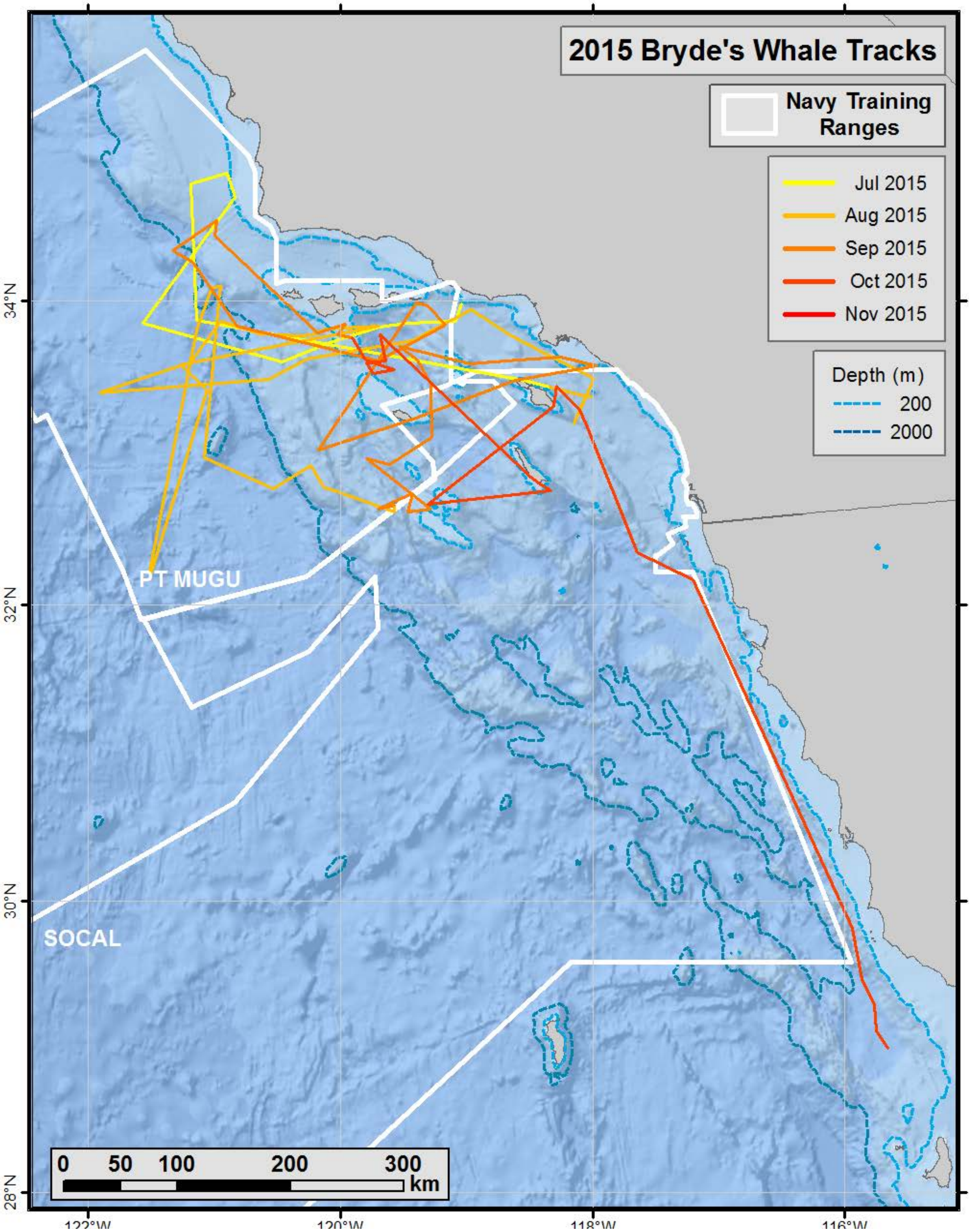

Figure 85. Satellite-monitored track of a Bryde's whale tagged with an LO tag off southern California, 2015 (from Mate et al. 2016).

This page intentionally left blank.

5. Acknowledgements

This project was funded by the U.S. Navy, Commander, Pacific Fleet under the U.S. Navy's Marine Species Monitoring Program, through an agreement with HDR, Inc. (Contract No. N62470-15-D-8006-17F4016) under contract to Naval Facilities Engineering Command. We thank Chip Johnson at Commander, Pacific Fleet, Jessica Bredvik at Naval Facilities Engineering Command Southwest, and Kristen Ampela at HDR for technical support, project management, and contractual support. This project was conducted under the authorization of NMFS Marine Mammal Protection Act/Endangered Species Act Research/Enhancement Permit No. 14856 and Oregon State University Institutional Animal Care and Use Committee Permit No. 4495. We thank pilots Steve and Roxanne Parker for their aerial survey efforts, Kristopher Bauer, Collin Gillin, Theresa Kirchner, Natalie Mastick, Kyle Milliken, Ken Serven, and Will Sheehy for field assistance, R/V *Pacific Storm* captains Ron Briggs, Donnie Hassler, and Ken Serven, cook David Marakeljovic, and crew Jeff Lawrence, Steve Pultz, and Ryan Reyes for field support. Kathy Minta, Mark Wilke, and Minda Stiles at the OSU Marine Mammal Institute office provided invaluable logistical and administrative support to this project.

The Argos Data Collection and Location System used for this project (http://www.argos-system.org/) is operated by Collecte Localisation Satellites. Argos is an international program that relies on instruments provided by the French Space Agency flown on polar-orbiting satellites operated by the U.S. National Oceanic and Atmospheric Administration, the European Organisation for the Exploitation of Meteorological Satellites, and the Indian Space Research Organization.

This page intentionally left blank.

6. Literature Cited

Aasen, E. and J.F. Medrano. 1990. Amplification of the ZFY and ZFX genes for sex identification in humans, cattle, sheep and goats. Nature Biotechnology 12:1279–1281.

Aguilar, A. 2009. Fin whale, *Balaenoptera physalus*. Pages 433-437 in W.F. Perrin, B. Würsig, and J.G.M. Thewissen, eds. Encyclopedia of Marine Mammals, 2nd Edition. Academic Press, Burlington, Massachusetts.

Ainley, D.G., and K.D. Hyrenbach. 2010. Top-down and bottom-up factors affecting seabird population trends in the California current system (1985–2006). Progress in Oceanography 84:242–254.

Allen, A.N., J.A. Goldbogen, A.S. Friedlaender, J. Calambokidis. 2016. Development of an automated method of detecting stereotyped feeding events in multisensor data from tagged rorqual whales. Ecology and Evolution 6:7522–7535.

Auth, T.D., E.A. Daly, R.D. Brodeur, and J.L. Fisher. 2018. Phenological and distributional shifts in ichthyoplankton associated with recent warming in the northeast Pacific Ocean. Global Change Biology 24:259-272.

Archer, F.I., P.A. Morin, B.L. Hancock-Hanser, K.M. Robertson, M.S. Leslie, M. Bérubé, S. Panigada, and B.L. Taylor. 2013. Mitogenomic phylogenetics of fin whales (*Balaenoptera physalus* spp.): genetic evidence for revision of subspecies. PLoS ONE 8:e63396.

Attard, C.R.M., L.B. Beheregaray, K.C.S. Jenner, P.C. Gill, M.N. Jenner, M.G. Morrice, P.R. Teske, and L.M. Möller. 2015. Low genetic diversity in pygmy blue whales is due to climate-induced diversification rather than anthropogenic impacts. Biology Letters 11(5):20141037.

Bailey, H., B.R. Mate, D.M. Palacios, L. Irvine, S.J. Bograd, and D.P. Costa. 2009. Behavioural estimation of blue whale movements in the Northeast Pacific from state-space model analysis of satellite tracks. Endangered Species Research 10:93–106.

Baker, C.S., R.W. Slade, J.L. Bannister, R.B. Abernethy, M.T. Weinrich, J. Lien, J. Urban, P. Corkeron, J. Calambokidis, O. Vasquez, and R. Palumbi. 1994. Hierarchical structure of mitochondrial DNA gene flow among humpback whales *Megaptera novaeangliae*, world-wide. Molecular Ecology 3:313–327.

Baker, C.S., D. Steel, J. Calambokidis, E. Falcone, U. González-Peral, J. Barlow, A.M. Burdin, P.J. Clapham, J.K.B. Ford, C.M. Gabriele, D. Mattila, L. Rojas-Bracho, J.M. Straley, B.L. Taylor, J. Urbán., P.R. Wade, D. Weller, B.H. Witteveen and M. Yamaguchi. 2013. Strong maternal fidelity and natal philopatry shape genetic structure in North Pacific humpback whales. Marine Ecology Progress Series 494:291–306.

Barnston, A. 2015. Why are there so many ENSO indexes, instead of just one? ENSO Blog, 29 January 2015. Available from <https://www.climate.gov/news-features/blogs/enso/why-are-there-so-many-enso-indexes-instead-just-one>.

Baumgartner, M.F., T. Hammar, and J. Robbins. 2015. Development and assessment of a new dermal attachment for short-term tagging studies of baleen whales. Methods in Ecology and Evolution 6:289–297.

Becker, E., K. Forney, P. Fiedler, J. Barlow, S. Chivers, C. Edwards, A. Moore, and J. Redfern. 2016. Moving towards dynamic ocean management: how well do modeled ocean products predict species distributions? Remote Sensing 8:149–26.

Bérubé, M., H. Jørgensen, R. McEwing, and P. J. Palsbøll. 2000. Polymorphic di-nucleotide microsatellite loci isolated from the humpback whale, *Megaptera novaeangliae*. Molecular Ecology 9(12):2181–2183.

Bjorkstedt, E.P., R. Goericke, S. McClatchie, E. Weber, W. Watson, N. Lo, B. Peterson, B. Emmett, J. Peterson, R. Durazo, G. Gaxiola-Castro, F. Chavez, J.T. Pennington, C.A. Collins, J. Field, S. Ralston, K. Sakuma, S.J. Bograd, F.B. Schwing, Y. Xue, W.J. Sydeman, S.A. Thompson, J.A. Santora, J. Largier, C. Halle, S. Morgan, S.Y. Kim, K.P.B. Merkens, J.A. Hildebrand, and L.M. Munger. 2010. State of the California Current 2009-2010: Regional variation persists through transition from La Niña to El Niño (and back?). California Cooperative Oceanic Fisheries Investigations Reports 51:39–69.

Bond, N.A., M.F. Cronin, H. Freeland, and N. Mantua. 2015. Causes and impacts of the 2014 warm anomaly in the NE Pacific. Geophysical Research Letters 42:3414–3420.

Brinton, E. 1962. The distribution of Pacific euphausiids. Bulletin of the Scripps Institution of Oceanography 8:51–269.

Brinton, E., and A. Townsend. 2003. Decadal variability in abundances of the dominant euphausiid species in southern sectors of the California Current. Deep-Sea Research Part II: Topical Studies in Oceanography 50:2449–2472.

Buchanan, F.C., M.K. Friesen, R.P. Littlejohn, and J.W. Clayton. 1996. Microsatellites from the beluga whale *Delphinapterus leucas*. Molecular Ecology 5:571–575.

Burtenshaw, J.C., E.M. Oleson, J.A. Hildebrand, M.A. McDonald, R.K. Andrew, B.M. Howe, and J.A. Mercer. 2004. Acoustic and satellite remote sensing of blue whale seasonality and habitat in the Northeast Pacific. Deep-Sea Research II 51:967–986.

Busquets-Vass, G., S.D. Newsome, J. Calambokidis, G. Serra-Valente, J.K. Jacobsen, S. Aguíñiga-García, and D. Gendron. 2017. Estimating blue whale skin isotopic incorporation rates and baleen growth rates: Implications for assessing diet and movement patterns in mysticetes. PLoS ONE 12:e0177880

Calambokidis, J., J. Barlow, J.K.B. Ford, T.E. Chandler, and A.B. Douglas. 2009. Insights into the population structure of blue whales in the eastern North Pacific from recent sightings and photographic identifications. Marine Mammal Science 25:816–832.

Calambokidis, J., G.H. Steiger, C. Curtice, J. Harrison, M.C. Ferguson, E. Becker, M. DeAngelis, and S.M. Van Parijs. 2015. Biologically Important Areas for selected cetaceans within U.S. waters – West Coast Region. Aquatic Mammals 41:39–53.

Calenge, C. 2006. The package "adehabitat" for the R software: A tool for the analysis of space and habitat use by animals. Ecological Modelling 197:516-519.

Carretta, J.V., K.A. Forney, and J. Barlow. 1995. Report of 1993-1994 marine mammal aerial surveys conducted within the U.S. Navy outer sea test range off Southern California NOAA Technical Memorandum NMFS-SWFSC-217. Southwest Fisheries Science Center, La Jolla, California.

Carroll, E.L., S.J. Childerhouse, R.M. Fewster, N.J. Patenaude, D. Steel, G. Dunshea, L. Boren, and C.S. Baker. 2013. Accounting for female reproductive cycles in a superpopulation capture–recapture framework. Ecological Applications 23(7):1677–1690.

Cavole, L.M., Demko, A.M., Diner, R.E., Giddings, A., Koester, I., Pagniello, C.M.L.S., and P.J.S. Franks. 2016. Biological impacts of the 2013–2015 warm-water anomaly in the Northeast Pacific: Winners, losers, and the future. Oceanography 29(2), 273–285.

Chavez, F.P., J. Ryan, S.E. Lluch-Cota, and C.M. Niquen. 2003. From anchovies to sardines and back: multidecadal change in the Pacific Ocean. Science 299:217–221.

Chavez, F.P., M. Messié, and J.T. Pennington. 2011. Marine primary production in relation to climate variability and change. Annual Review of Marine Science 3, 227–260. doi:10.1146/annurev.marine.010908.163917

Clark, C.T., A.H. Fleming, J. Calambokidis, N.M. Kellar, C.D. Allen, K.N. Catelani, M. Robbins, N.E. Beaulieu, D. Steel, and J.T. Harvey. 2016. Heavy with child? Pregnancy status and stable isotope ratios as determined from biopsies of humpback whales. Conservation Physiology 4, 1–13.

Claus, S., N. De Hauwere, B. Vanhoorne, P. Deckers, F. Souza Dias, F. Hernandez, and J. Mees. 2014. Marine Regions: Towards a global standard for georeferenced marine names and boundaries. Marine Geodesy 37(2):99–125.

Collecte Localisation Satellites. 2015. Argos Users Manual. Available at: http://www.argos-system.org/files/pmedia/public/r363_9_argos_users_manual-v1.6.4.pdf.

Costa-Urrutia, P., S. Sanvito, N. Victoria-Cota, L. EnrÌquez-Paredes, and D. Gendron. 2013. Fine-scale population structure of blue whale wintering aggregations in the Gulf of California. PLoS ONE 8:e58315.

Croll, D.A., B.R.Tershy, R.P. Hewitt, D.A. Demer, P.C. Fiedler, S.E. Smith, W. Armstrong, J.M. Popp, T. Kiekhefer, V.R. Lopez, J. Urban, and D. Gendron.1998. An integrated approach to the foraging ecology of marine birds and mammals. Deep-Sea Research II 45:1353–1371.

Croll, D.A., B. Marinovic, S. Benson, F.P. Chavez, N. Black, R. Ternullo, and B.R. Tershy. 2005. From wind to whales: trophic links in a coastal upwelling system. Marine Ecology Progress Series 289:117–130.

Dalebout, M.L., C.S. Baker, J.G. Mead, V.G. Cockcroft, and T.K. Yamada. 2004. A comprehensive and validated molecular taxonomy of beaked whales, Family Ziphiidae. Journal of Heredity 95:459–473.

Daly, E.A., R.D. Brodeur, and T.D. Auth. 2017. Anomalous ocean conditions in 2015: impacts on spring Chinook salmon and their prey field. Marine Ecology Progress Series 566:169–182.

Di Lorenzo, E., and N. Mantua. 2016. Multi-year persistence of the 2014/15 North Pacific marine heatwave. Nature Climate Change 6:1042–1047.

Di Lorenzo, E., N. Schneider, K.M. Cobb, P. Franks, K. Chhak, A.J. Miller, J.C. McWilliams, S.J. Bograd, H. Arango, and E. Curchitser. 2008. North Pacific Gyre Oscillation links ocean climate and ecosystem change. Geophysical Research Letters 35, L08607.

Donovan, G.P. 1991. A review of IWC stock boundaries. Report of the International Whaling Commission (Special Issue 13):39–68.

Dransfield A, E. Hines, J. McGowan, B. Holzman, N. Nur, M. Elliott, J. Howar, and J. Jahncke. 2014. Where the whales are: using habitat modeling to support changes in shipping regulations within National Marine Sanctuaries in Central California. Endangered Species Research 26:39–57.

Du, X., W. Peterson, J. Fisher, M. Hunter, and J. Peterson. 2016. Initiation and development of a toxic and persistent *Pseudo-nitzschia* bloom off the Oregon coast in spring/summer 2015. PLoS ONE 11:e0163977.

Excoffier, L., and H.E.L. Lischer. 2010. Arlequin suite ver 3.5: A new series of programs to perform population genetics analyses under Linux and Windows. Molecular Ecology Resources 10:564–567.

Falcone, E.A., B. Diehl, A.B. Douglas, and J. Calambokidis. 2011. Photo-identification of fin whales *(Balaenoptera physalus)* along the U.S. West Coast, Baja California, and Canada. Final Report for Order number JFI 3F09SE 516.National Marine Fisheries Service, Southwest Fisheries Science Center, La Jolla, California.

Falush, D., M. Stephens, and J.K. Pritchard. 2003. Inference of population structure using multilocus genotype data: linked loci and correlated allele frequencies. Genetics 164:1567–1587.

Fiedler, P., S. Reilly, R. Hewitt, D. Demer, V. Philbrick, S. Smith, W. Armstrong, D. Croll, B. Tershy, and B. Mate. 1998. Blue whale habitat and prey in the Channel Islands. Deep-Sea Research II 45:1781–1801.

Fiedler, P.C., 2002. The annual cycle and biological effects of the Costa Rica Dome. Deep-Sea Research I 49, 321–338.

Fiedler, P.C., J.V. Redfern, and L.T. Balance. 2017. Oceanography and cetaceans of the Costa Rica Dome region. NOAA-TM-NMFS-SWFSC-590.

Fisher J.L., W.T. Peterson, and R.R. Rykaczewski. 2015. The impact of El Niño events on the pelagic food chain in the northern California Current. Global Change Biology 21:4401–4414.

Fleming, A.H., C.T. Clark, J. Calambokidis, and J. Barlow. 2016. Humpback whale diets respond to variance in ocean climate and ecosystem conditions in the California Current. Global Change Biology 22:1214–1224.

Forney, K.A., and J. Barlow. 1998. Seasonal patterns in the abundance and distribution of California cetaceans, 1991-1992. Marine Mammal Science 14:460–489.

Fossette, S., B. Abrahms, E.L. Hazen, S.J. Bograd, K.M. Zilliacus, J. Calambokidis, J.A. Burrows, J.A. Goldbogen, J.T. Harvey, B. Marinovic, B. Tershy, and D.A. Croll. 2017. Resource partitioning facilitates coexistence in sympatric cetaceans in the California Current. Ecology and Evolution 7:9085–9097.

Frischknecht, M., M. Münnich, and N. Gruber. 2015. Remote versus local influence of ENSO on the California Current System, Journal of Geophysical Research Oceans 120:1353–1374, doi:10.1002/2014JC010531.

Gilson, A., M. Syvanen, K. Levine, and J. Banks. 1998. Deer gender determination by polymerase chain reaction: validation study and application to tissues, bloodstains, and hair forensic samples in California. California Fish and Game 84:159–169.

Gómez-Ocampo, E., G. Gaxiola-Castro, R. Durazo, and E. Beier. 2017. Effects of the 2013-2016 warm anomalies on the California Current phytoplankton. Deep-Sea Research Part II: Topical Studies in Oceanography. doi:10.1016/j.dsr2.2017.01.005.

Hazen, E.L., S. Jorgensen, R.R. Rykaczewski, S.J. Bograd, D.G. Foley, I.D. Jonsen, S.A. Shaffer, J.P. Dunne, D.P. Costa, L.B. Crowder, and B.A. Block. 2012. Predicted habitat shifts of Pacific top predators in a changing climate. Nature Climate Change 3:234–238.

Heide- Jørgensen, M.P., L. Kleivane, N. Oeien, K.L. Laidre, and M.V. Jensen. 2001. A new technique for deploying satellite transmitters on baleen whales: Tracking a blue whale (*Balaenoptera musculus*) in the North Atlantic. Marine Mammal Science 17:949-954.

Hintze, J.L., and R.D. Nelson. 1998. Violin plots: A box plot-density trace synergism. American Statistician 52:181–184.

Hooker, S.K., R.W. Baird, S. Al-Omari, S. Gowans, and H. Whitehead. 2001. Behavioral reactions of northern bottlenose whales (*Hyperoodon ampullatus*) to biopsy darting and tag attachment procedures. Fishery Bulletin 99:303–308.

Irvine, L.M., B.R. Mate, M.H. Winsor, D.M. Palacios, S.J. Bograd, D.P. Costa, and H. Bailey. 2014. Spatial and temporal occurrence of blue whales off the U.S. West Coast, with implications for management. PLoS ONE 9:e102959.

Jacox, M.G., E.L. Hazen, K.D. Zaba, D.L. Rudnick, C.A. Edwards, A.M. Moore, and S.J. Bograd. 2016. Impacts of the 2015-2016 El Niño on the California Current System: Early assessment and comparison to past events. Geophysical Research Letters 43:1–9.

Jonsen, I.D., J.M. Flemming, and R.A. Myers. 2005. Robust state-space modeling of animal movement data. Ecology 86:2874–2880.

Keister, J.E., E. Di Lorenzo, C.A. Morgan, V. Combes, and W.T. Peterson. 2011. Zooplankton species composition is linked to ocean transport in the Northern California Current. Global Change Biology 17:2498–2511.

Koslow, J.A., R. Goericke, and W. Watson. 2013. Fish assemblages in the Southern California Current: relationships with climate, 1951-2008. Fisheries Oceanography 22:207–219.

Lang, A.R. and R.L. LeDuc. 2015 Progress report: Genetic analysis of population structure and subspecies taxonomy of blue whales. Paper SC/66a/SD/5, presented at the 66a Annual Meeting of the Scientific Committee of the International Whaling Commission, 22 May – 3 June 2015, San Diego, USA. 3 pp. Available from <https://archive.iwc.int/pages/view.php?ref=5516&search=%21collection209&order_by=relevance&sort=DESC&offset=0&archive=0&k=&curpos=4&restypes=>.

Larkman, V.E., and R.R. Veit. 1998. Seasonality and abundance of blue whales off southern California. California Cooperative Oceanic Fisheries Investigations Reports 39: 236–239.

LeDuc, R.G., A.E. Dizon, M. Goto, L.A. Pastene, H. Kato, S. Nishiwaki, C.A. LeDuc, and R.L. Brownell. 2007. Patterns of genetic variation in Southern Hemisphere blue whales and the use of assignment test to detect mixing on the feeding grounds. Journal of Cetacean Research and Management 9:73–80.

Leising, A.W., I.D. Schroeder, S.J. Bograd, J. Abell, R. Durazo, G. Gaxiola-Castro, E.P. Bjorkstedt, J. Field, K. Sakuma, R.R. Robertson, R. Goericke, W.T. Peterson, R. Brodeur, C. Barceló, T.D. Auth, E.A. Daly, R.M. Suryan, A.J. Gladics, J.M. Porquez, S. McClatchie, E.D. Weber, W. Watson, J.A. Santora, W.J. Sydeman, S.R. Melin, F.P. Chavez, R.T. Golightly, S.R. Schneider, J. Fisher, C. Morgan, R. Bradley, and P. Warybok. 2015. State of the California Current 2014-15: Impacts of the warm-water 'Blob'. California Cooperative Oceanic Fisheries Investigations Reports 56:31–68.

Levine, A. F. Z., and M.J. McPhaden. 2016. How the July 2014 easterly wind burst gave the 2015–2016 El Niño a head start. Geophysical Research Letters 43:6503–6510.

Longhurst, A. 1998. Ecological Geography of the Sea, Academic Press, San Diego, California.

Longhurst, A. 2006. Ecological Geography of the Sea, Second Edition, Academic Press, San Diego, California.

Mantua, N.J., and S.R. Hare. 2002. The Pacific Decadal Oscillation. Journal of Oceanography. 58:35–44.

Mantua, N.J., S.R. Hare, Y. Zhang, J.M. Wallace, and R.C. Francis.1997. A Pacific interdecadal climate oscillation with impacts on salmon production. Bulletin of the American Meteorological Society 78:1069–1079.

Marshall, T.C., J. Slate, L.E. Kruuk, and J.M. Pemberton. 1998. Statistical confidence for likelihood-based paternity inference in natural populations. Molecular Ecology 7:639–655.

Mate, B., R. Mesecar, and B. Lagerquist. 2007. The evolution of satellite-monitored radio tags for large whales: one laboratory's experience. Deep-Sea Research II 54:224–247.

Mate, B., D.M. Palacios, L. Irvine, B. Lagerquist, T. Follett, M. Winsor, and C. Hayslip. 2015. Baleen (Blue & Fin) Whale Tagging in Southern California in Support of Marine Mammal Monitoring Across Multiple Navy Training Areas (SOCAL, NWTRC, GOA). Final Report. Prepared for Commander, U.S. Pacific Fleet. Submitted to Naval Facilities Engineering Command Pacific, Pearl Harbor, Hawaii, under Contract No. N62470-10-D-3011, Task Orders JP03 and KB27 issued to HDR, Inc., San Diego, California. 31 July 2015.

Mate, B.R., D.M. Palacios, C.S. Baker, B.A. Lagerquist, L.M. Irvine, T. Follett, D. Steel, C. Hayslip, and M.H. Winsor. 2016. Baleen (Blue & Fin) Whale Tagging in Southern California in Support of Marine Mammal Monitoring Across Multiple Navy Training Areas. Preliminary Summary. Prepared for Commander, U.S. Pacific Fleet. Submitted to Naval Facilities Engineering Command Pacific, Pearl Harbor, Hawaii under Contract Nos. N62470-10-D-3011, Task Order KB29, and Contract No. N62470-15-D-8006, Task Order KB01, issued to HDR, Inc., San Diego, California. July 2016.

Mate, B.R., D.M. Palacios, C.S. Baker, B.A. Lagerquist, L.M. Irvine, T. Follett, D. Steel, C.E. Hayslip, and M.H. Winsor. 2017a. Baleen Whale Tagging in Support of Marine Mammal Monitoring Across Multiple Navy Training Areas Covering the Years 2014, 2015, and 2016. Final Report Prepared for Commander, U.S. Pacific Fleet. Submitted to Naval Facilities Engineering Command Pacific, Pearl Harbor, Hawaii under Contract No. N62470-15-8006 (FZN1) issued to HDR, Inc., San Diego, California. August 2017.

Mate, B.R., L.M. Irvine, and D.M. Palacios. 2017b. The development of an intermediate-duration tag to characterize the diving behavior of large whales. Ecology and Evolution 7:585–595.

McCabe, R.M., B.M. Hickey, R.M. Kudela, K.A. Lefebvre, N.G. Adams, B.D. Bill, F.M.D. Gulland, R.E. Thomson, W.P. Cochlan, and V.L. Trainer. 2016. An unprecedented coastwide toxic algal bloom linked to anomalous ocean conditions. Geophysical Research Letters 43:10,366–10,376.

McClatchie, S., R. Goericke, and A.W. Leising 2016. State of the California Current 2015-16: Comparisons with the 1997-98 El Niño. California Cooperative Oceanic Fisheries Investigations Reports 57:5–61.

Melin, S., A.J. Orr, J.D. Harris, J.L. Laake, R.L. Delong, F.M.D. Gulland, and S. Stoudt. 2010. Unprecedented mortality of California sea lion pups associated with anomalous oceanographic conditions along the central California coast in 2009. California Cooperative Oceanic Fisheries Investigations Reports 51:182–194.

Mendelssohn, R. 2018. xtractomatic: Accessing Environmental Data from ERD's ERDDAP Server. R package version 3.4.1. https://CRAN.R-project.org/package=xtractomatic

Messié, M., and F.P. Chavez. 2017. Nutrient supply, surface currents, and plankton dynamics predict zooplankton hotspots in coastal upwelling systems. Geophysical Research Letters 44:8979–8986.

Monnahan, C.C., T.A. Branch, K.M. Stafford, Y.V. Ivashchenko, and E.M. Oleson. 2014. Estimating historical eastern North Pacific blue whale catches using spatial calling patterns. PLoS ONE 9:e98974.

Morin, P.A., K.K. Martien, F.I. Archer, F. Cipriano, D. Steel, J. Jackson, and B.L. Taylor. 2010. Applied conservation genetics and the need for quality control and reporting of genetic data used in fisheries and wildlife management. Journal of Heredity 101:1–10.

Murphree, T., S.J. Bograd, F.B. Schwing, and B. Ford. 2003. Large scale atmosphere-ocean anomalies in the northeast Pacific during 2002. Geophysical Research Letters 30(15):8026.

Nickels, C.F., L.M. Sala, and M.D. Ohman. 2018. The morphology of euphausiid mandibles used to assess selective predation by blue whales in the southern sector of the California Current System. Journal of Crustacean Biology 38:563-573, doi:10.1093/jcbiol/ruy062

NOAA (National Oceanic and Atmospheric Administration). 2018. Northwest Fisheries Science Center. Annual summary of ocean ecosystem indicators for 2017. Available from <https://www.nwfsc.noaa.gov/research/divisions/fe/estuarine/oeip/b-latest-updates.cfm>.

NWS (National Weather Service). 2018. Cold and warm episodes by season. Available from <http://origin.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ONI_v5.php>.

Ohman, M.D., N. Mantua, J. Keister, M. Garcia-Reyes, and S. McClatchie. 2017. ENSO impacts on ecosystem indicators in the California Current System. Ocean Carbon and Biogeochemistry News 10:7–13.

Oleson, E.M., J. Calambokidis, J. Barlow, and J.A. Hildebrand. 2007. Blue whale visual and acoustic encounter rates in the southern California Bight. Marine Mammal Science 23:574–597.

Palsbøll, P.J., M. Bérubé, A.H. Larsen and H. Jørgensen. 1997. Primers for the amplification of tri- and tetramer microsatellite loci in baleen whales. Molecular Ecology 6:893–895.

Peterson, W.T., and J.E. Keister. 2003. Interannual variability in copepod community composition at a coastal station in the northern California Current: a multivariate approach. Deep-Sea Research Part II 50:2499–2517.

Powell, R.A. 2000. Animal home ranges and territories and home range estimators. Pages 65–110 in: Boitani, L., and T.K. Fuller, Eds. Research Techniques in Animal Ecology: Controversies and Consequences. Columbia University Press, New York, New York.

Ross, H.A., G.M. Lento, M.L. Dalebout, M. Goode, G. Ewing, P. McLaren, A.G. Rodrigo, S. Lavery, and C.S. Baker. 2003. DNA surveillance: web-based molecular identification of whales, dolphins and porpoises. Journal of Heredity 94:111–114.

Rykaczewski, R.R., and D.M. Checkley, Jr. 2008. Influence of ocean winds on the pelagic ecosystem in upwelling regions. Proceedings of the National Academy of Sciences of the USA 105:1965–1970.

Sambrook, J., E.F. Fritsch, and T. Maniatis. 1989. Molecular Cloning: A Laboratory Manual. 2nd ed. Cold Spring Harbor Laboratory Press, Cold Spring Harbor, New York.

Santora, J.A., W.J. Sydeman, I.D. Schroeder, B.K. Wells, and J.C. Field. 2011. Mesoscale structure and oceanographic determinants of krill hotspots in the California Current: Implications for trophic transfer and conservation. Progress in Oceanography 91:397–409.

Scales, K.L., G.S. Schorr, E.L. Hazen, S.J. Bograd, P.I. Miller, R.D. Andrews, A.N. Zerbini, and E.A. Falcone. 2017. Should I stay or should I go? Modelling year-round habitat suitability and drivers of residency for fin whales in the California Current. Diversity and Distributions 52:123–12.

Schlötterer, C., B. Amos, and D. Tautz. 1991. Conservation of polymorphic simple sequence loci in cetacean species. Nature 354:63–65.

Schorr, G., E. Falcone, and J. Calambokidis. 2013. Summary of Tag Deployments on Cetaceans off Washington, May 2010 to May 2013. Prepared for Commander, U.S. Pacific Fleet, Pearl Harbor, Hawaii. Submitted to Naval Facilities Engineering Command Pacific (NAVFAC PAC), Pearl Harbor, Hawaii 96860-3134, and Naval Facilities Engineering Command Northwest (NAVFAC NW), Silverdale, WA 98315-1101, under Contract # N62470-10-D-3011, issued to HDR Inc., San Diego, California 92123. 12 June 2013.

Schoenherr, J.R. 1991. Blue whales feeding on high-concentrations of euphausiids around Monterey Submarine Canyon. Canadian Journal of Zoology 69:583–594.

Schwing, F.B., N.A. Bond, S.J. Bograd, T. Mitchell, M.A. Alexander, and N. Mantua. 2006. Delayed coastal upwelling along the US West Coast in 2005: A historical perspective. Geophysical Research Letters 33, L22S01.

Seaman, D.E., J.J. Millspaugh, B.J. Kernohan, G.C. Brundige, K.J. Raedeke, and R.A Gitzen. 1999. Effects of sample size on kernel home range estimates. Journal of Wildlife Management 63:739–747.

Simon, M., M. Johnson, and P.T. Madsen. 2012. Keeping momentum with a mouthful of water: behavior and kinematics of humpback whale lunge feeding. Journal of Experimental Biology 215:3786–3798.

Širović, A., L.N. Williams, S.M. Kerosky, S.M. Wiggins, and J.A. Hildebrand. 2013. Temporal separation of two fin whale call types across the eastern North Pacific. Marine Biology 160:47–57.

Širović, A., A. Rice, E. Chou, J.A. Hildebrand, S.M. Wiggin, and M.A. Roch. 2015. Seven years of blue and fin whale call abundance in the Southern California Bight. Endangered Species Research 28:61–76.

Sremba, A.L., B. Hancock-Hanser, T.A. Branch, R.L. LeDuc, and C.S. Baker. 2012. Circumpolar diversity and geographic differentiation of mtDNA in the critically endangered Antarctic blue whale (*Balaenoptera musculus intermedia*). PLoS ONE 7:e32579.

Stafford, K.M. 2003. Two types of blue whale calls recorded in the Gulf of Alaska. Marine Mammal Science 19:682–693.

Stafford, K.M., S.L. Nieukirk, and C.G. Fox. 2001. Geographic and seasonal variation of blue whale calls in the North Pacific. Journal of Cetacean Research and Management 3:65–76.

Steiger, G.H., J. Calambokidis, A.E. Douglas, E.A. Falcone, T.E. Chandler, D. Steel, and C.S. Baker. 2009. Physical and behavioral characteristics and genetic confirmation of live hybrid blue-fin whales in the eastern North Pacific. Abstracts, 18th Biennial Conference on the Biology of Marine Mammals, 12-16 October 2009.Quebec City, Quebec.

Sydeman, W.J., S.A. Thompson, M. García-Reyes, M. Kahru, W.T. Peterson, and J.L. Largier. 2014. Multivariate ocean-climate indicators (MOCI) for the central California Current: Environmental change, 1990–2010. Progress in Oceanography 120:352–369.

Tershy, B.R., and D.N. Wiley. 1992. Asymmetrical pigmentation in the fin whale: a test of two feeding related hypotheses. Marine Mammal Science 8:315–318.

Torres, L.G., D.R. Barlow, K. Hodge, H. Klinck, D. Steel, C.S. Baker, T. Chandler, P. Gill, M. Ogle, C. Lilley, S. Bury, B. Graham, P. Sutton, J. Burnett, M. Double, P. Olson, N. Bott, and R. Constantine. 2017. New Zealand blue whales: Recent findings and research progress. Unpublished Scientific Committee report SC/67a/SH02. International Whaling Commission, Cambridge, United Kingdom.

Torres-Florez, J.P., P.A. Olson, L. Bedriñana-Romano, H. Rosenbaum, J. Ruiz, R. LeDuc, and R. Hucke-Gaete. 2015. First documented migratory destination for eastern South Pacific blue whales. Marine Mammal Science 31:1580–1586.

Valsecchi, E. and W. Amos. 1996. Microsatellite markers for the study of cetacean populations. Molecular Ecology 5:151–156.

Vincent, C., B.J. McConnell, V. Ridoux, and M.A. Fedak. 2002. Assessment of Argos location accuracy from satellite tags deployed on captive gray seals. Marine Mammal Science 18:156–166.

Waits, J.L. and P.L. Leberg. 2000. Biases associated with population estimation using molecular tagging. Animal Conservation 3:191–199.

Waits, L.P., G. Luikart, and P. Taberlet. 2001. Estimating the probability of identity among genotypes in natural populations: cautions and guidelines. Molecular Ecology 10(1):249–256.

Waldick, R.C., M.W. Brown, and B.N. White. 1999. Characterization and isolation of microsatellite loci from the endangered North Atlantic right whale. Molecular Ecology 8:1763–1765.

Weinrich, M.T., R.H. Lambertson, C.R. Belt, M.R. Schilling, H.J. Iken, and S.E. Syrjala. 1992. Behavioral reactions of humpback whales *Megaptera novaeangliae* to biopsy procedures. Fishery Bulletin 90:588–598.

Wells, B.K., I.D. Schroeder, S.J. Bograd, E.L. Hazen, M.G. Jacox, A. Leising, N. Mantua, J.A. Santora, J. Fisher, W.T. Peterson, E. Bjorkstedt, R.R. Robertson, F.P. Chavez, R. Goericke, R. Kudela, C. Anderson, B.E. Lavaniegos, J. Gómez-Valdés, R.D. Brodeur, E.A. Daly, C.A. Morgan, T.D. Auth, J.C. Field, K. Sakuma, S. McClatchie, A.R. Thompson, E.D. Weber, W. Watson, R.M. Suryan, J. Parrish, J. Dolliver, S. Loredo, J.M. Porquez, J.E. Zamon, S.R. Schneider, R.T. Golightly, P. Warzybok, R. Bradley, J. Jahncke, W. Sydeman, S.R. Melin, J.A. Hildebrand, A.J. Debich, and B. Thayre. 2017. State of the California Current 2016-17: still anything but "normal" in the north. California Cooperative Oceanic Fisheries Investigations Reports 58:1–55.

Worton, B.J. 1995. Using Monte-Carlo simulation to evaluate kernel-based home-range estimators. Journal of Wildlife Management 59:794–800.

Yoshida, H. and H. Kato. 1999. Phylogenetic relationships of Bryde's whales in the western North Pacific and adjacent waters inferred from mitochondrial DNA sequences. Marine Mammal Science 15:1269–1286.

Zhang, Y., J.M. Wallace, and D.S. Battisti. 1997. ENSO-like interdecadal variability: 1900-93. Journal of Climate 10:1004–1020.

This page intentionally left blank.