

Satellite-based horizontal and vertical habitat estimation for
loggerhead turtles (*Caretta caretta*) and bigeye tuna (*Thunnus obesus*)
in the North Pacific Ocean

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Chapter 1

Introduction

1.1 The North Pacific Ocean

The Pacific Ocean is the largest of the world's oceans and spans several distinct oceanographic regions in the northern hemisphere. The North Pacific Subtropical Gyre (NPSTG) lies to the south and is characterized by warm, oligotrophic surface waters, while the North Pacific Subarctic Gyre (NPSAG) lies to the north and is characterized by colder, more productive surface waters (Pickard and Emery, 1990). The region between these two perennial gyre systems is referred to as the North Pacific Transition Zone (NPTZ; Roden, 1991) and is a basin-wide feature which contains surface frontal expressions that migrate meridionally on a seasonal basis.

1.2 The importance of bigeye and loggerheads to the fishery

The Hawaii-based longline fishery operates in the central North Pacific Ocean throughout the year primarily targeting the higher market value bigeye tuna (*Thunnus obesus*) and swordfish (*Xiphias gladius*). Bigeye tuna are a species of interest to both the fishing industry and to fishery management due to their high economic value and stock status. Overfishing of bigeye is occurring, with recent studies reporting vastly different viewpoints as to the current stock status of bigeye (Myers and Worm, 2003; Sibert *et al.*, 2006). This dichotomy in viewpoints highlights the need for accurate stock assessments of bigeye tuna to provide the ability to support or refute conflicting reports as required. Some stock assessments methods of bigeye tuna use available habitat information in conjunction with fisheries dependent data to obtain indices of abundance through CPUE standardization. Recent work using fishery dependent data has shown that temperature is more important than depth in standardization techniques (Bigelow and Maunder, 2007). This fishery dependent data is the depth of the longline gear where a tuna was caught, and not the actual depth and associated habitat where tuna may primarily reside. It would follow then that the ability to collect fishery independent bigeye habitat data would provide additional information which may benefit bigeye tuna stock assessments by providing a better indication of preferred vertical habitat of bigeye. This additional knowledge may also aid in the targeting of bigeye tuna by the longline fishery. A combination of refined stock assessments and targeting information for the fishery may lead to a successfully balanced system which allows

for fishing and bigeye stock recovery.

Swordfish are a species of interest to the fishery and managers due to their economic value, but also because of the high bycatch rates of protected species on shallow set longlines targeting swordfish. One protected species of concern in this area of the fishery is the threatened loggerhead sea turtle (*Caretta caretta*). The need to understand and minimize the bycatch of loggerhead sea turtles has been well documented (DiNardo, 1993; Ito 1998; Lewison *et al.*, 2004; Gilman *et al.*, 2007; Lewison *et al.*, 2007), yet the high amount of bycatch of loggerhead turtles by the Hawaii longline fishery during the 1990s led to a ban of all shallow sets from 2002–2004. The ban on shallow sets was removed in late 2004 but the fishery is subjected to gear requirements and mandatory federal observation of all shallow sets. Additionally, a sea turtle interaction limit was put into place, with a closure of the shallow set fisheries for the remainder of the year if 17 (16) interactions with loggerhead (leatherback) turtles occur. In March 2006, the 17 loggerhead turtle-take limit was reached, resulting in the closure of the shallow set portion of the fishery for the remainder of the year. The socio-economic repercussions of this event highlighted the importance of understanding better where and why interactions with loggerhead sea turtles and the longline fishery occur. The use of fishery dependent and fishery independent data will provide a better understanding of the spatial and vertical habitat of bigeye tuna and loggerhead turtles, two species that the Hawaii-based fishery wishes to target, or avoid, respectively.

1.3 Available information

1.3.1 Fishery dependent data

Fishery dependent data has been used in numerous fisheries oceanography studies due to its availability (Bigelow *et al.*,1999; Walsh *et al.*,2005; Howell and Kobayashi, 2006; Zainuddin *et al.*,2008), and can provide information on habitat of selected species based on geospatial information. In the Hawaii-based longline fishery, information on each set made is annotated in Federally-mandated logbooks which are collected by the National Marine Fisheries Service (NMFS). These geo-referenced fishery data can then be combined with satellite remotely-sensed environmental data available as synoptic fields through time. These data work well in providing high quality and resolution spatial information on habitat as inferred from catch rates and the environment, yet unfortunately provide very little information in the vertical dimension. Additionally, the information that can be provided, while high quality, is limited by the fishery dependence and can not accurately represent the actual spatial-temporal habitats that species of interest may occupy. The solution to this problem is to incorporate fishery independent data to these studies where possible, yet the difficulty and cost of in-situ observations is commonly a limiting factor, resulting in a dearth of historic fishery independent data for many species of interest.

1.3.2 Fishery independent data

The rapid growth of new technologies have facilitated the collection of fishery independent and environmental data. The use of computer tags to collect information

on animals has increased substantially over the last decade due to an increased ease of use with a decreased cost of operation. These computer tags are attached to species of interest and can collect geospatial positions, vertical dive and habitat information or a combination of these two depending on the type of tag used. The selection of tags is also dependent on the species of interest. For species that spend 100% of their time below the surface, a tag used must either be retrieved or programmed to jettison from the animal after a specific duration. To study a species such as tuna over a longer period of time, researchers have historically chosen either archival tags (e.g.: Schaefer and Fuller, 2002; Musyl *et al.*, 2003) or popoff satellite archival transmission (PSAT) tags (e.g. Horodysky *et al.*, 2007; Polovina *et al.*, 2008). Archival tags have the advantage of being able to collect raw information on vertical behavior, yet the tag must be recovered to access the collected data. The PSAT tags collect depth and temperature data of the same resolution as the archival tags, yet technological limitations necessitate the transformation of the raw data to summarized forms before transmission. Archival tags therefore provide the entire dive history of the study animal, while the PSAT tags provide frequency tables of dive information such as the amount of time spent in particular depth of temperature bins. The PSAT tags are designed to jettison from the animal at a pre-specified date, float to the surface, and transmit the summarized data to Service Argos receivers aboard NOAA satellites which then relay the summarized data to local computers for analysis. These tags then provide information on dive behavior and vertical habitat from the study location, most likely increasing

the amount of information recovered per study. The Wildlife Computers¹ PSAT tags were used in this study to provide summarized dive information, as well as modeled geospatial positions based on tag-collected light and surface temperature values.

For air-breathing species studied, it is possible to use tags which transmit collected data during surfacing events. Typically these tags are externally attached to study animals to facilitate the transfer of collected information while at the ocean surface. These tags collect higher quality geospatial information than the tags using the light-based method, and depending on the model, may also collect vertical dive information in raw or summarized form. Numerous studies have spatial data collected by the satellite tracking tags affixed to loggerheads to further understanding of migration and behavior patterns (Godley *et al.*, 2003; Polovina *et al.*, 2004; Polovina *et al.*, 2006). In many studies, the spatial data collected by the tag can be combined with remotely-sensed satellite data to provide information on habitat and environmentally-directed behavior. As stated before however, these data are mostly limited to the surface domain. As opposed to terrestrial systems, the ability to analyze the vertical movements of marine organisms can be essential to completely understand habitat and behavior in the oceanic environment. Dive information can be collected using several tag models, with different levels of data resolution depending on the tag. The same transmission limitations occur with the surface transmitting tags, and as a result many tag models continue the practice of summarizing the dive information before transmission. These summary records

¹Wildlife Computers 8345 154th Avenue NE Redmond, WA 98052 USA

however provide enough information to begin to understand variability in vertical behavior in these species of interest.

1.4 Goals of this dissertation

The main goals of this dissertation are to utilize fishery dependent and independent data to analyze spatiotemporal variability in dive behavior and habitat of bigeye tuna and loggerhead turtles, two species of interest to the Hawaii-based longline fishery. These results should aid in conservation and therefore management of these two species. For bigeye, this could be done by providing information which can be used to refine stock assessments or identify areas where bigeye tuna are most likely to occur in space in time. This would be preferential to managers and the fishery as it may help in the targeting of bigeye by the fishery, yet allow for more accurate stock assessments and management of this species. For loggerheads, a species that the fishery would like to avoid, the goal of this work is to provide information on where loggerheads are most likely to occur in space and time in order to avoid interactions with this species.

The work in these studies relies heavily on the data collected from satellite-based telemetry tags and remotely-sensed environmental data. The work in the second chapter focuses on the spatiotemporal dive variability of bigeye tuna in the central North Pacific Ocean. In this study data from 29 PSAT tags was used to increase our understanding of bigeye dive behavior in the region where the Hawaii-based longline fishery operates. As of the date of this dissertation, very little dive information was published for bigeye tuna in this area in the open ocean and not associated with Fish-Aggregating Devices (FADs). These results provide the first

large-scale study of bigeye dive behavior in this region, and should aid both in broadening our knowledge of tuna ecology as well as in management of bigeye².

The work in the third and fourth chapters are related as they both cover loggerhead turtles, yet the work in the third chapter is primarily based on fishery dependent data while the work in the fourth chapter is primarily based on fishery independent data collected from satellite tags. The work in chapter 3 addresses the issue of the bycatch of loggerhead turtles by the Hawaii-based longline fishery and was done in direct response to the closure of the shallow set fishery in 2006 after the loggerhead interaction limit was reached. The results of this study were used to create the NOAA TurtleWatch³ product, which was released in December 2006, and is still created and delivered daily to both the fishing industry and managers⁴. The work in chapter 4 was undertaken to further our understanding of loggerhead turtle ecology by analyzing the variability in dive behavior in the central North Pacific Ocean. Similar to bigeye, at the date of this work, very little dive information on loggerhead turtles in this region was published. The dive variability results were then used to attempt to understand the interaction dynamics better

²This chapter was accepted in manuscript form to the CLIOTOP special issue of Progress in Oceanography as Howell, E.A., Hawn, D.R., and Polovina, J.J. (2009) Spatiotemporal variability in bigeye tuna (*Thunnus obesus*) dive behavior in the central North Pacific Ocean.

³The NOAA TurtleWatch product is available on the web in English and Vietnamese at <http://www.pifsc.noaa.gov/EOD/turtlewatch.php>

⁴This chapter was published in manuscript form as Howell, E.A., Kobayashi, D.R., Parker, D.M., Balazs, G.H., and Polovina, J.J. (2008) TurtleWatch: a tool to aid in the bycatch reduction of loggerhead turtles *Caretta caretta* in the Hawaii-based pelagic longline fishery. Endangered Species Research, 5, 267–278

between loggerhead turtles and the fishery⁵. The results from these two studies should then aid in the conservation and management of loggerheads by increasing our knowledge of loggerhead ecology as well as helping the fishery to avoid the incidental capture of this species.

The two species in this dissertation have very different physiologies, yet are very important species to understand in the field of fisheries science. The ability to more accurately target or avoid a species of interest is a primary concern to the fishing industry, and may have large economic impacts as this would maximize target catch while minimizing bycatch. The knowledge of the dive behavior of these two species is of importance as well, as current stock assessments may benefit from fishery independent information on the vertical habitat of species. The results from the three studies contained within this dissertation aim to address these concerns, and provide information on these two important species with the hope of advancing the field of fisheries oceanography.

⁵This chapter will be submitted for publication post-graduation

Chapter 2

Spatiotemporal variability in bigeye tuna

(*Thunnus obesus*) dive behavior in the central North Pacific Ocean

2.1 Introduction

Bigeye tuna (*Thunnus obesus*) are a highly migratory and commercially targeted species distributed throughout the Pacific Ocean. Bigeye tuna are considered opportunistic feeders, and their forage base is made up of a variety of organisms such as fish, crustaceans, squid, and gelatinous creatures (Sund *et al.*, 1981; Josse *et al.*, 1998; Bertrand *et al.*, 2002), which can be found in the deep scattering layers (DSL) of the ocean. The DSL is made up of micronektonic organisms that descend to specific depth layers ranging from 250 to more than 500 m during the day depending on temperature and light conditions (Tont, 1976; Dagorn *et al.*, 2000; Domokos *et al.*, 2007). Simultaneous observations have provided evidence that bigeye tuna mirror the diurnal vertical movement of the DSL and that bigeye

vertically migrate to depth following this feature during the day (Josse *et al.*, 1998; Dagorn *et al.*, 2000).

Previous research from tracking and tagging studies and additional physiological studies on bigeye tuna, has provided insights into forage and behavior patterns. Unique physiological adaptations in bigeye tuna allow them to tolerate the low ambient temperature and oxygen regions in the water column, making it possible for them to follow DSL migration during daylight hours (Brill *et al.*, 2005). The use of these cold, low oxygen waters during the day is balanced by time that a bigeye spends near the sea surface warming its muscle tissue (Holland *et al.*, 1992; Holland and Sibert, 1994; Musyl *et al.*, 2003; Brill *et al.*, 2005). This typical daytime dive behavior, where the bigeye spend the majority of their daylight time at depths with migrations to the surface for thermoregulation, has been recorded by both sonic tracking (Dagorn *et al.*, 2000; Bach *et al.*, 2003) and tagging (Schaefer *et al.*, 2002; Musyl *et al.*, 2003) studies of bigeye tuna in the open ocean. Changes in the depth of the DSL due to environmental conditions may then have an impact on the amount of time that bigeye spend at depth, which is balanced by necessary thermoregulatory surface time.

The dive behavior of bigeye tuna in the open ocean has been described in several areas of the Pacific Ocean such as the Coral Sea (Gunn *et al.*, 2005), the South Pacific (Dagorn *et al.*, 2000; Bach *et al.*, 2003), the eastern Tropical Pacific (Schaefer *et al.*, 2002), and near Hawaii (Holland *et al.*, 1990; Musyl *et al.*, 2003), with regional differences in depth and habitat range reported between these study areas. These studies provide extensive information on bigeye dive behavior in their specific regions, yet very little information is available on the dive behavior

of bigeye tuna in the open ocean area of the central North Pacific. This region is of importance to many commercial fleets which target bigeye tuna, including the Hawaii-based longline fishery. Longline gear targeting bigeye tuna is set to depths between 100 and 400 m early in the day to catch bigeye as they migrate to these depths at dawn (Boggs, 1992; Bigelow *et al.*, 2006). Additional information on the daytime dive behavior of bigeye tuna may therefore aid in understanding the potential vulnerability of these animals to commercial longline fisheries. The Hawaii-based fishery targets bigeye through a large region in the central North Pacific spanning several defined oceanographic regions from the North Equatorial Counter Current (NECC) in the south to the Subtropical Front in the north. As regional differences in dive behavior have been reported in previous studies, the collection of depth and habitat information from each of these distinct areas is necessary to identify whether spatial, temporal or environmental factors affect bigeye tuna dive behavior in this expansive section of the central North Pacific. Identification of these factors would potentially allow for prediction of bigeye catch rates at associated times and areas.

In this study we analyzed variability in daytime dive behavior using data collected from 29 pop-up satellite archival transmission (PSAT¹) tags that were deployed on commercial size bigeye tuna within the central North Pacific. These satellite tag data enable the first comparison of bigeye tuna dive behavior across various oceanographic regions of the central North Pacific Ocean throughout the year. The data also represent the first reported dive information for bigeye tuna

¹Wildlife Computer models of PSAT tags are proprietarily referred to as popup archival transmission (PAT) tags, and will be referenced this way throughout the remainder of the text

tagged near Palmyra Atoll, a region which is geographically distant to the Hawaii-based longline fishery, yet associated with high bigeye catch rates (Howell *et al.*, 2006). Specific dive types based on time-at-depth during the day were defined, and the variability in these dive types across space, time, and surface habitat was analyzed. A generalized additive model (GAM) was used to identify additional potentially important biological and environmental covariates that could influence the potential vulnerability of bigeye to the longline fishery. The implications of these results to the longline fishery, as well as how potential climate, affect bigeye dive behavior and habitat are discussed.

2.2 Methods

Tag operations

Forty-nine Wildlife Computer PAT tags (models 2, 3, 4, and MK10) were deployed on bigeye tuna caught and released from U.S. commercial vessels that were targeting bigeye tuna during normal fishing operations. All tags were deployed over seven trips covering the last three quarters of the year during the 2002–2007 period (Table 2.1). These seven trips within the normal geographic boundaries of the Hawaii-based longline fishery (Fig. 2.1) represented distinct oceanographic regions. Regional terms were defined based on major climatological oceanographic features (Pickard *et al.*, 1990). The area from 4°–10°N was defined as the North Equatorial Counter Current (NECC) region, 14°–18°N was defined as the North Equatorial Current (NEC) region, and the area from 18°N–28°N was defined as the subtropical gyre (STG) region. The area north of 28°N was defined as the subtropical front (STF) region as this region or area represents the southernmost extent of the South Subtropical Front during the first quarter of the year and is the area with the highest temperature variability in the top 100 m (Seki *et al.*, 2002).

All PAT tag models (2, 3, 4, MK10) provided the same three data fields in pre-programmed temporal bins, time-at-depth (TAD), time-at-temperature (TAT) and PAT depth-temperature (PDT) values. The PAT 2, 3 and 4 tags were programmed to collect time-at-temperature and time-at-depth in 12 temperature and depth bins, while the PAT MK10 tags provided the capability of programming 14 depth and temperature bins. The temperature bins for the 12-bin tags were in increments

Table 2.1: Deploy and pop-up dates for PAT tags attached to bigeye tuna during 2002–2007 with size in fork length, SST measurements at deployment, tag time at liberty, and straight line distance from deploy to pop-up.

Trip	Tagging dates	Time bins (hours)	Number of tags	Time at liberty (days)	Straight-line distance (km)	Deploy SST (°C)	Fork Length Mean \pm SD (cm)
1	2002: April 25–May 6	1	3	18–53	179–399	25.1 \pm 0.4	120.3 \pm 8.7
2	2002: November 07–17	2,12	5	13–88	123–1408	26.0 \pm 0.3	126.2 \pm 10.5
3	2003: March 29–31	4	6	15–56	38–525	21.8 \pm 0.9	118.7 \pm 4.6
4	2003: August 01–10	4	6	18–66	116–736	24.3 \pm 0.2	123.5 \pm 5.9
6	2005: March 15–25	4	2	46–64	89–668	20.8 \pm 1.7	121.0 \pm 1.4
8	2006: June 21–29	4	2	17–91	249–747	22.5 \pm 0.1	114.0 \pm 18.4
9	2007: July 29–August 19	1,4	6	10–118	51–767	28.2 \pm 0.4	125.3 \pm 6.3

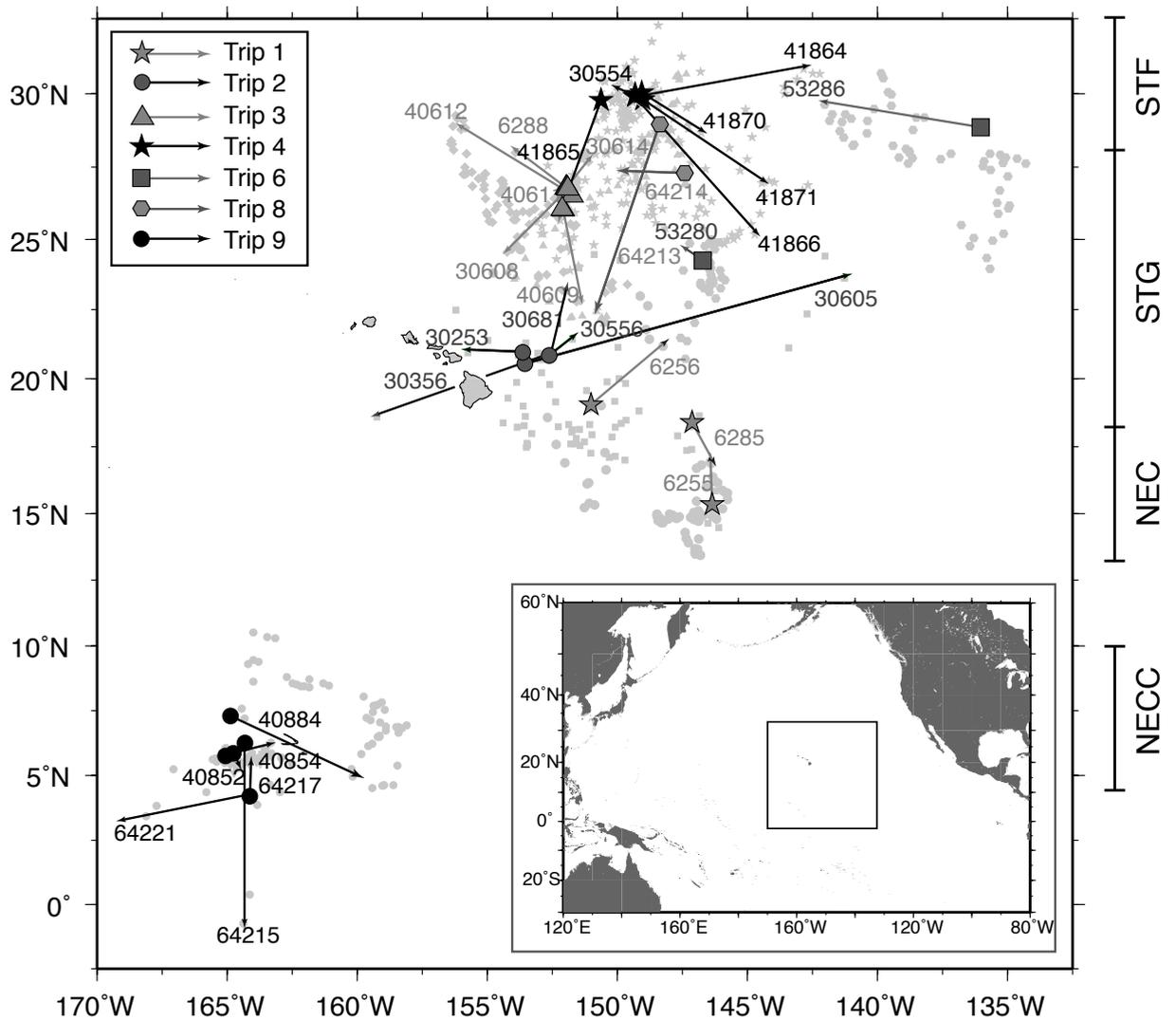


Figure 2.1: Map of study area including region names defined by oceanographic area. The solid symbols and arrow heads represent deploy and pop-up locations for the 29 tags used in this study. The lighter grey symbols represent the geolocation estimates using the UKFSST package. The inset map is the larger area of the Pacific Ocean, with the box representing the study area.

of 2°C between the top and bottom bins, > 26°C and < 6°C, respectively. The depth bins for the 12-bin tags were in 50-m increments from surface to 300 m and 100 m increments to 600 m, followed by bins of 600–750 m, 750–999 m, and > 999 m. To allow for comparisons of common bins across all tags, the additional bins on the MK10 tags were added at the depth ranges 0–25 m and 300–350 m. For temperature, the top bin was extended to > 30°C. All tags were programmed to compile the depth and temperature data in 1, 2, 4, or 12-hour time intervals (Table 2.1). Tags were programmed to pop-up after a fixed time period, set at 6 months for most of the tags, and to transmit these binned data after pop-up to the Argos satellite.

The attachment procedure of the PAT tags in this study was similar to methods used in Polovina *et al.*, (2008), yet several methods were changed to represent the use of bigeye tuna as a study animal. Bigeye tuna were generally selected during the first 2 hours of the longline haul back operation (1700–1900 h) and initially chosen, based on a primary visual assessment of the fish's liveliness and body size. The initial assessment included observing the brightness of body color, presence or absence of line damage to head and body, hooking location, eye and fin movement, and presence of blood. Tuna initially selected for tagging were transferred to a 40-m braided tarred line, guided into a knotless nylon dip net, and manually lifted into the gangway of the vessel and gently placed (with hook exposed) on a moistened padded fish bag extended slightly over the side of the vessel. Once a fish was settled, the dip-net mesh was removed and the fish was reexamined for additional gear damage to its body. The buccal cavity was inspected and any signs of stomach ejection physical damage, or barotrauma were noted. After a final

determination of the fish's condition, the hook was removed and a single fork-length (cm) measurement was recorded. The PAT tag was tethered to the tuna using a 3.5 x 1.7 cm modified titanium dart head attached to a 12.7-cm fluorocarbon line. The tag was inserted at the base of the second dorsal fin through the pterygiophores and anchored by applying a stainless steel applicator 10–12 cm deep into the epaxial muscle mass. The entire tagging procedure lasted between 60–90 seconds for each animal. Once the tag was attached, the fish was released by extending one end of the fish bag over the side of the vessel.

2.2.1 Tag processing

Collected data were transmitted to Argos satellites after successful detachment from the animal, and raw transmitted data were processed using the WC-AMP software provided by the tag manufacturer. To avoid any unintentional bias as a result of changes in software over the study period, a reprocessing of all raw tag data was performed using the most current available version of WC-AMP (1.02.0004). Two PAT (version 2) tags were successfully recovered allowing the retrieval of 100% of the recorded raw data on depth, temperature, and light at 1-minute resolution. These raw data were extracted from the tag using the latest version of the WC-TSP program (v1.02.0006) available. To be able to combine these raw data with other tag data used in this study, the raw 1-minute data were binned using the PAT2-4 depth-and-temperature bins and a 1-hour temporal bin. To allow for comparison of the TAD and TAT frequency distributions across all tags, distributions from the MK10 tags were pooled to provide 12 common depth-and- temperature bins for all PAT tags. Daily, 24-hour TAD and TAT frequency distributions were created

by pooling all available data for each individual day from each tag with a 1-, 2- or 4-hour time frequency bin. To represent the distinct day and night periods, TAD and TAT data from 1000–1359 hours (day) and 2200–0159 hours (night) were pooled for each day from all 1-, 2- or 4-hour time interval tags for TAD and TAT data. These time periods were chosen because they represented the center of the day or night periods while avoiding possible contamination from other temporal bins, such as those at dawn and dusk (Polovina *et al.*, 2008). While the 1000–1359 time range represents the central portion of the daytime period, based on visual inspection of both the hourly and raw archival tag data, this 4-hour time period is a strong proxy for dive behavior throughout a large percentage of daylight hours. From this point forward a "day" is defined as the daytime period from 1000–1359.

A large focus of this study was to analyze the variability in daytime dive behavior of bigeye tuna. Dive behavior has been previously described in terms of dive "type", with type-1 behavior signifying days when bigeye tuna spend a large percentage of their time at depths greater than 100 m (Schaefer *et al.*, 2002). This dive behavior has also been referred to as W-shaped behavior (Musyl *et al.*, 2003) as the TAD is interspersed with surfacing behavior. Dive types for each daytime period were defined in this study as either deep or shallow based on the percentage of time in specific depths. A shallow day was defined as a daytime 4-hour block where the animal spent more than 75% of its time shallower than 100 m. A deep day was defined as a daytime 4-hour block where the animal spent more than 75% of its time deeper than 200 m. The remaining days were labeled intermediate days as these represented a mixed behavior where time was spent in shallow, intermediate and deep bins. Depths of 0–100 m were chosen as the

surface layer because this measurement represents the boundary of the shallowest depth bin (50–100 m) and captures almost 100% of the mixed layer depths in the study area. A depth of 200 m was chosen as the upper boundary of the deep layer as this depth is within or near the base of the thermocline in all areas (Pickard *et al.*, 1990) and also has been shown to represent a shift in mesopelagic species and light penetration (Johnsen, 2005). The definition of shallow- and deep-dive day types represents the contrast in dive behavior between the epipelagic surface and mesopelagic deep W-shaped behavior types reported for open ocean bigeye (Schaefer *et al.*, 2002; Musyl *et al.*, 2003; Gunn *et al.*, 2005). To estimate the potential vulnerability of bigeye tuna with respect to commercial longline gear, the intermediate- and deep-dive components were added together to represent the percentage of days where the largest percentage of time was spent deeper than 100 m. Results from pelagic longline studies incorporating time-depth recorders (TDRs) show that the largest percentage of commercial longline gear targeting bigeye tunas is generally set during the day in the 100–400 m depth (Bigelow *et al.*, 2006; Hawn, data not shown), indicating that the summation of these two dive types should provide a relevant proxy for the amount of time where a potential interaction with longline fishing gear could occur.

Several hypothesized tag-based variables of importance were derived from the PDT data using the MATLAB programming environment. For each available day of data, the mixed-layer depth (MLD), the depth of the 10°C isotherm, and the sea surface temperature (SST) were calculated over the complete 24-hour period in local time. The PDT data provided 8 depths and 16 temperature measurements for each time interval, the 8 depth points representing the minimum and

maximum depth plus 6 selected depths between these extreme values. For each depth point a corresponding minimum and maximum temperature was recorded. A single temperature field was then calculated from the PDT data by averaging the minimum and maximum temperatures, with data filtered to remove any values where the temperature range was greater than 0.5°C . For each tag, all available data were pooled into 24-hour periods beginning at 0000 HST to create daily depth-temperature profiles. A mean, daily depth-temperature profile was fit using the Savitzky-Golay algorithm, and the MLD and depth of the 10°C isotherm were interpolated from this profile using a cubic spline function. The MLD was defined as the depth where the temperature was 0.8°C less than the surface temperature, which was considered appropriate for the North Pacific (Kara *et al.*, 2000). The mean gradient in temperature from the MLD to the 10°C isotherm was calculated to represent the overall slope of the thermocline. SST values were taken directly from the 24-hour PDT data for each tag, where SST was defined as the average temperature for all depths shallower than 16 m. This depth range was chosen because it is similar to the 15-m depth range used in previous tag experiments (Nielsen *et al.*, 2006) and is shallower than all estimated MLDs in this study.

Initial light-level geolocations were estimated using the WC-GCE software package provided by Wildlife Computers. As with the dive data, all tags were reprocessed with the latest available version of the software (1.02.0004). Where possible, dawn and dusk records were rematched and records were optimized using adjacent dawn and dusk values. Data were manually filtered, first by removing any records that were recorded before the deployment of the tag and then by visual inspection of light curves and longitude estimates and removal of records

with poor light curves or initial longitude estimates more than 15° from the deploy position. The latitudes were calibrated from both deploy and pop-off locations for all tags when possible; otherwise, either the deploy or pop-off location was used individually. Initial geolocation estimates based on light measurements have various, well-documented problems, such as the inability to determine latitude near the spring and autumn equinoxes (Hill *et al.*, 2001). The procedure to estimate these latitudinal locations also required a complete light curve during dawn and dusk. This presented a problem with our study animal; during these periods, the tagged bigeye tuna often occurred at extreme depths and at minimal light levels. To rectify the problems in determining geolocation, an unscented Kalman filter was used to predict the most probable track line for each tag from the raw light-based geolocations and SST (Lam *et al.*, 2008). These track estimations were performed in the statistical environment R using the package UKFSST². This approach is similar to a previous Kalman filter design that incorporated SST values (Nielsen *et al.*, 2006) but is thought to provide more accuracy (Lam *et al.*, 2008). Most probable tracks with daily geographic positions were estimated with UKFSST for each of the 29 tags used in this study, resulting in geolocation estimates for more than 75% of all days. Most missing days in the geolocation estimates were not sequential in time (89% of gaps ≤ 2 days, 1% of gaps ≥ 7 days), and missing values were interpolated linearly between points to produce daily geolocation estimates for all available days. A daily speed variable was estimated from these daily geolocation estimates as the straightline distance traveled per day.

²The add-on package for R UKFSST is available for free download at <http://www.nielsensweb.org/ukfsst/wwwukfsst/index.html>

2.2.2 Environmental covariates

Subsurface climatological oxygen fields were obtained from the National Oceanographic Data Centers World Ocean Atlas 2005 project (Boyer *et al.*, 2006). These data were delivered as monthly, seasonal, and annual climatological fields based on numerous historical in situ collection methods and mapped as an objectively analyzed global $1^\circ \times 1^\circ$ equal area grid on 16 discrete depth layers from 0 to 700 m. Oxygen is thought to be an important variable in the habitat of bigeye tuna (Bigelow *et al.*, 2002), with cardiac performance decreases observed at O_2 concentrations less than $2.1 \text{ ml l}^{-1} O_2$ (Brill *et al.*, 2005) and very low catch rates associated with oxygen in the $1.0\text{--}1.4 \text{ ml l}^{-1} O_2$ range (Hanamoto, 1987; Boggs, 1992). To test the importance of low oxygen waters to deep dive behavior, the depth of the 1 and $2.1 \text{ ml l}^{-1} O_2$ concentrations were interpolated with a cubic spline function for each tag date and position to match the closest time and space point in the monthly $1^\circ \times 1^\circ$ climatological oxygen fields.

Photosynthetically active radiation (PAR) and chlorophyll-*a* data were collected by the SeaWiFS sensor. PAR data version 1.2 and chlorophyll-*a* data version 5.1 were used. The PAR algorithm estimates daily (i.e., 24-hour averaged) PAR reaching the ocean surface, where PAR is defined as the quantum energy flux from the sun in the spectral range 400–700 nm expressed in Einstein $\text{m}^2 \text{ day}^{-1}$. Eight-day and monthly $9 \text{ km} \times 9 \text{ km}$ equal area gridded data images of PAR were obtained from NASA Goddard Earth Sciences Distributed Active Archive Center. PAR and chlorophyll-*a* values were then extracted for each individual tags

geolocation record from 8-day images using the Generic Mapping Tools³ routine `grdtrack` (Wessel *et al.*, 1991).

2.2.3 Modeling

A Generalized Additive Model (GAM) was used to identify significant candidate predictors that affect whether bigeye would have potential vulnerability to longline fishing gear during the day. Candidate variables were selected based on their hypothesized importance to daytime diving behavior. Latitude, quarter of the year, and SST were included, as these variables have been shown to be important factors affecting bigeye tuna (Holland *et al.*, 1990; Holland *et al.*, 1992; Bigelow *et al.*, 2002; Schaefer *et al.*, 2002; Brill *et al.*, 2005; Gunn *et al.*, 2005). Fork length was used to account for potential size effects on diving behavior. The daily estimated speed was entered, as it was hypothesized that speed may be inversely related to deep forage time, with animals moving large distances. The MLD, depth of the 10°C isotherm, depths of the 1 and 2.1 ml l⁻¹ O₂ concentration, chlorophyll-*a*, PAR, and moon phase were felt to be potentially important environmental covariates based on their expected direct effects on bigeye tuna or their prey in the DSL.

The dive types in this study are defined as shallow or deep, with a third type which represents days where an intermediate or mixed dive occurred. Longline gear may be set in depths between 100–400 m. Interactions with longline gear would most likely occur during days defined as either the deep- or intermediate-

³The free of charge Generic Mapping Tools are available at <http://gmt.soest.hawaii.edu>.

dive type. During shallow days, bigeye tuna by definition spend more than 75% of their time at depths shallower than the range where longline gear targeting bigeye is deployed. The potential vulnerability of bigeye to longline gear was then modeled as a binomial response variable where either a deep or intermediate day was defined as a "presence" of longline vulnerability and a shallow day was an "absence". GAMs were constructed in the R programming environment using the *gam* function of the *mgcv* package (Wood, 2006). The binomial family with a logit link function was used. Model selection was performed manually and candidate predictors were kept which were significant, minimized the Akaike Information Criterion (AIC), and increased the amount of deviance explained. All candidate variables were modeled as continuous variables except for quarter of the year, which was modeled as a factor. Model predictions were made using the *predict* function of the *mgcv* package.

2.3 Results

2.3.1 Tag returns

Thirty of the 49 (61.2%) deployed PAT tags successfully transmitted more than 10 consecutive days of collected data after their release from the fish; 29 of the tags providing data in 4-hour time intervals. Total times at liberty for the 29 tagged fish ranged from 10 to 118 days (Table 2.1). Ten of the 29 tags released prematurely after descending below 980 m, with 18 of the remaining tags releasing early and 1 tag releasing at the programmed date (118 days, Table 2.1). One of the PAT 2 tags (30556) from which high resolution data were recovered released after a dive to 980 m. Inspection of individual tag data suggested that vertical movement behavior of bigeye tuna appeared to stabilize, with animals occupying depths greater than 200 m after a 12-hour period following deployment of the tag. To maximize available data while conservatively removing any post-deploy behavior changes, all tag data excluding the initial 24-hour period were used. For premature releases following dives below 980 m, the 24-hour period prior to the last deep event was removed. For all other premature releases the period of time programmed by the tag to verify a premature release (24–72 hours) was removed. This resulted in retention of complete depth and temperature records for 700 out of 1149 possible days (60.9%). Straight-line distances traveled were calculated from deploy and pop-up positions for the 29 tags used in this study (Fig. 2.1). Distances traveled were variable, with bigeye tuna dispersing 51–1408 km from tag deployment locations to pop-up locations (mean: 402.5 km, SD: 303.4 km). Estimated speeds from daily geolocation points were from 0.3 to 174.1 km day⁻¹

(mean: 40.6 km day⁻¹, SD: 33.2).

2.3.2 Vertical depth and temperature distributions

To show the overall average time spent in the archived temperature and depth bins, the pooled TAD and TAT frequency distributions for tags with 1-, 2-, or 4-hour time bins were combined. The pooled TAD distributions from the 29 tags showed a strong bimodal signal during the overall 24-hour period, with apparent differences in dive behavior recorded for the day and night periods (Fig. 2.2a–c).

During the daytime period (1000–1359), bigeye tuna spent 42.3% of their time at depths shallower than 200 m and 23.7% of the time in the 0–50 m depth range (Fig. 2.2b). They spent 57.6% of their time in waters deeper than 200 m and 23.9% of the total time at 300–400 m. During the nighttime period (2200–0159), bigeye tuna spent 93.7% of their time in the top 100 m and 71.6% of their time at 0–50 m and (Fig. 2.2c). Only 1.1% of the total time was spent below 150 m. The TAT distributions were similar to depth distributions for day and night periods, as well as the 24-hour period (Fig. 2.2d–f). The largest variations for the 24-hour, day and night periods were in temperature values greater than 18°C, which reflects the variability in SST values over the different trips during this study (Table 2.1, Fig. 2.1). During the day period, 50.0% of the time was spent in the 8–14°C temperature range, with 21.4% between 10 and 12°C (Fig. 2.2e). During the night, when bigeye tuna were primarily in the top 150 m, 50.3% of the time was spent in the 24–26°C range (Fig. 2.2f).

TAD frequency distributions were pooled based on oceanographic regions (Fig. 2.1) and quarter of the year to show the variability in these data in time and space

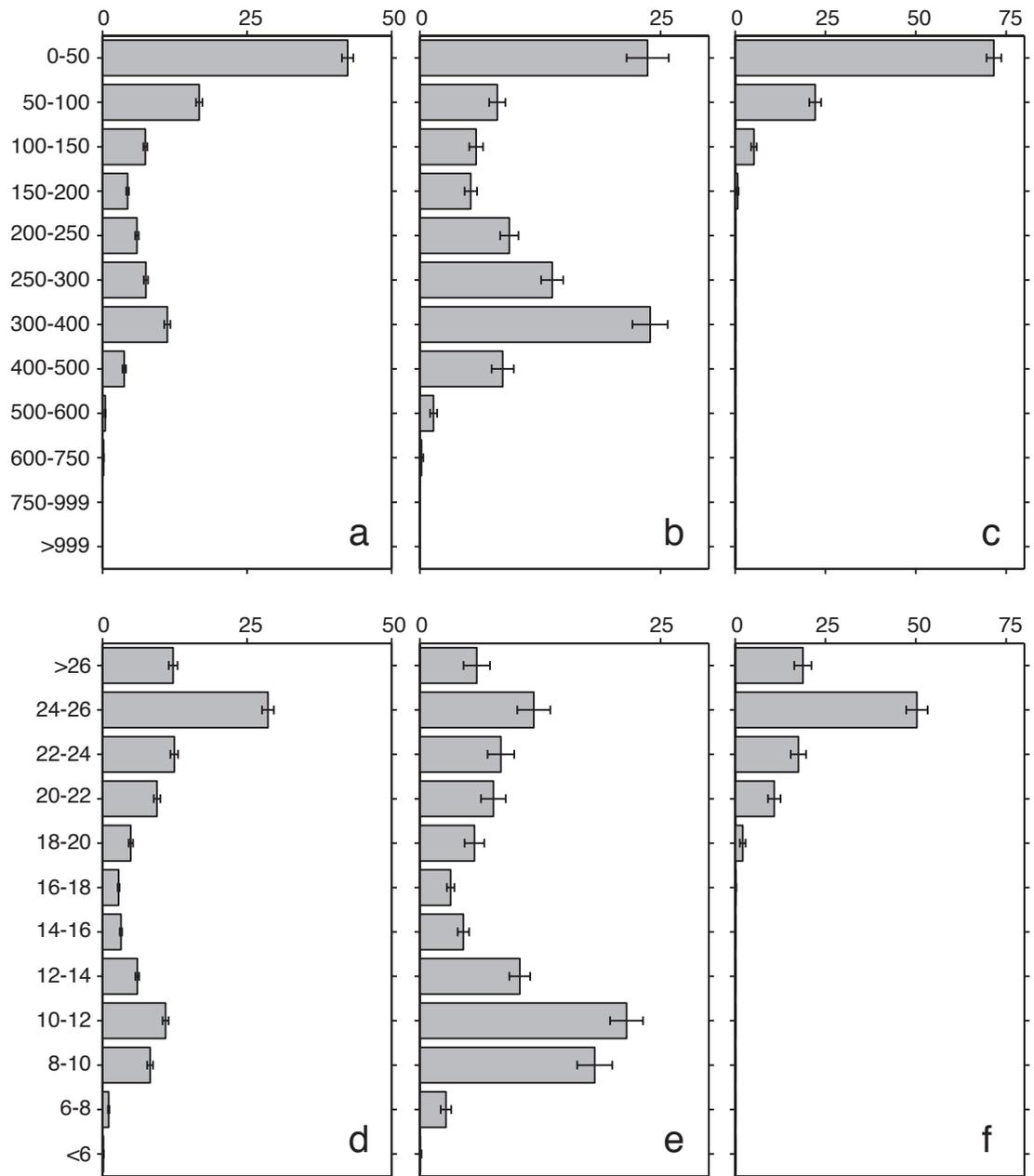


Figure 2.2: Time-at-depth frequency distributions from 29 PAT tags deployed on bigeye tuna in the central North Pacific for three time periods: (a) 24 hours, (b) daytime from 1000 to 1359, and (c) nighttime from 2200 to 0159. Time-at-temperature frequency distributions from 29 PAT tags deployed on bigeye tuna in the central North Pacific for three time periods: (d) 24 hours, (e) daytime from 1000 to 1359, and (f) nighttime from 2200 to 0159.

(Fig. 2.3a-f).

Bigeye tuna in the NECC region below 10°N (Fig. 2.3a) during the third quarter spent more than 60% of their time below 200 m, with 30% of the remaining time spread evenly within the 0–150 m depth bins. The deep, daytime mode for bigeye in this region was between 301–400 m. In the NEC region between 14° and 18°N during the second quarter of the year, bigeye spent 48.9% of their time below 200 m and 37% of their time in the top 100 m, with 25% in the top 50 m (Fig. 2.3b). The deep mode for the daytime period (1000–1359) was in the 251–300 m bin, with most time spent in the depth bins from 201–400 m. For the tag data pooled over the region covering the STG region from 23 to 28°N , there was an increase in time spent below 200 m from the second (Fig. 2.3c) to the third (Fig. 2.3d) quarters, with the main change being in the time spent in the 0–100 m range. The 301–400 m depth bin remained the mode through both seasons, yet more time was spent in the 401–500 m bin during the third quarter. The bigeye in the STF region north of 28°N during the second quarter spent the least amount of time at depths below 200 m, with almost 50% of their time in the 0–50 m range. A smaller mode was present at depths in the 251–300 m bin. More time was spent at depths greater than 200 m during the third quarter north of 28°N , yet more than 35% of the average time was spent in the 0–50 m bin. A deep daytime mode was present in the 301–400 m bin, yet in both quarters less overall time was spent at this depth in this northern region. Overall, most regions and seasons had a bimodal time-at-depth distribution similar to the pooled distribution, with more time at deeper depths recorded for bigeye tuna south of 10°N and in the subtropical gyre during the third quarter.

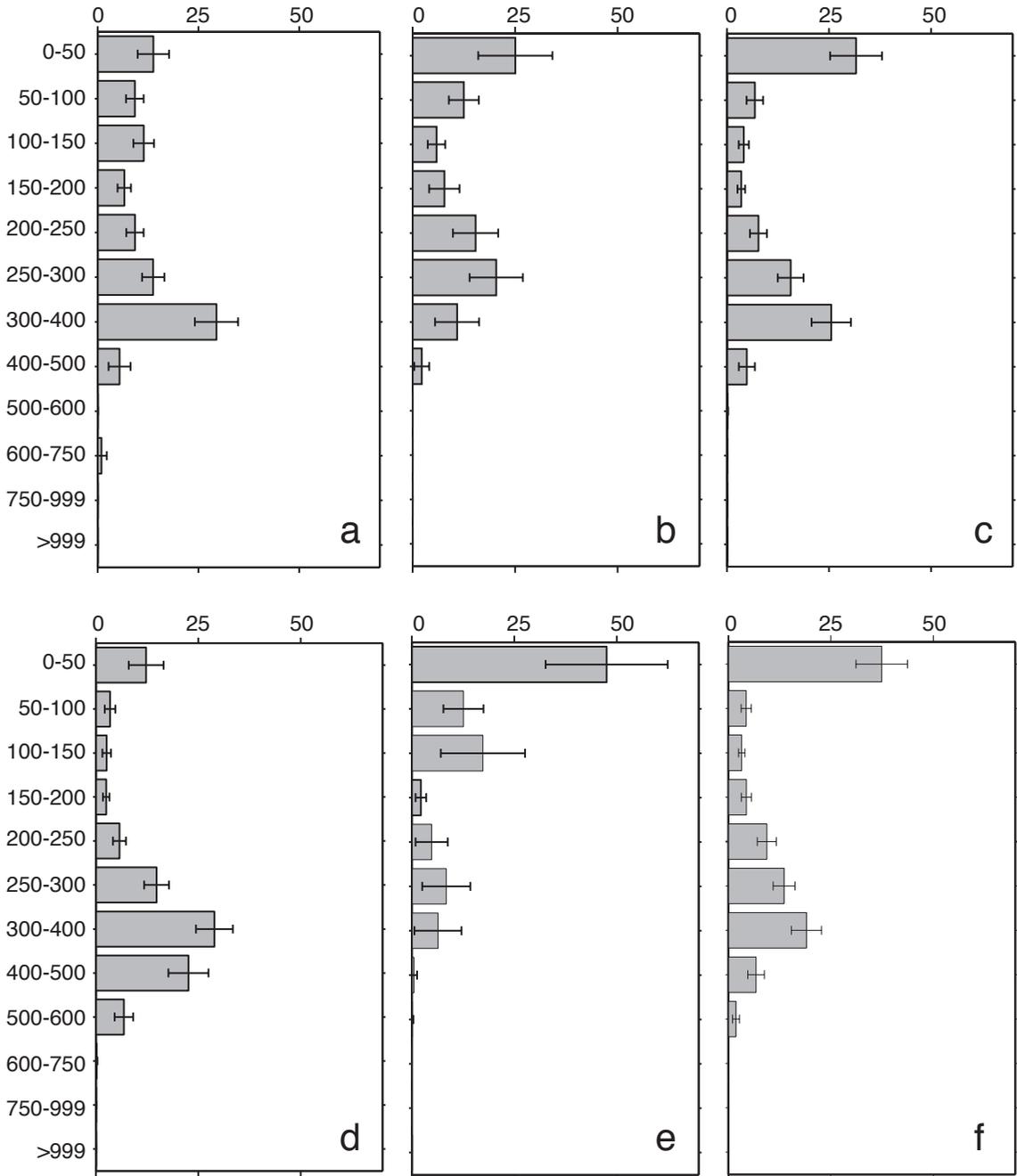


Figure 2.3: Time-at-depth frequency distributions from PAT tags deployed on 29 bigeye tuna during the 1000–1359 period in specific regions and seasons: (a) the NECC during quarter 3, (b) the NEC during quarter 2, (c) the STG during quarter 2, (d) the STG during quarter 3, (e) the STF during quarter 2, and (f) the STF during quarter 3.

2.3.3 Dive types

The pre-binned histogram information provided by the tags indicates that in most regions and seasons there is a bimodal time-at-depth distribution. The two main components of this distribution are shallow and deep components, with a depth mode that may vary due to space, time, or a combination of other factors. An initial indication from this bimodal signature could be that this represents two distinct dive states, representing the shallow and deep-dive signatures, with the time in the intermediary depth bins representing the transition between these two states. Data from the recovered PAT-2 tags provided a higher resolution picture of the dive behavior. Figure 2.4 shows three different dive types during five consecutive days for bigeye 30253 (118 cm FL) after a 3-day post-release period.

This illustrates three distinct types of diving behavior, with three of the 5 days (11/14, 11/17, and 11/18) representing the deep, Type-1 days where bigeye show the common W-shaped behavior. Seventy-nine to 93.3% of the time was spent below 200 m during these 3-day periods (1000–1359). On all three of these days the animal descended to 300 m at civil twilight⁴, and then spent most of its time during this daytime period near 300 m with interspersed movement to the 0–100 m layer. A second, shallow-day type is indicated during 11/15, where 100% of the time was spent shallower than 100 m during the 1000–1359. A third, transitional dive type is indicated on 11/16 where the animal spent most of its time oscillating between 50 and 150 m, with interspersed dives to 300 m and one

⁴Civil twilight times were calculated from the deploy date and location of tag 30253 using the online software provided by the US Naval Observatory Astronomical Applications department at <http://aa.usno.navy.mil>

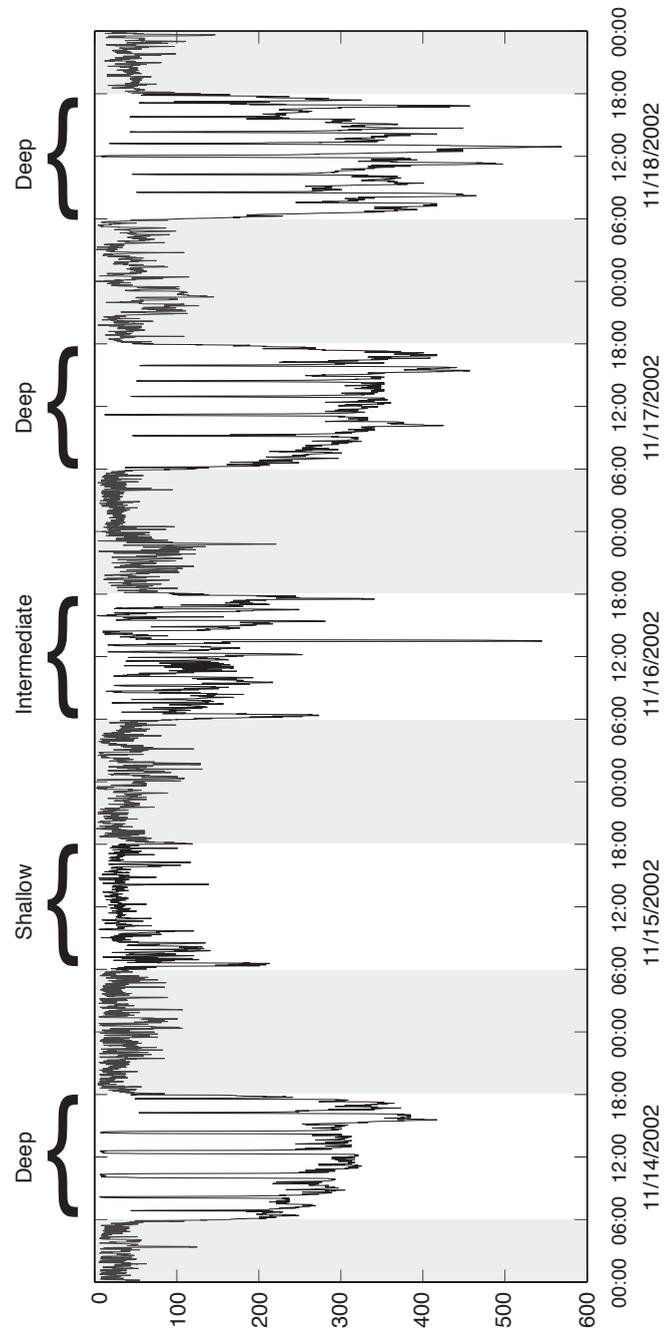


Figure 2.4: Five days of high resolution archival data from successfully recovered PAT-2 tag 30605. These 5 days are used to illustrate the shallow (epipelagic), deep (mesopelagic) and intermediate dive behaviors defined in the study. The grey shading indicates the period between dusk and dawn in local time.

deep dive below 500 m near midday. During this day the largest percentage of time (56.8%) was spent in the 100–200 m depth range. These three states can then be used to visually represent shallow, intermediate, and deep-dive types, where each type of day reflects the largest percentage of time spent in either the shallow, deep, or intermediate layer. These shallow, intermediate, and deep daytime dive types represented 24.4%, 18.8%, and 56.8% of the total number of days in the study, respectively. Additionally, from these examples, it can be seen that for each day there is a specific behavior which continues throughout the daylight period, with no change in the dive-type descriptions if a 12-hour time interval is used. Therefore the 4-hour time intervals used in this study are appropriate to describe a daily dive type over the entire daylight period.

2.3.4 Variability in dive type

Space, time, and thermal habitat were all hypothesized to be important, so variability in dive type was explored across these dimensions. Regional and seasonal variability in the percentage of days for each of the three dive types for bigeye tuna was observed (Fig. 2.5a–c).

The largest percentage of shallow days was in the first and second quarter from 24 to 30°N. Also, a large percentage of shallow days occurred in the third quarter north of 30°N, and in the region between 14 and 18°N during the second quarter. A very small percentage of surface days were found in the region south of 10°N and in any of the regions during the fourth quarter. Overall, a large amount of spatial and temporal variability occurred in the shallow dive-type days, ranging from 0 to 50% of all days depending on latitude and season. The percentage

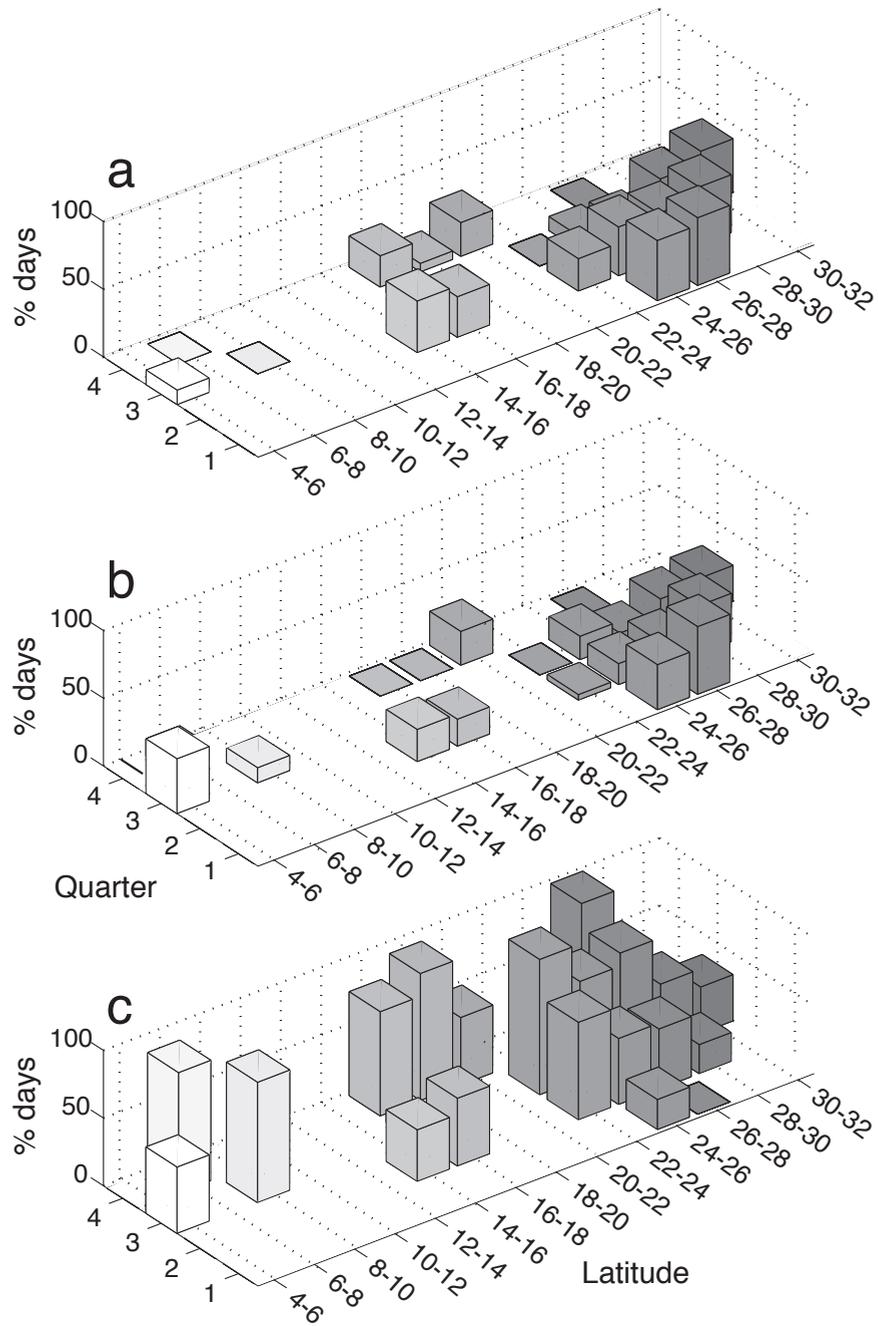


Figure 2.5: Temporal and spatial variability of the three defined daily dive types pooled by the quarter of the year and 2° latitude bins based on the geolocation estimates: (a) The shallow dive type, (b) the intermediate dive type, and (c) the deep dive type.

of intermediate days showed a similar pattern to the shallow days, with a larger percentage of days of the intermediate type in the region from 4 to 6°N during the third quarter. Overall, as with the shallow dive days, a large amount of spatial and temporal variability occurred, ranging from 0–50% of all days depending on latitude and season. The greatest variability was in the percentage of deep-dive type days ranging from 0–100% of all days. Overall, more deep days occurred in the fourth quarter, with a downward shift in the percentage of deep days occurring north of 28°N and during the first and second quarters.

The patterns of dive behavior across space and time, in addition to thermal habitat, were explored by pooling the dive-type data for each variable (Fig. 2.6a–c).

The amount of deep days varied from 35–90% depending on the region, with more than 80% of the days spent in deeper waters between 6° and 10°N; 18° and 20°N; and 22° and 24°N (Fig. 2.6a). More shallow and intermediate days below 6°N, near the NEC from 14° to 16°N, and north of 28°N occurred. There were similar patterns between the shallow and intermediate days in most of the regions, with a larger percentage of shallow than intermediate days except for 46°N, where almost 40% of the days were of the intermediate-dive type. When pooled across all latitudes, the amount of deep days rose from less than 40% in the first quarter to almost 80% in the fourth quarter (Fig. 2.6b). Generally, there was an equal or greater percentage of shallow days than intermediate days, with roughly 20% of the days defined as intermediate days in all quarters. The shallow and intermediate patterns are similar in SST, with decreases in the percentage of days for both dive types in relation to warmer SST values (Fig. 2.6c). Bigeye exhibited

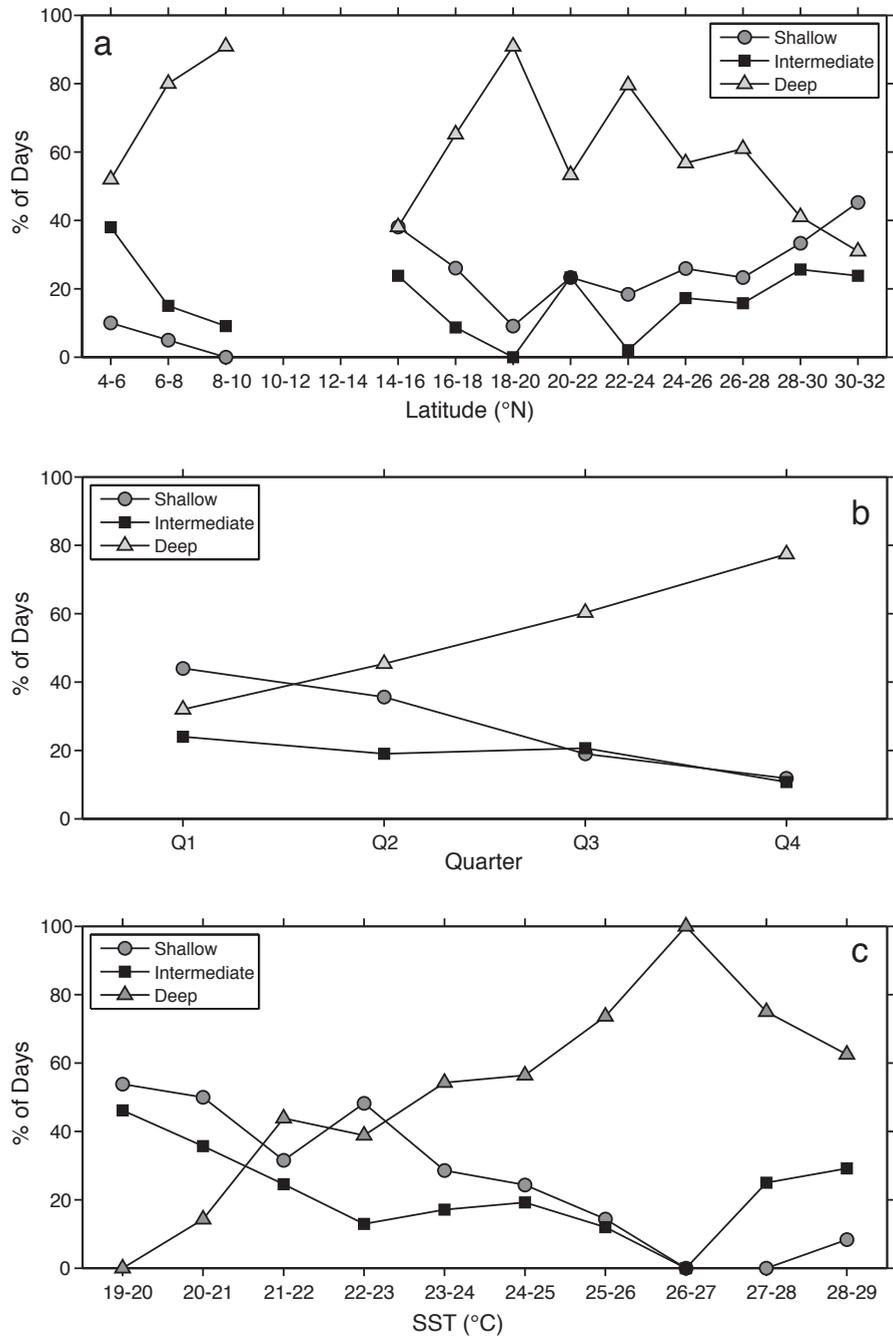


Figure 2.6: The variability of the three daytime dive types as a response to: (a) latitude, (b) the quarter of year, and (c) SST.

shallow behavior for less than 10% of the days where SST was warmer than 27°C. In contrast, more than 20% of the days were of the intermediate type in these warmer waters. The percentage of deep days varied from 0–100% over the SST range in this study. Less than 20% of the days were spent deep in the 20–21°C SST range, and there were no days with deep dive-type behavior in waters colder than 20°C. There was an overall linear increase in the percentage of deep days up to 27°C, with a slight decrease in deep behavior corresponding to the increase in intermediate behavior in surface waters warmer than 27°C.

2.3.5 Model results of potential vulnerability to longline gear

The results of the GAM indicated that three predictor variables were significant to describe the potential vulnerability of bigeye tuna to longline gear in this study. SST, latitude, and quarter of the year were all significant at the 5% level (Table 2.2) and had a large effect on the amount of time bigeye spent in the deeper mesopelagic region.

SST was highly significant and explained 13.9% of the deviance (Table 2.2).

Table 2.2: Analysis of deviance for a three variable generalized additive model of the potential vulnerability of bigeye to commercial longline gear.

Predictor variable	Δ AIC	d.f.	F	Deviance Explained	P
SST	102.6	7.1	43.75	13.9%	0
Latitude	31.36	5.5	44.74	8.3%	0
Season	4.07	3	9.69	4.9%	0.02

Aside from a decrease in effect around 23°C, the effect of SST generally increased with temperature. This indicated that in areas with cooler surface waters there were fewer deep-dive-type days. The effect of SST had the greatest increase from 23° to 26.5°C, with a decrease in the effect of SST for values greater than 26.5°C (Fig. 2.7a).

Latitude was also highly significant and explained 8.3% of the deviance (Table 2.2). Latitude had the largest effects between 5° and 10°N and in the center of the subtropical gyre from 23° to 27°N (Fig. 2.7b). There was less of an effect in the region close to the NEC from 13° to 17°N, and above 27°N. The quarter of the year explained 4.9% of the deviance (Table 2.2). Overall, a larger effect of quarter on deep-dive behavior was evident as the year progressed, with the first and fourth quarters having the smallest and largest effects on deep diving behavior, respectively. The FL, daily speed, MLD, depth of the 10°C isotherm, light (PAR), chlorophyll-a, average slope of the thermocline, and depths of the 1 and 2.1 ml l⁻¹ O₂ concentration were not significant predictors in the model at the 5% level. Model predictions of the potential vulnerability of bigeye tuna successfully capture the spatial and temporal variability in the data (Fig. 2.8), yet also include the additional effect of SST.

A higher percentage of days with potential vulnerability to commercial long-line gear was predicted in the regions below 10°N and in 18°–28°N during the third and fourth quarters of the year. The highest potential vulnerability (98.5%) was predicted for the fourth quarter between 18° and 20°N. A lower potential vulnerability was predicted in the first and second quarters of the year in all regions, with the lowest values occurring during the first quarter of the year and north of 28°N

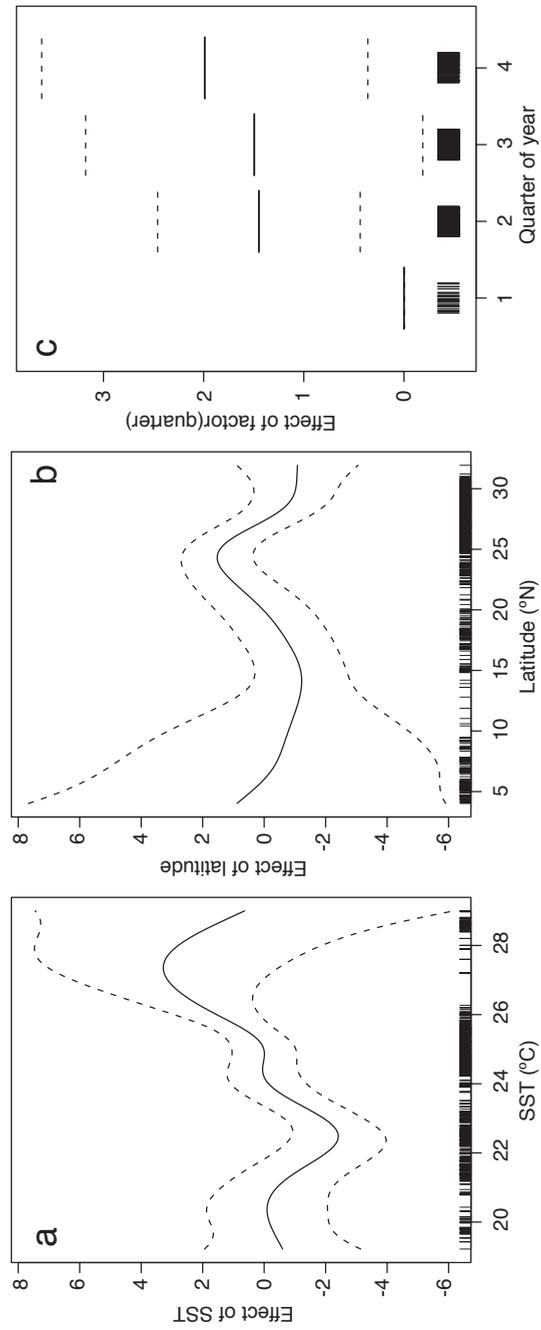


Figure 2.7: The GAM-derived effects on the potential vulnerability of longline gear from (a) sea surface temperature, (b) latitude, and (c) the quarter of the year modeled as a factor.

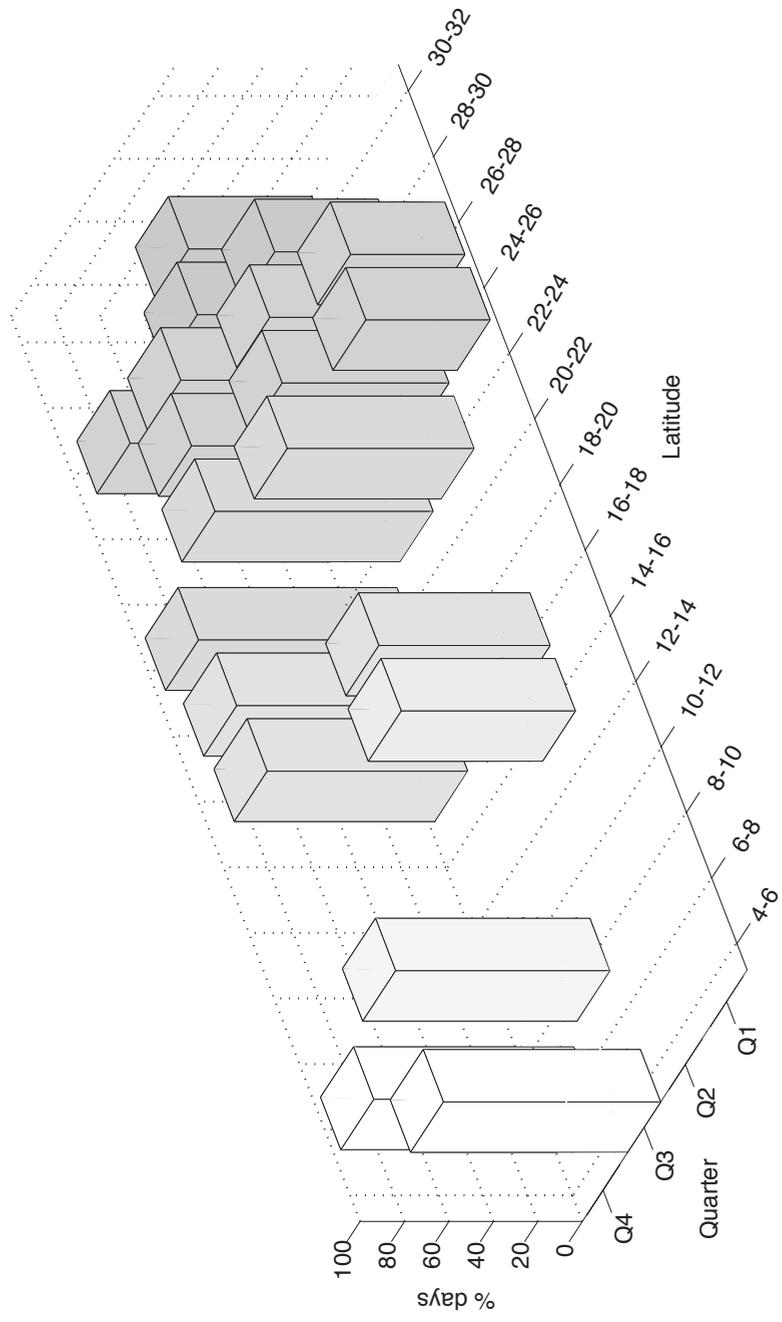


Figure 2.8: The model predicted percentage of days with expected potential vulnerability of bigeye tuna to longline gear pooled by the quarter of the year and 2° latitude bins based on the geolocation estimates.

during all quarters.

2.4 Discussion

Overall, the vertical behavior information captured by the tags was consistent with previous research on dive behavior of bigeye tuna in other open ocean regions of the Pacific (Dagorn *et al.*, 2000; Schaefer *et al.*, 2002; Musyl *et al.*, 2003; Gunn *et al.*, 2005), as well as off-FAD dive behavior for bigeye near the coast of Hawaii (Holland *et al.*, 1990). Bigeye tuna generally followed a diel migration pattern, spending time during the day at the surface and at depths below 100 m, and most of the time during the night in surface waters, presumably above the mixed layer. Previous research reported that bigeye dive behavior is related to the diel migratory patterns of the DSL (Dagorn *et al.*, 2000). This relationship was also inferred in previous tagging studies of bigeye (Musyl *et al.*, 2003), and analysis of stomach contents of animals near the Hawaiian Islands confirmed that bigeye tuna generally select prey from the mesopelagic DSL (Grubbs and Holland, 2003; Brill *et al.*, 2005). While all bigeye exhibited day-night differences in dive depth, there was variability in the daytime depth and temperature ranges across space and time. If one assumes that the largest percentage of dive behavior of bigeye tuna to depth is related to foraging on the DSL, then the difference in depth modes is most likely a reflection of the changes in the DSL or its composition over space and time. The depth and structure of the DSL during the day has been shown to change by region (Tont, 1976; Dagorn *et al.*, 2000; Domokos *et al.*, 2007), and this may explain the regional changes in the daytime depth mode of bigeye tuna.

Archival tag records show that during most days bigeye tuna spent the largest percentage of time at depth, yet there are days where bigeye only inhabit shallow surface waters or spend time in both surface and deep layers (Schaefer *et al.*, 2002;

Musyl *et al.*, 2003). In this study we defined three distinct dive types for bigeye tuna during the day. Bigeye tuna either spent most of their time in the mesopelagic layer deeper than 200 m (deep), in the epipelagic layer shallower than 100 m (shallow) or in an intermediate mixture between the deep and shallow layers. The largest percentage of days (56.8%) were spent in the deep, and this behavior has been previously defined as W-shaped (Musyl *et al.*, 2003) or "Type-1" (Schaefer *et al.*, 2002). This main dive type represents the classic dive behavior to depths where bigeye are associated with the DSL throughout most of the day while coming to the surface at regular intervals for thermoregulation to warm their muscles (Holland *et al.*, 1992; Holland and Sibert, 1994; Brill *et al.*, 2005). This behavior forms the main structure of the bimodal distribution observed in the time-at-depth and corresponding time-at-temperature histograms. The shallow-dive type accounted for 24.4% of the day periods. This shallower behavior has been defined as Type-2 (Schaefer *et al.*, 2002) and was reported for bigeye associated with floating objects (Holland *et al.*, 1990; Schaefer *et al.*, 2002; Musyl *et al.*, 2003) and in the open ocean (Schaefer *et al.*, 2002). A third intermediate behavior was indicated by the archival tag data and was used to represent the days when time was spent in the epipelagic surface and deeper mesopelagic layers. Bigeye tuna dive behavior similar to this has been reported by Schaefer and Fuller (2002) and attributed to a shift in the vertical distribution of prey. While analysis of stomach contents of bigeye tuna has shown that they mainly forage on mesopelagic species, surface species have been found in some stomach samples (D. Grubbs, unpublished data). The ability of bigeye to feed on aggregated surface or intermediate prey when available may be a more desirable behavior than consistent foraging at depth. It is possible

that the change from deep to shallow behavior may be a shift in prey base similar to mechanisms previously described.

There was a large degree of variability in these three dive types as a function of space and SST. The observed variability related to SST is most likely a result of the thermoregulatory requirements of bigeye tuna (Brill *et al.*, 2005). Bigeye tuna typically experience temperatures at depth which are 10–20°C lower than waters in the mixed layer (Dagorn *et al.*, 2000; Schaefer *et al.*, 2002; Musyl *et al.*, 2003; Brill *et al.*, 2005). Physiological adaptations of bigeye allow tolerance of large temperature changes and low oxygen conditions, yet maintenance of elevated muscle temperatures is required (Brill *et al.*, 2005). Thermoregulation is thought to explain the regular upward excursions into the warm surface layer by bigeye; time spent in conditions where ambient temperatures are considerably less than body temperature forces bigeye tuna to return to the warm surface layer to increase muscle temperature (Holland *et al.*, 1992; Brill *et al.*, 2005). If warming rates at the surface are a function of ambient temperature, it follows that in warmer surface waters less time would be required to elevate internal temperatures. This aspect is observed in the data, where up to 45% more time was spent in the shallow layers in areas with colder surface waters.

Latitudinal changes in daily dive-type represent changes in the surface waters as well as the more permanent biological and oceanographic spatial structures at depth. There were very distinct regions based on climatological subsurface temperature and oxygen. Bigeye tuna spent the largest percentage of deep days near the NECC south of 10°N and in the center of the STG, two very different oceanographic regions. The least amount of deep days was spent in the NEC from 14° to

18°N, and in waters north of 18°N. These areas have very different oceanographic features. In this study, the NECC region was characterized by the most extreme temperature gradients. Accordingly, in this area time-at-depth may be strongly affected by rapid heating in the very warm surface waters. Conversely, the STF region was associated with the coldest surface waters, which may inhibit the amount of time bigeye spend at depth as a result of physiological constraints. The study region in the NEC from 14° to 18°N near 150°W is associated with the shallowest oxycline in the study area, which could possibly impact the amount of time spent at depth in this region. Oxygen was not a statistically important covariate in the model of potential vulnerability where the deep and intermediate dive types were collapsed, yet it is known that oxygen can be physiologically limiting to bigeye tuna (Brill *et al.*, 2005). Interestingly, based on longitude and latitude estimates, the eight tagged bigeye which were in close proximity to the low oxygen region spent no time in this area. They remained north, west or south of the shallow low-oxygen tongue. Additional data in this oceanographically distinct region would help to uncover any effect of the oxycline on dive behavior and help to elucidate whether bigeye tuna actively avoid the area associated with a shallow oxycline.

The temporal effect of the time of year on deep-diving behavior may possibly be explained by changes in habitat, forage type or spawning behavior in the central North Pacific. Bigeye spent most of their days in the epipelagic surface layers during the first and second quarters of the year. The coldest surface temperatures occurred during the first quarter. This may explain the observed decrease in deep days during this quarter, because most of the data during this period pertained to one particular region. During the second quarter, however, data were available

over different regions spanning a wide SST range. The decrease in deeper dive behavior during the spring was also reported for bigeye in the Coral Sea (Gunn *et al.*, 2005), where it was reported that bigeye aggregated in surface waters of the northwestern Coral Sea in association with large spawning aggregations of myctophids during the spring months. This shift in forage base was also discussed as a possible factor related to the increase in shallow behavior in the eastern tropical Pacific (Schaefer *et al.*, 2002). A similar shift in the forage base may occur in the central North Pacific during the second quarter of the year as well. An increase in shallow behavior may result from a shift in surface forage after spring bloom events, in conjunction with increased stratification from warming in the upper layers. Reproductive information on the tagged bigeye was not available, but we cannot dismiss the possibility that surface dive behavior may be associated with spawning events. Previous research, however, suggests that scombrids prefer to spawn at night (Schaefer, 2001) in the equatorial or tropical Pacific, in surface waters warmer than 26°C (Hampton *et al.*, 1998). The tag data show that animals within the equatorial region had a very small percentage of surface days, and the STF region had a high proportion of surface days associated with surface temperatures well below 26°C. Spawning events may have occurred in the NEC region during the second quarter as surface temperatures ranged from 25° to 25.5°C, but without empirical reproductive data this is speculative.

The amount of time that bigeye spend below 100 m during the day is expected to have a direct effect on their catch rates. Longline gear targeting bigeye tuna is generally set during the early morning and hauled in the afternoon. Results from pelagic longline studies incorporating TDRs show longline gear targeting tunas

is generally set between 100 and 400 m, with the median deepest hook depth at around 250 m (Boggs, 1992; Bigelow *et al.*, 2006; Hawn, unpublished data). Vertical dive distributions from the 29 tags used in this study show that when bigeye travel to depths below 200 m, they generally distribute in the 250–500 m range depending on the location and quarter. As data from the tags also show a bimodal dive distribution, where time is spent either at depth or in the top 100 m, most of the interactions between bigeye and longline gear occur most likely during the transit times or while the bigeye are at depth. Acoustic backscatter measurements of the DSL concurrently with sonic tracking of bigeye tuna have shown that bigeye follow the DSL as it migrates down to depth at dawn, then diverge to remain in a layer slightly shallower than the DSL (Dagorn *et al.*, 2000). Increased time at a depth range reachable by longline gear would be expected to result in increased catch rates. The model predictions indicate that the largest percentage of days with potential vulnerability to longline fishing gear is expected to be in the fourth quarter from 18° to 20°N. Annual catch reports of bigeye tuna show that the largest amount of effort, highest catch and highest CPUE by the Hawaii-based longline fishery are in the fourth quarter of the year in the Hawaii region⁵. While additional dive information covering all quarters and regions used by the Hawaii-based longline fishery is needed to make more balanced predictions, these results suggest that a GAM using these three predictive variables may help in identifying areas of potentially high bigeye catch rates.

Additionally, the variability in dive behavior presented here may assist in stock

⁵NMFS reports of annual catch in the Hawaii-based pelagic longline fishery are available at <http://www.pifsc.noaa.gov/fmsd>

assessments of bigeye tuna in the North Pacific. Current stock assessments methods use habitat information in conjunction with fisheries dependent data to obtain indices of abundance through CPUE standardization. Recent work has shown that temperature is more important than depth in standardization (Bigelow and Maunders, 2007). These results in this study show that bigeye spent on average over 50% of their time during the day in the 8°–14°C temperature range in this study area, with variability in the amount of time in this habitat based on season, region, and surface temperature conditions. This information provides a better understanding of the temperature-based habitat of bigeye tuna, which will aid in the CPUE standardization step and potentially yield more accurate stock assessments.

Chapter 3

TurtleWatch: a tool to aid in the bycatch reduction of loggerhead turtles *Caretta caretta* in the Hawaii-based pelagic longline fishery

3.1 Introduction

The interactions of sea turtles with high seas fisheries are a global concern, with fisheries bycatch implicated as one of several factors in the population decline of many sea turtle species, including the loggerhead sea turtle *Caretta caretta* (Hatase *et al.*, 2002; Hays *et al.*, 2003; Peckham *et al.*, 2007). The loggerhead is a circumglobal turtle species (Dodd, 1988) that undergoes a series of ontogenetic shifts during its life cycle, with stages occupying a series of habitats that include nesting beach, oceanic, and neritic areas (Bjorndal, 2003). In the North Pacific, loggerhead nesting beaches are only found in Japan, where, during the last half of the 20th century a substantial decline (50–90%) in the size of the annual loggerhead nesting population at nesting beaches was reported (Kamezaki *et al.*, 2003).The

importance of the oceanic stage to juvenile loggerheads was hypothesized first by (Carr, 1987) with recent work by Polovina *et al.* (2006) reporting that specific pelagic regions, such as the Kuroshio Extension Bifurcation Region of the North Pacific Ocean, may be an important nursery habitat for juvenile loggerhead turtles.

Previous studies using satellite tags affixed to juvenile loggerheads in the North Pacific have found that during the first quarter of the year these turtles occupy a northern latitude range from 28° to 36°N (Polovina *et al.*, 2004). This area corresponds to the North Pacific Transition Zone (NPTZ), a region which separates the North Pacific Subarctic and Subtropical Gyres. To the south, the transition zone is bounded by the North Pacific Subtropical Frontal Zone (NPSTFZ), which is identified in winter by the 18°C isotherm (Roden, 1980; Roden, 1991). Within the transition zone, loggerheads were found to be associated with the biological feature described as the Transition Zone Chlorophyll Front (TZCF) (Polovina *et al.*, 2001; Polovina *et al.*, 2004; Polovina *et al.*, 2006) an important migration and forage pathway for many pelagic animals (Polovina *et al.*, 2001) which is associated with the 18°C isotherm in the central North Pacific (Bograd *et al.*, 2004). The TZCF is most commonly used as an indicator of this highly convergent area in the frontal zone, with increased accumulation of organic matter and sessile organisms. A diet study of juvenile loggerheads in the central North Pacific showed that 4 of the 5 major prey items for these individuals were neustonic species that would tend to concentrate in a highly convergent area such as a frontal zone (Parker *et al.*, 2005). Juvenile loggerhead turtles tend to stay within waters close to the surface in this region. Diving results from an archival tag affixed to a 61 cm straight carapace length (SCL) loggerhead turtle in the NPTZ showed the turtle spending most of its

time in the top 50 m during the day and night in the first quarter of the year, with minimal time spent below 100 m (Polovina *et al.*, 2003). Based on these studies, it is clear that the North Pacific Transition Zone, especially the 18°C isotherm demarcating the North Pacific Subtropical Frontal Zone, is an important migration and forage area for juvenile loggerhead turtles. This type of thermal habitat demarcation has also been seen for leatherback turtles *Dermochelys coriacea* in the North Atlantic. Satellite tracking results indicated that turtles in this region could be encapsulated by the 15°C isotherm (McMahon *et al.*, 2006), while a more recent study using leatherback sightings, strandings, and captures suggested that surface waters of 10 to 12°C were indicative of the lower threshold to prolonged occupation (Witt *et al.*, 2007).

The Hawaii longline fishery operates year round in the area 180°–140°W, 0°–40°N, targeting billfish and tuna species. Historically, during the first half of the year, the fishery has specifically targeted swordfish to the north of the Hawaiian Islands in the NPSTFZ (Seki *et al.*, 2002). Swordfish sets are generally set during the night, with the fishing gear configured to lie shallower in the water column than deep sets targeting tuna species (Boggs, 1992; Ito, 1998). Preliminary observations by timedepth recorder measurements from commercial longlines indicated that the mean depth of the deepest hook was 70.6 m (Bigelow *et al.*, 1999, C. Boggs, NMFS Pacific Islands Fisheries Science Center, unpubl. data). Combined, these operational fishery parameters place a large number of hooks on shallow sets less than 100 m in depth in the North Pacific Subtropical Frontal Zone during the first quarter of the year in the same temporal and spatial position as juvenile loggerhead sea turtles.

The importance of understanding and minimizing the bycatch of loggerhead sea turtles by the pelagic longline fisheries has been well documented (DiNardo, 1993; Ito 1998; Lewison *et al.*, 2004; Gilman *et al.*, 2007; Lewison *et al.*, 2007). Increasing numbers in the bycatch of loggerhead turtles by the Hawaii longline fishery during the 1990s led to temporary timearea closures in the early 2000s and the subsequent ban of all shallow sets by the Hawaii longline fishery in 2002. The shallow set fishery was reopened in late 2004 but as a limited entry fishery with several gear requirements in place. This included the use of larger circle hooks in an attempt to decrease the ingestion of hooks by sea turtles, a limit of 2,120 shallow sets per year, and the additional requirement of 100% coverage of these shallow sets by an observer (NMFS 2004). A take limit of 17 interactions with loggerhead turtles was also put into place, with a closure of the fishery for the remainder of the year in effect when this limit was reached. In March 2006, the 17 loggerhead turtle-take limit was reached, forcing the closure of the shallow set portion of the fishery for the remainder of the year. This repercussion increased awareness on the part of both fishers and managers of the importance of the first quarter of the year to the Hawaii longline shallow set fishery.

In response to the fishery closure, a project was initiated to create a dynamic product showing the highest areas of potential loggerhead turtle bycatch based on analysis of historical data and the environment. The goal of this project was to create a timely, science-based tool for recommendation which would be easily usable and understandable by fishers and management entities. An inter-disciplinary approach involving fishery, oceanographic, and satellite tracking data was used to aid in quantifying the relationship between habitat and loggerhead bycatch (God-

ley *et al.*, 2008). This chapter describes the scientific analysis used to create the experimental product named TurtleWatch and then use the fishery and loggerhead bycatch data from the first quarter of 2007 to evaluate whether any change in fishing behavior or loggerhead interactions was apparent after the release of the TurtleWatch product.

3.2 Methods

The purpose of this study was to better understand where turtle interactions may have occurred, based on available spatial and environmental data. To accomplish this, data on fishing locations and dates were imperative to match fishing activity to a corresponding environmental variable, which in this study was water temperature. Information on any interactions with loggerheads was also essential, as this would allow for the matching of an interaction position in time with the corresponding sea surface temperature (SST) signal.

3.2.1 Fisheries data

The fishing data used in this study were obtained from two logbooks sources, with data recorded by either fishers or federal observers depending on the data type. The Hawaii Longline Observer Program was established in March 1994 for the purpose of monitoring interactions between the longline fishery and sea turtles (DiNardo 1993, Walsh *et al.* 2005). During each observed set, observers monitor sets and record and log a large array of information on set, gear configuration, catch, protected species interactions (i.e. bycatch), and other environmental and operational parameters. In the present study, information on loggerhead interactions from 1994 to 2007 was used. In the period prior to shallow set regulation, i.e. between 1994 and 2002, observer coverage of shallow sets varied considerably. Observers were randomly placed aboard commercial fishing vessels targeting swordfish (DiNardo, 1993), with an average of 36% of the active vessels carrying an observer at least once a year prior to 2000 (Walsh *et al.*, 2005) and the observer coverage of sets remaining below 5%. Observer coverage levels increased after 2000, but cov-

erage levels were around 20 to 25% until after the shallow set fishery was reopened in 2004, when it was federally mandated that an observer be present to monitor all shallow sets deployed by the Hawaii longline fishery. This results in a dataset of loggerhead interactions representing a pre-legislation period in the years 1994 to 2002 with a smaller percentage of sets observed, and a post-regulation period from 2005 to 2007 with 100% of all sets observed.

Under a federal mandate, all information for each individual commercial longline set must be recorded onto a logbook page. The primary objective of the logbook system, implemented in November 1990, is to obtain statistically reliable information on (1) fishing effort and catch and (2) the take of protected species. These logbook reports then provide information comparable to information available from the observer logbooks such as set date, location, effort, and bycatch of protected species during the period from November 1990 through the present. However, a study comparing estimates of turtle take rate between logbook data reports and scientifically observed sets showed that the observed turtle take rate was considerably higher by observers than that reported by fishers in the logbook (DiNardo, 1993). Because the reported takes of protected species were likely downwardly biased from non-reporting, only operational fishery information (e.g. hooks, set time, etc.) was used from the longline logbooks in the present study to provide data from 1994 through 2002. These data were coupled with the post-ban observer reports, which provided a complete record of all set date, location, and effort for shallow sets from 1994 through 2007.

Data from both the federal logbooks and observer reports were filtered to focus on shallow sets targeting swordfish. Longline logbook data from 1994 to 2002 were

filtered by only retaining sets that were classified at that time as either swordfish or mixed sets. The mixed-set operations were mostly shallow set, and under current regulations all sets must be either shallow or deep. For each interaction, when available, the date and location coordinates of the turtle take were used. For the fishing sets, the date of the beginning of the haul was used along with the average of the beginning and ending haul coordinates. This was done to attempt the closest match of fishing sets and turtle interactions, as turtle captures were only recorded during the hauling of the gear. For 21 interactions no capture date or position was recorded, but the trip number and set number were available. For these interactions the trip number and set number from the interaction record were matched to the corresponding set information from the logbooks. The longline logbook haul date and average haul coordinates were then used.

We included any reported interactions of unidentified hardshell turtles in the present study, as these interactions are conservatively used in the interaction tally in the decision to close the shallow set fishery (because the great majority of hardshell turtles from shallow sets are loggerheads). For example, in 2006, 2 interactions were reported as unidentified hardshell, yet were added to the 15 reported loggerhead turtle interactions to bring the count to the 17 turtle limit.

3.2.2 Satellite tag data

Data from wild-caught and captive-reared turtles were used to represent fishery-independent locations of loggerhead turtles. Turtles were outfitted with satellite transmitters attached to the dorsal carapace using the procedures outlined in Balazs *et al.* (1996) and equipped with Telonics model ST-18, ST-19, ST-24, Wildlife

Computers SDR-T10, SDR-T16 or SPOT3 Argos-linked satellite transmitters. Locations were transmitted to ARGOS processors aboard NOAA polar orbiting satellites according to the tags set duty cycle resulting in a time series of positions with an associated quality flag assigned by ARGOS. Positions were screened using the methods described in Kobayashi *et al.* (2008) with only the highest quality position data with likely swimming velocities kept in the final data. This resulted in 10,778 unique positions from 105 individual turtles and covering the 1997 to 2006 time period.

3.2.3 Environmental data

SST data were derived from the 5-channel Advanced Very High Resolution Radiometers (AVHRR) on board the NOAA-7, -9, -11, and -14 polar orbiting satellites. The data used from 1985 to July 2003 were obtained from the descending (nighttime) passes that were processed using versions 4.0 and 4.1 of the AVHRR Pathfinder SST algorithms developed by the University of Miami (Vazquez *et al.*, 1998). These data are received as a 9 km product mapped to an equal area projection for each 8 d period. From July 2003 to the present, daily SST data processed using the National Environmental Satellite, Data, and Information Systems (NESDIS) global area coverage (GAC) algorithm were averaged to create weekly and monthly images that are comparable on a temporal and spatial resolution to the Pathfinder V4 SST product ($r^2 = 0.99$, $p < 0.01$). The SST used in the Turtle-Watch product was a daily, 3 day temporal mean image of the temperature field processed using the GAC algorithm. Sea surface height (SSH) data were mapped at a global $0.3^\circ \times 0.3^\circ$ resolution with orbit error reduction provided by the Ssalto

program of the Centre National d'études Spatiales, France. This altimetry product is a weekly average of the measured along-track sea level profiles mapped to a mercator projection. The average of these along-track profiles from 1993 to 1998 was used to create a mean profile that was then subtracted from the mapped product to obtain the sea level anomalies. For the October 1992–July 2002 time period, data from the TOPEX/POSEIDON altimeter were used. After July 2002, JASON-1 was put into operation along the same orbit as TOPEX/POSEIDON, and since then its data were used in the study. To compute the geostrophic currents, the 1994 NODC World Ocean Atlas Levitus long-term mean 1000 m dynamic height data set was added to the SSH anomaly files to create an absolute SSH. The east–west and north–south gradients were derived from this height and subsequently used to calculate the east–west and north–south components of the geostrophic current, as described in Polovina *et al.* (1999).

3.2.4 Data analysis

To identify the thermal region where loggerhead interactions and swordfish sets occurred, the averaged position data of swordfish sets and loggerhead turtle interactions were matched in time and space to the 8 day remotely sensed SST, which was the highest temporal and spatial temperature data available at the time of the analysis. Data was matched at each individual location using the bilinear interpolation method in the routine `grdtrack`, which is part of the Generic Mapping Tools software package (Wessel *et al.*, 1991). Using this method, temperature values were obtained for every position of each shallow set, loggerhead turtle interaction, and ARGOS satellite transmission of tagged turtles. Tests for normality were per-

formed using the Kolmogorov-Smirnov (K-S) goodness of fit test (Zar, 1984) in MATLAB (The Math Works) (K-S test).

3.3 Results

3.3.1 Fishery information

Table 3.1 provides information on the number of sets, hooks, and associated loggerhead turtle interactions for the first quarters from 1994 through 2006. Over the entire time period, 9,888 shallow sets were made by the fishery in the first quarter, with a total of 7,927,891 hooks deployed and 149 loggerhead interactions occurring. The maximum percentage of historical effort is north of the Hawaiian Islands, with a large percentage occurring in the transition zone north of 30°N during this period. The spatial pattern of the fishery in the transition zone follows an apparent diagonal axis with effort distributed from the northeast to the southwest (Fig. 3.1). There was a definite shift in the focus of the effort to the north after the reopening of the fishery in late 2004, with 98% of the effort distributed north of 28°N during the first quarters of 2005 to 2006 as compared to the pre-closure period, when 79% of the effort was north of 28°N during the first quarter (Table 3.1). Of all turtle interactions, 58.1% occurred in the first quarter during the pre-regulation period, with 94.6% of these first quarter interactions in latitudes north of 28°N . For the post-regulation period, 89.7% of all turtle interactions were in the first quarters of 2005 and 2006, with 100% of these interactions occurring in latitudes north of 27°N .

Table 3.1: Total operational fishery and loggerhead turtle interaction parameters for January–March during the pre (1994–2002) and post (2005–2006) regulation periods. The value in parentheses represents the amount above 28°N.

Period	1994–2002			2005–2006		
	Sets	Hooks	LH Int	Sets	Hooks	LH Int
Jan Total	2569 (69.7%)	2134548 (68.1%)	43 (38)	255 (100%)	214281 (100%)	8 (8)
Feb Total	2322 (82.3%)	1832153 (80.7%)	40 (39)	483 (99.8%)	407196 (99.8%)	15 (15)
Mar Total	3516 (88.1%)	2803598 (87.1%)	28 (28)	653 (95.7%)	536115 (95.5%)	15 (14)
Q1 Total	8497 (80.8%)	6770299 (79.4%)	111 (105)	1391 (97.9%)	1157592 (97.8%)	38 (37)

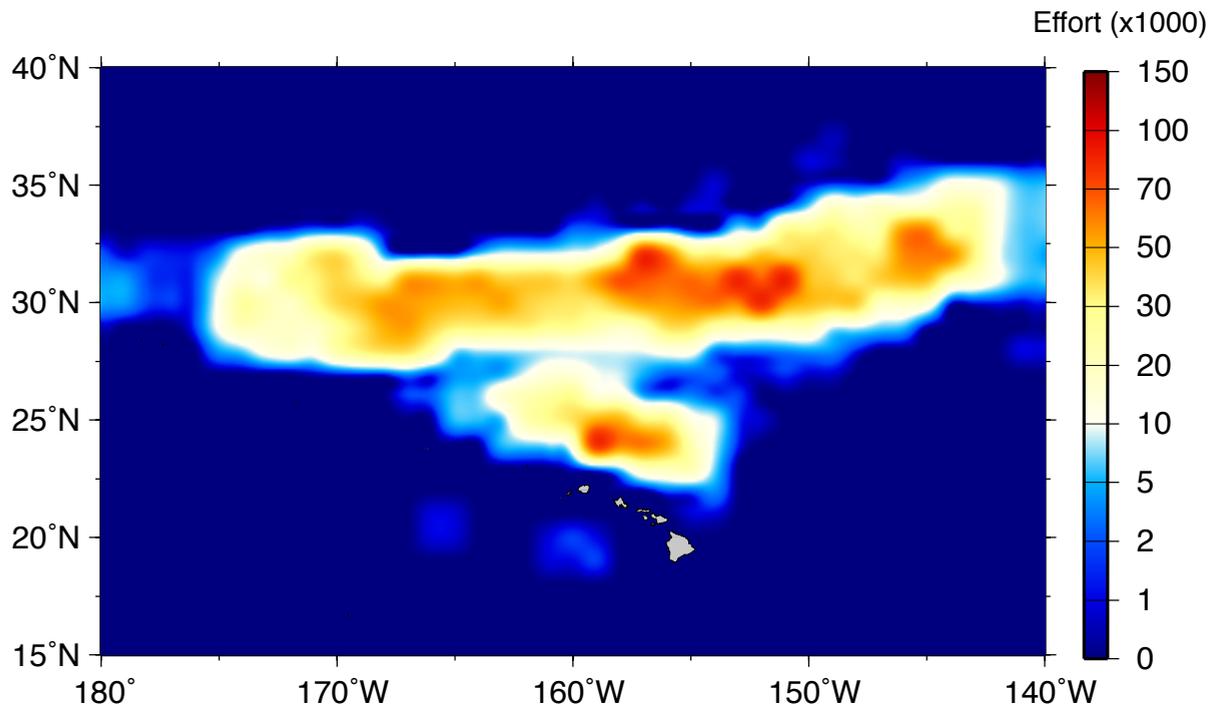


Figure 3.1: Pseudo-color representation of the total number of hooks (effort) deployed in shallow sets by the Hawaii longline fishery during the first quarters of 1994 to 2006. Data was binned to $1^\circ \times 1^\circ$ grid cells and then filtered due to confidentiality requirements. Colors represent the total effort for a $1^\circ \times 1^\circ$ region, not an individual pixel.

3.3.2 Environmental relationship between sets and loggerhead interactions

There is a strong relationship between the average latitudinal position of the 18°C isotherm shallow sets and loggerhead turtle interactions for all first quarters during the period 1994 to 2006 (Fig. 3.2). During these first 3 months, shallow sets as

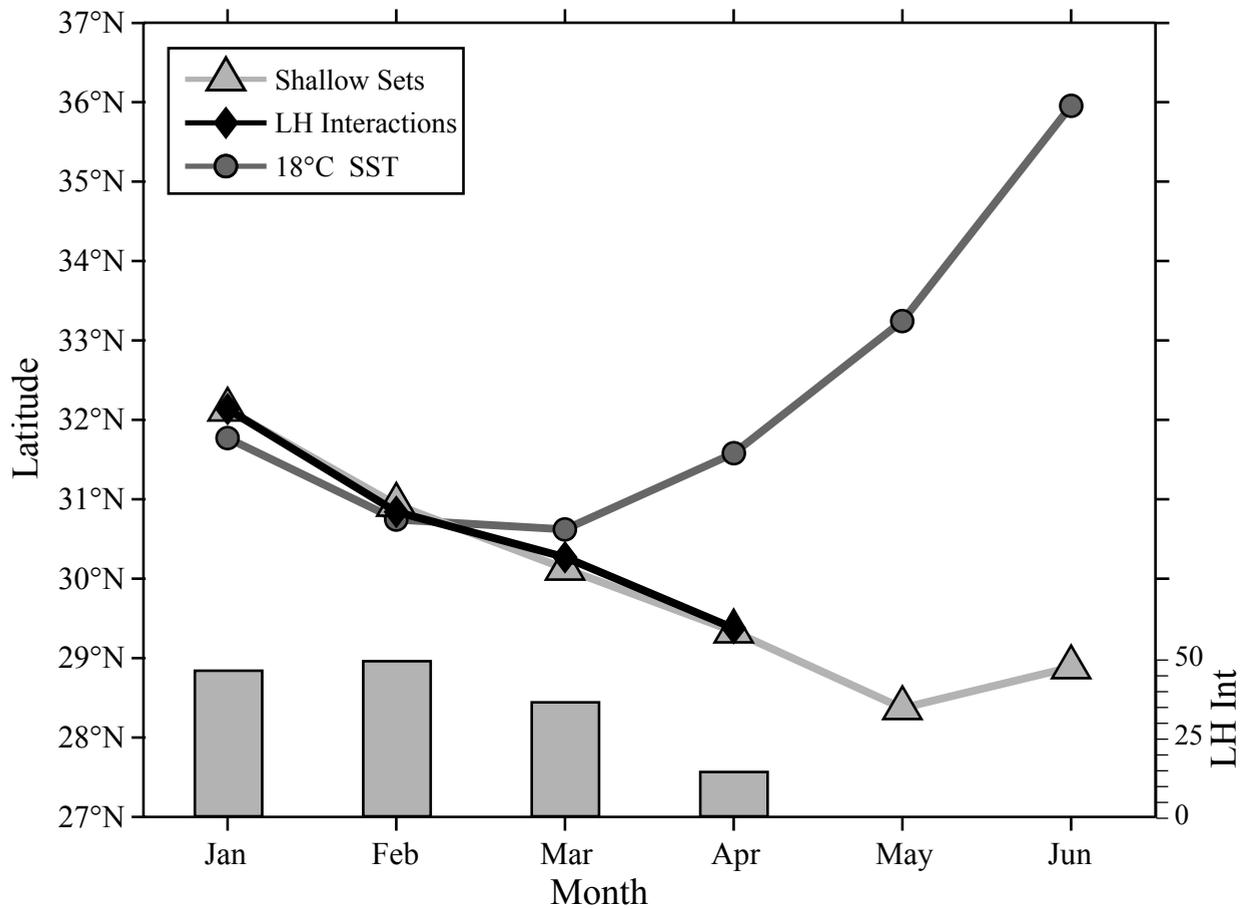


Figure 3.2: Relationship between month and average latitude of shallow sets, loggerhead turtle interactions (LH int), and the North Pacific Frontal Zone (represented by the 18°C isotherm proxy averaged from 180°–150°W) for 1994 to 2006. Bar plot at the bottom represents the total number of LH int for each month over the period 1994 to 2006. SST: sea surface temperature.

well as turtle positions closely track the latitudinal movement of the 18°C isotherm, which here is used as a proxy for the central location of the North Pacific Transition Zone. Beginning in April, the fishery moves to the south of the rapidly northward moving frontal zone, with a marked decrease in loggerhead turtle interactions. The divergence of the fishery and the frontal zone continues through May and June, with no loggerhead turtle interactions occurring above 28°N in these months.

Analysis of the temperature ranges associated with loggerhead turtle interactions, shallow sets, and turtle positions from satellite tags showed the overlap in thermal range across these 3 distributions (Fig. 3.3). SST values associated with loggerhead turtle interactions for the first quarters in 1994 to 2006 ranged from 15.1° to 20.1°C (mean = 17.9°C, SD = 0.8°C). The distribution of SST values relating to the position of shallow sets in the first quarter was similar to that of the interactions, ranging from 14.1° to 21.9°C, with a slight skew towards warmer SST values (mean = 18.1°C, SD = 1.0°C) (Fig. 3.3b). The distribution of SST associated with turtles affixed with satellite tags was much cooler overall, ranging from 11° to 21.6°C (mean = 16.3°C, SD = 1.6°C) (Fig. 3.3c).

The SST distribution for loggerhead turtle interactions was non-normal (K-S test, $p < 0.01$). The 50% (interquartile) and 95% percentile ranges for all 3 distributions are shown in Fig. 3.3. The interquartile range of SST for all loggerhead interactions in the first quarter for all fishing years in 1994 through 2006 was 17.5° to 18.5°C (Fig. 3.3a), which represents the SST range where 50% of all interactions occurred during this time period. This temperature range was used as the basis for a thermal warning band of avoidance to aid in the decrease of loggerhead turtle interactions by the shallow set fishery. As a result of the observed

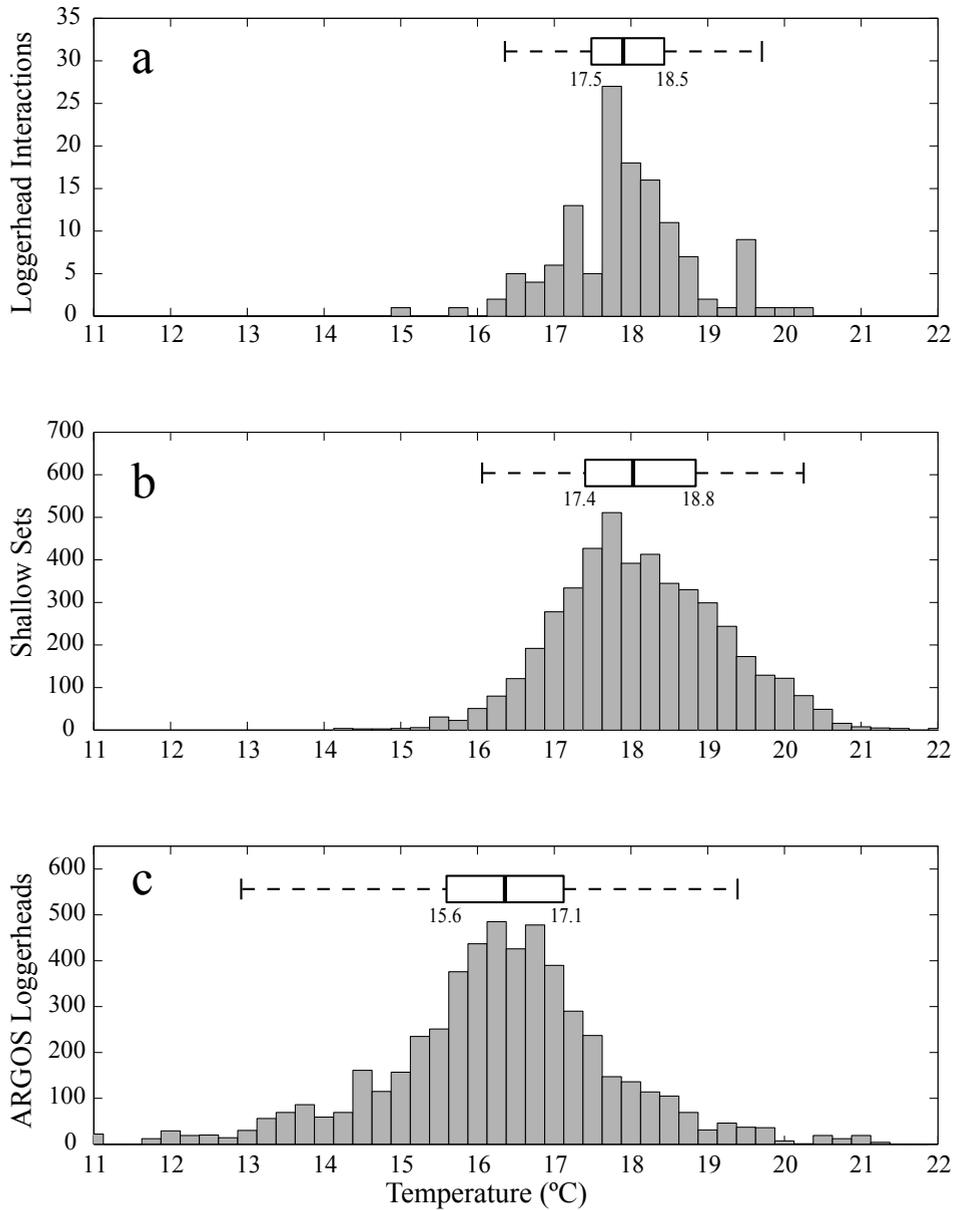


Figure 3.3: Frequency distributions of SST associated with positions of (a) loggerhead turtle interactions with the shallow set fishery, (b) shallow sets deployed by the fishery and (c) loggerhead turtles recorded by satellite tags. Solid line in the box and whisker diagrams represents the median, with the box representing the 25th and 75th percentiles, and the dashed line the range covering 95% of the data. Annotated numbers represent the SST values corresponding to the 25th and 75th percentiles of the distribution.

cooler SST distribution of fishery-independent turtle locations (from wild-caught and captive-reared turtles), the lower bound of the interquartile range was used as a northern recommended limit for the setting of shallow gear in the first quarter of the calendar year. As the metric system is not yet employed by the Hawaii long-line fishery, the 18.5°C recommended value was converted to degrees Fahrenheit and rounded to the closest 0.5°F. This translates into a value of 65.5°F which was used in conjunction with ocean currents to create the initial experimental product released as TurtleWatch (Fig. 3.4) a thermal map produced on a daily basis that covers the spatial area of greatest historical effort. Ocean currents were added at the request of the industry to aid in the selection of appropriate fishing conditions.

3.3.3 Comparison of sets pre- and post-TurtleWatch

Data from 2005 to 2007, in which 100% of all interactions were recorded, were analyzed to reveal changes in the location of the fishery in the season after the release of TurtleWatch in December 2006. The operational fishery information and loggerhead interactions for the first quarter for each of these years are displayed in Table 3.2. The greatest number of hooks during this 3 year period was deployed by the fishery in the first quarter of 2007. Effort by the fishery was more evenly spread out across the 3 month period during 2007, in contrast to the increase in effort from January through March in 2005 and 2006. The lowest average interaction rate for the first quarter of the 3 year period was in 2007. The hard cap of 17 turtle interactions was reached in March 2006, compared to 12 interactions reported in 2007. The largest variability in turtle interactions by month was in January.

There was an apparent geographic shift in the placement of the sets in 2007,

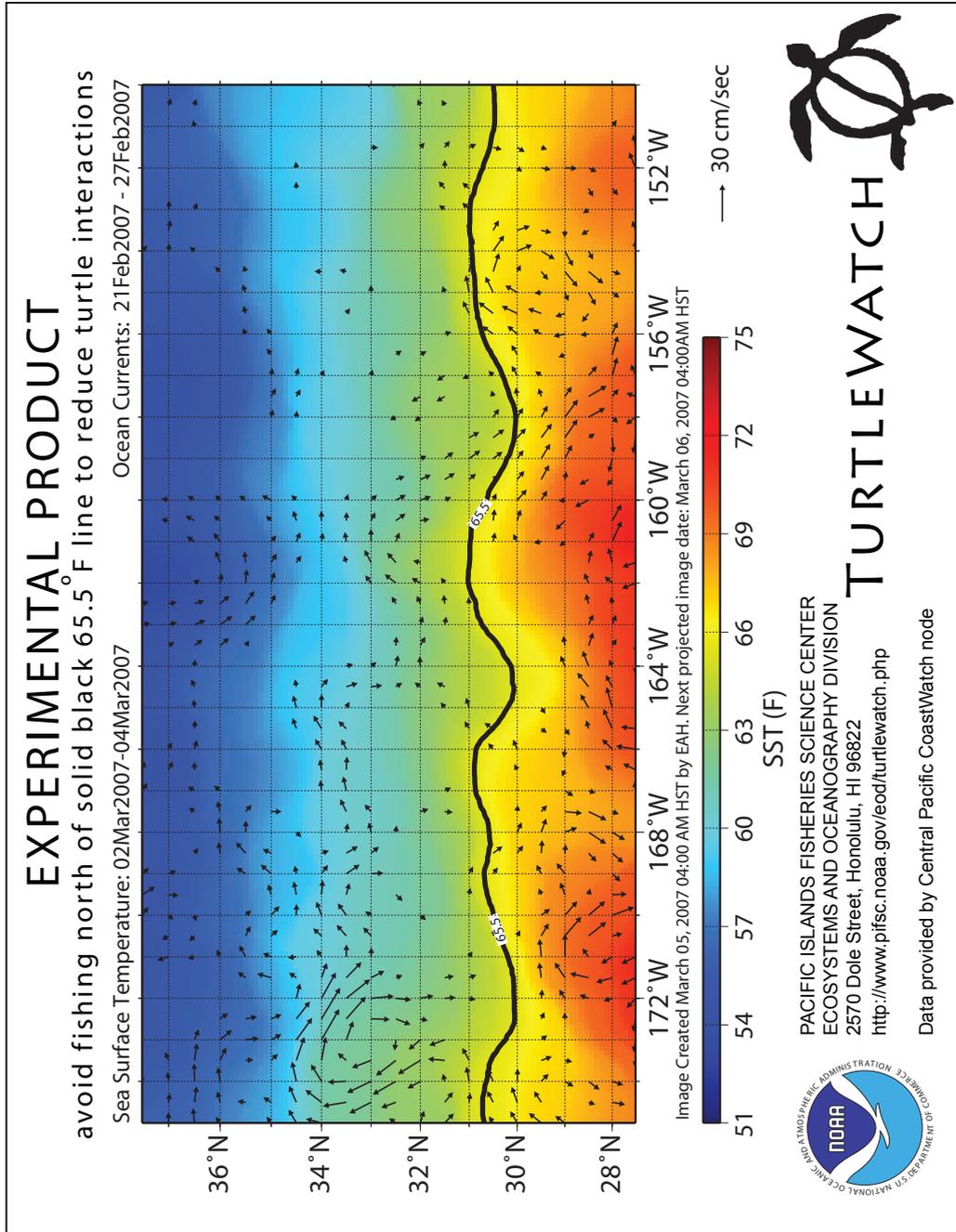


Figure 3.4: The TurtleWatch product. Pseudo-color image represents the sea surface temperature (SST) field ($^{\circ}\text{F}$). Grey arrows represent the magnitude and direction of the geostrophic currents derived from altimetry data. The black line represents the 65.5°F ($\approx 18.5^{\circ}\text{C}$) isotherm.

Table 3.2: Total operational fishery and loggerhead turtle interaction parameters for sets $> 28^\circ\text{N}$ in January-March during the post-regulation (2005–2007) period.

	2005			2006			2007		
	Jan	Feb	Mar	Jan	Feb	Mar	Jan	Feb	Mar
Sets	62	173	285	193	309	340	236	282	279
Hooks	49695	141940	237945	156136	238144	276634	202832	243027	243627
# of Interactions	1	7	1	7	3	7	0	5	7
Interaction rate	0.0201	0.0493	0.0042	0.0448	0.0126	0.0253	0.0000	0.0206	0.0287

with the majority of the sets in January occurring north of 33°N (Fig. 3.5a-c). This was similar to the latitudinal position of the sets in 2005, yet much farther to the north than the sets in January 2006. In addition to sets occurring farther to the north in the beginning of the first quarter, the fishery did not begin its southern movement until late in January, in contrast to the observed movement to the south during mid-January 2005 and 2006. Eight of the 12 turtle interactions (66.7%) in the first quarter of 2007 occurred in surface waters colder than 18.5°C and in the area where fishing was discouraged by the TurtleWatch product during that time period.

The interannual variability in the North Pacific Frontal Zone defined during the month of January from 2005 to 2007 is shown with the main area of shallow set placement and reported turtle interactions in Figs. (Fig. 3.6a-c). The axis and latitudinal position of the area between the 17.5°C and 18.5°C isotherms was substantially different in 2005 than in the following 2 years. In 2005, the frontal zone was farther to the north in the east and farther to the south in the west in January (Fig. 3.6a) and continuing through February and March. The placement of shallow sets by the fishery was also very different in 2005 than the other 2 years. The smaller number of sets was more broadly distributed, with no apparent core area fished. The position and axis of the frontal zone was very similar in 2006 and 2007 with a more constant latitudinal positioning during January (Fig. 3.6a-c) and continuing through February and March. While the axis and position of the frontal zone were very similar in 2006 and 2007, the core location of shallow set placement was not. In 2006, shallow sets were placed in 2 locations: one area to the northeast and a larger core area in the central area of the frontal zone directly

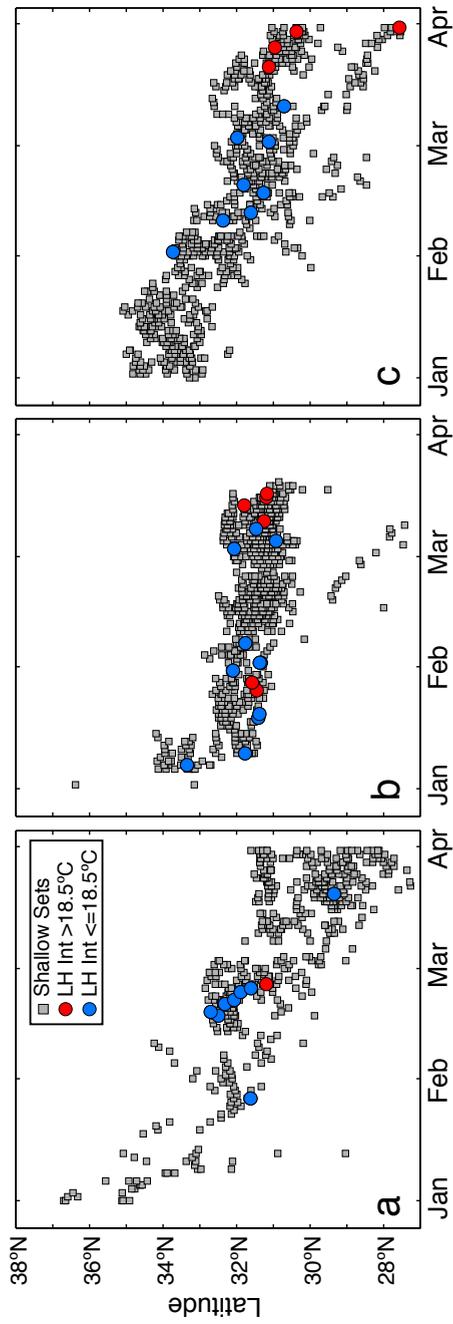


Figure 3.5: Change in the latitudinal position of shallow sets and loggerhead turtle interactions (LH int) through the first quarter of the year for 2005. Blue circles (n=25): turtle interactions in waters colder than 18.5°C; red circles (n=11): interactions in waters warmer than 18.5°C.

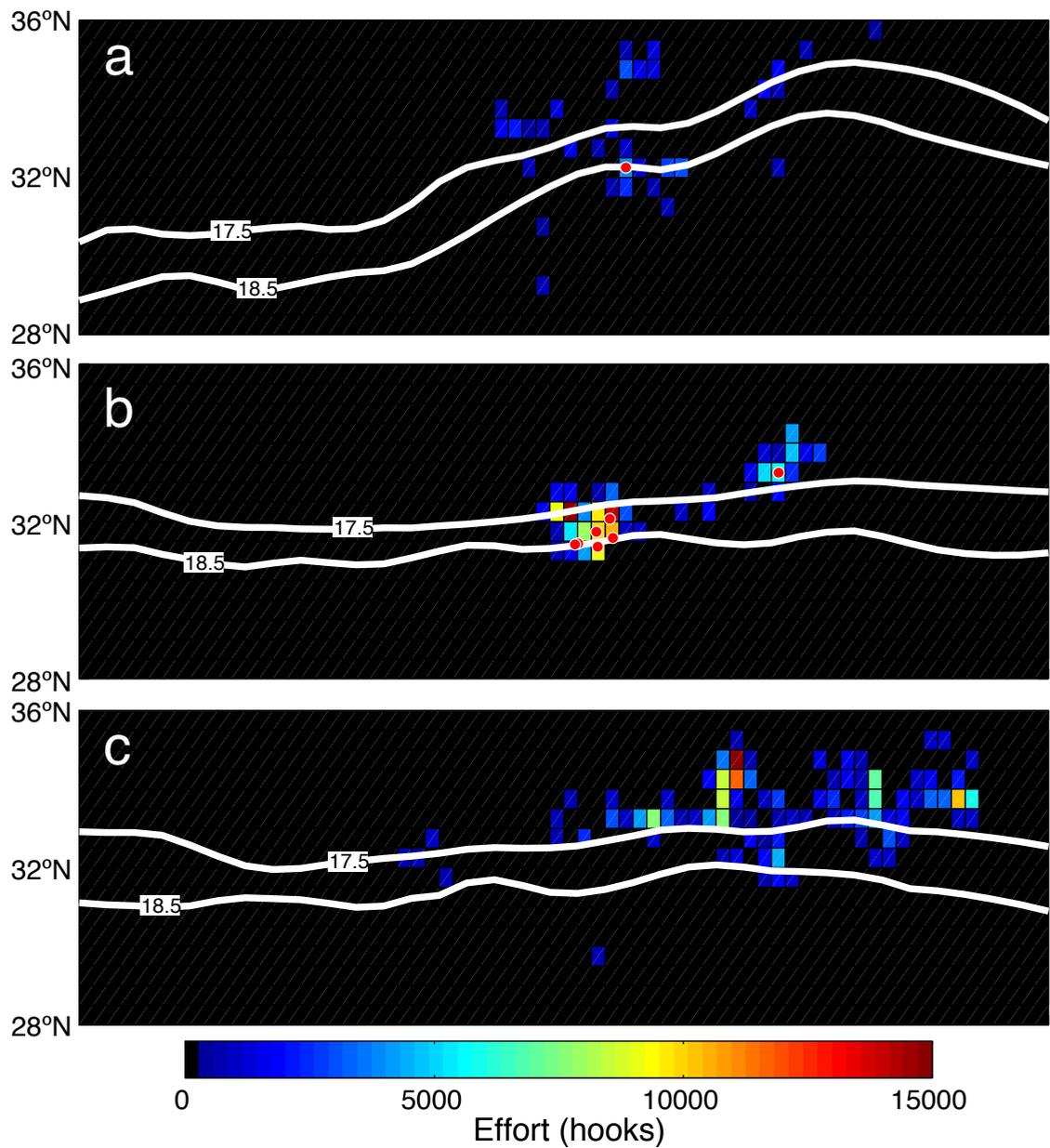


Figure 3.6: Spatial position of shallow sets (pseudo-color blocks) and loggerhead turtle interactions (red circles) for January 2005. White lines: average monthly position of the 17.5° and 18.5°C isotherms. Longitude values have been removed because of fishery confidentiality requirements of the data.

between the 17.5° and 18.5°C isotherms. In contrast to 2006, the majority of shallow sets were north of the 17.5°C isotherm in January 2007 (Fig 3.6c). In all years, the smallest geographic distance between the 17.5° and 18.5°C isotherms was in the central portion of the area fished (Fig. 3.6a-c).

3.4 Discussion

The TurtleWatch product was released on December 26, 2006, to provide information based on the best available science with the aim of decreasing the bycatch of loggerheads in the Hawaii-based pelagic longline fishery. The closure of the shallow set fishery in March 2006, less than 2 years after its reopening, was a concern both to industry and management. The main purpose of this research was 2-fold: (1) to gain a better scientific understanding of the possible environmental indicators for loggerhead interactions with shallow sets, and (2) to be able to provide a daily product to managers and the industry providing information on the dynamically changing area of high potential interactions during the first quarter of the year.

The combined effect of species overlap, gear restrictions, and increased concerns in regards to bycatch of loggerheads places additional emphasis on attempting to minimize interactions during the first quarter, a time when both the shallow set fishery and loggerheads appear to inhabit the same location near the North Pacific Subtropical Frontal Zone (Polovina *et al.*, 2000; Polovina *et al.*, 2001; Seki *et al.*, 2002; Polovina *et al.*, 2004). The minimization of loggerhead bycatch during the first quarter would allow the shallow set fishery to continue later through the year, as well as allow the fishery to begin operations prior to the start of a new year. Therefore, it is critical to have the ability to understand and ultimately map in near real time the area of highest potential loggerhead interactions with the fishery during the first quarter of the year to minimize interactions and allow the continuation of longline operations. Time area closures work in situations where the critical habitat of interest is static through time, a very different scenario from highly variable regions such as frontal zones. When averaged through time, the

thermal band between 17.5° and 18.5°C may appear closely aligned with a particular latitudinal range, yet any interannual changes in the position of the frontal zone may displace both the loggerhead turtles and the fishery either to the north or to the south. In these cases, there is a movement of the potentially higher interaction area that would be predicted by a dynamic, environmentally based map, yet not possible with a static, geographic time area closure.

The initial TurtleWatch product was created using the maximum amount of data from available sources for the first 3 months of each year from 1994 to 2006. The first quarter was important since this was the time of both the largest overlap in space between shallow sets, interactions, and the frontal zone (Fig. 3.2), but high interactions during this period also have consequences for the shallow set fishery during the remainder of the year. The year 2006 was an extreme example of this, as the loggerhead take limit was reached on March 17, thereby curtailing shallow set fishing during the first half of the year as well as delaying the start of the shallow set fishery until the next calendar year. This results in the first quarter of one year having potential ramifications over 2 seasons for the shallow set fishery.

The data sources used to research the appropriate environmental range were chosen to maximize the available data over the entire time period of interest. The observer logbook data was mandatory as it provided an unbiased total number of recorded loggerhead turtle interactions, yet observer coverage varied through the 1994 to 2002 time period (Walsh *et al.*, 2005), resulting in a partial dataset with regard to operational fishery information. For this reason, the operational data from the commercial fishery logbooks were used to provide the maximum amount of information on shallow sets during the same period. The maximum tempo-

ral period of loggerhead turtle positions transmitted from satellite tags occurred from 1997 through 2006. This resulted in a comparison of the fishery-based turtle locations (interactions) with the fishery-independent turtle locations in slightly different temporal periods as there were no satellite locations for the 1994 to 1996 period. This was justified, as results from previous studies clearly showed the persistent association of juvenile loggerhead turtles with specific isotherms within the North Pacific Transition Zone (Polovina *et al.*, 2001; Polovina *et al.*, 2004; Polovina *et al.*, 2006; Kobayashi *et al.*, 2008). Thus, any interannual variability in the frontal system would result in an associated movement of turtles, resulting in a constant thermal signal over the time period.

The decision to base this initial product solely on temperature was made both to simplify the data requirements necessary to create the product and to be able to use an environmental field familiar to the industry and managers. Fishers targeting swordfish with shallow sets use surface temperature as an indicator to find the optimal placement of gear near oceanic fronts (Ito, 1998; Bigelow *et al.*, 1999). Temperature has also been recognized as an important preferred habitat descriptor for loggerhead turtles in the North Pacific Ocean (Kobayashi *et al.*, 2008) as well as for leatherback turtles in the North Atlantic (McMahon *et al.*, 2006; Witt *et al.*, 2007; Witt *et al.*, 2008) This is not to say that other environmental signals such as ocean color (chlorophyll *a*) are not an important descriptor of habitat. On the contrary, chlorophyll *a* fields have also been shown to be an important habitat descriptor (Polovina *et al.*, 2004; Polovina *et al.*, 2006; Kobayashi *et al.*, 2008). However, as the main purpose of this product was to provide a near real-time, easily understandable product to managers and the fishery, the addition of chlorophyll

data was infeasible as even monthly images may contain a large percentage of cloud cover per image in the North Pacific Subtropical Frontal Zone during the first quarter. The ability to solely use SST data allows for a generalization of the product as well, as temperature information is easily available to fishers while at sea via fax or satellite data delivery. This, coupled with the knowledge of the thermal range with the highest probability of loggerhead interactions, allows for fishers to be able to more accurately avoid this high risk area. At the time of the data analysis performed to create the TurtleWatch product, the composite Pathfinder 4/GAC 9 km 8-d SST image provided the best spatial and temporal coverage over the 1994 to 2006 study period. In any study matching a fine scale point in time and space with a broader synoptic field, there is error associated with the movement in both dimensions from the finer point outward. In recent years, refinements to available SST products have improved coverage in both time and space, which may refine the thermal estimates for future turtle interactions.

The initial TurtleWatch product was constructed using the results of the thermal ranges associated with the fishery-dependent and -independent loggerhead locations. The decision to use the 65.5°F ($\approx 18.5^{\circ}\text{C}$) isotherm as the northern recommended area of fishing was a complex one based on several factors. The interquartile range was chosen as a balance between attempting to minimize future bycatch of loggerhead turtles yet accounting for the overlap in the thermal distribution with historical shallow sets by the fishery. The importance of the TZCF to the movement and migration of loggerheads has been documented (Polovina *et al.*, 2001; Polovina *et al.*, 2004; Polovina *et al.*, 2006), and work by Bograd *et al.* (2004) found that there was a strong association between the TZCF and SST,

specifically the 18°C isotherm, in the region north of the Hawaiian Islands. This helps to explain the importance of this surface temperature region to turtles and why a relatively high number of interactions are observed in this narrow thermal range. The idea to use the 95 percentile range was rejected as this would recommend against the deployment of shallow sets in almost the entire frontal zone, which is the area of highest historical use by the Hawaii-based longline fishery (Seki *et al.*, 2002). The initial response was to recommend the avoidance of shallow sets within this thermal band, which would result in a shift in effort to the north and south. Results from the positions of loggerhead turtles affixed with satellite tags, however, showed that during the first quarter these turtles were in a colder surface water habitat. A shift of the fishery to the north may, then, lead to the deployment of shallow sets in an area of higher potential interactions. From these results, the initial experimental product was then built on a recommendation that fishers stay only to the south of the thermal band.

The TurtleWatch product was automatically created daily and delivered both in electronic and paper formats to principal individuals in the industry and management to help ensure proper dissemination. Hard copies of the TurtleWatch product were also delivered daily in conjunction with the delivery of logbook sheets by NOAA personnel to departing vessel captains. This delivery method provided the product with information in a clearly understandable format which could be used in management decisions, thus addressing a concern raised in a recent paper by Godley *et al.* (2008). TurtleWatch was distributed to all parties with the emphasis that this was an experimental product to be taken under advisement. The results of the fishery locations during the first quarter 2007 clearly show that

the fishery did not remain below the recommended isotherm (Figs. 3.5). Conversely, the fishery was observed to move further north than in previous years and remained to the north for a longer time period than the 2 previous years (Figs. 3.5). While not entirely unexpected, this movement north, coupled with the location of the frontal zone in 2007, allowed for an opportunity to view the results of a shift in effort to the north of the frontal zone, the region with the highest observed satellite-tagged juvenile loggerhead turtles (Fig. 3.3). It was interesting to note that increased effort to the north in January had no associated interactions with loggerhead turtles, which is the opposite of what may be expected if potential interactions were expected based on the observed locations of the satellite tagged turtles. One factor of importance for potential interactions may be turtle size. Based on the information of loggerheads in the fishery recorded by observers, interactions to the north occurred with smaller loggerhead turtles. The average size of the turtles affixed with satellite tags in this study was 48.3 cm on release (Kobayashi *et al.*, 2008), with a large percentage of the satellite tagged turtle positions in the northern portion of the frontal zone in colder surface waters during the first quarter. There are several possible reasons for size-based selection, including changes in the operational aspects of the fishery and differences in diving and/or foraging behavior of the turtles. The average depth range of a 61 cm straight carapace length (SCL) loggerhead turtle associated with the frontal zone in the North Pacific was 0 to 60 m (Polovina *et al.*, 2003). Based on subsurface temperature records in the North Pacific Subtropical Frontal Zone during May 1996 to May 1999, the temperature values at 60 m are close to the 16°C isotherm (Seki *et al.*, 2002). If temperature is a limiting factor for juvenile loggerhead turtles, then it

may follow that turtles that prefer a surface temperature of 16°C may not dive to the same depths as those to the south in warmer surface waters. A constraint to the surface may minimize the time of overlap with fishery sets which are at depth. Another factor may be that the large circle hooks required by regulations to reduce turtle capture may be more effective on smaller turtles found to the north. Previous research has shown that hook size greatly influences turtle bycatch (Watson *et al.*, 2005).

The majority (65%) of all loggerhead turtle bycatch in 2007 occurred in the area where fishing was discouraged by the TurtleWatch product. In that respect, the TurtleWatch product was successful in indicating the area where turtle bycatch was most likely to occur, yet highlights that the Hawaii-based longline fleet did not modify its activity to avoid the area of highest potential loggerhead interactions during 2007. A main goal of the TurtleWatch product is to continue to promote the correlation between specific thermal habitat and increased interactions with loggerheads to fishers, with the hope that with this information fishers will voluntarily avoid the areas of highest potential bycatch. Four interactions also occurred late in the first quarter of the year in waters slightly warmer than the frontal zone and just barely south of the TurtleWatch avoidance boundary, where fishing was recommended. A decrease in the bycatch of loggerhead turtles may naturally extend the fishery later into the year. One point that needs to be considered is the seasonal differences in the bycatch of loggerhead turtles by the shallow set fishery. The TurtleWatch product was created in response to the relatively high numbers of interactions which occurred in the first quarter of the year and was based on the environmental crossover between loggerheads and the fishery during this time

period. As the fishery begins to move to the south later in the year, the frontal zone moves to the north (Fig. 3.2). Results from satellite tag locations of loggerhead turtles show that a large percentage of the juveniles went north, following the frontal zone in the spring and summer (Polovina *et al.*, 2001; Polovina *et al.*, 2006; Kobayashi *et al.*, 2008). This seasonal migration pattern must be explored further to fully understand the potential bycatch of loggerheads in other quarters of the year, as turtles may tend to lag behind the front. This would result in loggerheads occurring in waters in the colder portion of the frontal zone as the front moves south during the first quarter of the year, and occurring in the warmer portion of the frontal zone to the south as the front changes direction and began to move to the north during the second quarter of the year. A better understanding of the movements associated with the frontal zone would result in the ability to better predict the thermal range of highest loggerhead turtle interactions.

Chapter 4

Dive behavior of juvenile loggerhead turtles (*Caretta caretta*) in the North Pacific Ocean: responses to regional and seasonal changes in oceanography

4.1 Introduction

Loggerheads turtles (*Caretta caretta*) are a threatened species widely distributed throughout the Pacific. Genetic analysis has shown that loggerheads have distinct stocks in the north and south Pacific Ocean (Bowen *et al.*, 1995; Bowen and Karl, 2007), with loggerheads in the North Pacific born in Japan, and most of all South Pacific loggerheads born in Australia and New Caledonia (Bowen *et al.*, 1995; Bowen and Karl, 2007). Advances in satellite transmitter technologies over recent years have allowed researchers to collect geospatial information on loggerhead turtles in various coastal and oceanic regions to elucidate migration patterns

during early life stages (Renaud *et al.*, 1994; Polovina *et al.*, 2000; Hays *et al.*, 2002; Houghton *et al.*, 2002; Bentivegna *et al.*, 2003; Dodd *et al.*, 2003; Godley *et al.*, 2003; Polovina *et al.*, 2003; Polovina *et al.*, 2004; Polovina *et al.*, 2006; Hatase *et al.*, 2007; Peckham *et al.*, 2007; Alfaro Shigueto *et al.*, 2008; Casale *et al.*, 2008; Howell *et al.*, 2008; Kobayashi *et al.*, 2008). Results from work in the North Pacific Ocean shows that juvenile loggerheads have an oceanic phase which may last a decade or more, during which times turtle migrate and forage along convergent fronts of temperature and productivity that span the entire North Pacific Ocean (Polovina *et al.*, 2000; Polovina *et al.*, 2004; Kobayashi *et al.*, 2008) in a region defined as the North Pacific Transition Zone (NPTZ) (Roden, 1991; Polovina *et al.*, 2001; Seki *et al.*, 2002). Important hotspots also occur along this migratory pathway, with the Kuroshio Extension Bifurcation Region (KEBR) identified as an important nursery area for juvenile loggerheads (Polovina *et al.*, 2006). These two regions have specific oceanographic characteristics. The KEBR lies west of 180° and has been identified as a dynamic area with intense mesoscale variability (Qiu, 2001). The NPTZ is a region defined by strong physical and biological gradients that separate the oligotrophic North Pacific Subtropical Gyre (NPSTG) to the south from the cold, productive North Pacific Subarctic Gyre (NPSAG) to the north (Roden, 1980; Pickard and Emery, 1990; Seki *et al.*, 2002; Seki, 2003). The southern edge of the NPTZ is bounded by the North Pacific Subtropical Frontal Zone (NPSTFZ), which contains multiple fronts and microfronts (Seki, 2003). The NPSTFZ also contains the Transition Zone Chlorophyll Front (TZCF), an important migration and forage pathway for many pelagic animals (Polovina *et al.*, 2001) associated with the 18°C isotherm in the Central North Pacific (Bograd *et al.*, 2004).

The NPTZ, specifically the NPSTFZ to the south, has historically been used by the Hawaii-based longline fishery to target swordfish (*Xiphias gladius*) north of Hawaii during the first half of the year (Seki *et al.*, 2002). Large frontal features within the NPSTFZ can be represented by specific isotherms during this time, with the 17°C isotherm identifying the convergent Subtropical Front (STF) during this time (Roden, 1972, Roden, 1980; Seki, 2003). It is during this period of the year that interactions between the fishery and loggerhead turtles may occur. Previous research on the sea surface temperature (SST) range of the Hawaii-based swordfish fleet showed that they target a specific range centered near 18°C in the first quarter of the year (Howell *et al.*, 2008), which is the isotherm associated with the TZCF in this region. Tracking studies have shown that loggerhead turtles were also associated with this region during this time, with turtles in two studies in the North Pacific associated with the Transition Zone Chlorophyll Front (Polovina *et al.*, 2001; Polovina *et al.*, 2004), and turtles in one study additionally showing a strong association with the 17°C isotherm (Polovina *et al.*, 2000).

The spatial overlap between the fishery and loggerheads results in interactions. While statistically classified as rare events (McCracken, 2004), the bycatch of juvenile loggerheads by longliners is a concern, with recent federally-mandated requirements in place to attempt to minimize loggerhead interactions. A recent study on the historical bycatch of loggerheads by this fishery showed that the majority of interactions historically occurred within a specific SST range (Howell *et al.*, 2008). This information, coupled with loggerhead positions collected by telemetry studies, was used to create the TurtleWatch product; an SST map highlighting the predicted location of waters preferred by turtles where the highest interactions

have occurred. The TurtleWatch product¹ used results from previous telemetry studies of loggerheads, yet was defined based only on spatial location data, the only data available at the time. Dive behavior has been reported for loggerheads in various regions of the worlds oceans (Sakamoto *et al.*, 1990; Renaud *et al.*, 1994; Sato *et al.*, 1994; Minamikawa, 2000; Hays *et al.*, 2002; Houghton *et al.*, 2002; Godley *et al.*, 2003), yet to date only dive information for two juvenile loggerheads has been reported for the central North Pacific Ocean where the Hawaii-based longline fishery operates (Polovina *et al.*, 2003; Polovina *et al.*, 2004). The ability to incorporate the loggerhead dive information into the TurtleWatch product is important, since any spatiotemporal dive variability by loggerheads may change the possible vertical overlap between loggerheads and shallow set longline fishing gear.

This chapter presents the dive information from 17 juvenile loggerheads equipped with depth recorders in the central North Pacific Ocean. In this present study we analyze the variability in recorded dive behavior within three distinct regions of the North Pacific to identify any spatiotemporal variability in movements and dive behavior. The geospatial information from several of these tracks have been used in a previous study, which included a description of the spatial association of one turtle in the KEBR with a warm-core eddy event (Polovina *et al.*, 2006). Here we expound on the previous results by including the dive information for this tag as well as additional turtles that entered the KEBR region. The results of the dive information for turtles within the NPTZ in the first quarter of the year are used

¹The NOAA TurtleWatch Product is available in English and Vietnamese at <http://www.pifsc.noaa.gov/eod/turtlewatch.php>

to attempt to refine the NOAA PIFSC TurtleWatch product. The results of this chapter should increase our understanding of juvenile loggerhead turtle behavior during their oceanic phase, as well as continue to aid in management and conservation of this species through an increased understanding into why loggerhead turtle interactions with the fishery seem to occur within specific thermal habitats.

4.2 Methods

Study area and turtle tagging

17 juvenile loggerhead turtles were equipped with Wildlife Computers model SDR-SD-10 (n=3) and SDR-SD-16 (n=14) Argos-linked satellite transmitters to provide geospatial location and dive information. The geospatial information from 6 of the 17 tags has been previously reported, (Polovina *et al.*, 2006), but tagging methods will be repeated here to incorporate the 11 unreported tags as well as the methodology for the dive parameters of the tags. All 17 loggerheads in this study were incidentally caught during 2002-2004 by Long Beach, California-based longline vessels operating in the central North Pacific Ocean during the period of the Hawaii-based longline fishery shallow set closure (Table 4.1). All 17 turtles used in this study were juveniles and ranged in size from 44–66.5 cm straight carapace length (SCL). Upon capture the hooking condition was noted, and classified as: (1) lightly hooked, if the turtle was only externally tangled or snagged in the fishing gear but did not swallow the hook; or (2) deeply hooked, if the turtle swallowed the hook. Lightly hooked turtles were unhooked and released, while deep hooked turtles were released with the hook in the animal but with the monofilament leader cut close to the turtle's mouth. Turtles were outfitted with satellite transmitters attached to the carapace using the procedures outlined in (Balazs *et al.*, 1996). All turtles actively swam away or dove upon release. Data on daily location of the turtles were determined from the signals received by the Argos receiver on a NOAA satellite. The accuracy of each position was estimated by Argos as a function of the number and configuration of satellites and the number of transmissions received.

Table 4.1: Deploy and pop-up dates for SDR tags attached to juvenile loggerhead turtles during 2002–2004 with the duration at liberty from the deployment of the tag to the end of transmission, the straight line distance traveled during this period, the hooking classification, and size in straight carapace length (cm).

Tag	Dates		Longitude		Latitude		Liberty	SL Distance (km)	Hook class.	SCL (cm)
	Start	End	Start	End	Start	End				
16129	09/05/2003	07/07/2005	133.19°W	153.62°W	35.60°N	36.36°N	484	1854.54	DH	61
16131	11/03/2003	07/11/2004	140.24°W	173.49°W	37.72°N	36.47°N	252	2936.82	LH	57
21128	02/18/2003	04/19/2004	155.18°W	170.39°E	31.11°N	31.64°N	427	3255.48	DH	65.4
21130	02/18/2003	09/17/2004	149.82°W	157.82°W	31.69°N	40.09°N	578	1178.60	LH	46
21138	02/16/2003	09/27/2003	149.77°W	168.32°W	31.80°N	37.48°N	224	1806.91	DH	44
21411	09/03/2003	04/08/2004	132.16°W	175.08°W	35.06°N	30.99°N	219	3996.32	LH	62.5
21412	09/10/2003	11/12/2004	133.00°W	171.34°E	34.54°N	34.44°N	430	5032.84	DH	56.5
22277	01/04/2003	08/22/2003	139.00°W	164.10°W	32.91°N	37.78°N	231	2332.41	DH	43.5
22328	10/14/2002	09/07/2003	140.24°W	175.53°E	41.33°N	40.59°N	329	3673.99	LH	55.5
22329	12/27/2002	08/27/2003	140.91°W	162.59°W	34.48°N	37.24°N	244	1973.25	LH	45.5
24644	04/09/2003	06/27/2004	161.06°W	168.87°E	29.94°N	38.91°N	446	2916.75	LH	56.5
24645	11/17/2003	12/11/2004	150.14°W	166.91°E	37.25°N	38.17°N	391	3745.32	DH	66.5
24646	01/08/2004	07/27/2004	154.28°W	172.29°W	32.90°N	34.24°N	202	1673.05	LH	56
44359	01/08/2004	06/27/2004	154.64°W	177.65°W	33.74°N	35.93°N	172	2109.23	DH	61
44360	01/07/2004	08/19/2004	155.43°W	178.29°W	33.15°N	41.10°N	226	2202.52	DH	59.5
44361	01/11/2004	11/06/2004	155.83°W	175.45°W	32.52°N	34.81°N	301	1830.53	LH	53.5
44362	02/10/2004	03/31/2004	151.99°W	154.26°W	31.64°N	32.70°N	51	244.01	DH	49

Raw geographic positions for each individual track were filtered using a hierarchical state-space model (Jonsen *et al.*, 2006; Jonsen *et al.*, 2007). The state-space model filtered out erroneous records based on Argos position estimates and turtle velocities. Post-filtered data were then checked to ensure that no records were retained with speeds greater than 2.5 km h^{-1} . This final set of spatial data contained a daily geolocation for each individual based on the best available transmitted Argos data. The 17 turtles in this study traveled through three pre-defined regions in the central North Pacific Ocean (Fig. 4.1). The Kuroshio Extension Bifurcation region (KEBR) has been previously defined as the areas to the west of 180° and is a dynamic region characterized by warm-core and cold-core eddies as a result of meanders in the Kuroshio Extension Current (KEC) (Qiu, 2001; Polovina *et al.*, 2006). The Hawaii-based Longline Swordfish Fishing Grounds (HLSFG) have been previously defined based on historical effort as the region between the KEBR and 140°W (Seki *et al.*, 2002), and is characterized by three areas: the oligotrophic North Pacific Subtropical Gyre (NPSTG), the productive North Pacific Subarctic Gyre (NPSAG), and the seasonally migrating North Pacific Transition Zone (NPTZ) between them (Roden, 1980). To the south of the NPTZ is the North Pacific Subtropical Frontal Zone, which contains multiple fronts demarcated by representative temperature isotherms depending on the time of year (Seki, 2003). Finally, the California Current region (CC) was then defined as the area to the east of 140°W .

Dive information was collected and processed by software on-board the tags and transmitted to Argos receivers onboard NOAA satellites. An individual dive event was defined by the tag as the period between an initial vertical movement

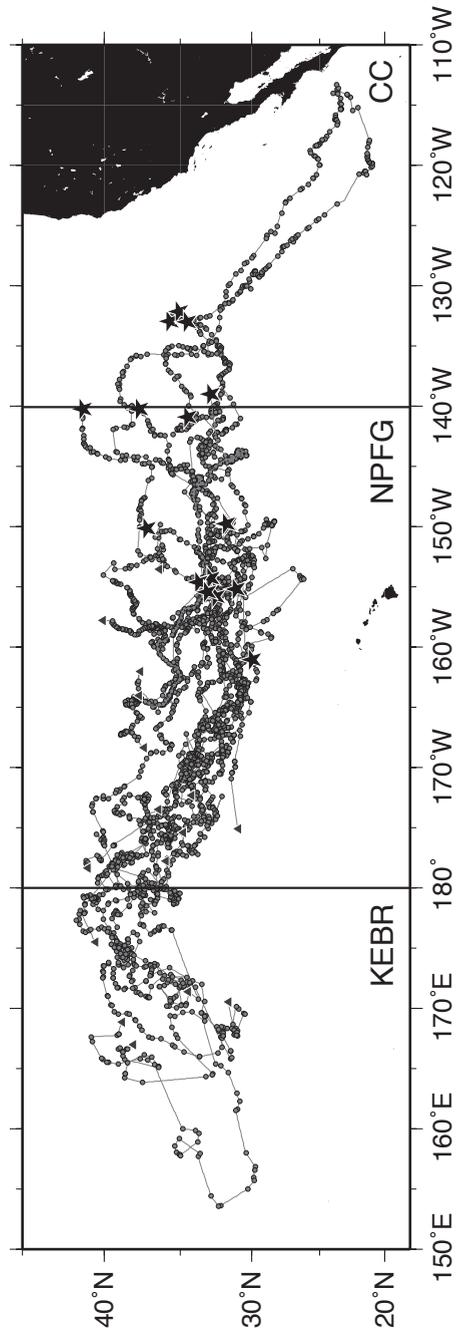


Figure 4.1: Movements of 17 juvenile loggerhead turtles after release from longline fishing gear with annotation of the defined study areas. Stars indicate release points. Triangles indicate final transmission locations of individuals.

below 1 m to the first time when the tag's salt water switch indicated a return to the surface. These raw dive events were tabulated into frequency tables of dive information by the tags software based on the maximum depth of the dive, the total duration of the dive, and the percentage of time spent in pre-defined depth ranges. These tables were aggregated over four 6-hour periods based binned in specific depth or time intervals. All 17 tags were programmed with the same configurations for the dive depth and dive duration bins. The lower ranges of the depth bins (in meters) for the dive depth distributions were 5, 10, 15, 20, 25, 30, 40, 50, 60, 70, 80, 100, 150, and > 150 . The lower ranges of the duration bins (in minutes) for the dive-duration distributions were 2, 5, 10, 20, 30, 45, 60, 75, 90, 105, 120, 180, 240, and > 240 . The time-at-depth bins for the SDR-SD-10 and SDR-SD-16 models were programmed with different depth criterion. The lower ranges of the depth bins (in meters) for the time-at-depth distributions collected by the three initially deployed SDR-SD-10 tags were 0, 5, 10, 15, 25, 35, 50, 60, 75, 100, 125, 150, 200, and > 200 . Initial collection and preliminary inspection of these reported data resulted in a modification of the programmed time-at-depth bins to capture the depth regions with the greatest activity. The lower ranges of the depth bins (in meters) for the time-at-depth distributions collected by the 14 subsequently deployed SDR-SD-16 tags were 1, 5, 10, 15, 20, 25, 30, 40, 50, 60, 80, 100, 150, and > 150 . Due to minimal crossover in the time-at-depth bins between the SDR-SD-10 and SDR-SD-16 tags, only the dive depth and dive duration information were pooled across all 17 tags. Time-at-depth dive information were only pooled for the SDR-SD-16 tags (n=14). All 17 tags were programmed to tabulate the collected dive information into 6-hour periods prior to transmission to Argos receivers. These

periods were programmed to correspond to Hawaii standard time as 2100–0300, 0300–0900, 0900–1500, and 1500–2100 h. These reflected a mid-night, dawn, mid-day and dusk period, respectively.

4.2.1 Fisheries data

Fishery data used in this study were obtained from the U.S. federal observer logbook information collected through the Hawaii Longline Observer Program as described in (Howell *et al.*, 2008). Only sets made during the first quarter of the year (January–March) during the post-closure period (2005–2008) were used in this study to maintain consistency in gear configuration and 100% observer coverage. Logbook data were then filtered to focus on shallow sets targeting swordfish. All sets with more than 10 hooks between floats or below 28°N were defined here as shallow sets targeting swordfish and discarded following the rationale of Howell *et al.* (2008). The date of the beginning of the haul was used along with the average of the beginning and ending haul coordinates. This was done to attempt the closest match of fishing sets and turtle interactions, as turtle captures were only recorded during the hauling of the gear.

4.2.2 Environmental data

A combination of in-situ and remotely-sensed environmental data was used to describe the oceanography for this study. In-situ temperature-depth profiles were obtained from oceanographic vessels and ARGO floats. Two meridional transects were occupied during July–August, 2005 and March–April, 2008. Hydrographic data during the 2005 transect was taken along the 165°W meridian aboard the

Hokkaido University training ship Oshoro Maru. Hydrographic data during the 2008 transect was taken along the 158°W meridian aboard the NOAA ship Oscar Elton Sette. In-situ data were analyzed and plotted using the Ocean Data View software package².

SST data were derived from two data sources. For the years 2003–2005 SST data collected by the 5-channel Advanced Very High Resolution Radiometers (AVHRR) on board the NOAA-7, -9, -11, and -14 polar orbiting satellites were used. 3-day averages of the raw data on a 9 km x 9 km spatial resolution were used in this study. AVHRR data was not available for 65 days in 2002, yet AVHRR and data collected from the radiometer sensor onboard the Geostationary Operational Environmental Satellite (GOES) for concurrent temporal periods were analyzed and were found to be significantly similar ($r^2 = 0.99$, $p < 0.01$). 3-day running averages of the raw GOES data on a re-sampled 9km x 9km spatial resolution were then used for the 65 missing days in 2002.

Sea surface height anomaly (SSHA) data mapped at a global 0.3° x 0.3° resolution with orbit error reduction were provided by the Ssalto program of the Centre National d'études Spatiales, France. This altimetry product is a weekly average of the measured along-track sea level profiles mapped to a Mercator projection. The average of these along-track profiles from 1993–1998 was used to create a mean profile that was then subtracted from the mapped product to obtain the sea level anomalies. JASON-1 data from 2002–2005 were used in the study. To compute the geostrophic currents, the 1994 NODC World Ocean Atlas Levitus long-term mean

²The free of charge Ocean Data View is available for download at <http://odv.awi.de>

1000 m dynamic height data set was added to the SSH anomaly files to create an absolute SSH. The eastwest and northsouth gradients were derived from this height and subsequently used to calculate the (east–west) and (north–south) components of the geostrophic current, as described in (Polovina *et al.*, 1999). Eddy kinetic energy (EKE) is a common key indicator of mesoscale variability where high EKE values correspond to areas of intense activity. EKE was calculated from the geostrophic components using the equation

$$EKE = \frac{1}{2}(u^2 + v^2) \quad (4.1)$$

where u and v are the geostrophic components as described above.

4.2.3 Statistical analysis of dive parameters

Raw dive frequency data were prepared for statistical analysis using the random deletion technique following Sims *et al.* (2005). Dive records were randomly deleted for each individual dive parameter to obtain the maximum equal number of 6-h periods for each of the respective dive parameters. Linear regression analysis and non-parametric Wilcoxon signed-rank tests were used to compare dive information and environmental data (Snedecor and Cochran, 1989), with significance reported at the 1% level.

Ordination techniques were used to classify dive behavior using the maximum dive depth and dive duration data. The maximum dive depth and dive duration frequency tables were combined, removing one column that contained no positive values (dive durations > 240 min). The resultant 5424 x 23 matrix was then stan-

standardized to mean 0 and standard deviation 1 and introduced to a non-hierarchical K-means cluster analysis (kmeans function; stats library, R version 2.8.1). Cluster analyses were repeated 100 times and the best solution was used based on the smallest value of the sum of within-groups sums-of-squares. Run sets were repeated using a monotonic range of K (centers) (cascadeKM function; vegan library, R 2.8.1³) with the best value of K chosen using the maximum value of the simple structure index. A lower limit of two centers was chosen as a minimum based on previous research which has indicated that loggerhead turtles have at least two distinct dive behaviors (Godley *et al.*, 2003; Houghton *et al.*, 2002; Polovina *et al.*, 2003; Renaud and Carpenter, 1994). An arbitrary higher limit of 10 centers was chosen as more than 10 clusters would negate any advantages that clustering would offer. The initial peak of the simple structure index occurred at K=4, which indicated that classification of dive type into 4 clusters was appropriate. These clusters then represented a dive behavior type for each 6-hour period of dive information and are referred to as dive types C1–C4 throughout the remainder of the text.

4.2.4 Estimations of fishery interactions

One aim of this current study was to incorporate the loggerhead dive information to the TurtleWatch product as defined in Howell *et al.* (2008). The aim was to combine the geospatial location and dive information collected by the satellite tags with the geospatial information from historical longline sets to estimate the poten-

³The free of charge statistical software package R is available for download at <http://cran.r-project.org>

tial number of fishery interactions that may occur within discrete oceanographic regions. To accomplish this, the number of potential fishery interactions was modeled as the number of probable gear crossings that may occur by turtles within regions corresponding to specific SST ranges. The probability of a gear crossing was calculated by combining three parameters: 1) the probability that a turtle would be present (probability of turtle occurrence), 2) the probability that a turtle would dive to depths where it could intersect with shallow gear at depth, and 3) the probability that a longline set would also be present (probability of shallow set occurrence). These parameters were calculated as a function of SST as this is the variable field used to construct the TurtleWatch product. SST distributions were partitioned into 0.25°C bins following Howell *et al.* (2008). Only data from the HLSFG during the first three months of the year was used as this space and time reflects the highest historical occurrence of juvenile loggerhead interactions with the longline fishery (Howell *et al.*, 2008). All available tag-based geolocations and historic longline set positions were matched in space and time to the corresponding 3-day running average SST image using the *grdtrack* routine (Wessel and Smith, 1991) which resulted in an SST value for every turtle geolocation and shallow set deployed within the HLSFG for the first quarter of the year. Dive depth data were pooled in 0.5°C SST bins to maintain consistency and maximize the amount of data within each SST bin. Bins were then replicated to match the spatial-based probabilities in 0.25°C SST bins. The depth where a gear crossing is expected to occur was calculated from information collected by time-depth recorders (TDR) affixed to shallow sets made by the Hawaii-based longline fishery during the period 2007-2008. TDR information from the shallow sets monitored showed that 95% of

all shallow set hooks were deeper than 15 m (D. Hawn, Unpubl. Data, NMFS). This depth value was then taken as the shallowest point where a turtle interaction may occur given a typical shallow longline set post-deployment and pre-haul. Analysis of shallow set gear configuration showed that the soak time (the time between the setting and hauling of the gear) was consistent for all sets used in this study (mean = 20.8 hours, SD = 2.58 hours). Because the soak times were close to 24 hours, all 6-hour periods were pooled for this stage of the analysis.

The empirical probability of turtle occurrence (pT_i) was then calculated from the turtles location-based SST frequency distributions for each 0.25°C SST bin i over the range $i = \{14.5, 14.75, \dots, 19\}^\circ\text{C}$. The probability of a turtle diving > 15 m was then calculated from the maximum dive depth frequency data for each 0.5°C SST bin i over the range $i = \{14.5, 15.0, \dots, 19\}^\circ\text{C}$. To do this the number of dives to depths > 15 m were first tabulated over all 6-hour periods for every SST bin i resulting in a series of vectors representing the number of times that turtles made dives to depths deeper than 15 m in each 0.5°C SST bin. Since these vectors were count data the probabilities were calculated using a Poisson distribution. The probability of 0 counts (i.e. dives > 15 m) is defined (Snedecor and Cochran, 1989) as

$$P(0) = e^{-\lambda} \quad (4.2)$$

where λ represents the mean number of counts. From this we can obtain the probability of a turtle diving more than 0 times. As the total probability is constrained to 1, the probability of a turtle diving more than 0 times is

$$P(> 0) = 1 - P(0) \quad (4.3)$$

Where $P(0)$ equals $e^{-\lambda}$ as shown in equation 4.2. The final equation to calculate the probability of a turtle diving to depths > 15 m in each 0.5°C SST bin i used was

$$PD_i = 1 - e^{-\lambda_i} \quad (4.4)$$

where λ_i is the mean number of dives > 15 m over all 6-hour periods within each SST bin i over the range $i = \{14.5, 15.0, \dots, 19\}^\circ\text{C}$. The probabilities were then duplicated to obtain values in equal bins as the empirical probabilities. The empirical probability of the occurrence of a shallow set occurrence (pS_i) was calculated from the SST frequency distribution of the historical shallow set placement during the first three months of the years 2005–2008 for each 0.25°C SST bin i over the range $i = \{14.5, 14.75, \dots, 19\}^\circ\text{C}$. The conditional probability of a gear crossing by a turtle was then calculated by

$$pGC_i = pT_i * pD_i * pS_i \quad (4.5)$$

This resulted in an probable gear crossing based on 0.25°C SST bins over the range for $i = \{14.5, 14.75, \dots, 19\}^\circ\text{C}$.

4.3 Results

4.3.1 Tag results

All 17 tags deployed on loggerheads transmitted data for more than 30 days, with many tags at liberty for over one year (Table 4.1). 16 of the 17 turtles traveled westward from their capture points, with one turtle moving eastward to offshore Baja, California before reversing direction and returning to the HLSFG (Fig. 4.1). 5 of the 17 turtles moved across the HLSFG and entered the KEBR region. Turtle size was not correlated to the time at liberty, yet there was a weak relationship between the size of the animals and the straight-line distance traveled ($r^2=0.23$, $p=0.03$). There were no significant differences between tagged turtles released with hooks ingested (DH) or with hooks externally removed (LH) for tag duration or straight-line distances traveled. Turtles were associated with an SST range of 15.0° – 23.6°C (95% of data) with 95% of the derived speeds less than 1.75 km h^{-1} (42.1 km d^{-1}).

4.3.2 Overall dive behavior

The pooled percent frequency distributions of dive depth ($n=17$), dive duration ($n=17$), and time-at-depth ($n=14$) data for all study regions are presented in Figure 4.2. The pooled dive depth distributions show that over 85% of the number of dives were to depths shallower than 5 m, with close to 95% of the dives shallower than 15 m (Fig. 4.2a). Overall the percentage of dives decreased with each increase in the depth bin, with the exception of a small mode at the 70 m depth bin that represented 0.6% of total dives. There were 56 (1%) dives deeper than 150 m

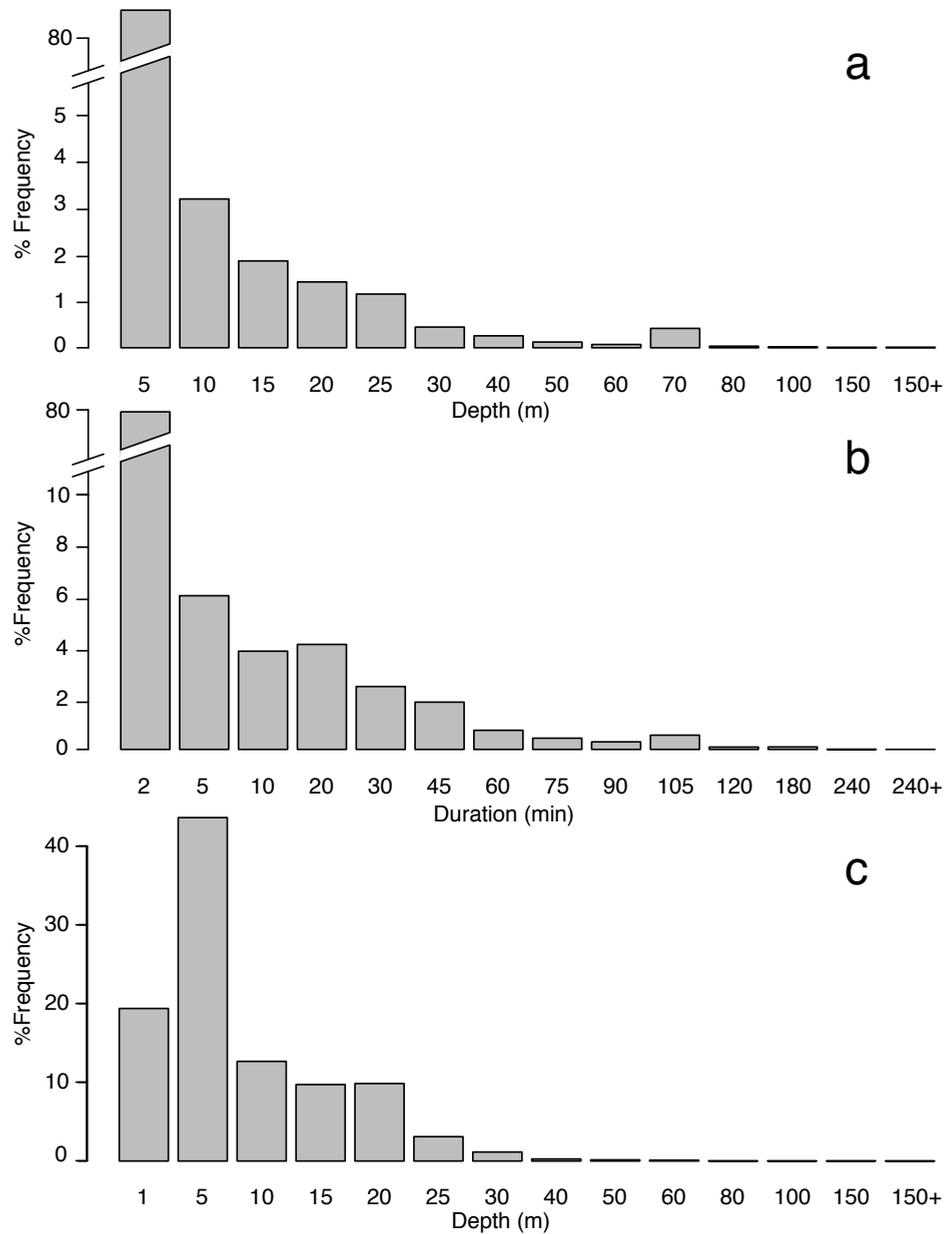


Figure 4.2: Frequency distributions of the number of dives to discrete depth bins (a), and dive durations (b) collected from the 17 SDR tags deployed on juvenile loggerhead turtles in the central North Pacific from 2002–2005. (c) Frequency distribution of the time-at-depth for the 14 SDR-16 tags deployed on juvenile loggerhead turtles in the central North Pacific from 2003–2005.

reported by the tags. The pooled frequency distribution of the dive durations show that close to 80% of the dives were less than 2 minutes in duration, and more than 95% of the dives were shorter than 30 minutes in duration (Fig. 4.2b). Similar to the dive depth distribution, the percentage of dives decreased with each increase in the time bin with the exception of modes at the 20 min and 105 min bins that represented 4.1% and 0.6% of all dives, respectively. There were no dives longer than 240 minutes in duration. The pooled frequency distribution of the time-at-depth shows that turtles spent more than 20% of their time within 1 m of the surface, and more than 85% (95%) of their time shallower than 15 m (20 m) (Fig. 4.2c). There was observed variability in the pooled distributions of all three dive parameters over the four 6-hour periods of the day. Overall, turtles made significantly more dives during the day than at night (Signed-rank test, $p < 0.01$), with a slightly larger percentage of dives to depths greater than 15 m during the day (6.1%) than during the night (4.6%, Fig 4.3a). Dive duration frequencies showed the opposite pattern, as turtles made longer dives during the night period than during the day (Fig. 4.3b). The time-at-depth distributions represent the dive depth and durations and show that turtles spent more time in the 0–15 m depth range at night (88.9%) than during the day (82.3%, Fig. 4.3c). The dawn and dusk bins reflected a combination of the day and night behavior (Fig. 4.3a-c).

4.3.3 Dive type classification

The frequency distributions of the dive depth and duration data for the four dive types classified by the cluster analysis are shown in Figure 4.4a-d. Cluster 1 (C1) represented 51.1% of the dives in this study and was characterized by a moderate

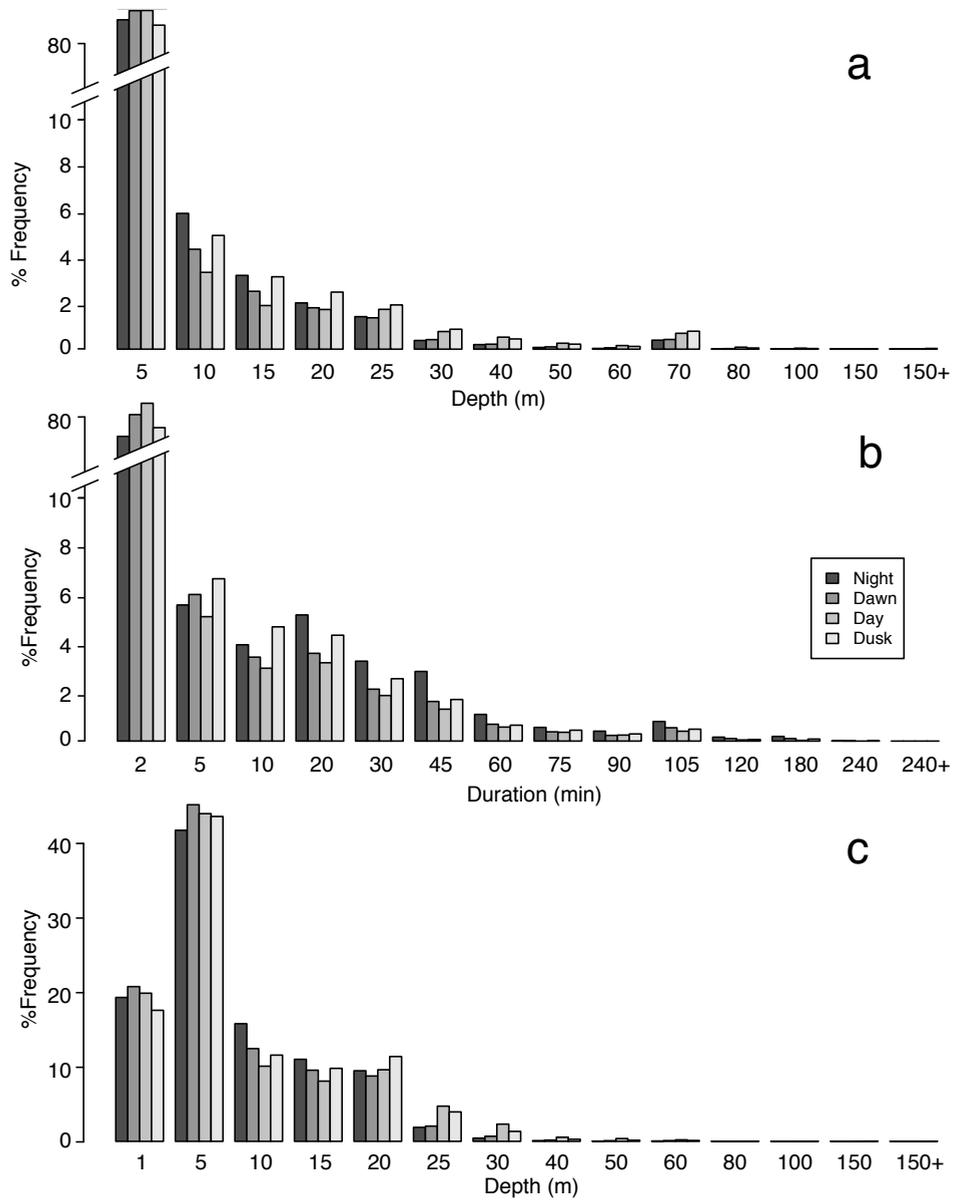


Figure 4.3: Frequency distributions of the number of dives to discrete depth bins (a), and dive durations (b) for the four 6-hour periods collected from the 17 SDR tags deployed on juvenile loggerhead turtles in the central North Pacific from 2002–2005. (c) Frequency distribution of the time-at-depth for the four 6-hour periods collected by the 14 SDR-16 tags deployed on juvenile loggerhead turtles in the central North Pacific from 2003–2005.

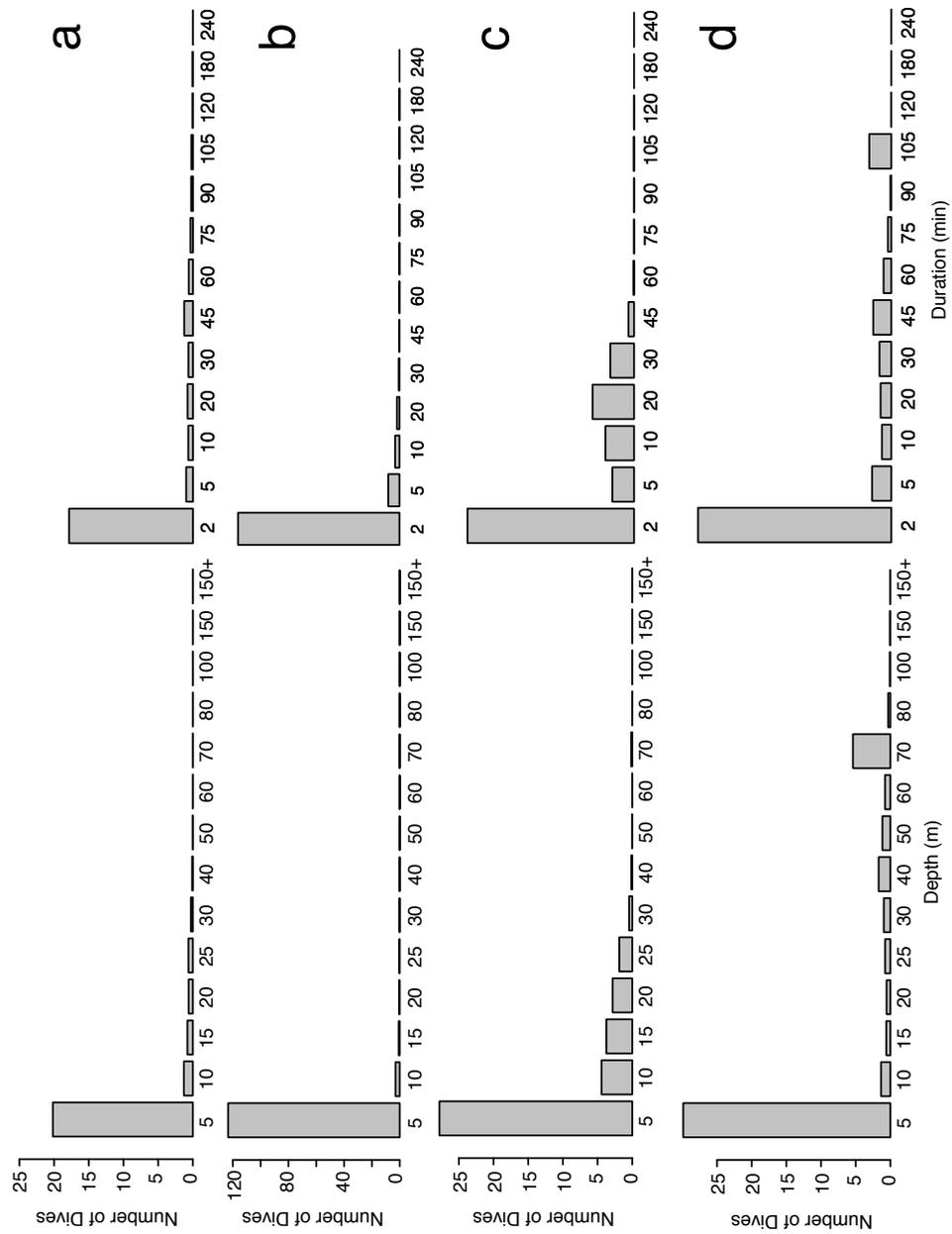


Figure 4.4: The average number of dives and dive durations based on the results of the k-means cluster analysis for the composite number of dive and dive duration frequency data from the 17 tags. (a) Average number of dives to depth (left) and average dive duration for cluster 1 (b) cluster 2, (c) cluster 3, and (d) cluster 4.

number of dives in the 0–5m depth range and shorter in duration. There were less overall dives to greater depths, but more dives of longer duration with a mode at 45 min (Fig. 4.4a). Cluster 2 (C2) represented 23.2% of the dives and was characterized by the greatest number of dives in the 0–5 m depth range and less than 2 minutes in duration. There were few dives to depths greater than 10 m and longer than 10 minutes in duration (Fig 4.4b). Cluster 3 (C3) represented 21.3% of the dives and was similar to C1, yet was characterized by more dives to shallower depths than C1 and more dives shorter in duration (Fig. 4.4c). Cluster 4 (C4) represented 4.4% of the dives and was characterized by both the deepest and longest duration dives in the study (Fig. 4.4d). The amount of time-at-depth information reflects the differences between the four dive classifications (Fig. 4.5a-d). Overall, the time-at-depth distributions showed that for C1 dives 61.0% of time was spent in the 0–5 m depth range, and 15.0% of the time deeper than 15 m (Fig 4.5a). C2 dives were very different, with close to 90% of the time spent in the 0-5 m depth range (Fig 4.5b). C3 dives were similar to C1 dives, yet with slightly less time in the 0-5 m depth range (51.5%) and deeper than 15 m (11.3%). More time was spent in the 5–15 m depth range for C3 dives (37.3%) than for C1 dives (24.0%). C4 dives represented the 6-hour periods with the most amount of time at depths greater than 15 m (58.5%), and the least amount of time in the 0–5 m depth range (32.1%), with a small amount of time spent in the 5–15 m depth range (9.4%, Fig. 4.5d).

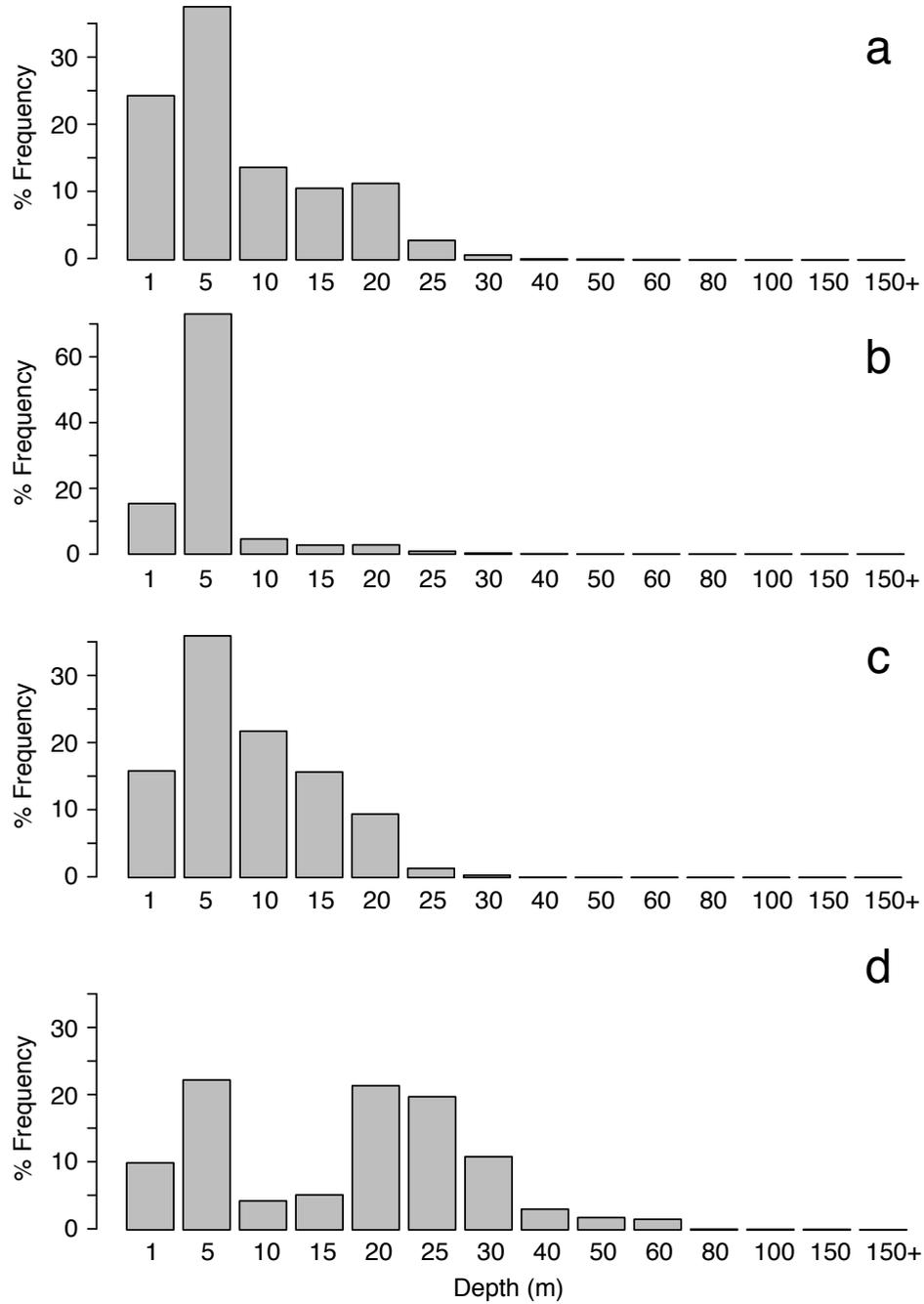


Figure 4.5: The percent frequency distribution of the time-at-depth data based on the results of the k-means cluster analysis of the composite number of dive and dive duration frequency data from the 14 SDR-SD-14 tags for (a) cluster 1, (b) cluster 2, (c) cluster 3, and (d) cluster 4.

4.3.4 Regional dive behavior: The HLSFG

78.5% of the dive information was collected in the HLSFG, which is the main region of interest to the Hawaii-based longline fishery. There was an observed seasonal migration, with turtles associated with a temperature band that changed throughout the year (Fig. 4.6a). Turtles were associated with the coldest (warmest) SST during the first (third) quarter of the year, and associated with increasing (decreasing) SST values during the second (fourth) quarters of the year. The seasonal change in SST represented the correlation of the movements of the turtles through time relative to the latitudinal movements of the North Pacific Subtropical Frontal Zone (NPSTFZ), with the 18°C isotherm here presented as a proxy for this region (Fig. 4.6b). During the first quarter, turtles were in the colder region of the NPSTFZ. During the second quarter turtles began to move to the north and transition to the warmer side of the frontal zone. During the third quarter the turtles were in the warmest waters and at their furthest point from the 18°C isotherm. Turtles began to move south during the fourth quarter, yet remained on the warm side of the frontal zone, not transitioning to the cold side until the first quarter (Fig. 6b). Three of the four dive classification types (C1–C3) represented 99.5% of the data in the HLSFG region. The percent frequency distributions of these dive classifications by month shows a seasonal change in dive behavior (Fig. 4.7a-c). During the first quarter of the year over 80% of the dive type is classified as C1, with a small amount of C3 dive types during this time. During the second quarter the percentage of C1 dives drops linearly, which C2 and C3 dive types increase. The percentage of C3 dive types is higher in the third quarter, accounting for more than 67% in September, and C1 and C3 dive types each accounting for 16%. Tur-

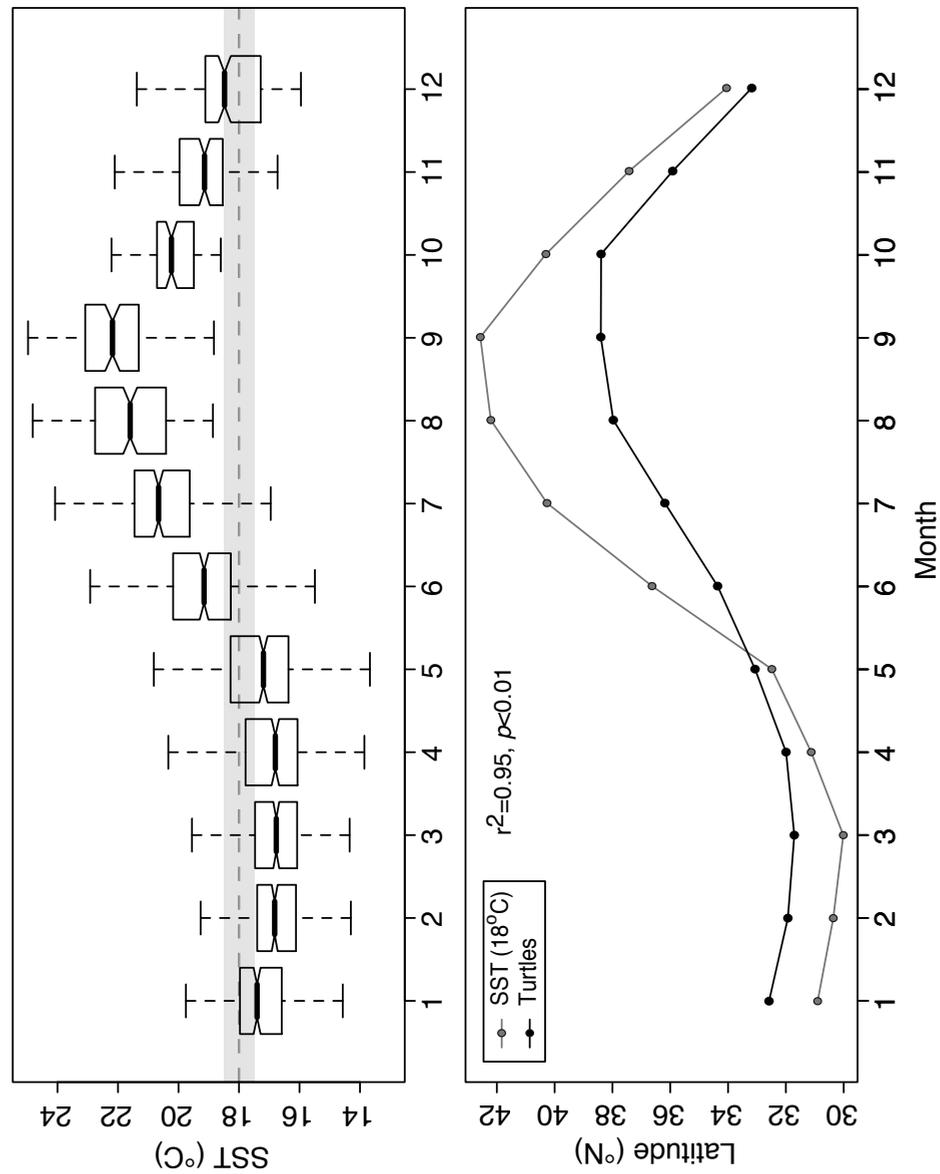


Figure 4.6: (a) Box and whisker plots of monthly SST values based on geolocations determined from 17 SDR tags. The solid line indicates the mean value for the month. The limits of the box indicate the 25% and 75% quantile levels of the data for each month. The dashed horizontal line indicates the 18°C isotherm. The grey box indicates the 17.5°–18.5°C isotherms. (b) The median monthly latitudinal positions of the 17 loggerheads (black line) and the 18°C SST isotherm (grey line).

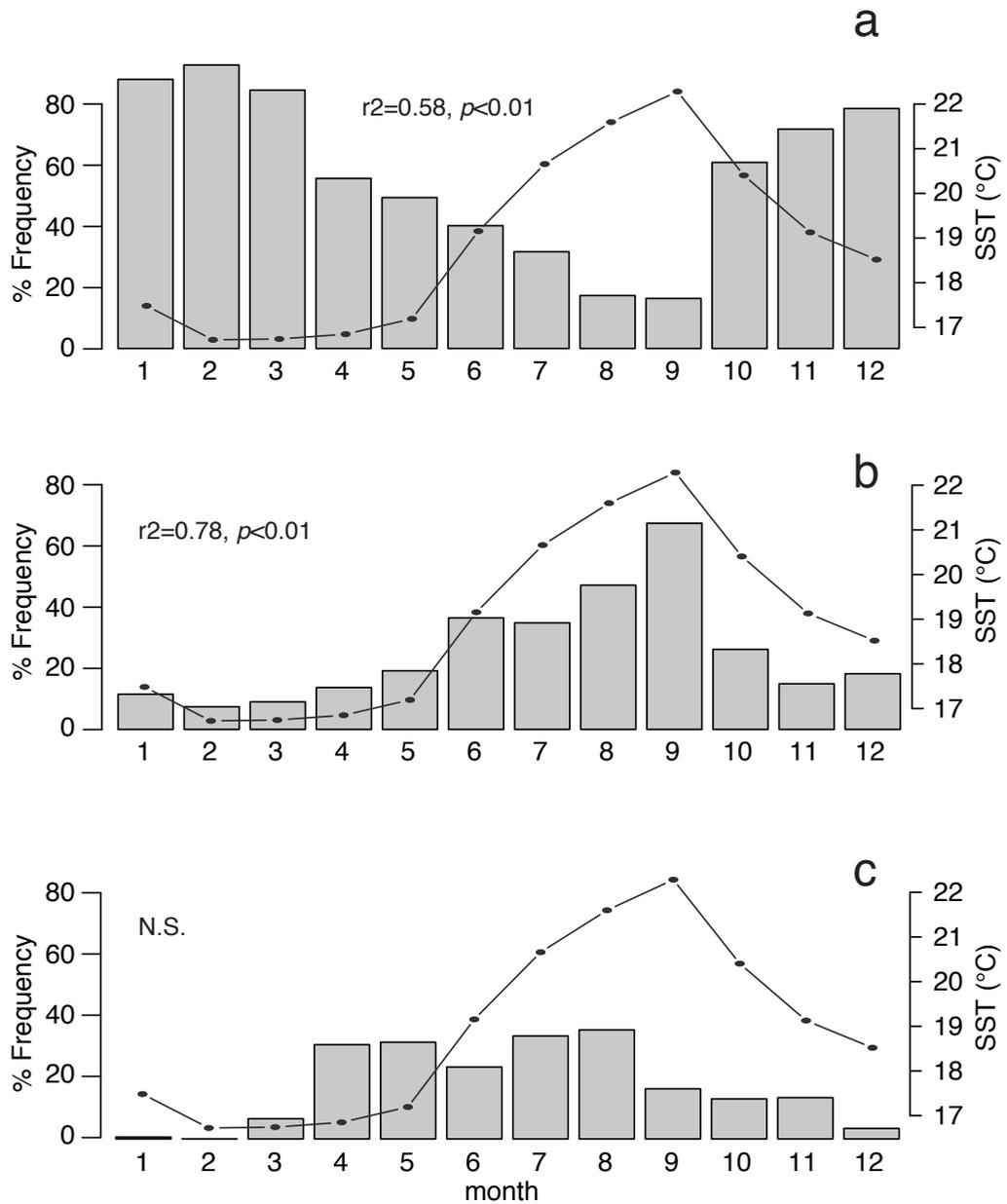


Figure 4.7: The monthly percent frequency of the dive cluster classifications of all 6-hour periods for 17 turtles in the HLSFG region for (a) dive cluster 1, (b) dive cluster 2, and (c) dive cluster 3. The red line represents the median monthly SST value for the 17 turtles in the HLSFG region (a-c).

tles began to exhibit more C1 dive types during the fourth quarter, with more than 78% in December. There was a significant relationship between the monthly percentage of the dive classification type and the median SST values for both the C1 and C3 types. The addition of the C1 and C3 monthly percentages resulted in a more significant relationship with temperature ($r^2=0.78$, $p<0.01$).

Meridional transects of temperature are shown to represent the turtle subsurface habitat during March-April (Q1) and July-August (Q3) (Fig. 4.8a-b). During the first quarter of the year the subsurface temperature in the area that loggerheads occupy in the North Pacific is well mixed through to the depths to at which the loggerhead turtles were diving, with a sharp latitudinal gradient in temperature through the 0–100 m depth range (Fig. 4.8a). During the third quarter of the year, the area that loggerheads occupy is highly stratified, with colder temperatures at depth south of the STF, the spatial region that loggerheads occupied at this time of year (Fig. 4.8b). This change in subsurface conditions is illustrated in the seasonal subsurface temperature-depth profiles collected by ARGO floats in the respective regions that loggerheads occupied during 2003–2005 (Fig. 4.9a-d). During the first quarter of the year the loggerhead habitat is characterized by a well-mixed water column, with the coldest surface waters, yet no temperature values below 15°C (Fig. 4.9a). During the second quarter the turtle begin to migrate to the north, with a thermocline beginning to develop at ≈ 40 m (Fig. 4.9b). Loggerheads were at their northern apex during the third quarter, with the habitat characterized by a stratified water column with the warmest surface waters, the shallowest thermocline, and the coldest waters at depth (Fig. 4.9c). Loggerheads began to move south during the fourth quarter, and the habitat during this time period was sim-

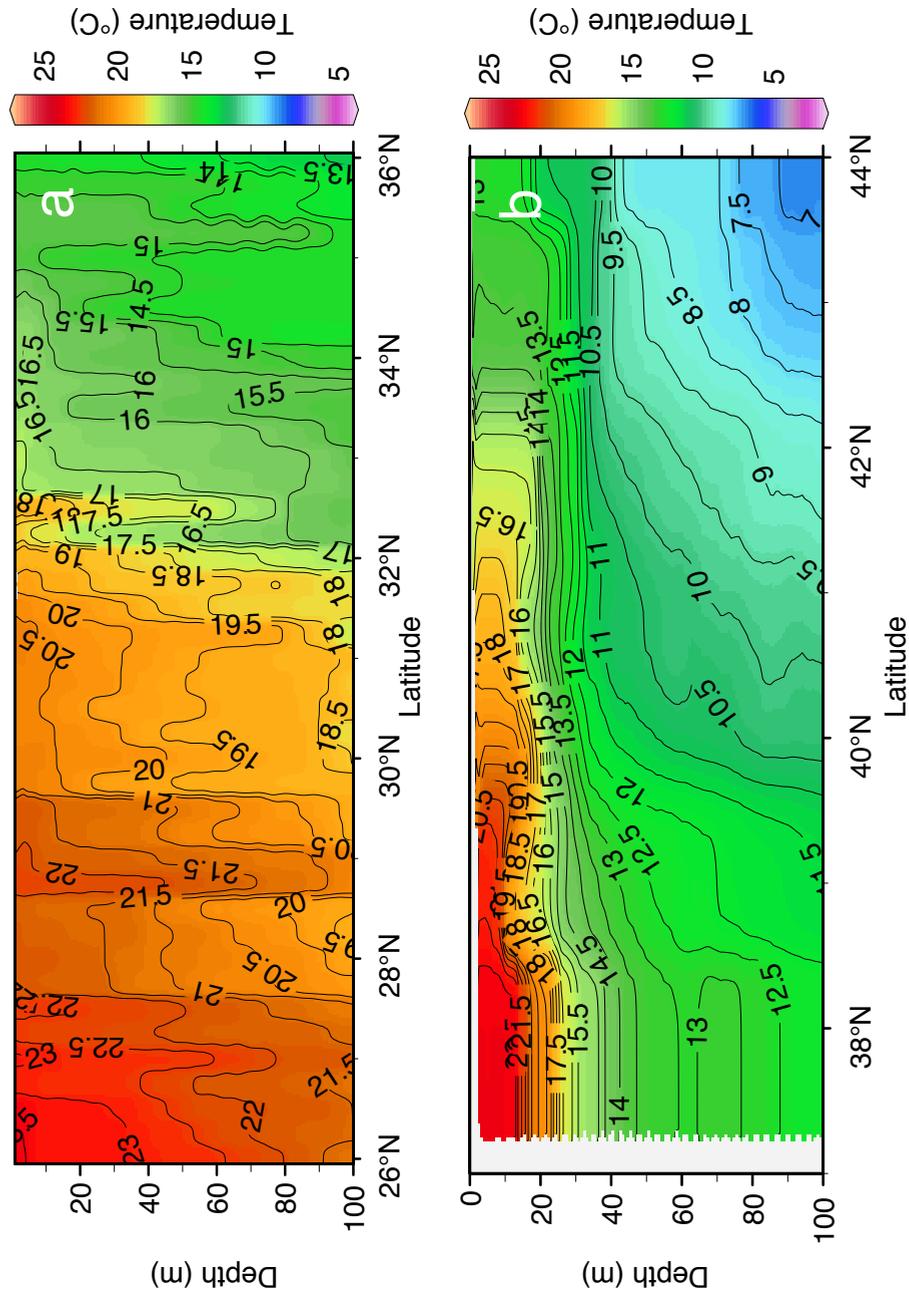


Figure 4.8: (a) Transect of potential temperature along 158°W during March 26–April 3 2008 aboard NOAA ship Oscar Elton Sette. (b) Transect of potential temperature along 165°W during July 29–August 1 2005 aboard Hokkaido University training vessel Oshoro Maru.

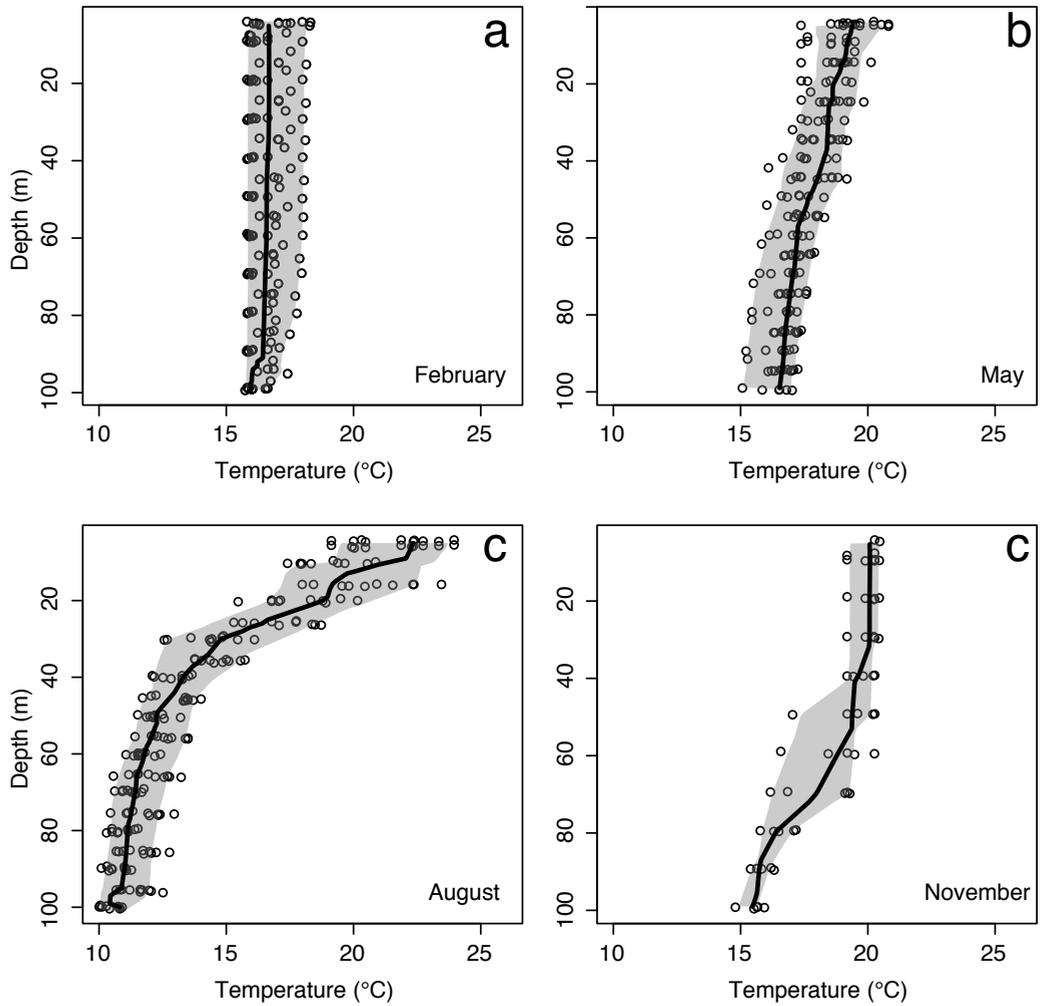


Figure 4.9: Temperature-depth profiles collected by ARGO floats in the HLSFG during 2003–2005 for (a) February, (b) May, (c) August, and (d) November. Circles indicate the raw profile data. The solid black lines represent the median temperature value at interpolated depth levels. The shaded areas represent the 95% range of temperature values at interpolated depth levels. Only profiles occurring in the interquartile (25–75%) range of turtle geospatial latitude positions for each respective month were used.

ilar to the second quarter, with warm surface waters and a mid-depth thermocline (Fig. 4.9d).

4.3.5 Regional behavior: The KEBR

Five individual turtles traveled into the KEBR, with three spending more than 60 days in this region. All tags for these five individuals ceased transmission while in the KEBR. Three individuals that spent more than 60 days in the KEBR (21128: 65.6 cm; 24644 : 56.5 cm; 24645: 66.5 cm SCL) were associated with two anticyclonic warm core (WC1, WC2) and one cyclonic cold core (CC1) eddy events. Turtle 21128 was associated with both WC1 and WC2 and these associations are described in chronological order. Turtle 21128 entered warm core eddy WC1 from the northeast in late September 2003 and remained associated with this eddy for 37 days before exiting to the southwest (Fig. 4.10a-d). This anticyclonic eddy was characterized by higher SSHA values in the center of the eddy and strong clockwise geostrophic currents. The turtle exhibited a clockwise circular movement pattern, with multiple rotations around the eddy within the highest currents. This was reflected by significantly higher EKE values than background EKE values (signed-rank test, $p < 0.01$) for the WC1 region during this time (Fig. 4.11a). Dive behavior outside and associated with the behavior was different, with a decrease in the C2 and an increase in C1 and C4 dive types (Fig. 4.11b). Turtle 21128 was also associated with eddy WC2; entering WC2 two weeks after leaving WC1 and almost one month after an additional turtle 24644 had entered the eddy (Fig. 4.12a-b). WC2 was characterized by higher SSHA values and stronger clockwise surface currents than WC1 (Figs. 4.10 and 4.12). Both turtles exhibited clockwise

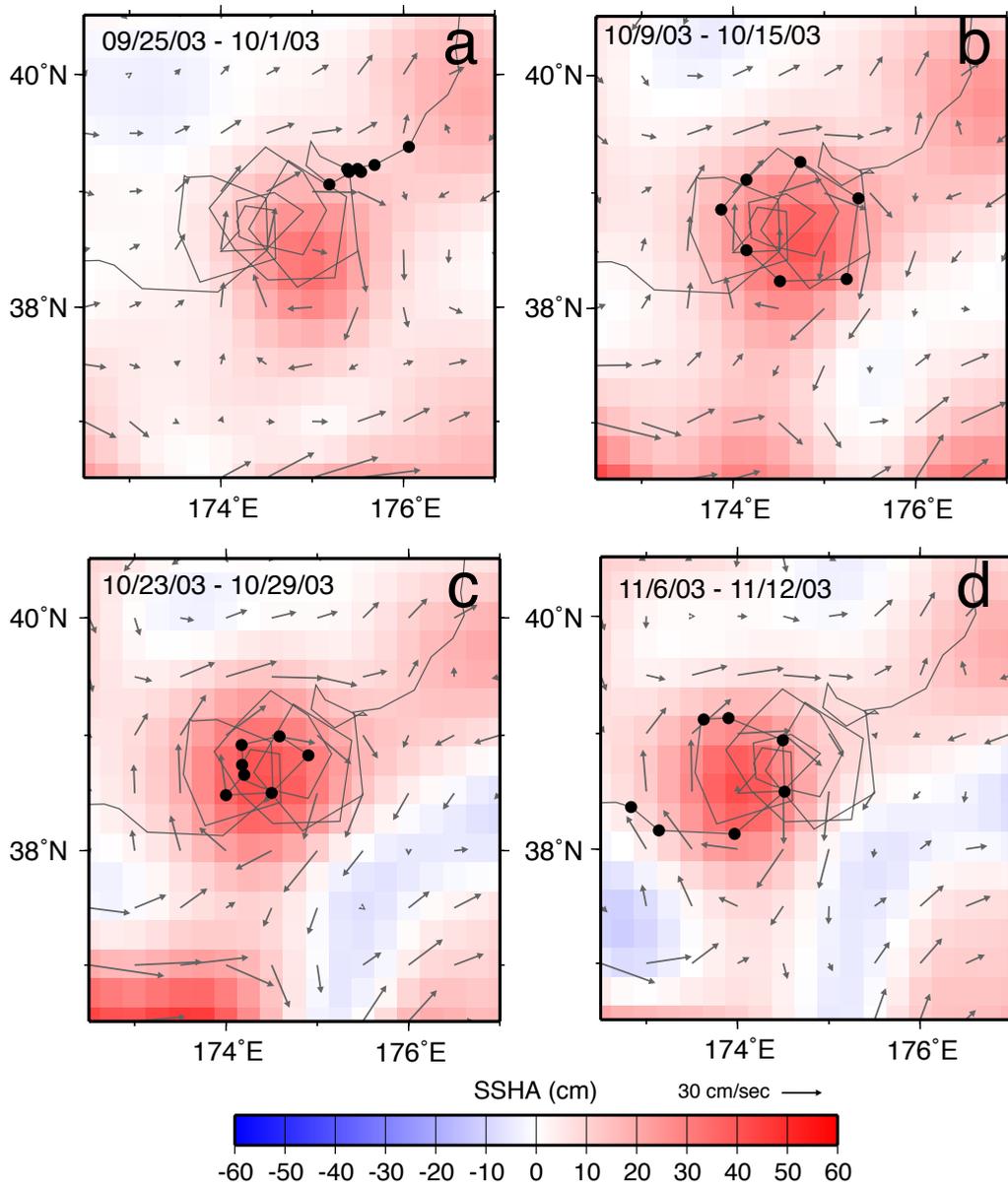


Figure 4.10: Sea surface height anomaly (false color) and geostrophic currents (grey arrows) of the region surrounding eddy WC1 with geolocations for loggerhead 21128 during four periods in 2003 (a) September 25–October 1, (b) October 9–15, (c) October 23–29, and (d) November 6–12. The solid grey line represents the full track line for the turtle. Black circles represent the geolocations of the turtle during the respective 7-day window.

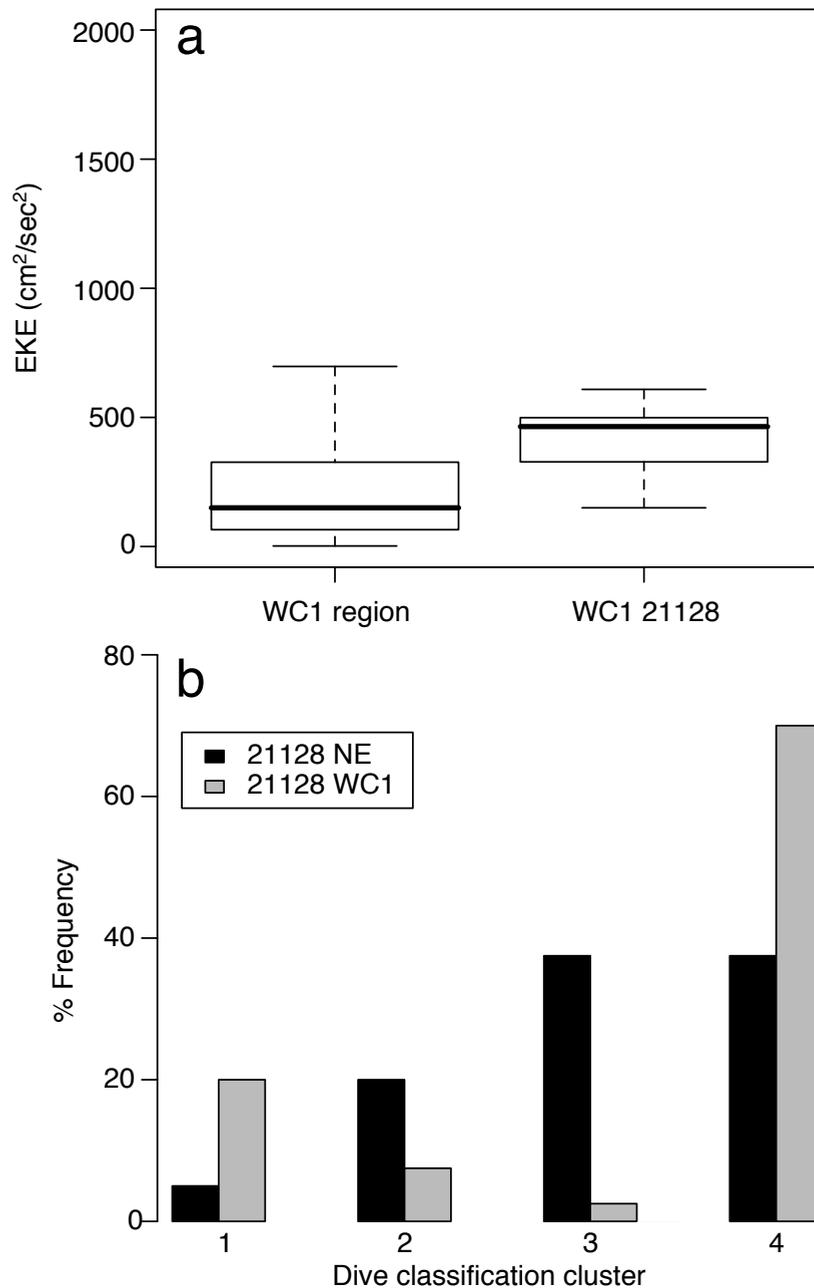


Figure 4.11: (a) Box and whisker plots of eddy kinetic energy values over the region associated with WC1 (left, 172°-177°E, 36.5°-40.5°N) and corresponding to the geolocations of loggerhead turtle 21128 while associated with eddy WC1 (right). (b) Percent frequency distributions of dive classification clusters for loggerhead 21128 outside (black) and associated with (grey) eddy WC1.

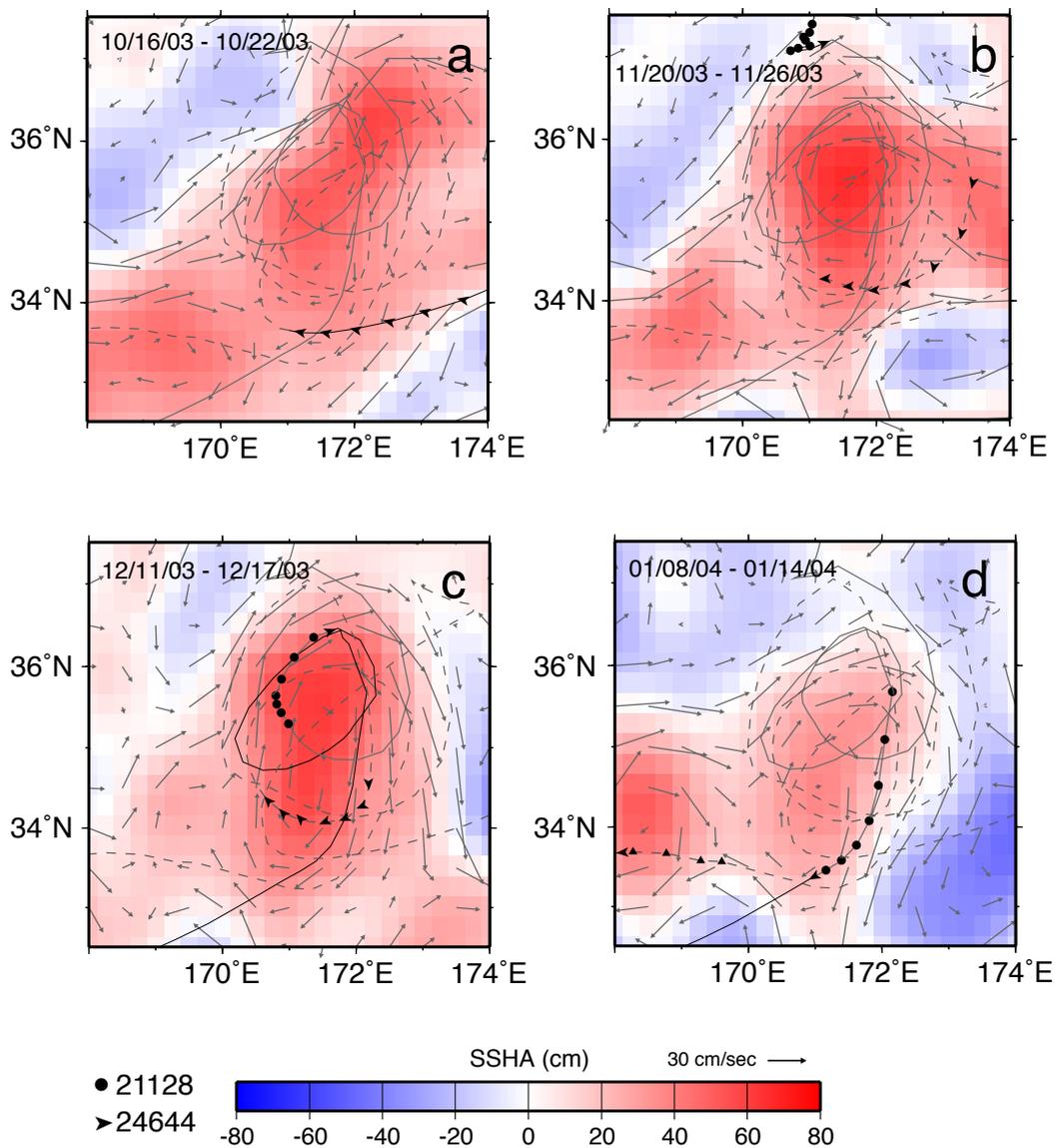


Figure 4.12: Sea surface height anomaly (false color) and geostrophic currents (grey arrows) of the region surrounding eddy WC2 with geolocations for loggerheads 21128 (black circles) and 24644 (black arrows) during four periods in 2003–2004 (a) October 16–22 2003, (b) November 20–26 2003, (c) December 11–17 2003, and (d) January 8–14 2004. The solid (dashed) grey line represents the full track line for turtle 21128 (24644). Black symbols represent the geopositions of the turtles during the respective 7-day window.

circular movement patterns with multiple rotations within high surface currents while associated with the eddy, yet turtle 24644 appeared to travel closer to the edge of WC2 (Fig. 4.12a-d). Turtle 21128 (24644) was associated with this eddy for 44 (85) days, with both turtles departing the WC2 region within 7 days of each other at a similar exit point (Fig. 4.12a-d). EKE values were significantly higher for turtle 21128 (signed-rank test, $p < 0.01$) than background EKE values in the WC2 region during the period it was associated with the eddy, yet were not significantly different for turtle 24644 (Fig. 4.13 a). Dive behavior was different for turtle 24644 while associated with and after departure from the eddy, as well as from turtle 21128 while both were associated with WC2 (Fig. 4.13b). While turtle 24644 was associated with the eddy, close to 40% of the dive types were classified as C1 and C2. After departure from WC2, more than 70% of the dive types were C1, with less than 10% of C4 dive types in either period. More than 75% (15%) of the dive types were classified as C4 (C2) for Turtle 21128 within the WC2 eddy (Fig. 4.13b). Turtle 24645 was associated for 29 days in 2004 with a cyclonic, cold core eddy (CC1) formed by a meander in the KEC (Fig. 4.14a-d). This turtle exhibited a circular, counter-clockwise circular movement pattern, yet only made one rotation during its association with the eddy. The turtle moved around the edge of the eddy within high currents, with EKE values significantly higher significantly higher during this time (signed-rank test, $p < 0.01$) than background EKE values in the CC1 region during this period (Fig. 4.15a). Turtle 24645 also changed its dive behavior after becoming associated with the cold-core eddy, with close to 60% of dive types classified as C4 during this time. This is in comparison to close to 60% combined C1 and C3 and 40% C2 dive types when not associated

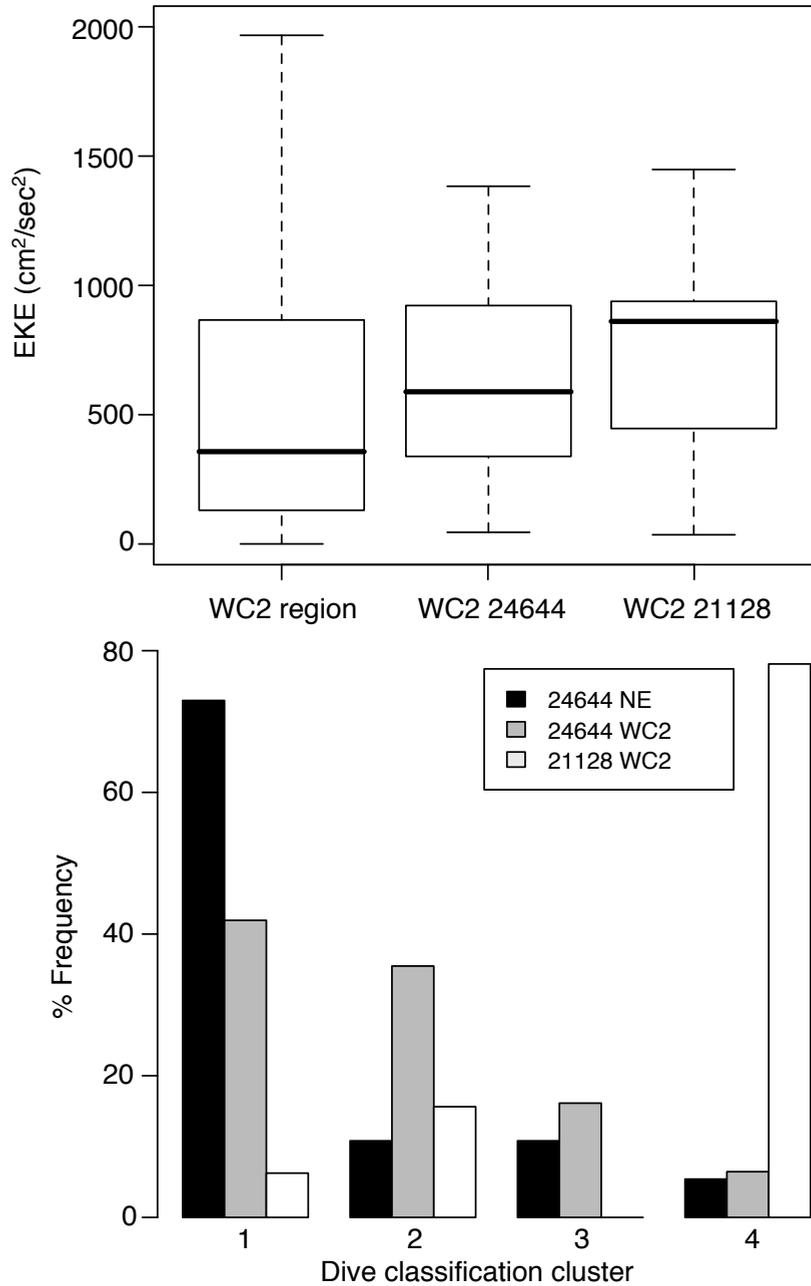


Figure 4.13: (a) Box and whisker plots of eddy kinetic energy values over the region associated with WC2 (left, 168°-174°E, 32.5°-37.5°N) and corresponding to the geolocations of loggerhead turtles 24644 (middle) and 21128 (right) while associated with eddy WC2. (b) Percent frequency distributions of dive classification clusters for loggerhead 24644 outside (black) and associated with eddy WC2 (grey) and for loggerhead 21128 associated with eddy WC2 (white).

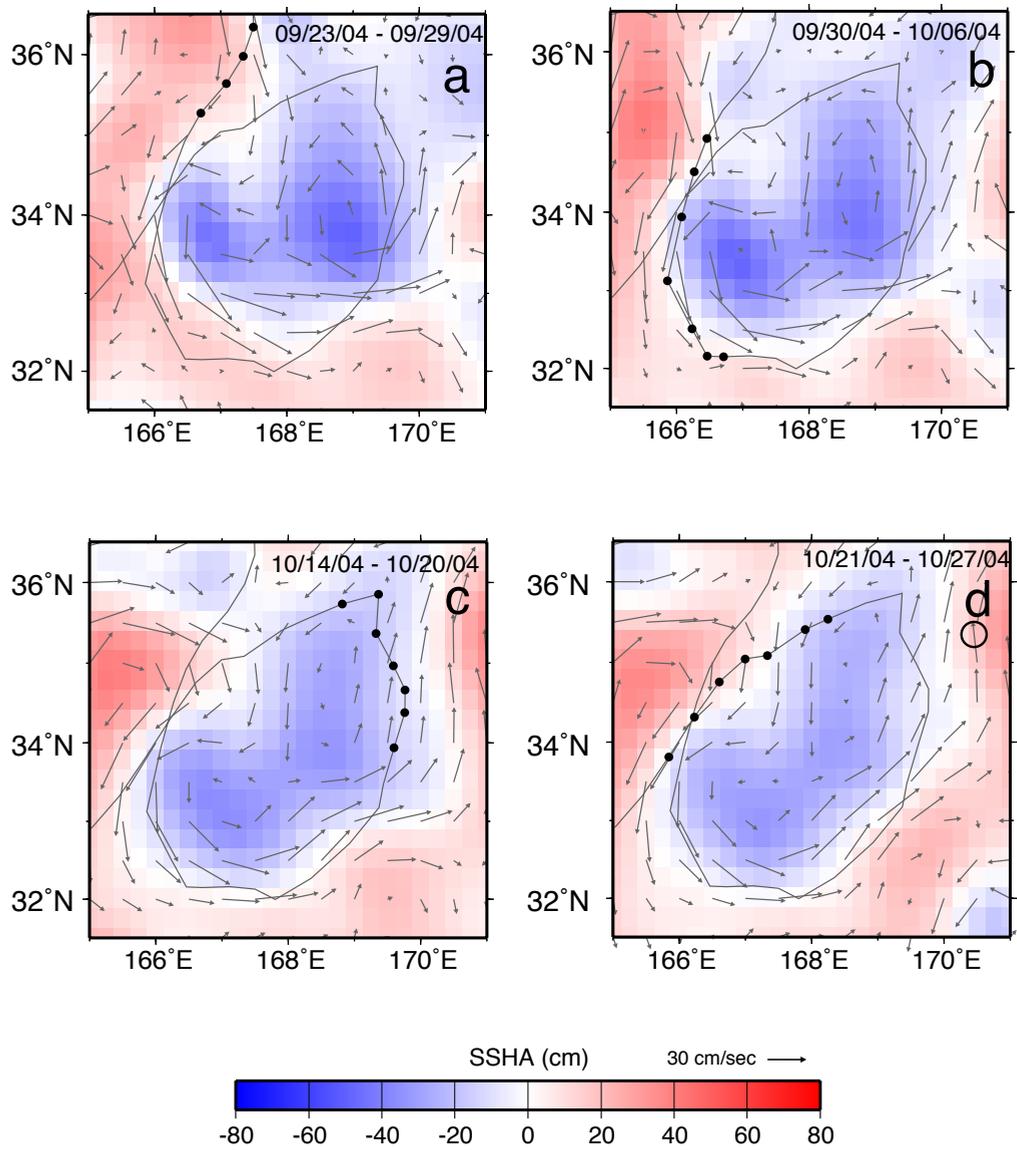


Figure 4.14: Sea surface height anomaly (false color) and geostrophic currents (grey arrows) of the region surrounding eddy CC1 with geolocations for loggerhead 24645 during four periods in 2004 (a) September 23–29, (b) September 30–October 6, (c) October 14–20, and (d) October 21–27. The solid grey line represents the full track line for the turtle. Black circles represent the geolocations of the turtle during the respective 7-day window.

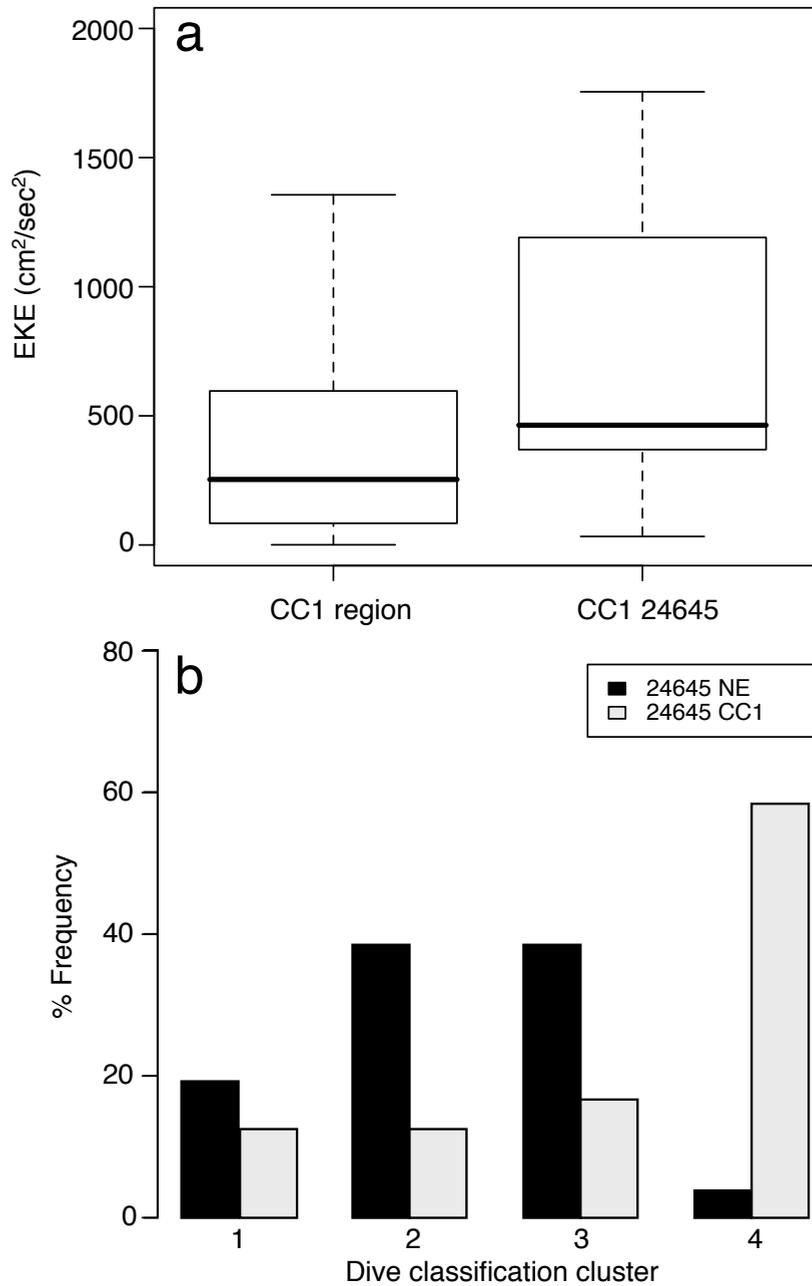


Figure 4.15: (a) Box and whisker plots of eddy kinetic energy values over the region associated with eddy CC1 (left, 165°-170°E, 31.5°-36.5°N) and corresponding to the geolocations of loggerhead turtle 24645 while associated with eddy CC1 (right). (b) Percent frequency distributions of dive classification clusters for loggerhead 24645 outside (black) and associated with (grey) eddy CC1.

with an eddy (Fig. 4.15b). A comparison of dive behavior for these three turtles associated with eddies show that the percentage of dive types was similar for three of the four eddy events (Fig. 4.16). The C4 dive type was the most prevalent, with 58-78% classification. Turtle 24644 exhibited different dive behavior, with 41% (35%) of dive types classified as C1 (C2).

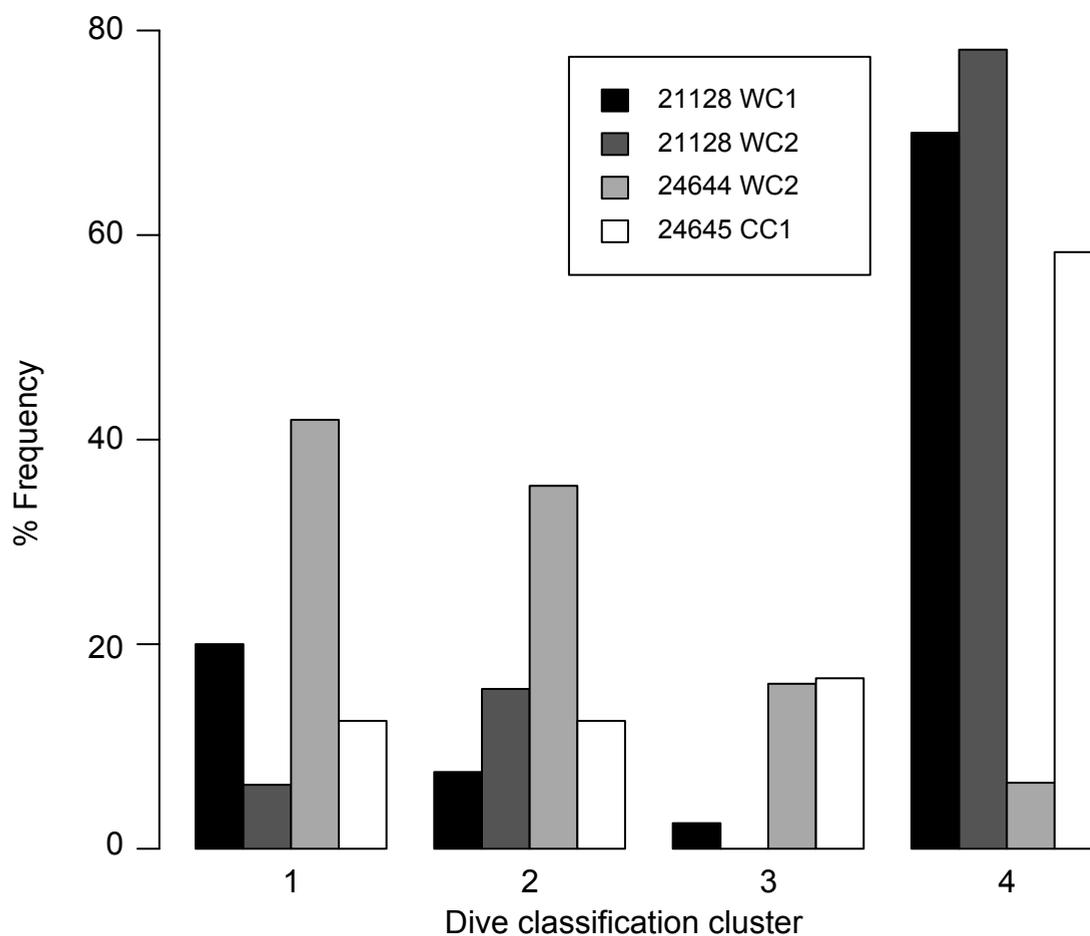


Figure 4.16: Comparison of percent frequency distributions of dive classification clusters for loggerheads 21128, 24644, and 24645 associated with three eddy events in the KEBR.

4.3.6 Regional behavior: The CC

Only one of the 17 turtles traveled east to the CC region (Fig. 4.1). This turtle (16129: 61 cm SCL) traveled in a southeastern direction after its release from the longline fishery in September 2003 (Fig. 4.17a). It continued along a southeastern trajectory for close to 180 days before switching to an eastern pathway and spent more than 90 days in the region east of 120°W. The turtle moved east towards the coastal region of Baja California before switching to a northeastern pathway. Once the turtle traveled west of 120°W it began a rapid northwestern transit, reaching the HLSFG within 90 days. This transit took approximately half the time of the southeastern transit, and the median speed during this northwestern transit was significantly higher than during either of the previous two periods (signed-rank test, $p < 0.01$). The percentage classification of dive types changed during these three transit periods. For all three periods the C1 dive type was the most prevalent, yet the amount of C2-C4 dive types changed depending on the transit region. More than 80% of the dive types were classified as C1 during the southeastern transit, with a 20% drop in C1 types for each successive transit period (Fig. 4.17b). There was a decrease (increase) in the percentage of C1 (C4) dive types after the animal crossed the 120°W meridian, with only a small percentage of C2 and C3 dive types during this period. There was an apparent change in dive behavior during the northeastern transit west of 120°W, with a 15-20% increase in the percentage of C2 and C3 dive types during this time.

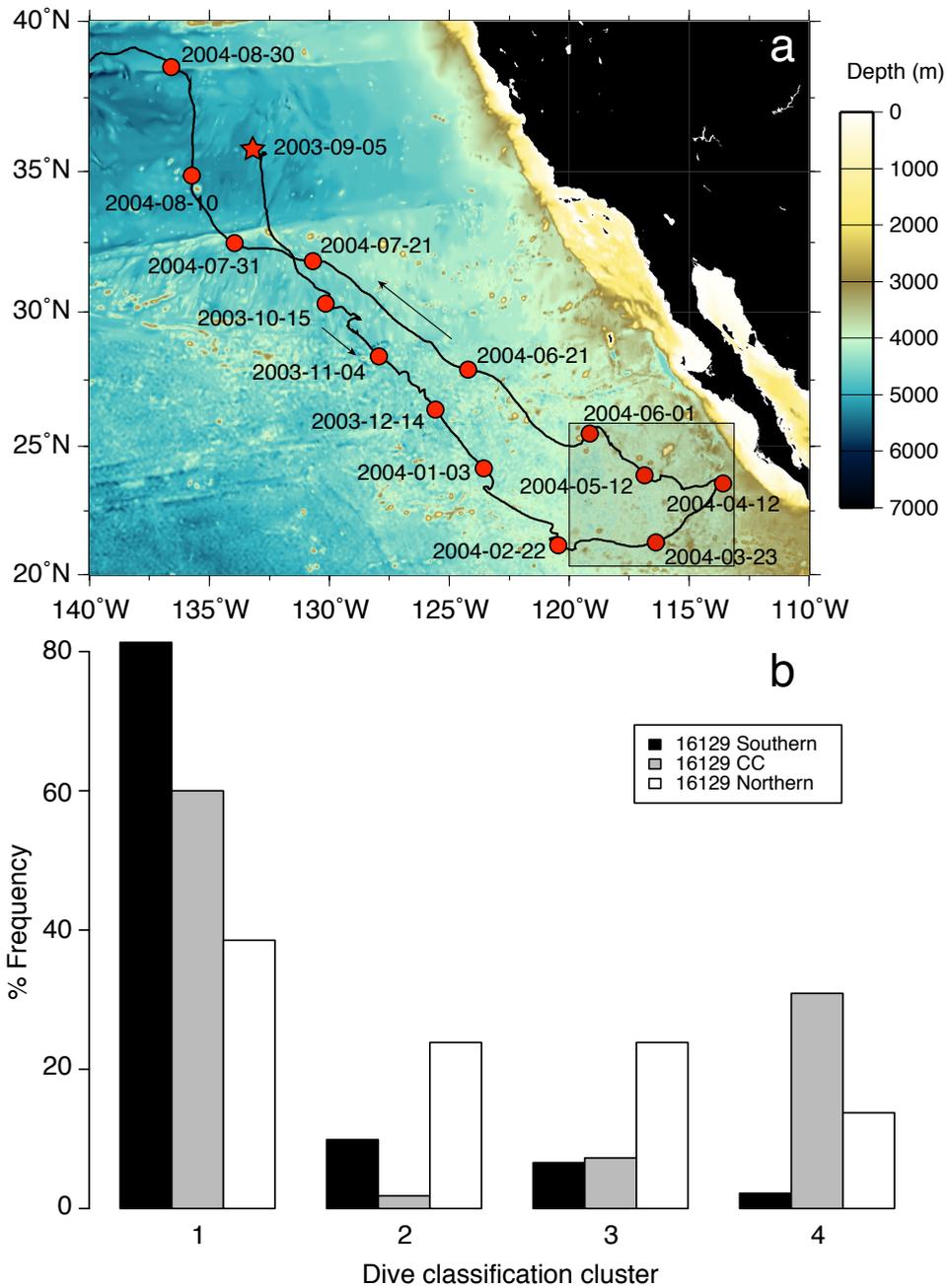


Figure 4.17: (a) Bathymetric map of CC region with movement of loggerhead 16129 superimposed. Red circles and corresponding dates represent selected geolocations along the track (≈ 10 -day spacing). (b) Percent frequency distributions of dive classification clusters for loggerhead 16129 within the CC region during the southern transit (black) east of 120°W (grey) and during the northern transit (white).

4.3.7 Implications to the Hawaii-based longline fishery

Dive behavior of juvenile loggerheads was observed in three distinct regions of the North Pacific throughout the year, yet the HLSFG during the first quarter is the area and time has the greatest possible implications to the Hawaii-based longline fishery. The probability of a turtle occurring and the average number of dives within an SST range show different patterns (Fig. 4.18a). The highest probabilities of a turtle occurring were centered in the 16.75°–17.25°C SST range. Conversely, the lowest probabilities of a turtle diving > 15 m were in the 17°–17.5°C SST range (Fig. 4.18b). The highest probabilities of dives to depths > 15 m were in waters colder than 16°C or warmer than 18.5°C. The highest probabilities of a shallow set occurrence were within the 17.5°–18.0°C SST range (Fig. 4.18c). The conditional probability of a turtle diving to depths > 15 m was highest in the SST range from 16.25°–17.25°C (Fig. 4.18e). The conditional probability of a gear crossing was highest in warmer waters, with the highest values close to 17.25°C (Fig. 4.18e). This can be seen more clearly in the cumulative probability distribution, where the interquartile range of the probable gear crossings occurs in the 16.75°–17.6°C SST range (Fig. 4.18f). This is in cooler waters than the observed loggerhead turtle interactions, which have an interquartile range in the 17.3°–18.3°C SST range.

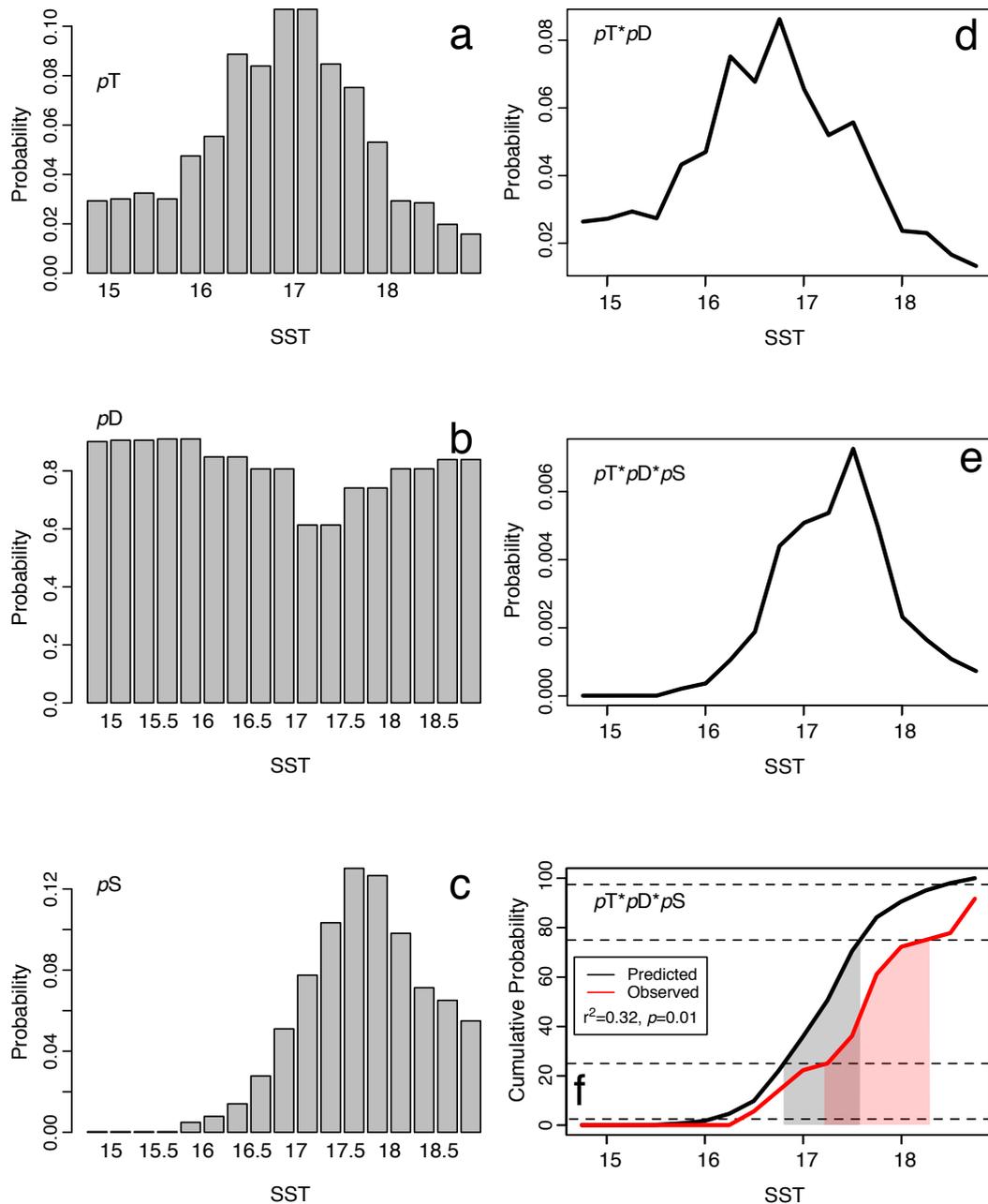


Figure 4.18: The probability within a 0.25°C SST bin of (a) a turtle occurrence (b) a turtle diving to depths > 15 m and (c) a shallow set occurrence. The conditional probability within a 0.25°C SST bin of (d) a dive to > 15 m given a turtle and (e) a gear crossing. (f) The normalized cumulative conditional probabilities of a gear crossing (black line) and the cumulative summary of recorded loggerhead interactions by SST (red line).

4.4 Discussion

Dive behavior results from the 17 turtles in this study are similar to previously reported behavior for two juvenile loggerhead turtles in the central North Pacific Ocean (Polovina *et al.*, 2003). The combined dive records showed that over 80% of the dives were to depths less than 5 m, with more than 60% of the turtles time spent in this depth range. This compares well to the reported dive behavior for individual loggerheads captured by the longline fishery in the North Pacific, where 90% of the dives were to depths less than 5 m, with most time spent shallower than 40 m for both day and night (Polovina *et al.*, 2003; Polovina *et al.*, 2004). Diel variability in the dive parameters was observed between the four 6-hour periods of the day, turtles making significantly more dives during the day of shorter duration than at night. This diel behavior was observed in loggerheads both in the Gulf of Mexico and in the Mediterranean sea (Renaud and Carpenter, 1994; Godley *et al.*, 2003) and was hypothesized to reflect resting (active) behavior during the night (day) (Godley *et al.*, 2003). Results from the cluster analysis of the dive information showed that turtles exhibited four distinct dive behaviors during this study period. Houghton *et al.* (2002) generalized six distinct dive types based on the previous dive studies of loggerhead and green turtles (Minamikawa *et al.*, 1997; Hochscheid *et al.*, 1999; Hays *et al.*, 2000). Five of these six dive types were similar, and were dives to greater depths than the sixth dive, which represented a more surface-oriented behavior. The C1, C3, and C4 dive types all represented behaviors where turtles made less overall dives, yet to greater depths and for longer durations. While each of this was similar in this regard, there were differences in the dive depths and durations between them. This behavior is similar to foraging

dives as described in the literature, which are thought to be linked to an increased number of dives, and a strong inverse relationship between the number of dives and dive durations (Renaud and Carpenter, 1994; Godley *et al.*, 2003).

The C2 dive behavior type was most different from the other three types, and represent 6-hour periods when turtles made numerous dives to shallow depths and short in duration. This behavior has been described as inter-breath submergences which occur when turtles travel (Hochscheid *et al.*, 2007). The C2 dive type is most likely a combination of transit and shallow foraging dive behavior. Previous studies have also reported these two extremes in dive behavior, with an inverse correlation observed between the number and duration of dives (Renaud and Carpenter, 1994) as well as diel patterns in dive durations (Godley *et al.*, 2003).

4.4.1 Regional dive behavior: The HLSFG

There was observed seasonal variability in the spatial location and dive behavior of the 17 loggerheads within the HLSFG region. Loggerheads spent the majority of their time in the 0–5 m range throughout the year, yet there were changes in the number and duration of dives to depth possibly reflecting oceanographic conditions. During the first quarter loggerheads occupied cooler waters to the north of the STF. A deep mixed layer characterized this region of the North Pacific during this time, with surface temperatures being a strong proxy for subsurface temperatures down to 100 m. More than 80% of the Loggerhead dive behavior during this time was classified as C1 type behavior, which reflected deeper dives of longer duration. This was observed in the time-at-depth for this season, where more than 15% of the time was spent deeper than 15 m. The increase in the depth and duration of

these deeper dives during this period is most likely a result of the oceanography. An increase in surface winds in this region in the first quarter results in a deeply mixed surface layer that may distribute non-surface oriented prey more evenly throughout the water column. Stomach content analysis showed that juvenile North Pacific loggerheads are opportunistic feeders that ingest items floating on or near the surface, but also take advantage of other prey items throughout the water column when available (Parker *et al.*, 2005). Turtles began to move to the north during the second quarter in apparent response to the seasonal movement of the NPTZ. The temperature-depth profiles reflect this spatiotemporal movement, with turtles inhabiting warmer surface waters with a shallower thermocline. A change in dive behavior with a 20% shift from C1 to C3 dive types occurred during this time. The C3 dive type was characterized by a greater number of slightly shorter dives to shallower depths than the C1 dive type, which may reflect a shallowing of the thermocline during this period and a vertical movement in the aggregation of subsurface prey at depth. The larger percentage of C2 dive types occurred when turtles were at their northernmost locations in the third quarter of the year. This region at this time is characterized by the warmest surface and coldest subsurface waters encountered. A sharp thermocline at shallow depths results in temperatures of less than 15°C at ≈ 20 m. Turtles exhibited the shallowest behavior in this period, with an increase in the C2 dive types, which are characterized by the greatest number of dives per day to shallow depths. These dives have been described in the literature as transit dives (Hochscheid *et al.*, 2007), but here may reflect the shallow aggregation of subsurface prey items due to the increased stratification in the water column. Similar to the observed decrease in

C1 dive types during the second quarter, there was an increase in the percentage of C1 types in the fourth quarter. Temperature-depth profiles from this period are similar to those from the second quarter, yet with a more defined thermocline. The observed increase in the percentage of C2 dives may reflect either a continuation of available prey in the surface waters, an increase in transit behavior by the animals or a combination of these two.

Temperature data was not collected by the satellite tags, yet can be inferred from the dive information and the temperature-depth profiles during this time. The importance of thermal niches in turtles has been postulated (Hays *et al.*, 2002; McMahon and Hays, 2006), and it has been shown that loggerheads have an internal thermal dependence on ambient temperatures which is stronger in smaller turtles (Sato *et al.*, 1998). The importance of the 15°C isotherm as a thermal niche limit has been discussed for leatherbacks and loggerheads (McMahon and Hays, 2006; Brazner and McMillan, 2008). This is more likely a thermal preference than limit, as turtles have been observed to make dives corresponding to temperatures less than 15°C (Hochscheid *et al.*, 2007). However, there is an observed importance to the 15C isotherm. More than 99% of all time was spent in depths corresponding to temperatures warmer than 15C, with turtles altering their dive behavior to shallower (deeper) depths seasonally as the thermocline shoaled (dropped). More information is necessary to define whether this change in behavior is due to a vertical shift in prey due to increased stratification of the water column during this time or due to thermal limitations.

4.4.2 Regional dive behavior: The KEBR

Five of the 17 animals in this study traveled through the HLSFG to the KEBR, with three tags transmitting more than 30 days within this region. It is difficult to ascertain exactly why those five particular turtles traveled to the KEBR. Size did not appear to be the primary factor, as these were not the five largest animals and three of these five turtles were of the median size in the study. It is more probable that a combination of the release location and time at liberty were important. The times at liberty for all five turtles were above the median value, with three in the upper quartile. It is difficult to infer results from this small sample however, as release locations and individual behavior may play important factors in travel to this region. Previous results from tracking studies have shown that turtles propagating west travel to this region (Polovina *et al.*, 2006) which can allow us to infer that longer times at liberty for tags may have resulted in more animals entering this region, yet without this data it is purely a speculative assumption.

The three tags that transmitted information in this region showed that turtles were associated with mesoscale eddies, at times in temporal succession. The spatial track from one of these turtles in addition to other examples of the use of mesoscale features were reported in Polovina *et al.* (2006), yet here additional track information coupled with dive information are added to expound on turtle behavior in this region. These tracks indicated that two of the three turtles were associated with the strongest currents in both warm-core and cold-core mesoscale events. However, Turtle 24644, which was reported in Polovina *et al.* (2006), was in the same feature as turtle 21128, yet was not associated with stronger than background currents. The dive behavior of these turtles appeared to correspond to

the eddy usage; with longer, deeper dives exhibited by the turtle associated within stronger currents associated with the eddy. Turtle 24644 was within weaker surface currents while associated with this eddy, and spent a greater percentage of time diving to shallower depths for shorter durations. This individual was smaller than the other two, yet with this sample size it is difficult to draw conclusions based on morphological differences. As the main prey of loggerheads are surface-oriented and aggregated in convergent areas, the use of the edges of warm-core eddies was unanticipated, yet this behavior may be more directed by physics rather than biology. The highest currents in this study were associated with the edges of both eddy types, yet surface convergence occurs in different areas for warm-core and cold-core events. While we would expect the highest surface convergence in the center (edge) of a warm-(cold-)core eddy, the physiological advantage given by the areas of high currents may outweigh the possible biological advantages. The appearance of a higher amount of C4 dive type behavior by two of the three individuals may be due to a combination of the turtles using the highest currents for transit with the ability to dive deeper due to warmer subsurface conditions. Temperature data collected by ARGO floats in this region show that subsurface temperature down to 100 m warmer in this region than in the HLSFG during these times (not shown). This may facilitate the ability for turtles to do deeper, longer, C4 type dives in this region, a behavior rarely observed in the HLSFG where subsurface temperatures are much colder. It may be also possible that sessile organisms are constrained to the edges of the eddy, as a submergence of organisms in the center of a warm-core eddy may result in a spread to the edges. Turtle 24644 did not occupy the region with the highest surface currents, yet did occupy the edge of the eddy at a dis-

tance further from the center than turtle 21128. This may imply that placement within the eddy edge may affect the dive behavior of turtles. The physiological explanation is also supported by the observation that turtles occupied areas of both warm- and cold-core eddies with the highest currents, rather than the areas where the greatest surface convergence would occur. Residence time within the eddies however, suggests that while dive behavior is similar for both warm-core and cold-core events, the amount of time that turtles spend within cold-core events is lower than warm-core eddies (Polovina *et al.*, 2006). Additional information on loggerhead prey items in this region, as well as additional dive information from more individuals would allow for a clearer explanation for the observed dive behavior in this region.

4.4.3 Regional dive behavior: The California Current region

One turtle (16129) of the 17 released turtles traveled east to the California Current region near Baja California. Caution should be exercised not to over-interpret results based on one animal, yet this turtle was included as this was the first juvenile loggerhead that we have seen travel this far east after capture from the oceanic phase during our studies. To date, no juvenile turtles captured and satellite tagged by the longline fishery in the North Pacific have traveled to Baja California, yet turtles of similar size are reported in large numbers and based on satellite telemetry results spend considerable time in this region (Peckham *et al.*, 2007). There is insufficient information to determine why this particular individual traveled east, rather than west. The size of the turtle may be important in determining both

the initial transit to Baja California and subsequent return to the HLSFG. Turtle 16129 was not the largest in the study (61 cm SCL), yet was in the upper quartile of the SCL ranges. However, the size of this turtle was significantly less than the mean size of turtles tracked in a previous study in this area (Peckham *et al.*, 2007).

Behavior changes were observed from the tag-recorded information across the three study-defined subregions within the CC. The transit speed and dive behavior exhibited by the turtles were very different during the southern and eastward transect than during the return transect. The dive type classifications made by the cluster analysis reflected this, with more C1 and C4 dive types present during these first two transects. Turtle behavior was similar to prior behavior on the initial return transect, yet once crossing the 120°W meridian the turtle abruptly altered its behavior, with an increase in speed and more C2 and C3 dive behavior recorded. The change in dive behavior to these shallower behaviors is most likely correlated to the increase in speed, with the C2 dives representing the transit dives made by the animal. While at this juncture the data provides an incomplete story, it is promising to see results that indicate a change in dive behavior by turtles in this region.

4.4.4 Implications to the Hawaii-based longline fishery

One aim of this current study was to attempt to incorporate the loggerhead dive information to the NOAA TurtleWatch product. Results from the dive behavior analysis show that there was seasonal variability in the dive behavior within the HLSFG, with deeper, longer dives during the first quarter of the year. Turtles during this quarter inhabited waters characterized by the coldest SST and deepest

mixed layer. 80% of the 6-hour periods were classified as C1, which represents a larger number of dives to deeper than 15 m, the vertical region where shallow set fishing gear is expected to occupy. These dives are also longer in duration, resulting in more time spent at depths greater than 15 m, during this time. Based on model results however, only a low probability of dives by individual turtles were expected to these depths, and variability in these probable dives was observed between different SST ranges. The lowest probability of dives to depths > 15 m occurred in the 17° – 17.5° C range, which contains the surface thermal expression of the STF and is a highly convergent region. If we assume that juveniles preferentially forage at the surface, the decrease in the number of dives to depth may reflect a larger availability of organisms at the surface due to higher convergence. The increase in the expected number of dives to depth in colder surface waters to the north may be a result of either subsurface forage opportunities or the avoidance of non-preferential surface conditions. The NPSTFZ is characterized by high winds and frequent storms during the winter (Seki, 2003), and turtles have been observed to spend more time below the surface in these conditions (J. Polovina, pers. comm.). The higher probability of dives > 15 m in warmer waters to the south of the frontal zone may be due to a subduction of organisms along isopycnals which outcrop at the STF.

Interestingly, the highest probability of a turtle occurrence is found near 17° C SST. This again may reflect increased surface aggregation of prey items as well as a physical movement of turtles based on the direction of the wind fields during this period. This results in the greatest probable occurrence in this temperature region, yet the lowest expected number of dives. The conditional probability of

a turtle diving to depths > 15 m is substantially decreased when combined with the modeled probabilities for the occurrence of juvenile loggerheads and shallow sets based on SST. Overall, these probable gear crossings are low in number, yet the interquartile range is still within colder waters than the observed loggerhead interactions with the Hawaii-based longline fishery for both historic interactions Chapter 3, (Howell *et al.*, 2008), or for only the years 2005-2007 shown in this Chapter. This result suggests that an additional factor is necessary to capture why interactions are occurring. These may include behavioral factors that the data in this study cannot address. Turtles are visual predators, and increased turbidity with decreased light penetration may inhibit interactions with gear in colder, more productive waters. Additionally, dives to depth in the transition zone may be a means to avoid adverse surface conditions, while the dives to depth in the oligotrophic gyre may be forage-based. Additional data from archival tags which allow for actual dive profiles could elucidate any subtle differences in dive behavior which cannot be seen with the frequency data provided by the SDR tags.

The initial TurtleWatch product contained a recommendation to avoid the placement of shallow set gear in waters colder than 18.5°C (Howell *et al.*, 2008). This was based on the interquartile SST range of historical interactions coupled with results from satellite telemetry where turtles inhabited colder waters than where interactions occurred. After observation of the fishery in 2007 and the absence of interactions in colder waters where maximum effort was placed, the TurtleWatch product was refined to recommend the avoidance of sets in the 17.5° - 18.5°C SST band. One goal of this present study was to incorporate the dive data into the TurtleWatch product. The probabilities of dives > 15 m were in close to

uniform distribution, and the pattern of gear crossings was more defined by the spatial-based probabilities. While the resultant conditional probabilities do not fit the observed interactions better than the existing TurtleWatch product, the modeled gear crossings may still be used in future research into this area.

Chapter 5

Summary

The main focus of this dissertation was to incorporate current satellite-based data collection methods with fishery dependent data to better understand the behavioral variability of two important species in the North Pacific Ocean, loggerhead turtles and bigeye tuna. While physiologically these two species are very different, they share a common thread in that they are both species of importance to the Hawaii-based pelagic longline fishery. Their importance to this fishery manifests itself in two very different ways: Bigeye tuna are a targeted species considered to be a desired catch, and loggerhead turtles are a species which is non-targeted and considered an undesired catch (i.e., bycatch). The recent advent of satellite telemetry tags coupled with satellite-collected environmental data allows us as researchers to observe by proxy the horizontal and vertical movements of pelagic species in the open ocean through their natural environments. The combination of these two types of data results in a better understanding of the three dimensional habitats that these two species occupy, and can begin to lead us to ways of more accurately targeting, or avoiding, specific species depending on our desires.

This was a major goal of the three studies contained in this dissertation. The first study focused on the dive variability of bigeye tuna in the North Pacific Ocean using satellite telemetry tags. The results from empirical data collected by the tags showed that there was large variability in the daytime dive behavior of commercial sized bigeye tuna in the central North Pacific Ocean. Three different dive behavior types were defined here, and the analysis of these three types indicated that while a classic, deep diving behavior was the most common type, bigeye also spent a large percentage of days in shallow or intermediate layers of the water column. Model results showed that while space and time were important parameters, SST was the most significant factor affecting the potential vulnerability of bigeye tuna to commercial longline gear. The model predictions of the area with the highest potential interactions with bigeye correspond well with fishery-based catch reports, indicating that with additional data to cover missing regions and quarters of the year, it may be possible to ultimately predict areas of high bigeye catch rates. Future incorporation of remotely-sensed sea surface temperature values can be used in the model to create potential vulnerability maps which could be used by fishers or managers to assess where the bigeye catch rates are expected to be highest.

The second study described the analysis that was done to create the NOAA TurtleWatch product. The TurtleWatch product was an initial effort to help reduce inadvertent interactions between Hawaii-based pelagic longline fishing vessels targeting swordfish and loggerhead turtles by providing a near real time product recommending the area in which the deployment of shallow sets should be avoided. This product was dynamic by nature as it used sea surface temperature, which captures the environmental variability of the system. A main goal of TurtleWatch was

also to provide a timely, easily understood and science-based tool to both the industry and managers to aid in decisions regarding the Hawaii longline fishery. As the fishery was closed prematurely in March 2006, the aim of TurtleWatch was to provide information to the industry and managers to minimize bycatch and maximize fishing. TurtleWatch was released in December 2006 and was correct in identifying an area where turtle bycatch would more likely occur (i.e. where over 65% of loggerhead turtle bycatch occurred during the first quarter of the year) during the first quarter of 2007. It was known at the time of release that additional refinement of this product could be done, as the product was built from fishery-dependent spatial data and essentially recommended avoiding the placement of sets in a large area.

The third and final study in this dissertation combined the data from satellite telemetry and satellite remotely-sensed environmental data to analyze the variability in dive behavior of loggerhead turtles based on space, time, and the environment. From previous research as well as work in this dissertation it was well known that seasonally shifting oceanographic features and dynamic hotspot areas are important habitat areas for juvenile loggerhead turtles during the pelagic phase of their life cycle. The dive information collected from the satellite telemetry tags showed that there is spatial and temporal variability in juvenile loggerhead turtle dive behavior that was associated with these large- and meso-scale features. A major goal of this project was additionally to incorporate the dive data into the NOAA TurtleWatch product, as a more complete understanding of coupled horizontal and vertical behavior can be used to minimize fisheries interactions. The addition of the dive data showed that while turtles occur through waters charac-

terized by a wide range of surface temperatures during the first quarter of the year, their dive behavior varies depending on the oceanographic system. This information can then be coupled with the historic fisheries data which can provide a proxy of swordfish abundance, and provide an indication of where the temperatures that the fleet primarily target. Combined, this provides a better estimate of where the greatest interactions between loggerhead turtles are expected to occur, and allow fishers to avoid these areas.

Chapter 6

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Chapter 7

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