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Enhancing the TurtleWatch product for leatherback sea turtles, a dynamic habitat model for ecosystem-based management

EVAN A. HOWELL,[1,*] AIMEE HOOVER,[2,4] SCOTT R. BENSON,[3] HELEN BAILEY,[4] JEFFREY J. POLOVINA,[1] JEFFREY A. SEMINOFF[5] AND PETER H. DUTTON[5]

[1]*NOAA Pacific Islands Fisheries Science Center, 1845 Wasp Blvd., Building 176 Honolulu, HI, 96818, U.S.A.*
[2]*Joint Institute for Marine and Atmospheric Research, 1000 Pope Road, Honolulu, HI, 96822, U.S.A.*
[3]*NOAA Southwest Fisheries Science Center, 7544 Sandholdt Road, Moss Landing, CA, 95039, U.S.A.*
[4]*Chesapeake Biological Laboratory, University of Maryland Center for Environmental Science, 146 Williams Street, Solomons, MD, 20688, U.S.A.*
[5]*NOAA Southwest Fisheries Science Center, 8901 La Jolla Shores Dr., La Jolla, CA, 92037, U.S.A.*

ABSTRACT

Fishery management measures to reduce interactions between fisheries and endangered or threatened species have typically relied on static time-area closures. While these efforts have reduced interactions, they can be costly and inefficient for managing highly migratory species such as sea turtles. The NOAA TurtleWatch product was created in 2006 as a tool to reduce the rates of interactions of loggerhead sea turtles with shallow-set longline gear deployed by the Hawaii-based pelagic longline fishery targeting swordfish. TurtleWatch provides information on loggerhead habitat and can be used by managers and industry to make dynamic management decisions to potentially reduce incidentally capturing turtles during fishing operations. TurtleWatch is expanded here to include information on endangered leatherback turtles to help reduce incidental capture rates in the central North Pacific. Fishery-dependent data were combined with fishing effort, bycatch and satellite tracking data of leatherbacks to characterize sea surface temperature (SST) relationships that identify habitat or interaction 'hotspots'. Analysis of SST identified two zones, centered at 17.2° and 22.9°C, occupied by leatherbacks on fishing grounds of the Hawaii-based swordfish fishery. This new information was used to expand the TurtleWatch product to provide managers and industry near real-time habitat information for both loggerheads and leatherbacks. The updated TurtleWatch product provides a tool for dynamic management of the Hawaii-based shallow-set fishery to aid in the bycatch reduction of both species. Updating the management strategy to dynamically adapt to shifts in multispecies habitat use through time is a step towards an ecosystem-based approach to fisheries management in pelagic ecosystems.

Key words: Central North Pacific, dynamic management, fisheries, leatherback sea turtles, sea surface temperature, swordfish

INTRODUCTION

Efficient ecosystem-based management within the world's oceans has been recognized as an essential element to balance species diversity, maintain viable marine populations and sustain the livelihood of the human entities that harvest them (Dutton and Squires, 2008; Game *et al.*, 2009; Zhou *et al.*, 2010). Management measures for fisheries have included geographically static time-area closures or marine-protected areas. While these management actions aim to be successful in reducing the bycatch of species of concern, these spatially static regions by definition may not be effective for managing highly migratory species (Game *et al.*, 2009). They can incur great economic cost to the fisheries (Li and Pan, 2011), and reduce the cost benefit as a conservation tool (Gjertsen *et al.*, 2014). For highly migratory species that may traverse entire ocean basins over the span of a year, it may be necessary to manage these species in a dynamic fashion, following animals as they move through their habitat in space and time (Hyrenbach *et al.*, 2000).

The advent of advanced technologies, such as satellite telemetry, has allowed the collection of information on marine species around the world to identify and characterize their habitat (Howell *et al.*, 2010a,b;

*Correspondence. e-mail: Evan.Howell@noaa.gov
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Benson *et al.*, 2011; Block *et al.*, 2011; Bailey *et al.*, 2012). These habitat data, which indicate their environment can vary greatly through space and time, can then in turn be used to inform dynamic management regions (Howell *et al.*, 2008; Hobday *et al.*, 2009, 2010). This 'dynamic management' strategy offers an improvement over more traditional, geographically defined static areas by allowing the management area to migrate with animals moving spatially through time (Howell *et al.*, 2008; Hobday *et al.*, 2010).

In the Central North Pacific Ocean, two highly migratory sea turtle species, loggerhead (*Caretta caretta*) and leatherback (*Dermochelys coriacea*), are classified as endangered under the US Endangered Species Act. Reducing fisheries interactions with these two species is central to fishery management plans for U.S. fleets, including the shallow-set Hawaii-based pelagic longline fishery (Gilman *et al.*, 2007). A recent study has reported a persistent and long-term decline of leatherbacks nesting at Bird's Head Peninsula in Papua Barat, Indonesia, an area which accounts for 75% of the total leatherback nesting in the western Pacific, and represents the last sizeable nesting population in the entire Pacific (Tapilatu *et al.*, 2013). While leatherbacks nest year-round at the Bird's Head beaches, the boreal summer nesters belonging to this nesting population have been shown to migrate and forage across an extensive area of the North Pacific (Benson *et al.*, 2011).

Fisheries bycatch is a major threat to marine megafauna and pelagic ecosystem balance, with lethal interactions between endangered sea turtle species and fishing gear being a global concern (Lewison *et al.*, 2004; Wallace *et al.*, 2010; Finkbeiner *et al.*, 2011). The Hawaii-based pelagic fishery targets swordfish north of Hawaii in the North Pacific Subtropical Frontal Zone (NPSTFZ) during the winter–spring months (Seki *et al.*, 2002). This biologically dynamic region is also used as a foraging area and migration pathway by many highly migratory species, including sea turtles (Polovina *et al.*, 2001). Historic interactions between loggerhead and leatherback turtles and the shallow-set Hawaii-based pelagic longline fishery prompted a 2-yr fishery closure in 2002 (Gilman *et al.*, 2007). This closure was specific to the fishery sector targeting swordfish in the 0–100 m depth range, as this was the depth range associated with higher sea turtle interactions (Polovina *et al.*, 2003). This sector of the fishery was reopened in 2004 with strict management regulations aimed to reduce the incidental capture of both leatherback and loggerhead turtles (NMFS, 2004; Gilman *et al.*, 2007), including the use of hard cap limits. If a hard cap limit is met, as occurred in 2006, the fishery is closed for all shallow sets for the remainder of the calendar year. These fishing closures can cause economic hardship for the fleet targeting swordfish (Li and Pan, 2009), and may lead to an increase in non-restricted foreign fleet effort and swordfish production owing to transfer effects, with an associated increase in sea turtle interactions (Chan and Pan, 2012).

The Hawaii-based shallow-set fishery closure of 2006 prompted a need for a better understanding of sea turtle habitat use, which became the foundation for the NOAA Pacific Islands Fisheries Science Center's (PIFSC) TurtleWatch product (Howell *et al.*, 2008). TurtleWatch Version 1.0 (V1) NOAA Fisheries Honolulu, HI, USA is currently in use as a dynamic tool that displays a daily map with real-time SST and ocean current information as well the predicted location of waters used by loggerhead turtles. Initial research indicated that 67% of loggerhead interactions occurred during the first quarter of the year in the region containing surface waters cooler than 18.5°C (Howell *et al.*, 2008).

TurtleWatch V1 was first released in December 2006 as an experimental product in the form of an online map covering a region from the International Date Line to 150°W and identifying the 65.5°F (~18.5°C) isotherm (Fig. 1a). This was later modified and released as Version 1.5 based on updated fishery data and feedback from sea turtle experts and the Western Pacific Regional Fishery Management Council (WPRFMC). The modified version was extended to 140°W and identified the region between the 63.5°F (17.5°C) and 65.5°F (18.5°C) isotherms as an area to be avoided by longline vessels deploying shallow-set gear in order to minimize interactions with loggerhead turtles (Fig. 1b). The decision to recommend a thermal band of avoidance was a trade-off to allow fishers to set gear within a larger area, while minimizing interactions with loggerheads and maintaining the dynamic nature of the product as a result of seasonally changing environmental conditions.

There is now great interest and demand to find solutions to also reduce the incidental capture of endangered leatherback turtles. An increase in available leatherback movement data from both fishery dependent and independent sources has recently become available. Benson *et al.* (2011) used tracks obtained from satellite telemetry tags affixed to 126 turtles to identify movement patterns and pathways of leatherbacks across the North Pacific. Since 2006, there has been a marked increase in the number of interactions between leatherback turtles and the Hawaii-based shallow-set fishery, primarily occurring north of the Hawaiian Islands, which prompted a

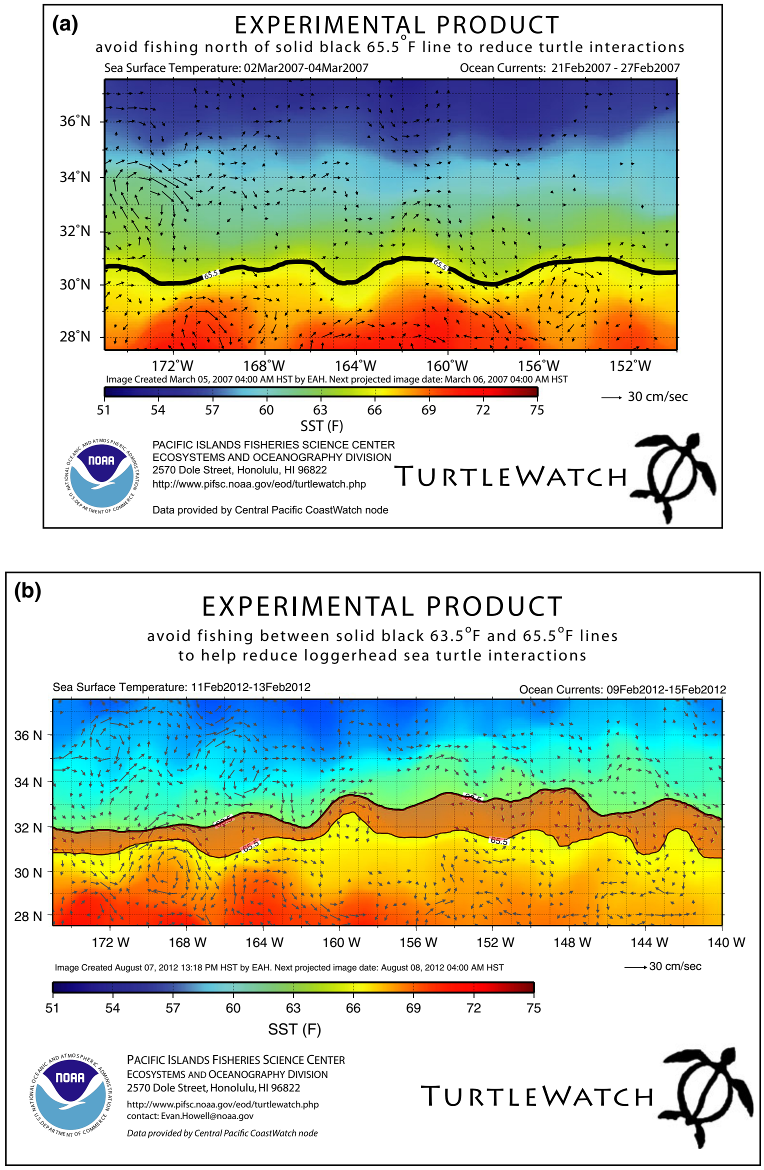


Figure 1. (a) The original TurtleWatch product (Version 1.0) was released in December 2006. The black line represents the 65.5°F (~18.5°C) isotherm. (b) The revised TurtleWatch product (Version 1.5) was released in December 2007. The solid red area is bounded by solid black lines representing the 63.5°F (~17.5°C) and 65.5°F (~18.5°C) isotherms. Both pseudo-color images represent the sea surface temperature (SST) field (°F). Black arrows represent the magnitude and direction of the geostrophic currents derived from altimetry data.

fishery closure in 2011 due to the hard-cap limit of 16 leatherback interactions having been reached.

The increased availability of leatherback data coupled with the increased emphasis of leatherback interactions to management of the fishery has prompted us to revisit the TurtleWatch product and modify the tool to help fishers also avoid interactions with leatherback turtles. The main goal of this paper is to expand upon the original TurtleWatch product using updated fishery, oceanographic, and satellite tracking data to identify habitat, movement and migration pathways of leatherback turtles. We then use this information to identify specific temporal and spatial regions of leatherback and loggerhead turtle interactions with the Hawaii-based pelagic longline shallow-set fishery. This expansion of TurtleWatch should increase utility of the product, and provide information to managers and the fishery to potentially help avoid interactions with these two endangered sea turtle species in the central North Pacific Ocean. The ability to use real-time products as dynamic management tools in shared-use regions can assist managers with ecosystem-based management endeavors.

METHODS

The objective of this study was to identify where leatherback turtle interactions with the Hawaii-based pelagic longline fishery might occur in space and time, and use this information to expand the utility of the

TurtleWatch tool. Point data on fishing locations and dates were used to match fishing activity to a corresponding remotely-sensed SST value. Satellite tracking data for leatherback sea turtles were analyzed to provide a fisheries independent view of their environmental habitats and migration pathways to prevent transferring fishing effort to other sensitive areas.

Fishery dependent data

Fishery dependent data were obtained from logbook information collected as part of the NOAA Fisheries' Hawaii Longline Observer Program. To capture information from the shallow-set sector of the fishery targeting swordfish, data from the observer logbooks were filtered by limiting sets to the geographic region 20°N–40°N and only selecting sets with <10 hooks per float. For each leatherback interaction recorded, the date and location coordinates of the turtle were used. The date of the beginning of the haul and the average of the beginning and ending haul coordinates were recorded and used for analysis. This allowed the closest match of fishing sets and turtle interactions, as turtle captures were only recorded during the hauling of the gear.

Satellite tag data

Fishery independent track information was obtained from a subset of the 126 leatherback turtles tagged by Benson *et al.* (2011), and tag descriptions and attachment methodologies are described therein. Satellite tags were attached to leatherback turtles at western Pacific nesting beaches and neritic California foraging grounds. Turtle locations were transmitted to ARGOS satellites according to the set duty cycles resulting in a time series of positions with an associated location quality flag assigned by the ARGOS satellite. The accuracy of each position was estimated by Argos as a function of Doppler shift in the frequency of the satellite tag and the number of transmissions received. Tracks were selected for this study only if the track intersected the area used by the shallow sector of the Hawaii-based pelagic longline fishery (n = 37). To be consistent with the methodologies in the original TurtleWatch study, raw tracks were filtered to retain the highest accuracy positions closest to noon for each available day (Howell *et al.*, 2008).

Environmental data

SST data were derived from the five-channel Advanced Very High Resolution Radiometers (AVHRR) on board the NOAA–7, –9, –11 and –14 polar-orbiting satellites. Daily SST data from July 2003 to present, processed using the NESDIS global area coverage (GAC) algorithm, were averaged to create custom 8-day images at 11-km resolution. The SST information used in the TurtleWatch product was a daily, 3-day temporal mean image of the temperature field processed using the GAC algorithm.

Statistical analysis

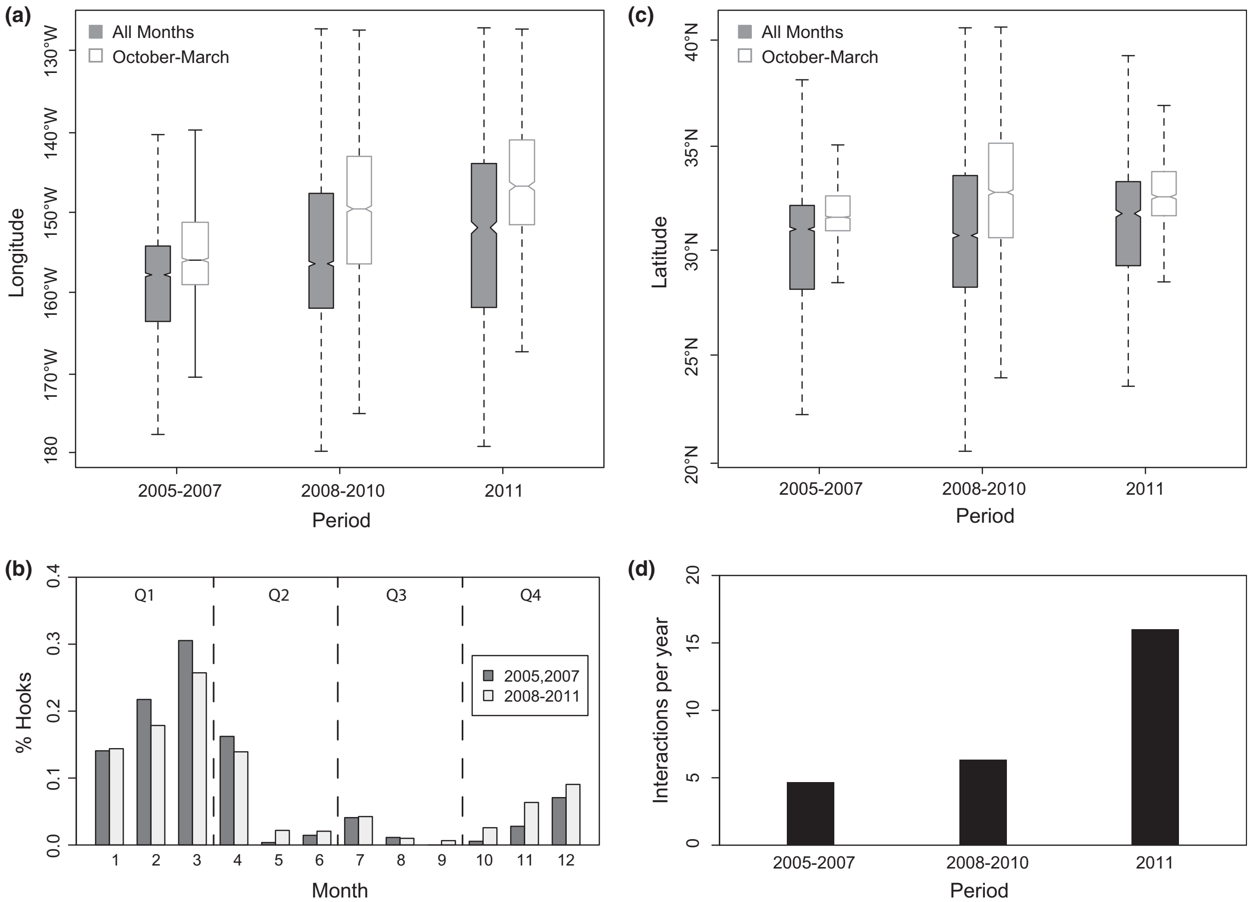
The averaged position data of swordfish sets, sea turtle interaction and sea turtle tracking locations were matched in time and space to SST data. Data were matched at each individual location using the bilinear interpolation method in the routine grdtrack, which is part of the Generic Mapping Tools software package (Wessel and Smith, 1991). All kernel density and probability estimation was done using the density and hist functions in the R statistical software environment (R Core Team, 2013). The joint probability SST distribution for leatherback interactions was estimated by multiplying the shallow-set effort and leatherback satellite tag SST distributions under the assumption that these were independent. Fishery-dependent logbook data from 2005 to 2011 were used to construct effort-based SST density distributions and the revised TurtleWatch product, whereas fishery-dependent data from 2012 was used to test the efficacy of the revised TurtleWatch product. Data from 2006 were only available through March 14 owing to the closure of the fishery; these truncated data were used in all analyses except for percentage calculations to avoid bias in the first quarter of the year.

RESULTS

Fishery information

The Hawaii-based pelagic longline fishery effort was focused in the region 180°–130°W, 20°–50°N (99.3% of effort), while effort distribution changed both spatially and temporally through the 2005–2011 time period (Fig. 2a–c). More effort was distributed both to the north and to the east during 2008–2011 compared with 2005–2007 (Fig. 2a,b). There was also a small shift in effort from the first quarter to the fourth quarter of the year during 2008–2011 relative to 2005–2007 (Fig. 2c), with 61.9% of the overall fishing effort occurring during October–March. Effort within the October–March months was concentrated even further to the northeast, with over 50% of the effort east of 150°W during these months. There was a minor increase in annual interactions between the shallow-set fishery and leatherbacks between 2005–2007 and 2008–2010, and a large increase in interactions observed during 2011 (Fig. 2d). Overall, there were 49 leatherback interactions from 2005 to 2011.

Figure 2. (a) Box and whisker plot of the longitude for effort, (b) box and whisker plot of the latitude for effort, (c) histograms of percentage effort by month and (d) leatherback interactions by the shallow-set fishery per year over the three periods.



A subset of satellite-tagged leatherbacks (n = 37) went through the area where shallow-set effort was concentrated, resulting in 1442 recorded daily positions spanning the North Pacific (Fig. 3). Many of the western Pacific leatherbacks that used the eastern North Pacific as a foraging area entered the southeast portion of the fishing effort area, regardless of where they were tagged. There was a difference in the eastward migration pathway, with turtles either using the Kuroshio Extension to the north or the North Equatorial Counter Current to the south. In contrast, all turtles moving southwest used a wide swath through the southeastern edge of the Hawaii-based shallow-set fishery area. These migration pathway choices are reflected in the SST distributions. Leatherbacks that migrated westward moved within a unimodal SST distribution with the mode centered on the SST range 22.5°–23.5°C (Fig. 4a). In contrast, leatherbacks that migrated eastward had a bimodal SST distribution that reflects the two pathways with modes centered at 16.5°–17.5°C and 22.5°–23.5°C (Fig. 4b). The combined SST distribution for all tagged turtles is bimodal, with modes centered at 16.5°–17.5°C and 22.5°–23.5°C (Fig. 4c).

Kernel densities constructed from SST distributions provide the probabilities of occurrence for shallow sets, satellite-based leatherback locations and leatherback interactions in SST space (Fig. 5a). The shallow-set effort SST kernel density estimates showed a bimodal distribution centered at 17.8° and 25.1°C, whereas the modes for the kernel density estimate for SST from satellite tag locations were centered at 17.2° and 22.9°C (see Fig. 4c). The kernel density estimation for SST values where leatherback interactions occurred also had a bimodal SST distribution, intermediate with the modes for shallow-set effort and tag locations centered at 17.7° and 23.6°C (Fig. 5a). The SST distribution for predicted leatherback interactions, calculated by taking the joint probability of the set and tag SST distributions, compares well to the actual interaction SST distribution (Fig. 5b), with modes from both distributions centered at the same values of 17.7° and 23.6°C.

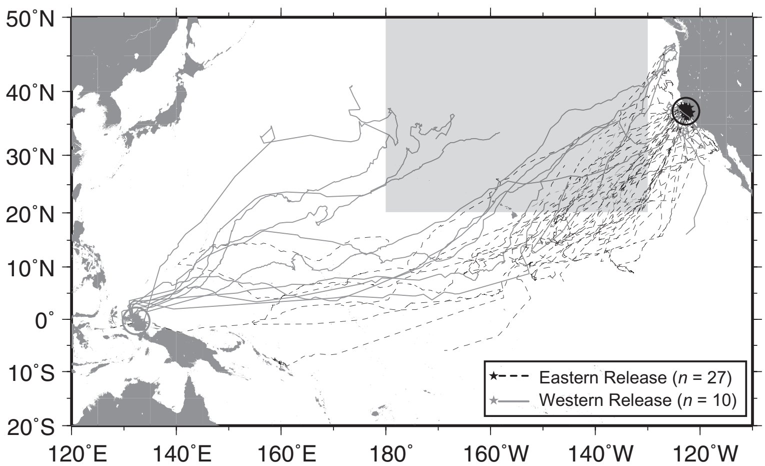
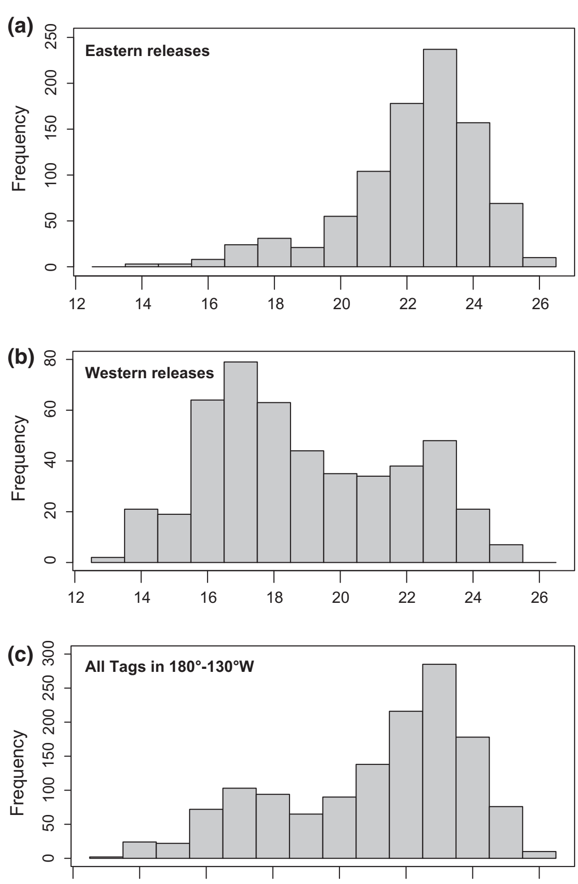


Figure 3. Tracks derived from satellite-tagged leatherback turtles in the Pacific Ocean (n = 37). Stars within larger circles indicate the first satellite track location with a location code in the range 0–3. The shaded area represents the area where >95% of the Hawaii-based pelagic longline fishery shallow-set effort occurred.

Figure 4. Sea surface temperature (SST) distributions for leatherback best daily locations closest to noon in the region 180°–130°W obtained from satellite tags for (a) leatherbacks released in the east Pacific migrating back-and-forth between California Current and Eastern Equatorial Pacific, (b) leatherbacks released in the west Pacific migrating through NPTZ (no data for return trips collected) and (c) all leatherbacks combined.



The placement of shallow sets and satellite-based leatherback positions gives the probable overlap of the shallow-set fishery and leatherbacks in time and space (Fig. 6a–d). In both the first (Jan–Mar) and fourth quarters (Oct–Dec) of the year the fishery places most of its effort in the NPSTFZ between 30°–40°N. When this effort is to the west of 140°W, it is within the leatherback migration pathway from the Kuroshio extension (where first-quarter effort occurs), and east of about 140°W it crosses into the migration pathway leading southwest from the western North American coastline (where some fourth-quarter effort occurs) (Fig. 6a,d). During the second quarter the fishery moves south out of the frontal zone, crossing the migration pathway from the North American coast (Fig. 6b). The third quarter is similar in effort placement to the second quarter (but slightly farther north), with less effort in this quarter during 2005–2011 (Fig. 6c).

Leatherback turtle interactions from 2011 (with brief fishery closure) and 2012 (test year) were separated into three zones identified as those with the highest probability of interactions based on the spatial patterns of tagged leatherbacks (east of 140°W, Table 1), and within SST ranges based on the current TurtleWatch SST range and the SST modes; 17°–18.5°C (62.6°–65.3°F) and 22.4°–23.4°C (72.3°–74.1°F), as identified in Figures 4c and 5a. Approximately 40% of the interactions within these three zones occurred in the 17°–18.5°C SST band representing the NPSFZ, whereas almost 15% of the interactions occurred in the spatial zone to the east of 140°W. The 22.4°–23.4°C SST band had a single interaction in both 2011 and 2012 (Table 1).

Shallow-set fishing statistics were calculated to understand possible effects of shifting fishing effort out of the three identified zones and to understand

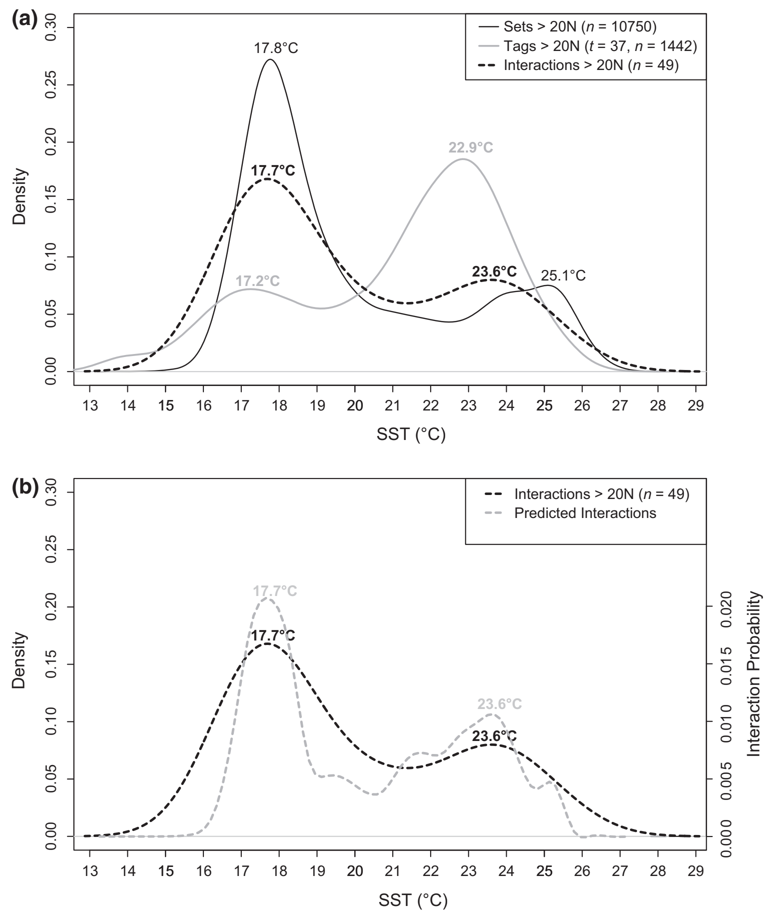


Figure 5. Kernel density estimates of the sea surface temperature (SST) north of 20°N for (a) shallow longline sets (n = 10 750), leatherback tag locations (37 tags, n = 1442) and leatherback interactions (n = 49) with the fishery; (b) kernel density estimate of SST for leatherback interactions (from panel a) and the interaction probability within SST space for leatherbacks calculated from the set and satellite tag location SST probability distributions in the region 180°–130°W.

how leatherback interactions were related to fishing effort (Table 2). In 2011 and 2012 approximately 15% of the shallow-set fishing effort was placed east of 140°W, resulting in roughly 14% of the total swordfish landed for these years. In both years, swordfish catch per unit effort (10^3 hooks) was lower east of 140°W than west of this latitude. Leatherback interaction rates were lower in the eastern area in 2012, but higher in 2011. A similar comparison for effort west of 140°W and within or outside the 17°–18.5°C SST band showed that swordfish catch rates and turtle interaction rates were higher within this SST band than outside the band. In contrast, swordfish catch rates were lower within the 22.4°–23.4°C SST band, whereas leatherback interaction rates were higher within this band compared with outside the band. These results were used to create the proposed updated TURTLEWATCH Version 2.0 product using the new and expanded SST bands as well as the area east of 140°W as areas of avoidance to assist in minimizing leatherback and loggerhead bycatch (Fig. 7).

DISCUSSION

Initial response to TurtleWatch

TurtleWatch has been well received by the scientific and management sectors since its release in 2006; however, informal feedback on its use and value varied from the fishing sector. During TurtleWatch presentations and outreach events, a subset of fishers reported favorably, whereas another subset reported that they had no awareness of the product. Specific feedback from all sectors included requests for increased distribution, language translation of the product to increase exposure and utility, as well as including information on predictions of presence of leatherback turtles. To address the first two concerns changes in the product and its distribution were made over time. TurtleWatch is currently distributed digitally via the internet, the TurtleWatch mailing list and by DigitalGlobe, a commercial vendor of digital imagery used by many vessel captains within the fishery. Additionally, English, Vietnamese and Korean versions are provided based on the demographic of the Hawaii-based pelagic

Figure 6. Fishery shallow-set locations (red circles) and leatherback satellite tag locations (grey tracks) over the combined temporal range available separated for (a) January–March, (b) April–June, (c) July–September and (d) October–December. Fishery information was re-gridded to 1°×1° squares and grid point locations with <3 vessels present were removed to avoid disclosure of confidential information.

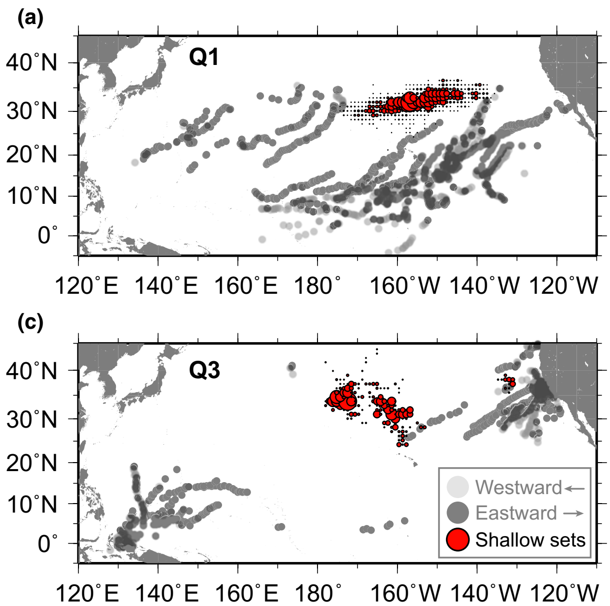


Table 1. Leatherback interactions in the shallow-set fishery within the individual and combined TurtleWatch zones for 2011 and 2012. Please note that spatial and environmental zones can overlap (e.g., 17°–18.5°C east of 140°W).

	LB interactions	
TurtleWatch zone avoided	2011	2012
Region east of 140°W (Z1)	3 (18.8%)	1 (12.5%)
17°–18.5°C Only (Z2)	6 (37.5%)	3 (37.5%)
22.4°–23.4°C Only (Z3)	1 (6%)	1 (12.5%)
East of 140°W, 17°–18.5°C (Z1, Z2)	8 (50%)	3 (37.5%)
East of 140°W, 17°–18.5° C, 22.4°–23.4°C (Z1, Z2, Z3)	9 (56.3%)	4 (50.0%)
Total	9 (56.3%)	4 (50.0%)

LB, leatherback.

swordfish fishery. The third concern has been addressed here by combining the fishery independent leatherback data from Benson *et al.* (2011) with the fishery information from federal logbooks. This allowed us to understand the fishery's behavior, leatherback turtle behavior, why interactions may occur and to evaluate how we could update the TurtleWatch product. Here we have provided this information as a dynamic management tool for endangered sea turtle species in the central North Pacific Ocean.

Changes in fishery behavior and effort patterns

There were apparent spatial and temporal changes in the effort of the Hawaii-based pelagic longline fishery during 2005–2012. The fishery increased effort in the east and in the fourth quarter over time. Personal communication with the industry has revealed that these shifts were in response to loggerhead interactions and the 2006 fishery closure. Historically, the shallow-set fishery targets swordfish from around October through to April in a progressively northeast to southwest diagonal pattern. This pattern follows the swordfish as they forage within the surface physical and biological fronts that move southward during this period (Seki *et al.*, 2002). The temporal shift may have been influenced by the interaction limits for loggerheads. An earlier start in the fall season can allow for more fishing in the east before the interaction tally resets to zero on January 1 of the following year. This shift in timing is also related to the shift in area, as the positions of the frontal systems earlier in the fall are further to the north than during later months. Additionally the relationship between the physical and biological fronts is different further to the east, especially east of the 140°–150°W region (Bograd *et al.*, 2004). These changes in fishery behavior were based on information provided on loggerhead turtles; however, the data

Table 2. Comparisons of swordfish catch (number of fish), shallow-set effort (number of hooks) and swordfish catch per unit effort (CPUE) (catch per 1000 hooks), and leatherback interaction rate within and outside the TurtleWatch zones for 2011 and 2012.

	Swordfish catch		Swordfish effort		Catch/1000 hooks		Interactions/ 1000 hooks	
Zone fished	2011	2012	2011	2012	2011	2012	2011	2012
Region east of 140°W (Z1)	2159 (12.7%)	2468 (16.7%)	216 685 (14.4%)	263 802 (18.0%)	10	9.4	0.014	0.004
Entire region west of 140°W	14 892 (87.3%)	12 276 (83.3%)	1 288 782 (85.6%)	1 204 637 (82.0%)	11.6	10.2	0.010	0.006
West of 140°W, 17.0°–18.5°C	6117 (41.1%)	3926 (32.0%)	471 378 (36.6%)	374 014 (31.0%)	13	10.5	0.013	0.008
West of 140°W, <17.0°C or > 18.5°C	8775 (58.9%)	8350 (68.0%)	817 404 (63.4%)	830 623 (69.0%)	10.7	10.1	0.009	0.005
West of 140°W, 22.4°–23.4°C	658 (4.4%)	594 (4.8%)	72 274 (5.6%)	69 851 (5.8%)	9.1	8.5	0.014	0.014
West of 140°W, <22.4°C or > 23.4°C	14 234 (95.6%)	11 682 (95.2%)	1 216 508 (94.4%)	1 134 786 (94.2%)	11.7	10.3	0.010	0.005

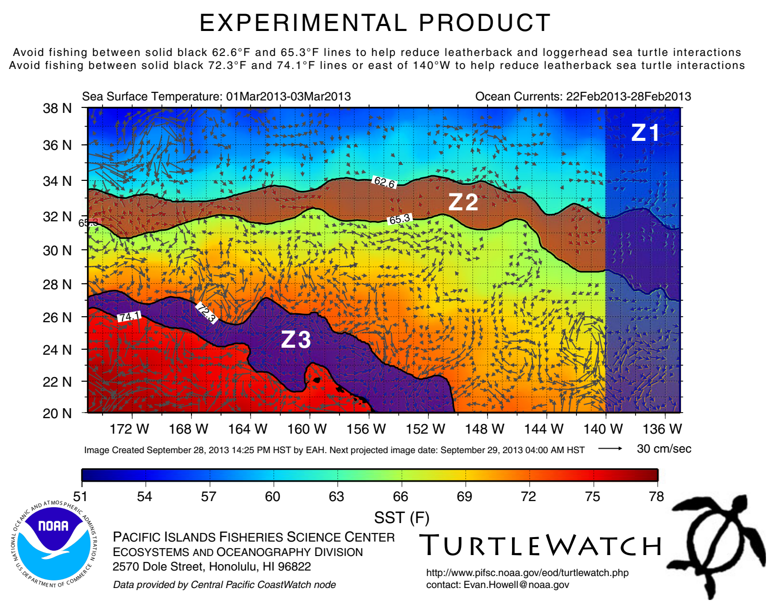


Figure 7. The updated TurtleWatch (Version 2.0) image including the SST zones identified as higher probability regions of interactions for leatherback turtles. The solid blue area represents Z1, the area east of 140°W where shallow-set fishing is not recommended to help in avoiding leatherback turtle interactions. The translucent red band identifies Z2, the 62.6°–65.3°F (17°–18.5°C) sea surface temperature (SST) region to avoid setting shallow gear to help avoid interactions with loggerhead and leatherback turtles. The translucent blue band identifies Z3, the 72.3°–74.1°F (22.4°–23.4°C) SST region to avoid setting shallow gear to help avoid interactions with leatherback turtles.

suggests interactions with leatherbacks increased after effort was shifted in time and space.

Habitat overlap as a cause for fishery interactions

The main cause for interactions between leatherback turtles and the Hawaii-based longline fishery is the overlap between habitat of the turtles and the habitat of swordfish that the fishery targets, which can be observed by the distribution of shallow sets and satellite-based leatherback positions. This overlap and associated risk for bycatch of leatherback turtles in the central Pacific was predicted by a previous study looking at the spatial overlap between these turtles and the longline fishery (Roe *et al.*, 2014). These data provide a qualitative view of why interactions may occur in time and space, yet there may be differences in habitat use by leatherbacks between the eastern and western sections of the fishing grounds. West of 140°W, both swordfish and leatherbacks use the productive NPSTFZ system as a migration pathway but also as an important forage area. Leatherbacks forage on up to 60–120 kg per day

(Jones *et al.*, 2012) of primarily gelatinous zooplankton (Jones and Seminoff, 2013), including salps and jellies that are prevalent within the convergent surface frontal zones in the NPSTFZ system. Swordfish are considered opportunistic foragers, but diet studies have shown a predilection for squid such as the neon flying squid *Ommastrephes bartramii*, especially during the winter months (Seki *et al.*, 2002). The winter–spring cohort of the neon flying squid forages in the productive NPSTFZ during winter, moving south in spring to spawn in warmer waters north of Hawaii (Ichii *et al.*, 2009). Therefore in winter months there is direct habitat overlap between the fishery targeting swordfish and leatherbacks based on forage grounds. To the east of 140°W more of the habitat overlap appears to be based on the crossover between the fishery and the southwestern migration pathway used by leatherbacks departing foraging grounds in the Eastern Pacific (Benson *et al.*, 2011).

While the leatherback's use of space may differ in the Hawaii longline fishing grounds, their SST habitat ranges through this area were consistent. The ability to model the probability of leatherback-fishery interactions through the SST distribution from the fishery and satellite tag data provides confidence that the SST range where fishing effort occurs is important in determining whether interactions may occur. This new information was used to refine the TurtleWatch product to include information on leatherback preferential habitat based on SST. It is interesting to note that the identified thermal habitat for leatherbacks overlaps with loggerhead turtles within the 17.0°–18.5°C SST range over a large area of the fishing grounds. This is to be expected, as both turtle species use the fronts within the fishing grounds for forage and migration (Polovina *et al.*, 2001, 2004), yet there are differences in prey type and dive behavior that might cause a slight geographic separation at times (Polovina *et al.*, 2003; Parker *et al.*, 2005). For example the habitat overlap is less apparent east of 140°W, as the physical and biological fronts in the NPSTFZ begin to spatially separate owing to spatial changes in the wind field (Bograd *et al.*, 2004). In this region east of 140°W leatherbacks stay within the biological Transition Zone Chlorophyll Front (TZCF) associated with the colder region of the 17°–18.5°C band, whereas loggerheads more closely follow the thermal fronts. This relationship still allows for the consistent use of these SST ranges to inform the TurtleWatch product, but attention must be paid to this eastern region over time as more information becomes available to understand the strength of these relationships. Future research that provides more tracking information on the eastward movement of turtles through the Kuroshio and North Pacific current towards the western US coast would help understand how habitat envelopes may change for these two turtle species in this eastern region. Regardless, this possible change in information for habitat east of 140°W does not negatively impact the use of TurtleWatch as a dynamic management tool, as we recommend that shallow-set fishing occurs west of the 140°W line.

Implications for the Hawaii-based shallow-set longline fishery

Analysis of additional data on fishery effort and leatherback behavior has allowed for an update of the TurtleWatch product to include habitat information for leatherbacks. This new information can help minimize leatherback interactions with the Hawaii-based pelagic longline fishery targeting swordfish with shallow sets. Based on the results presented here, updated information to managers and the industry should include both a static geographic measure, as well as two dynamic measures based on SST habitat (Fig. 7). The three proposed recommendations are as follows:

(1) A static boundary to restrict fishing effort to waters west of 140°W in the first and fourth quarters of the year
(2) A dynamic boundary to avoid fishing effort in the SST range 17°–18.5°C to minimize interactions with both loggerheads and leatherbacks
(3) A dynamic boundary to avoid fishing effort in the SST range 22.4°–23.4°C

By applying these rules to historical data, it is estimated that the fishery could have avoided more than 50% of turtle interactions. Expansion of the dynamic SST zone is consistent with the original TurtleWatch advisory (Howell *et al.*, 2008) and should further aid in minimizing interactions with loggerheads as well as leatherback turtles.

With any change in fishing behavior there may be consequential changes in the catch rates of swordfish, the primary target for the shallow-set fishery. This study suggests, however, that there should not be a reduction of swordfish catch rates if the fleet follows the TurtleWatch recommended areas of avoidance, as catch rates for swordfish in these regions are actually lower than in other regions of the fishery. In addition, the blue shark bycatch rate appears to be higher in the region east of 140°W (not shown). Lower catch rates for swordfish combined with an increased likelihood of blue shark catches and interactions with leatherback turtles provide a solid rationale for avoiding the region to the east of 140°W.

TurtleWatch as a 'dynamic management tool' for ecosystem-based management

The TurtleWatch product provides near real-time habitat information for two endangered sea turtle species in the North Pacific Ocean. This gives managers the ability to track habitat changes over time and make management decisions or issue advisories in this distant and expansive pelagic ecosystem. The management of these dynamic systems using information that follows environmental change and species habitat through time can provide refined information to identify potential interaction zones in shared use areas (Howell *et al.*, 2008; Hobday *et al.*, 2010; Zydelis *et al.*, 2011). This management style also addresses the short comings of the traditional place-based management strategies based on fishing effort restriction, which may not be as effective in mitigating interactions with species of interest and may come at an increased ecological and financial cost to the ecosystem and society (Game *et al.*, 2009; Li and Pan, 2011). Looking beyond TurtleWatch, application of dynamic management approaches in a region such as the NPSTFZ may have potential for reducing interactions with many species of interest that use this dynamic, productive system. These could include marine mammals, sea birds, and other species that occupy this region and encounter the fisheries operating there (Seki *et al.*, 2002; Howell *et al.*, 2008; Kappes *et al.*, 2010; Robinson *et al.*, 2012). A movement towards this type of management model would be a step forward towards ecosystem-based management (Ruckelshaus *et al.*, 2008).

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