Integrating Environmental, Fisheries, and Electronic Tag Data to Characterize Essential Sea Turtle Habitat in Areas of Significant Bycatch (NNH07AF70I)

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Executive Summary

NOAA Fisheries is mandated under the Endangered Species Act to protect threatened and endangered species from adverse fisheries interactions. Among the more serious conservation issues faced by NOAA Fisheries is the bycatch of the threatened loggerhead (*Caretta caretta*) and endangered leatherback (*Dermochelys coriacea*) sea turtles within longline fisheries in the central North Pacific and in multiple fisheries in the northwest Atlantic Ocean. This project will integrate data from a suite of satellite sensors, electronic tags, fishery observer logs, and high-resolution coupled physical-biological models to quantitatively characterize critical sea turtle habitat in a variety of oceanic environments managed by NOAA Fisheries. The end product will be a decision support tool that forecasts the likelihood of sea turtle-fishery interactions in near-real-time, which can be used by NOAA Fisheries to minimize sea turtle bycatch and reduce the time-area closures of pelagic longline fisheries.

Project Approach

During the first year of the project, scientists from the three collaborating NMFS science centers (and academic partners) focused on integrating the relevant biological and physical data sources, and began the task of regional analyses in the eastern Pacific (SWFSC), central North Pacific (PIFSC), and northwest Atlantic (NEFSC). During the second year of the project, detailed analyses to describe turtle habitat associations in each target region were performed. The general approach of each project component was to use existing data on sea turtle distributions, movements and bycatch, in combination with NASA earth observations and model output, to characterize the preferred habitat of threatened loggerhead turtles (*Caretta caretta*) in the Northwest Atlantic and central North Pacific and endangered leatherback turtles (*Dermochelys coriacea*) in the eastern Pacific. Results from these studies are being used in different capacities to forecast the likelihood of sea turtle-fishery interactions in various parts of the world ocean. Details of the data used, methods applied, and results achieved are provided in separate reports from each project component on the following pages.

Project Outcomes & Deliverables

This project partly or wholly supported a number of products and deliverables, including decision support tools for use in managing threatened and endangered sea turtles.

Peer-Reviewed Publications

(1) Bailey, H.R., G.L. Shillinger, D.M. Palacios, S.J. Bograd, J.R. Spotila, B. Wallace, F.V. Paladino, S.A. Eckert, and B.A. Block, 2008. Identifying and comparing phases of movement by leatherback turtles using state-space models, *Journal of Experimental Marine Biology and Ecology*, 356, 128-135.

(2) Howell E.A., D.R. Kobayashi, D.M. Parker, G.H. Balazs, and J.J. Polovina, 2008. TurtleWatch: A tool to aid in the bycatch reduction of loggerhead turtles (*Caretta caretta*) in the Hawaii-based longline fishery. *Endangered Species Research*, 5: 267-278.

(3) Howell E.A., P.H. Dutton, J.J. Polovina, H. Bailey, D. M. Parker and G.H. Balazs, 2010. Oceanographic influences on the dive behavior of juvenile loggerhead turtles (Caretta caretta) in the North Pacific Ocean. *Marine Biology*. doi:10.1007/s00227-009-1381-0.

(4) Shillinger, G.L., D.M. Palacios, H.R. Bailey, S.J. Bograd, A. Swithenbank, P. Gaspar, B. Wallace, J.R. Spotila, F.V. Paladino, R. Piedra, S.A. Eckert, and B.A. Block, 2008. Persistent leatherback turtle migrations present opportunities for conservation, *PLoS Biology*, *6(7)*, e171, doi:10.1371/journal.pbio.0060171.

(5) Shillinger, G.L., A Swithenback, S.J. Bograd, H.R. Bailey, M. Castleton, B. Wallace, J.R. Spotila, F.V. Paladino, R. Piedra, and B.A. Block, 2010. Environmental variability affects behavior of internesting leatherback turtles in the eastern Pacific: Implications for conservation, *Endangered Species Research*, in press.

Publications in Preparation

(1) Bailey, H.R., G.L. Shillinger, S.J. Bograd, D. Fossette, P. Gaspar, and G. Hays, 2010. A comparison of leatherback turtle habitat use in the western Atlantic and eastern Pacific, *Deep-Sea Research*, in prep.

(2) Shillinger, G.L., H.R. Bailey, S.J. Bograd, A. Swithenbank, J.R. Spotila, F.V. Paladino, R. Piedra, and B.A. Block, 2010. Movements, behaviors and habitat use of eastern Pacific leatherback turtles within postnesting migration and foraging habitats, *Ecological Applications*, in prep.

Student Training

(1) Howell, E.A., 2009. Satellite-based horizontal and vertical habitat estimation for loggerhead turtles (*Caretta caretta*) and bigeye tuna (*Thunnus obesus*) in the North Pacific Ocean. PhD Dissertation, Hokkaido Unversity, 157 pp.

(2) Shillinger, G.L., 2009. Satellite tracking reveals movement, behaviou, and distribution of endangered leatherback turtles in the eastern tropical and southeastern Pacific: Implications for conservation. *PhD dissertation*, Stanford University, 150 pp.

Management Tools

(1) TurtleWatch Product: http://www.pifsc.noaa.gov/eod/turtlewatch.php

TurtleWatch is a map providing up-to-date information about the thermal habitat of loggerhead sea turtles in the Pacific Ocean north of the Hawaiian Islands. It was created as an experimental product by the PIFSC Ecosystem and Oceanography Division to help reduce inadvertent interactions between Hawaii-based longline fishing vessels and loggerhead turtles. Derived from the best available scientific information, the TurtleWatch map displays sea surface temperature and ocean current conditions and the predicted location of waters preferred by the turtles.

(2) International Union for Conservation of Nature (IUCN) resolution on protection of the migratory pathway of eastern Pacific leatherback turtles.

During the 2008 IUCN World Congress, as a result of the Shillinger et al. (2008) publication in *PloS Biology*, IUCN delegates unanimously approved a resolution endorsing the formal creation of a 'high-seas migration corridor' that will potentially span the leatherback migration pathway (PNMB past the Galapagos Islands).

(3) Thermal habitat envelopes for Atlantic and Pacific loggerhead turtles and eastern Pacific leatherback turtles.

Synthesis of the individual components of this project have revealed that satellite-derived SST can be used to characterize critical habitat of two distinct sea turtle species in vastly different oceanic regions. This information is currently being actively used by the NMFS Pacific Islands Fisheries Science Center to reduce potential bycatch in the Hawaii longline fishery (TurtleWatch). These results are also being used to investigate and improve upon a Decision Support Tool that seeks to close the drift gillnet fishery in southern California during warm ocean events (e.g. El Niño). Preliminary information from the Atlantic also demonstrates a thermal association with loggerhead bycatch occurrences, and will be used to advise the commercial gillnet and bottom trawl fisheries on the temperature ranges associated with loggerhead bycatch.

SWFSC REPORT

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OBJECTIVES

- Improve position estimates from satellite telemetry data by accounting for measurement error.
- Infer turtle behavior from horizontal movements, which may affect susceptibility to fisheries interactions.
- Determine influence of environment on turtle movements using remote sensing satellite data

DATA SOURCES

- Satellite telemetry data from 46 female leatherback turtles nesting in Playa Grande, Costa Rica.
- Satellite altimeter measurements of absolute dynamic topography and associated sea level anomalies distributed by the Archiving, Validation, and Interpretation of Satellite Oceanographic data (Aviso) project at 1/3° resolution were used to calculate mean kinetic energy. Eddy kinetic energy was calculated as a long-term mean for 1992-2007 from the mean geostrophic velocity anomalies.
- Near-surface chlorophyll-*a* concentration (CHL), a proxy for phytoplankton standing stock, was obtained from Sea-viewing Wide Field-of-view Sensor (SeaWiFS) satellite ocean-color observations at 9-km resolution.
- Bathymetry was extracted from the global sea-floor topography of Smith and Sandwell, version 8.2 (November 2000) (http://topex.ucsd.edu/WWW_html/mar_topo.html). This data set combines all available depth soundings with high-resolution marine gravity information provided by the Geosat, ERS-1/2, and TOPEX/Poseidon satellite altimeters, and has a nominal resolution of 2 arc minutes (~4 km).
- Data on Earth's magnetic field (force and inclination) in the study area were calculated using the software GeoMag 6.0, available from the NOAA National Geophysical Data Center (http://www.ngdc.noaa.gov/seg/geom_util/geomutil.shtml), and the most recent (2005) International Geomagnetic Reference Field 10th generation (IGRF-10) coefficients.

MILESTONES

Year 1

1) State-space models of leatherback turtle movements.

Bayesian state-space models were applied to the turtle satellite telemetry data to simultaneously account for measurement error in the positions and variability in the movement dynamics. This improved the position estimates and allowed the behaviors internesting, migrating and foraging to be differentiated (Figure 1). These results were published in a peer-reviewed journal in 2008.

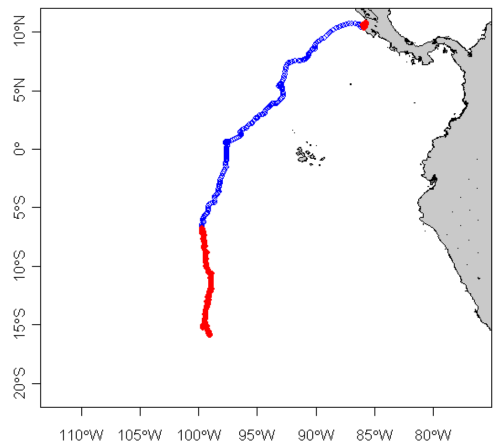

Figure 1: State-space model position estimates for a track with three behavioural phases. From Bailey, H., Shillinger, G., Palacios, D., Bograd, S., Spotila, J., Paladino, F. and Block B. (2008) Identifying and comparing phases of movement by leatherback turtles using state-space models. *Journal of Experimental Marine Biology and Ecology*, 356: 128-135.

2) Post-nesting migration of leatherback turtles in the eastern Pacific.

After completing nesting, the turtles migrated southward, traversing the dynamic equatorial currents with rapid, directed movements. After passing through this equatorial current field, turtles dispersed broadly within a low-energy, low-productivity region of the South Pacific (Figure 2). Our analyses revealed that ocean currents shaped this migration and influenced the breadth of turtle dispersal in the South Pacific. Real-time information on these ocean currents during the turtles' early migration in February to April could therefore allow predictions to be made of their movement patterns. This provides an opportunity for developing conservation strategies, such as dynamic time-area fisheries closures and increased monitoring and enforcement within existing Marine Protected Areas in the region. These results were published in a peer-reviewed journal in 2008.

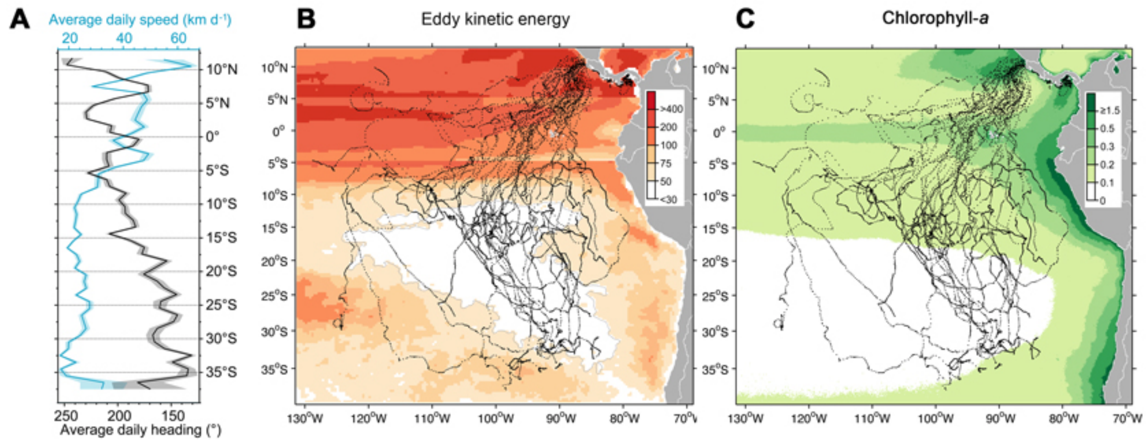

Figure 2: Large-scale oceanographic characteristics and leatherback movements in the Eastern Pacific. (A) Turtle median daily speed (blue line) and heading (black line), with corresponding standard-error envelopes, averaged in one-degree latitudinal bins, (B) Eddy kinetic energy ($cm^2\ s^{-2}$), (C) Near-surface chlorophyll-a concentration ($mg\ m^{-3}$). From Shillinger, G, Palacios, D., Bailey, H., Bograd, S., Swithenbank, A., Gaspar, P., Wallace, B., Spotila, J., Paladino, F., Piedra, R., Eckert, S. and Block, B. Persistent leatherback turtle migrations present opportunities for conservation, *PLoS Biology*, 6(7), 2008..

Year 2

3) Characterization of leatherback turtle internesting habitat in the eastern Pacific.

We characterized the interannual variability of high-use internesting habitats utilized by 44 (from 46 total) female leatherback turtles satellite-tagged at Playa Grande, Costa Rica during 2004 to 2007. A total of 1135 days of internesting movements were recorded across three tracking years. The core 25% utilization distribution (UD) remained predominantly centered within the marine protected area, Parque Nacional Marino Las Baulas (PNMB; Figure 3). The turtles generally dispersed in a northward or southward direction over the shallow continental shelf framing Costa Rica's Nicoya Peninsula. However, there was considerable interannual variation in the shape and area of the larger UD polygons, driven by variability in the thermal environment. The maximum swimming speeds and distance traveled from the nesting beach occurred during 2007. Significantly deeper and longer dive durations to cooler temperatures also occurred in this year, which may have been in response to the warming trend from the south driven by the strong Costa Rica Coastal Current. Our findings therefore validate the importance of PNMB as a critical habitat for internesting leatherbacks, but also suggest that a latitudinal expansion of the Park is warranted. These results will be published in a peer-reviewed journal in 2010.

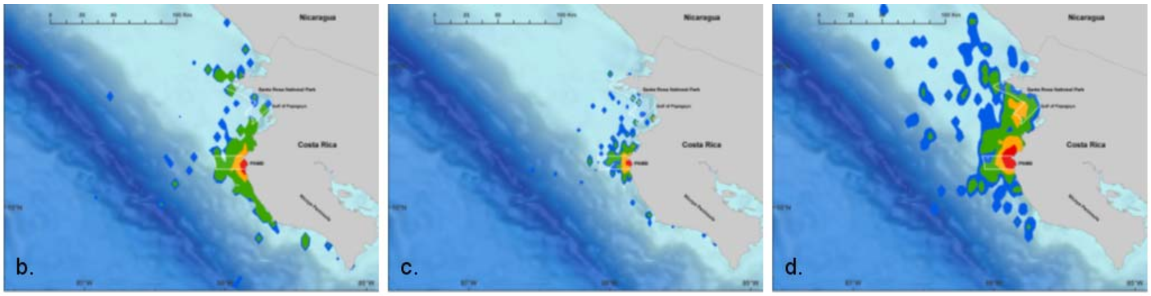

Figure 3: Utilization distribution (UD) maps of internesting region occupied by 44 leatherback turtles during (b) 2004, (c) 2005, and (d) 2007.

4) Post-nesting habitat use of leatherback turtles in the eastern Pacific.

We used the switches in behavior identified from the state-space model applied to the turtle tracks to define the postnesting period and distinguish between the initial migration and subsequent foraging phase. This has provided the first insight into postnesting movements of leatherback turtles in the eastern Pacific over multiple years and for large sample sizes. This has enabled us to identify changes in the diving behavior and movement rate as they move through a migration corridor into putative foraging grounds in the South Pacific. These changes suggest the turtles maximize swimming efficiency with short, shallow dives during migration through an area of strong zonal currents followed by deeper, longer dives that may indicate searching for prey in the South Pacific Gyre.

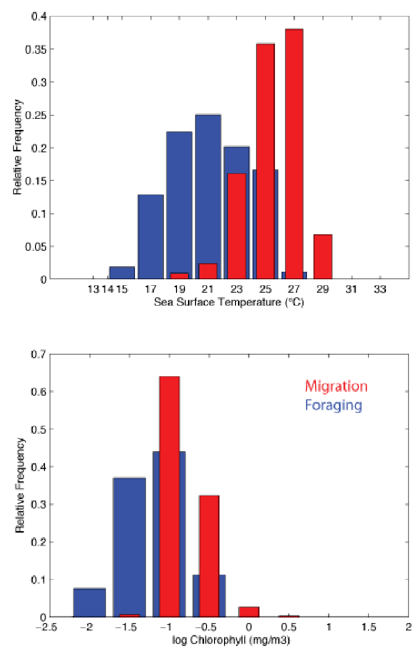

Figure 4: Histograms depicting the relative frequency of satellite-derived SST and surface chlorophyll values associated with state space switching model interpolated positions during the migration (red) and foraging (blue) movement phases.

We applied a generalized additive model (GAM) to identify the environmental factors, based on satellite-derived data, that were related to turtle speed. Higher turtle speeds were generally associated with warmer sea surface temperatures (SSTs) and the mid-range of chlorophyll *a* concentration (CHL; ~-0.55 mg m^3) as well as enhanced mesoscale activity, indicated by higher sea surface height root mean square (SSHRMS) and frontal probability index (FPI). However, each of these relationships was non-linear, revealing a dynamic and complex association between turtle behavior and oceanography.

The southern terminus, 35-37°S had high mesoscale activity that may act as a physical mechanism to aggregate their prey, gelatinous zooplankton, but may also act as a thermal limit to their distribution. Although there have been management efforts to protect the leatherback turtles on and near the nesting beach, much less has been done to protect them on the high seas. These insights into leatherback turtle postnesting habitat will inform the potential development of a pelagic protected area in the Southeast Pacific Ocean.

5) Atlantic-Pacific comparison of leatherback turtle habitat

The satellite tracks of postnesting leatherback turtles in the eastern Pacific and north Atlantic oceans were compared to further understand the factors affecting their movement and possible reasons for the dramatic population decline in the eastern Pacific. A switching state-space model was applied to the turtle tracks so that the location of foraging could be determined. This was then used as the response variable in a generalized linear mixed effects model, with satellite-derived oceanographic explanatory variables. In both populations, more foraging occurred where there were lower sea surface temperatures and higher frontal probabilities. In the north Atlantic more foraging occurred where there were higher chlorophyll a concentrations and lower sea surface height anomalies, whereas the reverse was found for the turtles in the east Pacific. Turtles in the eastern Pacific may have to search for food over larger areas and for longer periods, which may explain their long interval between nesting events and population decline.

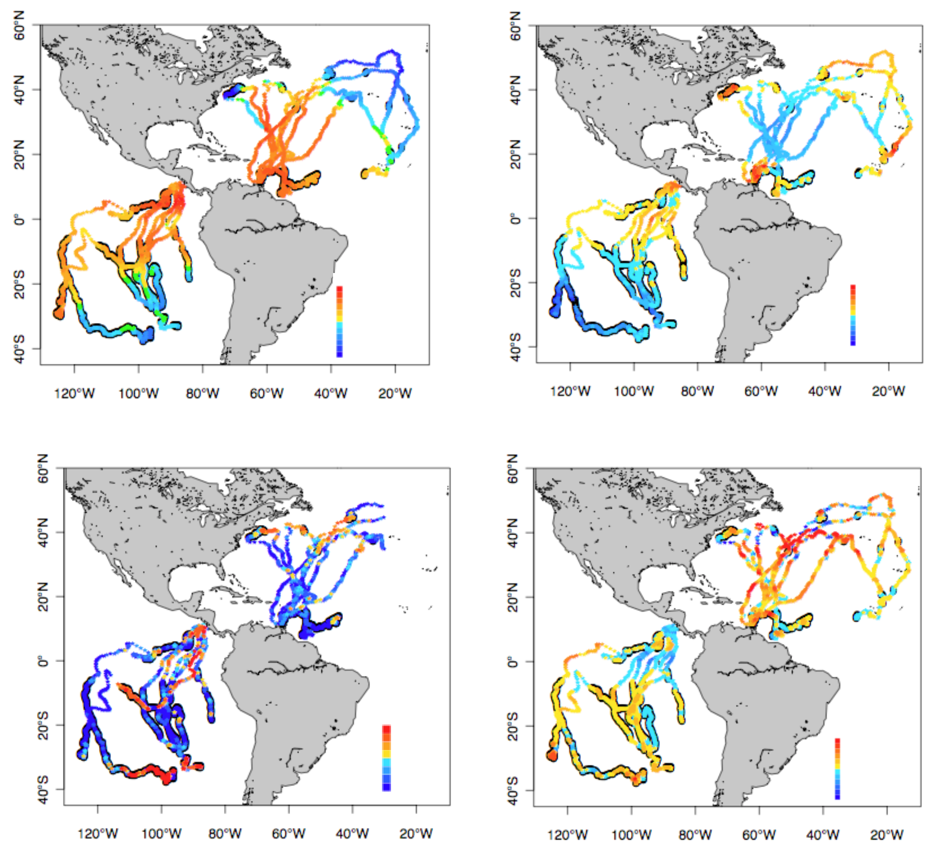

Figure 5: Oceanographic conditions (SST, CHL, FPI, SSHA) for each turtle position. Black outline around track indicates where turtles were foraging.

PIFSC REPORT

PIFSC point of contact: Evan Howell, (808) 983-5306, evan.howell@noaa.gov

OBJECTIVES

- Improve understanding of the critical thermal habitat of juvenile loggerhead turtles in the Central North Pacific Ocean.
- Locate the areas where the highest incidental loggerhead turtle bycatch by the Hawaii-based longline fisheries occurred in previous years.
- Create a near-real time bycatch avoidance map (TurtleWatch) based on the temperature range where the areas of highest loggerhead bycatch have occurred.
- Provide this avoidance map to individuals in management and the fishing industry to attempt to minimize the bycatch of loggerhead turtles.
- Analyze the results of the following fishing season to assess the results of this bycatch avoidance product.
- Analyze dive behavior patterns from satellite tags affixed to juvenile loggerheads and their relation to oceanographic features.
- Attempt to improve TurtleWatch product with information from dive behavior results.
- Translate TurtleWatch product into the Vietnamese language.

DATA SOURCES

- Satellite telemetry data from 105 juvenile loggerhead turtles was used that were either raised in captivity or taken as bycatch by the Hawaii-based longline fishery.
- Sea-surface temperature (SST) from the NOAA/NASA AVHRR Pathfinder climatological data record was matched to the locations of loggerhead turtle bycatch positions to provide information on the thermal range where loggerhead turtle bycatch occurred. This data was provided by NASA's JPL PODAAC website.
- Sea-surface temperature data from the Advanced Very High Resolution Radiometer (AVHRR) - Global Area Coverage (GAC) dataset provided by NESDIS were used to create 3-day composite images for the Central North Pacific which was used in the final TurtleWatch product.
- Sea surface height (SSH) data from the TOPEX/POSEIDEN and JASON-1 altimeters provided by AVISO/JPL were used in combination with the 1994 NODC World Ocean Atlas Levitus long-term mean 1000-m dynamic height dataset to derive the geostrophic current components. These currents were added as an overlay on the final TurtleWatch product.
- Satelite telemetry data including geolocation as well as the frequency data of the number of dives, duration of dives, and time at depth for 17 juvenile loggerheads taken as bycatch by the California-based longline fishery.
- Delayed-mode ARGO profiling float subsurface temperature data.
- In-situ subsurface temperature data from two oceanic transects.

MILESTONES

Year 1

Analysis of the fishery dependent (bycatch) and independent (satellite telemetry) data showed that the majority of shallow longline sets and associated loggerhead turtle bycatch were in the first quarter of the calendar year above 28°N, which corresponds to the area near the North Pacific Subtropical Frontal Zone. Based on the thermal ranges of bycatch, shallow sets targeting swordfish and the satellite-tagged turtles, it was recommended that the deployment of future shallow sets be in waters warmer than 18.5ºC (~65.5ºF) isotherm to decrease loggerhead turtle bycatch. These results were published in July 2008 in a special issue of the peer-reviewed journal Endangered Species Research covering problems and solutions of fisheries bycatch. This recommendation, the basis for the TurtleWatch product, was released to fishers and managers in electronic and paper formats to assist in decision-making during the first quarter of 2007.

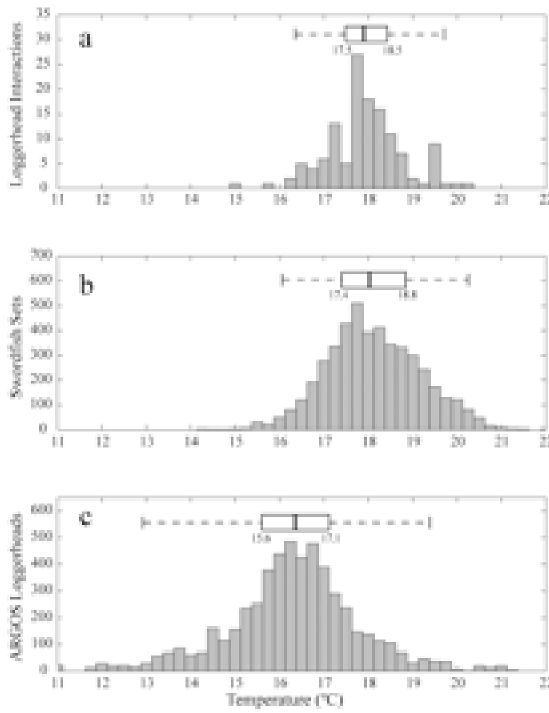

Figure 1. Frequency distributions of sea surface temperature associated with positions of (a) loggerhead turtle interactions, (b) shallow sets deployed and (c) loggerhead turtle positions recorded tags. The annotated numbers represent the SST values corresponding to the 25th and 75th percentiles of the distribution.

Fishery information from 2007 was later compared with data in the years 2005–2006 to assess the response of the fishery to TurtleWatch. The observed fleet movement during the first quarter of 2007 was to the north of the 18.5ºC (~65.5ºF) isotherm, (in the area recommended for avoidance by the TurtleWatch product) with increased effort and lower bycatch rates. This 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). The 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 and/or changes in turtle dive behavior based on SST values.

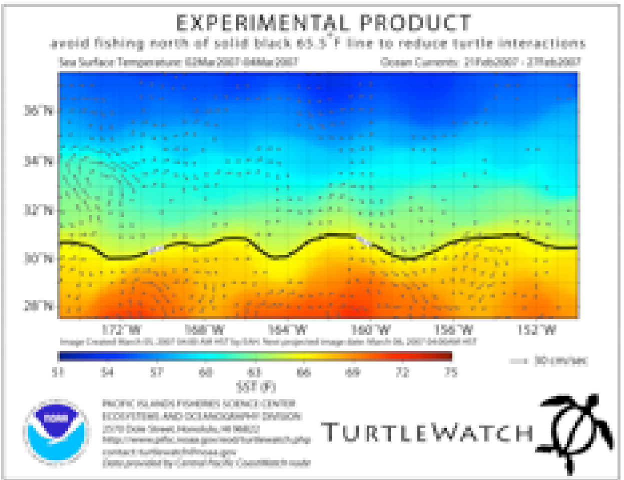

Figure 2. The TurtleWatch product. The pseudo-color image represents the SST field. Grey arrows represent the magnitude and direction of the geostrophic currents derived from altimetry data. The black line represents the 65.5ºF (~ 18.5ºC) surface isotherm.

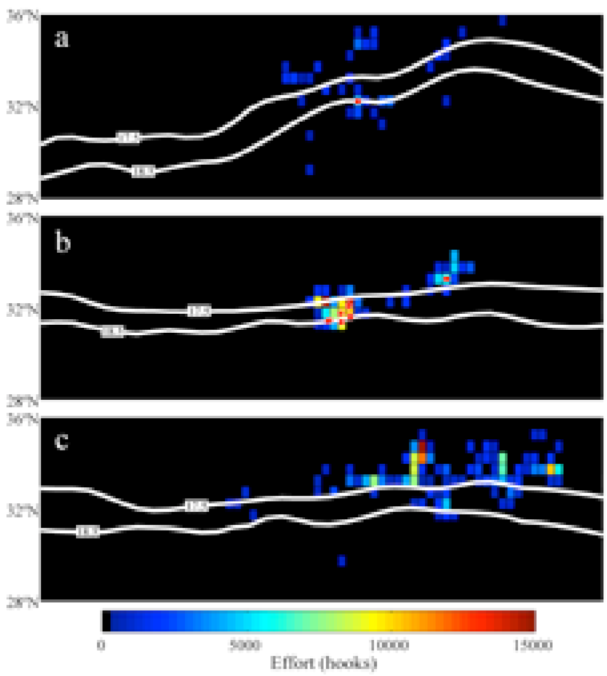

Figure 3. The spatial position of shallow sets (pseudo-color blocks) and loggerhead turtle interactions (red circles) for January (a) 2005, (b) 2006 and (c) 2007. The white lines represent the average monthly position of the 17.5ºC and 18.5ºC isotherms for each January. Longitude values have been removed because of fishery confidentiality requirements of the data.

Year 2

The TurtleWatch product was translated into Vietnamese at the start of year two. Both the English and Vietnamese versions were released daily to the Hawaii-based longline fishers. Additionally, based on the results from year one the TurtleWatch product was modified to recommend not setting gear within the thermal range 17.5º-18.5ºC which showed the highest probability of interactions between loggerheads and the fishery (Fig. 4).

Satellite telemetry dive data from 17 juvenile loggerhead turtles showed that turtles spent more than 80% of their time at depths < 5 m, and more than 90% of their time at depths < 15 m. Multivariate classifications of dive data revealed four major dive types, three representing deeper, longer dives, and one representing shallower dives shorter in duration.

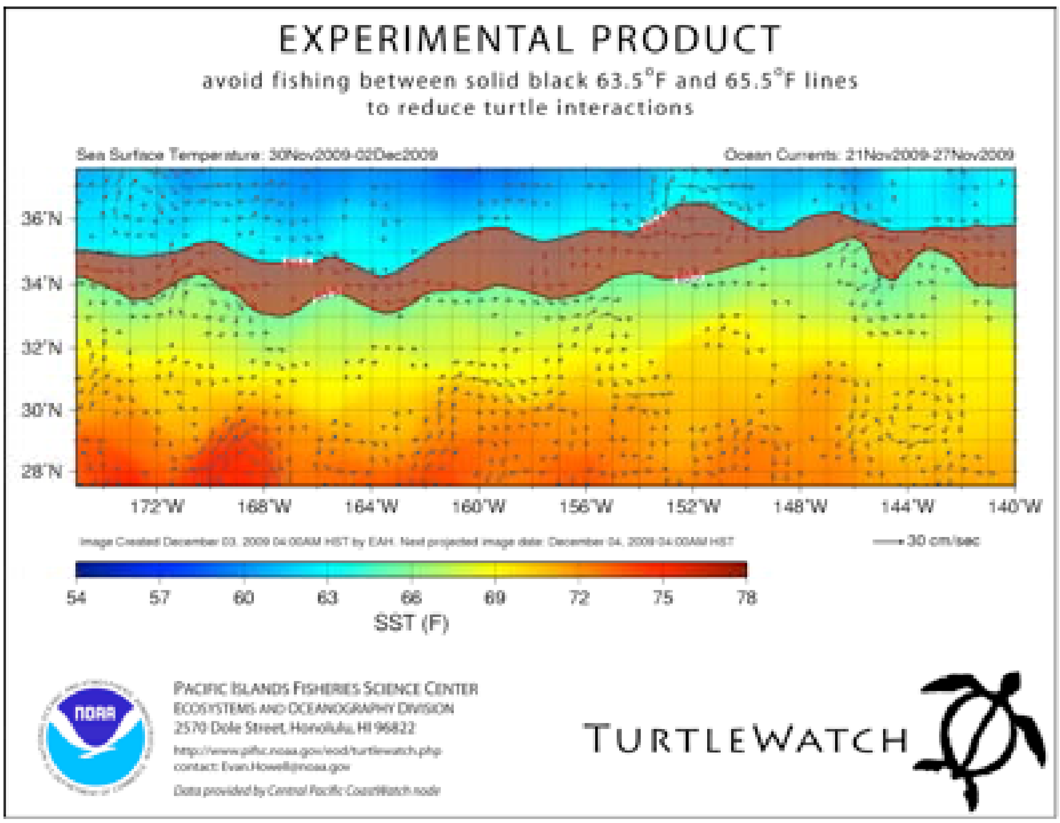

Figure 4. The current TurtleWatch product. The pseudo-color image represents the SST field. Grey arrows represent the magnitude and direction of the geostrophic currents derived from altimetry data. The black lines represents the 63.5ºF and 65.5ºF (~ 17.5ºC and ~ 18.5ºC) surface isotherms.

Turtles also exhibited variability in these dive types across oceanographic regions, with deeper, longer dives in the Hawaii longline swordfish fishing grounds during the first quarter of the year as well as in the Kuroshio Extension Bifurcation Region. Turtles in the central North Pacific exhibited seasonality in dive behavior that appeared to reflect synchronous latitudinal movements with the North Pacific Subtropical Front and the associated seasonal, large-scale oceanography (Fig. 6). Turtles made deeper, longer dives during the first quarter of the year within this region, the reported time and area where the highest loggerhead bycatch occurs by the longline fishery. These results represent the first comprehensive study of dive data for this species in this region. The increased understanding of juvenile loggerhead dive behavior and the influences of oceanography on dive variability should provide further insight into why interactions with longline fisheries occur and suggest methods for reducing the bycatch of this threatened species.

The dive data results from year two were accepted in manuscript form by Marine Biology in October 2009.

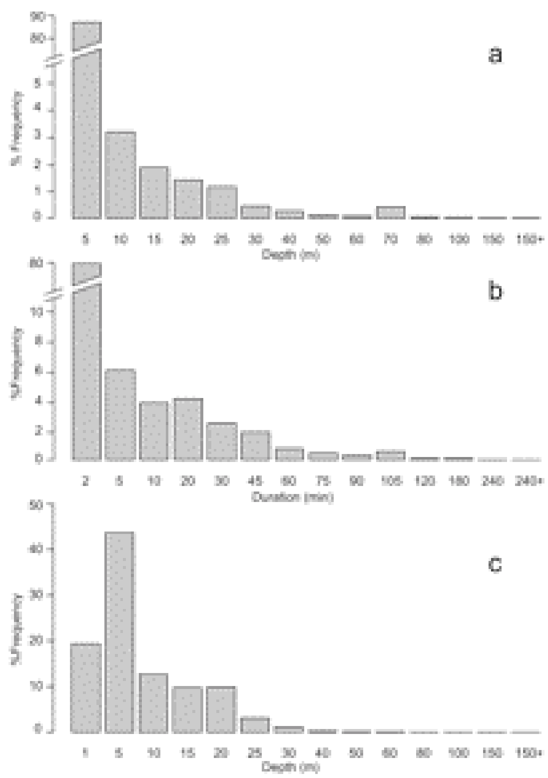

Figure 5. Frequency distributions of (a) dive depth (in discrete bins) and (b) dive duration collected from 17 SDR tags deployed on juvenile loggerhead turtles in the central North Pacific from 2002 to 2005. Frequency distribution of (c) the time-at-depth for 14 SDR-16 tags deployed on juvenile loggerhead turtles in the central North Pacific from 2003-2005.

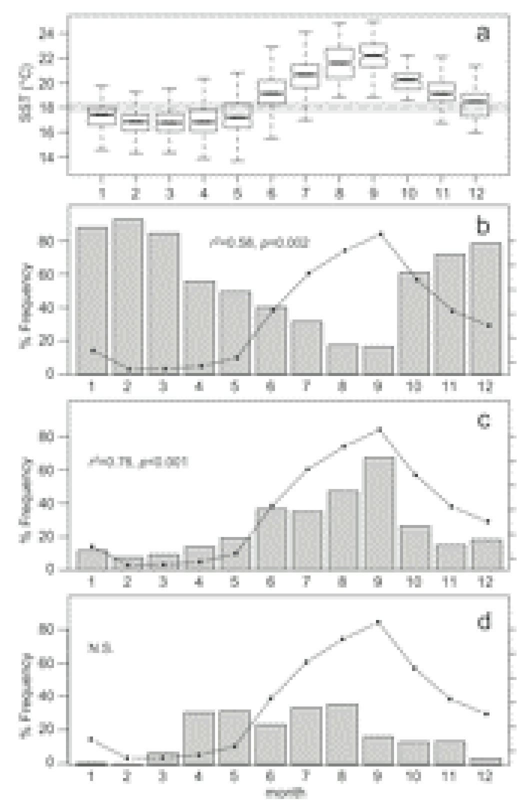

Figure 6. (a) Box plot of monthly SST values based on geolocations within the HLSFG region. The dashed horizontal line indicates the 18°C isotherm. The grey box indicates the 17.5°-18.5°C temperature range. (b-d) Monthly frequency of the dive types for (b) dive type 1, (c) dive type 2, and (d) dive type 3 based on all 6-hour periods for 17 turtles in the HLSFG region. The solid black lines represent the median monthly SST values during this space and time (b-d).

NEFSC REPORT

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OBJECTIVES

- Integrate data from satellite sensors, fishery observer logs, and ocean models to examine habitat of areas associated with loggerhead turtle bycatch.
- Examine oceanographic parameters correlated with loggerhead turtle bycatch across different fisheries in the Northwest Atlantic.
- Streamline bycatch estimation process and elucidate spatial and temporal patterns of high bycatch.
- Inform options for conservation management of threatened and endangered sea turtles in Northwest Atlantic waters.

DATA SOURCES

- Northeast Fishery Observer Program (NEFOP) data from 1997 through 2007 for gillnet, bottom trawl, and scallop dredge.
- Merged sea surface temperature (SST) 5-day median composites have been created through 2007 using MODIS Aqua and Terra, AVHRR Pathfinder, and GOES satellite data. NASA's JPL AVHRR Pathfinder climatology has been used to fill in missing SST values not present in the merged product mentioned above, and also to provide mean conditions.
- Chlorophyll 5-day and monthly composites through 2007 have been created using SeaWiFS and MODIS satellite data.
- Bottom depth data has been retrieved through several sources including: a) the National Geophysical Data Center (NGDC) Coastal Relief dataset, b) the Shuttle Radar Topography Mission bathymetry dataset, and c) the NODC ETOPOv2 dataset.
- ROFS and RTOFS ocean model data has been used to retrieve temperature at depth.

INTRODUCTION

Under the U.S. Endangered Species Act, the main statutory authority under which sea turtles are managed, bycatch of sea turtles in commercial fisheries must be minimized. The National Marine Fisheries Service monitors the bycatch of non-target species by commercial fisheries in U.S. waters. Loggerhead turtles (*Caretta caretta*) are the most commonly observed bycatch in fisheries operating in the U.S. Mid-Atlantic region, between Cape Cod and North Carolina. Loggerheads are listed as threatened under the U.S. Endangered Species Act (ESA), and considered endangered according to the IUCN Red List (Marine Turtle Specialist Group 1996a).

The Northeast Fisheries Science Center's Protected Species Branch (PSB) conducts research to understand factors affecting bycatch, as well as options for bycatch mitigation. Assessing both the distribution of turtle bycatch and factors influencing bycatch rates can help identify areas of elevated risk of bycatch (Sims et al. 2008, Gardner et al. 2008). In some cases fishing effort can be steered away from these bycatch "hotspots", so that fishing effort can continue while minimizing the potential for turtle bycatch (Howell et al. 2008).

Loggerhead turtles are typically present on a seasonal basis in the Mid-Atlantic, migrating to latitudes north of 35ºN in the late spring and summer and returning south in the autumn (Mansfield et al. 2009, Hawkes et al. 2007, Morreale and Standora 2005, Shoop and Kenney 1992). During this time loggerhead turtles are migrating to foraging areas, and some exhibit site fidelity to discrete areas (Witherington et al. 2006, Hawkes et al 2007, Seney and Musick 2007). Loggerheads migrate south to areas around or south of Cape Hatteras, NC during winter when water temperatures begin to decline (Mansfield et al. 2009). Some "overwinter" off North Carolina at the edge of the Gulf Stream, a strategy to help minimize the migratory distance, time, and energy required to reach foraging areas in late spring and summer, while avoiding lethally cold winter temperatures in inshore waters at the same latitude (Hawkes et al. 2007).

Studies of loggerhead bycatch in scallop dredge, scallop trawl, sink gillnet, and bottom trawl gear have shown associations between bycatch rates and sea surface temperature when the gear types are analyzed individually (Murray 2009, 2007, 2006, 2004). Generally high bycatch rates are associated with warmer sea surface temperatures, though the definition of "warm" differs across the gear types. These different "thresholds" for where the probability of bycatch is highest reflect the season and area in which the bycatch and fishery co-occur. For instance, south of 37N high bycatch rates may be associated with waters warmer than 15 ºC, while north of 37 ºN high bycatch rates may be associated with waters closer to 20 ºC. So, bycatch predictors based solely on a sea surface temperature threshold may not adequately describe or predict bycatch in various environments throughout the year.

Other factors besides sea surface temperature likely drive the distribution of sea turtles and bycatch events. Ocean salinity and its affect on currents and frontal activity may influence turtle distributions in the Mid-Atlantic, as could indicators of primary productivity such as chlorophyll. In the central North Pacific, the Transition Zone Chlorophyll Front (TZCF) appeared to be important forage and migration habitat for loggerhead turtles (Polovina et al. 2004). TZCF represents the boundary between stratified low surface chlorophyll (<0.15 mg m^{-3}) waters and high surface chlorophyll (>0.3 mg m^{-3}) vertically-mixed waters. A chlorophyll level of 0.2 mg m^{-3} was used to identify the TZCF.

The purpose of this project is to investigate whether: 1) distributions of loggerhead (*Caretta caretta*) sea turtle bycatch are correlated with oceanographic variables, and 2) bycatch events can be predicted from these environmental associations. Unlike other analyses of bycatch, this project integrates data from satellite sensors, fishery observer logs, and ocean models to examine a broader suite than normally considered of possible oceanographic correlates with bycatch.

This project is currently underway. To date, data have been compiled and explored. A rigorous statistical analysis will be completed during 2010 and results hopefully disseminated via a peer-reviewed journal. The statistical analysis will test our hypothesis that environmental parameters associated with loggerhead bycatch in winter differ from those in summer and fall. If accepted, different seasonal models to describe and predict loggerhead bycatch will need to be developed. Results of this study could elucidate spatial and temporal patterns of high bycatch across different fisheries in the Northwest Atlantic. Moreover, if certain oceanographic conditions are consistently associated with loggerhead bycatch, forecasting bycatch events may be possible if fishing effort distributions can be anticipated. Ultimately we hope this project will help inform options for conservation management of loggerhead sea turtles in Northwest Atlantic waters.

METHODS

Data Sources

Fishery Data

Data collected by Northeast Fisheries Science Center observers deployed aboard commercial gillnet, bottom trawl, scallop trawl, and scallop dredge vessels during 1997-2007 were used to describe associations between loggerhead turtle bycatch and oceanographic properties. Observers record characteristics of each fishing haul on a trip, the gear characteristics, environmental conditions, kept and discarded fish catch and incidental bycatch of protected species. Hauls with and without bycatch were analyzed, in the U.S. Mid-Atlantic region (south of Cape Cod to Cape Hatteras, NC, and westward to the shoreline). Geographic coordinates of each fishing haul were used to obtain oceanographic parameters from satellites or ocean models.

Oceanographic Data

To acquire oceanographic data for each haul in the fisheries dataset, sea surface temperature (SST) and chlorophyll satellite image time series were updated for recent years, as were extraction tools were used to add these data to the fisheries data used in this analysis. A new time series of SST and chlorophyll frontal data was created specifically for use in the project, and values were extracted from them to incorporate into the fisheries datasets. In addition, a custom written Matlab-based tool was created to retrieve ocean model data, so that values such as salinity could be retrieved. The creation of the frontal datasets and the custom ocean model tool was a significant undertaking which provided valuable data for this project, and for future projects to come.

Ocean Model Tool

The ocean model tool (Figure 1) works with archived RTOFS (Real Time Ocean Forecast System) ocean model data produced by NOAA's National Centers for Environmental Prediction, and with the RTOFS predecessor, ROFS (Regional Ocean Forecast System), (occasionally listed as COFS (Coastal Ocean Forecast System)). These models generate daily and short-term forecasts of ocean properties for the coastal ocean of the United States. ROFS and RTOFS are based on hydrodynamic, three-dimensional ocean circulation models (see http://oceanmodeling.rsmas.miami.edu/hycom/overview.html for the underlying HYCOM model for RTOFS, and http://www.aos.princeton.edu/WWWPUBLIC/htdocs.pom/ for the underlying Princeton Ocean Model for ROFS). ROFS and RTOFS data are archived at NODC (National Oceanographic Data Center) in GRiB (Gridded Binary) format.

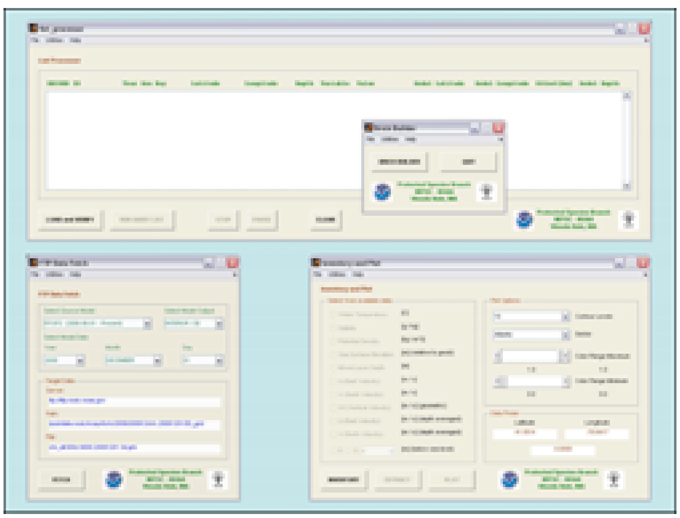

Figure 1. Windows of tool used to access ocean model data and link it with fisheries data (Brick Builder 1.0)

The tool is currently able to retrieve RTOFS or ROFS data from 1999 through mid-June of 2007. The tool contains three primary components: 1) an FTP data fetch component for locating and downloading individual daily 3D model files; 2) an inventory and plot component that examines the file downloaded, determines what variables and depth levels the file contains, and allows the user to plot the data and export the plotted data to value, latitude, and longitude text files; and 3) a list processing tool that reads in a text file with locations, dates, depths, and variables to retrieve, and returns that same text file with the ocean model data columns attached corresponding to the date, location, depth, and variable asked for on each line. Currently only one variable and depth can be specified per line of the input text file.

Several challenges are inherent when dealing with this RTOFS-ROFS time series. Chief among them are that the models have developed and changed over time and changes in the model data structure, filenames, etc. often are not well documented. Over time variables have been added and the number of depth layers available has increased, among other changes. The current tool adapts to these changes for the most part. However, due to changes in the data structure, the tool only can process data into June 2007. Because of these irregularities, we currently are overseeing a contract to update the tool's capabilities to work with data from June 2007 through May 2010, quality check the tool's retrieval of data for the entire time series (beginning in 1997), and improve the tool's ability to process data quickly and efficiently.

Salinity

For all observed hauls, surface salinity (parts per thousands) was obtained from either the RTOFS model (May 2006 to present) or the ROFS model (pre May 2006) (Brick Builder, version 1.0). Surface salinity was obtained for each haul location; otherwise, surface salinity was obtained from the next closest point available, with an offset value indicating the distance from the original location.

Chlorophyll (mg/m^3)

Chlorophyll data was obtained from five day composites of SeaWiFS high resolution satellite images (http://oceancolor.gsfc.nasa.gov) from 1997-2007. A chlorophyll variable was created by sampling the chlorophyll at point locations, and also by retrieving chlorophyll data from different size areas surrounding the fishing locations. Geometric mean values for the surrounding area are assumed to be more representative of actual conditions than point locations and were used for the final chlorophyll value if available. If not, values at point locations were used for the final variable.

SST (°C)

For all observed hauls, SST data was retrieved from two sources: 1) overlapping five-day SST composites for each day from 1997 through 2007; 2) non-overlapping 5-day climatology images, one for each consecutive 5-day periods during the year. Composite images for each year were created using data from as many as four satellites. These satellites sources included SST data from AVHRR Pathfinder, Modis Aqua, Modis Terra, and the GOES satellites. Data were used from whatever satellites were available for the given day. This maximized the accuracy of the data and provided the best spatial coverage by limiting cloud cover. Point locations are assumed to be more representative of actual conditions and were used for the final SST value if available. If not, median values for the surrounding area were used for the final variable.

Depth (m)

Observer-recorded depth values were used when available. When these data were missing, depth values were obtained at a given geographic location from either: (1) Coastal Relief data with a 3 arc second resolution (http://www.ngdc.noaa.gov/mgg/coastal/coastal.html);
(2) SRTM 30 version 1 data with a 30 arc second resolution (http://topex.ucsd.edu/WWW_html/srtm30_plus.html); and (3) National Geophysical Data Center ETOPO data with a 2-minute resolution.

SST Fronts

SST frontal data were obtained from a sea surface temperature fronts time series created by applying the Cayula and Cornillon (1992) Single Image Edge Detection (SEID) algorithm (Roberts et al. in prep.) to single day SST composites. Distance from fronts and intensity of front were obtained for each observation used in this study. Frontal maps were created by summing frontal activity in 5-day time periods across ~11km^2, ~155km^2, and ~1,600km^2 windows respectively. Frontal intensity maps were created by summing the frontal pixels detected in these spatial-temporal windows. For example, to construct a 5-day frontal intensity image using a 3x3 cell window, the maximum input from any one pixel was 5 (one for each input image), and the maximum output value for any pixel was 45 (values of 5 present in all 9 pixels in the 3x3 window used in the calculation). Distance measures were the distance from any fronts detected within the 5-day frontal images.

<u>Chlorophyll Fronts</u>

Chlorophyll frontal data were obtained from a chlorophyll fronts time series created by applying the Cayula and Cornillon (1992) Single Image Edge Detection (SEID) algorithm (Roberts et al. in prep.) to single day SeaWiFS chlorophyll composites. Distance from fronts were obtained for each observation used in this study. Frontal maps were created similar to those created for SST.

Exploratory Analyses

Prior to model building, observer data were explored to understand and properly model loggerhead bycatch and environmental correlates. These data were summarized by gear type, season, and month, and by environmental parameters including SST, chlorophyll concentrations, bottom depth, surface salinity, and SST and chlorophyll fronts. These variables were chosen based on either: 1) a priori knowledge of environmental variables associated with loggerhead bycatch rates; 2) environmental associations with turtle distributions in the literature; or 3) anecdotal reports of turtle distributions and oceanographic properties in the Mid-Atlantic. Methods used to explore the data included simple summaries, histograms, boxplots, and classification and regression trees (CART). Highlights of these preliminary results are provided in this report.

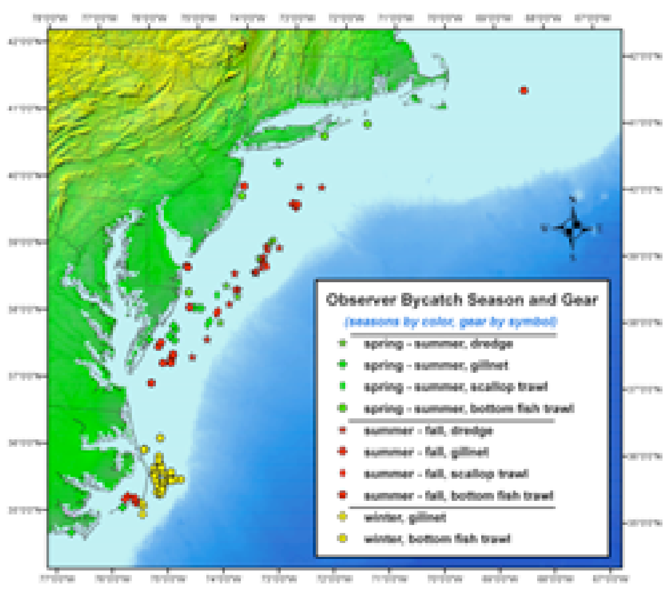

Figure 2. Distribution of observed loggerhead bycatch by season and gear type, 1997-2007

PRELIMINARY RESULTS

The distribution of observed bycatch in the Mid-Atlantic region reflects the seasonal distribution of loggerhead sea turtles. North of 37 ºN on the Mid-Atlantic shelf, bycatch mainly occurs in late spring and summer, reflecting when loggerheads are migrating or foraging in the region. Bycatch of loggerheads in sink gillnet and fish trawl gear occur year-round, though bycatch in the scallop fishery (dredge and scallop trawl gear) mainly occurs in the central Mid-Atlantic region from June to October, because the fishery does

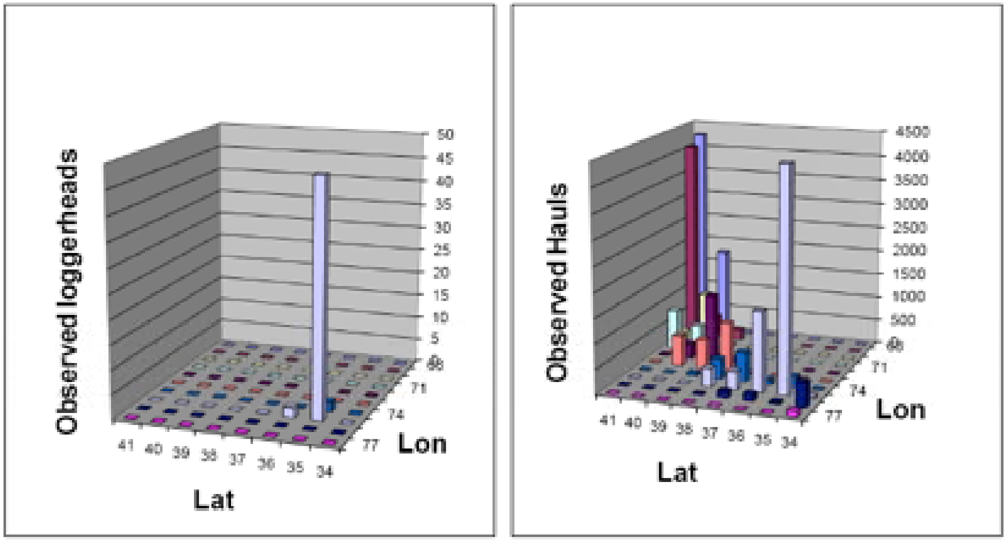

Figure 3. Winter (Dec-Mar) distribution of observed hauls and loggerhead bycatch in gillnet and trawl fisheries, 1997-2007

not operate off NC in the winter time (Figure 2). In winter (December – March), turtle bycatch occurs mainly south of 37 ºN, despite the presence of observed commercial fishing effort to the north (Figure 3).

The seasonal bycatch "modes" may differ not only in location, but in the environmental and oceanographic characteristics. Surface water temperatures at observed loggerhead bycatch events show a distinct difference between winter and non-winter water temperatures (Figure 4). Furthermore, mean log transformed chlorophyll values in hauls with loggerhead bycatch varied considerably by season (spring-summer = 0.038, summer-fall = 0.085, winter = 0.279), with winter chlorophyll levels being much higher than the other seasons. There were also large differences in chlorophyll levels by gear type (mean log transformed chla for scallop dredge = -0.226, scallop trawl = -0.172, gillnet = 0.278, and bottom fish trawl = 0.321). Some of this difference is likely due to the seasonal distribution of these fisheries, with scallop fisheries operating north of North Carolina.

Preliminary analyses suggested that winter and non-winter bycatch "modes" could be described by differences in salinity, SST, and chlorophyll frontal intensities. For instance, the CART analysis revealed that largest variation in bycatch rates could be described by salinity, with highest rates attributed to high salinity waters (i.e. >36.5 ppt) which occurred in winter off NC. In the non-winter habitat, sea turtle bycatch appears to generally align with chlorophyll gradients that run down the mid-shelf during the summer and fall (Figures 5). However, these gradients are variable on short time scales, and can also vary in intensity depending on the time of the year. Therefore, it may be difficult to detect a correlation between loggerhead bycatch and a sharp chlorophyll gradient. Our preliminary statistical analysis did not suggest loggerhead presence linked to a specific chlorophyll or density contour, as has been done in the North Pacific, where a 0.2 mg m^{-3} of chlorophyll front denotes the TZCF (Polovina et al. 2004). All of our preliminary results are exploratory and need to be further tested and evaluated with models appropriate for the non-normal data structure.

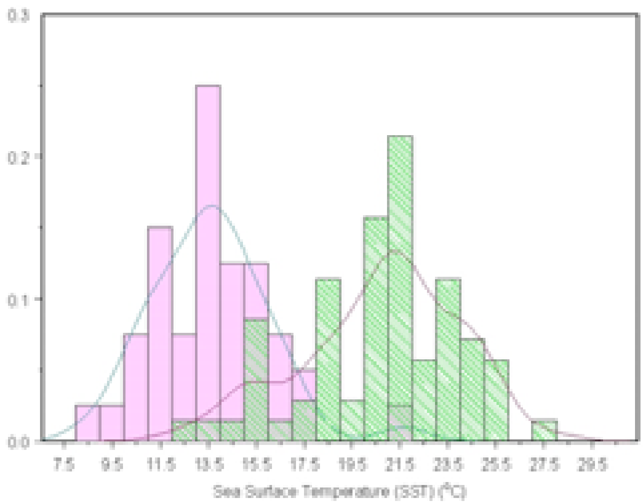

Figure 4. Histogram of SST (˚C) for hauls with loggerhead bycatch by season. Winter (Dec – Mar) is displayed in magenta, and the rest of year (Apr – Nov) is displayed hatched green.

DISCUSSION

Waters of the Mid-Atlantic and South Atlantic converge around Cape Hatteras, NC, profoundly impacting the physical properties of this area (Lohrenz et al. 2002, Flagg et al. 2002). It is also the area where the Gulf Stream separates from the shelf and heads east across the North Atlantic. In winter (Oct-Mar) waters off North Carolina are traversed by the "Hatteras front", a strong temperature and salinity front with light, relatively fresh, cold, stratified water on one side (from the Mid-Atlantic Bight), and denser, more saline, warmer, unstratified water on the other (from the South Atlantic Bight) (Savidge 2002). The interaction of major water masses in the vicinity of Cape Hatteras results in long-lasting stratification, which can facilitate the onset of the spring bloom (Flagg et al. 2002). Studies have shown high concentrations of chlorophyll (>10 mg/m^{-3}) during March off Hatteras (compared to July), and these high productivity regions were proximal to Gulf Stream circulation features (Lohrenz et al. 2002). Circulation at frontal regions increases nutrient and light availability, stimulating enhanced productivity (Lohrenz et al. 2002) which could benefit turtles by aggregating prey. Mansfield et al. (2009) suggested that the area off of Cape Hatteras acts as "migratory bottleneck" for juvenile loggerheads. Here the winter water temperatures dip below the temperatures normally occupied during the rest of the year, though many loggerheads do not continue further south to warm waters.

Loggerhead bycatch in winter occurs mainly in the waters off Cape Hatteras, NC. The unique physical characteristics of waters in this region, especially in winter and early spring, may set it apart from areas and seasons to the north. A model developed to predict bycatch in fishing gear off NC in the winter might not be applicable to fisheries operating on the Mid-Atlantic shelf during spring and summer, because the oceanographic properties of each season and area are different. Therefore, two different "modes" of bycatch will need to be described: a winter mode off NC, and a spring/summer mode on the shelf waters of the Mid-Atlantic.

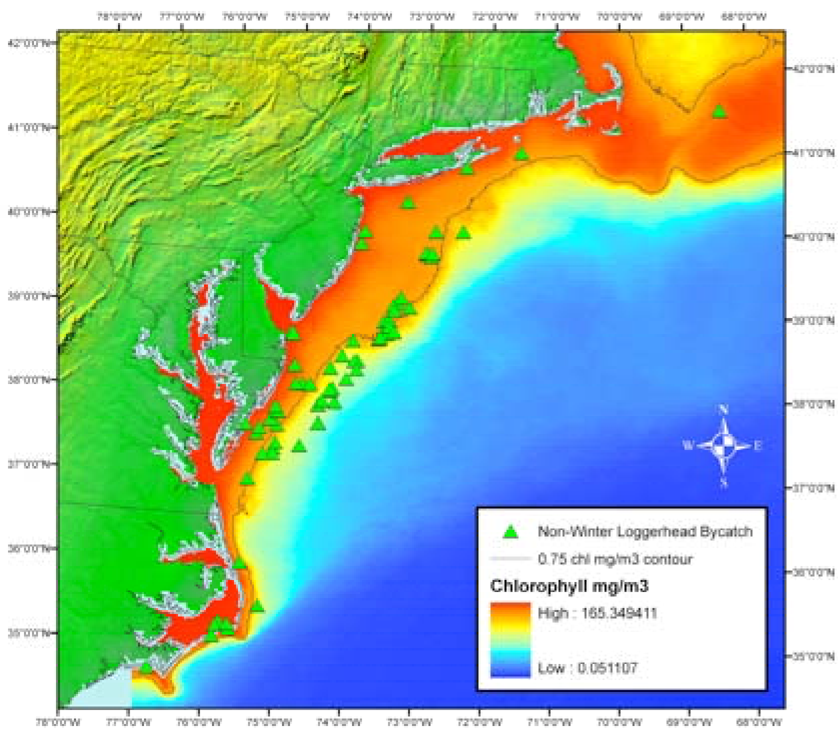

Figure 5. Observed 1997-2007 non-winter loggerhead bycatch overlaid on an August SeaWiFS-MODIS climatology of chlorophyll and the 0.75 mg/m3 chlorophyll contour.

While the waters in the Northwest Atlantic continental shelf ecosystem do exhibit seasonal patterns, the temporal and spatial consistency of these patterns is not as consistent as in the North Pacific. This provides difficulties with matching up satellite data with fishing observations. For the bulk of the satellite data used in this analysis, five-day satellite image composites were used. These images provide a trade off of covering a long enough time period to remove cloud contamination, while still providing a reasonable depiction of the conditions at the time of the fishing event. Conditions may be too variable to use 5-day composites and get a reasonable depiction of conditions such as frontal activity at the time of a bycatch event. Environmental data could either be taken from images from the exact day of the bycatch event if possible, or a monthly image where broader oceanographic patterns possibly emerge.

PAST CHALLENGES AND FUTURE ANALYSES

In undertaking this project, we began a very large project from scratch that required a lot of data gathering and data creation. This includes cleaning and assessing well over 100,000 observed fishing hauls, each with numerous fishing effort variables. It also includes updating satellite data time series of SST and chlorophyll, and making entirely new time series of frontal data based on SST and chlorophyll and incorporating these datasets into a framework used to link fisheries data with satellite data. Furthermore, we ambitiously aimed to include ocean model data into our analysis so that we could for the first time analyze this data relative to oceanographic parameters at depth, where the turtles actually spend much of their time. Attempting to integrate ocean model data from

1997 through 2007 proved challenging, as the models progressed in accuracy, precision, and formats across that time. Though the model data covering that time period was archived, documentation of the changes to the model over time was often lacking. Gathering and preparing all of these data has occupied the vast majority of our time spent so far on this project.

However, we are not finished with the data analysis or data gathering. The project was slowed by difficultly transferring funds (used for contractors to build the ocean model tool and assist in statistical analysis), and by the generally slow contracting process. Nevertheless, the money has been obligated to two contracts, currently underway. We are undertaking phase two of our ocean model tool which should greatly improve usability and allow us to more easily link oceanographic data at depth with fisheries data. Also, in early 2010 a contractor is starting at NEFSC to assist the PIs in a rigorous statistical analysis of the datasets. Associations between loggerhead bycatch and salinity, chlorophyll, SST and chlorophyll fronts will be analyzed in more detail to investigate potential predictors of bycatch.

We are also in the process of acquiring fishery independent data to verify and strengthen results from this current analysis which uses fishery-dependent data. These data include summertime aerial surveys for turtles, and quarterly NEFSC bottom trawl resource surveys that occur throughout the study area. Fishery independent data allows us to better describe potential loggerhead habitat, versus using fishery dependent data where we are describing conditions where fisheries bycatch occurs. Defining environmental characteristics of habitat could facilitate bycatch predictions, particularly if fishing effort can be anticipated. Results of this work will hopefully inform conservation strategies to reduce bycatch.

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