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Journal of Experimental Marine Biology and Ecology 356 (2008) 96–114

Journal of EXPERIMENTAL MARINE BIOLOGY AND ECOLOGY

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Pelagic habitat characterization of loggerhead sea turtles, *Caretta caretta*, in the North Pacific Ocean (1997–2006): Insights from satellite tag tracking and remotely sensed data

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Abstract

We analyzed satellite track data for 186 loggerhead sea turtles in the North Pacific Ocean using remotely sensed environmental data to characterize pelagic habitat. A large number of candidate habitat variables were merged to the satellite track data and statistically compared to background values over a large spatiotemporal grid which bounded overall occupancy. Five statistically significant variables were identified out of the 16 environmental variables examined. Two of these variables have strong seasonal, interannual, and spatial patterns (sea surface temperature and chlorophyll *a* concentration), while three others were primarily spatial (earth magnetic force, earth magnetic declination, and earth magnetic inclination). Habitat selectivity for these variables was quantified using preference curve methodology established in the foraging literature. The output from the selectivity curves was used to predict a multivariate loggerhead sea turtle habitat index across the pelagic North Pacific. This predicted habitat was ground-truthed with newly available satellite track data.

Keywords: Biotelemetry; Habitat use; Oceanography; Remote sensing; Resource utilization; Satellite tracking; Sea turtles

1. Introduction

The spatial distribution of pelagic organisms is determined by physical-forcing mechanisms (winds, waves, currents, tides, etc.) coupled with active movement processes by the organisms. Large pelagic macrofauna such as nekton (by definition) possess good swimming ability and can regulate their location actively. Despite the apparent homogeneity of the open ocean habitat, many scales of structure in the physical environment can be used by nektonic organisms to locate and maintain position in preferred habitat (Longhurst, 2006). The distribution and abundance of most studied nekton exhibit this type of patterned occupancy, i.e., they are not simply distributed randomly or uniformly throughout the open ocean. Sea turtles are one such group of nekton which displays structured pelagic distributions (Carr, 1987; Luschi et al., 2003; Polovina et al., 2000, 2006), presumably via some component of active orientation since even hatchling sea turtles possess good swimming ability (O'Hara, 1980; Davenport and

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doi:10.1016/j.jembe.2007.12.019

Clough, 1986). Some species, such as leatherback sea turtles (*Dermochelys coriacea*), have been shown to have complex patterns of pelagic habitat utilization, not always related to forage or biological "hot spots" (Hays et al., 2006). Loggerhead sea turtles (*Caretta caretta*), a threatened species under the US Endangered Species Act, are capable of traversing both major ocean basins during their ontogenetic migrations (Bowen et al., 1995; Bolten et al., 1998; Alfaro-Shigueto et al., 2004). Many of these long-distance migrations are between nesting grounds and foraging grounds. Juvenile, subadult, and adult loggerhead sea turtles in the North Pacific Ocean have been shown to occupy specific areas of the pelagic environment, possibly related to sea surface temperature and/or ocean productivity (Polovina et al., 2000, 2004, 2006). Based on these and previous studies (e.g., Zug et al., 1995), it is clear that loggerhead sea turtles use some portion of the open ocean for a large fraction of their life history, yet their particular habitat requirements are largely unknown.

Habitat characterization for broad-ranging pelagic organisms has historically been hampered by a lack of complete positional data as well as a lack of biologically pertinent and synoptic environmental data. With recent advances in satellite-mediated tagging technology and accessibility to many remotely sensed environmental data products, much more information is now available on location and movement of individuals and their exposure to a wide variety of environmental variables. We have been tagging loggerhead sea turtles in the North Pacific with Argos-linked satellite tags since 1997 via the collaborative efforts of a large, multinational group of marine turtle researchers (Table 1). Both captive-reared and wild-caught individuals have been tagged and tracked. Subsets of this satellite tag dataset have been used elsewhere to examine relationships to fronts (Polovina et al., 2000), diving behavior (Polovina et al., 2003), foraging behavior (Polovina et al., 2004), and characterization of geographic "hot spots" of distribution (Polovina et al., 2006). In this paper, we use the satellite tag data coupled with remotely sensed environmental data to characterize loggerhead sea turtle pelagic habitat across the North Pacific Ocean using quantitative approaches.

2. Methods

2.1. Satellite tracking

All wild-caught (fishery bycatch or nesting individuals) and captive-reared loggerhead sea turtles tagged in this analysis are summarized in Table 1, and the track data are shown graphically in Fig. 1. Turtles were outfitted with satellite transmitters attached to the carapace using the procedures outlined in Balazs et al. (1996). Turtles were equipped with Telonics (Mesa, AZ, USA) model ST-18, ST-19, ST-24, and Wildlife Computers (Redmond, WA, USA) model SDR-T10, SDR-T16, or SPOT 3/4/5 Argos-linked satellite transmitters. Only the highest quality position data (Argos codes 0–3) were kept initially, and only one dataset from a tag was used for twelve dual-tagged turtles. A subsequent screening removed satellite fixes which predicted unlikely sustained swimming velocities, similar to the methodology of McMahon and Hays (2006), although we used a slightly larger arbitrary cutoff of 5 m/s instead of 2.5 m/s since some of the surface current speeds in this area can be ~2.5 m/s.

Environmental data grids were merged to the satellite track data using the software package Generic Mapping Tools (GMT), extending the approach of Ellis and Balazs (1998). A GMT subroutine called *grdtrack* was used to extract trackline values from the weekly or monthly gridded data fields with a spatial bicubic interpolation. Monthly data fields were used when weekly resolution resulted in excessive missing values as a result of cloud cover, sensor malfunction or missing files. The GMT software package (Wessel and Smith, 1991) is available from http://gmt.soest.hawaii.edu/ and was used for most of the gridding, mapping, and analysis of this study. Missing values affected 11.30% of the total records in the satellite track data,

Table 1
Summary of loggerhead sea turtle satellite tag deployments by major dataset grouping

Data source	$Latitude_{min}$	$Latitude_{max}$	$Longitude_{min}$	$Longitude_{max}$	$Date_{min}$	$Date_{max}$	SCL_{min}	SCL_{max}	Datapoints	Percent	Tags
Nagoya	22.54°N	45.42°N	136.60°E	144.23°W	23-Apr-2003	30-Jun-2006	25.60	64.80	41509	90.23%	110
Historical	20.94°N	41.46°N	162.30°E	131.03°W	26-Jan-1997	23-Oct-2001	41.00	83.00	5392	97.50%	30
Japan	23.77°N	39.48°N	125.15°E	164.15°E	9-Dec-2002	12-Jun-2006	66.50	89.10	2170	26.87%	15
Taiwan	3.99°N	37.75°N	108.88°E	162.31°E	10-May-2002	1-Jul-2006	64.00	83.00	1459	10.08%	18
Baja	15.69°N	35.05°N	168.03°E	108.95°W	10-Oct-1998	14-Dec-2002	54.50	77.10	725	13.10%	13

Data source	Description of data
Nagoya	"Nagoya" refers to tag and release conducted upon reared turtles by Dr. Itaru Uchida, Masanori Kurita, Tomomi Saito, and other Port of Nagoya Public Aquarium staff.
Historical	"Historical" refers to tag and release conducted upon bycatch in the Hawaii-based longline fishery by Pacific Islands Fisheries Science Center, National Marine Fisheries Service staff and fishery observers.
Japan	"Japan" refers to tag and release conducted upon nesting individuals and bycatch in the Japanese pond net fishery by Dr. Naoki Kamezaki and colleagues.
Taiwan	"Taiwan" refers to tag and release conducted upon bycatch in the Taiwanese pond net fishery by Dr. I-Jiunn Cheng and colleagues.
Baja	"Baja" refers to tag and release conducted upon bycatch in the Baja California Sur, Mexico coastal gillnet fishery by Dr. Peter Dutton and colleagues (Wallace J. Nichols, Hoyt Peckham, Jeffrey Seminoff, and The Grupo Tortuguero of Baja California).

Summary includes latitude ranges (south to north), longitude ranges (east to west), date ranges, SCL size ranges (cm straight carapace length), number of high-quality satellite data hits, percent of track data in pelagic habitat, and number of tags deployed (not counting dual-tagged individuals). Latitude, longitude, and date ranges refer to the range of values throughout the satellite tracks, from deployment through to the time of this summary (July 2006). SCL ranges refer to the size upon release and does not account for growth. A description of the data is in the lower panel of the table.