

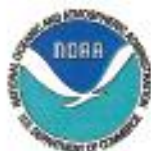


2 OF 2

**Satellite Tracking Manual for the Visiting Sea Turtle Researcher and
Information Exchange Program**

Host: Pacific Islands Fisheries Science Center
NOAA, National Marine Fisheries Service

Location: Pacific Islands Fisheries Science Center
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2570 Dole Street
Honolulu, Hawaii 96822-2396



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Exchange Program

Sponsored by:

Pacific Islands Fisheries Science Center
NOAA, National Marine Fisheries Service
Marine Turtle Research Program

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Lodging for Workshop Participants:

Lincoln Hall
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1821 East-West Road
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Turtles on the edge: movement of loggerhead turtles (*Caretta caretta*) along oceanic fronts, spanning longline fishing grounds in the central North Pacific, 1997–1998

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ABSTRACT

Nine juvenile loggerhead sea turtles tracked during 1997 and 1998 in the central North Pacific by satellite telemetry all travelled westward, against prevailing currents, along two convergent fronts identified by satellite remotely sensed data on sea surface temperature (SST), chlorophyll and geostrophic currents. These fronts are characterized by gradients in sea surface height that produce an eastward geostrophic current, with gradients in surface chlorophyll and SST. Six of the turtles were associated with a front characterized by 17°C SST, surface chlorophyll of about 0.2 mg m⁻³, and eastward geostrophic current of about 4 cm s⁻¹, while the other three turtles were associated with a front with 20°C SST, surface chlorophyll of about 0.1 mg m⁻³, and eastward geostrophic flow of about 7 cm s⁻¹. These results appear to explain why incidental catch rates of loggerheads in the Hawaii longline fishery are highest when gear is set at 17°C and 20°C, SST. Further, from the seasonal distribution of longline effort relative to these fronts, it appears that the surface longline fishing ground lies largely between these two fronts during the first quarter and well to the south of the 17°C front, but including the 20°C front, in the second quarter. These findings suggest seasonal or area closures of the longline fishery that could be tested to reduce incidental catches of loggerheads. Finally, these results illustrate

the insights which can be achieved by combining data on movement of pelagic animals with concurrent remotely sensed environmental data.

Key words: *Caretta caretta*, central North Pacific, loggerhead turtles, longline fishery, satellite remote sensing, subtropical front

INTRODUCTION

Loggerhead sea turtles (*Caretta caretta*) travel across the Pacific between their nesting beaches in Japan and Australia and their foraging habitat in the eastern Pacific. Large aggregations of juvenile loggerheads have been found off Baja California feeding on a pelagic red crab found in association with the coastal upwelling (Bowen *et al.*, 1995). Genetic analyses of the loggerheads off Baja California concluded that 95% came from Japanese nesting beaches and 5% from nesting colonies in Australia (Bowen *et al.*, 1995). The route these juveniles take during this remarkable migration across the North Pacific, travelling almost one-third of the way around the earth, and how they find food and avoid predation in these typically unproductive oceanic waters are not fully resolved.

However, about a decade ago, the hypothesis was developed that oceanic fronts provided nursery habitat for juvenile turtles, based on a compilation of occasional but persistent observations of juvenile turtles found in the middle of ocean gyres in the Atlantic and Caribbean Oceans, far from land, together with an understanding that convergent oceanic fronts could provide forage habitat for juvenile turtles (Carr, 1987). More recently, and in large part owing to significant catches of juvenile loggerheads in fishing gear from both the Atlantic and the Pacific, it has been hypothesized that juvenile loggerhead turtles (2–8 years old) inhabit mid-oceanic regions far from continental shelf environments and migrate with predominant ocean gyres from west to east (Musick and Limpus, 1997).

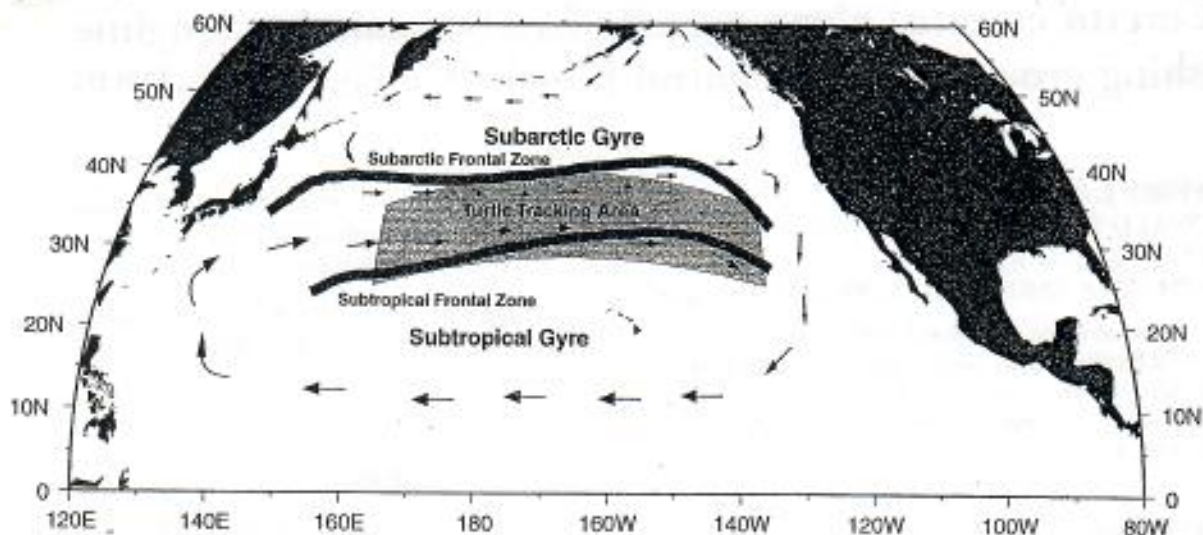
However, defining juvenile loggerhead distribution based on incidental catches in fishing gear may be a biased sampling of their habitat because the fishing

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Figure 1. Schematic of the winter central North Pacific oceanography indicating the Subarctic and Subtropical Gyres and Frontal Zones. Arrows show gyre rotation; grey box indicates the general region of the loggerhead turtle tracks in this study.



gear is not targeting turtles. In this paper we will describe the oceanic habitat of juvenile loggerheads in the central North Pacific and their movement relative to this oceanic habitat with a combination of data. The position and movement of nine loggerhead turtles are obtained from satellite telemetry; information on the environment around the turtle positions is derived from satellite remote sensing data. These data consist of sea surface temperature (SST), surface chlorophyll density, and geostrophic currents.

The general region occupied by the turtles in our study is the central North Pacific covering a latitudinal band of about 28°–40°N (Fig. 1). This region represents the North Pacific Transition Zone (NPTZ), consisting of a broad, weak, eastward-flowing surface current containing a series of fronts situated between the Subtropical Gyre to the south and the Subarctic Gyre to the north (Fig. 1) (Roden, 1980). During the winter and spring, westerlies in the northern portion of the NPTZ and trade winds to the south result in wind-driven transport of surface waters, creating fronts as colder (hence more dense) northern water converges with warmer and lighter water from the south (Roden, 1980). North of Hawaii, convergent fronts have been observed during winter to persist at about 28°N, 31°N, and 34°N latitude (Roden, 1980; Niiler and Reynolds, 1984). These fronts represent sharp boundaries in a variety of physical parameters, including temperature, salinity, chlorophyll, and sea surface height (geostrophic flow) (Roden, 1980; Niiler and Reynolds, 1984).

Biologically, these convergent fronts appear to represent zones of enhanced trophic transfer (Olson et al., 1994; Bakun, 1996). The dense, cooler, phyto-

plankton-rich water sinks below the warmer water, creating a convergence of phytoplankton (Roden, 1980). Buoyant organisms such as jellyfish, a common food of loggerheads, as well as vertically swimming zooplankton, can maintain their vertical position in the weak downwelling and aggregate in the front to graze on the downwelled phytoplankton (Olson et al., 1994; Bakun, 1996). The concentration of these organisms, in turn, attracts the higher-trophic-level predators, and ultimately a complete pelagic food web is assembled (Olson et al., 1994).

DATA AND METHODS

Data on the position of nine loggerhead turtles released after being hooked in the swordfish fishery north of Hawaii were provided from Argos-linked, 180 g, Telonics ST-10 transmitters attached to the turtles with glass-fibre cloth and resin, based on a successful and frequently used methodology (Balazs et al., 1996). Deployments were made by trained personnel of the National Marine Fisheries Service's Observer Program on commercial longline fishing vessels.

The transmitters attached to the turtles functioned for durations ranging from 2.2 to 6.9 months (Table 1). Reasons that the transmissions ended are unknown but could include failure or detachment of the transmitter, death of the turtle, or depletion of battery power (thought to be a frequent cause).

Hooking condition was classified as: (1) lightly hooked, if the turtle was only externally tangled or snagged in the fishing gear but did not swallow the hook; or (2) deeply ingested, if the turtle swallowed

Table 1. Information on nine loggerheads deployed with transmitters 1997 and 1998.

| Turtle ID no. | Carapace length (cm) | Deployment date | Date of last transmission | Deployment position | Last position recorded | Transmission time (months) | Hooking status* | Distance travelled (km) |
|---------------|----------------------|-----------------|---------------------------|---------------------|------------------------|----------------------------|-----------------|-------------------------|
| 1 | 52.0 | Feb 1997 | May 1997 | 29°N, 163°W | 34°N, 179°E | 3.9 | LH | 2592 |
| 2 | 41.0 | Feb 1997 | May 1997 | 30°N, 161°W | 30°N, 170°W | 3.0 | LH | 1311 |
| 3 | 62.0 | Mar 1997 | Jul 1997 | 31°N, 154°W | 37°N, 179°E | 4.5 | DI | 3480 |
| 4 | 81.0 | Apr 1997 | Oct 1997 | 29°N, 157°W | 32°N, 163°E | 5.9 | DI | 5199 |
| 8 | 45.0 | Sep 1997 | Nov 1997 | 38°N, 131°W | 34°N, 138°W | 2.2 | LH | 1703 |
| 5 | 45.5 | Jan 1998 | Aug 1998 | 33°N, 143°W | 36°N, 162°W | 6.9 | LH | 3136 |
| 6 | 48.0 | Jan 1998 | Jul 1998 | 34°N, 142°W | 35°N, 162°W | 6.4 | DI | 3492 |
| 7 | 58.0 | Feb 1998 | May 1998 | 31°N, 155°W | 34°N, 169°W | 3.5 | DI | 1876 |
| 9 | 61.0 | Feb 1998 | Apr 1998 | 31°N, 155°W | 33°N, 160°W | 2.4 | DI | 1442 |

*DI, deeply ingesting; LH, lightly hooked; see text for definitions.

the hook. Lightly hooked turtles were unhooked and released, while deep ingesting turtles were released with the hook in the animal but with the monofilament leader cut close to the turtle's mouth. All nine turtles were determined, by mtDNA analysis, to have originated from nesting beaches in Japan (Dutton *et al.*, in press).

The physical and biological environmental data that were used to describe the environment at and around the migrating loggerheads are sea surface temperature (SST), surface chlorophyll *a* density, and geostrophic current. The SST data are multichannel SST (MCSST) from the University of Miami, with weekly temporal resolution and one-tenth of one degree of longitude and latitude spatial resolution. Global comparisons between MCSST and ship-based temperature measurements indicated MCSST is 0.3–0.4°C lower than ship-based temperature with cross correlations ranging from +0.3 to +0.7 (McClain *et al.*, 1985). The chlorophyll density is estimated from two

satellite sensors. For January–June 1997 we use the Ocean Color and Temperature Scanner (OCTS) version 3 data from the Japanese Adeos satellite (Shimada *et al.*, 1998), while for September 1997–August 1998 we use Sea-viewing Wide Field-of-view Sensor (SeaWiFS) version 2 data (O'Reilly *et al.*, 1998). The data resolution is monthly at 0.088 degree of latitude and longitude. The accuracy of SeaWiFS chlorophyll estimates is within 30–50% of ship-based observations (McClain *et al.*, 1998). Geostrophic currents are computed from satellite altimetry data from TOPEX/Poseidon with 10-day and 0.5 degree of latitude and longitude resolution (Polovina *et al.*, 1999). Comparisons between current speed determined from an acoustic Doppler current profiler along TOPEX/Poseidon track lines around the Hawaiian Archipelago agreed with estimates from TOPEX/Poseidon to within a few cm s^{-1} (Mitchum, 1996).

The environmental data are linked to the turtle's position by spatial interpolation of the environmental

Figure 2. Track lines of nine loggerhead turtles tracked during 1997 and 1998. Numbers on track lines identify turtle ID nos in Table 1 and tracking period in figure legend. 'S' on each track indicates where turtle was released with transmitter.

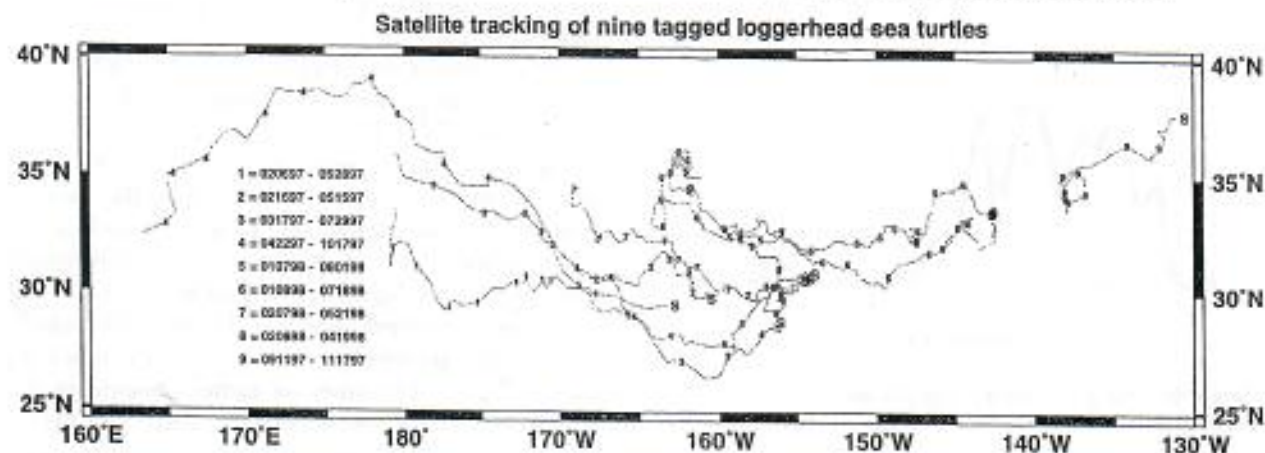
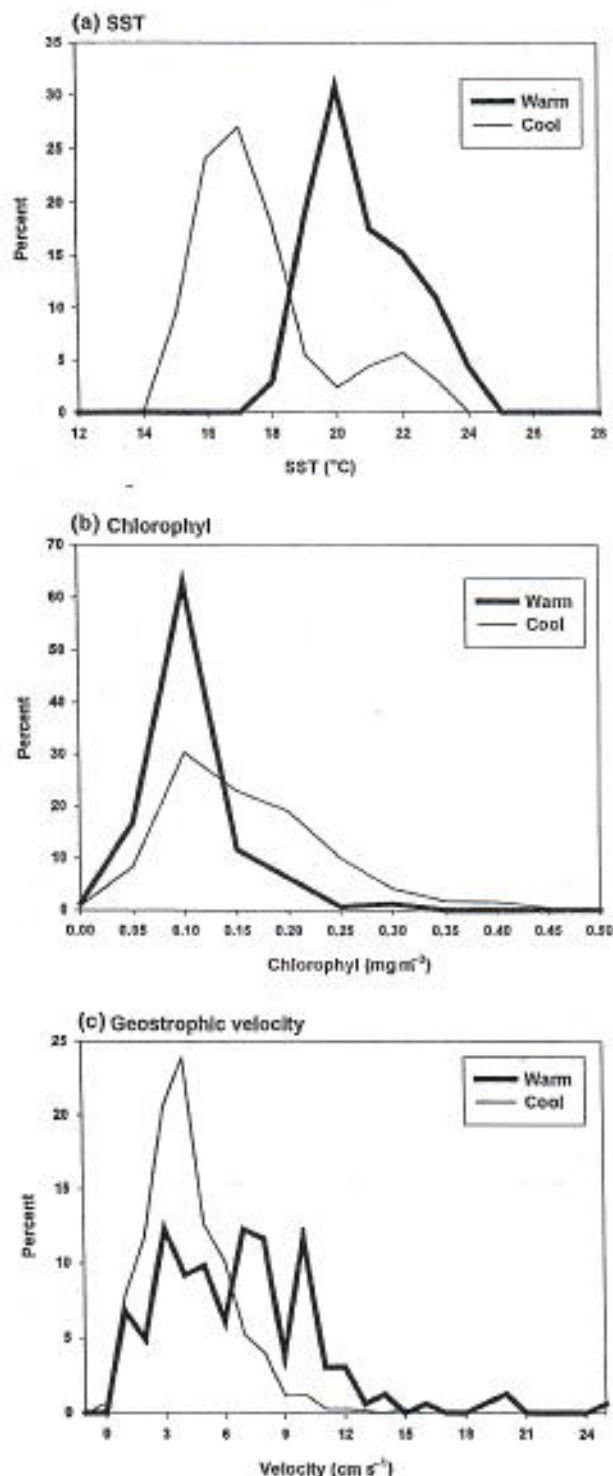


Figure 3. Frequency distribution of (a) SST, (b) chlorophyll, and (c) geostrophic current speed averaged over all turtles' positions, for the warm ($N = 211$ observations) and cool ($N = 676$ observations) temperature groups.



data between grid points. Specifically, a cubic polynomial was used to estimate the environmental data at

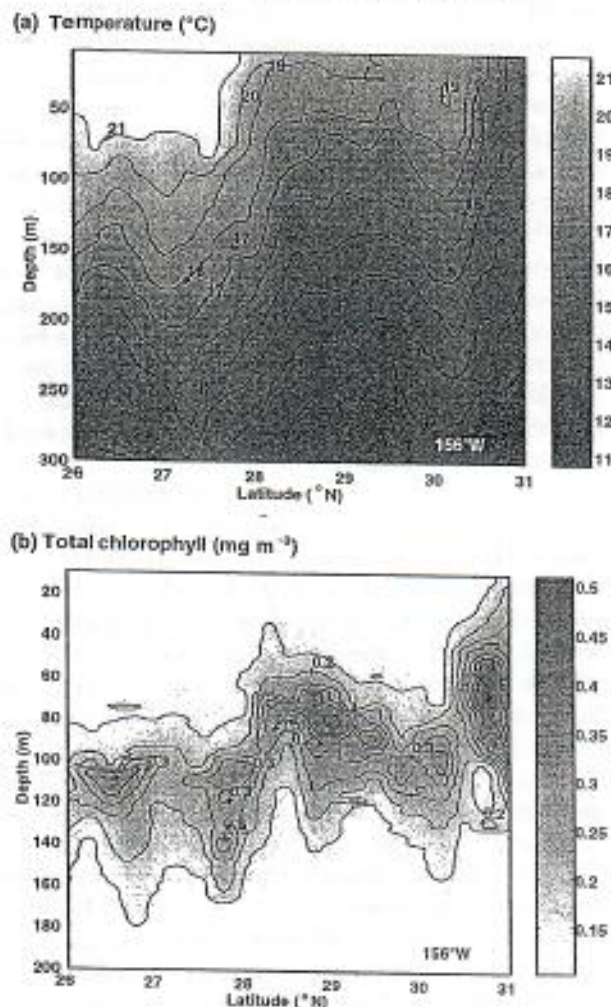
and around all turtles' locations from the observed environmental grid. A computer routine, 'grtrack', within Generic Mapping Tools (GMT) was used for the interpolation.

RESULTS

Tracks for all nine turtles over both 1997 and 1998 are shown in Fig. 2. They ranged from 26°N to 39°N latitude and from 164°E to 131°W longitude but most observations occur between 30–35°N latitude and 150–180°W longitude (Fig. 2). A series of location accuracy classifications are assigned to the reported turtle positions by Argos, computed as a function of the number and configuration of satellites and number of transmissions received for each position calculation. For the set of all of our loggerhead positions, we estimated the distance between the reported and true positions to be less than 1 km for about 57% of the positions, and at least 1 km for 37% of the positions, but the accuracy of the remaining 6% could not be determined. All position data were used in subsequent analyses. The dates of the positions cover all months except July, August and December, with most of the coverage from the period February to June. While we do not know the extent of trauma that turtles may incur from the hooking, in terms of time tracked and their speed, there does not appear to be any difference in performance between the two groups of turtles. For the five deeply ingesting turtles, their mean tracking duration was 4.5 months (range: 2.4–6.4 months) compared to 4.6 months (range: 2.2–6.9 months) for the four lightly hooked turtles. Mean speeds for the two groups of turtles were not statistically different at 30 cm s⁻¹ (SE 0.03 cm s⁻¹) and 35 cm s⁻¹ (SE 0.02 cm s⁻¹) for the lightly hooked and deeply ingesting groups, respectively ($P > 0.05$). Further, two turtles (nos 5 and 6, Fig. 2), one deeply ingesting and the other lightly hooked, were released within a day of each other and exhibit nearly identical tracks and speed over their entire 7-month tracking period (Fig. 2).

A histogram of the frequency of SST for all turtles' positions shows pronounced bimodality with modes at 17°C and 20°C. The bimodal distribution arises because some turtles associate with the cooler temperature and colleagues associate with the warmer temperature. Specifically, one group (denoted as the warm group) consisted of three turtles, two deeply ingesting and one lightly hooked, all from 1997, which consistently occupied warmer SST, lower chlorophyll, and stronger geostrophic currents than the other six turtles (Fig. 3). The other six turtles (denoted as the cool group), three deeply ingesting and three lightly

Figure 4. (a) Vertical temperature and (b) chlorophyll profiles measured from the Townsend Cromwell research cruise along 156°W longitude, 22–24 March 1997.



hooked, two from 1997 and four from 1998, consistently occupied relatively cooler water with higher chlorophyll and weaker geostrophic currents (Fig. 3). The mean SST, chlorophyll, and geostrophic current encountered by the two groups were statistically different for all three parameters (SST, chl $P < 0.01$, current $P < 0.05$). For the warm group the mean SST, chlorophyll, and geostrophic current were 20.7°C, 0.11 mg m⁻³, and 6.7 cm s⁻¹, respectively, compared with the means for the cool group of 17.6°C, 0.22 mg m⁻³, and 4.2 cm s⁻¹, respectively (Fig. 3). The SST encountered by the turtles tightly clusters around the modes for each group, 17°C and 20°C, with very little overlap (Fig. 3).

Oceanographic cruises and satellite remote sensing work recognize 20°C and 17°C, SST isotherms as indicators of two persistent fronts within the Sub-

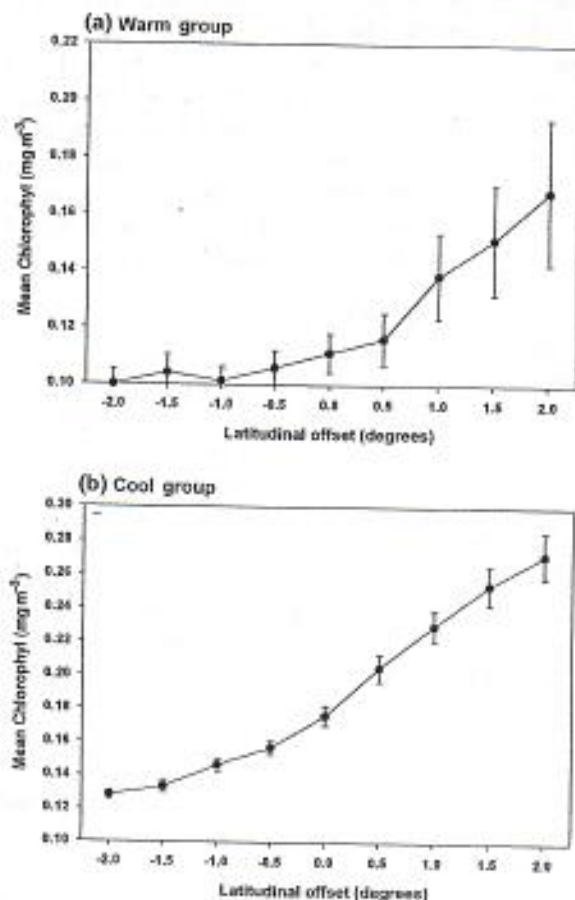
tropical Frontal Zone (Fig. 1) in the central North Pacific (Roden, 1991). For example, temperature–depth profiles from a cruise in March 1997 along 156°W longitude, through the centre of the area occupied by the turtle tracks, show that 20°C and 17°C surface temperatures occur at 28° and 30.5°N latitude as sharp temperature fronts formed when cool, dense water converges and sinks below warmer and lighter water to the south (Fig. 4) (Roden, 1991). Coincidentally, turtle no. 3 was at the 17°C front at 30.5°N and 156°W in March 1997 when the cruise track in Fig. 4 was conducted.

Seasonally, the 17°C and 20°C isotherms move north and south over 10 degrees of latitude (Roden, 1991). As the turtles travel westward they also appear to move north and south coherent with these isotherms. This coherence can be measured as the correlation, over all turtles' positions, between the latitude of the turtle and the latitude of the appropriate (17°C or 20°C) isotherm at the longitude of the turtle. The temporal correlation between the latitude of the six cool-group turtles and the latitude of the 17°C isotherm is 0.71 ($N = 676$), while this correlation for the latitude of the warm-group turtles and the 20°C isotherm is 0.84 ($N = 887$).

While specific SST levels can serve as indicators of fronts, fronts are primarily defined by horizontal gradients. We will further examine the position and movement of loggerheads with respect to horizontal gradients specifically in surface chlorophyll and sea surface height. While horizontal gradients in SST are also part of the fronts, the spatial resolution of our remotely sensed SST data does not generally capture sharp SST gradients.

We will first look at horizontal gradients in surface chlorophyll, which are particularly evident at the cooler 17°C, SST front (Fig. 4). Further, because most of the horizontal structure in the central North Pacific surface chlorophyll has primarily a meridional (north–south) rather than zonal (east–west) gradient, we can simplify the analyses by examining meridional gradients. Plots of chlorophyll north and south of each turtle's position have been averaged over all positions for all turtles in each group to provide a north–south profile of the chlorophyll habitat encountered by these turtles (Fig. 5). The turtle's average position lies along a chlorophyll gradient or front which increases most sharply to the north, indicating that the turtles occupy its south side (Fig. 5). The averaging of the chlorophyll over all turtles' positions and time smooths the meridional structure of the chlorophyll front. For an individual turtle from the cool group, we frequently see an even sharper increase in the monthly chloro-

Figure 5. Mean chlorophyll observed at all turtles' positions and one and two degrees north and south of those positions for (a) warm-group turtles and (b) cool-group turtles.



phyll density to the north of the turtle's position (Fig. 6). The close and continuous association between the latitude of the turtle and the front is shown from their coherence over time (Fig. 6). For example, in February the turtle and the southern edge of the front are at about 33°N latitude; in March both have moved about 200 km south to 31°N latitude; and then by June both are more than 300 km to the north at 34°N latitude (Fig. 6).

Another view of the association of loggerheads with the chlorophyll front is provided from their response to the seasonal movement of the front. The 0.2 mg m⁻³ chlorophyll density level is used as an indicator of the position of the chlorophyll front occupied by the six cool-group turtles (Figs 5, 6). In 1998, between the first and second quarters, the mean position of the front appears to have shifted northward by about 770 km, while in 1997 it shifted only about 330 km (Fig. 7). The two cool-group loggerheads we tracked in 1997 exhibited a largely westward movement along

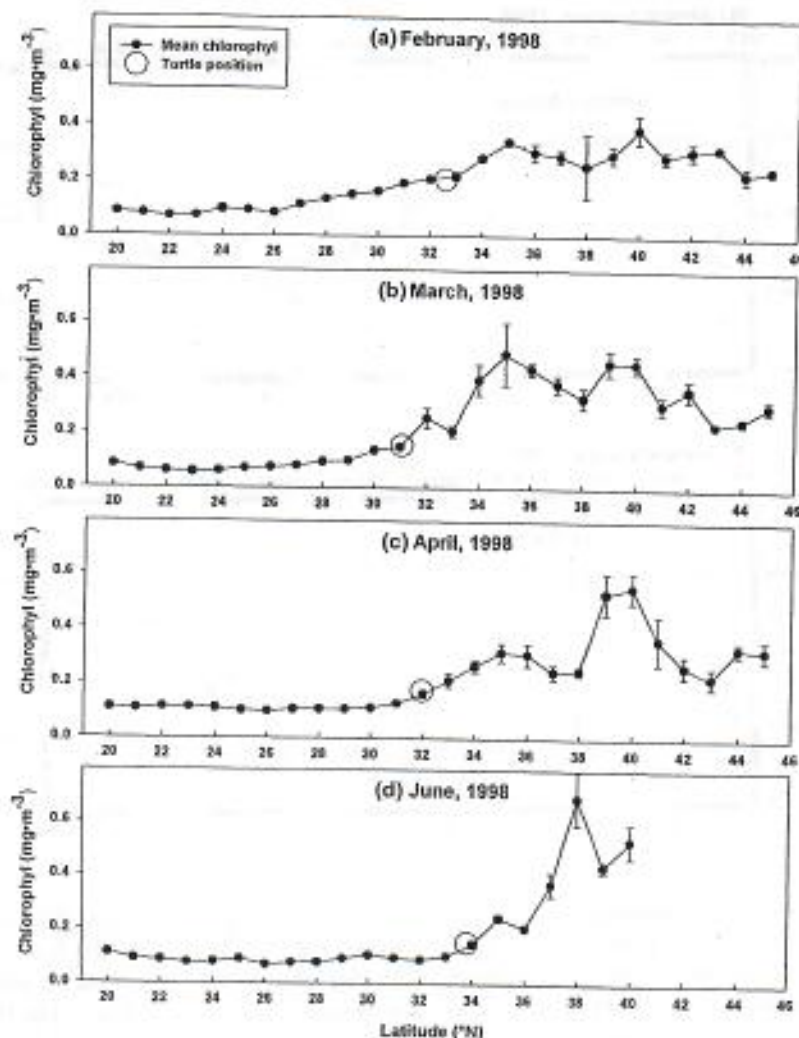
the relatively stationary front, whereas the four cool-group loggerheads tracked in 1998 showed a considerable northward movement, apparently in response to the rapid northward movement of the front (Fig. 7).

The association of loggerheads with fronts is also seen when we examine horizontal gradients in sea surface height. In particular, both fronts are characterized by geostrophic currents running from west to east along the frontal edge. These currents are the result of the drop in sea surface height across the front, with high sea surface height on the southern side of the convergence caused by warm, less dense water and low sea surface height on the north side owing to cool, denser water. As turtles swim along the front from east to west, they swim directly against this weak geostrophic current. For all nine turtles, movement is predominantly westward against a largely eastward geostrophic flow (Fig. 8).

A map of geostrophic currents in mid-May 1997 shows geostrophic currents associated with fronts and eddies (Fig. 9). Two west-to-east-flowing currents are seen beginning at about 36°N latitude and 180°W longitude, with one continuing due east at about 34°N latitude while the other dips south reaching 28°–30°N latitude at about 165°W longitude (Fig. 9). The track lines of two warm-group turtles over the period March–July 1997 are superimposed with the geostrophic currents for mid-May 1997 (Fig. 9). The geostrophic currents do not vary appreciably over the time period covered by the turtles' track lines; therefore, the 10-day current snapshot provides a good estimate of the current over the entire period of the tracks. The currents and tracks show that the two turtles following the southern current generally swam directly against the weak current of up to 10 cm s⁻¹ for 5 months (Fig. 9). Transmission from one of these turtles ceased in July but the remaining one continued, and its track line during July–October 1997 is superimposed with the geostrophic currents estimated in mid-September 1997 (Fig. 9). As this turtle, which at 81 cm carapace length was the largest of the nine turtles and possibly sexually mature, continued westward past the dateline it encountered stronger currents of the Kuroshio Current Extension (Fig. 9). In the presence of the stronger flow, it avoided swimming directly against currents in excess of 25 cm s⁻¹ and instead stayed to the edge of the strong flow except to cross it (Fig. 9).

Turtle speed and direction are computed from the change between estimated locations from each satellite fix, generally at daily intervals. These estimates of speed and direction assume the turtle moves in a straight line at a constant rate between the two posi-

Figure 6. Latitude of turtle ID no. 6 in (a) February, (b) March, (c) April, and (d) June 1998, together with surface chlorophyll density north and south of the mean monthly turtle position.



tions. We don't have any evidence that the turtle meanders widely between adjacent positions, but if this were the case, the estimated speed would underestimate the true speed.

All the turtles travelled primarily westward with a mean velocity of about -20 cm s^{-1} (20 cm s^{-1} to the west, 0.7 km h^{-1}) (Fig. 10). There was both north and south movement, with a mean of about 0 (Fig. 10). Total turtle speed averaged about 33 cm s^{-1} (1.2 km h^{-1}) with speeds of $50\text{--}80 \text{ cm s}^{-1}$ observed but not common (Fig. 10). The geostrophic currents they swam against averaged only about 5 cm s^{-1} , or about 1/7 of their speed.

The Hawaii-based longline surface swordfish fishery incidentally catches loggerhead, primarily during the first and second quarters of the year. To discover how much the fishery for swordfish overlaps with the same fronts used by the loggerheads, we examined the SST distribution of surface longline sets. The spatial dis-

tribution of surface longline sets in the Hawaii-based fishery indicates that effort is distributed between 175°W and 145°W longitude. During the first quarter, the longline sets are largely between the 17°C and 20°C , SST fronts used by loggerheads (Fig. 11). During the second quarter, the fishery is well to the south of the 17°C SST front but overlapping the 20°C SST front (Fig. 11). The fishery is targeting swordfish, which are believed to be moving south through the fronts, perhaps following squid, which constitute their primary prey. The distribution of SST occupied by the loggerheads tracked during the first quarter of 1997 and 1998 shows a mean of 17°C but considerable overlap with the SST occupied by the fishing fleet in the northern portion of the fishing ground (Fig. 11). While none of our tracked turtles moved along the 20°C front through the fishing ground during the first quarter, the position of the 20°C SST isotherm in the southern part of the fishing ground implies that log-

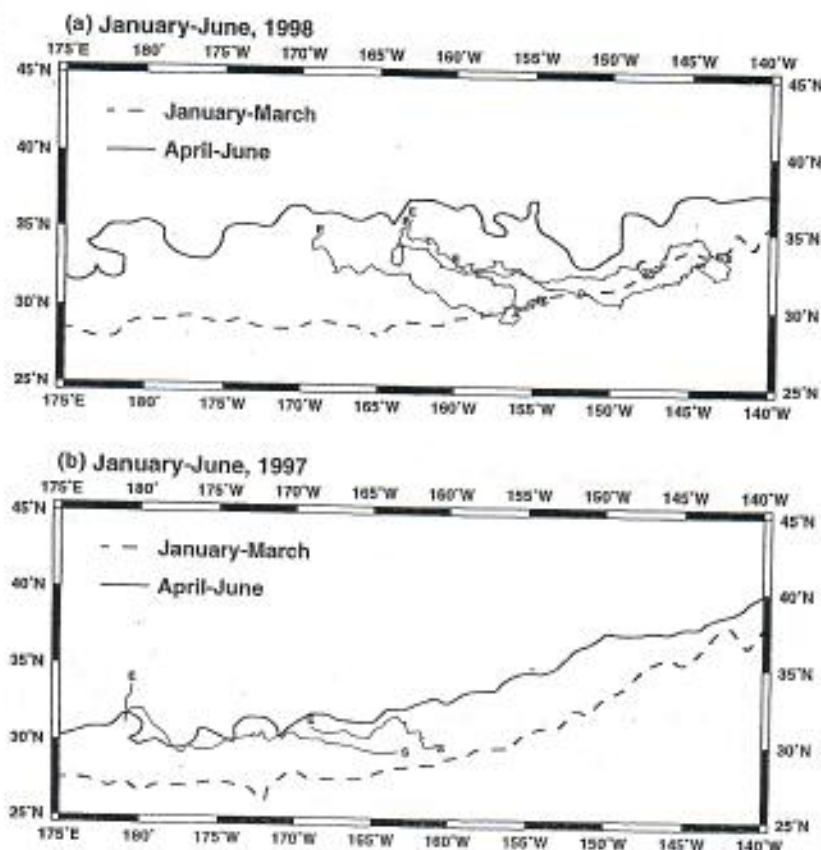


Figure 7. Positions of surface chlorophyll fronts and tracks of cool-group turtles for first and second quarters of 1997 and 1998. 'S' and 'E' denote starting and ending positions of each turtle's track. The dashed and solid lines mark the mean positions of the 0.2 mg m^{-3} chlorophyll front in the first and second quarters, respectively.

loggerheads following the 20°C front will move through the southern portion of the fishing ground (Fig. 11). In the second quarter, loggerheads following the 17°C front will likely be well north of the fishing ground, but those following the 20°C front will be within the fishing ground (Fig. 11).

DISCUSSION AND CONCLUSIONS

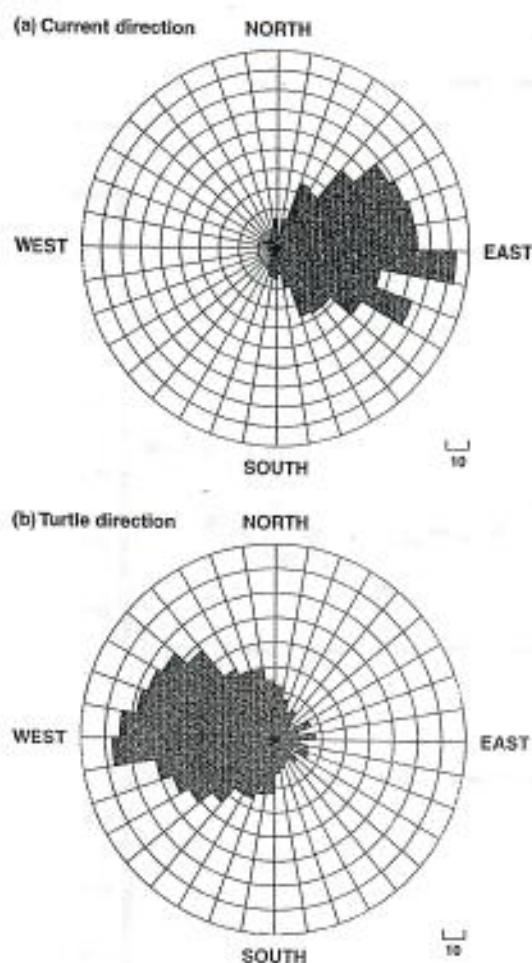
While earlier work has speculated that fronts are important habitat for juvenile loggerheads (Carr, 1987), we provide evidence that describes the habitat of loggerheads in the central North Pacific as being strongly linked to fronts. In particular, three of the loggerheads were associated with a front characterized by SST of about 20°C , an eastward geostrophic current of about 7 cm s^{-1} , and 0.1 mg m^{-3} surface chlorophyll. The other six loggerheads were associated with a front further to the north, with an SST of about 17°C , characterized as a sharp surface chlorophyll front with a mean of 0.2 mg m^{-3} and a mean eastward geostrophic flow of 4 cm s^{-1} . The 17°C SST front with its sharp surface chlorophyll gradient would appear to be an especially productive site for surface-feeding organisms based on a food chain driven by the high

phytoplankton density converging from the north side of the front.

Diet studies of loggerheads add support to our evidence that they are foraging at the convergent fronts. Stomach analyses from 55 loggerheads caught in the high-seas drift net fishery in the central North Pacific (Wetherall et al., 1993) suggest that loggerheads are opportunistic, omnivorous predators of the neuston layer, both consuming floating prey and grazing on items attached to floating objects (Unpublished data, Honolulu Lab, NMFS). The most common floating prey included the predatory gastropod *Janthina* sp. and its prey, *Vellela vellela* ('by the wind sailor'), while common prey items typically associated with floating objects included gooseneck barnacles, *Lepas* sp. and the pelagic crab *Planes cyanus*, which ride on logs, floats, and often *V. vellela*. The only common diet item not found exclusively at the surface was the heteropod *Carinaria cithara*. All these prey items would likely be concentrated at convergent fronts as a result of physical processes (convergence and weak downwelling) associated with the fronts and would themselves find prey at the front (Bakun, 1996).

While the use of fronts as forage habitat has been indicated for some tunas and billfishes, there is con-

Figure 8. (a) Polar histogram of the direction of geostrophic current at all recorded positions of all nine turtles. (b) Movement direction at all recorded positions for the nine turtles.



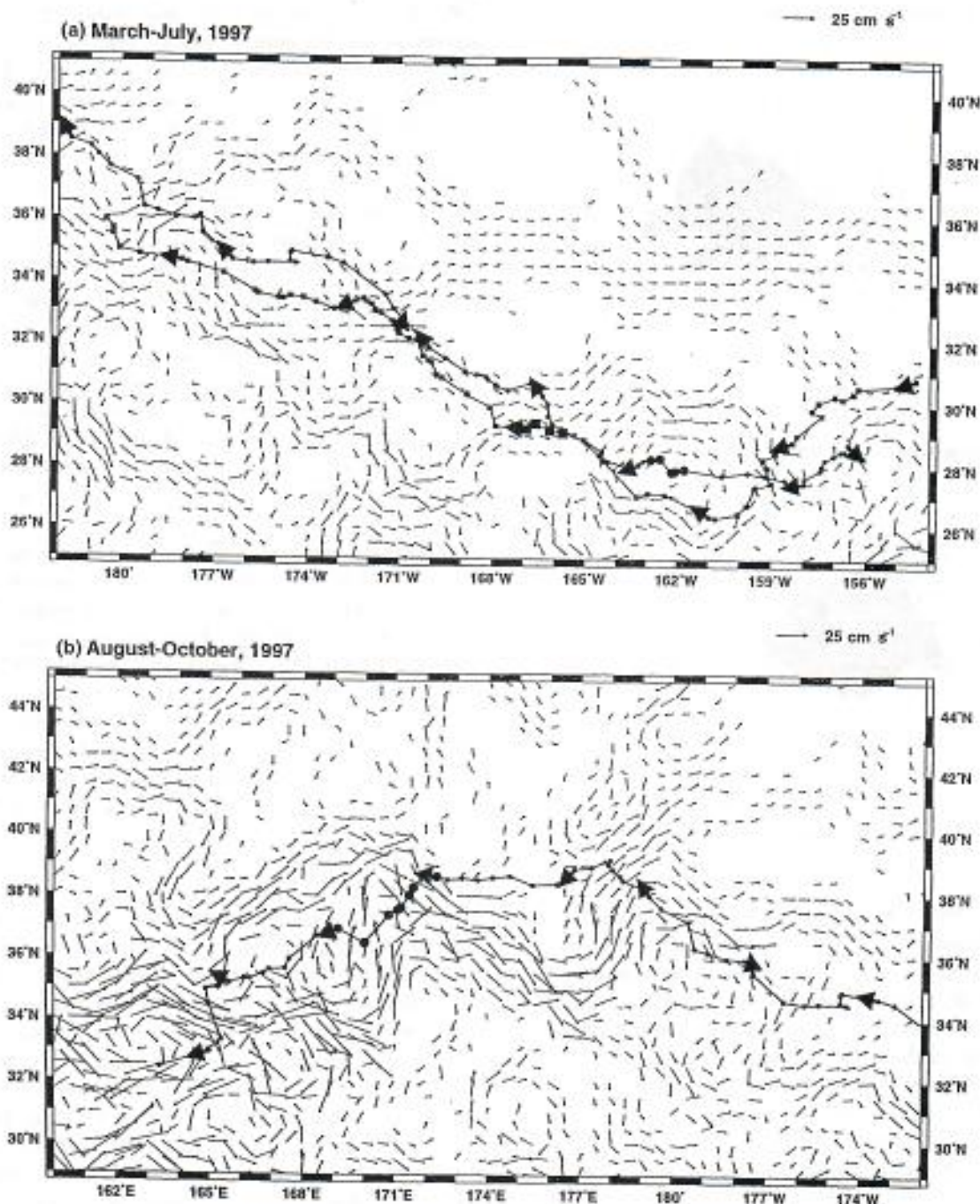
siderable debate regarding the extent that fronts are used as migratory pathways (Olson *et al.*, 1994). Our results show that the westward movement of loggerheads in the central North Pacific occurs along fronts, moving north and south to stay with a specific front. Horizontal gradients in temperature, current, chlorophyll, and possibly prey abundance levels around the fronts may provide cues that loggerheads would use to maintain their association with fronts.

The geostrophic current estimated with TOPEX/Poseidon is a clear indication of a front, but our estimate, derived from the altimeter, of current velocities encountered by the turtles is based on two conditions: firstly, that the satellite-derived estimates of geostrophic current are accurate; and secondly, that other components of the surface current, specifically wind-driven surface (Ekman) transport, are not significant.

While ground-truthing of TOPEX/Poseidon currents in the Subtropical Frontal Zone has not been conducted, several comparisons between TOPEX/Poseidon estimates of geostrophic current and estimates derived from at-sea sampling and drifters find good agreement in the western and central North Pacific (Yu *et al.*, 1995; Mitchum, 1996). Regarding Ekman transport, a study of the circulation with satellite-tracked drifters in the same region as occupied by our tracked loggerheads indicates that Ekman transport is minimal and in the same direction as geostrophic current, thus geostrophic current provides a good description of the surface circulation in this area (Niiler and Reynolds, 1984). Specifically during the winter, surface drifters travelled eastward at an average speed of $3\text{--}4\text{ cm s}^{-1}$, with occasional speeds of 30 cm s^{-1} . Further, the drifters travelled along the contours of sea surface height, indicating that geostrophic current is the dominant component of the surface flow, and hence, the estimates we derived from TOPEX/Poseidon satellite altimetry are consistent with those observed from drifting buoys (Niiler and Reynolds, 1984).

Hypotheses regarding migrations of juvenile loggerheads in both the Atlantic and Pacific assume that they travel with the prevailing currents, rather than actively swimming against them (Bowen *et al.*, 1995; Hays and Marsh, 1997; Musick and Limpus, 1997). In contrast, all nine of our loggerheads, ranging in size from 41.0 to 81.0 cm carapace length, swam westward along the northern side of the subtropical gyre against the prevailing currents and specifically against geostrophic currents at the edge of fronts. However, the geostrophic currents they opposed averaged only about 1/7 of their swimming speed. Perhaps by swimming into the weak current the loggerheads increased their encounter rate of prey sufficiently to offset their increased energy expenditure. It is intriguing that all the turtles' movements are predominately westward. At some point, these juvenile turtles will return to the east. Two of the turtles, nos 5 and 6, began some eastward movement in July and August, just before their transmissions ended, suggesting an eastward movement during the second half of the year. However, three other turtles, nos 3, 4 and 9, tracked during the second half of the year, showed only westward movement (Fig. 2, Table 1). Further tracking with transmitters that function longer to increase the temporal coverage or initiating tracking in the western North Pacific will be necessary to understand loggerhead spatial and temporal patterns completely. The turtles' speed we estimated in this study, averaging 1.2 km h^{-1} , is similar to that observed in other log-

Figure 9. (a) Tracks of movement of loggerheads ID nos 3 and 4 during March–July 1997, together with geostrophic currents during 15–25 May 1997. (b) Track of movement of loggerhead ID no. 4 during August–October 1997, together with geostrophic current during 11–21 September 1997. Large circles and squares on the track lines indicate position of turtles during the same 10-day time period for which the geostrophic currents are calculated. Arrows on track lines show turtle movement direction.

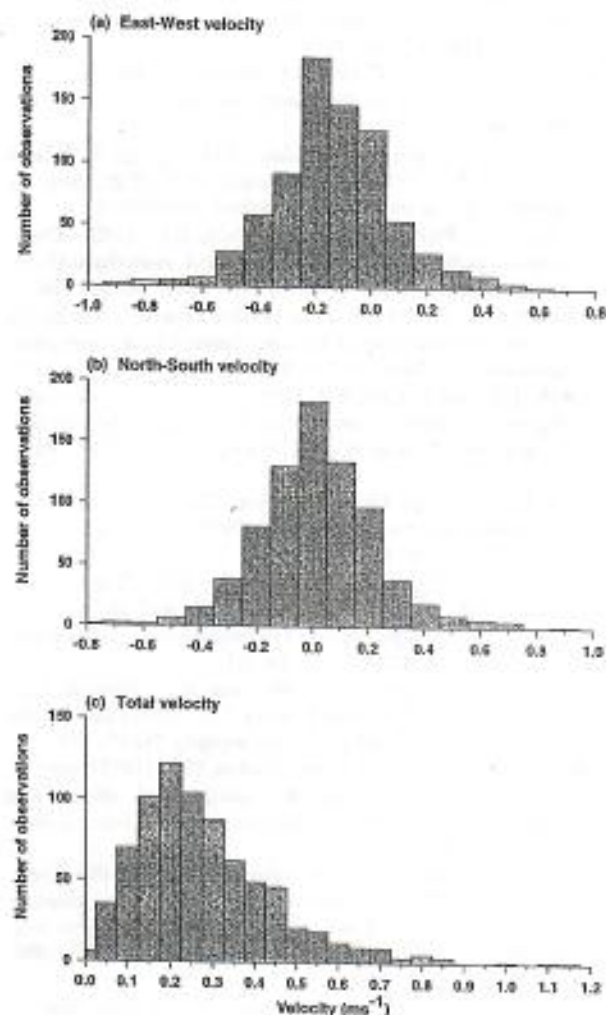


gerhead studies (Byles and Dodd, 1989; Papi *et al.*, 1997).

Data on incidental catches of loggerheads in the Hawaii-based longline fishery recorded by onboard NMFS observers indicate that during the first quarter of

the year, the highest capture rates occur at about 17°C SST whereas during the second quarter the highest capture rates occur at about 20°C SST (P. Kleiber, Honolulu Lab, NMFS, pers. comm.). Our findings that loggerhead use the 17°C and 20°C SST fronts,

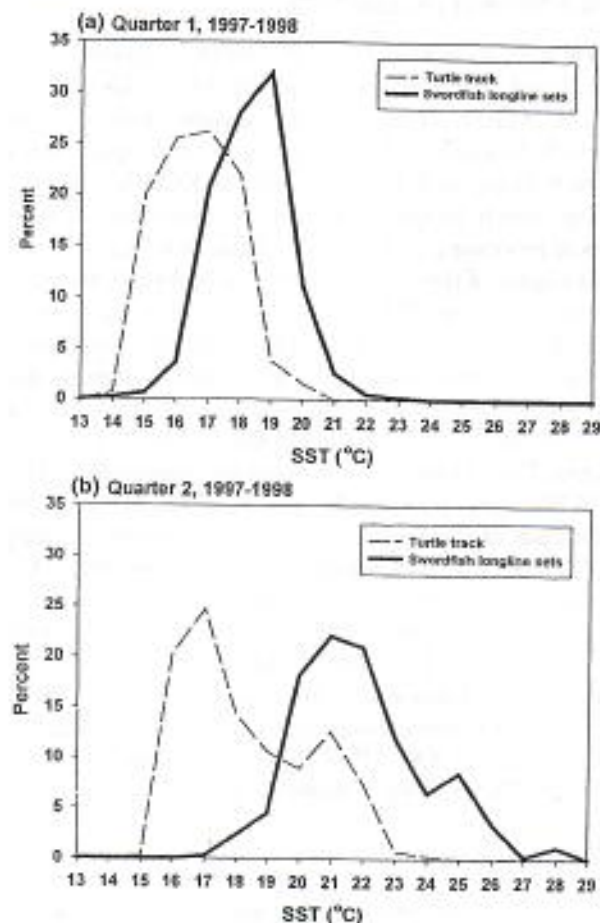
Figure 10. Frequency distribution of turtles' movement in (a) east-west direction, (b) north-south direction, and (c) absolute velocity.



together with the quarterly distribution of fishing effort in the longline fishery, explain this pattern.

Initially, these findings do not appear to offer any simple way to reduce overlap between the fishing ground and turtle habitat without closing a large portion of the fishing ground. For example, in the first quarter the spread of loggerheads around their two fronts at the north and south of the fishing ground will likely cover the entire fishing ground, making it impractical to restrict the fishing ground sufficiently away from the two fronts. Likewise, in the second quarter a large portion of the fishing ground around the 20°C front would have to be closed to reduce incidental catches at this front. However, data from onboard observers indicate that interaction rate, turtles per longline set, is substantially greater at

Figure 11. SST distribution of Hawaii-based longline effort for swordfish during (a) first quarter and (b) second quarters of 1997 and 1998, together with the distribution of SST occupied by the loggerheads tracked in the fishing grounds during the same period.



17°C, SST than at 20°C SST (P. Kleiber, Honolulu Lab, NMFS, pers. comm.). This may indicate that a higher density of loggerheads are found at the 17°C front than at the 20°C front. If this is the case, then incidental catches of loggerheads in the longline fishery may be reduced by keeping the fishery away from the 17°C front. This could be achieved by an area closure based on SST, because all longline boats have temperature recorders. The approach would be to prohibit fishing in water colder than 18°C or 18.5°C. Alternatively, because the fishery and the 17°C front overlap to a large extent only during the first quarter, a closure of the fishery during some portion of the first quarter would also separate the fishery and the front.

Finally, this study shows the power of combining data from instruments on animals that describe their

movements together with remotely sensed environmental data covering the region around the animal during its movement to describe its habitat and its movement relative to oceanic features.

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Forage and migration habitat of loggerhead (*Caretta caretta*) and olive ridley (*Lepidochelys olivacea*) sea turtles in the central North Pacific Ocean

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ABSTRACT

Satellite telemetry from 26 loggerhead (*Caretta caretta*) and 10 olive ridley (*Lepidochelys olivacea*) sea turtles captured and released from pelagic longline fishing gear provided information on the turtles' position and movement in the central North Pacific. These data together with environmental data from satellite remote sensing are used to describe the oceanic habitat used by these turtles. The results indicate that loggerheads travel westward, move seasonally north and south primarily through the region 28–40°N, and occupy sea surface temperatures (SST) of 15–25°C. Their dive depth distribution indicated that they spend 40% of their time at the surface and 90% of their time at depths <40 m. Loggerheads are found in association with fronts, eddies, and geostrophic currents. Specifically, the Transition Zone Chlorophyll Front (TZCF) and the southern edge of the Kuroshio Extension Current (KEC) appear to be important forage and migration habitats for loggerheads. In contrast, olive ridleys were found primarily south of loggerhead habitat in the region 8–31°N latitude, occupying warmer water with SSTs of 23–28°C. They have a deeper dive pattern than loggerheads, spending only 20% of their time at the surface

and 60% shallower than 40 m. However, the three olive ridleys identified from genetics to be of western Pacific origin spent some time associated with major ocean currents, specifically the southern edge of the KEC, the North Equatorial Current (NEC), and the Equatorial Counter Current (ECC). These habitats were not used by any olive ridleys of eastern Pacific origin suggesting that olive ridleys from different populations may occupy different oceanic habitats.

Key words: loggerhead turtle, olive ridley turtle, pelagic habitat, turtle migration

INTRODUCTION

While it is known from incidental hookings by fishing gear that loggerhead (*Caretta caretta*) and olive ridley (*Lepidochelys olivacea*) sea turtles occupy oceanic regions, far from coastal habitats, their forage and migration habitat in these oceanic regions have not been well described. In the Pacific, loggerheads travel between their nesting beaches in Japan and Australia and foraging habitat in the eastern Pacific. Genetic analyses of the loggerheads off Baja California concluded that 95% came from Japanese nesting beaches and 5% from nesting colonies in Australia (Bowen *et al.*, 1995). Data on the location and movement of nine loggerhead turtles tracked during 1997–98 in the central North Pacific by satellite telemetry indicated that oceanic fronts, particularly the chlorophyll front known as the Transition Zone Chlorophyll Front (TZCF), provided mid-oceanic forage and migration habitat for juvenile loggerheads in the central Pacific (Polovina *et al.*, 2000, 2001).

Olive ridleys are regarded as the most abundant sea turtles in the world with the largest nesting population occurring in the Indian Ocean along the north-east coast of India. The second largest nesting population is located in the eastern Pacific, along the west coasts of Mexico and Central America (National Marine Fisheries Service and US Fish and Wildlife Service, 1998). Genetic analysis has shown that olive ridleys from both western and eastern Pacific nesting populations

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forage in the central North Pacific (Dutton *et al.*, 1999).

During 1997–2001 observers on Hawaii-based longline fishing vessels attached Argos satellite-linked transmitters to juvenile loggerhead and juvenile olive ridley turtles caught by longline gear. We investigated the oceanic habitat and movements of these two species of turtles based on satellite telemetry of 26 loggerheads, including nine loggerheads used in Polovina *et al.* (2000), and 10 olive ridleys together with information on their oceanic habitats obtained from satellite remotely sensed and ship-based oceanographic data.

DATA AND METHODS

The Argos-linked Telonics (Mesa, AZ, USA) ST-10 or ST-18 position transmitters were attached to 32 turtles. Additionally, two loggerhead and two olive ridley turtles were instrumented with a Wildlife Computer (Redmond, WA, USA) Argos-linked satellite transmitter with dive recorder capabilities (SDR-T10). This transmitter provides, in addition to position data, three frequency distributions for each of four 6-h time periods. One frequency distribution presents the distribution of time spent in each of 14 preset depth bins. The second frequency distribution contains the distribution of the duration of each dive. The third frequency distribution contains the distribution of the maximum depth for each dive. The 6-h periods were 21:00–03:00, 03:00–09:00, 09:00–15:00, and 15:00–21:00 hours, Hawaii standard time. The lower range of the depth bins (in meters) were: 1, 3, 5, 10, 15, 25, 35, 50, 60, 75, 100, 125, 150, 150+. Personnel of the National Marine Fisheries Service's Observer Program attached transmitters to the turtles onboard commercial fishing vessels. They used fiberglass cloth and resin to attach the transmitter as recommended by Balazs *et al.* (1996).

The Argos transmissions ranged from 30 to 458 days and spanned the time period from January 1997 to August 2001 for a total of 2470 transmission-days. Transmitters had 3 duty cycles, i) 2 h on, 4 h off, ii) 12 h on, 48 h off, iii) 24 h on, 216 h off. The reasons the transmissions ended are not known but they could have been caused by failure or detachment of the transmitter, depletion of battery power, or the death of a turtle. All loggerheads used in this study were determined by genetic analysis to have come from Japanese nesting beaches. Genetic analyses of nine of the tracked olive ridleys showed that six (67%) came from eastern Pacific nesting beaches and the remaining three came from the western Pacific. Three of the

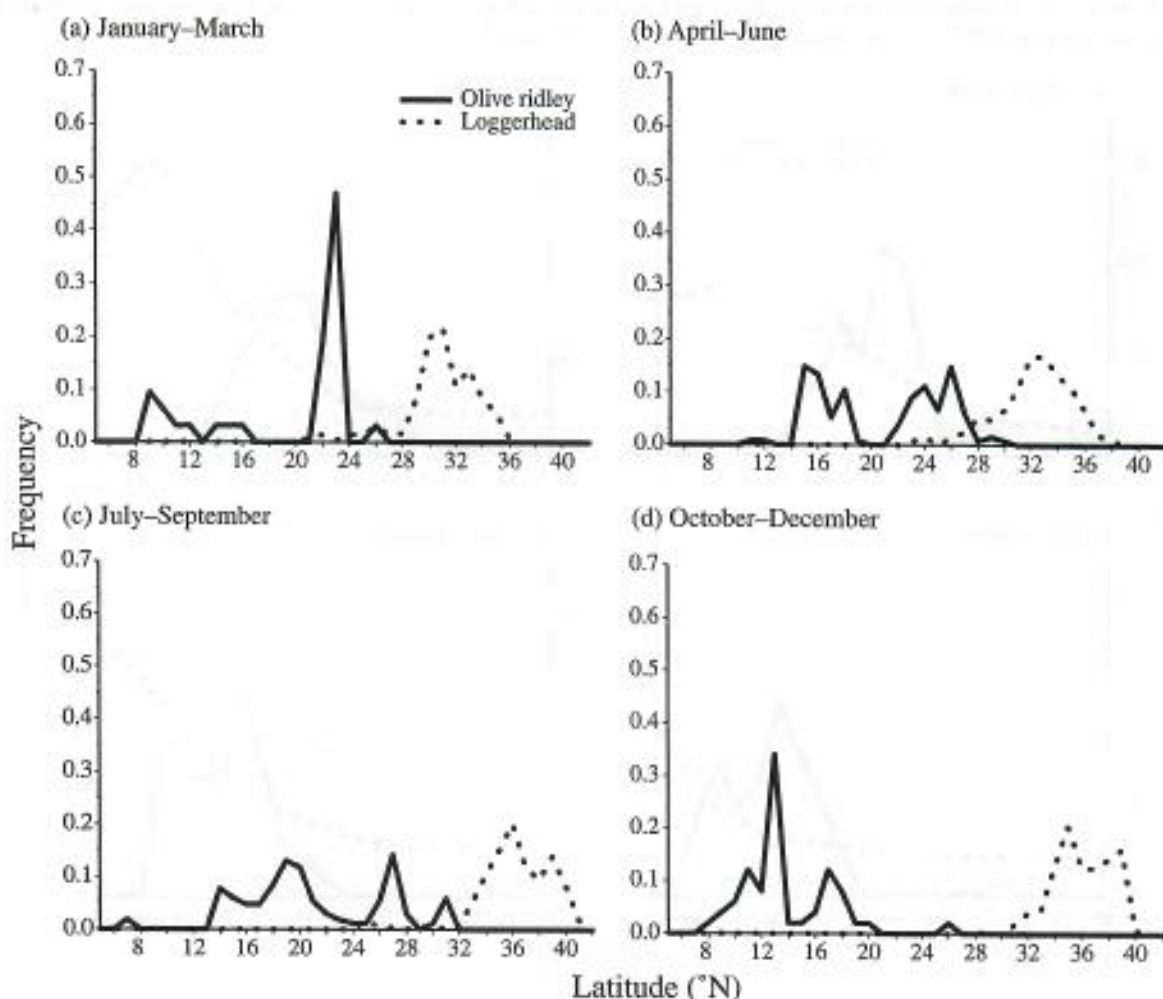
loggerheads [83, 83 and 81 cm straight carapace length (SCL)] and two of the olive ridleys (66 and 61 cm SCL) may have been large enough, based on their carapace lengths, to be sexually mature; however, all the other turtles were likely immature.

The physical and biological environmental data used to describe the environment at and around the migrating loggerheads and olive ridleys are sea surface temperature (SST), surface chlorophyll *a* concentration, and geostrophic current. The SST data were multichannel SST (MCSST) from the University of Miami, with weekly temporal resolution and one-tenth of one degree of longitude and latitude spatial resolution. Global comparisons between MCSST and ship-based temperature measurements indicated that MCSST is 0.3–0.4°C lower than ship-based temperature with cross-correlations ranging from +0.3 to +0.7 (McClain *et al.*, 1985). Chlorophyll *a* concentration was estimated from the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) version 2 data (O'Reilly *et al.*, 1998). The data resolution was monthly, September 1997–August 2001, at 0.088° latitude and longitude. The accuracy of SeaWiFS chlorophyll estimates were within 30–50% of ship-based observations (McClain *et al.*, 1998). Geostrophic currents were computed from satellite altimetry data from TOPEX/Poseidon with 10-day and 0.5° latitude and longitude resolution (Polovina *et al.*, 1999). Comparisons between current speed determined from an acoustic Doppler current profiler along TOPEX/Poseidon track lines around the Hawaiian Archipelago agreed with estimates from TOPEX/Poseidon to within a few cm s^{-1} (Mitchum, 1996).

The environmental data were linked to the turtle's position by spatial interpolation between grid points. Specifically, a cubic polynomial was used to estimate the environmental data at and around all turtle locations from the observed environmental grid. A computer routine, 'grdtrack,' within the software package Generic Mapping Tools (GMT) (<http://gmt.soest.hawaii.edu>) was used for the interpolation. Finally, data on subsurface temperature and chlorophyll in the region occupied by loggerhead and olive ridley turtles were obtained from two shipboard oceanographic transects.

A series of location accuracy classifications was assigned to the reported turtle positions by Argos, and then computed as a function of the number and configuration of satellites and number of transmissions received for each position calculation. In our subsequent analyses, when there were multiple Argos positions at different times of the day for the same turtle, we selected the most accurate position. If two

Figure 2. Quarterly latitude–frequency distributions for loggerheads (dashed) and olive ridleys (solid), pooled for 1997–2001.

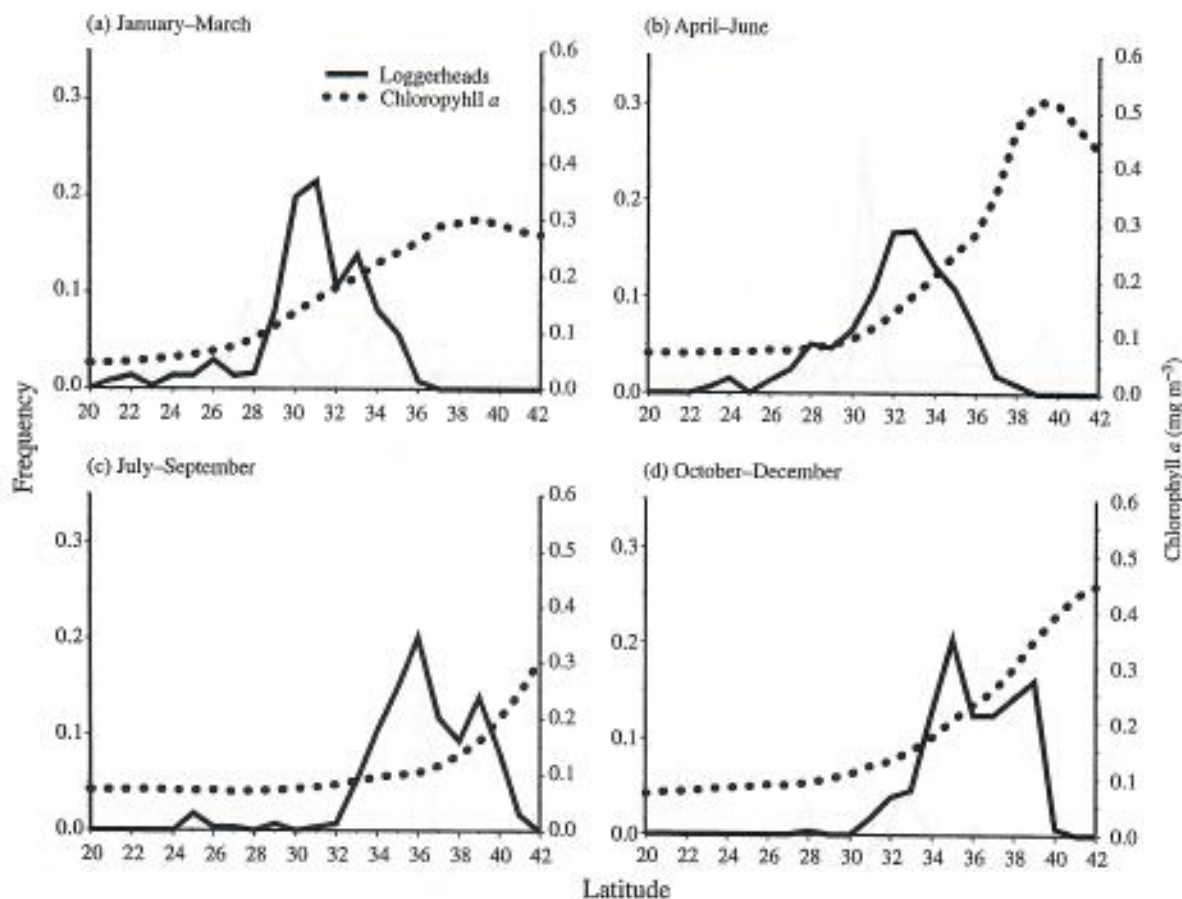


range, 23–28°C during all quarters, but within that range they appeared to be found centered at 24 and 27°C (Fig. 3). Loggerheads occupied cooler water and covered a broader 10°C SST range, 15–25°C, occupying cooler temperatures in winter and spring and warmer temperature in the summer (Fig. 3). Many of the turtles remained in very narrow SST ranges during their entire transmission time, while others occupied SSTs throughout the broader ranges shown for pooled quarterly SST–frequency distributions.

A relationship between loggerhead habitat and the sharp gradient in surface chlorophyll, termed the TZCF, has been observed (Polovina *et al.*, 2000, 2001). The TZCF represents the boundary between the stratified low surface chlorophyll (<0.15 mg m⁻³) waters of the Subtropical Gyre and the high surface chlorophyll (>0.3 mg m⁻³) vertically mixed waters in the Transition Zone and Subarctic Gyre. A chloro-

phyll level of 0.2 mg m⁻³ was used to locate this feature (Polovina *et al.*, 2001). The relationship between the TZCF and loggerheads is further examined here with comparison between the quarterly loggerhead latitude–frequency distribution and the mean quarterly surface chlorophyll density by latitude, estimated from SeaWiFS, pooled from 1997 to 2001, and averaged over the region 160°E–140°W (Fig. 4). These plots indicated that during all quarters a substantial portion of the loggerhead distribution included the TZCF as indicated by the sharp gradient in surface chlorophyll centered on the mean 0.2 mg m⁻³ (Fig. 4). Further there was agreement between the seasonal north–south movement of the region of sharp chlorophyll gradient and the seasonal shift in the latitudinal distribution of the loggerhead positions. However, a substantial portion of the latitude–frequency distribution was located south of the TZCF

Figure 4. Quarterly latitude–frequency distributions for loggerheads (solid) and surface chlorophyll density from SeaWiFS by latitude averaged over 1997–2001 and between 160°E and 140°W longitude (dashed).



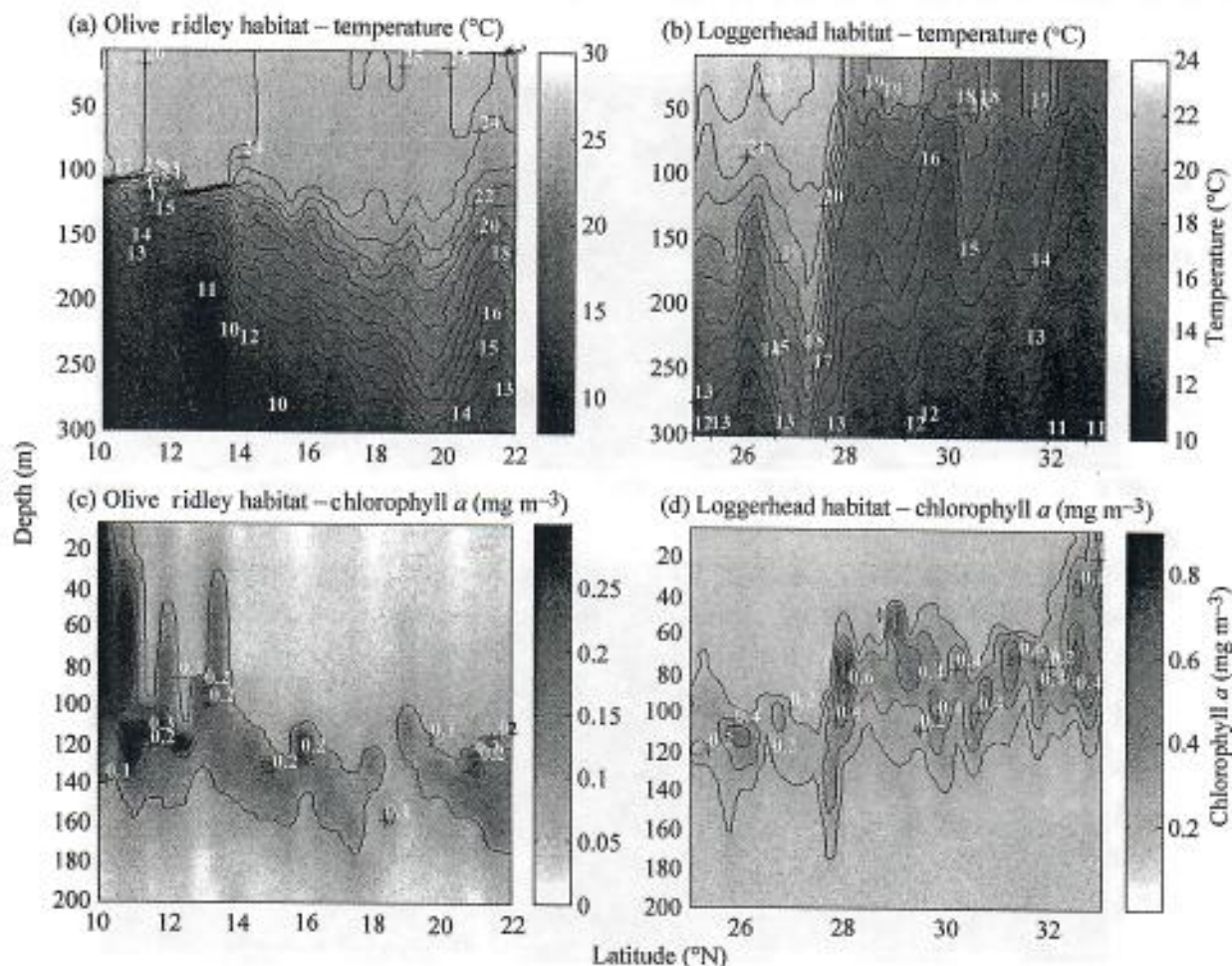
depth bin was 150 m, it is not known how deep the turtles dove below 150 m.

The Wildlife Computer dive depth transmitters did not record temperature; however, temperature and chlorophyll profiles as a function of depth were available from two oceanographic surveys. One survey in April 1998 provided a meridional depth section north of Hawaii, covering 25–34°N latitude, the region of loggerhead habitat, and reaching the TZCF at 32°N latitude (Fig. 6). The second survey in April 2001 provided a depth section south of Hawaii from 10 to 22°N latitude, including much of the region of olive ridley habitat and reaching the North Equatorial Current (NEC) at about 10°N (Fig. 6). The temperature–depth profiles indicated important differences between the thermal structure in the loggerhead and the olive ridley habitats. The olive ridley habitat was characterized by a deep thermocline at 100 m and minimal horizontal surface temperature fronts (Fig. 6). In contrast, the loggerhead habitat was characterized

by a shallow thermocline at 50 m and several strong horizontal surface temperature fronts at 20 and 17°C located at 28 and 32°N, respectively (Fig. 6). Similar depth differences in the chlorophyll–depth profiles were also observed, with the subsurface chlorophyll maximum above 100 m in the loggerhead habitat and reaching the surface at 33°N when it became the TZCF, a key feature for loggerhead habitat (Fig. 6). In the region of olive ridley habitat between 12 and 22°N latitude, the chlorophyll maximum was deeper than 100 m, although it shoaled to the surface at 10°N latitude at the northern edge of the NEC (Fig. 6).

Among the 26 loggerheads and 10 olive ridleys, one loggerhead and one olive ridley were remarkable in having transmitters that worked much longer than those of all the other turtles in their groups and hence provided our longest movement data. The loggerhead (60.0 cm SCL) traveled over 9000 km during 458 days, more than twice the distance of any other loggerhead, and the olive ridley (52.0 cm SCL)

Figure 6. Temperature depth and chlorophyll depth plots for (a) olive ridley habitat (10–22°N latitude, April 21–30, 2001), and (b) loggerhead habitat (25–34°N latitude, April 24–May 1, 1998).



meanders and eddies represent regions of enhanced surface chlorophyll as seen from surface chlorophyll estimated from SeaWiFS data for February 2001 (Fig. 9). The two cyclonic eddies at 165 and 180°E and the meander at 170°E seen in the altimetry data for February 12–22 are regions of enhanced surface chlorophyll (Fig. 9). The loggerhead remained for 3 months along the edge of the meander and eddy at 170°E which represents surface convergence zones and a likely site of concentrated prey for the loggerhead (Figs 8 and 9).

The olive ridley traveling the longest distance was identified as having hatched on a western Pacific nesting beach. This turtle also went westward from Hawaii well past the dateline and showed some north-south movement as well (Fig. 7). As it headed westward, this turtle dipped south in December and January and for 40 days rode westward on the NEC (Fig. 10). While in the NEC it traveled westward at an

average speed of 71 cm s⁻¹ (SE 12 cm s⁻¹, *N* = 73) compared with an average speed of 48 cm s⁻¹ (SE 6 cm s⁻¹, *N* = 37) outside the NEC. The speed of the NEC at the daily positions of the olive ridley during its 40 days in the NEC, estimated from Topex/Poseidon satellite altimetry, was 32 cm s⁻¹ (SE 3 cm s⁻¹). When the olive ridley was in the NEC it traveled at about 71 cm s⁻¹ and as the NEC traveled at only 32 cm s⁻¹, the turtle appeared to be actively swimming and not just drifting as it rode the NEC.

This olive ridley is not the only one to use the equatorial currents. A second olive ridley, the easternmost track line in Fig. 1, used both the Equatorial Counter Current (ECC) and the NEC. It traveled eastward along the eastward-flowing ECC in September and then north and westward during October and November in the NEC (Fig. 11). The two olive ridleys that used the NEC and the ECC were identified from genetic analysis to be of western Pacific origin. The

Figure 8. Geostrophic currents and sea surface height estimated from Topex/Poseidon satellite altimetry together with the track line and positions (dots) of the loggerhead turtle for (a) February 12–22, (b) March 13–23, and (c) April 12–22, 2001. The Kuroshio Extension Current is apparent as the strong eastward flow at 35°N.

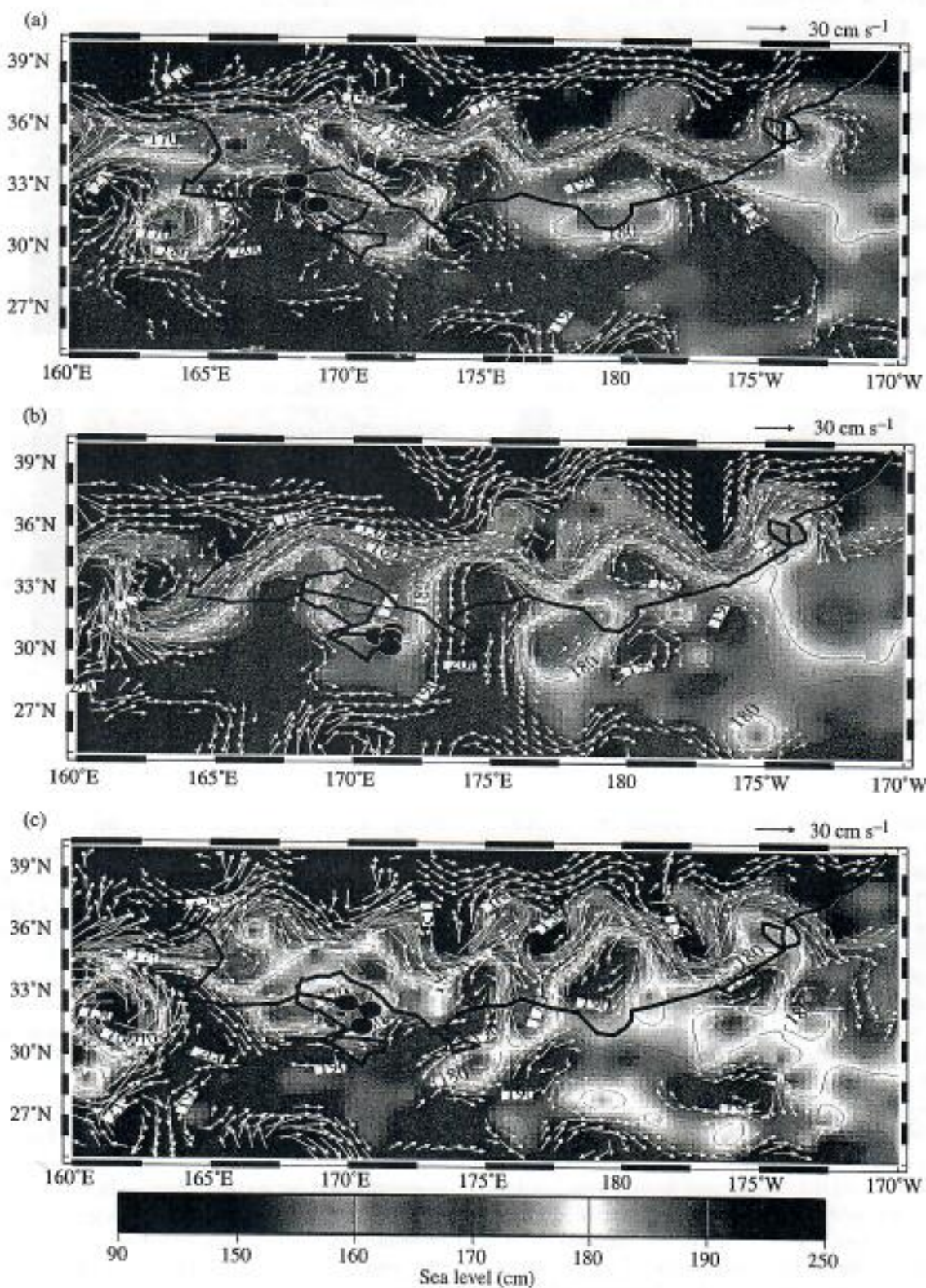
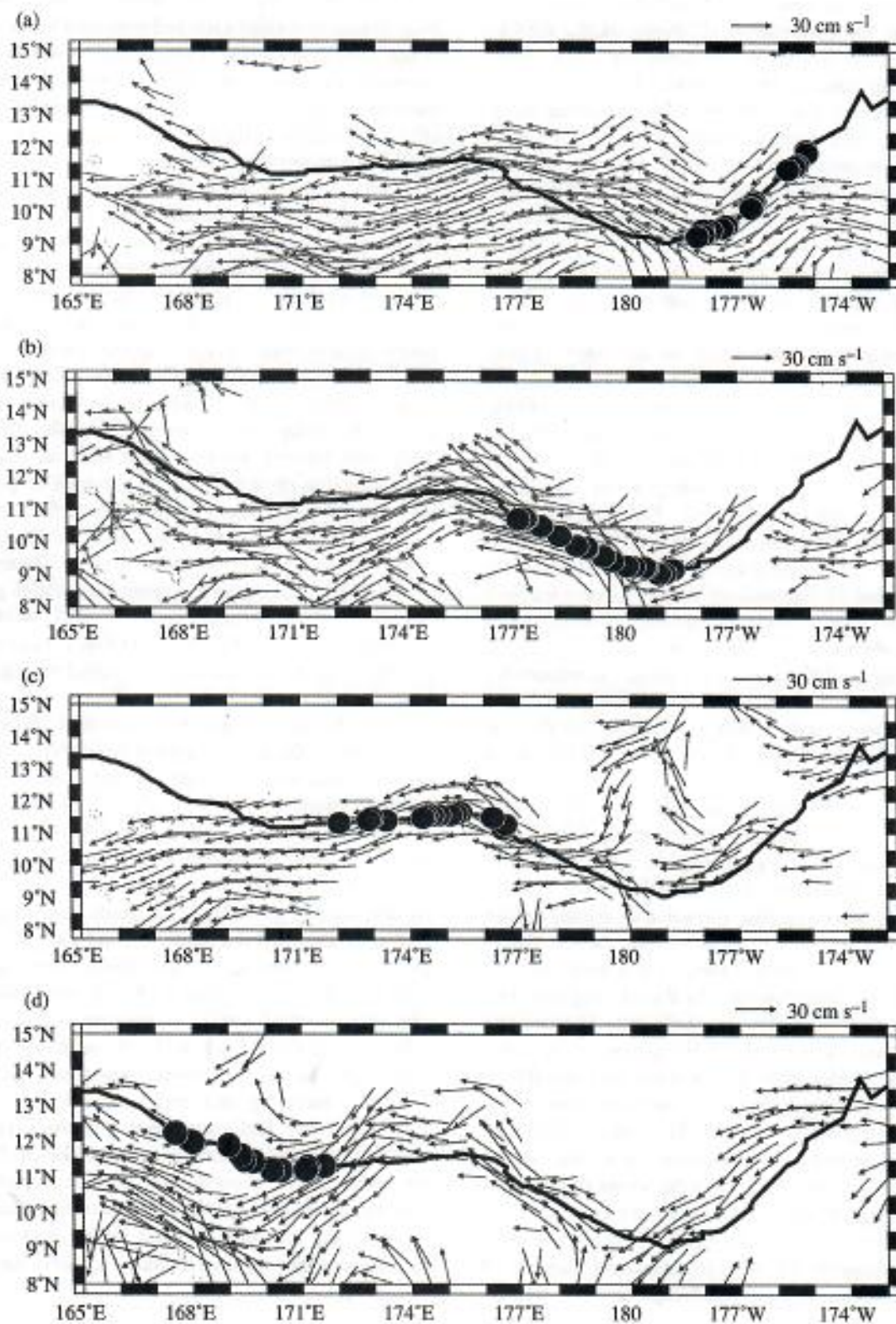


Figure 10. Geostrophic current along the North Equatorial Current estimated from Topex/Poseidon satellite together with olive ridley track line and positions (dots) for: (a) December 9–19, 1997, (b) December 19–29, 1997, (c) December 29, 1997–January 8, 1998, and (d) January 8–18, 1998.



south (Polovina *et al.*, 2000). Loggerheads also occupy the region just south of the TZCF in considerable abundance, and this is also consistent with earlier work indicating that another convergent front south of the TZCF, without a surface chlorophyll signature, was also habitat for loggerheads (Polovina *et al.*, 2000). All the fronts in this region, including the TZCF, have cooler, denser water at the northern edge and warmer, lighter water on the southern edge, resulting in a gradient in SSH that generates a weak eastward-flowing geostrophic current which the loggerheads swim against as they travel westward. It has been estimated that the speed of the opposing current at these fronts is about one-seventh of the loggerhead's mean swimming speed (Polovina *et al.*, 2000).

The loggerhead's seasonal migration from about 30°N in the winter, reaching 40°N in the summer, and returning to 30°N latitude by the next winter, represents a round-trip movement of about 2000 km and occurs while the turtles are also traveling westward. This north-south seasonal movement is also observed in the TZCF as well as in many Transition Zone species including squid, albacore, and pomfret (Shimazaki and Nakamura, 1981; Murata, 1990; Polovina *et al.*, 2001). While two of our easternmost loggerheads traveled south-east, all the remaining 24 loggerheads traveled westward. No loggerheads were observed heading directly east. Perhaps these turtles stay in the western Pacific until they mature and then nest in Japan. Alternatively, they may migrate eastward again before they mature, perhaps passing well north of Hawaii during the summer when the Hawaii fishery is not longlining in the area.

The southern edge of the KEC may be a very important forage habitat for turtles. While we observed only one loggerhead in this region, it remained in the region for 6 months. Several other loggerheads were heading toward this region before transmissions ended. In addition, the northernmost olive ridley we observed spent 2.5 months in this region during June-August. As the chlorophyll data suggest, this region may be productive because the strong meanders from the KEC entrain deep cool, productive waters rich in nutrients and possibly a biological community from the northern side of the KEC into cyclonic eddies. The counter-clockwise circulation of these eddies creates upwelling at the center and convergence at the edge where the buoyant prey of loggerheads would likely concentrate. Our tracking data show that loggerheads occupy the edge of these features for months. Archival tagging of juvenile bluefin tunas, which forage near the surface,

found that the southern edge of the KEC centered at about 33°N latitude between 140 and 180°E was an important habitat of juvenile bluefin from December through June (Inagake *et al.*, 2001).

Olive ridleys inhabit two different oceanic regions. Most of the olive ridleys tracked remained in the center of the Subtropical Gyre characterized by warmer more vertically stratified water with a deeper thermocline without strong surface thermal and chlorophyll gradients. In this habitat, they spend less time at the surface and have a deeper depth distribution than loggerheads. An analysis of stomach contents from eight olive ridleys caught in the Hawaii-based longline fishery indicates that while they do forage on some surface-associated organisms including *Janthina* sp. and cowfish (*Lactoria diaphana*), their most common prey are pyrosomes (*Pyrosoma atlantica*) and salps (*Salpidea*), which are found subsurface (unpublished data, Honolulu Laboratory, NMFS). Similar dietary preference has been described for olive ridleys in the eastern tropical Pacific (Kopitsky *et al.*, in press). Thus the diet data, while very limited, are consistent with our dive data suggesting that olive ridleys tend to forage deeper than loggerheads. The amount of time olive ridleys spend at 27°C SST reflects the fact that, south of Hawaii, the distance between SST isotherms is very wide and that olive ridleys can move over a range of several degrees of latitude and still remain in 27°C SST water. For example, the olive ridley shown in Fig. 7 spent 90% of its time at 27°C SST although it moved through 5° of latitude.

In addition to inhabiting stratified Subtropical Gyre waters, three olive ridleys occupied a different habitat consisting of major oceanic currents. One traveled along the southern edge of the KEC at the north boundary of the Subtropical Gyre while two traveled in the equatorial region south of the Subtropical Gyre using the NEC and EOC. In addition to the strong geostrophic currents, the equatorial region is also characterized by wind-induced upwelling and a shoaling of the thermocline, possibly allowing the olive ridleys to forage more shallowly and in regions of surface convergences. An obvious advantage of this habitat is the strong zonal currents, which can provide substantial energetic advantages to turtles traveling east and west. The olive ridley that used the NEC to travel westward past the dateline rode the current for 40 days, almost doubling its speed in the process, and then it departed the current and headed north. It is interesting that while in the NEC the turtle did not simply drift passively but apparently swam, most likely to continually find needed prey.

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Dive-depth distribution of loggerhead (*Carretta carretta*) and olive ridley (*Lepidochelys olivacea*) sea turtles in the central North Pacific: Might deep longline sets catch fewer turtles?

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The Hawaii-based longline fishery operates over a large area in the central North Pacific, from the equator to latitude 45°N, between longitudes 130°W and 180°W. In 2000, 125 vessels were active in the fishery, producing total landings estimated at 24 million pounds and exvessel (wholesale) revenues of \$50 million. The target species include bigeye tuna (*Thunnus obesus*), yellowfin tuna (*T. albacares*), and albacore tuna (*T. alalunga*), and swordfish (*Xiphias gladius*).

Caught incidentally with these target species are leatherback (*Dermochelys coriacea*), loggerhead (*Carretta carretta*), olive ridley (*Lepidochelys olivacea*), and green (*Chelonia mydas*) sea turtles.

Over the period 1994–99, it was estimated that an annual average of 418 loggerhead, 112 leatherback, 146 olive ridley, and 40 green sea turtles were caught in the Hawaii-based longline fishery (McCracken¹).

Historically, the Hawaii longline fishery has set longlines considerably shallower than 100 m to target swordfish (*Xiphias gladius*) or substantially deeper than 100 m to target bigeye tuna. Incidental hookings of loggerhead turtles have been reported in the Hawaii longline fishery observer data, which cover about 5% of the total annual effort. Analyses of these data found that loggerhead turtles were caught only when gear was set shallow enough to target swordfish, primarily in the northern portion of the fishing ground. No loggerhead sea turtles were caught when longline gear was set deep to target bigeye tuna, primarily in the southern portion of the fishing ground. These analyses suggest that a ban of shallow sets in the fishery since 1 April 2001 may reduce future incidental catches of loggerhead sea turtles. However, analyses based only on observer data suffer from the

limited observer coverage and the dependence between depth of setting and area fished. For example, swordfish are targeted at night in the north, whereas tuna are targeted during the day in the south. To better understand the depths inhabited by sea turtles, we used diving depth distributions collected from satellite-linked dive recorders attached to two loggerhead and two olive ridley sea turtles caught and released in the Hawaii-based longline fishery. Although other studies on the dive depths of olive ridley and loggerhead sea turtles have been conducted in the Pacific, these have been conducted with sea turtles in coastal areas rather than in the oceanic central Pacific (Sakamoto et al., 1993; Beavers and Cassano, 1996).

Materials and methods

We attached Wildlife Computer Argos satellite-linked depth recorders (SDR-T10) to two loggerhead and two olive ridley sea turtles that had been caught with commercial longline fishing gear. One loggerhead and one olive ridley were hooked in the mouth and were released after the hook and line had been removed. The other loggerhead and olive ridley sea turtle had deeply ingested hooks, and for both of these turtles the fishing line was cut close to the mouth but the hook was not removed. Trained observers on the fishing vessel attached transmitters to the carapace of each of the four sea turtles, using fiberglass cloth strips and polyester resin patterned after the method presented in Balazs et al. (1996). The observers noted that all four sea turtles swam vigorously away after release.

¹ McCracken, M. L. 2000. Estimation of sea turtle take and mortality in the Hawaiian longline fisheries. Southwest Fish. Sci. Cent. Admin. Rep. H-00-06. 29 p. Southwest Fish. Sci. Cent., Honolulu Lab., Natl. Mar. Fish. Serv., NOAA, Honolulu, HI 96822-2396.

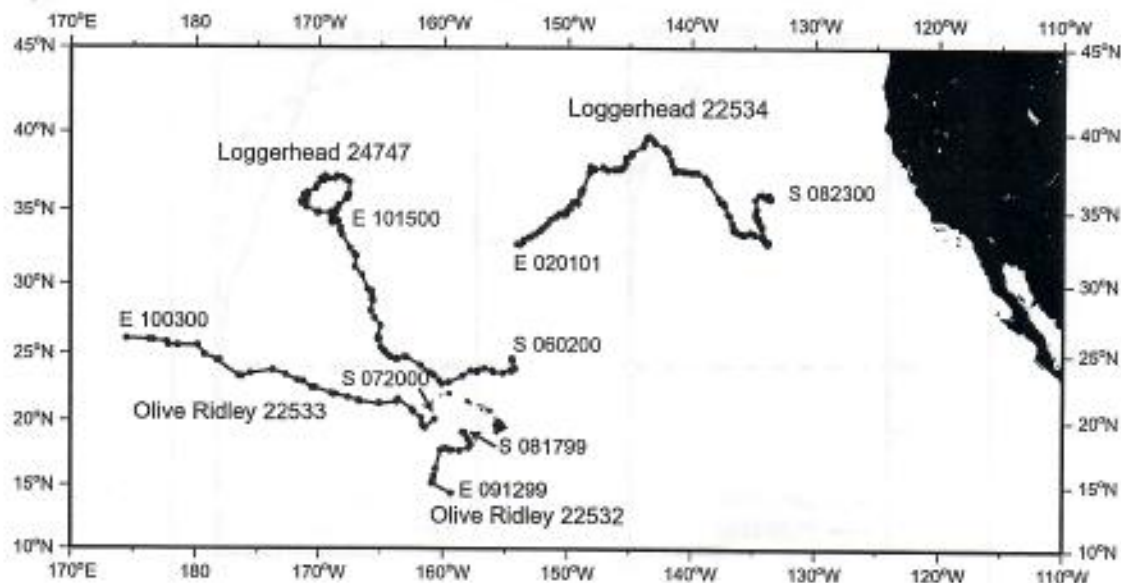


Figure 1

The start (S) and end (E) dates and track lines for the four turtles with satellite-linked dive recorders.

Data on daily location of the turtles were estimated from the signals received by the Argos receiver on a NOAA satellite. The position data were edited, and only the single most accurate daily position was plotted. The accuracy of each position was estimated by Argos as a function of the number and configuration of satellites and the number of transmissions received. Data on the dive behavior transmitted by the Argos receiver were not individual dive profiles but rather frequency distributions of time at depth, dive duration, and maximum dive depth, aggregated over four 6-hour periods and binned in specific depth or time intervals. The lower range of the depth bins (in meters) for the time-at-depth distributions were 1, 3, 5, 10, 15, 25, 35, 50, 60, 75, 100, 125, 150, 150+. Each time the turtle descended below 2 m, it was recorded as a dive. The lower range of the depth bins (in meters) for the dive-depth distributions were 5, 10, 15, 20, 25, 30, 40, 50, 60, 70, 80, 100, 150, 150+. The 6-hour periods over which the time-at-depth and dive-depth data were pooled were programed in Hawaii standard time as 2100–0300, 0300–0900, 0900–1500, and 1500–2100 h. One period was night, another mid-day; one included dawn, the other dusk. Mean time-at-depth and dive-depth distributions for each turtle in each of the four time periods were computed as the average of all frequency distributions for each 6-hour period. Mean time-at-depth and dive-depth distribution for the combined four time periods for each species were computed as the average of the four mean time-at-depth and dive depth distributions for each turtle, then averaged by species.

Finally, after every 20 transmissions a special status message that contained technical data about the operation of the transmitter and the maximum dive depth of that day was transmitted. Both the loggerhead and the olive ridley sea turtles made some dives below 150 m; however,

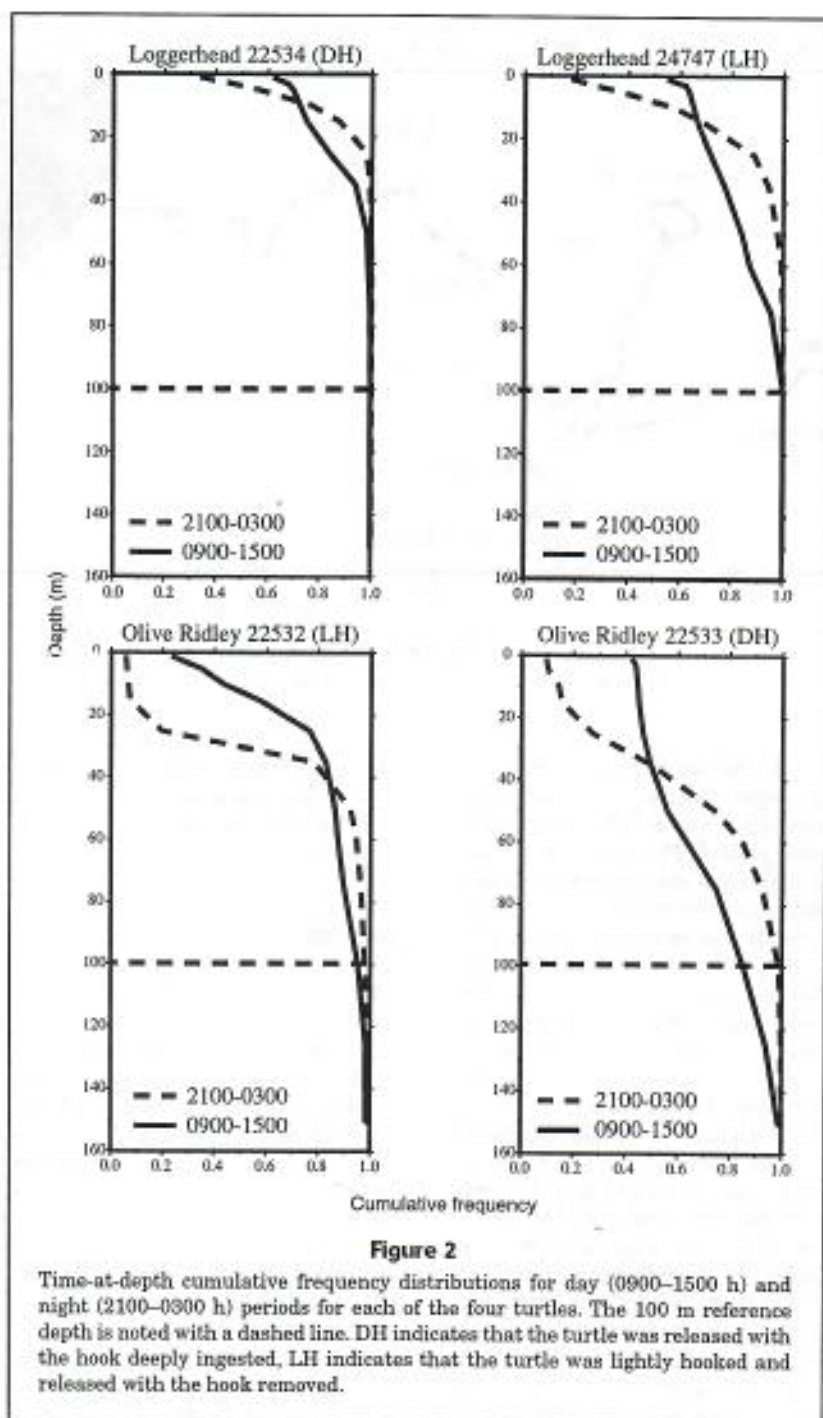
the histogram data did not indicate how much deeper than 150 m these animals dived. The maximum dives sent in the status messages were used to obtain some data on the deep dives.

Results

The positions of the four turtles showed that the turtles were occupying the characteristic habitats for each species: the loggerhead sea turtles were found in the northern portion of the subtropical gyre, and the olive ridley sea turtles were found farther south, well within the center of the subtropical gyre (Fig. 1). Loggerhead no. 24747, which was released with the hook removed, measured 83 cm (straight carapace length (SCL)) and transmitted data for 5.4 months. Loggerhead no. 22534, released with the hook deeply ingested, measured 61 cm SCL and transmitted data for 5.2 months. Olive ridley no. 22533, released with the hook deeply ingested, measured 57 cm SCL and transmitted data for 3.4 months. Olive ridley no. 22532, which was released after a hook was removed, measured 58 cm SCL and transmitted data for 0.8 months.

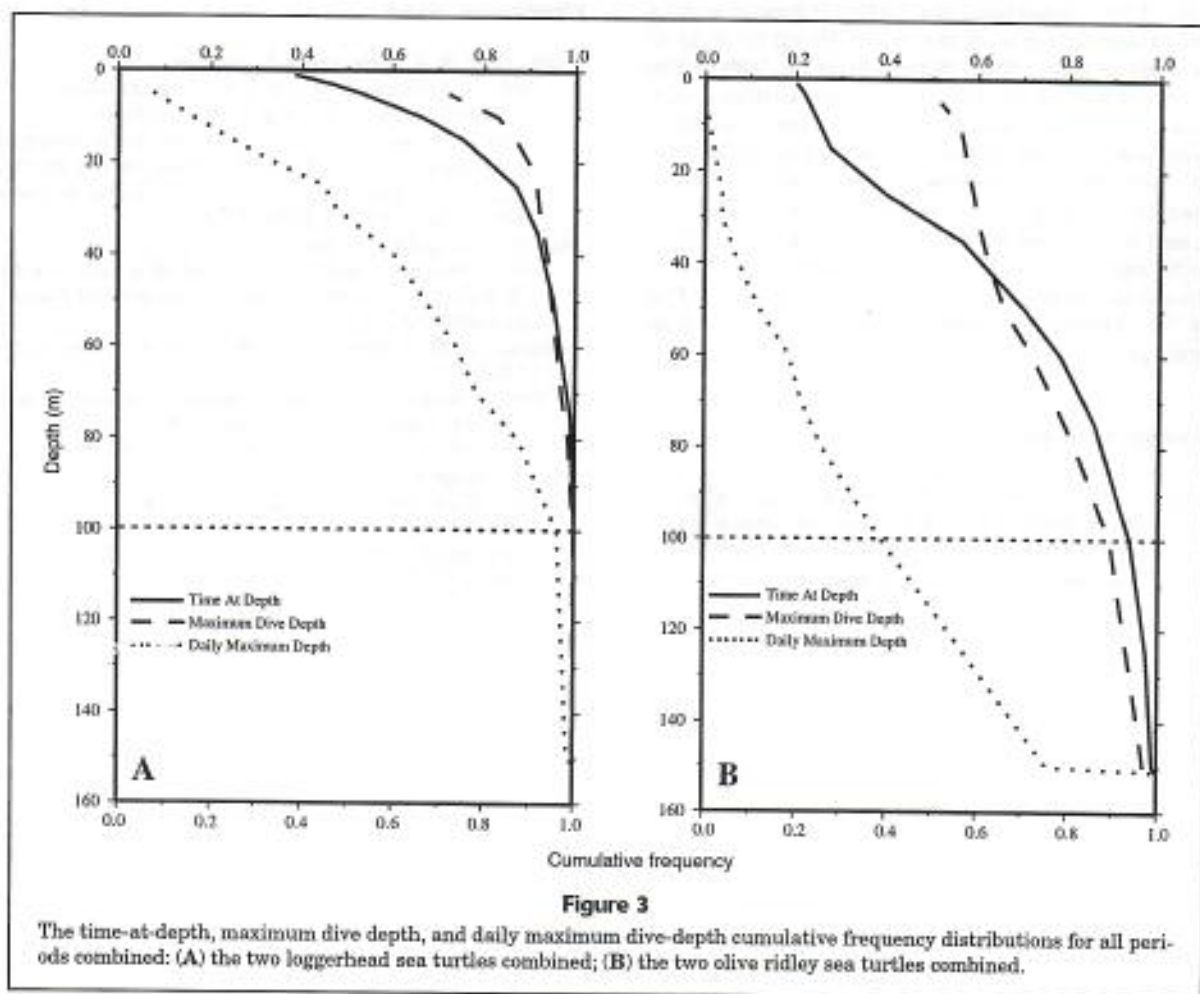
The time-at-depth frequency distributions for day and night periods for each of the sea turtles showed consistent diurnal and species differences in their dive-depth distributions (Fig. 2). The turtles spent more time at the surface during the day than at night and also dived deeper during the day (Fig. 2). We do not show the dive-depth distribution for the dawn and dusk periods, but these frequency distributions fell between the distribution for day and night periods.

Because it can often take as long as 20 hours to completely set and retrieve a longline, we examined time-at-



depth and dive-depth distributions pooled over the four 6-hour time periods by species. The time-at-depth frequency distribution showed that the loggerhead sea turtles spent about 40% of their time in the top meter and virtually all their time shallower than 100 m (Fig. 3). We also examined the frequency distribution of the maximum depth of each dive and the deepest dive in a 24-hour period. The cumula-

tive distribution of maximum depth of each dive indicated that most dives were very shallow: 70% of the dives were no deeper than 5 m (Fig. 3). The cumulative distribution of the maximum dive depth achieved over a 24-hour period indicated that for approximately 5% of the days, a dive exceeded 100 m (Fig. 3). Status messages reported that the deepest daily dive recorded was 178 m.



By comparison, the time-at-depth and maximum depth-frequency distributions of the two olive ridley sea turtles showed considerably deeper depth distribution (Fig. 3). These sea turtles spent only about 20% of their time in the top meter and about 10% of their time deeper than 100 m (Fig. 3). Their daily maximum depth exceeded 150 m at least once in 20% of the days (Fig. 3). Status messages reported that daily dives of 200 m occurred—one dive recorded at 254 m.

Discussion

The loggerhead dive-depth distributions indicated that these animals tended to remain at shallower depths than that of 100 m. If shallow longline sets were replaced with deep longline sets, the incidental takes of loggerhead sea turtles should be reduced substantially. Further, even though olive ridley sea turtles dived deeper than loggerhead sea turtles, only about 10% of their time was spent deeper than 100 m. Therefore, their incidental catches should also be substantially reduced with the elimina-

tion of shallow longline sets. However, when deep sets are being made or retrieved or when current shear prevents the gear from sinking to its expected depth, hooks will be present in relatively shallow depths and could result in incidental catches of turtles.

Results to date in the fishery confirm the reduction in incidental catches of turtles that can be achieved from the elimination of shallow sets. Beginning in April 2001, shallow sets were prohibited in the Hawaii-based longline fishery. Data from the onboard observers in the longline fleet, which now comprise 20% of the fishing effort, showed that no loggerhead and only two olive ridley sea turtles were caught from April through December 2001.

The relatively shallow dive-depth distribution for loggerhead sea turtles in the central North Pacific is consistent with our understanding of their ecology; they forage and migrate along convergent fronts where they encounter a shallow aggregation of forage (Polovina et al., 2000). Although oceanic loggerhead sea turtles have a shallower dive behavior than that of olive ridley sea turtles, they appear to dive deeper in oceanic habitat than loggerhead sea turtles in coastal habitat. For example, the dive dis-

tribution of two loggerhead sea turtles between nesting periods off Japan indicated that virtually all their dives were shallower than 30 m (Sakamoto et al., 1993). The deeper-dive distribution of olive ridley sea turtles is also consistent with their oceanic habitat, which is south of the loggerhead habitat in the central portion of the subtropical gyre. The oceanography of this region is characterized by a warm surface layer, a deep thermocline depth, and an absence of strong horizontal temperature gradients and physical or biological fronts. It is likely that the deeper diving seen in the olive ridley sea turtles results from foraging at depths associated with the deep scattering layer.

Acknowledgments

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Modelling post-release mortality of loggerhead sea turtles exposed to the Hawaii-based pelagic longline fishery

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ABSTRACT: Loggerhead sea turtles *Caretta caretta* are an endangered species exposed to anthropogenic hazards such as pelagic longline fisheries. Many loggerheads caught in these fisheries are alive when released from the gear, but many probably die soon after because of hook injuries or line entanglement. Robust estimates of post-release mortality are essential for stock assessment and evaluating the benefit of releasing turtles caught alive in the gear, yet none are available for any sea turtle species. Here, the post-release mortality of 40 loggerheads caught in the Hawaii-based pelagic longline fishery was investigated using satellite telemetry deployed by a National Marine Fisheries Service (NMFS) observer program. We modelled time-to-failure of all transmitters using nonparametric statistical modelling (Kaplan-Meier-Turnbull, local regression) to derive survival and hazard functions for light and deep hooked loggerheads. There was a significant difference between the survival functions for light and deep hooked loggerheads within 90 d of release, but no difference between survival functions after this time. But satellite transmitters fail for many reasons (defects, battery failure, transmitter detachment, turtle death), which results in a hazard function that confounds these competing risks. Hence we propose that it might not be possible to infer true post-release mortality based on satellite telemetry unless the cause of each transmitter failure is known, which is rarely the case. We discuss other survey design and statistical modelling challenges involved in the evaluation of post-release mortality based on satellite telemetry.

KEY WORDS: Loggerhead sea turtles · Pelagic longline fisheries · Satellite telemetry · Post-release mortality · Failure time modelling · Competing risks

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INTRODUCTION

There is increasing global concern about the incidental mortality of sea turtles caught in commercial fisheries (Hall et al. 2000). Some populations of loggerhead turtle *Caretta caretta* are in serious decline, especially in Pacific waters where there are 2 distinct genetic stocks (see Fig. 1), an Australian stock and a Japanese stock (Bowen et al. 1994). The decline of both stocks has been attributed to several hazards, including fox predation of eggs, nesting habitat destruc-

tion and exposure to coastal and pelagic fisheries (Chaloupka 2003, Kamezaki et al. 2003) and perhaps direct harvesting of the Japanese stock (Gardner & Nichols 2001).

Most studies of fishery-related loggerhead mortality have focused on estimates of pre-release mortality (Poiner & Harris 1996, Cheng & Chen 1997, Julian & Beeson 1998, Laurent et al. 1998, Slater et al. 1998, McCracken 2000), which is usually attributable to drowning (Work & Balazs 2002). Many sea turtles caught in fishing gear are alive when released from

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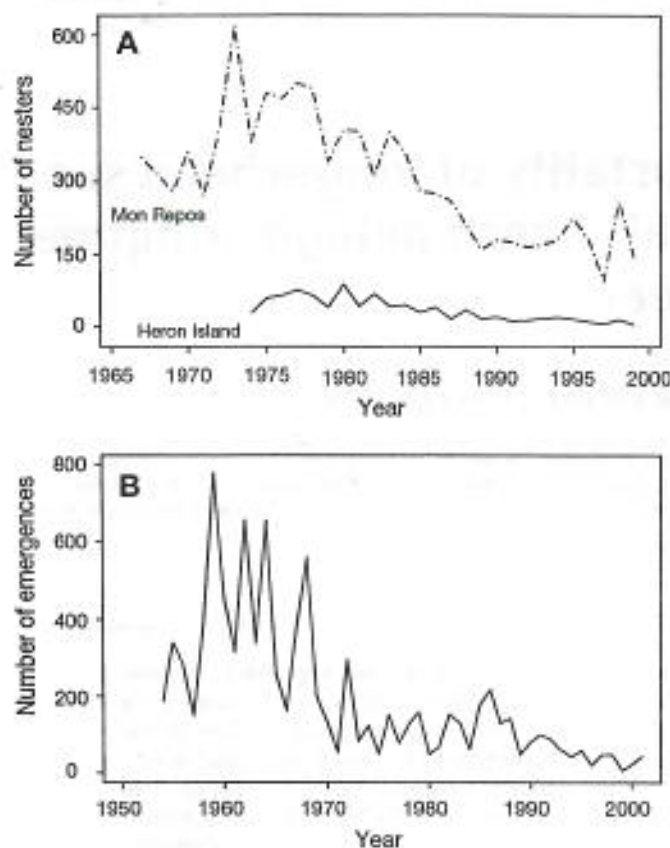


Fig. 1. *Caretta caretta*. Long-term trends in the female nesting abundance of the 2 Pacific loggerhead stocks. (A) Number of female nesters recorded for Australian stock loggerheads at the Heron Island (Chaloupka & Limpus 2001) and Mon Repos rookeries (Limpus & Limpus 2003). (B) Number of female beach emergences or haulouts recorded for Japanese stock loggerheads at the Kamouda rookery in the Tokushima Prefecture (Kamezaki et al. 2003)

the gear, but it is assumed that many will die anyway because of injuries caused by the hooks or line entanglement (Aguilar et al. 1995, Hall et al. 2000).

However, very few studies have empirically addressed the issue of post-release mortality for sea turtles by monitoring the behavior and short-term survival of sea turtles released alive from the fishing gear (Parker et al. in press). Reliable information on post-release mortality could be useful for loggerhead stock assessment and for evaluating the benefit of releasing loggerheads caught alive in the longline gear (Chaloupka & Limpus 2002, Chaloupka 2003).

Satellite telemetry has been proposed as a useful technology for evaluating post-release mortality of sea turtles (Balazs & Pooley 1994, Bjørndal et al. 1999, Parker et al. in press) and for other large and mobile pelagic species such as billfish (Goodyear 2002, Graves et al. 2002). Satellite tracking of individual loggerheads in North Pacific waters has already proved use-

ful for investigating migratory pathways of mature turtles (Sakamoto et al. 1997) and the post-release dispersal and pelagic ecology of immatures caught in longline gear (Polovina et al. 2003b).

In the present study satellite telemetry was used to investigate the post-release mortality of loggerheads caught in the Hawaii-based pelagic longline fishery that operated in the central North Pacific between 1997 and 2000. All loggerheads caught in this fishery were from the Japanese genetic stock, as there is no evidence of any Australian loggerheads (Dutton et al. 1997). More details on the Hawaii-based longline fishery can be found in Polovina et al. (2003a).

MATERIALS AND METHODS

Satellite transmitter deployment. Trained NMFS observers were randomly assigned aboard ca. 5% of the Hawaii-based commercial longline fishing fleet from 1997 to 2000 (Parker et al. in press). The observers retrieved 267 sea turtles captured on longline gear, 168 of which were loggerheads and of this number, 2 were dead on retrieval from the gear. For each trip, each observer was supplied with 1 or 2 satellite transmitters to attach to any hard-shelled sea turtle retrieved alive during their 2 to 6 wk observation period.

All turtles brought on board alive were scored by the NMFS observer as either (1) deep hooked, if the longline hook was present in the gastrointestinal tract caudal to the glottis, or (2) light hooked, if the hook was lodged in the mouth or externally, or the turtle was entangled in the line (see Work & Balazs 2002). If the loggerhead was light hooked, then the study protocol required the hook to be removed. If deep hooked then the hook was left in place in accordance with veterinarian recommendations (Balazs et al. 1995).

The observers attached Argos-linked satellite transmitters to 40 loggerheads that were released alive after incidental capture by the longline gear (Parker et al. in press). Transmitter assignment was based on the following criteria given transmitter availability: (1) the turtle was alive when retrieved, (2) the shell size was big enough for transmitter attachment (>40 cm straight carapace length, SCL), and (3) the sea conditions and weather (wind, rain) were suitable to allow attachment using fiberglass strips and polyester resin as described by Balazs et al. (1996).

A total of 38 loggerheads were fitted with Telonics ST-10 or ST-18 transmitters, while a further 2 were fitted with Wildlife Computers satellite-linked depth recorder (SDR-T10) transmitters (see Polovina et al. 2003a for more details). Each loggerhead with a transmitter was then released alive by the observers shortly

Table 1. Summary of the 40 transmitters deployed on the 40 loggerhead sea turtles released alive in the study and arranged by hooking position and transmitter duty cycle

| Hook position | Transmitter duty cycle (on/off, in h) | | | | Total |
|---------------|---------------------------------------|-------|-----|--------|-------|
| | 2/4 | 12/48 | SDR | 24/216 | |
| Light | 9 | 1 | 1 | 2 | 13 |
| Deep | 12 | 5 | 1 | 9 | 27 |

after attachment with no apparent signs of morbidity. In this study, 4 satellite transmitter duty cycles were used: (1) 2/4 h, (2) 12/48 h, (3) 24/216 h, and (4) the SDR transmitters. A 24/216 duty cycle means that transmission to the satellite network comprised a cycle of 24 h on followed by 216 h (or 9 d) off. The longer duty cycles were used in an attempt to conserve battery power and extend the tracking period.

A summary of the 40 satellite transmitters arranged by hooking position and transmitter duty cycle is given in Table 1. The data set for all 40 transmitters is available on request from G. H. Balazs (NMFS, Honolulu, Hawaii). More details on the NMFS observer program and deployment of these transmitters are given in Parker et al. (in press) while Polovina et al. (2003b) analyzed post-release movement patterns of some of these loggerheads using satellite telemetry and remote sensing data. Note that Polovina et al. (2003b) did not address post-release mortality of any of the satellite-tracked loggerheads in their study.

Statistical modelling approach. The satellite transmission duration in days from release until all transmissions ceased was determined for each of the 40 loggerheads summarized in Table 1. The transmission duration only reflects the time period until failure of the transmitter and is thus not a direct measure of the short-term survival duration of the tag-and-released turtle. This is because satellite transmissions can cease for many reasons, such as transmitter loss due to improper attachment, transmitter defects, battery failures, and of course death of the turtle carrying the transmitter. Post-release loggerhead death could be due to injuries sustained during capture in the longline gear or due to natural mortality.

There are many competing risks that could lead to transmitter failure so identifying cause-specific transmission failure is extremely difficult, let alone inferring cause-specific loggerhead mortality. Chaloupka & Musick (1997) discuss in more detail these sorts of competing risks in the context of tag loss from sea turtle capture-mark-recapture studies while Goodyear (2002) discusses similar issues in relation to billfish tag-and-release studies.

Not only do these data confound cause-specific risks, there are also significant data censoring issues in-

involved such as left and right censoring and interval censored data structures. Right (or left) censored survival time data occur when there are subjects in the sample for which only an upper (or lower) bound on the survival (transmitter failure time) time is known. Right censored data usually occur because the study ends before all subjects in the sample fail or die. Left censored data can occur when some subjects fail soon after the study starts, but before the first time that an event such as death (transmitter failure) can be recorded. Interval censored data occur when there are subjects in the sample for which it was only possible to record a lower and an upper bound (an interval) on the survival time (transmitter failure time). These 3 data structures can be analysed in more detail as follows:

Right censoring: It is important to note that not all the data reflect an event time, which is the time period in days until the known transmission failure. The original data set used by Parker et al. (in press) comprised 39 of the 40 transmitters used here, but 4 were excluded as they were still transmitting at the time of the analysis (~experiment-end). Excluding these data is unnecessary and could result in biased survival function estimates. The data are easily included by identifying the transmission duration times for those 4 transmitters as right censored. In other words, the time period until failure would be at least as long as the time estimated at the end of the experiment. Preliminary analyses of the data used right censoring of these 4 turtles but now all 40 transmitters have ceased functioning for various reasons. Therefore right censoring is not needed here, but is a potential feature of the analysis undertaken in this study.

Left censoring: It is important to note that 10 of the 40 transmitters failed to produce any transmissions and so were identified as left censored observations here to reflect that failure occurred, for whatever reason, sometime between the time of release and the next available time the transmitter could provide a transmission to the Argos network. This is particularly important if failure occurred for a transmitter that was programmed on a long cycle such as 24/216, since the failure could have occurred within the first 24 h after release or perhaps for as long as 9 d after release.

We adopted a left censored scoring to reflect that failure occurred before the first transmission to the Argos network was possible (see Meeker & Escobar 1998 for more details on left censored mechanisms). Parker et al. (in press) discarded these early failures, but we find this unnecessary and furthermore, it could lead to biases in the survival functions and a misunderstanding of the underlying hazard or time-specific mortality function, as it is also possible that the turtle did in fact die soon after release from the longline gear. All we can determine is that there were a significant

number of early failures between release (time = 0) and first successful transmission, but the cause for each failure was unknown.

Interval censored data: Not only could the data set comprise both right and left censored data—it also comprised variable interval data, which is a significant complication. Left censoring is also a form of interval censoring but with the lower bound being zero. Recall that the transmission data set comprised 2 SDR transmitters and 38 transmitters programmed with either a 2/4, 12/48 or 24/216 duty cycle. The longer duty cycles (12/48, 24/216) indicated that it was not possible to acquire daily fixes and that a transmission signal was only possible within a time window perhaps as long as 10 d apart. Hence transmitter durations derived from the longer duty cycle satellite transmitters represent interval censored data and few survival models exist (nonparametric, semiparametric or parametric) that are capable of dealing with such data.

Therefore, this data set of 40 transmission failure times for 27 deep hooked and 13 light hooked loggerheads now comprises left and interval censored data, and originally also comprised right censored data. Lawless (1982) provides a thorough discussion of censored data types and various approaches for dealing with such data in a statistical modelling framework.

We modelled the distribution of the transmitter failure times for the deep and light hooked groups using the extended and generalized form of the nonparametric Kaplan-Meier survival function estimator developed by Turnbull (1976). The standard form of the Kaplan-Meier estimator accounts only for right censored data (see review in Lawless 1982). The generalized Kaplan-Meier-Turnbull (KMT) estimator, also known as the Peto-Turnbull estimator (Meeker & Escobar 1998), enabled us to derive group-specific survival functions from the failure times without assumptions about the form of the underlying hazard function while accounting for left, right and interval censored data.

The survival function here is the probability of the Argos network, for any specified time t since post-release, recording a signal from the transmitter at least to time t . All KMT survival functions were estimated using the `kaplanMeier(censor(...))` function in SPLUS (MathSoft 1999), which is an extension of the S statistical language. Complementary log-log confidence bands were used to constrain the KMT survival function estimates to the $[0,1]$ interval. We then used the KMT estimated group-specific transmitter survival functions to infer group-specific post-release survival for this sample of loggerheads.

It was not possible to use the standard G^P family of tests (Harrington & Fleming 1982) of the difference between the KMT survival functions because, as we

shall see, the hazard functions are neither proportional nor monotonic, but most probably of the bathtub type (Glaser 1980). A bathtub hazard function is a function that refers to a broad class of U- or J-shaped hazard functions and is the term widely applied to such functions in the medical, reliability, engineering, actuarial, economic and ecological literature (Glaser 1980, Lawless 1982, Paranjpe & Rajarshi 1986, Meeker & Escobar 1998). Instead, we used visual examination of the KMT survival functions and 95% complementary log-log confidence bands to evaluate any group-specific survival function differences.

The hazard function gives for any specified time t the instantaneous risk of failure at time t among transmitters still operating at least until time t . We used local log-quadratic likelihood regression smoothing (Loader 1999) of the transmitter failure times to derive preliminary estimates of the underlying group-specific hazard rate functional form using the `locfit()` library in R (Ihaka & Gentleman 1996). The hazard function reflects the time-specific mortality or failure rate of the transmitters. This local regression smoothing approach cannot fully account for the interval and censored data structure, so it is only useful for exploring the functional form rather than deriving robust estimates of the hazard function. Moreover, while this is the largest data set of this type, it is nonetheless far too small for attempting to derive robust estimates of the hazard function.

In deriving the KMT survival functions it was assumed that the censoring mechanism (left, right, interval) is noninformative and not due to some characteristic of a subset of transmitters or loggerheads (see Lawless 1982 for a discussion of this important issue). This assumption can be tested using a multinomial logit regression with the vector that identifies the transmitter censoring type (0 = right, 1 = actual event, 2 = left and 3 = interval) as the response variable to be conditioned on covariates such as duty-cycle, loggerhead size and tagging cohort year. Unfortunately, the data set is too small for robust evaluation of non-informative censoring.

RESULTS

All 40 loggerheads were probably immature and ranged in carapace size from 41 to 83 cm SCL (median size = 58 cm SCL, interquartile range [see Cleveland 1993] = 53 to 65 cm). All turtles were smaller than the known adult size for this stock (Hatase et al. 2002). The duration of satellite transmissions for the 40 loggerheads ranged from 0 to 597 d (median duration = 97 d, interquartile range 3 to -154 d). Distance traveled ranged from 0 to 13 864 km, with a mean distance of ca.

1311 km (see Parker et al. in press, and Polovina et al. 2003b for details on estimating location and distance travelled).

Recall that 27 of the 40 loggerheads were recorded as deep hooked, while 13 were recorded as light hooked. The expected KMT survival functions for these 2 groups given the left and interval censoring are shown in Fig. 2A with 95% complementary log-log confidence bands, and then again in Fig. 2B without the confidence bands to avoid visual clutter. There is little or no overlap between the 2 survival functions (Fig. 2A) between ca. 60 and 90 d of release from the longline gear. The confidence bands are necessarily broad because of the small sample size, but are suggestive of a meaningful difference between the 2 survival curves until around 90 to 100 d post-release (Fig. 2A).

The general behavior of the 2 functions is clearer in Fig. 2B, where the deep hooked survival function declines immediately following release. The light hooked survival function declines after a short delay and then most rapidly after 90 d post-release. Median transmitter failure time for the deep hooked group was ca. 50 d post-release, while median transmitter failure time for the light hooked group was ca. 100 d post-release (Fig. 2B). The group-specific survival functions converge by ca. 120 d post-release.

The survival functions for the 2 groups suggest very different underlying hazard functions (Fig. 2C), which display distinct bathtub shapes (Glaser 1980, Paranjpe & Rajarshi 1986) with a period of early failure followed by a period of low mortality or failure and then followed by an accelerating period of failure after at least a couple of months. The underlying bathtub-type hazard functions (U- or J-shaped functions) and the fact that they cross each other (Fig. 2C) are the reasons why it was not possible to use the G^P family of rank tests (Harrington & Fleming 1982) to test for a difference between the KMT survival functions in Fig. 2A.

These hazard functions were not well defined because of the small sample size and because only the deep hooked turtles had transmitters functioning >200 d. The longer-term hazard function for the deep hooked group is due to 3 loggerheads released towards the end of the study, all with 12/48 duty cycle transmitters attached. Therefore, little attention should be given to the longer-term behavior of the deep hooked function or to the various intermediate bumps in either function, except for the distinct and temporary rise in the hazard or time-specific failure rate for the deep hooked group around 50 d since release (Fig. 2C). Whether this reflects an abrupt increase in time-specific mortality for the deep hooked loggerheads or transmitter failure, due perhaps to battery failure, is unknown.

Recall that the study comprised the satellite transmission durations for 40 transmitters deployed over 4 annual sampling cohorts and using 4 different transmission duty cycles. A total of 21 transmitters were

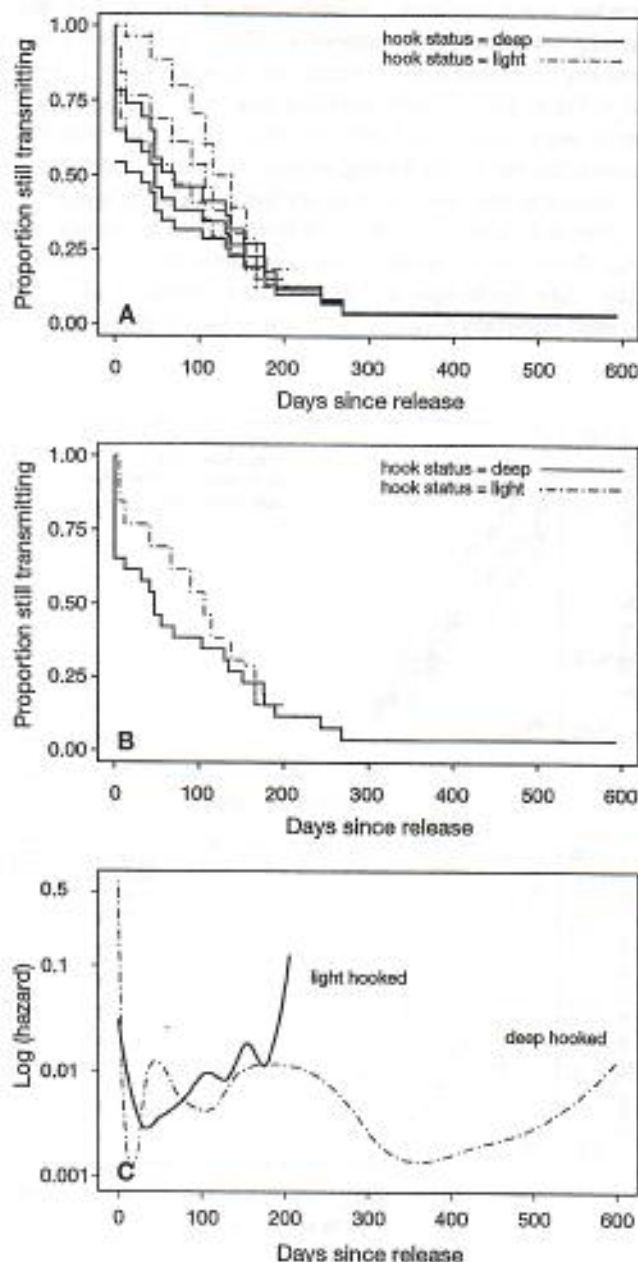


Fig. 2. *Caretta caretta*. Kaplan-Meier-Turnbull (KMT) survival functions or smoothed hazard functions for the 40 satellite tracked deep and light hooked loggerheads. (A) Expected group-specific survival functions including 95% complementary log-log confidence intervals. (B) Expected survival functions only without confidence intervals. (C) Expected local log-quadratic likelihood hazard functions for the deep and light hooked loggerhead groups derived using the `locfit` library (see Loader 1999)

programmed with a 2/4 duty cycle and there were 2 SDR transmitters; 17 transmitters were programmed with longer duty cycles comprising 11 on 24/216 and 6 on 12/48. Furthermore, 9 transmitters were deployed in 1997, 16 in 1998, 7 in 1999, and 8 in 2000. The satellite transmitters programmed with the longer duty cycles were deployed mainly toward the end of the study, resulting in potential duty cycle-sampling cohort confounding. It would be preferable to condition the group-specific survival functions on duty cycle and sampling cohort effects, but this is not feasible given the very small sample size.

Nonetheless, we can explore the main effects of duty cycle and sampling cohort on the survival functions for the 40 satellite transmission durations. Fig. 3A shows the duty cycle-specific survival functions with 95% complementary log-log confidence bands included for

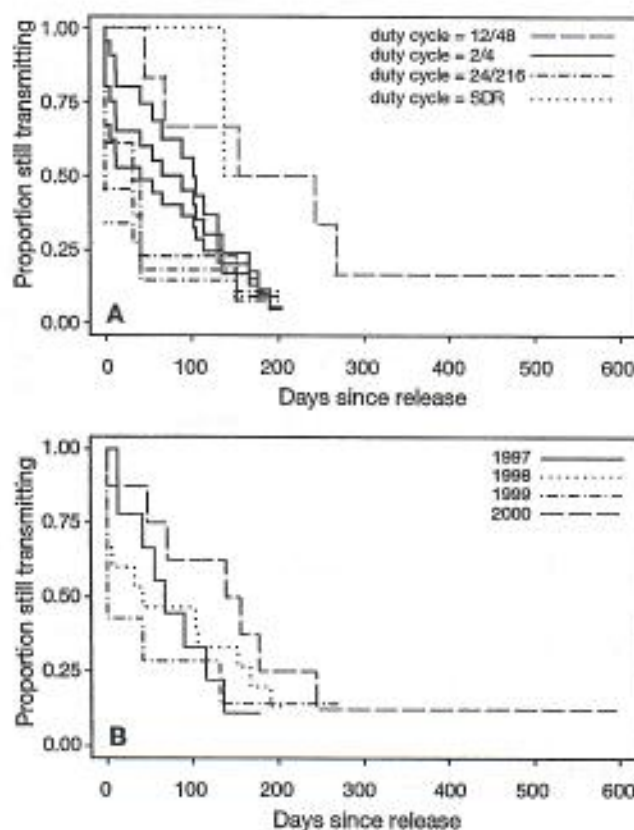


Fig. 3. *Caretta caretta*. Kaplan-Meier-Turnbull (KMT) survival functions for the 40 satellite tracked deep and light hooked loggerheads. (A) Expected duty cycle-specific survival functions for the 4 programmed duty cycles, including 95% complementary log-log confidence intervals for the 2/4 and 24/216 cycles. Confidence intervals are not included for 12/48 or SDR cycles due to very small sample sizes and to avoid visual clutter. (B) Expected year-specific survival functions for the 4 annual sampling cohorts without confidence intervals

the 2/4 and 24/216 duty cycles that had reasonable sample sizes. It would seem that duty cycle has a significant effect on the survival functions with the longest cycle (24/216: median failure time ca. 30 d) having significantly lower survival than the shortest cycle (2/4: median failure time ca. 60 d).

However, as already mentioned, the duty cycle and sampling cohort effects are confounded. Fig. 3B shows the sampling cohort-specific survival functions without confidence bands to avoid visual clutter. The 1999 sampling cohort is the lowest survival function simply because there were no light hooked loggerheads in that year, and there were a disproportionate number of both 24/216 duty cycle transmitters deployed and left censored transmission durations recorded. Recall that the survival function modelling here assumes that the censoring mechanisms are noninformative, but it would seem that during 1999 this was probably not a valid assumption. This might also be so for the 2000 sampling cohort when there was a disproportionate number of the interval censored durations, although there was no apparent bias with respect to censor type or whether the loggerhead was deep or light hooked. Again, the sample size in this study is too small to draw strong inferences about differences between transmitter failure times.

DISCUSSION

The satellite tracking of 40 loggerheads released alive in the Hawaii-based longline fishery suggests that there is a difference between the survival functions of transmitters attached to deep and light hooked turtles. The difference in the survival functions occurs within ca. 90 d of release, with no apparent difference between survival functions after this time (Fig. 2B). However, the survival function differences between the 2 groups of tagged loggerheads (deep and light hooked) is not a strong inference because of the small sample size and the potential confounding of survey sampling design involving the use of different and long-duration duty cycles (see Fig. 3A).

Also, it is not clear whether it is possible to infer loggerhead post-release survival from the transmitter failure times used to derive the survival functions. The bathtub- or U-shape hazard functions (Fig. 2C) suggest that transmitter failure was a complex function comprising several competing risks or cause-specific failures (see discussion of this important issue in Lawless 1982 or Chiang 1991). The high early failures might have resulted from transmitter loss due to various component defects, improper attachment, or from early post-release mortality (see also Goodyear 2002, Graves et al. 2002 for similar comments regarding billfish tag-

and-release studies). The early hazard or time-specific mortality rate is certainly much higher for the deep hooked group during this period (Fig. 2C), but loggerhead mortality and transmitter failure cannot be disentangled, so a reliable direct estimate of mortality for either group shortly after release is not possible.

Nonetheless, the KMT estimate of the deep hooked group failure rate during the first week after release was ca. 0.34 (95% complementary log-log confidence interval: 0.22 to 0.45) while the light hooked group estimate was ca. 0.08 (0.0 to 0.21). These KMT hazard or time-specific failure rates confound transmitter failure rates and loggerhead mortality if in fact any mortality did occur. Hence these estimates reflect at best the upper bounds on the apparent level of loggerhead mortality for the 2 groups shortly after release. These estimates must be viewed with extreme caution as they clearly reflect over-estimated failure and hence mortality probabilities attributable to capture in the longline gear. If all the transmitter failures during this period were due solely to equipment failures or tag loss then these estimates would not reflect loggerhead mortality in any way whatsoever.

The subsequent period of relatively constant time-specific mortality or failure (Fig. 2C) could reflect fewer failures, either because the early defective transmitters were already lost or that the likelihood of a turtle dying during this period had decreased: it is not possible to distinguish between these possibilities. The later accelerating period of time-specific failure or mortality could reflect the increasing likelihood of breakdown of the aging transmitters, the increasing likelihood of battery failure or the increasing likelihood of natural mortality of the turtle.

If the expected group-specific hazard functions reflect loggerhead time-specific mortality then it might be that deep hooked loggerheads were far more likely to die during the first 50 to 60 d after release from the longline gear than light hooked loggerheads. If the deep hooked loggerheads survived this long, there was apparently little difference thereafter between the survival chances of deep or light hooked loggerheads in this study, at least until around 200 d post-release. If this was the case then future studies using satellite telemetry might consider a 60 to 90 d sampling period as sufficient for estimating short-term survival or time-specific mortality for the released turtles. Battery power would not be an issue, and there would be no need to use long duty cycles such as 24/216, which serve only to considerably complicate any post-release survival study.

Using longer-term studies (>90 d) is not helpful, as the longer the time period, the greater the likelihood of confounding mortality risks, including the increasing risks of natural mortality and equipment failure (see

also Goodyear 2002). Of course, transmitter failure during a short-term study does not ensure that it is possible to distinguish between early equipment failure from defects or mortality of the turtle from being hooked. The only way to distinguish between fishery-related loggerhead mortality and equipment failures, or loss due to improper attachment, is to determine the reason for each failure and to conduct a necropsy of all turtles that died while carrying a transmitter (see Work & Balazs 2002). Unfortunately, determining cause-specific failure at sea is not feasible (the turtles are not retrievable), although auxiliary information derived from time-depth recorder transmitters or perhaps pop-up tags could be useful here. This use of pop-up satellite tags was proposed by Graves et al. (2002) to study the post-release survival of billfish caught in recreational fisheries.

Another important issue that should be considered in future post-release survival studies concerns satellite tag assignment to a particular turtle retrieved alive from the longline gear. The NMPS observers were trained in many study protocols including how to identify the species of sea turtles retrieved from the longline gear, how to determine transmitter assignment and how to attach the satellite transmitter. We assume that there was no bias in the selection of a particular loggerhead for transmitter attachment because such bias could have a profound effect on estimation of the group-specific survival function. For instance, it is assumed that an observer did not assign transmitters to loggerheads that were thought likely to survive rather than assigning one to a turtle that was in poor condition when retrieved from the longline gear. This issue must be vigorously reinforced in any observer training program, just as it was in the present study.

Other major issues for consideration in future studies include issues such as what constitutes sufficient sample size and an appropriate experimental control for evaluation of post-release survival. While this was the largest data set of this type, comprising 40 satellite transmitters and a substantial observer program, it was nonetheless far too small to draw any strong inferences (see also Goodyear 2002 for similar conclusions regarding billfish tag-and-release studies). It is not known what a suitable sample size would be, but we estimate in the hundreds, even for an experiment comprising few treatment effects and no spatial or individual heterogeneity in turtle response to capture and release. A suitable and logistically feasible control for this type of quasi-experiment remains unclear.

Another important issue to consider in future studies is the potentially confounding problem of delayed or staggered entry into the study, since not all turtles were captured and released at the same time within each of the 4 sampling years. For instance, some turtles

were caught and released in March, others in May, others in August, and so on. None of the transmitter failure times were right censored, so this is not an issue here. Delayed entry designs can be addressed using left truncation to account for variable entry time into the study (see Meeker & Escobar 1998 for detailed discussion of this issue), but should be avoided if possible. This is because such a study would involve an extremely complex and arbitrary censoring strategy possibly comprising left, right and interval censoring, as well as left truncation. Estimation of such a model would not be simple, and complex censoring design strategies seem pointless when it appears that the cause-specific hazards cannot be disentangled.

Recently, Hays et al. (2003) reported that various fisheries around the world account for an annual mortality probability of 0.31 for all sea turtle species exposed to those fisheries. Hays et al. (2003) based this estimate on satellite telemetry data. This study is problematic for many of the reasons discussed above for deriving satellite telemetry based mortality estimates. The Hays et al. (2003) study comprised no control, used tracking data that extended for more than 1 yr and so confounds natural mortality with any potential fishery-induced mortality, used transmitter failure as the basis for assigning a death to a particular turtle, failed to determine cause-specific failure for all transmitter failures and assumed all failures were due to turtle death, confounded duty cycle, transmitter types and research group methodologies, failed to use the transmission duration data to derive hazard functions, and used an extremely small sample size comprising 50 turtles from 3 species across all ocean basins with only 3 known deaths and so on. Hence the global annual mortality probability estimate of 0.31 of all sea turtle species exposed to fisheries that was proposed by Hays et al. (2003) is highly questionable at best.

Reliable estimates of natural and anthropogenic sources of mortality are known to be important for modelling the population or metapopulation dynamics of sea turtle stocks exposed to various hazards (Chaloupka 2002, 2003, 2004). While reliable estimates of natural mortality are becoming increasingly available for sea turtle populations (Chaloupka & Limpus 2002, Bjorndal et al. 2003, Seminoff et al. 2003), this is not the case for estimates of fishery-induced mortality. Satellite telemetry may be one useful approach for redressing this deficiency, but there are many challenges facing the use of this technology for robust evaluation of post-release survival of loggerhead sea turtles.

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THE POST-NESTING LONG RANGE MIGRATION OF THE GREEN TURTLES THAT NEST AT WAN-AN ISLAND, PENGHU ARCHIPELAGO, TAIWAN

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Wan-An Island, PengHu Archipelago is one of the remaining green turtle nesting sites in Taiwan. The nesting beaches have been designated as a sanctuary by the Council of Agriculture since December 1995 (Cheng, 1995; Council of Agriculture, 1995). Nesting ecology has been studied extensively (Chen and Cheng, 1995). However, little is known of the whereabouts of the nesting turtles while they are in the ocean. The purpose of this study was therefore to use satellite telemetry to determine the post-nesting migration routes and resident foraging areas of the Wan-An Island nesting green turtles.

MATERIAL AND METHODS

Seven adult female turtles were equipped with Argos-linked satellite transmitters (Telonics, Mesa, AZ, U.S.A.) during the nesting seasons of 1994 through 1996. Two models of PTT's (platform terminal transmitter) were used, ST-6 and ST-14. After nesting or false-crawling, the turtles were captured before reaching the ocean and held in a rectangular plywood "pen" in a natural prone position. The procedures for attachment followed Balazs *et al.* (1966). The dates of capture and release of the seven green turtles are listed in Table 1.

The repetition rate for both types of PTT's was 50 seconds. The duty cycle of the ST-14 was 3 hours on, 3 hours off. The ST-6 PTT's were on constantly. The transmitted data were received and processed by the Argos system. The completion of a migration was defined as a tagged turtle stayed in the last location of the migration route for at least 7 days.

RESULTS AND DISCUSSION

PTTs lasted from just over one month (Wan-An No. 7) to 13.7 months (Wan-An No. 5) (Table 2). All but two (Wan-An Nos. 1 and 7) PTTs operated for more than 3 months and provided enough information to reveal post-nesting migrations.

The migration routes of the seven turtles are shown in Fig. 1. Four of the seven turtles migrated to the northeast and the others migrated to the southwest of Wan-An Island. The migration distances ranged from 317 km (Wan-An No. 2) to 1954 km (Wan-An No. 6), and the migration periods lasted from 9 (Wan-An No. 4) to 66 days (Wan-An No. 3). The turtles' estimated swimming speeds ranged from 1.1 to 2.4 km/h, with a mean of 1.6 km/h (Table 3). These rates of travel are comparable to those found in other studies. The final locations of the turtles are shown in Fig. 1 with a star mark.

The results of the present study, which is the first to investigate the post-nesting migrations of green turtles in northeast Asia, suggest that dispersal occurs from Wan-An Island to various locations on the continental shelf to the east of mainland China. Genetic analysis of mtDNA has shown that the Wan-An rookery is distinct from other rookeries that have been examined to date in the Pacific, including Japan, Hawaii, and Australia (Dutton, personal communication).

The present study demonstrated clearly that the green turtles that nest at Wan-An Island are an internationally shared resource. Because the turtles dispersed into the waters of Japan, Taiwan, mainland China and the Ryukyu Archipelago, conservation of the Wan-An rookery clearly cannot depend solely on Taiwan or PengHu County. Thus, a regional program and strategy for long-term research and conservation of green turtles and their habitats, are urgently needed to save this endangered species (IUCN, 1995). Such a program would necessarily involve international cooperation and multinational agreements.

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Table 1. The date of capture, transmitter tagging and release of green turtle nesting at Wan-An Island, PengHu Archipelago, Taiwan between 1994 and 1996.

| Turtles | No. 1 | No. 2 | No. 3 | No. 4 | No. 5 | No. 6 | No. 7 |
|----------------|-------|-------|-------|-------|-------|-------|-------|
| PPT | ST-6 | ST-6 | ST-14 | ST-14 | ST-14 | ST-14 | ST-14 |
| Capture date | | | | | | | |
| year | 1994 | 1994 | 1995 | 1995 | 1995 | 1996 | 1996 |
| month/day | 8/27 | 8/28 | 8/4 | 8/6 | 8/9 | 8/8 | 8/9 |
| tagged/release | | | | | | | |
| month/day | 8/28 | 8/29 | 8/5 | 8/7 | 8/10 | 8/9 | 8/10 |

Table 2. Duration of transmission of PTT's deployed on the green turtles nesting at Wan-An Island, PengHu Archipelago, Taiwan between 1994 and 1996.

| Turtles | No. 1 | No. 2 | No. 3 | No. 4 | No. 5 | No. 6 | No. 7 |
|-----------------|-------|-------|-------|-------|-------|-------|-------|
| PPT | ST-6 | ST-6 | ST-14 | ST-14 | ST-14 | ST-14 | ST-14 |
| year deployed | 1994 | 1994 | 1995 | 1995 | 1995 | 1996 | 1996 |
| duration (days) | 60 | 166 | 328 | 161 | 410 | 141 | 32 |

Table 3. The post-nesting migration distance, duration and swimming speed of the green turtles nesting at Wan-An Island, PengHu Archipelago, Taiwan between 1994 and 1996.

| Turtles | post-nesting migration distance (km) | traveled duration (days) | swimming speed (km/h) |
|--------------|--|--------------------------------|-----------------------------|
| Wan-An No. 1 | 1703 | 59 | 1.2 |
| Wan-An No. 2 | 317 | 10 | 1.5 |
| Wan-An No. 3 | 1756 | 66 | 1.1 |
| Wan-An No. 4 | 305 | 9 | 1.4 |
| Wan-An No. 5 | 928 | 16 | 2.4 |
| Wan-An No. 6 | 1954 | 41 | 1.9 |
| Wan-An No. 7 | 562 | 15 | 1.6 |

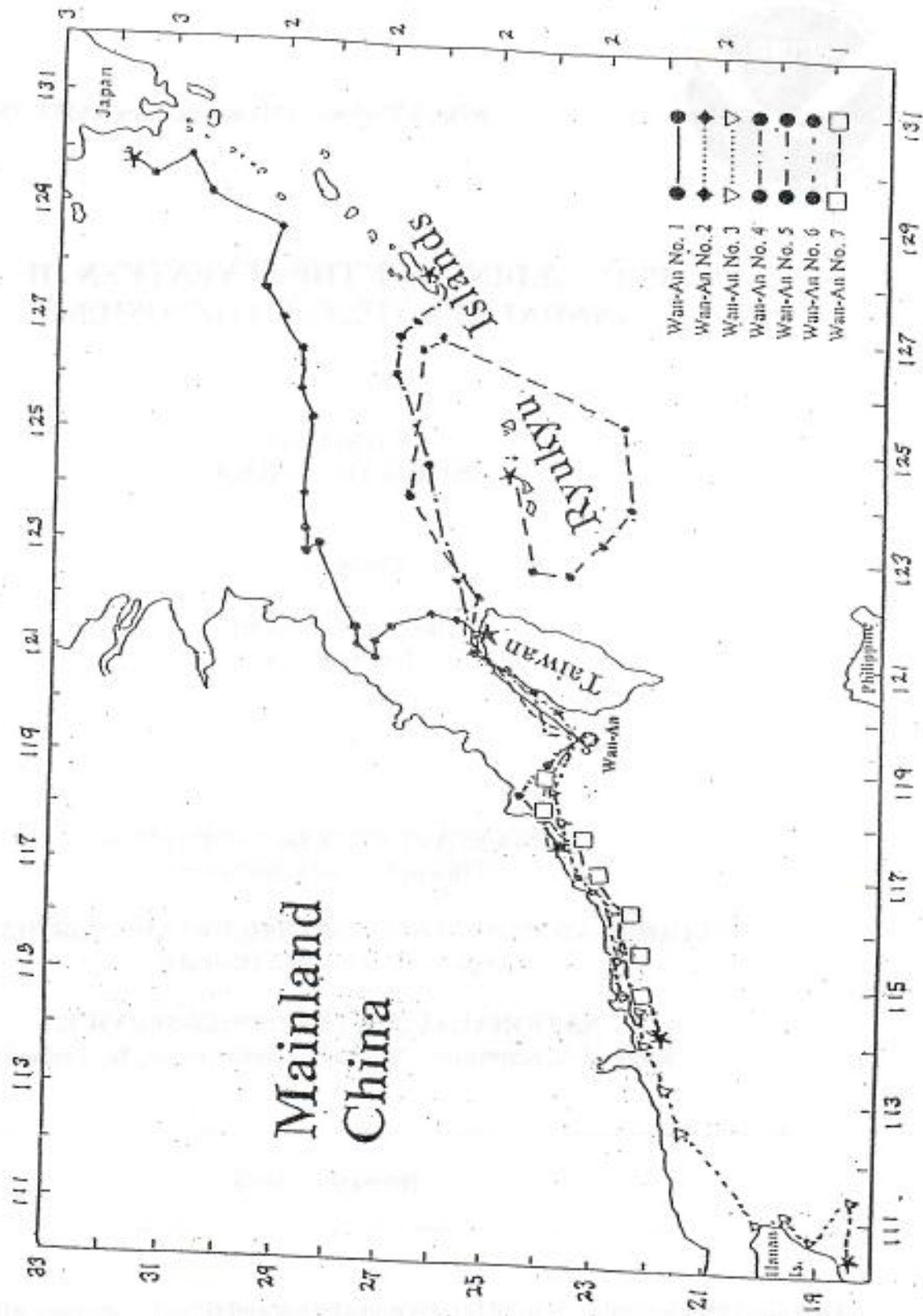


Figure 1. The post-nesting migration routes of seven green turtles that nested at Wan-An Island, PengHu Archipelago, Taiwan between 1994 and 1996. The end points are denoted by a star (★).



NOAA Technical Memorandum NMFS-SEFSC-415

**PROCEEDINGS OF THE SEVENTEENTH
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**4-8 March 1997
Orlando, Florida U.S.A.**

Compilers:

**Sheryan P. Epperly
Joanne Braun**

**U. S. DEPARTMENT OF COMMERCE
William M. Daley, Secretary**

**NATIONAL OCEANOGRAPHIC AND ATMOSPHERIC ADMINISTRATION
D. James Baker, Administrator**

**NATIONAL MARINE FISHERIES SERVICE
Rolland A. Schmitten, Assistant Administrator for Fisheries**

December 1998

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USE OF THE GENERIC MAPPING TOOLS PROGRAM TO PLOT ARGOS TRACKING DATA FOR SEA TURTLES

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Satellite telemetry is used to track the movements of sea turtles and other animals worldwide. One challenge a scientist faces is how to present the numerical data received from transmitters as a publication-quality graphic. Presented here is one way to convert tracking data into such a format using a powerful system called the Generic Mapping Tools (GMT) program, created by Paul Wessel and Walter H. F. Smith. Many GIS integrated systems, such as Argos' ELSA, and ARC/INFO or MapInfo, are available, but can range upwards of US\$4500 for the initial purchase. High resolution maps of locations worldwide can be created relatively easily using GMT, a free, public-domain collection of over 50 tools that run on UNIX, an operating system similar to DOS (Wessel and Smith, 1991; Smith and Wessel, 1990). GMT uses the WGS-84 ellipsoid as its default global projection and can be customized with personal preferences through the .gmtdefaults file. More information about GMT can be obtained over the Internet at: <http://www.soest.hawaii.edu/wessel/gmt.html> or by writing to: GMT c/o Paul Wessel, SOEST, 2525 Correa Road, Honolulu, Hawaii 96822 U.S.A. (Wessel and Smith, 1995).

The first step in making a map, such as shown in Fig. 1, is to create an executable ASCII file containing all the required command lines as follows: #!/bin/sh, where the pound sign (#) is used to "comment out" or exclude from execution that particular line, and simply notes 'this is a shell script.' The line, PSFILE=<filename>.ps, indicates the PostScript file where the output of all commands will be compiled. The map scale is created with: SCALE=X/Yd, where X and Y are the number of centimeters per degree for the corresponding axis; here, both the x and y-axes are 1.57 cm per degree. The line: gmtset DEGREE_FORMAT 3, sets the labeling so longitudes are displayed as 0 to 180 and latitudes as 0 to 90 degrees with the letters W, E, S and N appended as appropriate. Four basic commands are then used to create a map as follows:

1) psbasemap. This program creates a basic map frame for a selected area. A base map was created using the command, -R177/192.2/-21/-13, where each number specifies a corner (W/E/S/N). Map projection with the previously designated SCALE (20 available including Mercator, Hammer, etc.) was selected with the command, -Jx{SCALE}, where x specifies a linear projection. The position of the map was set at 2.5 cm from the left margin (-X2.5) and 3.8 cm from the bottom edge (-Y3.8). The tickmarks and their labels are situated every 5 degrees on the left and bottom of the frame by the command, -B5/5WeSn. For tick marks on the right and top of the frame, the 'e' and 'n' would be capitalized. The command, -K, allows you to append additional commands to the PostScript file. The line, > \$PSFILE (or >> \$PSFILE), at the end of each command line sends the results to the named PSFILE.

2) pscoast. This program includes land and water masses on the basic map. Each mass can be shaded (0-255, where 0 is black and 255 is white), colored (red/green/blue, where 0-255 provides intensity), or textured. The -G command sets the 'painting' for 'dry' areas with black as the default, -G155/240/90, colors land masses green. The -S command sets the 'painting' for 'wet' areas with white as the default, -S100/255/255 colors the water blue. GMT draws coastlines, rivers, and political boundaries with different commands. Coastlines were included as a black line with a pen size of 3 with the command, -W3/0/0/0. There are five resolutions (-D) of which the intermediate resolution (-Di) that plots polygons greater than 20 km², is probably sufficient for most maps or high resolution (-Dh, features > 1 km²) could be used. The -O command overlays output from this command line onto the previous map. Note -R and -J are not appended as no changes were made.

3) psxy. This program includes the database latitude and longitude files that were created and displays them as lines or symbols. Longitude values should be entered as 0 to 359.999. Latitude values should be entered as 0 to 90, positive in the northern hemisphere and negative in the southern hemisphere. Data files will be read into GMT as X, Y pairs (longitude, latitude). The command, -, allows the data to be read as Y, X pairs (latitude, longitude). Database files for each turtle were inputted twice, once to create tracklines and the second time to create symbols. Various types of lines (-W) and symbols (-S) can be created. Here, three lines with a pen size of six were created. The command, -W6/255/0/255, created a solid, hot pink line, -W6/255/50/50ta, an orange, dashed line, and -W6to, a black, dotted line. Three black symbols were created by -Si0.15, an inverted triangle with a side length of 0.15 cm, -Ss0.13, a square with a side length of 0.13 cm, and -Sc0.15, a circle with a diameter of 0.15 cm. Again -R and -J are not appended and -O indicates commands are overlaid.

4) pstext. This program positions text such as labels, titles, and other text onto the map. Seven fields of information are needed to create the text: X, Y, size, angle, fontno, justify, and text. X and Y can be either longitude, latitude data, or x, y values in cm (position of text is relative to map position). The 'fontno' field contains the number for a particular font, the default, 0, is Helvetica. The 'justify' field indicates the part of text on the x, y position. Text files can be included with the command line or as a separate file. The positioning for the base map (-R) of the second pstext was changed to cm (-R0/27.9/0/21.6) from latitude, longitude and the scale was set at 1:1 (-Jx1). The command line, 7.62 7.62 12 0 0 1 25693, placed "25693" as a 12 point, Helvetica string at 0 angle, and justified on the lower left corner (1) of text 10.2 cm from the left margin and 11.4 cm from the bottom. No -K command was included in the last command line, which indicates the map is finished to GMT. The final product is obtained by executing the program in UNIX and printing the output file on a PostScript compatible printer (Fig. 1, a black and white version). A high quality graphic is the reward for the time expended modifying the programs and is an excellent complement to manuscripts and presentations.

Our thanks to K. Bigelow and R. Uyeda for their time and assistance with GMT and UNIX, and to S. K. K. Murakawa, F. A. Parrish, J. Kendig, S. Beavers, and J. Nichols for providing review comments.

EXAMPLE OF A GMT COMMAND FILE

```
#!/bin/sh
PSFILE=Samoa_Fiji.ps
SCALE=1.57/1.57d
gmtset DEGREE_FORMAT 3
psbasemap -R177/192.2/-21/-13 -Jx${SCALE} -X2.5 -Y3.8 -B5/5WeSn -K > $PSFILE
pscoast -R -Jx -Di -G155/240/90 -S100/255/255 -W3/0/0 -O -K >> $PSFILE
psxy 25692_96.dat -Jx -R -W6/255/0/255 -O -K -:>> $PSFILE psxy 25694_96.dat -Jx -R -W6/255/50/50ta -O
-K -:>> $PSFILE psxy 25693_96.dat -Jx -R -W6to -O -K -:>> $PSFILE
psxy 25693_96.dat -Jx -R -Si0.15 -G0 -O -K -:>> $PSFILE psxy 25694_96.dat -Jx -R -Ss0.13 -G0 -O -K -:>>
$PSFILE psxy 25692_96.dat -Jx -R -Sc0.15 -G0 -O -K -:>> $PSFILE
pstext -R177/192.2/-21/-13 -Jx -O -K <<END>> $PSFILE
191.400 -14.000 12 0 0 1 Rose
191.400 -14.300 12 0 0 1 Atoll
178.500 -16.000 12 0 0 2 Fiji Islands
187.000 -13.300 12 0 0 1 W. Samoa
END
pstext -R0/27.9/0/21.6 -Jx1 -O <<@END>> $PSFILE
7.62 7.62 12 0 0 1 25693
7.62 5.84 12 0 0 1 25692
7.62 2.54 12 0 0 1 25694
20.62 2.41 12 0 0 1 Niue
0.5 13.97 16 0 0 1 Post-nesting Migrations of Green Turtles from Rose Atoll, American Samoa to Fiji, 1995-96
@END
```

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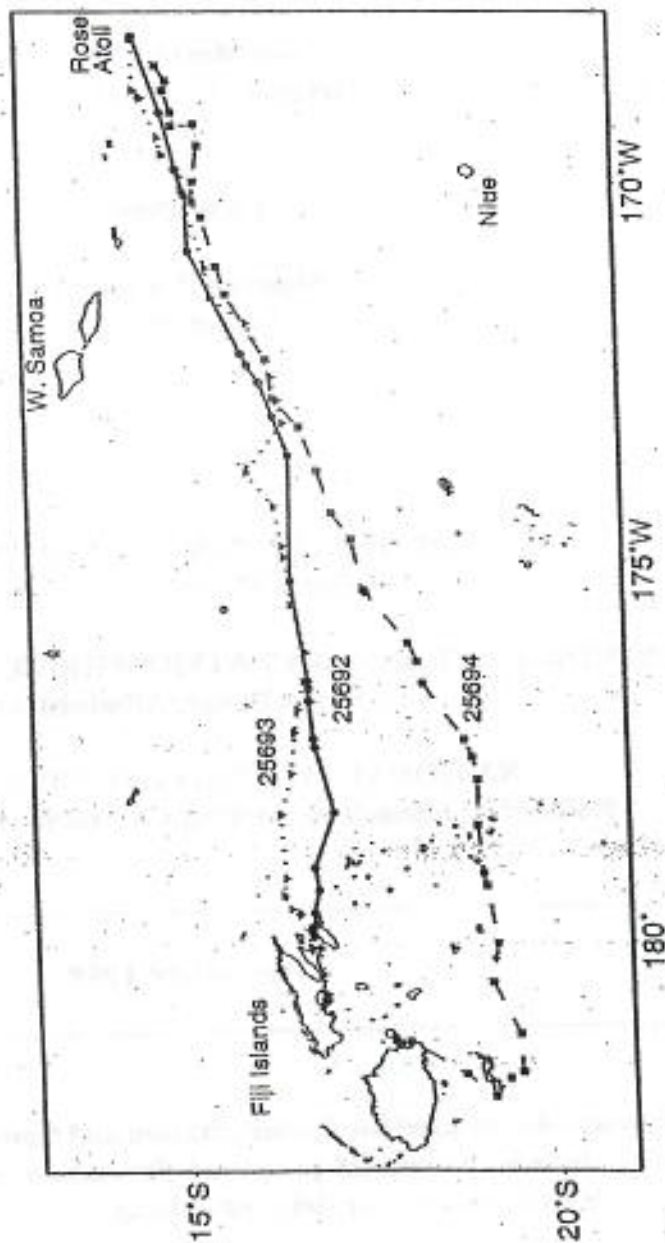


Figure 1. Graphic produced using the Generic Mapping Tools Program showing post-nesting migrations of three green turtles from Rose Atoll, American Samoa to Fiji, 1995-96



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The International Workshop on the Management
of Marine Turtles: February 3-4, 1997, Kuta, Bali, Indonesia.

USE OF SATELLITE TELEMETRY TO DETERMINE THE MIGRATORY ROUTES AND
RESIDENT FORAGING HABITATS OF NESTING HAWKSBILL TURTLES: A CASE
STUDY IN THE HAWAIIAN ISLANDS

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INTRODUCTION

Few studies have been undertaken using satellite telemetry to determine the post-nesting migrations of the hawksbill turtle, Eretmochelys imbricata. Furthermore, except for the work described herein, research involving the satellite tracking of hawksbills has not been reported for the Pacific region (Balazs et al. in press, Byles and Swimmer 1994, Groshens and Vaughn 1994).

Along with research to determine genetic identities, the use of satellite telemetry holds great potential for answering critical questions essential to the conservation and management of hawksbills and other sea turtle populations worldwide. Where do the adult turtles reside prior to and after their migrations to breed at a particular location? What oceanic or coastal routes are taken when swimming between resident foraging pastures and nesting beaches? Are these two discrete habitats, and the pathways connecting them, within the boundary of a single nation? Or do they involve multiple countries, thereby considerably complicating management efforts? This paper describes how satellite telemetry is being successfully utilized to address these questions in the Hawaiian Islands. The methodology employed is deemed entirely suitable for hawksbills nesting elsewhere, including Cuba and the wider Caribbean.

BACKGROUND

In the Hawaiian Islands the hawksbill, known as honu'ea, is a rare and endangered species (Balazs 1978, Balazs et al. 1992, 1994). Probably not more than 30 females nest in any one year at 10 different beaches scattered along shorelines of the islands of Hawaii, Maui, Molokai and Oahu. Hawksbills are not known to reside or nest in the distant Northwestern Hawaiian Islands, where green turtles, Chelonia mydas (honu), seasonally migrate to breed from foraging pastures throughout the 2400 km expanse of the archipelago (Balazs 1976).

Kamehame, a small remote beach at 19° 8.8'N, 155° 28.2'W on the southeastern coast of the island of Hawaii, hosts a major portion of all hawksbill nesting in the Hawaiian Islands. Since 1989, females arriving here have been monitored, tagged, and protected by biologists from the nearby Hawaii Volcanoes National Park (Katahira et al. 1994). However, no tagged turtles have been recaptured away from the nesting beach. In addition, there are virtually no reports of adult hawksbills being sighted by scuba divers anywhere in Hawaiian coastal waters.

Knowledge of the whereabouts of marine foraging habitats occupied by the Hawaiian hawksbill is considered essential to adequately understand, protect, and manage this local population. Although the Hawaiian Islands are located in an isolated region of the North Pacific, international migrations by hawksbills to other island groups are considered possible. Therefore, the principal objective of the ongoing study reported in this paper is to locate and map the resident foraging areas used by adults and implement appropriate management measures.

METHODS

Telonics (Mesa, Arizona USA) ST3/ST14 satellite transmitters were attached to four nesting hawksbills, two during late August 1995 and two during late August 1996. In addition, Telonics MOD-225 VHF transmitters were attached to the two turtles tracked during 1996 to obtain information on their short-range movements within the foraging areas identified by long-range satellite telemetry.

Deployments of electronic hardware on the turtles were scheduled to coincide with the latter part of each year's nesting season. The satellite transmitters were programmed with a duty cycle of six hours on, six hours off. The units were turned on at a time computed for the latitude and longitude of Hawaii to synchronize with optimum satellite overpasses during the tracking period. Each 765 g satellite transmitter was safely and securely attached to the first central scute of the carapace using Silicone Elastomer and thin layers of fiberglass cloth soaked with polyester resin. Each 85 g VHF transmitter was attached in a similar manner immediately posterior of the satellite

transmitter. The turtles were harmlessly confined on the nesting beach in a prone position inside a portable plywood pen during the attachment process. The same protocol successfully used to satellite-track the reproductive migrations of green turtles in the Hawaiian Islands, American Samoa, Florida, and Taiwan was carried out with hawksbills in the present study (Balazs et al. 1994, 1996; Cheng and Balazs 1996, Schroeder et al. 1996).

RESULTS

1995 NESTING SEASON

Hawksbill 22126- This turtle measured 88 cm in straightline carapace length (SCL) and was equipped with a satellite transmitter on 22 August 1995 after an unsuccessful nesting attempt at Kamehame. Flipper tags (N439/N440) showed that she had originally nested here in September 1991 and again in 1993. Two days after being released with the transmitter the turtle came ashore again at Kamehame and successfully nested. This event demonstrated that the transmitter attachment process had not adversely affected the turtle's behavior in any lasting manner.

During the following seven months 90 signals were relayed by Argos from hawksbill 22126. Six of these transmissions supplied useful locational data of latitude and longitude (Fig. 1). The remaining reports were limited to diving data showing that the turtle was usually surfacing only 9-12 times during each 12-hour period computed by Argos. Individual dives frequently lasted more than 50 minutes. The six positions were sufficient to show that the turtle had traveled to the windswept northeastern side of the island known as the Hamakua Coast. A position on 9 September 1995 off the eastern point of Cape Kumukahi indicated that the turtle had taken the shortest route around the island, in a counter-clockwise direction. This post-nesting migration involved a coastal distance of about 180 km. Two of the six positions were during February 1996, thereby demonstrating an extended and likely permanent residency by the turtle along the Hamakua Coast until her next reproductive migration.

Hawksbill 22134- A satellite transmitter was deployed on hawksbill 22134 on 24 August 1995 after an unsuccessful nesting attempt. A month earlier this 83 cm SCL female had been flipper-tagged (B773/B774) at Kamehame when encountered there for the first time. Five days after transmitter attachment the turtle emerged again to successfully nest at this same site.

During the following eight months over 100 transmissions were relayed by Argos, 50 of which included positions of varying levels of accuracy. Seventeen of these are shown in Figure 2. Three of the positions that occurred during December 1995, and January and April of 1996, were highly accurate (LC 1 or LC 2).

These data revealed that the turtle had also traveled to the Hamakua Coast and established residency. Like the migration of hawksbill 22126, hawksbill 22134 took the shortest route in a counter-clockwise around the island from Kamehame to the Hamakua coast. The LC 1 and LC 2 positions placed the turtle in the nearshore waters of Honomu, a minimum coastal distance of about 135 km from Kamehame. The infrequent surfacing intervals (long submergence times) supplied by Argos for this turtle were similar to those recorded for hawksbill 22126.

1996 NESTING SEASON

Hawksbill 24191 - Satellite and VHF transmitters were deployed on hawksbill 24191 on 30 August 1996 after successfully nesting. This 82 cm SCL turtle had been originally tagged (B706/R109) in August 1993 while nesting at Kamehame. The turtle departed from Kamehame shortly after the transmitters were attached, thereby indicating it was her final nesting for the 1996 season.

During the following five months 101 transmissions were relayed by Argos, 14 of which provided reliable locational data on the turtle's movements and destination (Fig. 3). As with the two turtles tracked in 1995, hawksbill 24191 migrated to the Hamakua Coast. However, unlike the turtles tracked in 1995, a coastal pathway of about 255 km in a clockwise direction was taken around the island. Calm seas prevail in the nearshore waters of the island's western coast where the turtle traveled. This undoubtedly explains the greater number (9) of very accurate positions (LC 1, LC 2 or LC 3) that Argos was able to compute.

Hawksbill 24191 swam at an average speed of 1.1 km/hr for 10 days to migrate from Kamehame to the final destination of Paauilo on the Hamakua Coast. Upon arrival, VHF transmissions were used to determine the turtle's exact location. This resulted in visual confirmation of the turtle's presence. Periodic monitoring continued for five months, during which time the turtle remained in nearshore foraging habitat at Paauilo.

Hawksbill 25695 - Satellite and VHF transmitters were attached to hawksbill 25695 (85 cm SCL) on 29 August 1996 after she successfully nested. This turtle was originally flipper tagged (B565/B566) at Kamehame 17 days earlier on 12 August 1996. After the transmitters were attached the turtle returned to Kamehame to re-nest on 16 September and 8 October 1996.

Shortly after 8 October 1996, hawksbill 25695 left the nearshore waters of Kamehame and migrated along the coastline in a clockwise direction (Fig. 4) similar to the route of hawksbill 24191. However, instead of proceeding to the Hamakua Coast, this turtle swam 115 km across the channel separating the islands of Hawaii and Maui. She then followed the coastline along Maui's northern shore until arriving at Kahului Bay. Approximately

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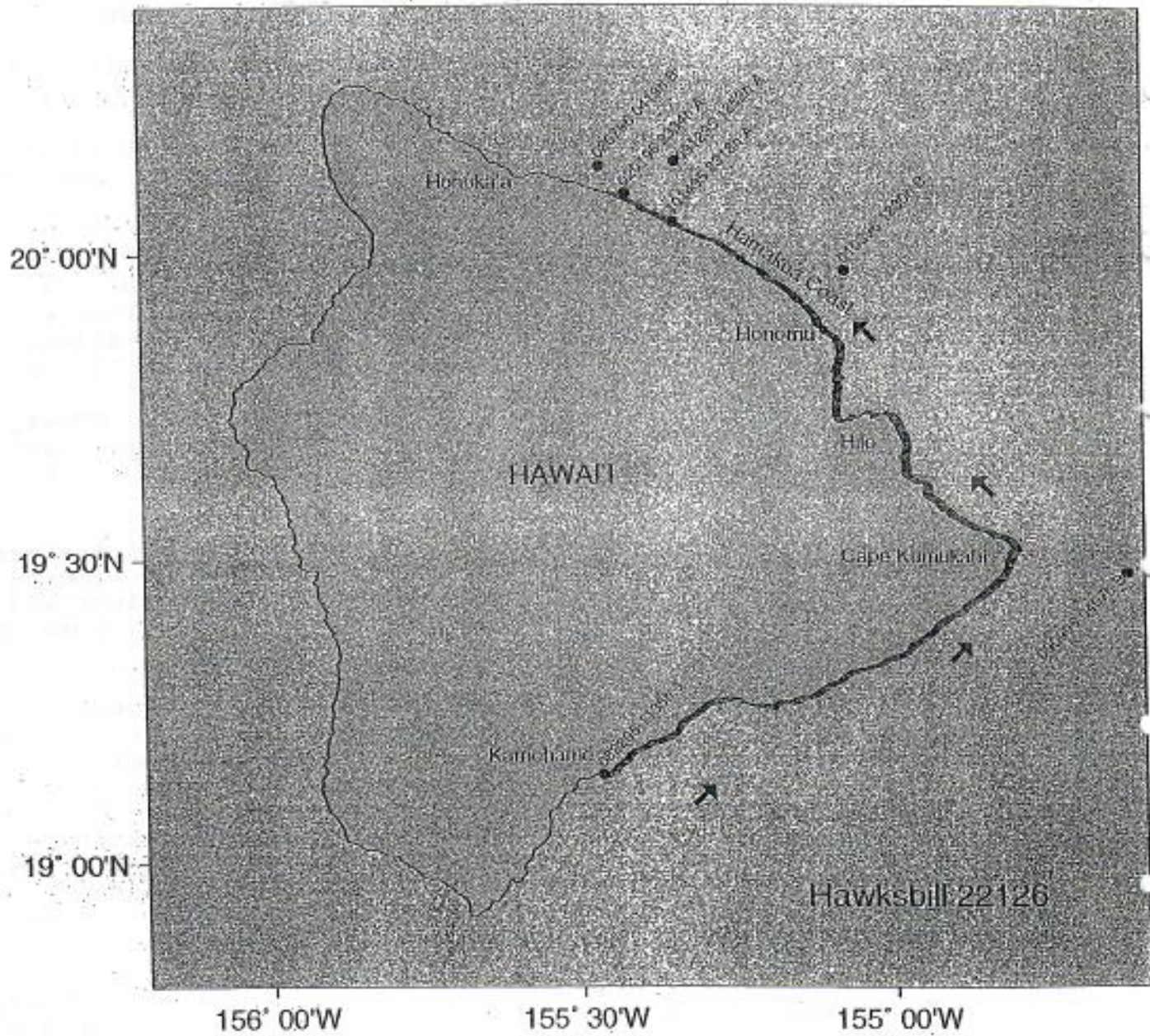


Figure 1. Post-nesting migration of hawksbill 22126 from Kamehame to the Hamakua Coast, a distance of approximately 180 km.

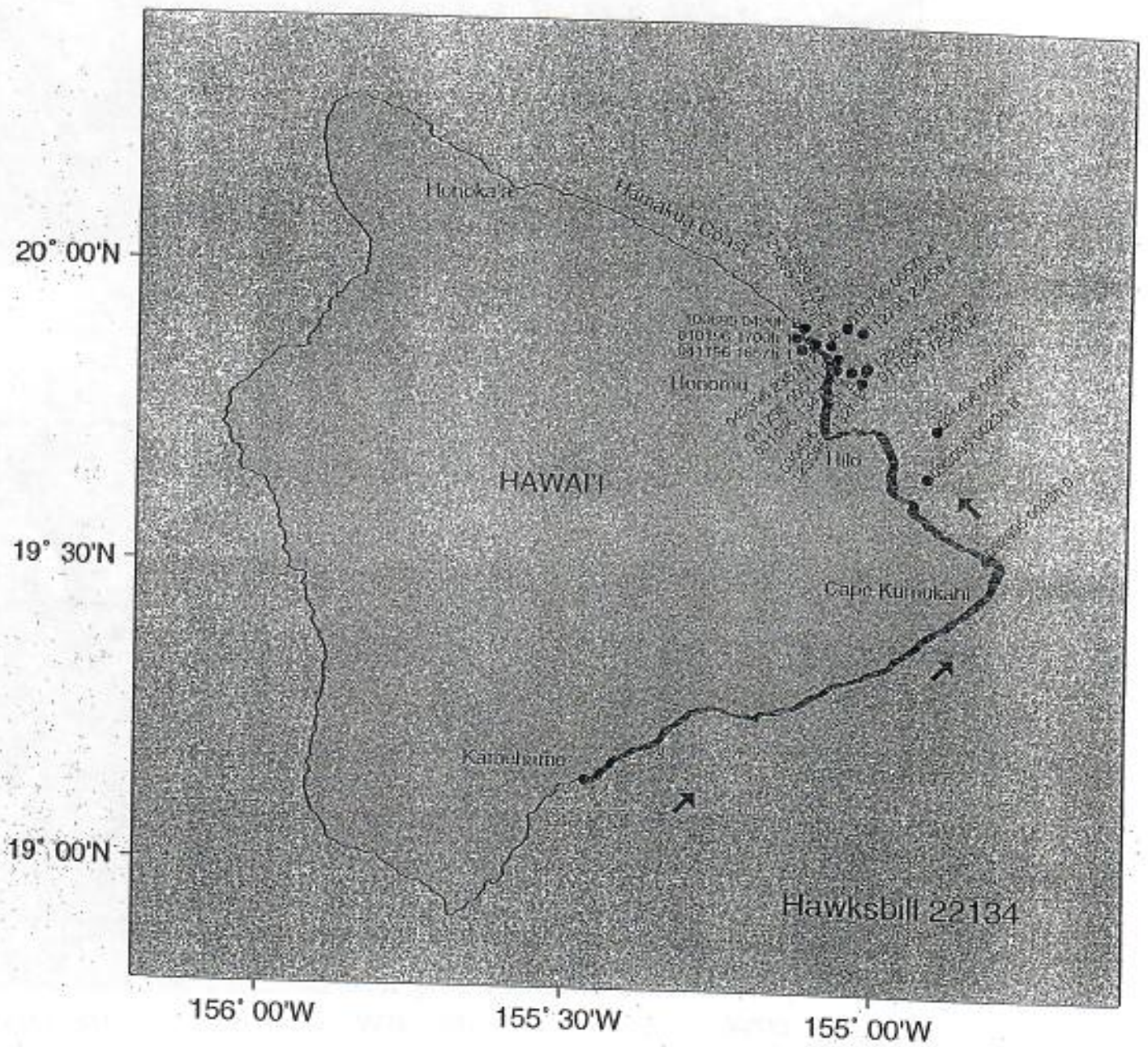


Figure 2. Post-nesting migration of hawksbill 22134 from Kamehame Beach to Honoumuli on the Hamakua coast, a distance of approximately 135 km.

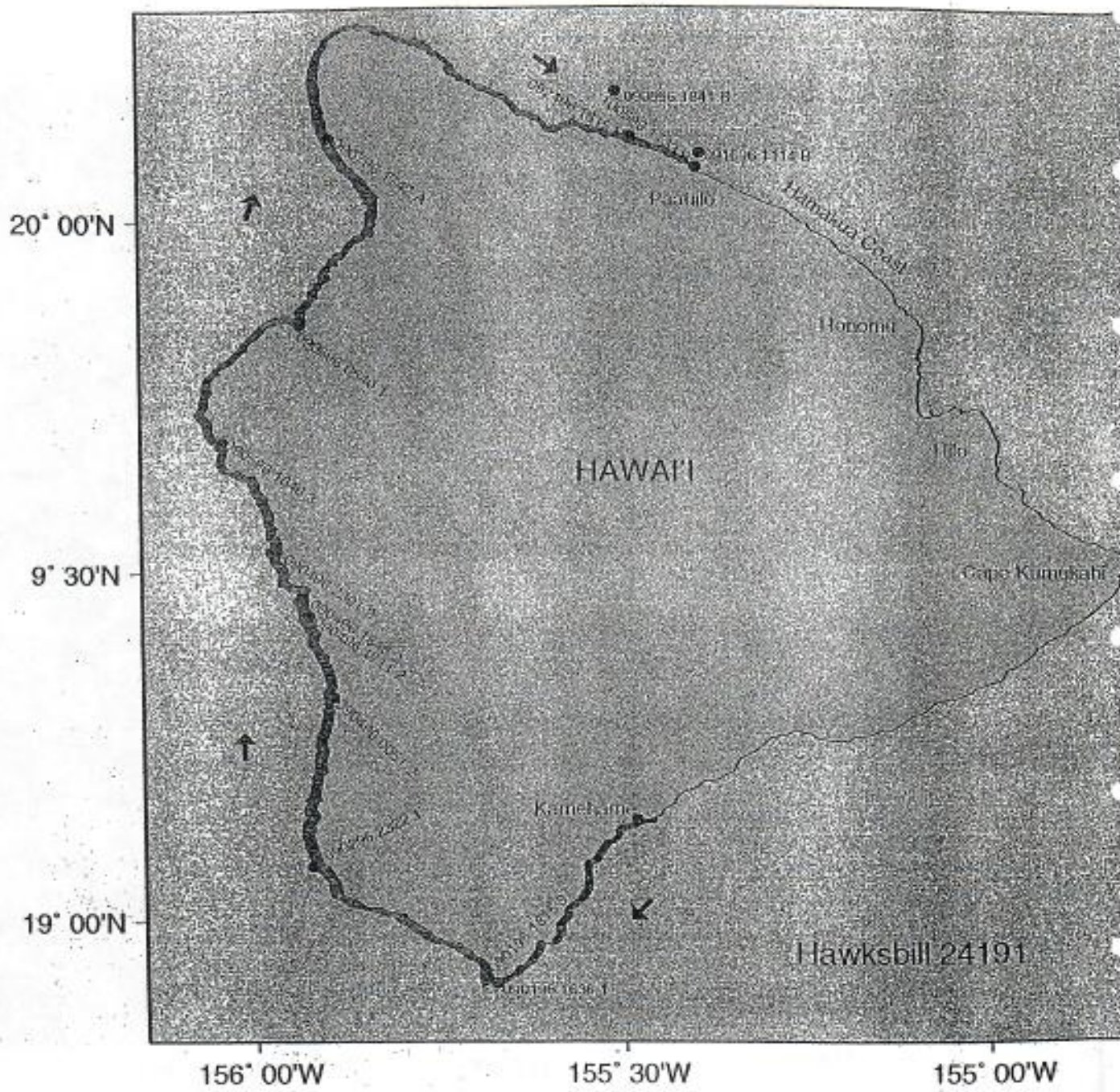


Figure 3. Post-nesting migration of hawksbill 24191 from Kamehame to Paauilo on the Hamakua coast, a distance of approximately 255 km.

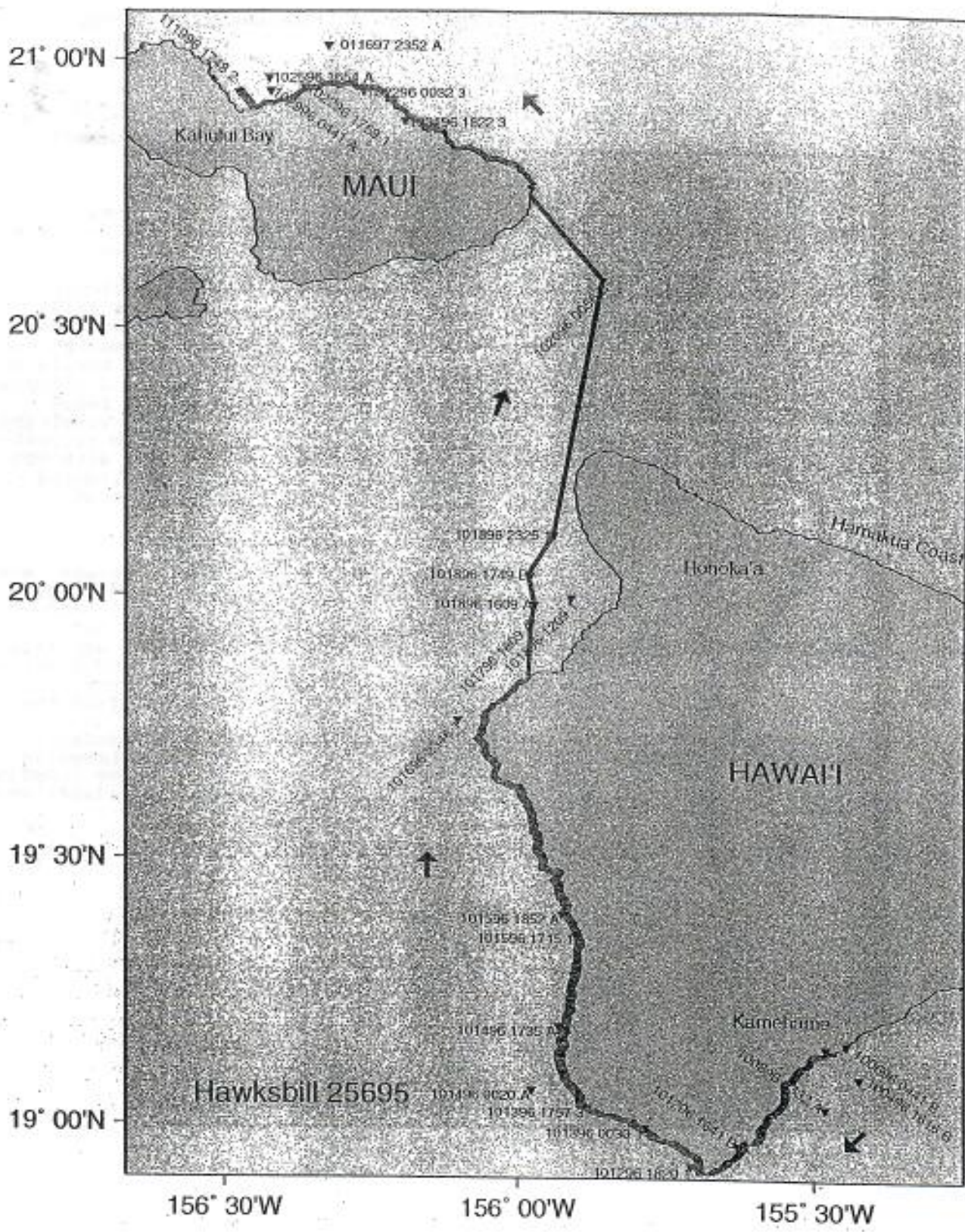


Figure 4. Post-nesting migration of hawksbill 25695 from Kamehame to Kahului Bay, Maui, a distance of approximately 315 km.

SIMPLE BIOPSY TECHNIQUE FOR SAMPLING SKIN FOR DNA ANALYSIS OF SEA
TURTLES

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PROCEDURE

Disks of skin 6mm in diameter were sampled from live green turtles, as well as frozen dead turtles. In addition, skin plugs were taken from a frozen green, leatherback, and loggerhead that had died from various causes and were being held for eventual necropsy. All samples were rapidly and easily taken using an Acu-Punch 6mm biopsy punch available from Acuderm, Inc., of Ft. Lauderdale, Florida 33309.

The plastic handle of the punch was held by the thumb and index finger, with the circular surgical blade resting against the smooth skin located immediately dorsal to the turtle's hind flipper. The turtle was placed on its back to facilitate access to this biopsy site. A circular cut 2-4 mm deep was rapidly made by rotating the tool once or twice while gently pressing down. After withdrawing the blade, the resulting disk of tissue was removed with forceps and stored in 20% DMSO saturated with salt. In the case of live turtles, the skin was cleaned with 90% alcohol prior to sampling. Virtually no bleeding occurred following biopsy, and a suture was not deemed necessary, upon the advice of a consulting veterinarian.

DNA ANALYSIS

Extraction of DNA from each of the 0.02-0.04 g tissue "plugs" was carried out using the proteinase K digestion protocol of Maniatis *et al.* (1982) as modified by Hillis and Davis (1986). All samples yielded visible DNA pellets which were washed in ice cold 70% ethanol and resuspended in sterile water. The d-loop region of mtDNA was amplified by the polymerase chain reaction (PCR) (Innis *et al.*, 1990) and resulted in a single-band product of the correct size. PCR products were sequenced on an Applied Biosystems automated sequencer to confirm the fragment was from the correct region of mtDNA.

This work demonstrates that DNA can be obtained of sufficient quality and quantity for PCR analysis from small skin tissue biopsies of sea turtles, using a quick, simple, and relatively non-invasive sampling procedure. Small biopsy punches (down to 1.5mm) are also available and

could be used for hatchlings without creating undue tissue trauma.

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John A. Musick
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**U.S. DEPARTMENT OF COMMERCE
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**NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
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**NATIONAL MARINE FISHERIES SERVICE
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Design and Field Testing of an Internal Helix Antenna Satellite Transmitter for Sea Turtles

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The use of satellite telemetry to study the migrations of marine turtles opened up a new avenue of investigation during the 1980's. Technological improvements have reduced transmitter size and increased the sophistication of satellite transmitters to enable the collection of data including geographic position and even dive profiles. Although the specific objectives of satellite telemetry research vary, the desire for regular and long-term, high quality locational data are universal. We have been studying the post-nesting movements of Hawaiian and Floridian green turtles (*Chelonia mydas*), respectively, since 1992 and 1994. While the results of our work, using Telonics ST-14 backpack-style transmitters, are considered highly successful and have elucidated the migratory pathways and identified the resident foraging grounds, we began to see a similar pattern of satellite transmitter performance and transmitter life. Locational data transmitted along the migratory routes were generally frequent and of good quality, but this was followed by a drop in quality once the turtles arrived at their foraging habitat, and rapidly degraded thereafter until locational data ceased.

Conventional satellite transmitters used on sea turtles for the past two decades have been built with an external vertical wire antenna. When used on sea turtles in benthic (non-pelagic) habitats, we suspected vulnerability of the antenna, resulting in signal attenuation or loss. The conclusions most frequently drawn when a satellite transmitter is no longer sending data are that either the unit has fallen off or the batteries have been depleted. Our evidence, working with post-nesting green turtles, indicates that these reasons are unlikely when transmitter models with a proven track record are used and when proven attachment techniques are used. In studying our results over a several year period, and encountering turtles in subsequent nesting seasons that had been previously outfitted with satellite transmitters, we concluded that the antenna was the weakest link of the system. In all cases where transmitters were recovered, the antenna was sheared off at the insertion point of the housing, while the transmitter itself was intact. These recoveries, in both the Atlantic and Pacific, corroborate our suspicion that the external antenna, in contrast to battery capacity, is the primary limiting factor in the duration and quality of successful transmissions.

We met with the manufacturer of our satellite tags, Telonics, Inc. (Mesa, Arizona, USA), in late 1997, to discuss the problem of antenna damage and how it might be overcome. During that visit with Boyd Hansen, Brenda Burger, and Stan Tomkiewicz, we sketched out a satellite transmitter housing that would encase a helix antenna and

would be more streamlined than the boxy standard ST-14 unit, in order to provide improved hydrodynamic performance (see Watson and Granger, 1998). Over the next few months, Telonics used these to design and build a prototype ST-14 unit with an internal helix antenna. In 1998, we tested four prototype units, two in Florida and two in Hawaii and, at the same time, deployed three standard ST-14 units, one in Florida and two in Hawaii. The duty cycle (time in hours that the units cycle on and off) was identical within study sites but differed between study sites. The testing of the prototypes was not designed as a comparative study between Hawaii and Florida, but was integrated into our respective, ongoing studies and was intended to compare standard vs. prototype transmitter performance at each location. The attachment technique consisted of an initial layer of silicone elastomer as a base for the transmitter, followed by three applications of polyester resin and fiberglass cloth strips (Balazs *et al.*, 1996). The standard ST-14 units were attached with the antenna posterior and a cylinder of fiberglass cloth with an outside layer of kevlar cloth resined in directly in front of the antenna to provide increased protection to the base of the antenna. The prototype units were attached in the same manner, except that the internal antenna was placed anterior and no cylinder was needed.

Results from Hawaii

Data resulting from the prototype units used in the Hawaii component of the study are depicted in Fig. 1. The location class codes indicate the relative accuracy of the calculated positions. Codes 1,2,3 have estimated accuracies of less than 1000 m; code 0 has an estimated accuracy of greater than 1000 m; and no accuracy estimates are defined for codes A or B, however these locations can be highly accurate and the researcher must interpret these locations judiciously. The standard external antenna units resulted in twice as many transmissions overall (1835 vs. 767) and about twice as many transmission that resulted in calculated locations. Seventy percent of the transmissions from the prototype did not result in a calculated position ("Z" class data). Despite the reduction in the number of locations calculated from the prototype units, there were enough valid locations to provide a clear definition of the migratory track to the resident foraging habitat.

Results from Florida

Data from the Florida turtles were dissimilar to the Hawaii results in that many fewer overall transmissions were received from both the standard and prototype units (Fig. 2). The migratory track and residential endpoint at the

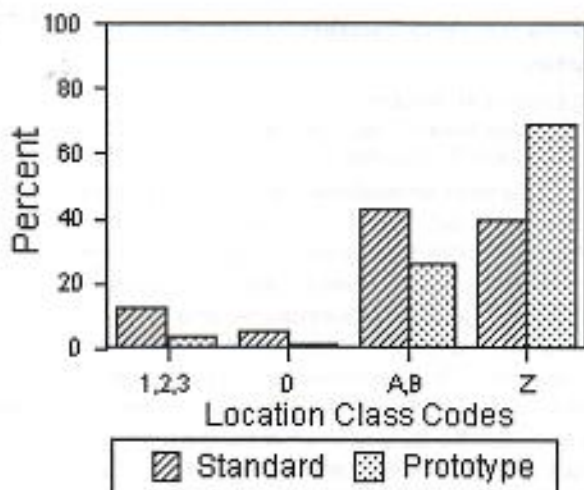


Figure 1. Results from Hawaii, combined standard units vs. combined prototype units.

foraging ground were clearly defined by the data resulting from the standard unit. In contrast, so few data points were received from the two prototype units that neither a clear definition of the migratory track nor confirmation of taking up residence on the foraging grounds could be demonstrated. The standard and prototype units performed similarly with regard to location class codes 1,2,3 and 0, but the standard unit generated a greater percentage of location class A and B positions than the prototype units, which enabled definition of the migratory pathway and confirmation of residence at the foraging site. Ninety-three percent of the prototype unit transmissions were location class code "Z" and no positions could be calculated.

Conclusions

The external antenna outperformed the internal helix antenna with regard to the number and quality of transmissions yielding locational data, six months post-deployment.

As of March 1999, of the three external antenna units, only one (a Hawaii unit) is still transmitting.

As of March 1999, of the four prototype units, all are continuing to transmit regularly, however, only the Hawaii units are currently transmitting location data.

We recommend the standard external antenna ST-14 over the prototype unit when migration routes and resident foraging habitats are unknown for post-nesting green turtles. The rolled cylinder and reverse antenna orientation (antenna posterior) are recommended for improved performance.

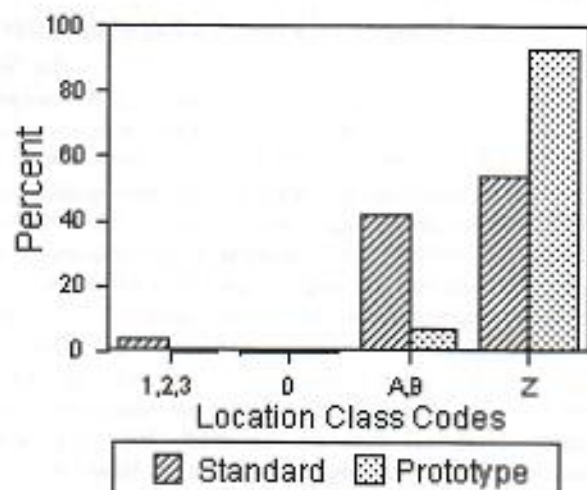


Figure 2. Results from Florida, standard unit vs. combined prototype units.

Under certain conditions, and for certain applications, the prototype internal antenna unit may be useful for collecting longer-term data. Additional testing on other sea turtle species or under different conditions may be warranted. Telonics, Inc. will build the prototype unit on a cost-order basis. This project has resulted in the mold being available at no additional cost.

Acknowledgments

We thank Denise Ellis, Marc Rice, Randy Miller, Skippy Hau, Shawn Murakawa, the U.S. Fish and Wildlife Service Refuge Division, the University of Central Florida Marine Turtle Group, Dean Bagley, Lew Ehrhart, Andrea Mosier, Steve Morreale, and Michael Coyne for their assistance with various aspects of the studies. Special thanks to Brenda Burger, Stan Tomkiewicz, and Boyd Hansen of Telonics, Inc. for their expertise and collaboration on the prototype design.

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NOAA Technical Memorandum NMFS-SEFSC-443

**PROCEEDINGS
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National Marine Fisheries Service
Penelope Dalton, Assistant Administrator for Fisheries

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Technical Memoranda are used for documentation and timely communication of preliminary results, interim reports, or special-purpose information, and have not received complete formal review, editorial control or detailed editing.

USE OF THE GENERIC MAPPING TOOLS PROGRAM TO PLOT ARGOS TRACKING DATA FOR SEA TURTLES

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Satellite telemetry is used to track the movements of sea turtles and other animals worldwide. One challenge a scientist faces is how to present the numerical data received from transmitters as a publication-quality graphic. Presented here is one way to convert tracking data into such a format using a powerful system called the Generic Mapping Tools (GMT) program, created by Paul Wessel and Walter H. F. Smith. Many GIS integrated systems, such as Argos' ELSA, and ARC/INFO or MapInfo, are available, but can range upwards of US\$4500 for the initial purchase. High resolution maps of locations worldwide can be created relatively easily using GMT, a free, public-domain collection of over 50 tools that run on UNIX, an operating system similar to DOS (Wessel and Smith, 1991; Smith and Wessel, 1990). GMT uses the WGS-84 ellipsoid as its default global projection and can be customized with personal preferences through the .gmtdefaults file. More information about GMT can be obtained over the Internet at: <http://www.soest.hawaii.edu/wessel/gmt.html> or by writing to: GMT c/o Paul Wessel, SOEST, 2525 Correa Road, Honolulu, Hawaii 96822 U.S.A. (Wessel and Smith, 1995).

The first step in making a map, such as shown in Fig. 1, is to create an executable ASCII file containing all the required command lines as follows: `#!/bin/sh`, where the pound sign (#) is used to "comment out" or exclude from execution that particular line, and simply notes 'this is a shell script.' The line, `PSFILE=<filename>.ps`, indicates the PostScript file where the output of all commands will be compiled. The map scale is created with: `SCALE=X/Yd`, where X and Y are the number of centimeters per degree for the corresponding axis; here, both the x and y-axes are 1.57 cm per degree. The line: `gmtset DEGREE_FORMAT 3`, sets the labeling so longitudes are displayed as 0 to 180 and latitudes as 0 to 90 degrees with the letters W, E, S and N appended as appropriate. Four basic commands are then used to create a map as follows:

1) `psbasemap`. This program creates a basic map frame for a selected area. A base map was created using the command, `-R177/192.2/-21/-13`, where each number specifies a corner (W/E/S/N). Map projection with the previously designated SCALE (20 available including Mercator, Hammer, etc.) was selected with the command, `-Jx{SCALE}`, where x specifies a linear projection. The position of the map was set at 2.5 cm from the left margin (`-X2.5`) and 3.8 cm from the bottom edge (`-Y3.8`). The tickmarks and their labels are situated every 5 degrees on the left and bottom of the frame by the command, `-B5/5WeSn`. For tick marks on the right and top of the frame, the 'e' and 'n' would be capitalized. The command, `-K`, allows you to append additional commands to the PostScript file. The line, `> $PSFILE` (or `>> $PSFILE`), at the end of each command line sends the results to the named PSFILE.

2) `pscoast`. This program includes land and water masses on the basic map. Each mass can be shaded (0-255, where 0 is black and 255 is white), colored (red/green/blue, where 0-255 provides intensity), or textured. The `-G` command sets the 'painting' for 'dry' areas with black as the default, `-G155/240/90`, colors land masses green. The `-S` command sets the 'painting' for 'wet' areas with white as the default, `-S100/255/255` colors the water blue. GMT draws coastlines, rivers, and political boundaries with different commands. Coastlines were included as a black line with a pen size of 3 with the command, `-W3/0/0`. There are five resolutions (`-D`) of which the intermediate resolution (`-Di`) that plots polygons greater than 20 km², is probably sufficient for most maps or high resolution (`-Dh`, features > 1 km²) could be used. The `-O` command overlays output from this command line onto the previous map. Note `-R` and `-J` are not appended as no changes were made.

3) psxy. This program includes the database latitude and longitude files that were created and displays them as lines or symbols. Longitude values should be entered as 0 to 359.999. Latitude values should be entered as 0 to 90, positive in the northern hemisphere and negative in the southern hemisphere. Data files will be read into GMT as X, Y pairs (longitude, latitude). The command, -, allows the data to be read as Y, X pairs (latitude, longitude). Database files for each turtle were inputted twice, once to create tracklines and the second time to create symbols. Various types of lines (-W) and symbols (-S) can be created. Here, three lines with a pen size of six were created. The command, -W6/255/0/255, created a solid, hot pink line, -W6/255/50/50ta, an orange, dashed line, and -W6to, a black, dotted line. Three black symbols were created by -Si0.15, an inverted triangle with a side length of 0.15 cm, -Ss0.13, a square with a side length of 0.13 cm, and -Sc0.15, a circle with a diameter of 0.15 cm. Again -R and -J are not appended and -O indicates commands are overlaid.

4) pstext. This program positions text such as labels, titles, and other text onto the map. Seven fields of information are needed to create the text: X, Y, size, angle, fontno, justify, and text. X and Y can be either longitude, latitude data, or x, y values in cm (position of text is relative to map position). The 'fontno' field contains the number for a particular font, the default, 0, is Helvetica. The 'justify' field indicates the part of text on the x, y position. Text files can be included with the command line or as a separate file. The positioning for the base map (-R) of the second pstext was changed to cm (-R0/27.9/0/21.6) from latitude, longitude and the scale was set at 1:1 (-Jx1). The command line, 7.62 7.62 12 0 0 1 25693, placed "25693" as a 12 point, Helvetica string at 0 angle, and justified on the lower left corner (1) of text 10.2 cm from the left margin and 11.4 cm from the bottom. No -K command was included in the last command line, which indicates the map is finished to GMT.

The final product is obtained by executing the program in UNIX and printing the output file on a PostScript compatible printer (Fig. 1, a black and white version). A high quality graphic is the reward for the time expended modifying the programs and is an excellent complement to manuscripts and presentations.

Our thanks to K. Bigelow and R. Uyeda for their time and assistance with GMT and UNIX, and to S. K. K. Murakawa, F. A. Parrish, J. Kendig, S. Beavers, and J. Nichols for providing review comments.

EXAMPLE OF A GMT COMMAND FILE

```
#!/bin/sh
PSFILE=Samoa_Fiji.ps
SCALE=1.57/1.57d
gmtset DEGREE_FORMAT 3
psbasemap -R177/192.2/-21/-13 -Jx${SCALE} -X2.5 -Y3.8 -B5/5WeSn -K > $PSFILE
pscoast -R -Jx -Di -G155/240/90 -S100/255/255 -W3/0/0/0 -O -K >> $PSFILE
psxy 25692_96.dat -Jx -R -W6/255/0/255 -O -K -; >> $PSFILE psxy 25694_96.dat -Jx -R -W6/255/50/50ta
-O -K -; >> $PSFILE psxy 25693_96.dat -Jx -R -W6to -O -K -; >> $PSFILE
psxy 25693_96.dat -Jx -R -Si0.15 -G0 -O -K -; >> $PSFILE psxy 25694_96.dat -Jx -R -Ss0.13 -G0 -O -K -;
>> $PSFILE psxy 25692_96.dat -Jx -R -Sc0.15 -G0 -O -K -; >> $PSFILE
pstext -R177/192.2/-21/-13 -Jx -O -K <<END>> $PSFILE
191.400 -14.000 12 0 0 1 Rose
191.400 -14.300 12 0 0 1 Atoll
178.500 -16.000 12 0 0 2 Fiji Islands
187.000 -13.300 12 0 0 1 W. Samoa
END
pstext -R0/27.9/0/21.6 -Jx1 -O <<@END>> $PSFILE
7.62 7.62 12 0 0 1 25693
7.62 5.84 12 0 0 1 25692
7.62 2.54 12 0 0 1 25694
20.62 2.41 12 0 0 1 Niue
0.5 13.97 16 0 0 1 Post-nesting Migrations of Green Turtles from Rose Atoll, American Samoa to Fiji, 1995-96
@END
```


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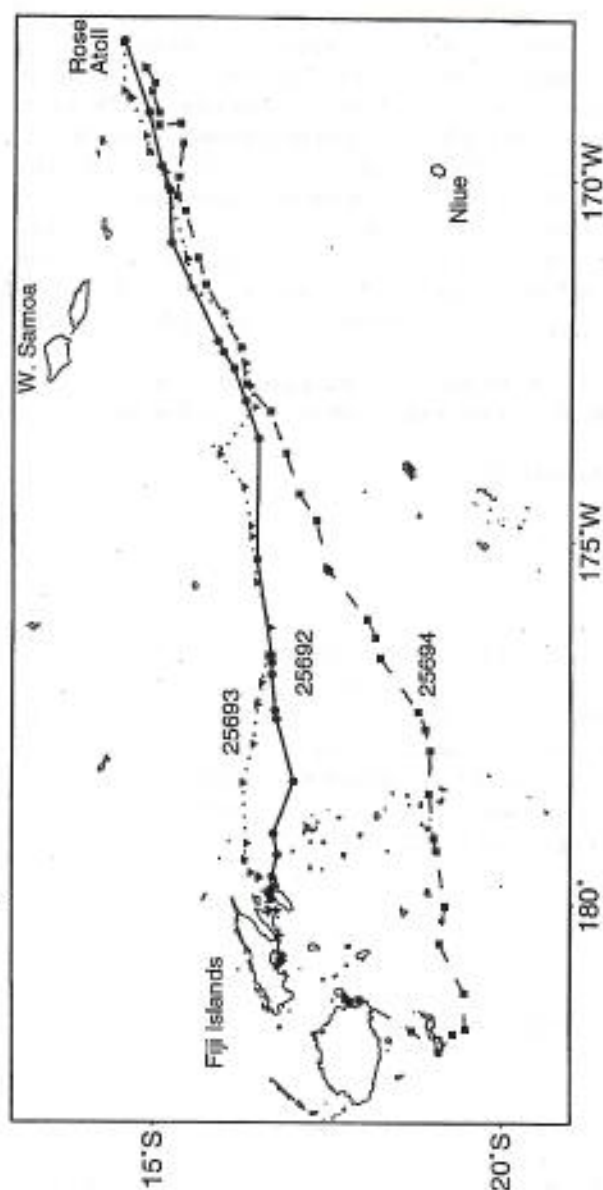
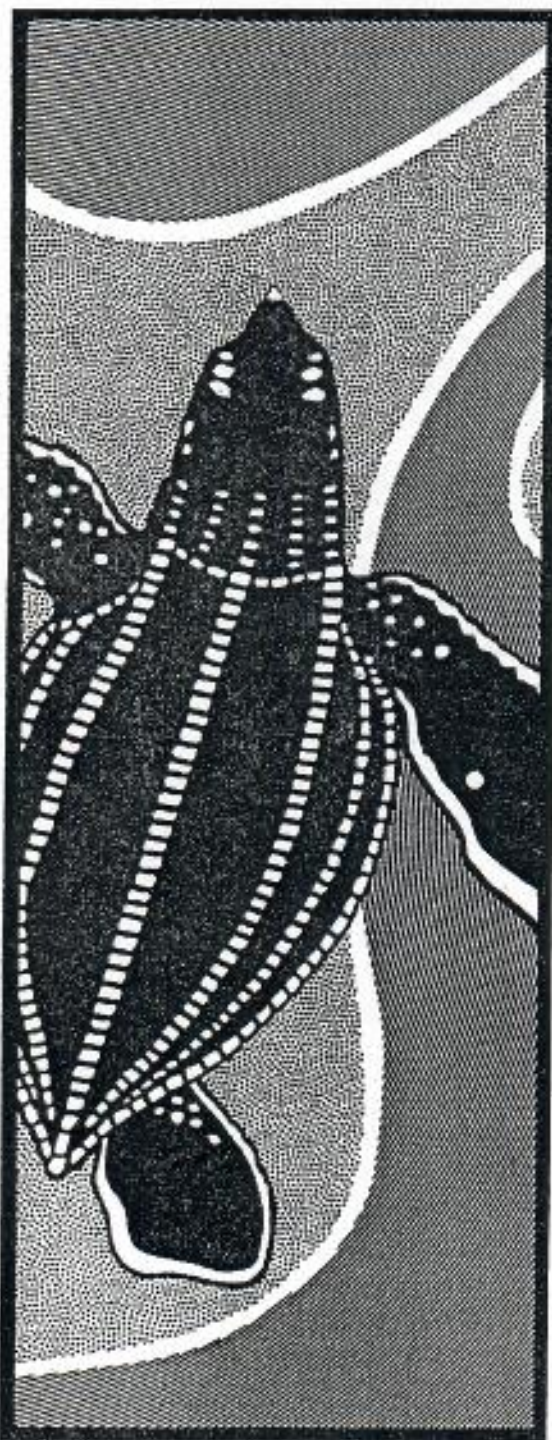


Figure 1. Graphic produced using the Generic Mapping Tools Program showing post-nesting migrations of three green turtles from Rose Atoll, American Samoa to Fiji, 1995-96



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POST-NESTING MOVEMENTS OF FLORIDA GREEN TURTLES: PRELIMINARY RESULTS
FROM SATELLITE TELEMTRY

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Studies of the green turtle population that nests in Florida have focused almost exclusively on aspects involving nests and hatchlings, including basic reproductive parameters such as remigration intervals, nest site fidelity, and the number of clutches per female per season. Only a few hundred nesting Florida green turtles have been tagged using traditional flipper tags. No recaptures away from the Florida nesting beaches have ever been reported. The principal objective of our study was to collect information on the migratory pathways and resident foraging habitats of the adult Florida green turtle population. This information is critical to identifying and protecting marine habitats that are essential for the recovery of this species.

Telonics ST-3, back-pack designed transmitters linked to the Argos satellite system were used. Transmitters were attached to three Florida green turtles nesting at the Archie Carr National Wildlife Refuge in southern Brevard County, Florida, during July 1994. Two of the three transmitters yielded data that provided insight into post-nesting movements. After departing the vicinity of the nesting beach, both turtles made very similar and directed movements southward along the east Florida coastline, turning westward as they approached the Florida Keys, and continuing along the Keys to the west. One individual remained for at least 50 days just offshore the lower Florida Keys, until the last transmission was received in late October. The second turtle continued west stopping near the Marquesas Keys, approximately 40km west of Key West. She remained in this area for at least 10 days after which no further location data were received. There was no evidence that either turtle made any stopovers as they travelled from the nesting area to the Florida Keys. We offer a working hypothesis that Florida green turtles make use of the extensive seagrass meadows and coral reefs in the Florida Keys as resident foraging habitat. We plan to continue this research and augment our sample size during the 1995 nesting season.



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**U.S DEPARTMENT OF COMMERCE
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**NATIONAL MARINE FISHERIES SERVICE
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HOMEWARD BOUND: SATELLITE TRACKING OF HAWAIIAN GREEN TURTLES FROM NESTING BEACHES TO FORAGING PASTURES

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Telonics ST-3 satellite transmitters linked to the Argos system were deployed on three green turtles, *Chelonia mydas*, nesting at East Island, French Frigate Shoals (FFS) during August 1992. The objectives of this study were to determine 1) migratory pathways to the foraging areas; 2) degree of fixation on a foraging area; 3) diving behaviors during the migrations; and 4) differences in migratory abilities between healthy turtles and ones moderately afflicted with fibropapillomas.

The intensive flipper tagging of nesting females and basking males has been underway in the Hawaiian Islands since 1973. Results show that reproductive migrations are carried out between FFS and numerous distant foraging areas throughout the 2400-km span of the archipelago (Balazs 1976, 1983). Isolated Johnston Atoll, situated 830 km to the south, also constitutes one of the foraging areas (Balazs 1985).

METHODS

A safe and secure method of attaching the transmitters was pretested on captive green turtles at Sea Life Park Hawaii. Silicone Elastomer, a two-part compound, was first used to firmly position the transmitter against the contour of the carapace along the second central scute. This product cures within five minutes and produces no heat. Final attachment was then achieved by applying two layers of fiberglass cloth and resin, similar to what has been used by Beavers et al. (1992) and Renaud (1990). A sturdy plywood container was devised to place around the turtle to safely hold her in a prone position during the attachment process.

Two of the three turtles selected for satellite telemetry were already identified with flipper tags that had been applied at Johnston Atoll (U306) and Kaneohe Bay, Oahu (U260). The third turtle (U236) had not been tagged and was moderately afflicted with fibropapillomas. This tumorous disease is of major concern for green turtle populations in Hawaii, Florida, and elsewhere worldwide (Balazs and Pooley 1991). However, severe cases of the disease are seldom seen in the breeding assemblage at FFS. This is presumably due to the inability of heavily diseased individuals to achieve reproductive readiness and accomplish the required migration. The duty cycle of the transmitters used on U260 and U236 was 6 hours on, 6 hours off. The duty cycle of U306 was 10 hours on, 50 hours off.

The study was initiated during the latter part of the nesting season to increase the chances of the turtles leaving on their homeward voyage shortly after transmitter attachment. Short-range radio telemetry of green turtles within FFS had already been conducted in 1980 early in the nesting season to determine habitat utilization during interesting intervals (Dizon and Balazs 1982).

RESULTS AND DISCUSSION

All three turtles were successfully tracked by satellite during their homeward migrations. Two of the turtles, (U260 and U236) departed within four days of one another and swam in excess of 1100 km against prevailing winds and currents to Kaneohe Bay (Fig. 1). Instead of using the islands and shoals of the archipelago as navigational guideposts, as might be expected, both turtles followed similar paths to the

south of the chain, beyond sight of land over water thousands of meters deep. The third turtle (U306) also traveled across open ocean, but directly south to Johnston Atoll (Fig. 2). The navigational system used on these voyages remains unknown. However, olfactory reception of chemical cues carried by currents from the islands is a plausible component to the piloting process (Carr 1972).

Both of the previously tagged turtles migrated to the same foraging area where they had been encountered earlier. The turtle with tumors took a less direct path, traveling 130 km farther than the healthy turtle, to arrive at the same foraging area of Kaneohe Bay. Short diving times for all three turtles indicated that they were mainly swimming close to the surface during their migration. However, mean submergence intervals regularly recorded by the transmitter over 12-hour periods revealed they were only at the surface 4-5% of the time.

This is the first reported study where green turtles have been successfully tracked on their high-seas migrations from a nesting beach to nearshore foraging areas (see Byles and Kalnath 1990).

TURTLE U260 SUMMARY--This healthy 87 cm turtle covered a distance of 1130 km averaging 2.0 km/hr during her 23-day migration from FFS to Kaneohe Bay. During this transit the average dive times ranged from 2.3-5.1 min. Five individual dives were registered lasting 11-34 min. Ambient temperatures during the migration, as recorded by a sensor in the transmitter unit, ranged from 26-27° C. Transmissions from U260 continued for 3.5 months after the migration was completed, during which time the turtle remained within Kaneohe Bay.

The tagging history of U260 showed that she had been first encountered nesting on East Island during the 1989 season. In March 1992 she was hand-captured by the author in Kaneohe Bay while resting under a coral ledge at a depth of 5 m. In June 1992 she was seen back at East Island where four nestings occurred prior to transmitter attachment in August 1992. These data demonstrate two lengthy return trips to the same nearshore area of Kaneohe Bay, thereby suggesting a strong affinity for this particular foraging location.

TURTLE U236 SUMMARY--This 85 cm previously untagged turtle had 12 tumors ranging from 1-6 cm in diameter on her front flippers, neck, and eyes. Three nestings took place on East Island in 1992 prior to transmitter attachment. In addition, the turtle was seen ashore attempting to nest on 7 other nights. U236 traveled 1280 km averaging 2.0 km/hr during the 26 days it took to reach Kaneohe Bay. During this voyage average dive times ranged from 2.2-3.3 min. Four individual dives were registered lasting 26-29 min. Ambient temperatures ranged from 24-27° C.

Since her arrival, U236 has made at least one round trip excursion outside of Kaneohe Bay along Oahu's coastline to a reef area 11 km away. Transmissions were still being received from this turtle in April 1993, 8 months after deployment.

TURTLE U306 SUMMARY--This healthy 91 cm turtle had been originally captured by net and tagged nearly 9 years earlier at Johnston Atoll when she measured 87 cm (Balazs 1985). The principal foraging area for green turtles at Johnston Atoll is adjacent to a chemical munitions disposal facility operated by the U.S. Army.

Unlike the other two turtles tracked in this study, U306 nested at least once on East Island after the transmitter was attached. She was also seen nesting on three earlier occasions during the 1992 season. She departed FFS in mid-September 1992, about one month after transmitter attachment. The 830 km trip directly to Johnston Atoll took about 22 days at an average speed of 1.6 km/hr. However, during the last 70 km of the voyage the swimming speed was only 0.5 km/hr. The average dive times ranged from 2.3-3.3 min and were very similar to those exhibited by turtle U236. Two individual dives of 28 and 29 min were registered during the migration. Ambient temperatures ranged from 26-29° C. Transmissions from U306 at Johnston Atoll ceased during late February 1993, 6 months after deployment.

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This research and similar tracking planned for the future is dedicated to the memory of Dr. Archie Carr. Many years ago Dr. Carr was the first to recognize that satellites would eventually be used to unlock the mysteries of green turtle migrations. Much remains to be accomplished to fulfill this goal, but the technology is now at our disposal in a simplified form at relatively low cost.

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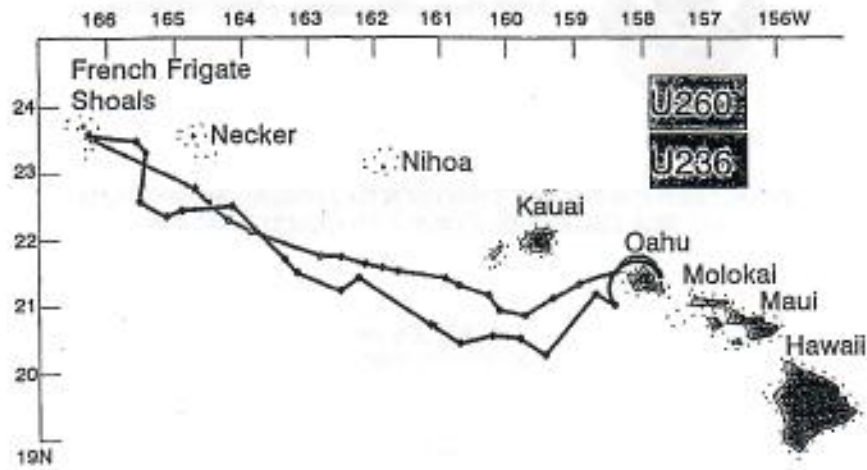


Figure 1. Migratory pathways taken by healthy turtle U260 and tumored turtle U236.

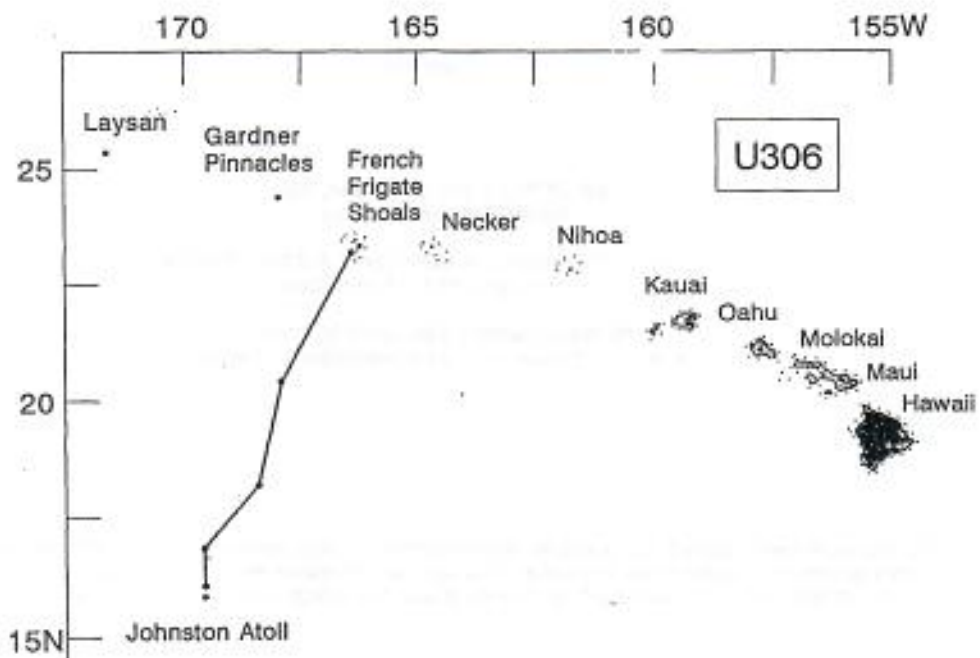


Figure 2. Migratory pathway taken by healthy turtle U306.



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SATELLITE TELEMETRY OF GREEN TURTLES NESTING AT FRENCH FRIGATE SHOALS, HAWAII, AND ROSE ATOLL, AMERICAN SAMOA

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Biotelemetry using the Argos satellite system was conducted for the second consecutive year in the Hawaiian Islands to determine migratory routes, swimming behaviors, and resident foraging pastures of green turtles, *Chelonia mydas*, nesting at French Frigate Shoals. In addition, in a cooperative study with the American Samoa Government, transmitters were deployed in the South Pacific during 1993 on green turtles nesting at Rose Atoll, the easternmost island of the Samoan Archipelago.

Satellite telemetry of sea turtles in Hawaii was initiated in 1992 and resulted in the first known successful high-seas tracking of a green turtle migrating from a nesting site to a resident foraging pasture (Balazs 1994). Satellites have not been previously used to study sea turtle migrations elsewhere in the oceanic islands of Polynesia, Melanesia, and Micronesia. Both French Frigate Shoals (Balazs 1976, 1983) and Rose Atoll (Sachet 1954, Balazs 1982, Tuato'o-Bartley et al. 1993) are historically prominent nesting sites for green turtles in this region. Although relatively small numbers nest at these isolated rookeries, both are important components to the overall survival and ecologic understanding of green turtles in the insular Pacific.

Intensive flipper tagging at French Frigate Shoals since 1973 has shown that reproductive migrations of green turtles take place to and from numerous coastal foraging areas throughout the 2400 km span of the Hawaiian Archipelago. In contrast, few turtles (50 since 1980- all *C. mydas*) have ever been tagged at Rose Atoll. Only two distant recoveries have thus far resulted from this intermittent work. A turtle tagged at Rose in 1980 was captured and killed in a net in 1986 at Kadavu, Fiji; and another one tagged at Rose in 1988 was reported speared in the Sikatoka area of Viti Levu, Fiji, in 1992 (Balazs 1993).

METHODS

Telonics ST-3 transmitters configured for backpack mounting were deployed on two turtles at French Frigate Shoals during August 1993, and on three turtles at Rose Atoll during November 1993. The transmitters were safely and securely attached using thin layers of fiberglass cloth and polyester resin. This technique was patterned after procedures used by Byles and Keinath (1990), Beavers et al. (1992), and Renaud et al. (1993). However, Rolyan Silicone Elastomer, a two-part splinting agent used in human medicine, was incorporated into the procedure. This product made it possible to rapidly and effectively custom-mount the transmitter against the contour of the carapace (at the second central scute). Silicone Elastomer cures within a few minutes after mixing, and no heat is produced in the process. During the two hours required to accomplish transmitter attachment, the turtles were harmlessly confined in a prone position using a shaded portable plywood container designed for this purpose. The ST-3 transmitters weighed 765 g and measured 17 x 10 x 3.5 cm with the antenna extending 13 cm from the top. The transmitters were programmed with a duty cycle of 6 hours on, 6 hours off.

RESULTS

Detailed high-seas tracking was successfully accomplished for the post-nesting migrations of all five turtles, as shown in Figures 1 and 2. These results are summarized as follows.

HAWAIIAN TURTLE 4803--Turtle 4803 departed French Frigate Shoals on 9/4/93, 11 days after being fitted with a transmitter during the latter part of the nesting season. She accomplished an 1180 km migration to the southeast, arriving at Kaneohe Bay, Oahu, on 9/30/93. The voyage took 26 days and followed a course well away from land, against prevailing winds and currents, over water thousands of meters deep. Her swimming speed averaged 1.9 km/hr. After reaching Kaneohe Bay, satellite monitoring continued for another 3.5 months. During this time she stayed entirely within the bay. Turtle 4803's route was very similar to those taken by the two turtles satellite-tracked from French Frigate Shoals to Kaneohe Bay in 1992 (Balazs 1994). Both of these previous turtles swam 2.0 km/hr during their migrations, taking 23 and 26 days each to cover 1130 and 1260 km.

HAWAIIAN TURTLE 4804--Turtle 4804 departed French Frigate Shoals on 9/1/93, 7 days after being deployed with a transmitter. She also swam southeast to Kaneohe Bay but, unlike other satellite-telemetered turtles traveling to this location, turtle 4804 followed a route mainly between the islands and reefs along the Hawaiian chain. On this pathway she periodically encountered relatively shallow water and benthic habitats. However, the total distance covered (1100 km), the time in transit (26 days), and the swimming speed (1.8 km/hr) of turtle 4804 were almost the same as the turtles that traveled offshore over open ocean. After arrival, turtle 4804 was recorded within Kaneohe Bay for 3.5 months before the transmitter signal terminated.

SAMOAN TURTLE 4807--A transmitter was deployed on turtle 4807 on 11/4/93. She subsequently stayed within or near Rose Atoll for 72 days, renesting on several occasions. On 1/15/94 she embarked on a 36-day migration, traveling to the southwest, across 1475 km of open ocean to the north of Tonga. She arrived in the Lau Group of Fiji on 2/20/94, averaging 1.7 km/hr. As of late March 1994, turtle 4807 was still transmitting from Lau in the vicinity of Argo Reefs (Mbukatatanoa), just south of Lakemba Passage.

SAMOAN TURTLE 4808--Turtle 4808 was fitted with a transmitter on 11/3/93 and subsequently remained within or near Rose Atoll for 47 days, renesting on several occasions. She departed on 12/20/93 and migrated 1450 km to the southwest, following a route well to the north of the one taken by turtle 4807. She arrived at Vanua Levu, Fiji, in the vicinity of Nateva Bay and Undu Peninsula, on 1/23/94. Her trip took 34 days and averaged 1.8 km/hr. As of late March 1994, she continued to remain in this same nearshore area.

SAMOAN TURTLE 4809--Turtle 4809 remained within or close to Rose Atoll for 22 days after being fitted with a transmitter on 11/3/93. She then left on a 10-day excursion, traveling 60 km to the south on a figure-eight course that covered 300 km at an average speed of 1.4 km/hr. She arrived back at Rose Atoll on 12/5/93 and remained there for 22 more days before departing again on 12/27/93. This time she continued to the southwest, across open ocean, following a route very similar to the one taken by turtle 4807. Turtle 4809 arrived at Vanua Levu, Fiji, on 2/10/94, after swimming 1750 km in 45 days at an average speed of 1.6 km/hr. Her migration terminated in the vicinity of Naweni Point, to the east of Savu Savu Bay on the south shore of Vanua Levu. As of late March 1994, transmitter signals were still being received from this same coastal area.

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U.S. Fish and Wildlife Service, National Park Service, and Sea Life Park Hawaii. Dr. Archie Carr is remembered for giving inspiration to track the ocean migrations of green turtles using earth-orbiting satellites.

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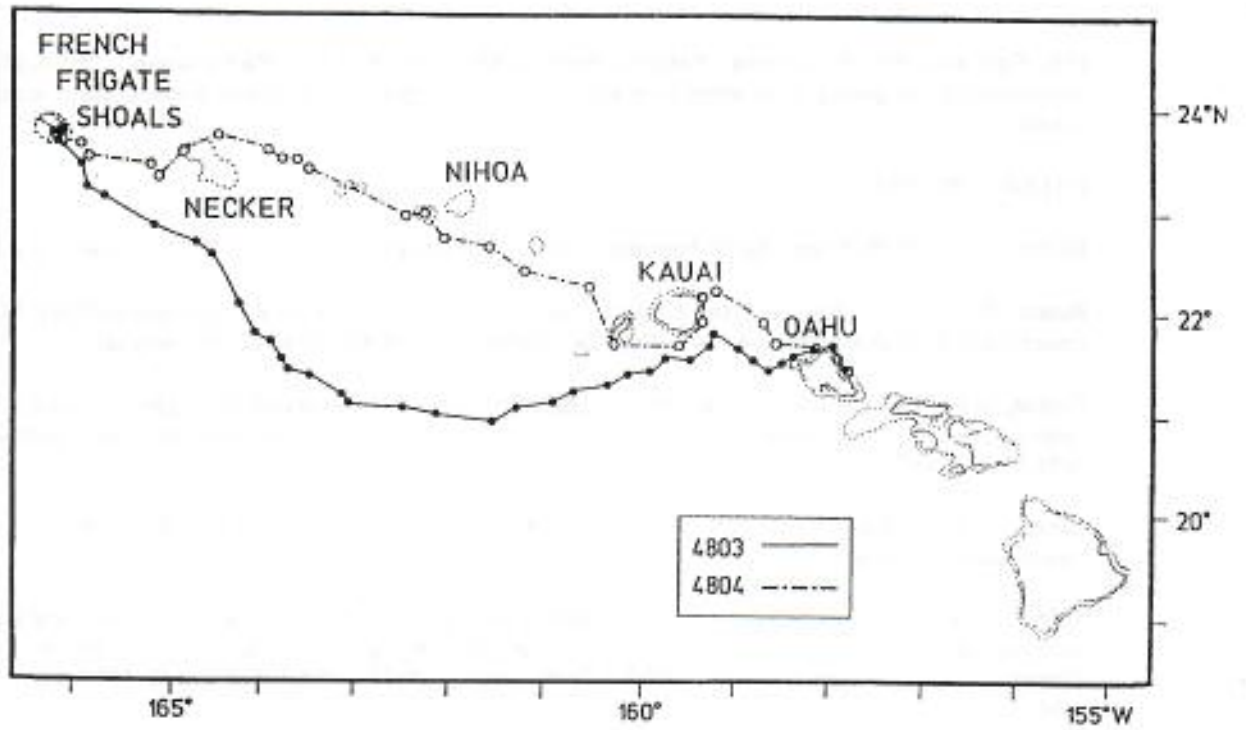


Figure 1. Migratory routes taken by Hawaiian turtles 4803 and 4804 from French Frigate Shoals to Kaneohe Bay, Oahu, in the North Pacific Ocean.

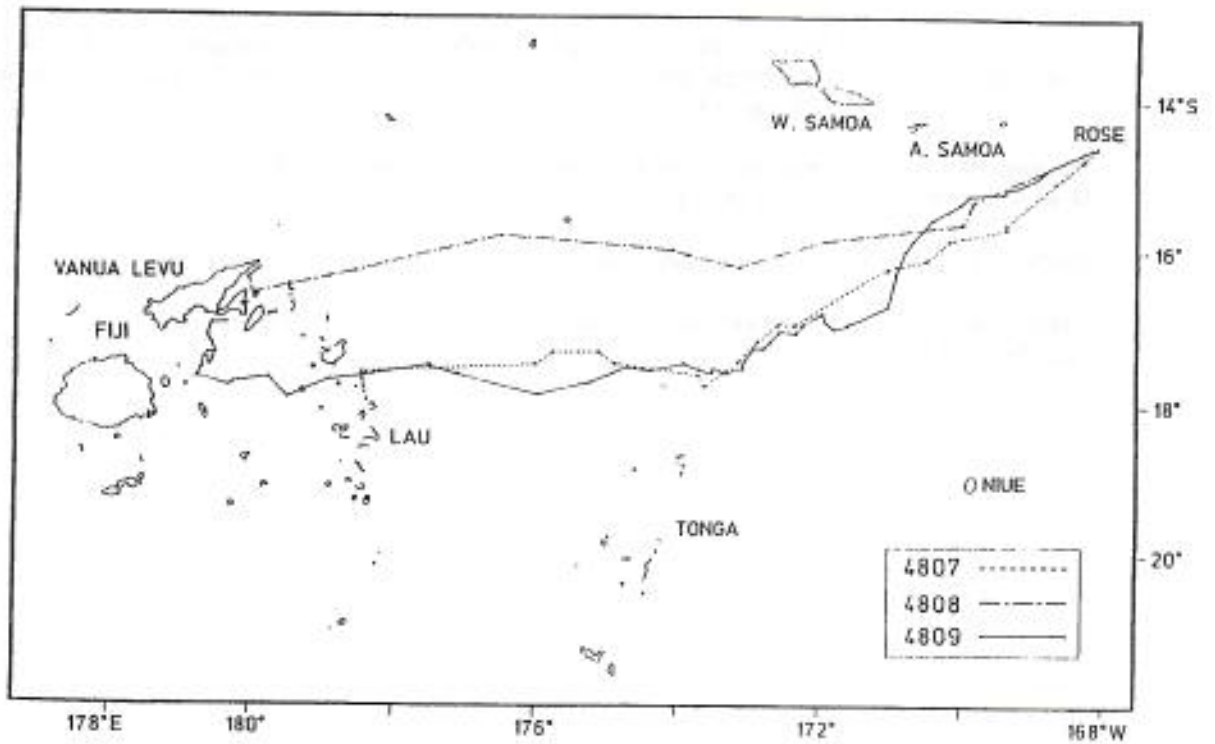


Figure 2. Migratory routes taken by Samoan turtles 4807, 4808, and 4809 from Rose Atoll, American Samoa, to the Fiji Islands in the South Pacific Ocean.



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