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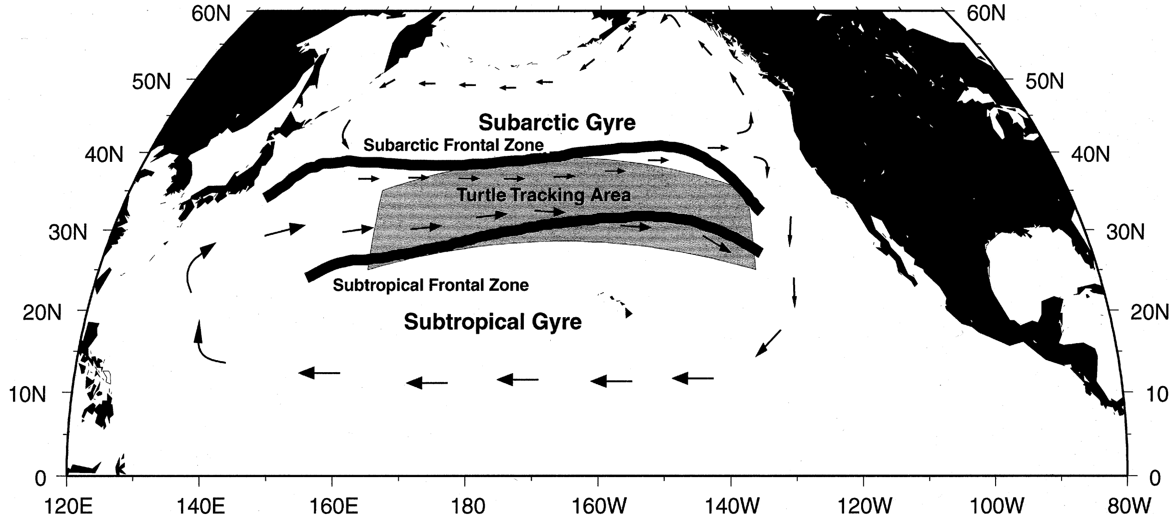
Figure 1. Schematic of the winter central North Pacific oceanography indicating the Subarctic and Subtropical Gyres and Frontal Zones. Arrows show gyre rotation; grey box indicates the general region of the loggerhead turtle tracks in this study.



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, phytoplankton-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[a]	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

[a] 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.

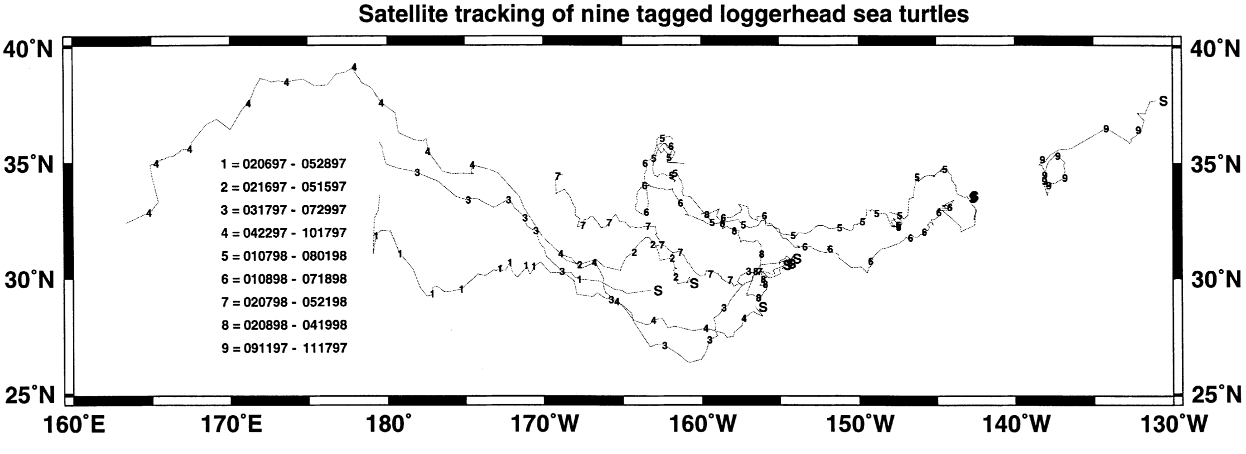
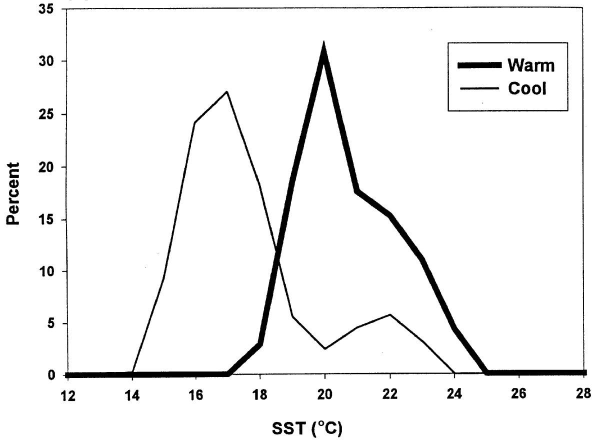
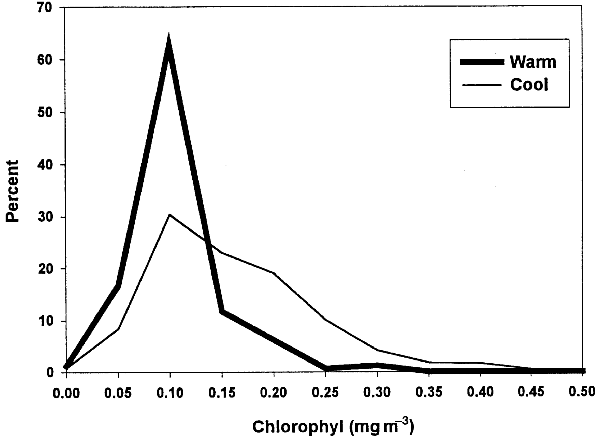


Figure 3. Frequency distribution of (a) SST, (b) chlorophyll, and (c) geostrophic current speed averaged over all turtles' positions, for the warm ($N = 211$ observations) and cool ($N = 676$ observations) temperature groups.

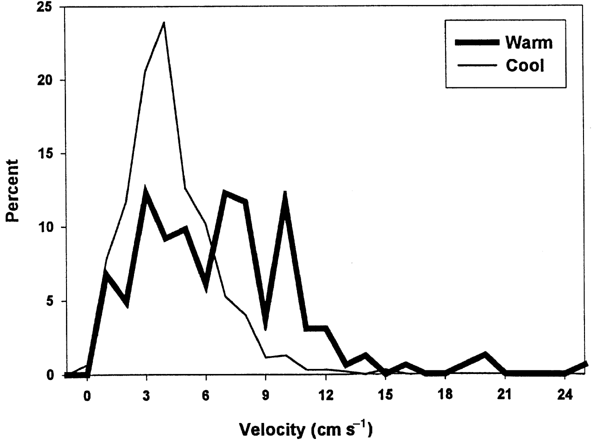
(a) SST



(b) Chlorophyl



(c) Geostrophic velocity



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, 'grdtrack', within Generic Mapping Tools (GMT) was used for the interpolation.

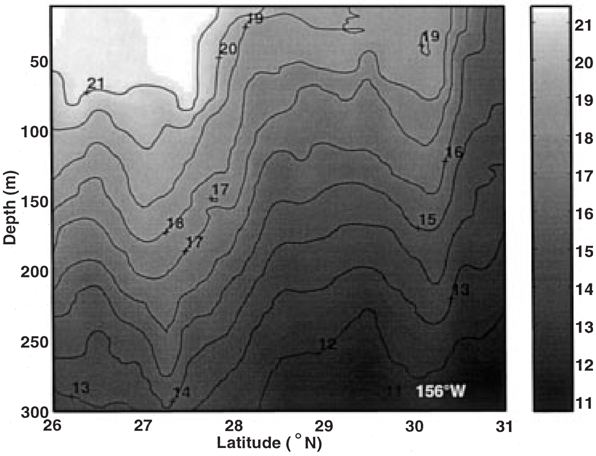
RESULTS

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).

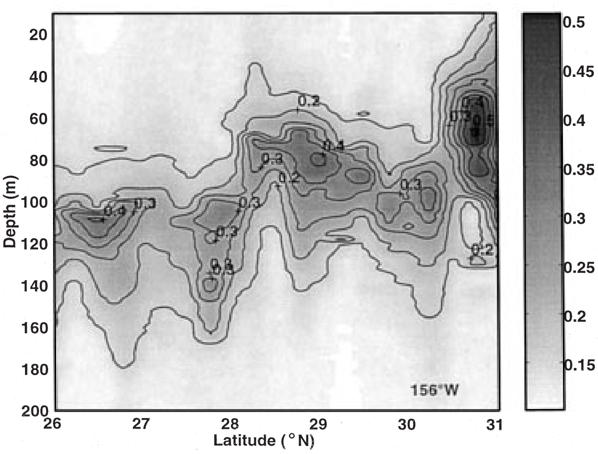
A histogram of the frequency of SST for all turtles' positions shows pronounced bimodality with modes at 17°C and 20°C. The bimodal distribution arises because some turtles associate with the cooler temperature and colleagues associate with the warmer temperature. Specifically, one group (denoted as 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.

(a) Temperature (°C)



(b) Total chlorophyll (mg m^{-3})



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).

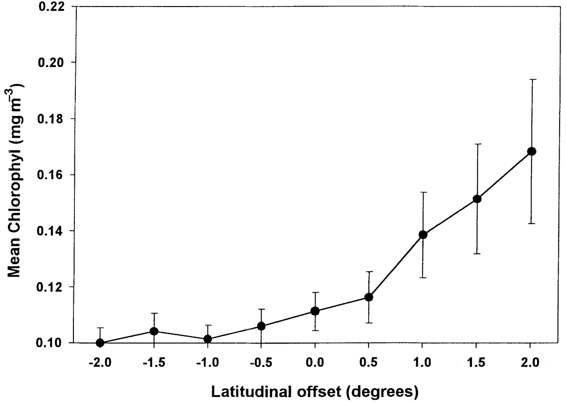
Oceanographic cruises and satellite remote sensing work recognize 20°C and 17°C, SST isotherms as indicators of two persistent fronts within the Subtropical Frontal Zone (Fig. 1) in the central North Pacific (Roden, 1991). For example, temperature–depth profiles from a cruise in March 1997 along 156°W 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.

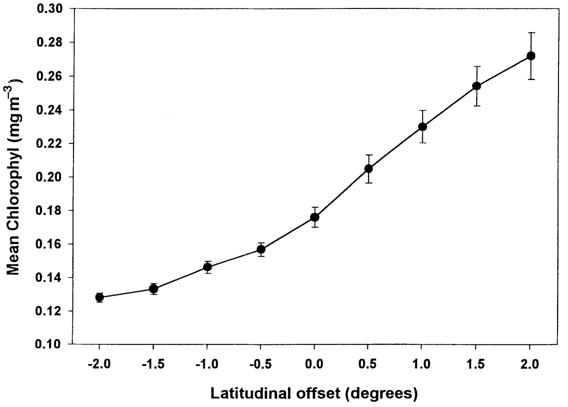
Seasonally, the 17°C and 20°C isotherms move north and south over 10 degrees of latitude (Roden, 1991). As the turtles travel westward they also appear to move north and south coherent with these isotherms. This coherence can be measured as the correlation, over all turtles' positions, between the latitude 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.


(a) Warm group


(b) Cool group

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).

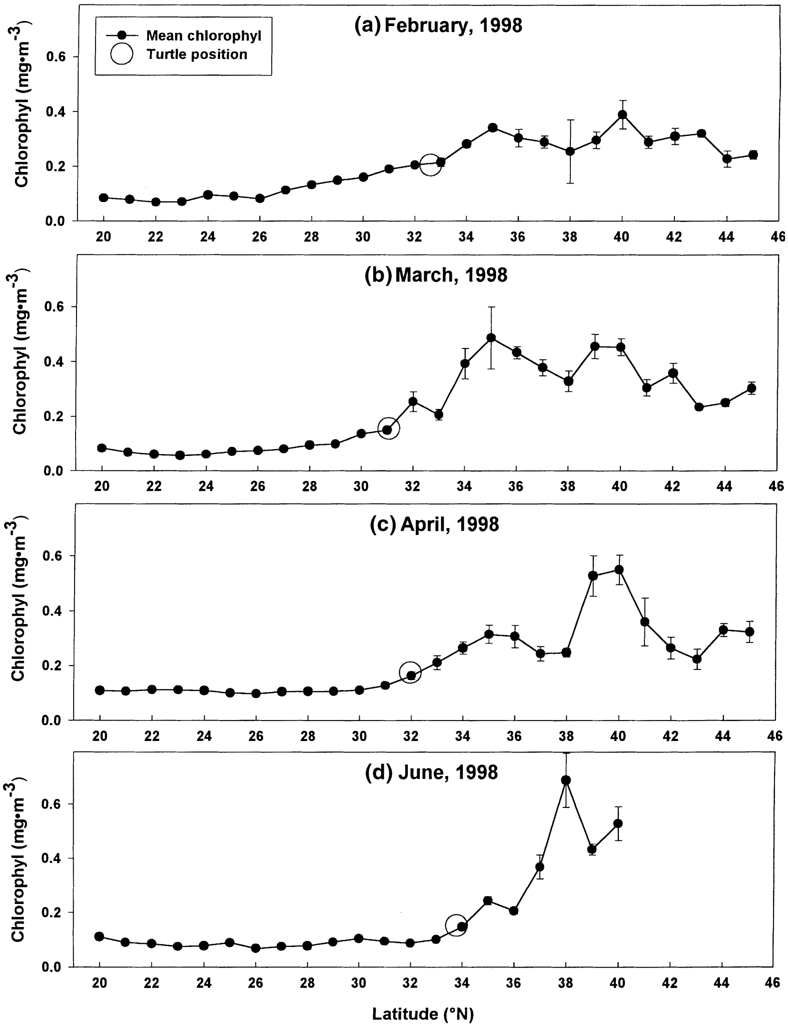
Another view of the association of loggerheads with the chlorophyll front is provided from their response to the seasonal movement of the front. The 0.2 mg m^{-3} chlorophyll density level is used as an indicator of the position of the chlorophyll front occupied by the six cool-group turtles (Figs 5, 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.

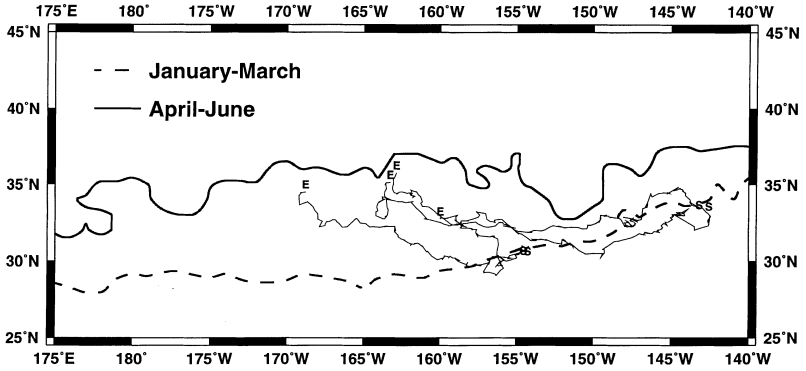


tions. We don't have any evidence that the turtle meanders widely between adjacent positions, but if this were the case, the estimated speed would underestimate the true speed.

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 50–80 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 distribution 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-

(a) January-June, 1998



(b) January-June, 1997

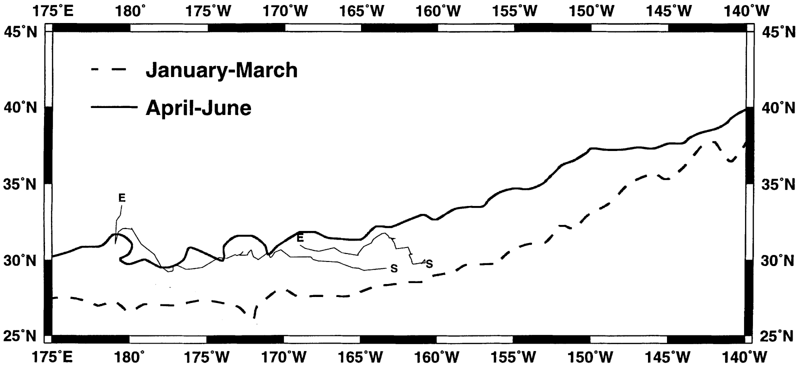


Figure 7. Positions of surface chlorophyll fronts and tracks of cool-group turtles for first and second quarters of 1997 and 1998. 'S' and 'E' denote starting and ending positions of each turtle's track. The dashed and solid lines mark the mean positions of the 0.2 mg m^{-3} chlorophyll front in the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

gerheads 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).

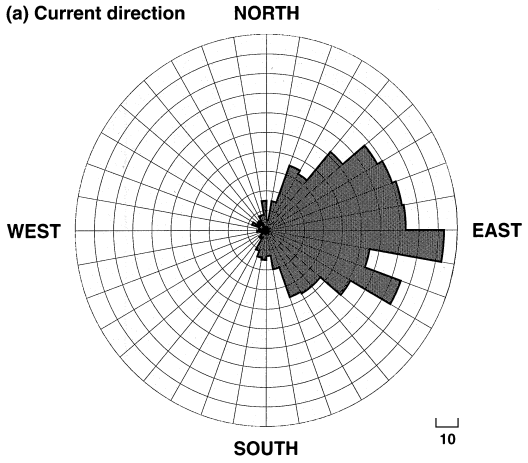
DISCUSSION AND CONCLUSIONS

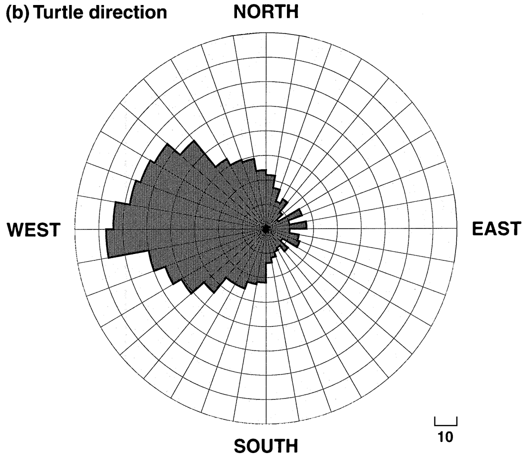
While earlier work has speculated that fronts are important habitat for juvenile loggerheads (Carr, 1987), we provide evidence that describes the habitat of loggerheads in the central North Pacific as being strongly linked to fronts. In particular, three of the loggerheads were associated with a front 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 cyaneus*, 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.


(a) Current direction

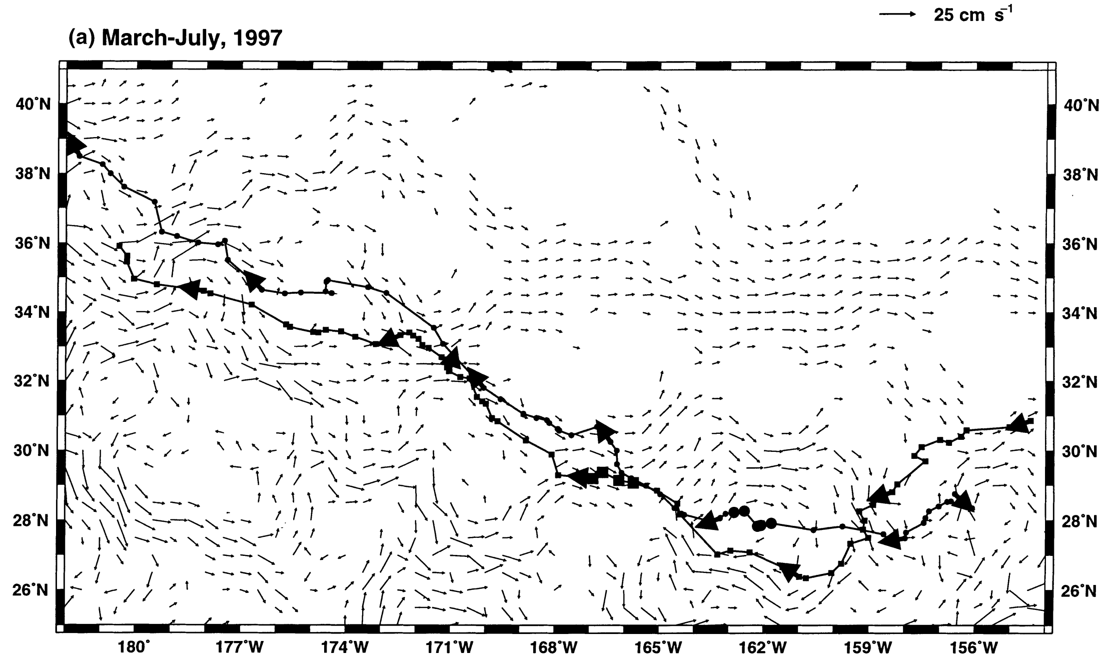

(b) Turtle direction

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.

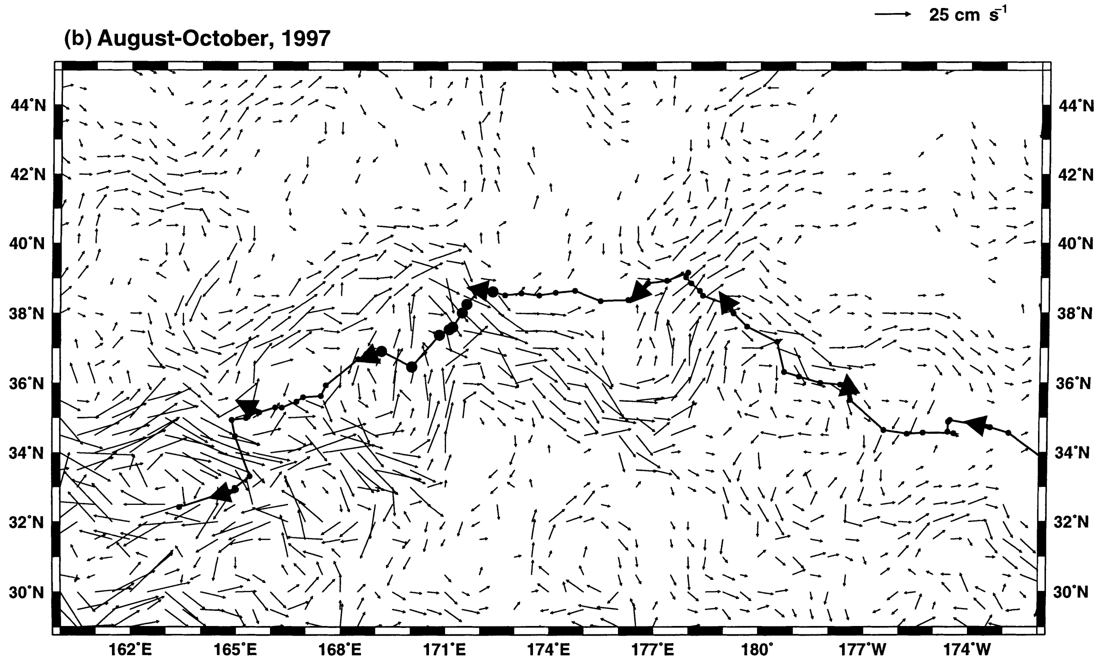
The geostrophic current estimated with TOPEX/Poseidon is a clear indication of a front, but our estimate, derived from the altimeter, of current velocities encountered by the turtles is based on two conditions: firstly, that the satellite-derived estimates of geostrophic current are accurate; and secondly, 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 3–4 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.



(a) March-July, 1997



(b) August-October, 1997

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.

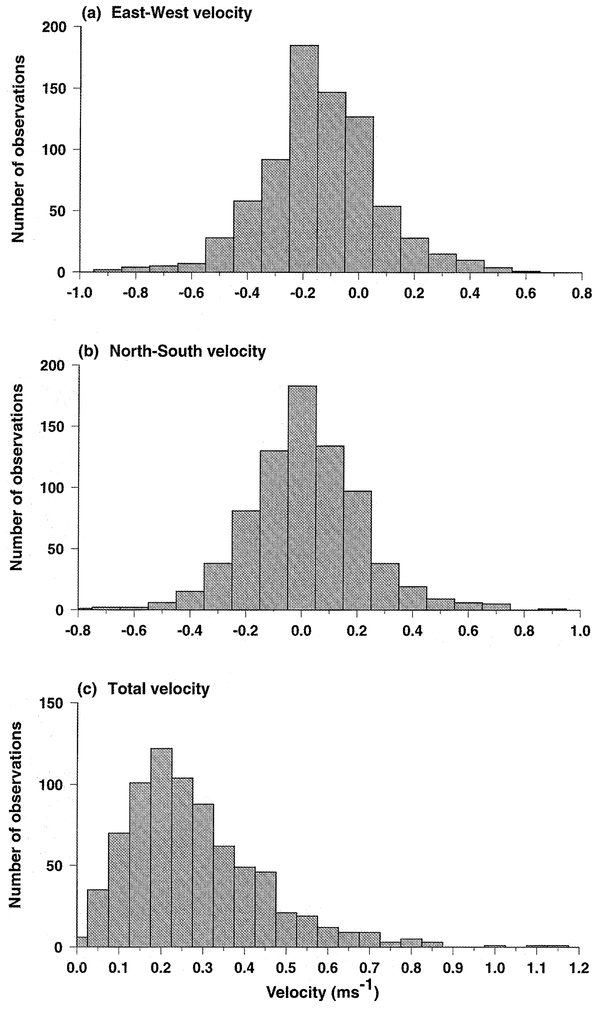
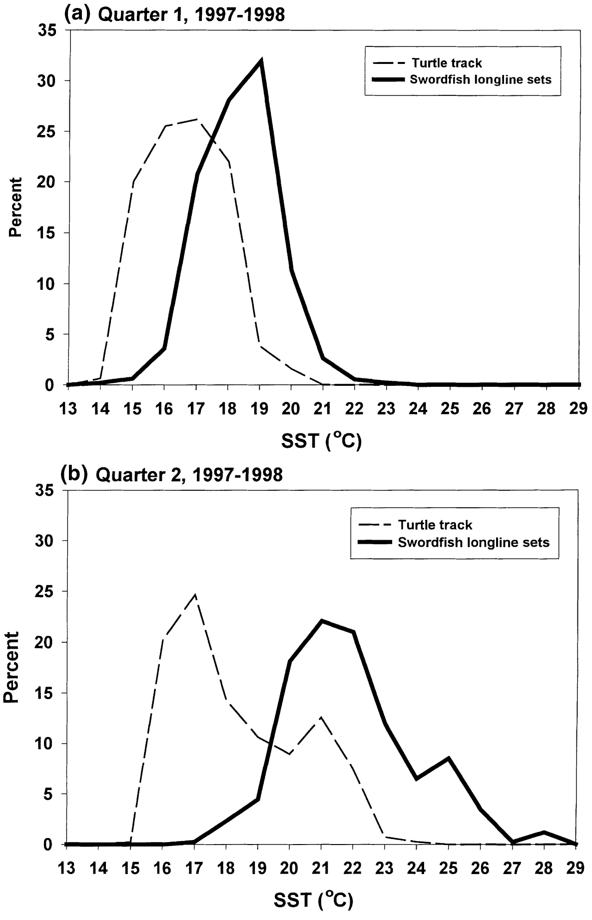


Figure 11. SST distribution of Hawaii-based longline effort for swordfish during (a) first quarter and (b) second quarters of 1997 and 1998, together with the distribution of SST occupied by the loggerheads tracked in the fishing grounds during the same period.



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 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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