INT. J. REMOTE SENSING, 2001, VOL. 22, NO. 8, 1403–1411

# Movements of migrating green turtles in relation to AVHRR derived sea surface temperature

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(*Received 23 December 1999*)

**Abstract.** Previous studies have shown that for some populations of marine turtle, individuals move along narrow migration corridors in the open ocean. It has been suggested that these migration corridors may correspond with near-surface oceanographic features that can be detected by remote sensing. This idea is examined by superimposing the tracks of green turtles (*Chelonia mydas*) migrating from Ascension Island to Brazil, on sea surface temperature (SST) data derived from Advanced Very High Resolution Radiometer (AVHRR) images. The turtles did not follow specific isotherms during migration nor make turns en-route where specific thermal cues were encountered. These results suggest that for this population, SST plays a minimal role in influencing the exact route that individuals follow.

## 1. Introduction

The long-distance movements of marine turtles are one of the wonders of the natural world, with mark-recapture techniques showing how some species may move thousands of kilometres across the oceans (Meylan 1995). For example, green turtles (*Chelonia mydas*) nesting on Ascension Island (7°57′ S, 14°22′ W) in the South Atlantic have been marked with numbered flipper tags and have subsequently been recaptured over 2000 km away on the coast of South America (Mortimer and Carr 1987). Over the last decade, the advent of reliable satellite tracking technology using the Argos system, has breathed new life into the study of such long-distance movements by allowing accurate reconstructions of the courses followed by individual animals (e.g. Papi and Luschi 1996).

One of the most startling discoveries from these tracking studies is that, for

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*International Journal of Remote Sensing*
ISSN 0143-1161 print/ISSN 1366-5901 online © 2001 Taylor & Francis Ltd
http://www.tandf.co.uk/journals
DOI: 10.1080/01431160010016790

certain populations, individuals may follow very consistent routes across the open ocean. For example, between 1992 and 1995, Morreale *et al*. (1996) satellite tracked seven leatherback turtles (*Dermochelys coriacea*) as they left their nesting area on the Pacific coast of Costa Rica. These individuals were tracked for up to 2780 km and all followed similar courses as they moved across the equatorial Pacific, giving rise to the suggestion that this population utilises a narrow migration corridor. More recently, green turtles have been tracked during their migration from Ascension Island to Brazil and, again, individuals followed very similar routes as they departed from their nesting beaches (Luschi *et al*. 1998). These results have provoked speculation as to what signposts may identify the migration corridors. One suggestion is that turtles might use two properties of the Earth's magnetic field, the inclination and intensity, to form a map of the migration area which allows them to set the appropriate course (Lohmann and Lohmann 1996). A second suggestion is that migration corridors might, in some areas, be identified by odours in the water (Koch *et al*. 1969). Alternatively, the corridors might correspond with specific oceanographic features (Morreale *et al*. 1996).

Testing these various ideas is logistically challenging and so, to date, they have remained speculative. As suggested by Morreale *et al*. (1996) one possibility of examining whether the migration corridor of sea turtles corresponds with an oceanographic feature, is to examine tracks in relation to remote sensed imagery. For example, it is well known that frontal regions may be characterised by sharp temperature gradients and hence may be readily evident on satellite images (e.g. Burrage *et al*. 1996). Here we develop this approach by superimposing the routes followed by green turtles migrating from Ascension Island, with satellite derived images of sea surface temperature. In this way we examine whether the migration corridor for this population corresponds with a thermal corridor across the Atlantic.

## 2. Methods

### 2.1. *Turtle tracks*

Detailed methodology has been reported previously (Luschi *et al*. 1998). In short during 1997, five turtles (turtles B-F following the terminology in Luschi *et al*. 1998) were tracked by satellite as they migrated from Ascension Island to Brazil. To accomplish this tracking, satellite transmitters (also termed platform terminal transmitters or PTTs) (model ST-14, Telonics Inc.) were attached to female turtles while they were nesting on Ascension Island and were subsequently located using the Argos system (see Luschi *et al*. 1998, for a full description of how the tracks were reconstructed). The Argos system involves PTTs transmitting radio signals (401.650 MHz), termed uplinks, at a predetermined interval (typically 50–90 seconds for animal tracking) to either of two polar-orbiting NOAA satellites, with the PTT location being obtained from the Doppler shift recorded as the satellite approaches and then moves away from the PTT.

### 2.2. *AVHRR image processing*

The raw Multi-Channel Sea Surface Temperature (MCSST) data, which is derived from the 5-channel Advanced Very High Resolution Radiometers (AVHRR) on board the NOAA series polar orbiting satellites, was downloaded from the NASA Physical Oceanography Data Analysis Center (PODAAC) web site (http://podaac.www.jpl.nasa.gov/mcsst). Weekly averaged night-time data were obtained at a resolution of 18 km for the region of interest for the 10 weeks between

4 June and 7 August 1997. The data were interpolated to remove the effects of clouds and retained in the raw format so that SST data could be extracted on a pixel by pixel basis.

### 2.3. *Overlaying turtle tracks with AVHRR imagery*

Turtle tracks were overlaid on the AVHRR images using the software package, The Environment for Visualizing Images (ENVI). To extract the SST for each turtle location, we used the AVHRR image for the particular week that the location was obtained. For each turtle location we therefore also determined the SST for that 18 km by 18 km patch of the ocean.

## 3. Results

Transmitters were attached between 12 May and 2 July 1997, with turtles being tracked for up to 2300 km over the subsequent weeks (table 1). Detailed analysis of the routes followed by the five individuals have been reported elsewhere (Luschi *et al.* 1998). In short, all the turtles departed from Ascension Island in an approximately WSW direction and followed very similar routes for the first few hundred kilometres of migration. Subsequently, individuals turned and headed WNW before all the tracks eventually converged on the most westward point of Brazil (figure 1). Since turtle B was released on 12 May, there is a delay of about 20 days before the first available AVHRR image. However, since the temporal change in the SST field is slow, this time gap is unlikely to be important in the following data analysis and interpretation.

The general spatio-temporal patterns in SST during the period that turtles were

Table 1. Details of the release date for turtles, the tracking duration (d), the distance covered (km), and the mean ambient AVHRR derived SST (n ± 1 SD).

| Turtle | Release date | Tracking duration (d) | Distance covered (km) | SST (°C) |
|---|---|---|---|---|
| B | 12 May | 35 | 2321 | 26.9 ( 99, 0.6) |
| C | 22 June | 39 | 2347 | 26.2 ( 94, 0.4) |
| D | 25 June | 33 | 1793 | 25.9 ( 56, 0.2) |
| E | 28 June | 47 | 2095 | 26.0 (102, 0.3) |
| F | 2 July | 36 | 2285 | 25.4 (105, 0.3) |

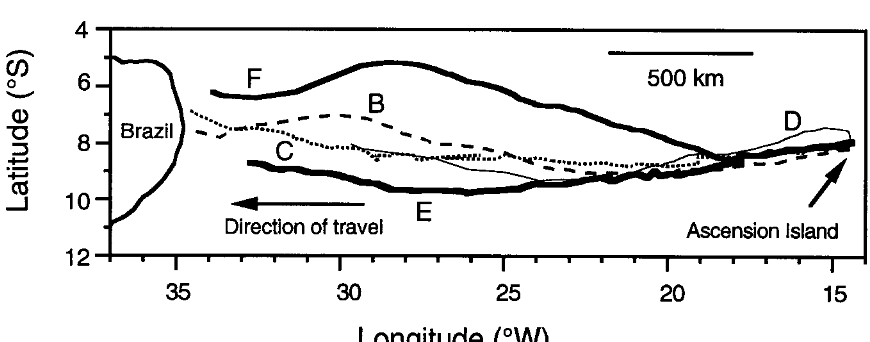


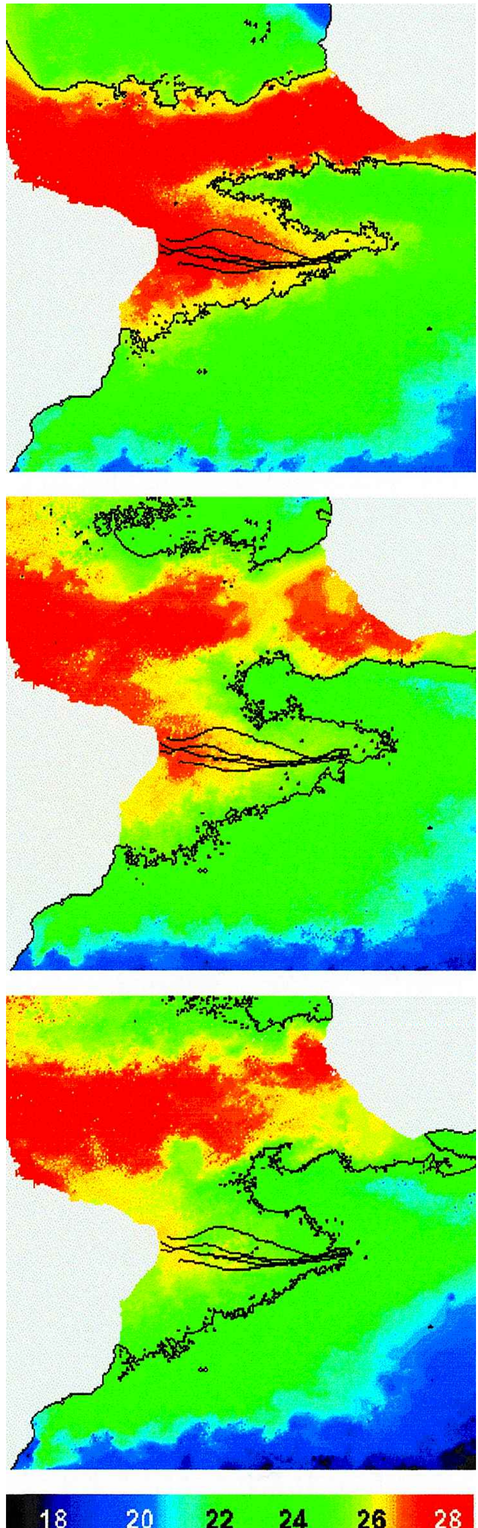

Figure 1. The routes followed by five turtles (turtles B–F) migrating from Ascension Island to Brazil in 1997.

tracked are evident in figure 2. These images are colour coded to maximise the visual impact of the observed temperature differences. Note, however, that there is a fairly limited range of temperatures within the entire set of images (18–28°C). Between Ascension Island and West Africa there was a distinct area of cool water (approximately 22.5°C). Isotherms from Ascension Island ran in approximately WSW and WNW directions, so that all the turtles' movements occurred within warm water (>25°C) between Ascension Island and Brazil. However, movements were not constrained within a distinct thermal corridor containing warm water bounded by markedly cooler water, since everywhere (*a*) the water tended to be warm, and (*b*) the spatial temperature gradients small. For example, in the general area between Ascension and Brazil the typical thermal gradients were only about 0.1°C per 100 km.

To consider whether turtles simply followed an isothermal temperature to Brazil, for each image we identified the isotherm which ran closest to Ascension Island (24.5–26°C depending on the image) and then examined the direction of this isotherm. These isotherms consistently headed WSW with a mean angle of 240°, eventually reaching the coast of Brazil at a latitude of between 16° and 18°S. The angle of these isotherms was less than the departure direction of turtles from Ascension Island (range 257–264° between Ascension Island and 18°W), and furthermore, the points of arrival of the turtles at Brazil (calculated by extrapolation if tracks ended prematurely) was between 6° and 8°S, several hundred kilometres north of the arrival point of isotherms. The turtles therefore did not simply follow an isotherm when migrating from Ascension Island to Brazil. This fact is clearly evident in figure 2 since all the turtles' routes are further north than the position of the highlighted isotherm.

As a further assessment of the importance of SST to the routes followed by the turtles, we examined the SST associated with the pixel within which each location occurred. As the turtles migrated westwards there was a general tendency for the ambient SST to increase, reflecting the general warming of the ocean that was evident in the AVHRR images between Ascension and Brazil (figure 3). The absolute SST encountered by turtles was influenced by the time of year that individuals migrated and by the course that they followed. For example, turtle B which began its migration several weeks earlier than the other individuals, encountered the warmest SSTs, ranging from approximately 26°C close to Ascension up to 28°C near Brazil. Conversely, the lowest SSTs (dropping down to 25°C) were generally encountered by turtle F which turned and headed WNW relatively close to Ascension and so at most longitudes was located much further north (and hence in cooler water) than any of the other tracked animals. SST did not seem to play a role in influencing when the turtles turned from a WSW direction to a WNW direction during migration. This point can be illustrated by considering the four turtles (turtle C–F) that departed from Ascension over a 10-day period in June and July. The spatial pattern of SST was essentially identical for all these turtles and they all departed along similar WSW courses. If changes in their route were caused by SST, then we would predict

Figure 2. AVHRR derived maps (weekly averages) of SST in the equatorial Atlantic during the study period with an overlay of the tracks of the five turtles. The position of the isotherm running close to Ascension is highlighted in each image. Each image covers the area 19.6875°N to 31.2890°S and 51.5039°W to 0.5277°W. Each pixel represents the same angular distance of 0.17578 degrees of latitude and longitude. Top image = 4 June (highlighted isotherm = 24.5°C), middle image = 2 July (highlighted isotherm = 25.0°C), bottom image = 6 August (highlighted isotherm = 26.0°C).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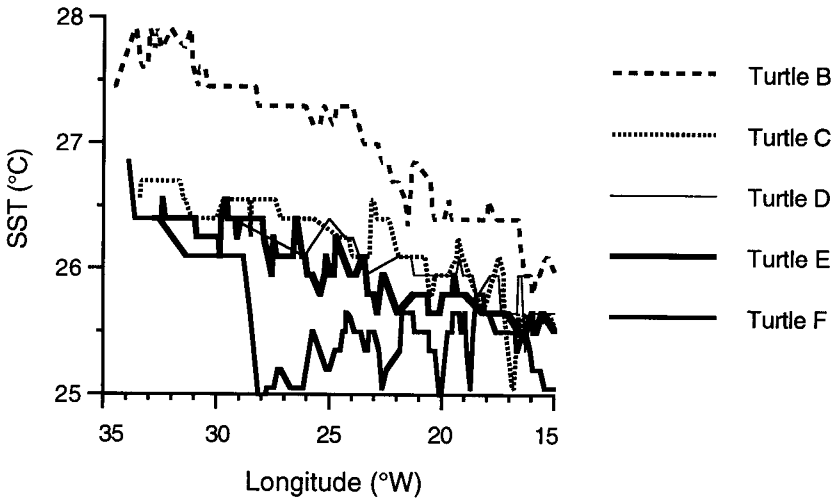


Figure 3. The satellite derived SST (°C) plotted against the longitude of the turtle in order to show how these temperatures changed as the turtles headed westwards on their migration to Brazil.

that all four turtles would have changed direction in a similar position. However this was not the case. For example, turtle F turned WNW at about 18°W (400 km from Ascension Island) when the ambient SST was about 25.5°C, while turtle E maintained a relatively straight course only heading WNW at about 28°W (1500 km from Ascension Island) when the ambient SST had risen to about 26.25°C.

## 4. Discussion

Relating marine animal movements to satellite derived images of SST is conceptually simple and for many years has been identified as an important goal for behavioural ecologists (e.g. Priede 1984, Gitschlag 1996). However, efforts to interleave satellite tracking of animals with remote sensing are sparse, which probably reflects the lack of union between the respective areas of expertise within the biological and remote sensing communities. To date, those studies which have related animal movements to remote sensed imagery, have focussed on whether oceanic foraging patterns correspond with oceanographic features indicative of high productivity (e.g. Rodhouse *et al.* 1996, Guinet *et al.* 1997, Hull *et al.* 1997, Mate *et al.* 1997). For example, Hull *et al.* (1997) satellite tracked royal penguins (*Eudyptes schlegeli*) and overlaid the tracks on satellite derived SST images to show that penguins foraged within the Polar Frontal Zone, a region believed to support high levels of prey for the penguins as a result of enhanced primary productivity.

In contrast, there has been little explicit consideration of how SST might effect migration routes. In the broadest sense it is well known that water temperature influences the distribution of marine turtles. Green turtles, for example, have a circumglobal distribution in tropical and sub-tropical areas of the ocean, but if they inadvertently move into cooler waters (< 10°C) they become lethargic and eventually die of hypothermia (Spotila *et al.* 1997). Consequently green turtles would not be able to traverse cold water as part of their routine migration. However, AVHRR imagery revealed that the SST between Ascension Island and Brazil was universally relatively warm (> 25°C). Hence as long as turtles had a strong westward component to their migration route, they would not encounter lethal SSTs regardless of their exact route. Even the area of relatively cold water between Ascension and Africa (22.5°C) was still warm in absolute terms and so unlikely to have presented a serious migratory hurdle to the turtles if they had headed in this direction.

While lethal SSTs would not be encountered between Ascension and Brazil, there are a number of more subtle ways in which SST might potentially effect the turtles' migration routes. For many ectothermic animals, locomotory performance is temperature dependent with a restricted thermal range over which optimum performance occurs (e.g. Stevenson *et al.* 1985). Potentially, therefore, in areas where the prevailing oceanography leads to this optimum temperature range occurring along a narrow transect, then animals might be expected to migrate along an optimum thermal corridor. In such cases, as the animals encountered the sub-optimum conditions, they would be expected to turn to remain within the optimum thermal corridor. However we found no evidence to support such a scenario, first because there was no clear thermal corridor between Ascension and Brazil and second because the ambient temperatures experienced by the turtles did not oscillate with a certain range, but rather increased linearly.

Alternatively, in the absence of a clear thermal corridor, animals might potentially still follow a particular isotherm to reach their goal, using an isotherm for navigational rather than physiological purposes. If this was the case, then we would have expected that tracks would straddle a particular isotherm, with the turtles making turns when they had moved a certain distance from the isotherm and hence had experienced a sufficient change in temperature. However, there was no support for this hypothesis, with migrating turtles certainly not following the direction of the isotherms between Ascension and Brazil.

A third possible way in which SST might influence migration is if the turtles simply leave Ascension along some preferred WSW compass direction and then make their turns towards the WNW once they have experienced a specific change in temperature along the migration track. However, again this was not the case, with several turtles departing from Ascension within the same SST field, but changing course at quite different positions.

In short, therefore, it would appear that SST played no discernible role in influencing the exact routes followed by turtles migrating between Ascension Island and Brazil. This observation may reflect the fact that there are no clear thermal features that are consistently available from one year to the next in this region of the Atlantic. It might be argued that following an isothermal temperature would have eventually taken the turtles to Brazil (i.e. along a course of approximately 240°), but this would have necessitated a longer crossing (2800–2900 km, depending on the date of migration) before Brazil was reached, compared to the realised crossing distances of approximately 2400 km. Since green turtles are principally herbivorous, and hence are not thought to feed during their trans-Atlantic migration (Carr *et al.* 1974), the optimum route to follow between Ascension Island and Brazil would be expected to be that which minimises the crossing time. The observed routes may minimise this crossing time through a combination of a short crossing distance combined with a maximal benefit from the WSW current that flows past Ascension Island (Luschi *et al.* 1998).

To conclude, this study provides the first comprehensive examination of sea turtle migration tracks in relation to satellite derived SST. For green turtles migrating from Ascension Island to Brazil, our analysis suggests that the SST plays no role in determining the exact routes followed by individuals. As such the method by which migration corridors are identified by sea turtles remains enigmatic. While SST played no role for green turtles, we would predict that for oceanic foragers, such as the leatherback turtle, a tight coupling between movements and oceanography might occur, in line with studies showing how marine birds may concentrate their foraging in highly productive frontal regions.

**Acknowledgments**

We thank Roger Huxley, Administrator of Ascension Island, for permission to work on the island and for his encouragement and welcome during our stay. This work was supported by grants awarded to GCH by the Natural Environment Research Council (NERC) and by the Department of the Environment, Transport and Regions (DETR, UK) within their Darwin Initiative for the Survival of Species programme.

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