Using GPS tracking to determine flight patterns of red-footed boobies *(Sula sula)* near Palmyra Atoll

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Abstract

Efforts to understand Palmyra Atoll's natural systems have concentrated mostly on marine communities, but recent work has been undertaken to investigate its terrestrial communities. Red-footed boobies represent one of many bird populations inhabiting Palmyra. We investigated the flight and foraging movements of red-footed boobies nesting on the north-western side of the atoll using GPS data logging tags. The birds flew in a westerly direction from their nest sites towards an area of patchy ocean primary productivity, suggesting that wind direction and nest location may be stronger factors than primary productivity in determining flight direction. In seagoing flights, the birds demonstrated two modes of behavior, "directed movement" and "meandering", which differed significantly in speed and linearity of flight. These two modes of movement at sea suggest a foraging strategy that emphasizes searching for food over large areas and catching prey in small patches.

Introduction:

Seabirds play an important role in both marine and terrestrial ecosystems and provide a link between land and ocean communities. They feed on pelagic fish and cephalopods, acting as top marine predators, as well as transferring those nutrients to land systems. Because they often nest in dense colonies, the concentration and abundance of seabird defecation can strongly affect soil nutrients and plant community composition (Moller et al, 2000). Full understanding of the terrestrial and marine ecosystems which these birds utilize cannot be achieved without knowledge of where they nest and forage.

In the past, seabird research consisted mostly of land-based observations of seabird colonies. More recently, advances in bio-logging technology have allowed scientists to observe and study long-distance migration tracks over 60,000 km long using archival tags, GPS, and satellite telemetry (Shaffer et al 2005, 2006). The data collected from such bio-logging devices provides insight into animal foraging, physiological functioning, and also information about the animals' physical environments including the factors of light level, depth, and temperature (Boyd 2004, Kooyman 2004). Given the capabilities of animal tags, the increasing use of bio-logging devices to study pelagic birds is unsurprising. For example, in 2003, Weimerskirch et al. (2005) successfully used Platform Terminal Transmitters (PTTs), GPS loggers, Immersion Monitor Version 2 activity recorders, accelerometers, and time-depth recorders to study the movements, activity patterns, and diving depths of red-footed boobies on Europa Island in the Indian Ocean.

Considered to be the "most pelagic booby," red-footed boobies (RFBs) *Sula sula* can travel up to 150km from their colony to forage (Weimerskirch et al., 2005). Most leave their nests in the morning and return from foraging in the evening (Nelson 2005, Schreiber 1996). They may dive up to eight meters into the water to catch prey, feeding primarily on flying fish and squid (Croxall and Prince 1996, Diamond 1971, Le Corre 1997, Nelson 2005). RFB foraging strategies involve feeding in areas of enhanced ocean productivity near fronts, eddies, and upwelling (Diamond 1978, Ballance and Pittman 1999). However, in the largely oligotrophic tropical oceans, feeding associated with sub-surface predators (tuna and dolphins), which chase prey to the ocean surface, is of singular importance for seabirds, including RFBs (Ballance and Pitman 1999). The association with schooling, surface-feeding tuna occurs more often in areas of a deep and stratified thermocline (Spear et al. 2001).

Red-footed boobies from Europa Island, in an area of strong cyclonic and anticyclonic eddies within the Indian Ocean, appear to forage in zones of relatively high primary production (Weimerskirch et al., 2005). In the Central Pacific, previous data collected has demonstrated enhanced productivity around the Line Island chain due to the island mass effect (Clowes and Reinman 2003, Chaput et al. 2006). The flight and foraging patterns of Palmyra red-footed boobies in relation to such biological and oceanographic features around the Line Islands are unknown.

Palmyra Atoll lies toward the northwest end of the Line Island chain at 5°53' N 162°05' W. The desire to preserve and understand the "pristine" biological communities of the island led to The Nature Conservancy purchase of Palmyra in 2000, as well as the designation of its waters as a National Wildlife Refuge in 2001 (TNC Press release, TNC website). Among others, Stanford @ SEA student researchers have characterized the physical oceanographic features as well as the coral reef communities around Palmyra, but to our knowledge, no one has yet studied the boobies that also impact, and are impacted by, these systems.

To better understand the foraging patterns of the Palmyra red-footed boobies, we used archival GPS tags to observe and describe the flight patterns of the birds. Others who have used similar methods have observed seabirds feeding in areas of enhanced biologic productivity, due to greater food availability (Spear et al., 2001, Weimerskirch et al., 2005). As far as we are aware, ours was the first effort to track the movements of red-footed boobies from Palmyra, and the first to compare *in situ* proxy measurements of primary productivity to areas of booby activity at sea.

We expected that any given track would consist of distinguishable types of behavior, specifically, that concentrated feeding effort would demonstrate different characteristics from regular flight. We expected to observe red-footed booby flight towards, and feeding behaviors in, concentrated areas of increased productivity, as identified by high measured levels of chlorophyll-a at the sea surface.

Materials and Methods:

The study was conducted on and around Palmyra Atoll between 23 May and 31 May 2007. The study of boobies in Palmyra continued, but this paper is limited to three days of tracking data. All tagging was conducted under a research permit for handling of birds extended by the US Fish and Wildlife Service. To minimize nest abandonment and loss of tags, we tagged one partner of a nesting pair from nest sites (Fig.1) with incubating eggs or young chicks. Because RFBs are diurnal foragers that feed at sea during the day and return to their nests in the evening, all capture of birds as well as deployment and recovery of tags took place at night.

As the birds generally nest in *Tournefortia* trees, they were captured using a noose at the end of a two-meter pole. The birds were massed, banded, equipped with a GPS tag, and marked with a blue permanent marker for easy identification upon recapture and recovery of the tags. A minimum of two nights later, the birds were recaptured, massed, and tags were recovered. If unsuccessful in attempts to recapture tagged birds, nests were monitored for returns, and recapture was attempted the following night. Other studies (Lewis et al. 2004, Weimerskirch et al. 2005) have reported that boobies undergo apparently little stress during this procedure, but we observed two cases of nest abandonment, and had difficulty in recapturing birds to recover the data loggers.

We captured 17 birds, tagged 13, and recovered five tags that recorded data. The GPS tags (GiPSy) have an integrated antennae, and when turned on, calculate position every second, storing this information in an 8 MBit memory card (Dell'Omo G., 2007). The GPS tags and their battery units were placed and knotted into (non-lubricated) condoms which were then sealed into small plastic bags for waterproofing. The total weight of each packet was roughly 22g, or 2.6% of the body mass of the smallest RFB tagged. The loggers were taped flat on the underside of the four central tail feathers using waterproof Tesa tape.

The data obtained from the GPS tags were downloaded and analyzed using Arcview 3.3 with Animal Movement Analysis Extension (Hooge and Eichenlaub, 1997). Since the GPS tags yield highly accurate position data, we did not undertake any corrections of it. However, instead of using the derived quantity speed as given by the tag, we calculated speeds using the tag position data. We used a linearity index, defined as the ratio of net distance moved over total track length, to describe and distinguish the tracks quantitatively.

Continuous oceanographic measurements were recorded on the S211 cruise into and out of Palmyra on 27 May and 31 May respectively. The ship automatically recorded sea surface chlorophyll-a concentrations by *in situ* fluorometry. The flow-through system yields a relative measure of chlorophyll-a content in volts of fluorescence. The data was viewed and analyzed using Ocean Data View 3.0.1. An eight day composite MODIS on Aqua satellite image of chlorophyll-a concentrations for the region surrounding Palmyra (±2°N/S/E/W) was obtained during our sampling period.

Results

We obtained five tracks from five different boobies that collected data on the 26th, 27th or 28th of May, 2007. Due to difficulties with the tags, possibly involving their operation and programming, moisture exposure, and misalignments of the antennae, the tracks are incomplete.

The shortest length of time a single tag recorded data was 7 hrs, and the longest period a single tag recorded data was 24 hrs. Within these time periods, up to several hours of data was missing, and this may be seen in the large gaps in the otherwise closely-spaced position data points (Fig. 2). Two tracks show that the tagged birds returned to the island, but do not show the paths taken between the time the tag stopped storing position data at sea and when it resumed storing data by the time the bird returned to the island. Though incomplete, the tracks did yield useful data. For example, Fig. 2 shows that the four tracks that left the island all head to the northwest and west and cross similar areas of the ocean.

Table 1 lists basic track data for each of the individual tracks. The boobies left their nests for foraging flights at 3 different times of day. Two of the birds (Booby 1 and Booby 2) left shortly after sunrise, and two others (Booby 2 and Booby 5) left later in the day. Track 1 (Booby 1) is the longest recorded track, and has the most movement recorded at sea, so it gives us the closest approximation of a complete foraging track. Booby 1 covered a total of 275 km within 9.4 hrs. It also reached the greatest distance from land, 80.5 km. The maximum recorded speed was 111 km/hr. Average speeds at sea ranged from 34.9-48.7 km/hr for Boobies 1, 2, and 4. Booby 5 stood out with an average speed at sea of only 5.7 km/hr. Average speeds for all tracks around the nests varied between 0.4 km/hr and 7.3 km/hr.

Different types of movement can be discerned from the track images. What appears as a clustering of points or a "knot" on the track on a large scale also reveals a clustering and intricate movement patterns when it is viewed more closely (Fig. 3 and Fig. 4). Visually this pattern contrasts strongly with the straight parts of the track. Relatively, we defined the first type of movement as "meandering" and the second as "directed movement", and then compared the two types of movement across the tracks. Within each track, linearity for each mode of movement was consistent, as can be seen by the small standard errors (Fig. 5). There was a distinct difference between the linearities of the two modes within each track as well as between all the tracks. The mode of flight referred to in this paper as “directed movement” is characterized by fast flight (41.63 ± 1.80km/hr) and strong linearity (0.870 ± 0.022). The mode of flight referred to as “meandering” is characterized by slower flight (18.275 ± 2.69 km/hr) and weaker linearity (0.243 ± 0.015) (Fig.5, Fig. 6).

Chlorophyll-a concentrations are variable in the waters surrounding Palmyra (Fig. 7). Relative fluorometry data around the atoll shows that high chl-a levels, producing up to 8V of fluorescence, are observed in the surface waters south of the island, and in areas to the west and north fluorescence is relatively lower, only 4V (Fig 7). The Aqua MODIS image also shows that the waters south of the island had higher concentrations of chl-a than the waters in the region west of the island to which the boobies flew (Fig. 8). However, the satellite imagery shows significant patchiness of primary productivity in the area of booby flight.

Discussion:

Ocean Utilization

The greatest distance from nest sites that we observed (80.5km) fell within the maximum distance from land (701km) boobies were observed along the Robert C. Seamans S211 cruisetrack (Schamel, 2007), as well as maximum distances from land (148km) observed by others also using GPS tags (Weimerskirch et al., 2005). It also agreed with the average range red-footed boobies from Europa Island were observed to fly (67.2 ± 34.0 km) from nest sites, but was considerably greater than the mean distance from land boobies were observed during segments of the S211 cruisetrack close to the Line Islands (18 km) (Schamel, 2007). This difference suggests a wide range of flight distances covered by individual boobies. Our observations may differ from Schamel's because our data is RFB specific whereas her data does not distinguish between different species of boobies occurring within the Line Islands (brown, masked, and red-footed). The flight distances of red-footed boobies in particular may not be accurately described by these numbers.

The four tagged red-footed boobies that left Palmyra on foraging trips (Tracks 1, 2, 4, and 5) all flew west of their nest sites. Because their nests were located on the northwest tip of the atoll, westward flight may simply provide the most accessible route to the open ocean for foraging. The wind patterns around Palmyra may also contribute to the birds' outbound flight direction. The dominant wind pattern of north east trades would facilitate flying to the south and west on departure from the nest, and inhibit outbound flight to the north and east. Given these physical factors, flying trips to the west of Palmyra are unsurprising.

While the flight areas observed via GPS positions did fall over an area of varying levels of primary productivity, the boobies tagged did not appear to fly in the direction of larger patches of relatively higher primary productivity as predicted. The longest, most complete booby track recovered (Track 1) showed a strong westward movement, though for the same distance in a southerly direction, it could have reached more productive waters, as indicated by hourly in-situ chlorophyll-a measurements taken along the S211 cruise track (Fig.7). The MODIS chlorophyll-a data also indicate larger patches of greater primary productivity to the south and east of Palmyra within the flight range observed (Fig. 8). This observed pattern is consistent with the phenomenon of island mass effect in the region around Palmyra, and closely follows the findings of Clowes and Reineman (2003). They also observed increased raw chlorophyll-a fluorescence to the south and east of Palmyra. If this is a predictable distribution of productivity, it is particularly striking that the boobies flew elsewhere to forage. While ocean primary productivity may influence the abundance of prey, the GPS tracks obtained indicate that it may not be as strong a predictor of booby foraging areas as wind direction or nest location. It would be of great interest to investigate flight and foraging directions of red-footed boobies from the same atoll in different colonies with varying proximities to open ocean and orientation with respect to wind direction and areas of high/low oceanic primary productivity.

Flight Behavior

Having identified two modes of flight - directed movement and meandering - we can go on to discuss general patterns we see in the different types of track segments.

Track 5 shows strong linearity, but slow speed in flight from land. In contrast, Tracks 1, 2, and 4 show both strong linearity and high speed upon departure from the nest, demonstrating behavior that would minimize the time required to reach food resources far from the boobies' nests. Following fast, linear flight segments upon departing their nests, boobies went into periods of meandering. The characteristics of meandering, a slow and sinuous flight path, suggest areas in which the boobies were searching for and possibly catching prey in those small, restricted areas. This energetically favorable method of foraging is called Area Restricted Search (Weimerskirch et al., 2005). It is possible that if the boobies were to continue fast, linear flight upon approaching a patch of prey, they could quickly pass it, but a more sinuous track and lower speeds would allow them to better target prey occurring in concentrated areas. Faster, more linear flight, similar to flight immediately upon leaving the nest, between feeding bouts would optimize the time spent searching for small prey patches over a much larger area.

We saw great differences in flight behavior between Booby 1 and Booby 5. Booby 1's behavior closely followed that described by Weimerskirch of RFBs on Europa Island. The bird left its nest at 06:46 local time, and returned to its nest around 19:51. This time period encompasses a whole day of foraging at sea. Furthermore, it showed meandering and feeding behavior at the greatest distance from land in the track (80.5km).

In contrast to the pattern described in Weimerskirch et al. (2005) and exhibited by Booby 1 and the two other tracks (Booby 2 and Booby 4) that leave in the morning, Booby 5 left its nest in the afternoon at 14:12. Because RFBs share nest tending duties, alternating between nest sitting and foraging, the late departure of Booby 5 may indicate a late or early return of its partner to the nest after foraging. Track 5 began to show meandering flight much closer to Palmyra (1.13km), and greater concentration of meandering flight in a given area than any of the other boobies (Fig. 4). The daylight during which to forage was significantly less than for Booby 1 and Booby 4, which left their nests about 8 hours in the day before Booby 5 did. This pattern of late departure and spatially intensified feeding close to Palmyra is similar to observations made of red-footed boobies at Johnston Atoll (Lewis et al 2004). Lewis et al. observed a positive relationship between departure time and frequency of dives in pursuit of prey and a significantly negative relationship between departure time and interval between departure and first dive. Hence, Booby 5’s closely spaced intervals of meandering flight nearer to Palmyra may reflect its need to obtain food in less time of remaining daylight.

The GPS data loggers we worked with provided high resolution for both space and time. However, all the tracks analyzed were incomplete in some way – some had large gaps in time, and others did not collect location points for both departure and return to the nest. Full track data from a greater number of birds would help to better represent and understand booby flight and behavior around Palmyra. Tracking birds from spatially distant colonies (on opposite sides of the atoll, for example) would help to understand how nest location may affect flight direction.

Along our cruise track from Hawaii to the Line Islands, boobies were observed much farther from land than what we observed with the GPS data. Because red-footed boobies are supposedly the "most pelagic" of the boobies, identifying the particular species of booby, would be of interest in understanding where Palmyra red-footed boobies go.

Conclusions:

Red-footed boobies were found to fly west from their nesting sites on the northwest end of Palmyra atoll. The westward direction of flight indicated feeding outside of large patches of relatively high primary production near Palmyra, as indicated by *in situ* surface chlorophyll-a fluorometry readings and MODIS satellite imagery. These results suggest that nest location, prevailing wind direction, or some other factor may have greater importance in determining booby flight and foraging locations than primary productivity of ocean water.

The GPS tracks obtained consisted of two distinguishable modes of flight at sea. Directed movement was significantly faster and more linear than meandering segments of the tracks, which were slow and had low linearity. This bi-modal pattern reflects the foraging strategy of red-footed boobies involving quick, efficient flight to prey patches dispersed over large areas and concentrated feeding efforts within those small prey patches.

This study is particularly interesting because it is the first of its kind on boobies in Palmyra. GPS position data with one second resolution has an amazing potential to help characterize the flight and behavior even beyond what is covered in this paper.

Finding out exactly where they go, and what ocean resources they utilize, helps us to understand and quantify the nutrient cycle links between the land and sea.

Acknowledgements

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Figures:

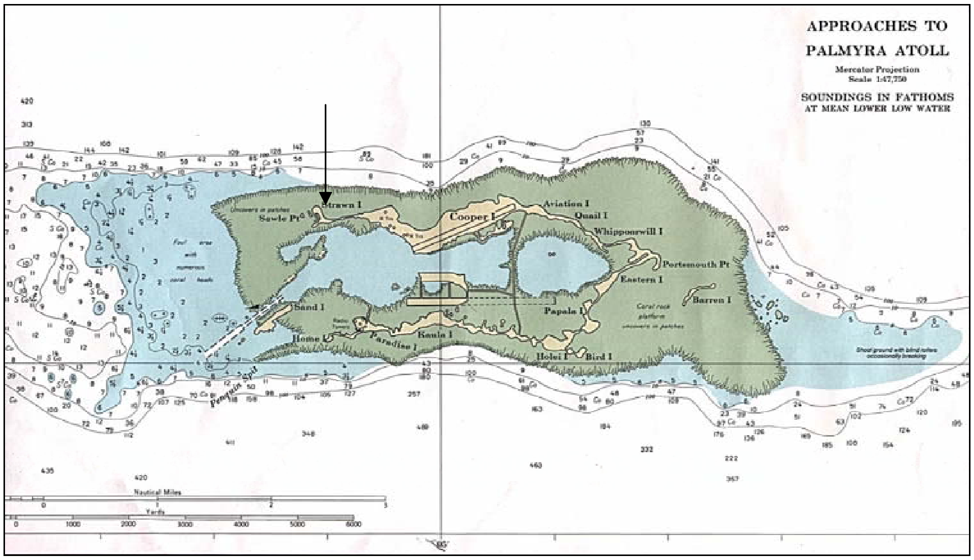

Figure 1. Study location on Palmyra Atoll. The colony site on the northwest tip of the island is indicated with an arrow. In this map, the white outlines are islands above sea level, the green is corals awash, and the blue is substantial coral reef.

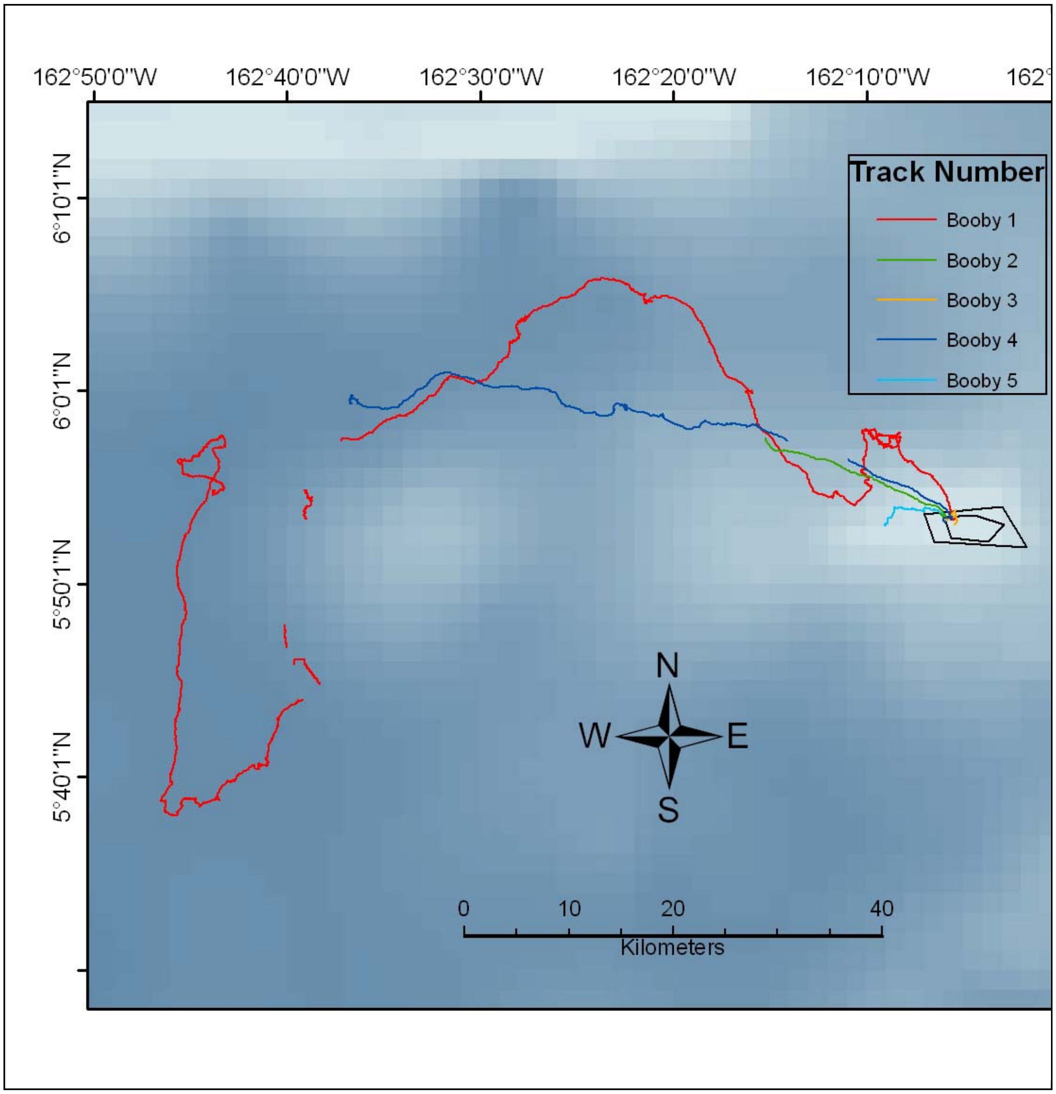

Figure 2. GPS position data from 5 RFB tracks. The outline of Palmyra in black shows the outer edge of the reef as well as the outer edge of the islands. Darker background color indicates deeper bathymetry. The south edge of Kingman Reef is visible.

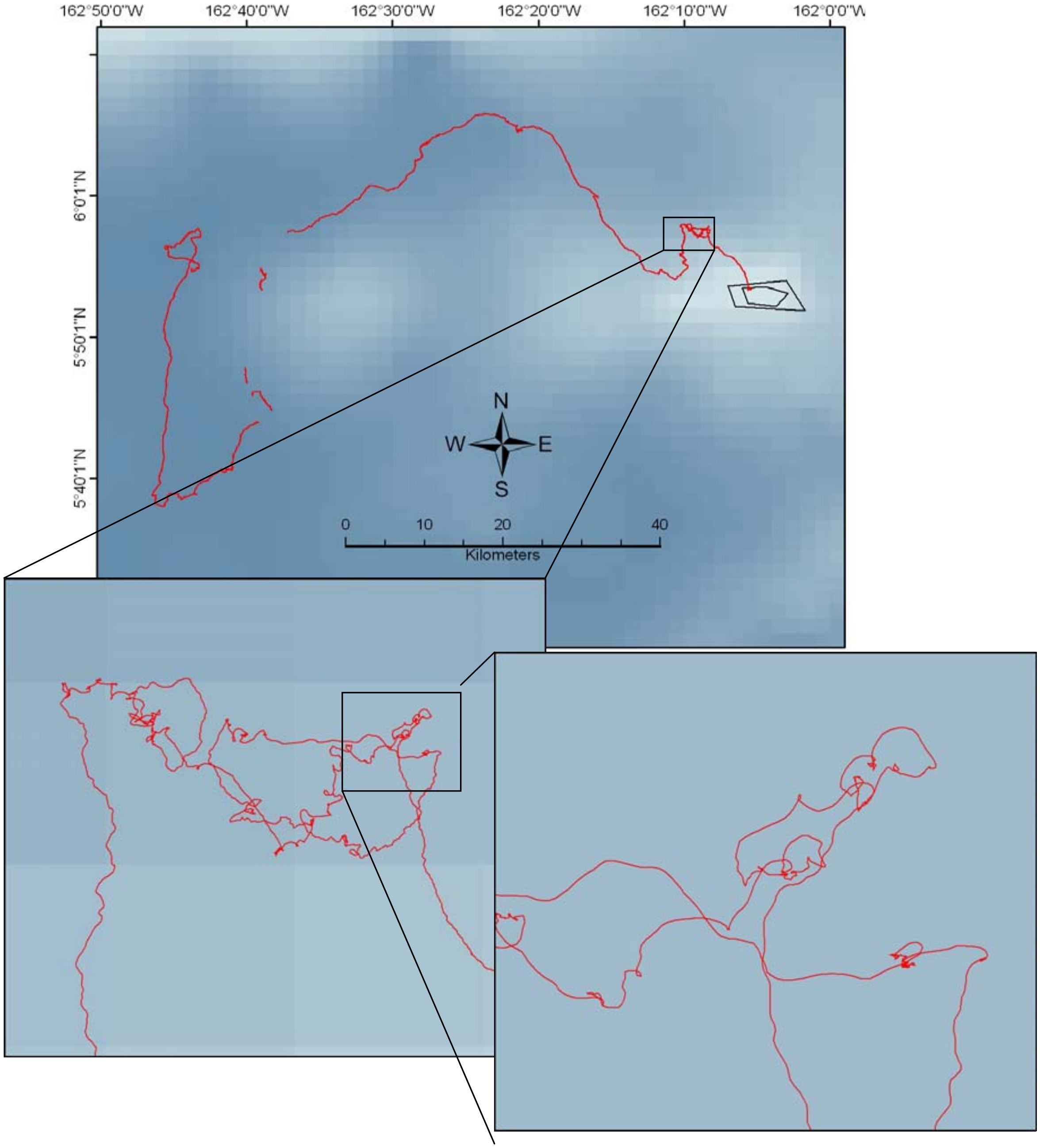

Figure 3. Detail of Track 1 and meandering flight pattern of Booby 1 from Palmyra. The outline of Palmyra in black shows the outer edge of the reef as well as the outer edge of the islands. Darker background color indicates deeper bathymetry.

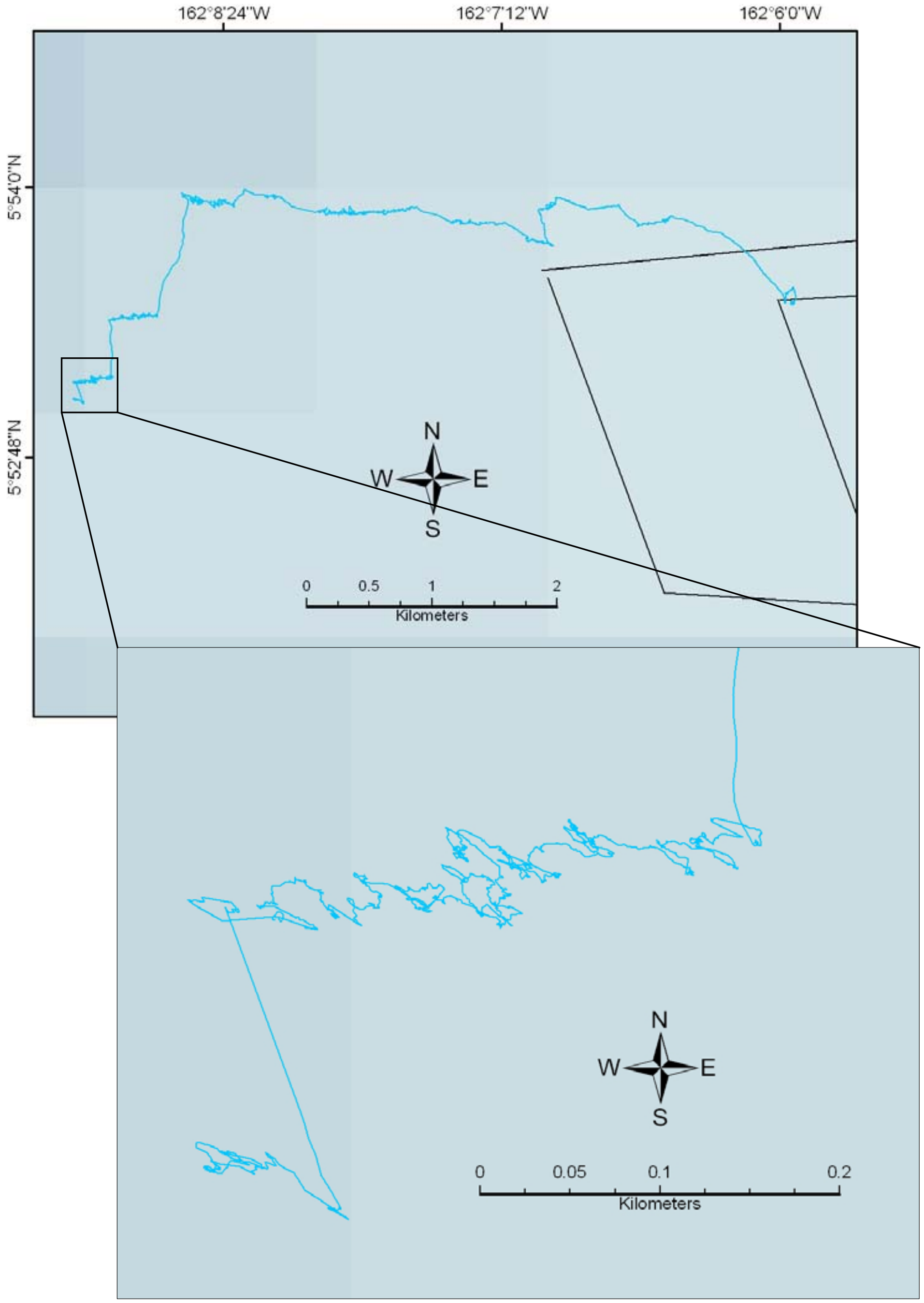

Figure 4. Detail of Track 5. The outline of Palmyra in black shows the outer edge of the reef as well as the outer edge of the islands. Darker background color indicates deeper bathymetry.

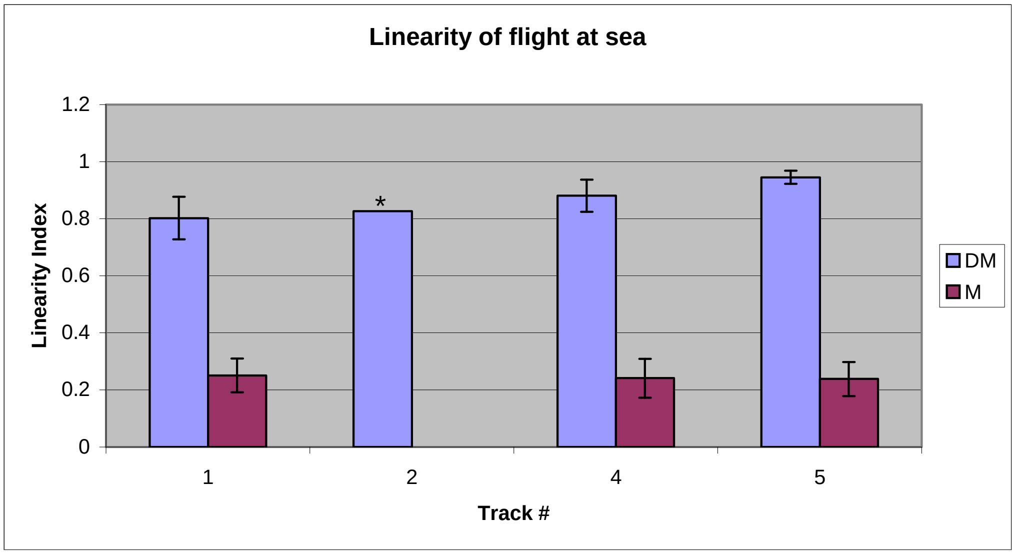

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Figure 5. The average linearity (±S.E.) for the segments of meandering (M) and directed movement (DM) observed in 4 individual tracks of sea-going RFBs. * Track 2 displayed only directed movement for the period position data was stored.

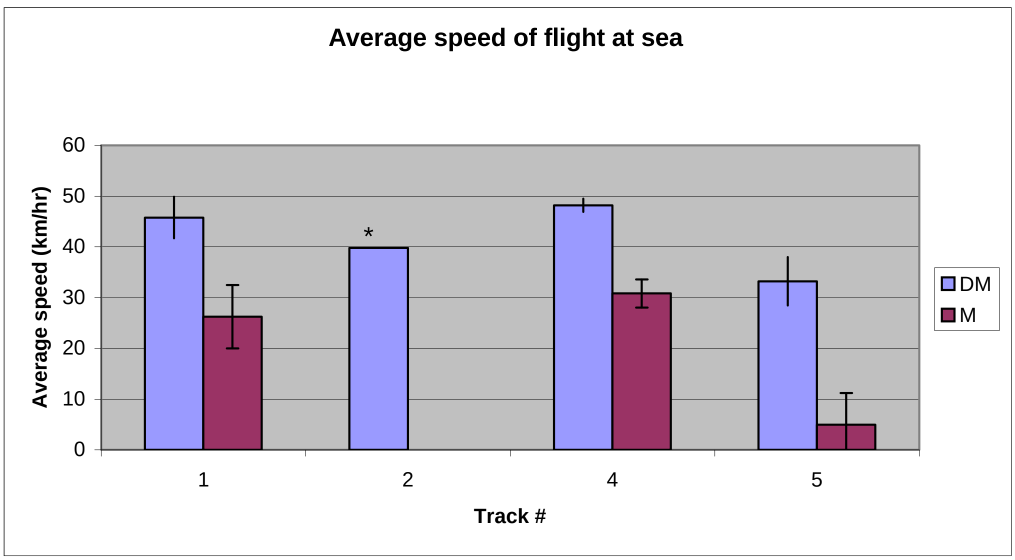

Figure 6. The average speed (±S.E.) of RFB flight at sea while meandering (M) and traveling using directed movement (DM). Track 3 did not leave the vicinity of the nest. * Track 2 displayed only directed movement for the period position data was stored.

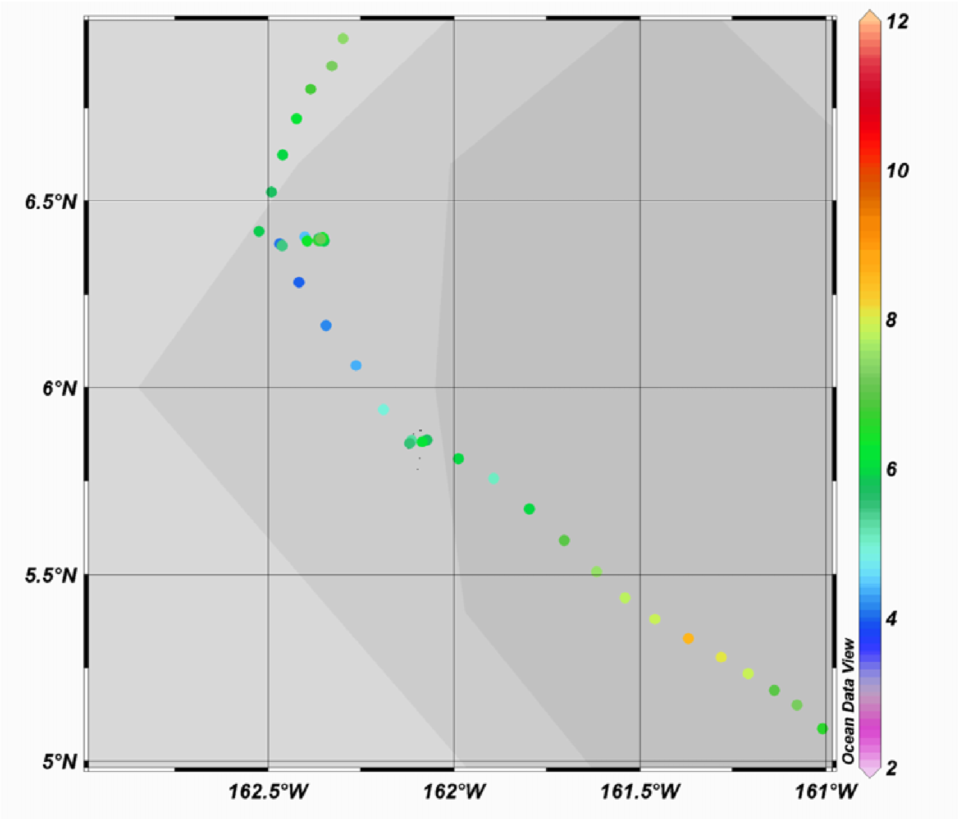

Figure 7. Surface fluorescence (V) on the cruise track of S211 into and out of the vicinity of Palmyra atoll, collected on May 27 and May 31. Lighter background shades indicate deeper bathymetry.

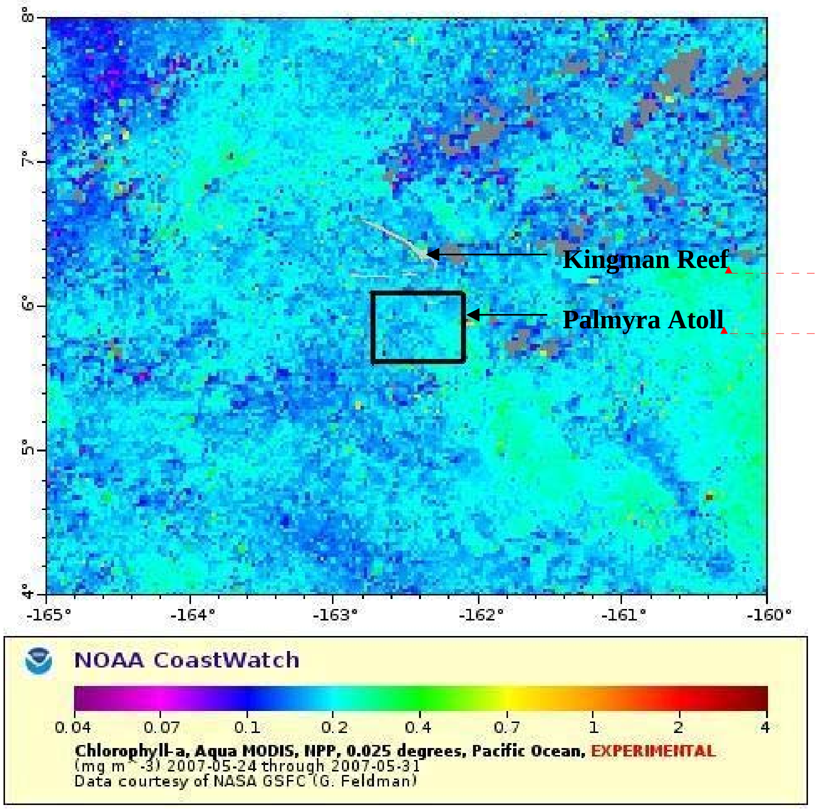

Figure 8. An 8-day composite satellite image from Aqua MODIS showing surface chlorophyll-a in the region surrounding Palmyra (±2° E/W/N/S). The location of Kingman reef is marked on the map, as is Palmyra. The box is an outline of the area that the RFBs used in their tracks.

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Table 1. Summary of the 5 booby tracks. Asterisk (*) indicates unavailable values due to partial GPS tracks.

	Track 1	Track 2	Track 3	Track 4	Track 5
Maximum distance from land (m)	80500	19600	900	58700	6600
Total distance traveled (m)	275726	20347	*	75958	20217
Maximum speed (km/hr)	111.8	76.8	*	73.4	71.5
Average speed at sea (±S.E.) (km/hr)	34.9±0.2	48.7±2.3	*	45.1±0.3	5.7±0.1
Average speed at nest (±S.E.) (km/hr)	0.697±0.04	4.57±0.2	1.1±0.05	7.27±0.1	0.4±0.02
Overall linearity of track at sea	0.255707	0.922396	*	0.774375	0.283969
Departure time	06:46	09:27	*	06:32	14:12
Return time	19:51	*	*	19:39	*

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