AT-SEA MOVEMENTS OF THE WHITE TERN *GYGIS ALBA* IN WATERS OFF EASTERN AUSTRALIA

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ABSTRACT

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We present the first tracked movements of the medium-sized tropical White Tern *Gygis alba*, using Global Location Sensors (GLS), from a breeding colony on Lord Howe Island, South Pacific, Australia. The tracking period encompassed pre-breeding in 2018 to potential chick provisioning in the following season. Terns remained near Lord Howe Island during breeding, with some pre-egg-laying and post-nest-failure trips 1 000 km distant. The average departure date from Lord Howe Island was 08 April (range: 21 March–22 April). The tern's migration route was northwest towards the eastern Australian coast, skirting the Great Barrier Reef. Terns then spent the non-breeding period (50% utilisation distribution) in the northwestern Coral Sea bounded by the New Guinea archipelago to the north and North Queensland, Australia, to the west. The mean transit time to the core non-breeding areas was five days (standard deviation ± 2.5 d). The core non-breeding area was 2 200 km from Lord Howe Island. The mean time spent in the core non-breeding area was 93 d (± 10 d). The return passage completed a clockwise journey with a mean passage time of 12 d (± 3.8 d) and an average arrival on Lord Howe Island of 18 August (range: 08 August–02 September). Over 51% of their core foraging and non-breeding areas were within dedicated marine park networks. We documented the day visits to the island and approximate incubation shifts and nest attendance from changes in light levels of GLS devices. We determined, using saltwater immersion data, that the species exhibited almost no contact with the sea surface during darkness. Peak activity during daylight hours commenced at 12h00, probably indicating resting after foraging at sea. From the limited samples, instrumenting of the terns did not appear to impede breeding attempts during the 14 months of attachment.

Key words: White Terns, GLS tracking, post-breeding migration

INTRODUCTION

The tracking of seabird movements is a widely used tool to further our understanding of their annual activities. The advent of Global Location Sensors (GLS) permitted the relatively cheap, fully annual, and large-scale monitoring of seabird movements (Croxall *et al*. 2005, Shaffer *et al*. 2005). Within the family Laridae, successful device deployment and recovery has not been as broadscale as in other families such as the Procellariidae, particularly in tropical and subtropical species. This shortcoming among Laridae is due to their relatively smaller size, surface or occasionally tree-nesting habits, and variability in their fidelity to nest site (i.e., Burger 1982, González-Solís *et al.* 1999, Naves *et al.* 2006, Francesiaz *et al.* 2017). Within the subfamily Sterninae, tracking studies for five of the 25 tropical or subtropical species have been published (Soanes *et al*. 2015, Maxwell *et al*. 2016, Jaeger *et al*. 2017, Surman *et al*. 2017, Surman *et al*. 2018, Shephard *et al*. 2019, Thiebot *et al*. 2020). Considering that some species within this subfamily are the most populous seabirds in the world (e.g., Sooty Tern *Onychoprion fuscatus*: 23 000 000; Birdlife International 2020), this lack of attention to movements has broader implications for understanding seabird ecology and the functioning of island biodiversity.

One subject deserving additional attention relates to the diversity of breeding seabird assemblages that have significant impacts on local fish biomass (Benkwitt *et al*. 2022). Moreover, large tern populations, particularly those concentrated on coralline atolls, drive the productivity of local reef systems by depositing concentrated marine-derived nutrients in guano (Graham *et al*. 2018). However, as stated above, little is known about the source from which their guano is derived because of the dearth of information on the migration and at-sea distribution of this diverse and ecologically important group of seabirds. For many tropical seabird species, adequate knowledge about their breeding ecology and status for their conservation is lacking (Oro 2014), and a scarcity of tracking studies for this group is likely why they are often not included in assessments of protected marine park networks (i.e., Klein *et al*. 2015). Thus, there is a need to develop techniques for the deployment of devices that will enable a better understanding of tern life histories. Such an attempt was made in this study with the White Tern *Gygis alba*.

The White Tern breeds on tropical and subtropical islands throughout the Pacific, Indian, and South Atlantic oceans and has a global population of 150 000 to 1 100 000 pairs (Delany & Scott 2006). White Terns lay a single egg in naturally occurring depressions on tree branches. Egg-laying to fledging is a minimum of 126 d (Miles 1986). Recent multi-year studies on the species have occurred at colonies on Oahu, Hawaiʻi (Miles 1986, VanderWerf 2003, VanderWerf & Downs 2018) and Lord Howe Island, Australia (Carlile & Priddel 2015, Segal *et al*. 2022). Observational studies of White Tern behaviour at sea in the central

Pacific (Spear *et al*. 2007) report feeding by dipping, contact dipping, and surface plunging, almost always in flocks associated with predatory fish (e.g., tuna). The movements at sea for both breeding and non-breeding periods are poorly understood. Within Australasia, Higgins & Davies (1996) suggest that White Terns are found in all seasons on the east coast of Australia. However, this is based on only five individual sightings (Cooper *et al*. 1977) and does not depict their seasonal occurrence in this region. Occasional ship-board sightings along the continental shelf along 34°S have been made, mainly during the breeding season (Reid *et al*. 2002). A foraging range of 40–80 km from a nesting site is based only on observations of individuals during the breeding season (Cocus-Keelings: Gibson-Hill 1950, Central Pacific: King 1967). Non-breeding season movements from regional breeding sites are unknown (Higgins & Davies 1996), and the species is generally considered non-migratory (Waite 2008, Niethammer & Patrick 2020). In this study, we (1) use GLS loggers to track bird movements at sea, within the limitations of accuracy available; (2) elucidate foraging ecology from immersion data, and (3) glean on-island breeding activity from changes in light levels of instrumented individuals, a first using GLS data.

METHODS

This study was carried out concurrently with population studies on Lord Howe Island (Segal *et al*. 2022). White Terns were selected for geolocator attachment based on known breeding sites from previous seasons. This increased the confidence of capturing the bird the following season for data recovery. However, individual birds were not previously banded. We attempted to maximize breeding season movement data by fitting loggers early in the 2018 breeding period. To identify potential nesting pairs, we used a combination of local resident knowledge of previous breeding sites (in proximity to commercial businesses along the lagoon foreshore) and our previous research experience of the species at this location (Fig. 1).

Logger deployment and recovery

We fitted Migrate Technology Intigeo-W65A9 light-level geolocators (15 × 6 × 6 mm, 0.7 g, immersion recorded, nil temperature, 22-month battery life) to an Australian Bird and Bat Banding Scheme (ABBBS) size 05 modified incoloy band. The band was drilled with two sets of opposing 1-mm holes opposite the ring-join, and the logger was attached by a 202 stainless steel wire in a method applied to the White-faced Storm Petrel *Pelagodroma marina* in Atlantic colonies (F. Zino & M. Biscoito pers. comm.; Fig. 2). Total package mass was 0.9 g (0.7% of average body mass; see Results). Given that the logger was attached to the leg, impairment of any plunging by drag relative to logger cross-section area was deemed not to be an issue. Loggers were calibrated at the breeding site for seven days before attachment and for three to five days after removal. All calibrations were outside the equinox periods and allowed a measure of clock drift, thereby improving position analysis. We used the species' tolerance to approach by humans to capture birds (Marks & Hendricks 1989). Birds were caught by torchlight at night either by hand when sitting on an egg or using a long-handled entomological sweep net (®Australian Entomological Supplies) when disturbed from their nesting/roosting sites 2–4 m from the ground. We attached the logger by closing the band around the bird's leg using long-nosed pliers. A second ABBBS band, with a stamped number, was fitted to the opposite leg for identification. To avoid unnecessary disturbance when attempting to catch the bird's partner, we temporarily marked the chest and back of the head with a water-proof marker pen. Loggers were removed upon recapture using expanding pliers that were slid between the package and the bird's leg.

GLS logger data processing

We downloaded light data from GLS logger units using Migrate Technology hardware and software in the Intigeo-IF kit (©Migrate

Fig. 1. Breeding locations (yellow dots) of tracked White Terns *Gygis alba* on the lagoon foreshore of Lord Howe Island, South Pacific, Australia. Inset: Location of breeding sites on Lord Howe Island.

Fig. 2. White Tern *Gygis alba* showing stainless steel wire attachment of Global Location Sensor (GLS) unit to a bird band.

Technology Limited, 2015). We estimated positions twice per day using the statistical software environment R, version 3.5.1 (R Core Team, 2019). We automated twilight event (i.e., sunrises and sunsets) annotation in raw light-level data using the function *preprocessLight* in the package "TwGeos" (Wotherspoon *et al.* 2016). The geolocation analysis package "FLightR" was used to estimate the spatial likelihood of locations from annotated light-level data with land-masking. With water temperature unavailable, the spatial accuracy of 260 ± 305 km was expected (Halpin *et al.* 2021). Clearly erroneous locations associated with the shading of the logger sensor during sunset and sunrise events, or sequential days of incubation activity, were also removed by filtering in a geographic information system (GIS). Kernel densities (50% and 95% kernel) were calculated for breeding and non-breeding areas of individuals using the *kernelUD* function of the R package "adehabitatHR" (Calenge 2006). Breeding season and non-breeding season departure and arrival dates were based on the day that individual birds moved outside the 50% derived kernels. We present all values as means plus or minus (±) one standard deviation.

On-water activity from water immersion records

Immersion data (recorded by conductivity between connection terminal points on the logger) were sampled every 30 sec, with the number of wet samples summed every four hours. Samples were summed at approximately 04h00, 08h00, 12h00, 16h00, 20h00, and 00h00 (local time at breeding and non-breeding locations). Data summed for the 20h00 and 04h00 periods were considered during full darkness because these terns are subtropical and tropical in their distribution (Higgins & Davies 1996).

Adult breeding behaviour from GLS loggers

The graphical interpretation of the light sensor that follows the dawn to dusk period of exposure (Hill 1994), recorded at 10-min intervals, is generally indicative of a seabird traveling at sea with a minimal diminishment of light intensity and no periods of nil light records during the diurnal period. For the branch-nesting tern, the light levels during daylight hours vary depending on behaviour at the breeding site. We used the length of time and lux intensity to determine behavioural activities. Moderately diminished light levels during daylight hours indicated that birds were loafing in trees on island. Heavily shaded light levels during daylight hours, with occasional single 10-min intervals of light peaks, indicated birds were carrying out incubation duties. Birds nesting near artificial light sources (urban streetlights or security lighting at commercial premises) also provided light 'spikes' during nocturnal periods. These light spikes could indicate presence on the island only at night without actual diminishment of diurnal light levels, as an individual could return to roost at night and depart before daylight. This would be recorded in a light logger as a spike in the nocturnal period with no other impact on day length. Confirmation of such unnatural light sources was possible at some tree-nesting sites associated with the island's loading wharf. Ship provisioning of the island's community, scheduled for every second weekend during the breeding season, occurred under artificial light. Such regular nocturnal activity was captured by instrumented birds nesting and roosting adjacent to this area.

RESULTS

Device deployment, recovery, and impact on breeding

We visited the colony to search for available, accessible nesting pairs on 04–09 September, 29 September–03 October, 31 October–09 November, and 25 November–08 December 2018. We searched for returning birds 13–23 November and 04–05 December 2019, and 10–11 January 2020. We fitted 19 units to potential and breeding birds (mass mean = 133 ± 9 g). Five birds originally fitted with loggers were not observed after instrumentation and were likely not breeding birds because the perch where they were captured was later used for breeding by other terns. We recovered nine loggers (47%) in 2019, of which six had accessible data. No instrumented birds, where functional devices were recovered, bred successfully in the 2018 season, with chicks lasting less than 12 d (Table 1); no successful breeding was observed within the colony that year (Segal *et al.* 2022; Table 4). When we removed functional loggers in mid-November 2019, one individual was not attending an active nest site while three individuals and one pair were incubating or brooding a chick (mass mean = 135 ± 12 g). These chicks subsequently failed, as did breeding generally within the colony in 2019 (Segal *et al.* 2022; Table 4). Four of five breeding birds instrumented in 2018 that were not seen subsequently in 2019 had lost eggs early in the 2018 season due to a storm event and may have abandoned their previously selected site as not suitable for successful breeding. No other birds were seen to use these former breeding sites in 2019.

TABLE 1

The number of days for breeding activities (incubation, chick-rearing, and days to re-lay) of six tracked White Terns *Gygis alba* on Lord Howe Island, South Pacific, Australia, as determined by changes in Global Location Sensor (GLS) logger light levels

GLS[a]	Status	2018/19 season[b]					2019/20 season[b]	
		1st incubation	1st chick	Time to re-lay	2nd incubation	2nd chick	1st incubation	1st chick
235F	Breeding	34	1	15	35	11	35	11[c]
226M	Breeding							
231	Breeding	35	10				35	17[c]
225	Breeding	10	–	40	24	–	15[c]	
238	Non-breeding	–	–	–	–	–	–	
230	Breeding	14	–	51	34	12	33[c]	

[a] F, M indicates sex and a breeding pair.

[b] Blanks in table indicate no data was expected from the bird in the specific period. Dashes indicate no further data was collected.

[c] Indicates incomplete data because tracking device was removed.

Viewing their at-sea movements, White Terns clearly differentiated between core breeding and non-breeding areas (Fig. 3). Approximately 26% of core foraging movements were within the Lord Howe Marine Park boundaries during the breeding season, and 2% were in other Temperate East Marine Park network areas. Movements away from the island during the breeding season were mostly within the range of discrepancy expected from GLS tracking (under 500 km), so they could not be measured confidently. However, two movements away from Lord Howe Island occurred during this period. GLS 235 (female, based on incubation shifts) travelled 1 000 km north of the colony after the second nest failure at the chick phase before returning to the island 12 weeks before undertaking the post-breeding migration. A second bird (GLS 225) was recorded outwards of 1 000 km to the northwest of the colony immediately before the start of a successful incubation in 2018. This individual did not repeat this behaviour prior to commencement of incubation in 2019.

In early April, birds departed the colony and spent approximately another week within the core breeding area (Table 2). The individual tracks taken from Lord Howe Island followed the western edge of the Tasman Basin (van de Linden 1970) into the Coral Sea and were bounded by the eastern extent of the Great Barrier Reef. The transit time to the core non-breeding area ranged 3–10 d (Table 2). The core non-breeding area was approximately 2 200 km from Lord Howe Island with 75% contained within the Coral Sea Marine Park (Fig. 3). Birds began their return approximately three months later

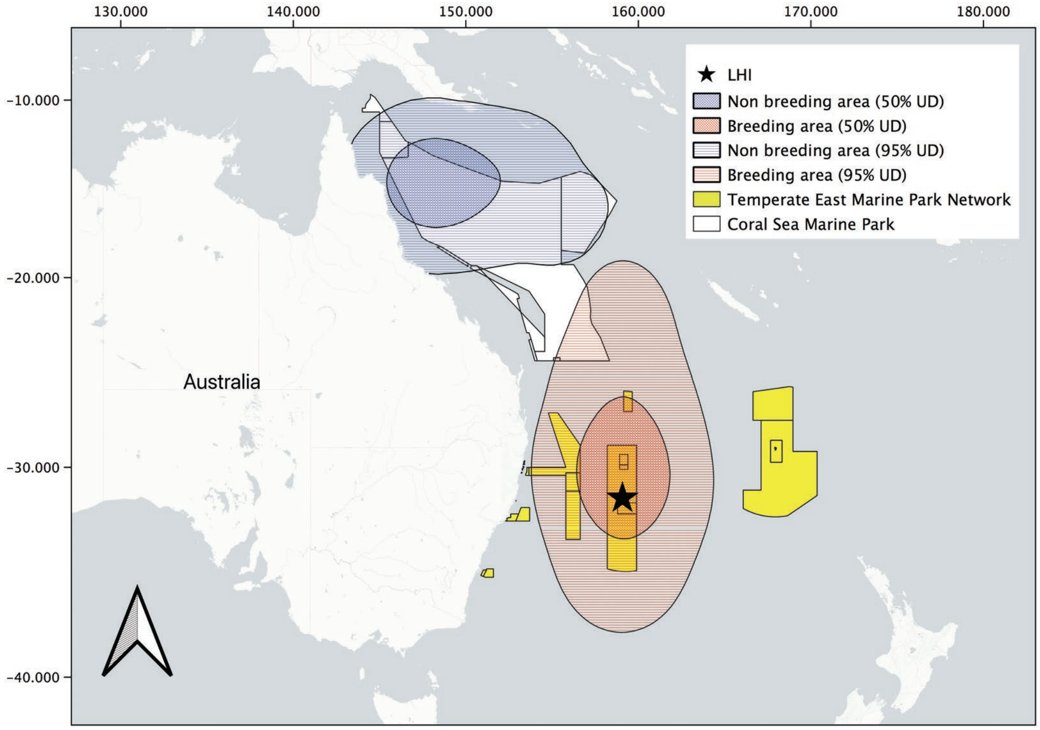

Fig. 3. White Tern *Gygis alba* area of occurrence for core breeding and non-breeding areas by kernel density at 50% and 95% utilisation distribution (UD), from October 2018 to November 2019. Marine Park boundaries are indicated by white and yellow shading. Lord Howe Island (LHI), South Pacific, Australia is indicated by a black star.

TABLE 2
Specific dates and total days for six White Terns *Gygis alba* departing from Lord Howe Island, South Pacific, Australia, transiting between the core breeding (CB) and the core non-breeding (CNB) areas in 2019, as determined by changes in Global Location Sensor (GLS) logger light levels

GLS ID	Depart island	Depart CB	In transit	Arrived CNB	At CNB	Depart CNB	In transit	Arrived CB	Arrived island
235	27 Apr	05 May	10	15 May	73	27 Jul	10	06 Aug	16 Aug
226	31 Mar	09 Apr	7	16 Apr	101	26 Jul	13	08 Aug	08 Aug
231	22 Apr	28 Apr	3	01 May	90	30 Jul	16	15 Aug	02 Sep
225	21 Mar	11 Apr	4	15 Apr	104	28 Jul	7	04 Aug	18 Aug
238	06 Apr	12 Apr	3	15 Apr	96	20 Jul	8	28 Jul	16 Aug
230	08 Apr	12 Apr	5	17 Apr	95	21 Jul	17	07 Aug	18 Aug
Ave.	09 Apr	17 Apr	5.3	23 Apr	93.2	25 Jul	11.8	06 Aug	18 Aug

(Table 2) and moved more centrally through the southern Coral Sea, following the Lord Howe Rise and New Caledonia Basin, bounded to the east by the Norfolk Ridge (van de Linden 1970). Birds then turned towards Lord Howe Island after crossing the 30°S parallel and entering the Tasman Sea (Ceccarelli *et al*. 2013). The return transit time ranged 7–16 d, arriving back from a clockwise migration on the island, on average, by mid-August (Table 2).

Only five of the six recovered GLS units returned with complete immersion data. The tracked terns showed little time in contact with seawater (2.78% ± 0.21% of their total time; Table 3). Over the year, they exhibited a peak four-hour period daily from 12h00 (local time) in contact with the sea surface, encompassing 33%–62% of all daily immersions. The birds spent 2.4% of the total time available during the breeding season (August to March) and 8.9% of the total available time during the non-breeding season (April to July) in contact with seawater (Table 3). Annual peak monthly contact with seawater occurred in July (37%–62% of all water contact records). During the bulk of nocturnal hours (20h00–04h00) they were not in contact with water, accounting for only 0.11% of the time during the breeding period and 0.06% of the time during the non-breeding period.

We documented the day visits to the island and approximate incubation shifts from changes in light levels of GLS devices. Five out of the six birds attended nests, one as a pair (Table 1). One was a non-breeder as it did not attend an active nest. From six full incubation periods (34.7 ± 0.48 d) at four nests over the two seasons (Table 1), each bird carried out approximately 10 stints (± 1.25 stints), averaging 1.7 d (± 0.54 d) per stint. The GLS235/GLS226 pair exhibited overlapping days of presence but did not both actively incubate at the nest at the same time, with one two-day period of temporary egg abandonment. When the same pair lost their first egg in the 2018 season, the time to re-lay was 15 d (Table 1) with other periods before re-laying of 40 and 51 days. From three nests where artificial light was recorded on GLS from the pair (226/235) and two single tracked individuals, birds were present only at night following nest failure, from 5–14 weeks prior to their final departure for migration. The tracked non-breeding bird was present only during nights for 17 weeks before migration.

DISCUSSION

The White Terns breeding on Lord Howe Island are unequivocally migratory. The data presented in this study showed movements of all birds (five breeding and one non-breeding) to a defined area in the northwestern Coral Sea for three months of their yearly cycle. Their transit to this area was relatively uniform in timing and route (Fig. 4, Table 2). The Coral Sea has not previously been considered within the area of occurrence for this species (Birdlife International 2021; Harrison *et al*. 2021), although this species has been reported from here in mid to late May (Stokes & Corben 1985), possibly involving post-breeding birds from Lord Howe Island (Figs. 3, 4).

These data show that 51% of White Tern's core movements are within protected boundaries of Australia's Marine Park network, mostly at Lord Howe Island. The Lord Howe Marine Park area covers 110 000 km^2. It surrounds the island group to a distance of 650 km north-south and 180 km east-west (Director of National Parks 2018) within the expected range of uncertainty. Future tracking studies using GPS would provide a more accurate estimate of overlap in movements across these boundaries (i.e., Maxwell *et al*. 2016, Shephard *et al*. 2019). However, even with these inaccuracies, the Coral Sea Marine Park is sufficient in size to contain 75% of the core non-breeding movements of White Terns (Fig. 3). The lack of tracking studies is the likely reason for seabirds often not being included in the assessment of species coverage in protected marine networks (i.e., Klein *et al*. 2015). Few studies have reported their presence associated within their networks (Young *et al*. 2015, Maxwell *et al*. 2016). Our results with White Terns are the first to show a pelagic seabird species using significant portions of Marine Protected Areas in both breeding and non-breeding periods. This migration route for the terns adds to the required data for the management of this species within their breeding areas (Department of Environment and Climate Change 2007) and core non-breeding areas (Ceccarelli *et al*. 2013) and adds to an otherwise poor understanding of the status of tropical seabirds (Oro 2014).

After nesting, White Terns spent an average of 8.9% ± 0.28% of their time in contact with seawater. This is higher than Sooty Terns (5.03% ± 5.22%; Jaeger *et al*. 2017) and similar to Common Terns *Sterna hirundo* (8.6%–13.9%; Becker *et al*. 2016). Unlike Common Terns, White Terns are fully pelagic in their foraging, not visiting coastal locations, and are similar to Sooty Terns. Their peak immersion occurred from 12h00 daily, possibly indicating resting on the water surface. The species is known to occasionally alight during foraging (Dorward 1963) and capture surface prey without fully submerging (Niethammer & Patrick 2020), possibly indicating extended periods of contact with water. During winter they record almost no immersion during hours of darkness (Table 3). Sooty Terns have also been found to do nonstop flights at night (Jaeger *et al*. 2017). For tern tracking studies, it has been suggested that a higher level of water immersion during the non-breeding period may reflect the requirement for individuals to transfer body heat in the tropical environments that they are frequenting (Becker *et al*. 2016). White Terns had higher immersions during the non-breeding period, with annual peaks in July. As a tropical and sub-tropical breeding species, it is less likely that increased immersions were related to the maintenance of body temperature in the non-breeding area. More likely, the increased immersions indicate that the increasing energetic requirements of flight when moulting require increased periods of floating on the sea surface. With sufficiently miniaturized devices, this could be confirmed in future studies by accelerometer monitoring of migrating birds.

White Terns return annually each September to Lord Howe Island (McAllen *et al*. 2004), although occasionally this return occurs earlier (Carlile & Priddel 2015). Based on our preliminary tracking, it appears that all birds were on-island by mid-August (range: 08 August–02 September), indicating their nocturnal visits may be brief during the first weeks of a breeding season and thus go undetected. While the GLS units could not determine the general at-sea movements during the breeding season, two significant trips were recorded outside the expected error of the methods employed (Halpin *et al*. 2021.). The longer post-provisioning or pre-laying trips may indicate behaviour to improve body condition, as seen with Sooty Terns (Jaeger *et al*. 2017), where longer journeys beyond the normal core foraging areas were undertaken. When study birds departed from the nesting sites, they did not immediately commence migration. Instead, they spent a week in local waters, much shorter than the month recorded for Common Terns, which were principally feeding young before departure (Nisbet *et al*. 2011, Mostello *et al*. 2014, Becker *et al*. 2016). The White Tern may have a similar extended pre-migration delay in years when there is successful breeding. Still, all birds that were studied were without offspring following the first breeding season of device attachment. It is unlikely that the delay in departure for White Terns was a deliberate pre-migratory staging due to the short delay to eventual departure. Roseate Terns *Sterna dougallii* exhibited pre-migratory staging that lasted three and six weeks (Redfern *et al.* 2021); however, they travelled three times the distance to core non-breeding areas.

GLS light levels show incubation length to be 35.3 d and replacement following egg loss from 15 d to 36 d, depending on whether this followed a period of sustained provisioning of a chick before failure or not (Carlile & Priddel 2015). Incubation shifts were estimated at 1.7 d, similar to that reported elsewhere (1.3 d, *n* = 57: Niethammer & Patrick 2020). This study has established a significant period of the strictly nocturnal presence of adults at the breeding colony before the final departure at the season end. This suggests that observational studies limited to diurnal periods may significantly underestimate the total colony attendance of failed and non-breeding individuals.

Impacts of devices

The use of known (banded) birds may have yielded a greater return of tracking devices in the subsequent season of our study. The position of an unbanded pair at an apparent 'known breeding perch' during the courtship period in September 2018 was not a reliable indicator that they would lay and incubate an egg. Elsewhere, terns fitted with loggers had a delayed return to breeding colonies compared to non-instrumented birds (Mostello *et al*. 2014), but Redfern *et al*. (2021) reported negligible effects on the same species. When birds did return, their body mass was lower, and they did not attempt breeding. Other researchers have also recorded egg breakage attributed to the logger itself (Becker *et al*. 2016). It is unknown if the act of attaching loggers caused birds to abandon

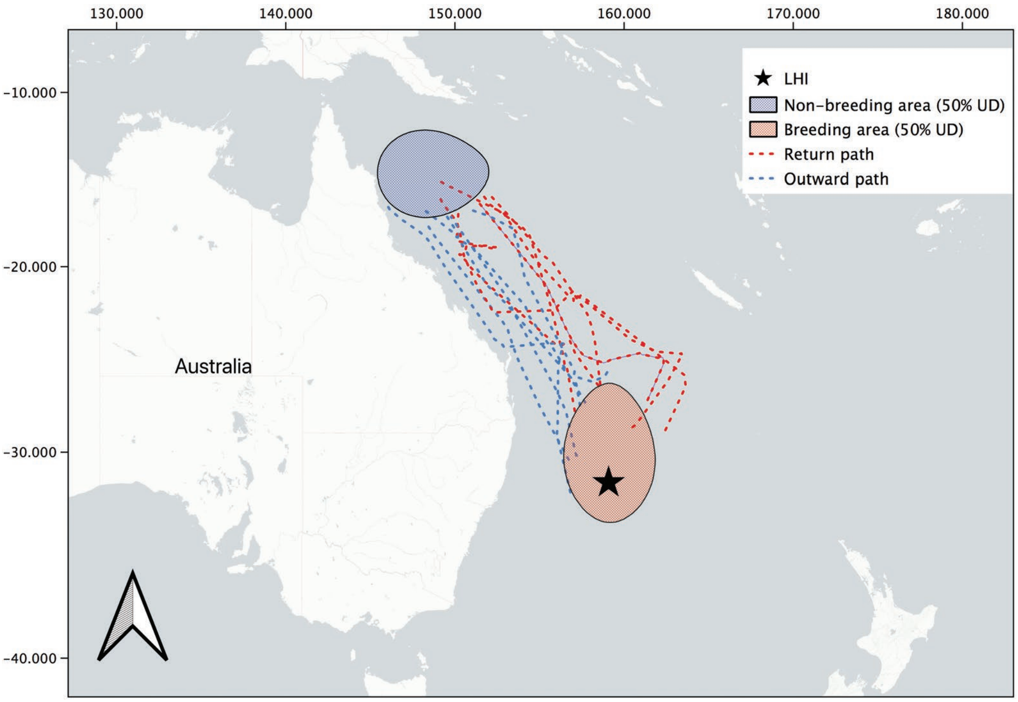

Fig. 4. Tracks of post-breeding migration (April–May) and return (July–August) to the breeding island of six White Terns *Gygis alba* in 2019 based on twice-daily Global Location Sensor-derived positions. Lord Howe Island (LHI), South Pacific, Australia is indicated by a black star; UD is utilisation distribution.

potential breeding sites in 2018 and their failure to return to these sites in 2019. All the 'known birds' indicated by island residents (three nests) returned to their breeding perch and had devices removed. Our observations of other birds were less certain due to a lack of familiarity from just a few previous observational records. Observers also informed us that nest losses of instrumented birds in both seasons were due to depredation by owls (hybrid *Tyto novaehollandiae castanops* × *novaehollandiae*; Hogan *et al*. 2013) and egg dislodgement due to strong winds in the second season. Segal *et al*. (2022) found breeding success across the colony that was only 1.3% in one of three years encompassing this study, and Carlile & Priddel (2015) similarly found low breeding success here in the face of high nest depredation. Our study birds returned to breed in 2019, and although breeding was unsuccessful due to likely depredation, our study shows that breeding was possible in both seasons with loggers attached. This gives some confidence that methods used had minimal impact on birds.

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