

Fledging behaviour of juvenile northern royal albatrosses (*Diomedea sanfordi*): a GPS tracking study

BINDI THOMAS*

EDWARD O. MINOT

JOHN D. HOLLAND

Institute of Natural Resources, Massey University, Private Bag 11-222, Palmerston North, New Zealand

Abstract Using GPS technology, we tracked 3 juvenile northern royal albatrosses (*Diomedea sanfordi*) as they fledged from Taiaroa Head, Otago Peninsula, New Zealand. All birds flew north along the east coast of New Zealand before undertaking a trans-Pacific easterly migration to Chile. During their 8500 km migration, the maximum daily distance and speed reached were 1047 km and 110 km h⁻¹, respectively, and the maximum altitude was 38 m a.s.l. Upon leaving New Zealand waters, the 3 albatrosses took between 16 to 34 days to reach the coast of Chile where they remained between 23°S and 58°S. The tracked albatrosses generally kept to within 100 km of the coast where the depth of water varied between 1000 and 2000 m. Overall, the tracked albatrosses on the Chilean coast spent 72% of the time resting on the water, primarily between 1800 h and 2400 h local time. Fix success rate of the GPS technology ranged from 56% to 85%. The use of solar charging and a long attachment period allowed birds to be followed continuously for 134 to 362 days. Our study confirms the value of GPS technology in uncovering the movements and life history of wide-ranging oceanic birds.

Thomas, B.; Minot, E.O.; Holland, J.D. 2010. Fledging behaviour of juvenile northern royal albatrosses (*Diomedea sandordi*): a GPS tracking study. *Notornis* 57(3): 135-147.

Keywords: northern royal albatross, *Diomedea sanfordi*, juvenile, GPS, tracking, migration, New Zealand

INTRODUCTION

Classified as 'endangered' and decreasing in population (IUCN 2010), the northern royal albatross (*Diomedea sanfordi*) is one of 24 albatross species worldwide (Chambers *et al.* 2009) and one of 13 species of albatross endemic to New Zealand. The total breeding population is estimated to be approximately 6,500 to 7,000 pairs (Croxall & Gales 1998). Ninety-nine percent of this population breeds on the Chatham Is (800 km east of New Zealand) with small colonies located on Enderby I (Auckland Is) and Taiaroa Head (Otago Peninsula, New Zealand). The Taiaroa Head colony (45°45' S, 170°44' E) is the only mainland breeding colony of any albatross species in the southern hemisphere

and consists of a 5.3 ha grassy Nature Reserve rising to 75 m a.s.l. The population currently is comprised of approximately 140 adult albatrosses (Lyndon Perriman, *pers. comm.*). Although it represents only a small proportion of the total population, the ease of access to the colony has led to it becoming an important scientific and tourist attraction.

Prior studies of adult northern royal albatrosses on both the Chatham Is and Taiaroa Head show they forage in the waters over the shelf or shelf edge around New Zealand during breeding. They then migrate across the Pacific Ocean to Chile and Argentina where they remain during the non-breeding season, possibly returning to the breeding grounds via a circumpolar route between 30°S and 45°S (Nicholls *et al.* 1994, 2002; Waugh *et al.* 2005; Nicholls 2007). However, little research has

Received 23 Jul 2010; accepted 26 Oct 2010

*Correspondence: bindi.thomas@uni.massey.ac.nz

been reported on the movements of any species of juvenile albatross (Birdlife International 2003; Robertson *et al.* 2003; Nicholls & Robertson 2007a) and none at all for the juvenile northern royal albatross. Through banding recoveries, it has been suspected that juvenile northern royal albatrosses fly eastward after fledging to the coast of Chile (Robertson & Kinsky 1972), but there are no direct data to support this hypothesis. Mortality is thought to be greatest during the first year that juveniles disperse (Warham 1990). Thus, understanding the movements and life history of juvenile albatrosses is critical to their proper management. The objective of our study was to examine the movements and habitat-use of juvenile northern royal albatrosses during the period immediately after fledging. By documenting the movements during the first year at sea of 3 juvenile northern royal albatrosses after they fledged, we sought to further understand their post-fledging ecology.

Earlier studies of the distribution of seabirds have employed Very High Frequency (VHF) telemetry (Anderson & Ricklefs 1987), the Argos® satellite system (C.L.S, Ramonville Saint-Agne, France) (Prince *et al.* 1992; Nicholls *et al.* 1994; Nicholls *et al.* 2002; Walker & Elliott 2006; Nicholls & Robertson 2007a), light-based geolocators (Shaffer *et al.* 2005) and, more recently, the Global Positioning System (GPS) (Weimerskirch *et al.* 2002; Waugh *et al.* 2005; Weimerskirch *et al.* 2007). These methods provide varying accuracy levels, data download intervals, transmitter sizes, weights and costs. The impracticality of using VHF to track seabirds and location errors of up to a few kilometers of the true location for Argos transmitters (Shaffer *et al.* 2005; Nicholls & Robertson 2007b; Nicholls *et al.* 2007) make these technologies less than ideal, particularly for small scale analysis. As well, the lower mass (< 10 g) and cheaper features of light-based geolocators have been overshadowed by accuracy issues (errors of 34 to 1,043 km from known locations; Phillips *et al.* 2004). Although still the heaviest transmitters, GPS technology can provide a way of obtaining very accurate (<5 m) locations (Hulbert & French 2001) and has been identified as an effective method to gather long-term continuous location data to map albatross movements around the earth (Cohn 1999; Webster *et al.* 2002). Regular preset schedules can be programmed and these highly accurate locations can be sent to the researcher without the need for recapture.

Only 2 previous studies have tracked juvenile albatrosses. Walker & Elliott (2006) followed 3 juvenile Antipodean albatrosses (*Diomedea antipodensis*) for 9 to 13 months after fledging using Argos satellite tracking. Weimerskirch *et al.* (2006) used the same method to follow 13 juvenile wandering albatrosses (*Diomedea exulans*) during their first year at sea (2 to

13 months). One reason so few studies have been undertaken with juveniles is that upon fledging, this age group leave the breeding grounds and do not return for 5 to 8 years (Robertson 1993). As attachment methods and transmitter lifetimes are still considerably less than this time frame, it makes retrieval of the transmitter and tracking of juveniles difficult (Walker & Elliott 2006).

We used GPS technology to track the movement of juvenile royal albatross. Our objectives were to: (1) identify the broad-scale movements during the first year at sea, (2) analyse the daily activity of juveniles, (3) identify areas of high use, and (4) evaluate the technical performance of the transmitters under field conditions.

METHODS

During our year-long spatial study, we recorded 4 daily GPS locations of 3 juvenile northern royal albatrosses (♂ = 2, ♀ = 1) hatched during the 2006/2007 breeding season. This sample size represented approximately 13% of the juvenile population of 23 chicks that fledged from Taiaroa Head during the 2006/2007 season. We considered 4 aspects of performance: (1) the number of locations obtained (fix success) and whether there were any significant daily, monthly or seasonal differences, (2) whether the number of locations declined as the transmitters approached their theoretical life expectancy, (3) the solar charging efficiency, and (4) the accuracy of the system. The transmitters used in this study were 30-g Solar Argos/GPS PTT-100 with dimensions of 62 x 22 x 21 mm (Microwave Telemetry Inc., Maryland, U.S.A). Between Sep 2007 and Aug 2008, they recorded a GPS location 4 times a day, every 6 hours at 0600, 1200, 1800 and 2400 h (local time of the day). These were relayed back to the researcher every sixth day utilising a 12-hour window of the ARGOS® satellite system (C.L.S, Ramonville Saint-Agne, France).

When the albatrosses were 9 months old, they were approached whilst on their nests, lightly restrained, tagged, and released within 30 to 45 minutes of their capture. The transmitter was attached to dorsal feathers using adhesive tape (Tesa tape 4651), teflon tube and cable ties. The weight of the transmitter and attachment materials was approximately 40 g, which was less than 1% of the body weight of the animal. It was hoped this attachment method would last 12 to 18 months, until either failure of the tape or loss of the feathers from moulting. The exact time of moulting is not known; however, the first moult is thought to be around 12 months (Lyndon Perriman, *pers. comm.*). The longest known tape attachment lasted approximately 14 months on juvenile Antipodean albatrosses (Walker & Elliott 2006).

While the use of a harness attachment might lengthen the period of tracking, a number of researchers report that this method could lead to mortality, while taped or glued-on transmitters had no discernable effect on foraging efficiency, rates of nest desertion and mortality (Phillips *et al.* 2003; Walker & Elliott 2006). The albatross chicks in our study remained at the colony for 3 to 5 weeks after the transmitter was attached and no adverse reaction or change in behaviour was observed.

The data were downloaded from the Argos® online data access system and maps were generated using ArcGIS® ArcMap® 9.2 (Environmental Systems Research Institute, Redlands, California, USA). The data locations were recorded in latitude/longitude WGS84 and transformed to an equirectangular projection for analysis with other GIS layers.

Three data files were received during each download period. The first file contained the GPS location, date, time, speed, course and altitude, obtained at 6-hourly times. The second file contained technical information on the internal functioning of the transmitter, such as voltage, ambient temperature and GPS fix time. The third file contained ARGOS® locations for backup purposes. Data from the second and third files were obtained only during the 12-hour Argos download period every sixth day. Error estimates for the GPS latitude/longitude location and altitude were < 18 m and < 22 m, respectively. For speed, the error was < 1 km h⁻¹ at speeds of > 40 km h⁻¹ (Microwave Telemetry Inc., Maryland, U.S.A.).

Three stages of juvenile movement were identified during this study, similar to those identified by Nicholls & Robertson (2007a). First, 'fledging' was defined as the period of departure from their Taiaroa Head nest up the east coast of New Zealand just prior to the direct easterly movement. Second, 'migration' involved the period of rapid and consistent direct easterly movement over a longitude range of 175° W to 75° E. Third, 'foraging' was defined as periods of sedentary behaviour on the Chilean continental shelf where the longitude fluctuated over a range of 10°.

Time spent resting on water was determined using locations with speeds of < 9 km h⁻¹ to allow for possible surface drift resulting from winds and ocean currents (Weimerskirch *et al.* 2006). The calculation of the minimum distance was based on the straight line distance moved between consecutive 6-hourly locations or the addition of these to account for a daily period. However, albatrosses rarely fly in a straight line, and these distance calculations are minimum values. Both the speed and altitude were calculated by the GPS system, obtained at the same time as the longitude/latitude locations every 6 hours. The speed and

altitude values are also assumed to be minimum values.

We used the kernel-based territory size estimate to calculate the foraging home range at a 95% probability using the Animal Movement Analyst extension to ArcView 3.2 (Hooge & Eichenlaub 1997). The same method using the 50% probability contour was used to calculate core areas during foraging. Upon evaluation of the different effects of the varying smoothing factors (Nicholls *et al.* 2005), we used the least-squares cross validation procedure to determine the smoothing parameter for each kernel distribution.

RESULTS

Dispersal of Albatross

The 3 juvenile northern royal albatrosses, namely female 1 (F1), male 1 (M1) and male 2 (M2), were tracked for 327, 362 and 134 days respectively. Fig. 1 shows the track taken by each during their first year at sea after fledging. Table 1 shows the dates and time periods of the 3 stages during this post-natal year, as well as the distances travelled, speeds, and altitude. The total minimum distances travelled during the tracking period were 35,978, 46,066 and 15,149 km for F1, M1 and M2, respectively.

Movements after fledging

During the first 2 weeks after fledging, the 3 juveniles flew north-east off Taiaroa Head, staying within 150 km of the New Zealand coastline over the coastal continental shelf before heading east towards the Chatham Rise (Fig. 2). The maximum depth of the ocean in this region is 1000 m. F1 and M2 then veered north of the Chatham Rise into deeper oceanic waters (up to 4000 m), whilst M1 continued towards the Chatham Is, reaching to within 20 km of the coast. F1 and M1 stayed within 650 km of the New Zealand coast for 15 and 19 days, respectively (Table 1), before undertaking a direct easterly migration. M2 remained within approximately 350 km of the New Zealand coast for 46 days before beginning its direct easterly migration.

Migration

Upon leaving the coastal area of New Zealand all 3 albatrosses flew east across the Southern Ocean in a corridor between 34°S and 48°S. F1 and M1 flew directly across with no backtracking. M2, however, appeared to back-track up to 450 km on 2 occasions (Fig. 1). It took 18, 16 and 34 days for F1, M1 and M2, respectively, to cross the ocean. The maximum daily distance (and fastest speed in parentheses) attained during this stage were recorded at 730 km (110 km h⁻¹), 1047 km (109 km h⁻¹) and 534 km (105 km h⁻¹) for F1, M1 and M2, respectively (Table 1). Maximum altitudes recorded during this stage

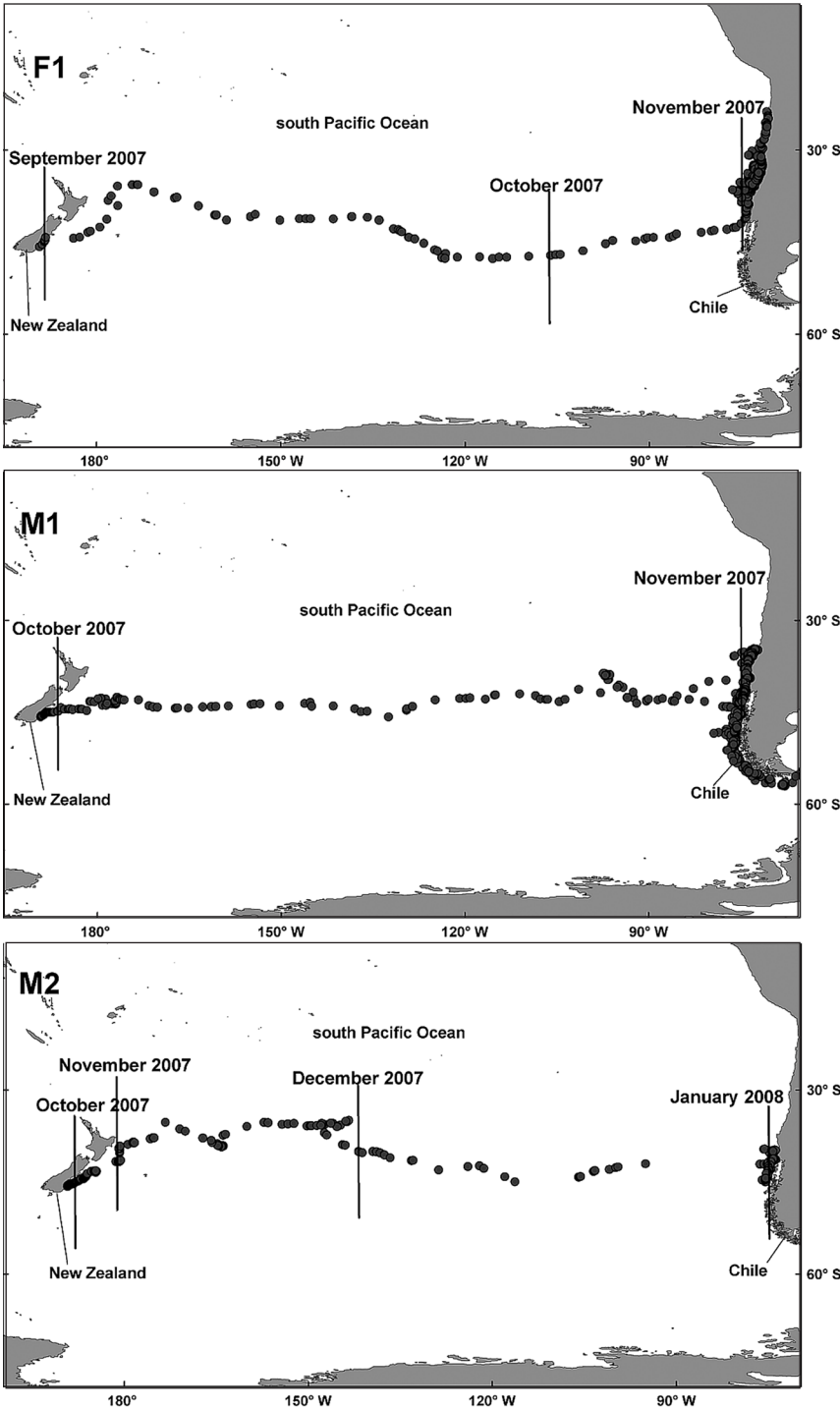


Fig. 1. Tracks of 3 juvenile northern royal albatrosses (*Diomedea sanfordi*) during their first year at sea taken from 6-hourly GPS locations. They all fledged from the Albatross Colony at Taiaroa Head on the Otago Peninsula, New Zealand and flew across to the coast of Chile.

ranged from 36 to 38 m a.s.l. (Table 1). With the exception of altitude for M2, for all 3 albatrosses, speed, altitude and average daily distance were greater during migration than during both fledging

and foraging (Fig. 3). Throughout the tracking period, the albatrosses flew at speeds over 80 km h⁻¹ only 3% of the time, with more than half of these higher speeds occurring during migration.

Table 1. Tracking details of 3 juvenile northern royal albatrosses that fledged from Taiaroa Head, New Zealand.

	Stage	Starting date	Days	Total distance (km)	Mean daily distance (km)	Maximum daily distance (km)	Mean speed (km h ⁻¹)	Maximum speed (km h ⁻¹)	Mean altitude (m)	Maximum altitude (m)
Female ¹	Attachment	30 Aug 07	-	-	-	-	-	-	-	-
	Fledging	4 Oct 07	15	1619	96	177	13	83	4	6
	Migration	19 Oct 07	17	9039	517	730	31	110	6	36
	Foraging	6 Nov 07	295	25,320	88	283	13	87	1	37
	End tracking	31 Aug 08 ²								
	Total		327	35,978	109	730	14	110	2	37
Male 1 ³	Attachment	30 Aug 07	-	-	-	-	-	-	-	-
	Fledging	22 Sep 07	19	1508	104	290	8	90	8	27
	Migration	11 Oct 07	16	8993	553	1047	43	109	7	38
	Foraging	27 Oct 07	327	35,565	127	690	19	104	3	38
	End tracking	24 Sep 08								
	Total		362	46,066	158	1047	20	109	3	38
Male 2 ⁴	Attachment	30 Aug 07	-	-	-	-	-	-	-	-
	Fledging	25 Sep 07	45	1796	51	205	4	56	5	26
	Migration	10 Nov 07	34	10,559	219	534	18	105	4	29
	Foraging	14 Dec 07	55	2,794	83	194	12	80	7	36
	End tracking	9 Feb 08								
	Total		134	15,149	112	534	11	105	5	36

¹Weight immediately prior to fledging was 6.8 kg. Age at time of fledging was 248 days.

²This is the date the transmitter stopped working.

³Weight immediately prior to fledging was 9.2 kg. Age at time of fledging was 240 days.

⁴Weight immediately prior to fledging was 11 kg. Age at time of fledging was 242 days.

Foraging

All 3 albatrosses reached South America at different times (Table 1) at latitudes between 40°S and 44°S, before dispersing along the narrow Chilean continental shelf edge between 23°S and 58°S (Fig. 1). The estimated area of the foraging ranges off the coast of Chile was 145,000, 950,000 and 115,000 km² for F1, M1 and M2, respectively. The albatrosses largely remained within 100 km of the coast, over the shelf edge in waters between 1000 and 2000 m deep. Occasionally, they were located up to 200 km from the coast in 4000 m deep water, but were rarely located further than 200 km from the coast where depths reached 5000 m. Only rarely were locations recorded over the Peru-Chile Trench where depths reached 6000 m. None of the albatrosses were located closer than 5 km from the coast during the study period.

F1 ventured the furthest north, foraging between 23°S and 38°S off the coast of Valparaiso

(33°S), Chile. At one point it ventured 270 km off the coast at an ocean depth of 4000 m. M2 remained within 39°S and 45°S in depths of 1000 m during its time on the coast, displaying the least movement of all 3 albatrosses. M1 ranged between 34°S and 57°S and generally remained no further than 150 km from the coast, repeatedly moving up and down the coastline. It flew rapidly southwards on 3 separate occasions, once on a 2-month trip between 20 Jan and 25 Mar 2008. On this trip it travelled at least 7500 km reaching the very southern tip of the Patagonian coast (170 km from the Falkland Is) before returning north to the starting point. The other 2 southward return flights included a 1200 km trip over 16 days in May and another 49-day trip starting in early Jun where the albatross travelled 3800 km southwards and back. In Aug 2008, it also made a 2000 km trip directly westward into the southern ocean on a reverse heading of its migration flight.

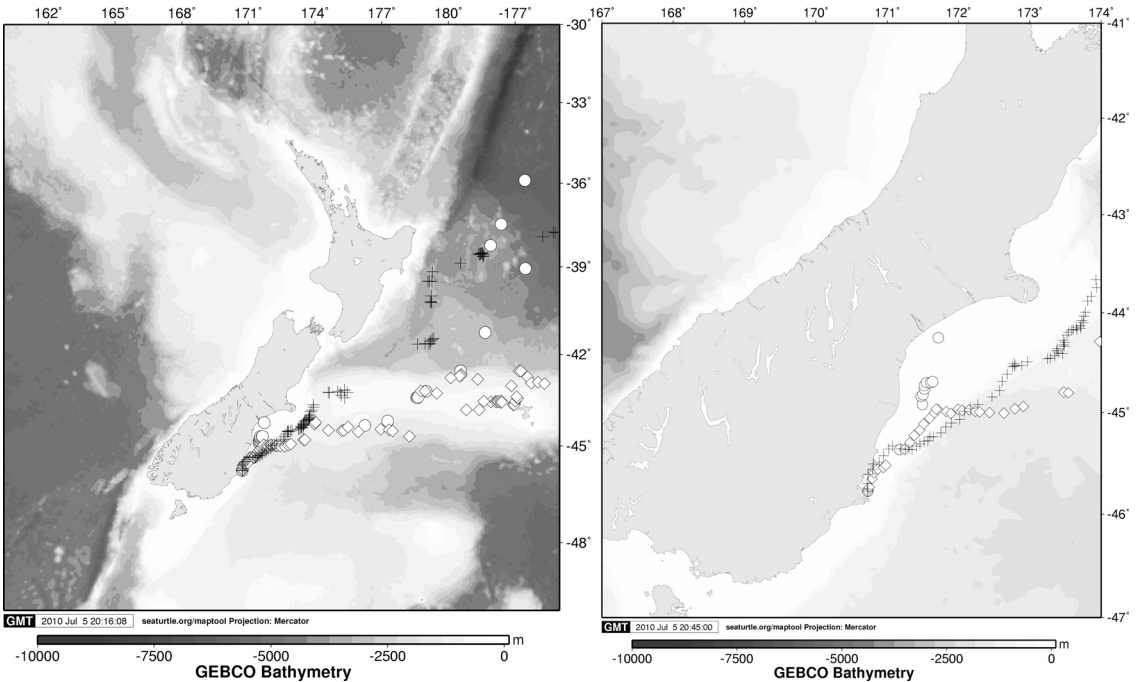


Fig. 2. Six-hourly GPS fledging locations of 3 juvenile northern royal albatrosses (*Diomedea sanfordi*) F1 (circle), M1 (diamond) and M2 (cross) within New Zealand waters. On the right is an enlarged image of the South Island, New Zealand.

For each albatross, the core area identified during foraging on the coast of Chile was approximately one fifth to one tenth the size of the entire home range during foraging. The core areas spanned a large area of latitude (31°S to 50°S) and whilst the entire core area of M2 overlapped with a portion of the core area of M1, there was no other overlap (Fig. 4).

General behaviour

During the year-long tracking period, the 3 albatrosses spent, on average, 72% (± 7.9 , range 63 – 79%) of their time resting on the water. Resting on the water varied according to their dispersal stage (Fig 3). Based on individual averages, the birds rested the most during fledging (range 37 – 45%), followed by foraging (range 31 – 37%), and the least during migration (range 21 – 29%) ($F = 6.6$; $df = 2, 6$; $P = 0.031$). The percentage of time spent resting on the water for both F1 and M1 was biased towards foraging; however, the time spent resting on the water by M2 was spread over all 3 stages (Fig 3). There was no significant variation in time spent resting on the water by time of day ($F = 0.85$; $df = 3, 8$; $P = 0.505$); however, a larger percentage of resting locations was obtained at 2400 h (range 31 – 45%). The remaining resting locations were evenly spread over the other time periods (range

10 – 25%) showing a decrease toward the evening (Fig. 5).

The average daily distance flown varied significantly by stage ($F = 9.82$; $df = 2, 6$; $P = 0.013$), with the highest recorded during migration, followed by foraging, and fledging (Table 1). The average distance travelled between 2 consecutive location points varied according to the time of day ($F = 16.8$; $df = 3, 8$; $P = 0.001$) with larger average distances being covered between 0600 h and 1800 h. Over the course of the day, overall average distances per 6-hour period ranged from 32 to 52 km, compared with 10 – 22 km between 1800 h and 0600 h (Fig. 5). The corresponding pattern of percentage of time spent resting on the water during the night with increased movement during the day is shown in Fig 5.

There was some evidence of M1 reacting to the Chaiten volcano eruption on 2 May 2008 which produced a plume of volcanic ash and steam nearly 17 km high. On that day, M1 was located approximately 160 km directly west of the volcano and had been at this location for 3 weeks. Between 0600 and midday on 2 May 2008, it began the second of his rapid southward movement travelling 80 km during these 6 hours. It continued south for a further 9 days travelling 1100 km before turning around to head up north again and returning to

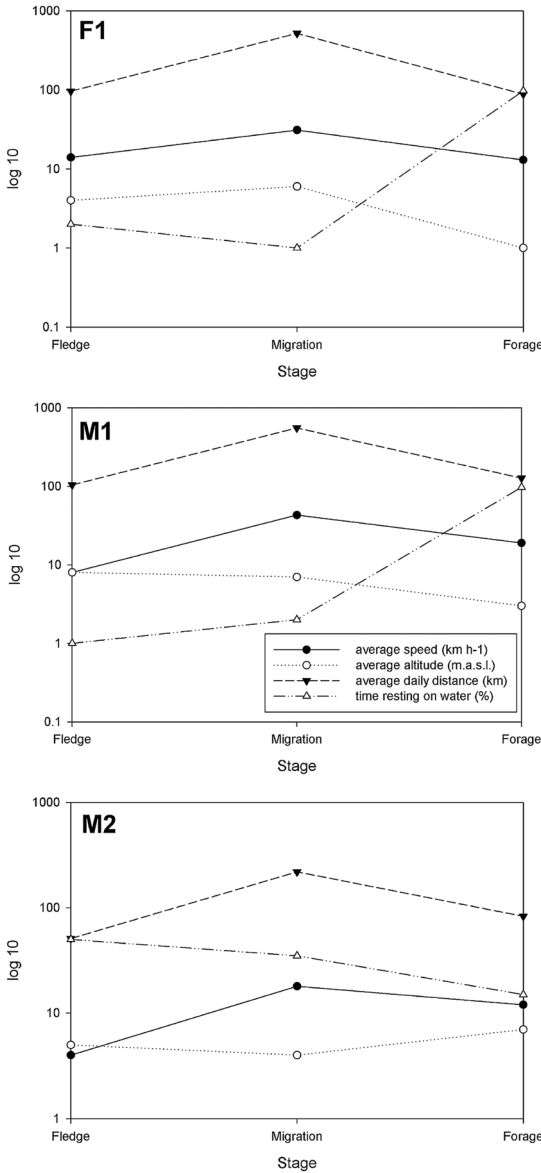


Fig. 3. Average speed, altitude, daily distance and time spent resting on the water during each stage during the first year at sea for 3 juvenile northern royal albatrosses (*Diomedea sanfordi*).

near the same location 160 km west of the volcano on approximately 20 May. Winds pushed the major ash plume directly east into Argentina, so he probably did not react directly to the ash. Although based on a single observation, this suggests that these birds may react to small changes in air pressure, smell, temperature or even underground tremors associated with a volcanic eruption.

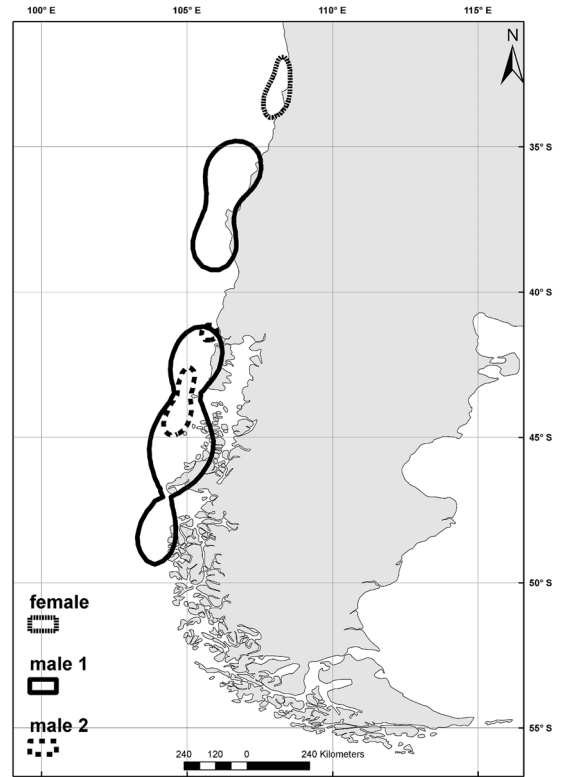


Fig. 4. Core areas (50% kernel) of 3 juvenile northern royal albatrosses (*Diomedea sanfordi*) foraging off the coast of Chile during their first year at sea.

Performance of the system

GPS transmitter locations were verified by a hand-held Garmin Etrex Vista GPS unit (Garmin International Inc.; Olathe, KS, USA). During the 3 to 5 week period between attachment and fledging, the differences between nest locations recorded by the GPS tracking units and the hand-held GPS unit were 25 m (± 15), 24 m (± 10) and 16 m (± 8) for F1, M1 and M2, respectively. Location fix success of the GPS tracking units prior to fledging and whilst the albatrosses were still on their nests was 42% (n = 56), 80% (n = 80) and 92% (n = 92) for F1, M1 and M2, respectively.

From the time of fledging until the end of tracking, the 3 transmitters registered 85% (n = 1107), 81% (n = 1169) and 56% (n = 299) location fix success rates for F1, M1 and M2, respectively, with 66 to 83% of these location points accurate to 18 m. Transmitter acquisition rates were higher during migration (70 – 99%) than during the fledging or foraging periods (Table 2). There was no significant difference between seasonal ($F = 0.49$; $df = 3, 6$; $P = 0.7$) or monthly location fix rates ($F = 0.93$; $df = 11, 18$; $P = 0.536$). Acquisition success did not vary by time

Table 2. Location fix success of GPS transmitters.

	Stage	Days tracked ¹	Possible locations ²	Successful locations (%)	3D ³ (%)	2D ⁴ (%)	Voltage (V) average (\pm sd)	Temperature (°C) average
Female	Fledging	15	60	22 (37)	16 (73)	6 (27)	3.7 (0.1)	23
	Migration	17	68	67 (99)	58 (87)	9 (13)	4.1 (0.1)	17
	Foraging	295	1180	1018 (86)	845 (83)	173 (17)	4.0 (0.2)	22
	Total	327	1308	1107 (85)	919 (83)	188 (17)	4.0 (0.2)	22
Male 1	Fledging	19	76	64 (84)	56 (89)	7 (11)	3.8 (0.0)	23
	Migration	16	64	63 (98)	54 (86)	11 (17)	4.1 (0.1)	19
	Foraging	327	1308	1042 (80)	752 (72)	289 (28)	4.0 (0.1)	33
	Total	362	1448	1169 (81)	862 (74)	307 (26)	4.0 (0.1)	19
Male 2	Fledging	45	180	103 (57)	75 (73)	28 (27)	3.8 (0.1)	27
	Migration	34	136	95 (70)	76 (80)	19 (20)	4.1 (0.1)	22
	Foraging	55	220	101 (46)	47 (47)	54 (53)	3.9 (0.2)	20
	Total	134	536	299 (56)	198 (66)	101 (34)	3.9 (0.2)	22

¹ The days tracked is the number of days the transmitters were active.

² The possible locations were calculated using the days tracked times 4 as there were 4 locations per day.

³ Three dimensional fix based on more than three satellites.

⁴ Two dimensional fix based on three satellites only.

of day ($F = 0.04$; $df = 3, 8$; $P = 0.987$). The median time required for the transmitter to acquire the satellites ranged from 66 to 77 seconds, and the 5th to 95th percentiles of time to fix for all transmitters ranged between 39 to 125 seconds. On average, 5 satellites were acquired for each successful GPS location.

Even as the transmitters approached the end of their theoretical lifespan, they functioned as well, or better, than at the start. There was no significant change in the number of locations per month for any of the 3 birds (M1, $r = -0.169$, $n = 13$, $P = 0.581$); (M2, $r = -0.156$, $n = 6$, $P = 0.767$); (F1, $r = 0.314$, $n = 12$, $P = 0.321$). The minimum required operating battery voltage for the transmitters used in this study was 3.6 V. Table 2 shows the average battery charge held by each transmitter and was similar for the 3 birds. The voltage of the solar-charged batteries varied by season ($F = 126.35$; $df = 3, 927$; $P < 0.001$), with the lowest reading in winter (3.8 ± 0.1 V) and highest in summer (4.0 ± 0.1 V). The effect of movement stage on solar charge was also statistically significant ($F = 70.67$; $df = 2, 928$; $P < 0.001$) with the highest average voltage readings occurring during migration (4.1 ± 0.07).

Seventy-five percent of the failed satellite acquisition attempts occurred for 1 of 3 reasons. Firstly, 'no fix' was obtained when the receiver turned on at the designated time and timed out after a 2-minute period. Secondly, 'battery drain' occurred when the receiver turned on to get a fix,

but the battery voltage then dropped too low to continue after 15 seconds. Finally, failure occurred through a 'low voltage' signal, which was obtained if the battery voltage was too low to attempt a fix and the GPS receiver did not turn on. Of all the failed transmission attempts, most were due to 'no fix' readings (range 46 – 80%) when the average battery charge was 3.9 V, a high enough voltage for a successful reading. For a period of 18 days during Oct 2007, we received no locations from M2. The voltage reading at the start of this black out was 3.56 V and when it started up again it was 3.95 V, indicating that this blackout may have been due to insufficient battery charge.

DISCUSSION

The 3 fledging juvenile northern royal albatrosses in this study dispersed from Taiaroa Head, migrating across the south Pacific Ocean to Chile in South America where they remained off the coast. This first year at sea consisted of 3 main stages, post-fledging movement, migration and foraging. The fastest speeds and maximum daily distances occurred during migration, whilst the albatrosses generally showed more sedentary behaviour during fledging and foraging, staying within the continental shelf area of New Zealand and Chile, respectively. The foraging range on the Chilean shelf ranged between 23°S and 57°S. More time resting on the water

occurred around midnight, coinciding with higher average daily distances during the day. The GPS transmitters functioned well with sufficient solar charge.

Ecological outcomes

Post-fledging movements

After fledging, the albatrosses remained in New Zealand waters for 15 (F1), 19 (M1) and 46 (M2) days, and all spent some of this time over the Chatham Rise. This is an undersea platform in 500 to 1000 m of water approximately 1000 km from the New Zealand coast and an important feeding area for seabirds (Waugh *et al.* 1999). It lies beneath a convergence zone for warm subtropical surface waters from the north and cold subantarctic waters from the south, creating nutrient-rich waters ideal for plankton and many animals that feed on them. This tracking stage comprised the first 2 to 7 weeks after fledging and it is likely that these initial weeks were spent developing flying and foraging skills (Burger 1980).

Migration

The migration period in this study ranged from 16 to 34 days for the 3 juvenile albatrosses. This was also the period when the greatest distances and speeds were achieved. This behaviour was similar to adult northern royal albatross which also migrate rapidly across the Southern Ocean to the coast of Chile (Nicholls 2007). The influence of wind on albatross movements is well documented (Weimerskirch *et al.* 2000; Shamoun-Baranes *et al.* 2003), and the start of the long westerly migration was likely caused by the seasonally predictable prevailing westerly winds that dominate the Southern Ocean between 30°S and 60°S. Weimerskirch *et al.* (2000) noted that albatrosses do not wander aimlessly across the Southern Ocean. Rather, they travel in flyways created by favorable winds that enable them to cover large distances with little effort by 'storm riding' (Cstry *et al.* 2009). The changes in wind regime and variability that are predicted with possible future climate changes (Pachauri & Reisinger 2007), could mean that the increasing frequency of storm events may have a biological consequence for this species, potentially interrupting migration patterns and reducing food stocks (Weimerskirch *et al.* 2000).

The variable flight speed patterns for juvenile northern royal albatrosses in this study are similar to those recorded for other albatrosses. Chatham albatrosses (*Thalassarche eremita*) tracked by Nicholls *et al.* (2007) had consistent differences in flight speeds between their trans-ocean migrations and their 'rest and recreation' phases. Flight speeds for adult wandering albatrosses (*Diomedea exulans*) have been recorded at 135 km h⁻¹ (Weimerskirch *et al.* 2002), whilst in this study maximum speeds of

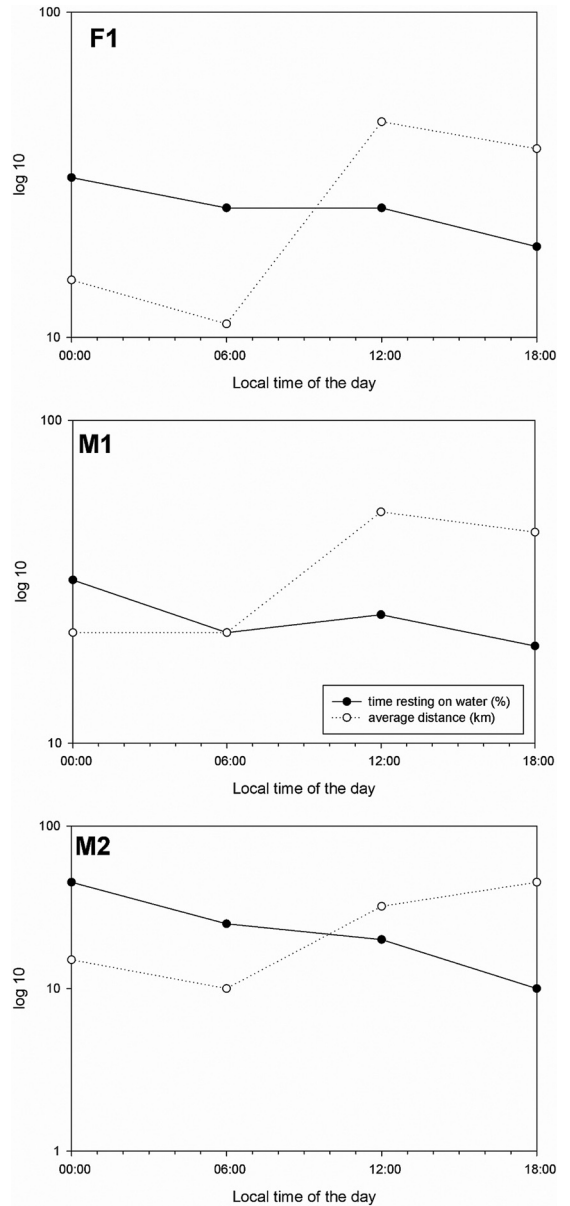


Fig. 5. Average distance travelled and time spent resting on the water by time of day during the first year at sea for 3 juvenile northern royal albatrosses (*Diomedea sanfordi*).

110 km h⁻¹ were reached. The difference may be due to variation in tracking methods. The high speeds reported for wandering albatrosses were calculated based on the use of the Argos system. Apparently, speeds were determined by dividing the distance between 2 Argos locations by the intervening time interval, thus confidence in the reported speeds can be compromised if the location inaccuracy is

high (Hays *et al.* 2001). In contrast, the speed was calculated by the GPS transmitter at a set time in our study, and is thought to comprise an error of < 1 km h⁻¹ at speeds of > 40 km h⁻¹.

Foraging

Banding studies show that young (0 – 1 years) southern royal albatrosses were commonly found during summer on the highly productive coastal area of Chile at 30°S to 40°S, with few recovered between 45° – 50°S latitudes (Roberston & Kinsky 1972). Our results, however, show that our juvenile northern royal albatrosses were between 23°S and 58°S on the coast of Chile. The juveniles were often over the shelf edge where the ocean depth was 1000 to 2000 m, and rarely where depths exceeded 2000 m. Adult northern royal albatrosses are reported to prefer shelf feeding in 200 to 1000 m waters (Nicholls *et al.* 2002; Walker & Elliott 2006).

The high use areas of M1 and M2 overlapped, but M1 and the female occupied areas of different sizes and locations on the coast. The variation in range between the juveniles was similar to that for the 3 juvenile wandering albatrosses (*D. antipodensis*) tracked by Walker *et al.* (2006), indicating that albatrosses of the same species may use different areas of the Chilean coast. The high-use areas may be attributable to foraging activity, prevailing wind patterns, roosting and commuting (Nicholls *et al.* 2005).

General behaviour of fledglings

The satellite tracking technology allowed us to estimate time spent on different activities. During the study, 75% of all locations were identified as resting points on the water with one third of these obtained at 2400 h. This coincides with an increased average distance per 6-hour period between 0600 h and 1800 h, suggesting a division between resting at night and foraging during the daytime.

Dispersal behaviour of albatrosses upon fledging in our study was similar to that of the juvenile wandering albatrosses (*D. exulans*) studied by Weimerskirch *et al.* (2006). Upon fledging, the juveniles in their study immediately landed on the water and drifted for 1 to 15 days until southerly winds started to blow. The juveniles then flew directly east, crossing the subtropical convergence 600 km north of the Crozet Is and continuing onto the subtropical waters (Weimerskirch *et al.* 2006). They also found that female juvenile *D. exulans* flew further than males each day, covering an average of 183,800 km during their first year. Whilst their general pattern of dispersal is similar to our 3 juveniles, the distance covered by our study birds during the first year was substantially lower (15,000 – 46,000 km). However, variation in distance travelled between the 2 studies may be attributed to a different tracking method. The distances

calculated by Weimerskirch *et al.* (2006) were based on the use of the Argos system, known to provide locations with a larger error (Nicholls *et al.* 2007), and potentially providing inflated distances.

Albatrosses are reported to frequent nutrient-rich areas of high productivity, transition and convergence zones, as well as areas of upwelling where prey are pushed to the surface and become concentrated and accessible to surface feeders (Waugh *et al.* 1999). The nutrient-rich Chatham Rise and the coastal area of Chile were both utilised by our study birds. This coastal area of Chile is a well-known foraging area for other age groups of northern royal albatross (Nicholls *et al.* 2002; Nicholls 2007) and for other albatross species (Imber 1999; Spear *et al.* 2003; Nicholls & Robertson 2007a).

The Humboldt Current is a cold, low-salinity ocean current flowing along much of the coast of Chile. It is one of the most highly productive (>300 gC/m²-yr) marine ecosystems of the world (Paulik 1981). Albatrosses feed on surface planktonic crustaceans, squid and pelagic fish (Marchant & Higgins 1993). Southern royal albatrosses (*D. epomophora*) are thought to have a preference for the greater hooked squid (*Moroteuthis ingens*) (Imber 1999). These squid are distributed on the continental shelf break and inner slope of southern New Zealand, Chile and Argentina, and this might be one of the reasons for different albatross species migrating between the 2 areas. Robertson *et al.* (2003) suggest that knowledge of good feeding locations is learned during the long period of adolescence.

Bycatch of seabirds by pelagic and demersal longline fishing boats has been implicated in the decline of many seabird species in the Southern Ocean (Prince *et al.* 1992). However, a study of birds caught by trawlers and longliners within New Zealand waters show numbers of northern royal albatross are small in comparison with numbers of other species caught (Robertson *et al.* 2004). Whilst the literature reports no connection between the decline of this species and bycatch in New Zealand waters, juvenile ranges analysed in this study spatially overlap with areas of substantial longline fishing in New Zealand, Chile and the south Pacific Ocean. Therefore, it is possible they are still at risk of becoming bycatch. Fleets from Japan, Taiwan, Korea, New Zealand, Argentina and Chile fishing for southern blue fin tuna (*Thunnus maccoyii*), albacore tuna (*T. alalunga*), ling (*Genypterus blacodes*), hake (*Merluccius hubbsi*) and Patagonian toothfish (*Dissostichus eleginoides*) (Tuck *et al.* 2003) are frequent in the areas traversed by the 3 juvenile albatrosses. As well, the Chatham Rise is New Zealand's most productive and important commercial fishing ground, providing 60% of the national catch. Although spatial overlap is highly

likely, temporal overlap is far more difficult to ascertain and is beyond the scope of this study.

Although we tracked only 3 birds, we found differences between individuals. For example, M2 behaved consistently differently from the other juveniles. He took longer to leave New Zealand, took longer to migrate across the Pacific Ocean (backtracking on 2 occasions), had the lowest average daily distance, provided more locations spent resting on the water spread throughout all 3 stages, had the lowest percentage of successful GPS locations and went offline 7 months earlier than F1. Whether this was due to transmitter problems or behavioural problems is unclear. He was noticeably heavier prior to fledging, therefore the longer periods during fledging and migration may have been due to his weight and/or indicate that he was not as strong as the other 2 juveniles. This would require that he rest more often during these stages which would have in turn meant more time with the wings covering the solar panels of the transmitter. However, his transmitter reported only a slightly lower average voltage (Table 2).

Technical effectiveness

It is important to know the limits of the technology and quality of the data because they reveal the sources of potential bias which can affect interpretation of the data. The field test showed the accuracy of the 3 GPS units ranged from 16 to 25 m. Lewis *et al.* (2007) report that most stationary test locations have an accuracy of < 30 m but that they can be accurate to < 3 m. Awkerman *et al.* (2005) attained a ground truthing average of 4.6 m (± 2.8 m) during their study of waved albatrosses (*Phoebastria irrorata*). It is thought that juvenile northern royal albatrosses may move 5 – 50 m while at the nest colony (C. Robertson, *pers. comm.*), which may account for some of the GPS error in our study.

The mean rates of successful transmissions in this study (Table 2) are similar to those of Kawakami *et al.* (2006) who tracked black-footed albatrosses (*Diomedea nigripes*) in southern Japan using GPS technology. The lack of statistical significance between fix success and seasonal, monthly or daily time differences in our study indicates there was little bias in data acquisition. The higher location acquisition rates achieved during migration (Table 2) over the ocean may be attributable to extended periods when the wings of the albatrosses were spread, leaving the solar panels unobstructed and able to fully charge. In contrast, during fledging and foraging periods, more time is spent resting on the water with wings closed, covering the solar panels. It should be noted that 2 of the 3 transmitters had a similar or higher location fix success whilst still at their nests, when the wings might be covering the transmitter for much of the time. However, because

there was no difference in fix success with time of the day, we suggest that in general, a transmitter obstructed by albatross wings may have a reduced solar charge, but the effect is not apparent within the short-term or daily time periods.

Solar charging of the transmitters provided an adequate voltage for the duration of the study (Table 2). Whilst we could not measure direct sunlight, we found a seasonal effect on the solar levels, with a mean winter charge of 3.8 V (± 0.12 V) compared with summer when the charge averaged 4.0 V (± 0.14 V). Many factors can affect the regularity and extent of charging, such as the number of daylight hours, intensity of the sun, and amount of cloud cover. At the equator our transmitters would require 4 hours of direct sunlight to fully recharge. However, as birds (and thus their transmitters) move towards the poles, a longer charging period is needed due to the lower intensity of the sun.

We obtained a high level of fix success for 2 of the transmitters and they all functioned well with no significant decline over the tracking period. However, we recommend that consideration be given to the choice of duty cycle or transmission schedule. The GPS location schedule in this research (every 6 hours) did not provide locations with enough frequency to correlate with oceanographic predictors such as Sea Surface Temperature (SST), chlorophyll concentration, and wave height. The accuracy of GPS technology is sufficient to perform that kind of analysis, so if the frequency of data acquisition increases, an accurate understanding of fine-scale habitat use can be obtained. Depending on the specific research objectives, for the size of transmitter and solar array (30 g) that we used, we recommend that the location schedule be increased to 6 per day (every 4 hours) and downloading via the Argos system every fourth day. However, increasing the location acquisition schedule could shorten the life of the transmitter or require more battery/solar power, which would need a larger solar array, and increase the size of the transmitter. It should also be noted that there can be a data storage limit, after which time the locations are over-written. For our transmitters, a maximum of 24 locations could be stored, necessitating the 6-day download schedule. Given the large size of albatross, we could have used a 45 g GPS transmitter, increasing the location schedule even further to every 2 or 3 hours, and downloading to Argos every second or third day. However, we chose to reduce the transmitter load to a minimum, following the advice of Phillips *et al.* (2003). As Argos costs are dictated by the amount of time used by that system, an increase in the data download schedule will increase costs. Continued reductions in the size of GPS transmitters and improvements in solar technology are rapidly paving the way for this technology to surpass other telemetry options.

Conclusion

The GPS technology enabled us to achieve our research objectives and we would recommend its use. From our study we found that these juvenile northern royal albatrosses flew up the New Zealand coast before beginning a direct easterly migration across the Pacific Ocean to the Chilean coast to forage for up to 1 year. Their behaviour showed similarities to both breeding and non-breeding adult northern royal albatrosses, which also traverse across the Southern Ocean from breeding grounds in or near New Zealand to the continental shelf area of Chile as well as the Patagonian coast of Argentina (Nicholls *et al.* 2002; Nicholls 2007), before migrating back to their breeding grounds. This study has provided useful movement information for this species, but there still remains an information gap of about 4 years between the ages of 1 year and adulthood, where their movement is unknown. Whilst the GPS technology performed well during this study, we recommend that future studies consider using a duty cycle with more frequent locations as this would allow researchers to take advantage of remote sensing data to improve fine-scale analysis. As well, improvements in long-term attachment methods may contribute to addressing the information gap between 1 year and adulthood.

M1, known to the public as Toroa, the 500th chick hatched at Taiaroa Head, was selected as one of the juveniles to track in this study. His lineage was well known to the public after his grandmother successfully raised 13 chicks during her 61 years at the colony. Updates of the albatross locations from this study were made public via a website (<http://albatross.org.nz/toroa.html>), and along with the media reporting of the tracking study, the educational interest and profile of the species to non-scientists were increased.

This study is the first to report on the first year-at-sea movements of juvenile northern royal albatrosses. The precise tracking of the movement of these juvenile birds over a 1-year period has improved our understanding of their preliminary dispersal patterns. Because northern royal albatross disperse to the economic zones of other nations and may interact with international commercial fisheries, the results of our study will contribute towards effective transboundary conservation strategies to protect this species.

ACKNOWLEDGEMENTS

We gratefully acknowledge the invaluable contributions of the following individuals and organisations: New Zealand Lotteries Grants Board, Lyndon Perriman, Graeme Elliott and David Agnew (Department of Conservation), Sam Inder and Robyn McDonald (Otago Peninsula Trust), Guides at the Royal Albatross Colony, Hoani Langsbury

(Te Runanga o Otakou Inc.), Mathieu Lecointe (CLS Argos), Matthew Irwin (Massey University, GIS lab), the Institute of Natural Resources (Massey University), Christopher Robertson (Wild Press), Julie Fletcher (Meteorological Service of New Zealand), Donna Patterson-Fraser (Polar Oceans Research Group), Jill Awkerman (Wake Forest University), Mayra Pazos (NOAA) and Susan Waugh (Ministry of Fisheries). Approval for this study was obtained from the Department of Conservation, Massey University Animal Ethics Committee and Te Runanga o Otakou Inc., the local Iwi. Some of the analyses and graphics in this paper were performed with Maptool, a product of SEATURTLE.ORG (www.seaturtle.org).

LITERATURE CITED

- Anderson, D.J.; Ricklefs, R.E. 1987. Radio-tracking masked and blue-footed boobies (*Sula* spp.) in the Galapagos Archipelago. *National Geographic Research* 3: 152-163.
- Awkerman, J.A.; Fukuda, A.; Higuchi, H.; Anderson, D. J. 2005. Foraging activity and submesoscale habitat use of waved albatrosses (*Phoebastria irrorata*) during chick-brooding period. *Marine Ecology-Progress Series* 291: 289-300.
- BirdLife International 2003. Tracking ocean wanderers: The global distribution of albatrosses and petrels. *The Global Procellariiform Tracking Workshop*. Gordon's Bay: South Africa.
- Burger, J. 1980. The transition to independence and postfledging parental care in seabirds. pp. 367-448 In: Burger, J., Olla, B., Winn, H. (eds.) *Behavior of marine animals*. New York: Plenum.
- Catry, P.; Phillips, R.A.; Croxall, J.P.; Burger, A.E. 2009. Sustained fast travel by a gray-headed albatross (*Thalassarche chrysostoma*) riding an antarctic storm. *Auk* 121: 1208-1213.
- Chambers, G.K.; Moeke, C.; Steel, R.; Trueman, J.W.H. 2009. Phylogenetic analysis of the 24 named albatross taxa based on full mitochondrial cytochrome b DNA sequences. *Notornis* 56: 82-94.
- Cohn, J.P. 1999. Tracking wildlife: high-tech devices help biologists trace the movements of animals through sky and sea. *Bioscience* 49: 12-17.
- Croxall, J.P.; Gales, R. 1998. An assessment of the conservation status of albatrosses. pp. 46-65 In: Robertson, G. & Gales, R. (eds.) *Albatross biology and conservation*. Chipping Norton: Surrey Beatty & Sons.
- Hays, G.C.; Akesson, S.; Godley, B.J.; Luschi, P.; Santidrian, P. 2001. The implications of location accuracy for the interpretation of satellite-tracking data. *Animal Behaviour* 61: 1035-1040.
- Hooge, P.N.; Eichenlaub, B. 1997. *Animal movement extension to ArcView. Version 1.1*. Anchorage: Alaska Biological Science Center, US Geological Survey.
- Hulbert, I.A.R.; French, J. 2001. The accuracy of GPS for wildlife telemetry and habitat mapping. *Journal of Applied Ecology* 38: 869-878.
- Imber, M.J. 1999. Diet and feeding ecology of the royal albatross *Diomedea epomophora* - king of the shelf break and inner slope. *Emu* 99: 200-211.
- IUCN 2010. *IUCN red list of threatened species. Version 2010.2*. www.iucnredlist.org Downloaded 29 June 2010.

- Kawakami, K.; Suzuki, H.; Horikoshi, K.; Chiba, H.; Fukuda, A.; Higuchi, H. 2006. The foraging ranges of black-footed albatross *Diomedea nigripes* breeding in the Bonin Islands, southern Japan, as determined by GPS tracking. *Ornithological Science* 5: 187-191.
- Lewis, J.S.; Rachlow, J.L.; Garton, E.O.; Vierling, L.A. 2007. Effects of habitat on GPS collar performance: using data screening to reduce location error. *Journal of Applied Ecology* 44: 663-671.
- Marchant, S.; Higgins, P.J. 1993. *Handbook of Australian, New Zealand and Antarctic birds*. Melbourne: Oxford University Press.
- Nicholls, D.G. 2007. Plumages of northern (*Diomedea sanfordi*) and southern royal (*D. epomophora*) albatrosses observed in Chilean seas on September 2004. *Notornis* 54: 158-167.
- Nicholls, D.G.; Murray, M.D.; Robertson, C.J.R. 1994. Oceanic flights of the northern royal albatross *Diomedea epomophora sanfordi* using satellite telemetry. *Corella* 18: 50-52.
- Nicholls, D.G.; Robertson, C.J.R. 2007a. Assessing flight characteristics for the Chatham albatross (*Thalassarche eremita*) from satellite tracking. *Notornis* 54: 169-179.
- Nicholls, D.G.; Robertson, C.J.R. 2007b. Validating locations from CLS: Argos satellite telemetry. *Notornis* 54: 121-136.
- Nicholls, D.G.; Robertson, C.J.R.; Murray, M.D. 2007. Measuring accuracy and precision for CLS:Argos satellite telemetry locations. *Notornis* 54: 137-157.
- Nicholls, D.G.; Robertson, C.J.R.; Naef-Daenzer, B. 2005. Evaluating distribution modelling using kernel functions for northern royal albatrosses (*Diomedea sanfordi*) at sea off South America. *Notornis* 52: 223-235.
- Nicholls, D.G.; Robertson, C.J.R.; Prince, P.A.; Murray, M.D.; Walker, K.J.; Elliott, C.P. 2002. Foraging niches of three *Diomedea* albatrosses. *Marine Ecology-Progress Series* 231: 269-277.
- Pachauri, R.K.; Reisinger, A. (eds.) 2007. *Contribution of working groups I, II and III to the fourth assessment report of the intergovernmental panel on climate change*. Geneva, Switzerland: IPCC.
- Paulik, G. 1981. Anchovies, birds and fishermen in the Peru Current. pp. 35-79 In: Glantz, M. & Thomson, D. (eds.) *Resource management and environmental uncertainty: Lessons from coastal upwelling fisheries*. New York: Wiley.
- Phillips, R.A.; Silk, J.R.D.; Croxall, J.P.; Afanasyev, V.; Briggs, D.R. 2004. Accuracy of geolocation estimates for flying seabirds. *Marine Ecology Progress Series* 266: 265-272.
- Phillips, R.A.; Xavier, J.C.; Croxall, J.P.; Burger, A.E. 2003. Effects of satellite transmitters on albatrosses and petrels. *Auk* 120: 1082-1090.
- Prince, P.A.; Wood, A.G.; Barton, T.; Croxall, J.P. 1992. Satellite tracking of wandering albatrosses (*Diomedea exulans*) in the South Atlantic. *Antarctic Science* 4: 31-36.
- Robertson, C.J.R.; Kinsky, F.C. 1972. The dispersal movements of the royal albatross (*Diomedea epomophora*). *Notornis* 19: 289-301.
- Robertson, C.J.R. 1993. Survival and longevity of the northern royal albatross *Diomedea epomophora sanfordi* at Taiaroa Head 1937-93. *Emu* 93: 269-276.
- Robertson, C.J.R.; Bell, E.; Schofield, P. 2004. Autopsy report for seabirds killed and returned from New Zealand fisheries, 1 October 2001 to 30 September 2002. *Department of Conservation Science Internal* 155: 1-43.
- Robertson, C.J.R.; Bell, E.A.; Sinclair, N.; Bell, B.D. 2003. Distribution of seabirds from New Zealand that overlap with fisheries worldwide. *Science for Conservation* 223: 1-102.
- Shaffer, S.A.; Tremblay, Y.; Awkerman, J.A.; Henry, R.W.; Teo, S.L.H.; Anderson, D.J.; Croll, D.A.; Block, B.A.; Costa, D.P. 2005. Comparison of light- and SST-based geolocation with satellite telemetry in free-ranging albatrosses. *Marine Biology* 147: 833-843.
- Shamoun-Baranes, J.; Baharad, A.; Alpert, P.; Berthold, P.; Yom-Tov, Y.; Dvir, Y.; Leshem, Y. 2003. The effect of wind, season and latitude on the migration speed of white storks *Ciconia ciconia*, along the eastern migration route. *Journal of Avian Biology* 34: 97-104.
- Spears, L.B.; Ainley, D.G.; Webb, S.W. 2003. Distribution, abundance and behaviour of Buller's, Chatham Island and Salvin's Albatrosses off Chile and Peru. *Ibis* 145: 253-269.
- Suryan, R.M.; Anderson, D.J.; Shaffer, S.A.; Roby, D.D.; Tremblay, Y.; Costa, D.P.; Sievert, P.R.; Sato, F.; Ozaki, K.; Balogh, G.R.; Nakamura, N. 2008. Wind, waves, and wing loading: morphological specialization may limit range expansion of endangered albatrosses. *PLoS ONE* 3: e4016.
- Tuck, G.N.; Polacheck, T.; Bulman, C.M. 2003. Spatio-temporal trends of longline fishing effort in the Southern Ocean and implications for seabird bycatch. *Biological Conservation* 114: 1-27.
- Walker, K.; Elliott, G. 2006. At-sea distribution of Gibson's and Antipodean wandering albatrosses, and relationships with longline fisheries. *Notornis* 53: 265-290.
- Warham, J. 1990. *The petrels: their ecology and breeding systems*. London: Academic Press.
- Waugh, S.; Filippi, D.; Fukuda, A.; Suzuki, M.; Higuchi, H.; Setiawan, A.; Davis, L. 2005. Foraging of royal albatrosses, *Diomedea epomophora*, from the Otago Peninsula and its relationships to fisheries. *Canadian Journal of Fisheries and Aquatic Sciences* 62: 1410-1421.
- Waugh, S.M.; Weimerskirch, H.; Cherel, Y.; Shankar, U.; Prince, P.A.; Sagar, P.M. 1999. Exploitation of the marine environment by two sympatric albatrosses in the Pacific Southern Ocean. *Marine Ecology Progress Series* 177: 243-254.
- Webster, M.S.; Marra, P.P.; Haig, S.M.; Bensch, S.; Holmes, R.T. 2002. Links between worlds: unraveling migratory connectivity. *Trends in Ecology & Evolution* 17: 76-83.
- Weimerskirch, H.; Akesson, S.; Pinaud, D. 2006. Postnatal dispersal of wandering albatrosses *Diomedea exulans*: implications for the conservation of the species. *Journal of Avian Biology* 37: 23-28.
- Weimerskirch, H.; Bonadonna, F.; Bailleul, F.; Mabile, G.; Dell'Omo, G.; Lipp, H.-P. 2002. GPS tracking of foraging albatrosses. *Science* 295: 1259.
- Weimerskirch, H.; Guionnet, T.; Martin, J.; Shaffer, S.A.; Costa, D.P. 2000. Fast and fuel efficient? Optimal use of wind by flying albatrosses. *Proceedings: Biological Sciences* 267: 1869-1874.
- Weimerskirch, H.; Pinaud, D.; Pawlowski, F.; Bost, C.-A. 2007. Does prey capture induce area-restricted search? A fine-scale study using GPS in a marine predator, the wandering albatross. *American Naturalist* 170: 734-743.