

## Diving patterns of breeding female rockhopper penguins (*Eudyptes chrysocome*): Noir Island, Chile

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**Abstract** The diving behaviour of female southern rockhopper penguins (*Eudyptes chrysocome*) was studied at Noir Island (54°30'S–73°00'W), Chile, in the southeast Pacific Ocean. This isolated island is located at the edge of the continental shelf in an area where the Humboldt Current originates, and holds a population of more than 150,000 breeding pairs. On 13 December 2005, four TDRs were successfully attached to females at the end of the brooding period and recorded diving activity at intervals of 2 s over the next 4 weeks. In total, 40 complete foraging trips were recorded. Trip duration was on average  $42.4 \pm 40.1$  h and the proportion of overnight trips (60%) was the highest value found so far for this species. Mean dive depth and dive duration was  $20.6 \pm 19.4$  m and  $63.7 \pm 36.4$  s, respectively. The diving effort was higher than that of brooding females from the Indian Ocean and comparable with that of

conspecifics from colonies in the southwest Atlantic in terms of diving rate ( $38 \pm 14.2$  dives  $h^{-1}$ ), but slightly lower as regards the proportion of time spent underwater ( $61 \pm 10.5\%$ ). This study confirms that the diving behaviour of rockhopper penguins varies as a function of the physical and biological characteristics of the foraging areas and of the particular stage of the breeding season.

**Keywords** Rockhopper penguin · *Eudyptes chrysocome* · Noir Island · Diving behaviour · Chile

### Introduction

Rockhopper penguins (*Eudyptes chrysocome*) have a circumpolar distribution, breeding on sub-Antarctic and temperate islands in the Southern Ocean (Williams 1995). The taxonomic status of the different rockhopper penguin populations has been subject to strong debate. Recently, after genetic analysis of the genus *Eudyptes*, it was proposed that it be split into two (Jouventin et al. 2006) or even three separate species (Banks et al. 2006). BirdLife International has decided on the former and split the genus into two species, the southern *E. chrysocome* (previously southern and eastern subspecies) and the northern *E. moseleyi* (previously northern subspecies) (BirdLife International 2008). Over the past two decades, dramatic population declines have been observed across the genus' breeding range (Moors 1986; Cooper 1992; Cooper et al. 1997, Ellis et al. 1998, Guinard et al. 1998, Crawford et al. 2003; Pütz et al. 2003). The reasons for these declines are still unclear, although concurrent changes in sea surface temperatures are assumed to have reduced primary productivity, resulting in a shift to a diet of lower trophic status (Hilton et al. 2006). In spite of the uncertainty related to their taxonomic status,

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the widespread reduction in the rockhopper penguin population has resulted in its classification as “Vulnerable” under IUCN (World Conservation Union) guidelines (Bird-Life International 2008). Given their widespread decline, knowledge of their biology, including foraging ecology, is crucial in order to develop appropriate measures for species and ecosystem conservation.

During the past 10 years, several studies have been carried out on the foraging ecology and diving behaviour of rockhopper penguins in the Indian Ocean (i.e. Cherel et al. 1999; Tremblay and Cherel 2000, 2003) and in the southwest Atlantic Ocean (i.e. Schiavini and Raya Rey 2004; Pütz et al. 2006a). Rockhopper penguins appear to be well adapted to changes in the marine environment and show phenotypic plasticity in their diving behaviour related to differences in oceanography (Tremblay and Cherel 2003) and light periods (Schiavini and Raya Rey 2004), which depend on the geographical location of the colonies and the breeding stage (Pütz et al. 2006b).

The southern rockhopper penguin population is confined to sub-Antarctic islands in the Indian, Atlantic and Pacific Oceans. Populations from the southwest Atlantic Ocean consist essentially of breeding colonies on the Falkland/Malvinas Islands (UK), Staten and Penguin Islands (Argentina), and a number of islands along the Pacific coast (Chile), including Diego Ramírez and Idefonso. Numerous studies into various aspects of the breeding and foraging ecology have been conducted on the populations in the Falkland/Malvinas Islands (i.e. Pütz et al. 2003, 2006a) and Staten Island (i.e. Schiavini and Raya Rey 2004; Raya Rey and Schiavini 2005; Pütz et al. 2006b; Raya Rey et al.

2007a, b). Furthermore, new estimates for breeding pair numbers have been given for Diego Ramírez and Idefonso islands (Kirkwood et al. 2007). The breeding colonies from the southeast Pacific have been less studied, although new estimates indicate that Noir Island holds about 11% of the global population (Kirkwood et al. 2007; Oehler et al. 2008). Given the observed differences in their breeding and foraging ecology in relation to the marine environment, our aim was to investigate, for the first time, the diving behaviour of rockhopper penguins in the southeast Pacific during the crèche period at Noir Island (Chile).

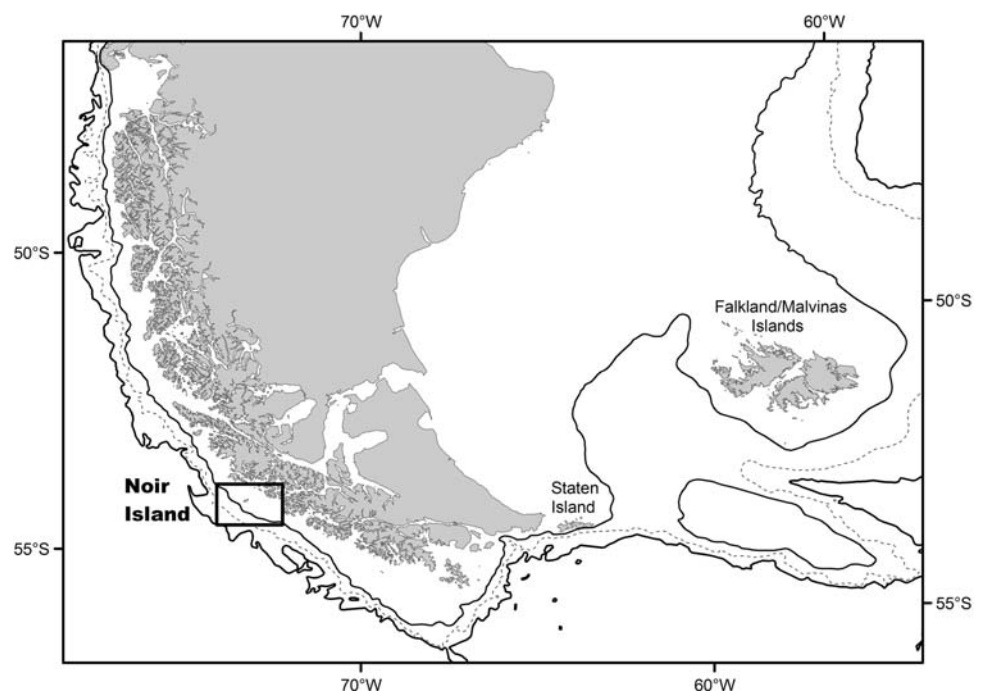
## Methods

### Study area and equipped birds

The study was conducted at Noir Island (54°30'S–73°00'W), Chile, in the southeast Pacific Ocean (Fig. 1). This isolated island has a population of 158,200 breeding pairs (Oehler et al. 2008). It is the outermost island of the Fuegian Chilean Archipelago, located near the continental shelf in an area where the west wind drift creates the Cape Horn Current that then turns into the Falkland/Malvinas Current towards the Atlantic and the Humboldt or Peru Current towards the Pacific. Given its location, Noir Island is subjected to strong westerly and south-westerly winds and thus surrounded by constantly rough seas.

Female rockhopper penguins alone are responsible for provisioning the chicks regularly with food from hatching until they are 20–25 days old, and so only females behav-

**Fig. 1** Southern portion of SE Pacific Ocean, showing location of study site and the 200, 1,000 and 2,000 m isobaths (straight line, dotted and dark straight line, respectively)



our were studied. After the chicks have entered the so-called crèches, both parents engage in chick-provisioning (Williams 1995; Raya Rey et al. 2007b). Four females were equipped with time-depth recorders (TDR) from the end of the guard (13 December 2005) until the middle of the crèche periods (11–12 January 2006). Female rockhopper penguins associated with a specific nest were caught by their feet using a 1.5 m length of wire bent into a hook at one end. After covering the head and immobilising the penguin to minimise disturbance, the birds were weighed and bill dimensions measured to determine their sex (sensu Hull 1996). The TDRs were attached on the midline of the back using black tape (Tesa, Beiersdorf AG, Hamburg, Germany) and two-component glue according to the method described by Wilson et al. (1997). The devices were then covered with a layer of quick epoxy (Loctite® 3430, Loctite Deutschland GmbH, München, Germany) to prevent the birds from removing the tape with their beaks. The whole process took less than 20 min per bird.

#### Technical details of TDRs

The time-depth recorders (MK9, Wildlife Computers, Redmond, USA) weighed approximately 30 g, equivalent to 1% of the mean penguin body mass, and their maximum dimensions were  $67 \times 17 \times 17 \text{ mm}^3$ , corresponding to about 2% of the penguin's body cross-sectional area. They were programmed with MK9HOST (Wildlife Computers), with a measurement interval of 2 s. Data were stored on a 64-Mb non-volatile Flash EEPROM, allowing the Mk9 to record 8–16 million measurements. The TDRs were each equipped with a pressure sensor, a light sensor and a temperature sensor. A saltwater switch prevented data being recorded while at the surface; the overall measurement period therefore varied depending on the amount of resting time at the surface. The pressure sensor recorded the dive depth between 0 and 350 m, accurate to within 0.5 m (range 0–20 m), 1 m (range 20–200 m) and 5 m (range 200–350 m). The temperature and light measurements were not considered in this study.

#### Data analysis

We analyzed dive data using MULTITRACE (Jensen Software Systems, Kiel, Germany). Data were corrected for a drifting surface level. A dive was deemed to occur when the maximum dive depth was  $\geq 3$  m (after Chappel et al. 1993; Tremblay and Cherel 2000, 2003; Schiavini and Raya Rey 2004). For each dive, duration, onset, maximum depth, pre-dive interval (from which we derived post-dive interval), bottom time (time spent at 75% of maximum dive depth attained during the dive: after Cherel et al. 1999; Tremblay and Cherel 2000, 2003), descent rate (from beginning of the dive to the start of bottom phase), and

ascent rate (from the end of bottom phase to the end of dive) were calculated. Successive dive data are partially auto-correlated, as the maximum depth of a dive is influenced by the previous depths attained. As a consequence, data are temporally pseudo-replicated (Hurlbert 1984). To overcome this, we followed the method of Tremblay and Cherel (2003). We performed a partial auto-correlation analysis, which verified that maximum dive depth failed to correlate after six successive dives. Thus, only every sixth dive was chosen for further analysis. Then from the remaining dives a thousand from each bird were randomly selected. The resulting set was used for graphical display and to calculate mean dive parameters (i.e. dive duration, depth, efficiency, etc.). Vertical travel distance (VTD) was defined as twice the maximum dive depth achieved in all dives performed during each trip (Horning and Trillmich 1997). Diving efficiency was estimated following Ydenberg and Clark (1989) as diving efficiency = bottom time/(dive duration + post-dive interval). We considered dives  $\leq 5$  m depth as travelling dives and dives  $>5$  m depth as foraging dives (Tremblay and Cherel 2003). The distance travelled from the colony to where a penguin started to forage was defined as the time elapsed between the initial dive after entering the water and the first of at least three consecutive dives  $\geq 10$  m depth (after Cherel et al. 1999). We assumed that penguins travel continuously at a constant speed of  $7.4 \text{ km h}^{-1}$  (Brown 1987) and in a straight line. The return journey was defined as the time elapsed between the last three consecutive dives  $\geq 10$  m depth and the final dive before leaving the water. The time of sunrise and sunset at the breeding colony was (for the mean date of device deployment on December 31) 04:19 and 21:29 h, respectively (local time = GMT  $-4$  h), giving a solar day length of 17.17 h. Dawn and dusk were at 01:31 and 00:18 h, respectively, following the nautical definition, i.e. when the sun is  $12^\circ$  below the horizon. Thus, the twilight period (dawn and dusk together) lasted 5.6 h and night time was restricted to 1.2 h (73 min). All mean values are presented with  $\pm$ SD.

## Results

### Trip characteristics

We recorded 41 foraging trips and 47,126 dives from four successfully equipped female rockhopper penguins during late brooding at Noir Island, Chile (Table 1). However, one female performed only three trips until 18 December, and the third trip was incomplete, probably due to a device failure, and was not considered in further analysis.

The calculated mean foraging parameters for each rockhopper penguin are shown in Table 1. Mean foraging trip

**Table 1** Summary of foraging trip and dive characteristics for individual penguins

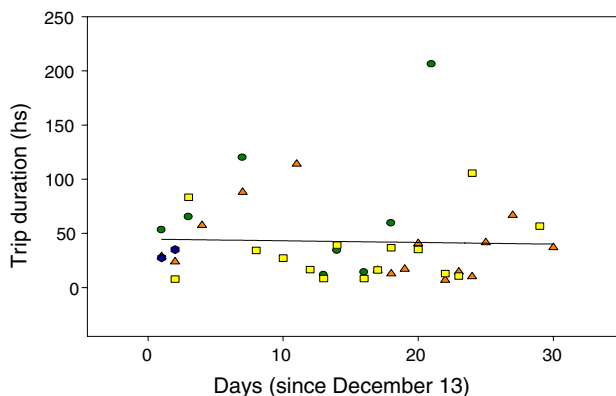
	48	49	53	73	Mean
No. of trips	8	15	15	3	
Trip duration (h)	70.3 ± 64.6	38.3 ± 31.2	33.2 ± 29.0	31.1 ± 3.7	42.4 ± 40
Total number of dives >3 m ( <i>n</i> )	2,212 ± 1,672	1,130 ± 830	1,179 ± 832	1,932 ± 729	1,417 ± 1,108
Foraging dives >5 m (%)	93	87	73	50	81
Time spent underwater (% of foraging trip)	60 ± 6	65 ± 10	54 ± 9	79 ± 4	61 ± 10
Dives per hour ( <i>n</i> )	34 ± 6	33 ± 6	41 ± 17	61 ± 16	38 ± 14
Vertical distance (m) per hour underwater	1,300 ± 260	1,397 ± 339	959 ± 358	2,394 ± 131	1,260 ± 449
Bottom time (min) per hour underwater	18 ± 2	18 ± 2	14 ± 2	22 ± 2	17 ± 3
Mean dive depth (m)	20 ± 4	22 ± 7	12 ± 4	21 ± 6	21 ± 19
Maximum dive depth (m)	67 ± 11	73 ± 18	52 ± 13	96 ± 4	65 ± 19
Deepest dive (m)	85	95	70	101	101
Mean dive duration (s)	65 ± 7	73 ± 10	50 ± 10	49 ± 13	64 ± 36
Maximum dive duration (s)	156 ± 29	156 ± 28	136 ± 27	203 ± 44.74	150 ± 49
Longest dive (s)	186	174	182	252	252
Mean bottom time (s)	33 ± 4	34 ± 6	22 ± 6	23 ± 6	31 ± 19
Diving efficiency	0.4 ± 0.02	0.4 ± 0.03	0.3 ± 0.05	0.30 ± 0.10	0.4 ± 0.20
Mean descent velocity (m/s)	1.1 ± 0.1	1.0 ± 0.2	0.8 ± 0.1	1.6 ± 0.2	1.1 ± 0.5
Mean ascent velocity (m/s)	0.9 ± 0.2	0.8 ± 0.14	0.7 ± 0.1	1.5 ± 0.2	1.0 ± 0.5

Values are means ± SD

duration was  $42.4 \pm 40.1$  h, and 60% of the trips were overnight trips. No significant temporal trend in trip duration over the study period was detected (Fig. 2;  $F = 0.04$ ,  $P = 0.8$ ). Most departures (73%,  $n = 29$ ) occurred between 05:00 and 10:00 h, with a peak at 06:00 (44%,  $n = 13$ ). Arrival times were widely distributed between 08:00 and 24:00 h, with a peak at 20:00 h (16%,  $n = 6$ ). There was no difference in departure times between birds performing daily and overnight trips ( $t$  test, departure times,  $t_{40} = -1.3$ ,  $P = 0.2$ ), although birds performing daily trips arrived later than birds that stayed overnight at sea ( $t$  test, arrival times,  $t_{40} = 2.4$ ,  $P < 0.05$ ). Periods on land averaged  $11.8 \pm 5.2$  h. Outbound travelling time to foraging areas

was  $1.53 \pm 1.09$  h, and return time was  $1.01 \pm 0.58$  h, the difference between the two times being significant ( $t$  test,  $t_{40} = 2.5$ ,  $P < 0.05$ ). Foraging ranges for the outbound and return trips were estimated at  $11.4 \pm 8.1$  and  $7.5 \pm 4.3$  km with a maximum of 44 and 20 km, respectively.

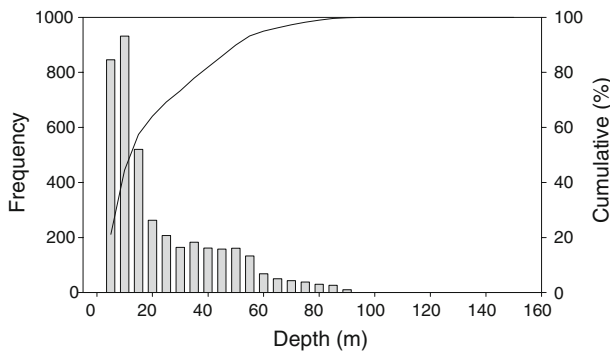
The penguins spent on average  $61 \pm 10\%$  of the trip duration underwater. The number of dives >3 m per foraging trip averaged  $1,417 \pm 1,108$  and 82% were foraging dives. The mean dive rate (based on trip duration) was  $38.0 \pm 14.2$  dives  $h^{-1}$ . Dive rate was not significantly different between daily and overnight trips ( $t$  test,  $t_{40} = 1.3$ ,  $P = 0.2$ , Table 1). Bottom time (min) per hour underwater was on average  $17.0 \pm 3.3$  min. The VTD was on average  $54.5 \pm 45.7$  km  $h^{-1}$  per foraging trip.



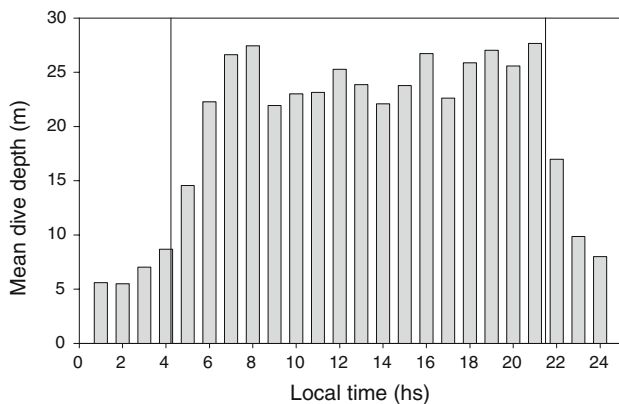
**Fig. 2** Foraging trip duration (h) in relation to the departure date. Bird 48: circle, Bird 49: triangle, Bird 53: square, Bird 73: hexagon

### Dive characteristics

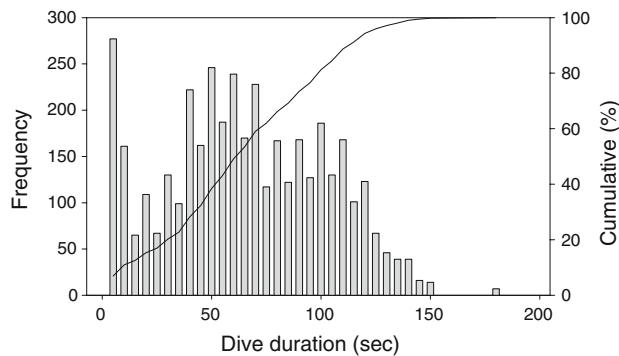
The maximum dive depth achieved was 101 m and the maximum dive duration recorded was 252 s. Mean dive depth was  $20.6 \pm 19.2$  m, with almost half of the dives performed to depths less than 10 m (45%) and 78% of the dives to depths less than 35 m (Fig. 3). Dive depths during twilight and night hours were generally less than 20 m (Fig. 4). The mean dive duration was  $64 \pm 36$  s, with 60% of the dives lasting  $\leq 70$  s. The frequency distribution presented a maximum at 5 s and between 45 and 70 s, with fewer dives up to 150 s (Fig. 5). Bottom time was on average  $31 \pm 19$  s with 90% of the bottom times less than 55 s. Dive duration was positively correlated to dive depth:



**Fig. 3** Frequency distribution of dive depths obtained from female rockhopper penguins from Noir Island during the brooding period

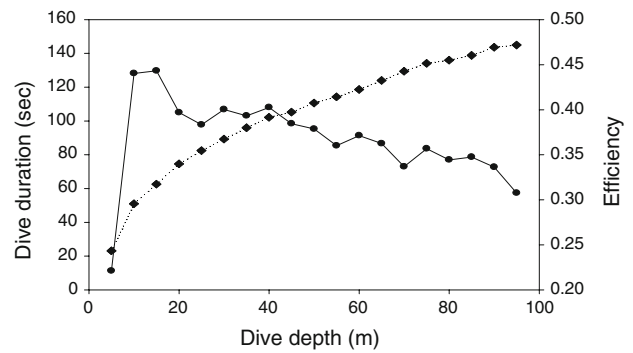


**Fig. 4** Mean dive depths in relation to local time of female rockhopper penguins from Noir Island. Lines indicate sunrise and sunset time for the study area (mean date of the study period)



**Fig. 5** Frequency distribution of dive durations obtained from female rockhopper penguins from Noir Island during the brooding period

Duration (s) = 41.6 ln dive depth (m) – 48.7 (Fig. 6,  $F = 207$ ,  $P < 0.001$ ). Diving efficiency averaged  $0.4 \pm 0.2$ , and its maximum was attained at 15 m dive depth (Fig. 6). The distribution of post-dive intervals was highly skewed, with 50% of the post-dives  $\leq 15$  s and 95%  $\leq 40$  s. Excluding intervals  $> 180$  s, post-dive intervals averaged  $17 \pm 21$  s. The mean descent and ascent rates were  $1.1 \pm 0.5$  and  $1.0 \pm 0.5$  m s<sup>-1</sup>, respectively. Descent rates were higher than ascent rates ( $t$  test:  $t_{40} = 8.4$ ,  $P < 0.001$ ).



**Fig. 6** Relationship between dive duration and diving efficiency [bottom time/(dive duration + post-dive interval)] with dive depth of female rockhopper penguins from Noir Island. Circles efficiency and diamond dive duration

### Discussion

This study provides the first description of the diving behaviour of southern rockhopper penguins foraging in the southeast Pacific Ocean. Despite the small sample size, all diving information gathered compares well with data from conspecifics breeding at other locations. Furthermore, these data are important given that it has only recently been established that this location is a very important breeding ground, holding at least 11% of the global population of southern rockhopper penguins (Kirkwood et al. 2007; Oehler et al. 2008). Data collection was hampered by logistical difficulties while accessing the island, due to the highly exposed nature of the island’s location.

Foraging trip duration and the percentage of overnight trips were comparable with values obtained from southern rockhopper penguins from Staten Island during the crèche period (Raya Rey et al. 2007b), but shorter compared with birds from the Falklands/Malvinas colonies during the same stage (Table 2, Pütz et al. 2006b). Also, longer foraging trips, in comparison with the other stages, were recorded during the crèche stage in rockhoppers from the Indian Ocean colonies (Tremblay and Cherel 2005). It is interesting to note that the breeding chronology appears to be similar to the Staten Island population (Raya Rey et al. 2007b), but starts two weeks earlier than the Falkland/Malvinas population (Pütz et al. 2006b) and one week later than the Ildefonso and Diego Ramírez Islands populations (Kirkwood et al. 2007). Another factor, apart from the stage, that could at least partly explain the longer foraging trip durations recorded in Noir birds could be related to the distance to the foraging ground which appeared to be higher compared with values obtained from Staten Island and Southern Indian Ocean populations during the guard period (Tremblay and Cherel 2003; Schiavini and Raya



**Table 2** Comparison of selected dive parameters from southern rockhopper penguins at different breeding colonies

Location	Noir Island (this study)	Staten Island (Schiavini and Raya Rey 2004)	Falkland Islands (Pütz et al. 2006b)	Kerguelen Islands (Tremblay and Cherel 2003)	Crozet Islands (Tremblay and Cherel 2003)
Study period	Late brooding	Early brooding	Late brooding	Early brooding	Early brooding
Dives analysed	≥3	≥3	≥3	≥5	≥5
Trip duration (h)	42	16	15	12	11
Overnight trips (%)	60	53	<2		10
Foraging dives (%)	82	90	83	84	83
Time spent underwater (% of foraging trip)	61	69	63	64	64
Dives per hour ( <i>n</i> )	38	32.7	39.4	29.6	27.1
Vertical distance (m) per hour underwater	1,260	2,634	1,716	2,397	2,880
Bottom time (min) per hour underwater	17	26.6	23.6	37.6	34.1
Mean dive depth (m)	21	28.9	14	29.1	40.4
Deepest dive (m)	101	113	66.5	85	104
Mean dive duration (s)	64	79	58.6	87.4	101
Longest dive (s)	252	164	189	177	190
Mean bottom time (s)	31	35	23.1	54.7	57.4
Postdive Interval (s)	17	20	nr	33	36
Diving efficiency	0.36	0.34	0.26	0.45	0.42
Mean descent velocity (m/s)	1.1	1.2	0.9	1.6	1.7
Mean ascent velocity (m/s)	0.97	0.8	0.8	1.3	1.3

Recalculated values from Pütz et al. (2006b)

Rey 2004). This study again confirmed both the plasticity shown by Pütz et al. (2006b) regarding the breeding duties and, given the differences in the foraging environment, that rockhopper penguins exhibited changes in their foraging trip characteristics (Tremblay and Cherel 2003). Departure and arrival times resembled the ones found for the Staten Island population (Raya Rey et al. 2007b) with both being generally widespread throughout the day, but showing peaks in the morning and afternoon.

It is well known that diving behaviour depends on the foraging area of the study population (Tremblay and Cherel 2003; Chiaradia et al. 2007) and that diving characteristics are influenced by the prey taken by the penguin species (Takahashi et al. 2004). The diet of rockhoppers from Noir Island is similar to that found in colonies located in the southwest Atlantic (Pütz et al. 2001; Clausen and Pütz 2002; Raya Rey and Schiavini 2005), with *Sprattus fuegensis*, *Thysanoessa* spp. and non-identified cephalopods making up the bulk of the diet (Venegas 1998). However, unfortunately Venegas (1998) provided no further details on the relative importance of each prey item. Given the distribution of *Sprattus fuegensis* in shallow waters (Sanchez et al. 1995), it is not surprising that the mean maximum dive depth was shallower compared with other locations except for the Falkland/Malvinas Island population (Table 2). Furthermore, the presence of *S. fuegensis* in the diet of rockhoppers from Staten Island during the guard and

crèche periods varied between years; hence the availability of this prey item may vary in the area (Raya Rey and Schiavini 2005; Raya Rey et al. 2007b). In line with this assumption, dive duration, bottom time and post-dive intervals were lower compared with other localities except again for the Falkland/Malvinas Island population (Table 2). This could be due either to a higher proportion of other prey items in the diet and/or differences in the foraging areas between locations. It has been shown that Falkland/Malvinas Islands foraging birds spent more time over the Patagonian platform (Pütz et al. 2006b) than birds from Staten Island that may forage over the shelf break (Schiavini and Raya Rey 2004). Foraging activity of birds from Noir Island was probably concentrated over the huge continental shelf in the southeast Pacific Ocean with the colony located 60 km from the shelf slope. Rockhopper penguins from Noir Island dive at a high rate with a great proportion of travelling dives. This resembles the findings of Tremblay and Cherel (2003) among northern rockhopper penguins from Amsterdam Island, and suggests that swarms of *Thysanoessa Gregaria*, an important prey item for the Noir colony (Venegas 1998), occur around the island but are difficult to locate.

Apart from the approx. 158,000 rockhopper penguin breeding pairs, two other penguin species breed sympatrically on Noir Island and thus may compete for the same foraging areas: Macaroni (*E. chrysolophus*) and Magellanic

(*Spheniscus magellanicus*) penguins, with 3,470 and ~35,000 pairs, respectively (Venegas 1998; Oehler et al. 2008). The diet of Magellanic penguins from the study area comprised mainly *S. fuegensis* (Venegas 1998), and the same author speculated that Macaroni penguins consumed mainly *Thysanoessa* spp., both preferred prey species of rockhopper penguins on Noir Island. Therefore, rockhopper penguins from Noir Island may experience high intra- and inter-specific competition especially when breeding duties restrict foraging distance from the colony. Hence, this inter-specific competition could at least partly explain the high proportion of overnight trips and the high percentage of time spent foraging, as was suggested by Schiavini and Raya Rey (2004).

Differences in foraging behaviour related to local oceanographic conditions have been reported in other seabird species or other localities such as cormorants (Grémillet et al. 1998; Kato et al. 2000), gentoo penguins (Lescroëil and Bost 2005) and little penguins (Chiaradia et al. 2007) and, as mentioned before, rockhopper penguins from different colonies (Tremblay and Cherel 2003; Schiavini and Raya Rey 2004; Pütz et al. 2006a). Therefore, habitat utilization by predators is assumed to reflect the quality and availability of resources in an area (Davoren et al. 2003; Laidre et al. 2004) and helps us to understand the marine ecosystem. More information about the foraging ecology of rockhopper penguins from Noir Island is needed to address some of the issues raised as regards intraspecific comparison and interspecific competition.

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