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Maximum diving depths of northern rockhopper penguins (*Eudyptes chrysocome moseleyi*) at Amsterdam Island

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Abstract The mean maximum dive depth from 49 foraging bouts by northern rockhopper penguins, measured using capillary-tube depth gauges, was 66 ± 4 m (12–168 m). There were no differences in the maximum dive depths between male and female penguins. Northern rockhopper penguins dived deeper in early than in late creche stages (83 ± 7 vs 57 ± 4 m), and this was associated with probable dietary changes, squid dominating the diet by mass (44%) in November, and fish (64%) in December 1994 at Amsterdam Island.

Introduction

Crested penguins (genus *Eudyptes*) are the most numerous penguins, both by number of individuals and number of species. Of the six *Eudyptes* species, only the diving behaviour of the largest, the macaroni penguin (*E. chrysolophus*), has been investigated in detail and this at only one locality, South Georgia (Croxall et al. 1988, 1993). No information is available on the foraging behaviour of the other five species of crested penguins, except a report that two individuals of the southern rockhopper penguin (*E. chrysocome*) were capable of dives to ca. 100 m (Cooper and Brown 1990).

The rockhopper penguin is the smallest of the eudyptids and one of the smallest penguins, being larger only than the little penguin (*Eudyptula minor*) (Williams 1995). Three subspecies of rockhopper penguins are currently recognised but, due to differences in behaviour and morphology, there is now a move to split them into two distinct species, the northern (*moseleyi*) and southern (*filholi* and nominate *chrysocome*) rockhopper penguins (Jouventin 1982). Southern rockhopper penguins are primarily considered to be neritic feeders,

preying upon pelagic crustaceans during reproduction (Cooper et al. 1990). The limited information available on the northern rockhopper penguin at Gough Island (40°20'S; 09°54'W) indicates that it preys mainly on crustaceans (> 90% by mass), like its southern relative, while fish and squid are minor components of the diet (Klages et al. 1988). In the Atlantic and Indian Oceans, northern rockhopper penguins breed on volcanic islands devoid of periinsular shelf. They are consequently obligatory oceanic foragers, a unique feature among crested penguins during breeding.

This paper reports the first data on maximum diving depths attained by northern rockhopper penguins while rearing chicks. Sexual and temporal differences in diving depths were investigated in male and female penguins during the early and late creche stages. Stomach contents were also collected during the two periods to investigate the poorly known diet of northern rockhopper penguins at Amsterdam Island (Duroselle and Tollu 1977) and to allow the examination of possible relationships with diving behaviour.

Materials and methods

Fieldwork was carried out at Pointe d'Entrecasteaux (Amsterdam Island; 37°50'S, 77°31'E) during 4–8 November and 5–13 December 1994, when northern rockhopper penguins were rearing medium and large creching chicks, respectively. Adult penguins were fitted with recorders attached to back feathers by means of waterproof adhesive tape and released quickly. Instrumented birds were recaptured upon their return to the colony to feed chicks. Maximum dive depth recorders were essentially the capillary-tube depth gauges described by Burger and Wilson (1988). Each recorder with tape weighed ca. 2 g, i.e. < 0.1% of penguin body mass. Calculation of maximum depths followed the methods of Burger and Wilson (1988). Study penguins were sexed by means of bill measurements (Duroselle and Tollu 1977). Stomach contents were obtained, using a water off-loading technique (Gales 1987), from instrumented and non-instrumented birds caught within the breeding area when they returned ashore after foraging. In the laboratory, samples were weighed and sorted into principal prey components (crustaceans, fish and squid), which were weighed separately. Accumulated items,

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including squid beaks, were excluded from the analysis. Species composition of the food was determined from otoliths and skeletal remains of fish, external features and/or beaks of squid, and exoskeletons of crustaceans. Data were compared for statistically significant differences using Peritz's *F* test. Values are means \pm SE.

Results

Of 148 recorders that were attached, 70 (47%) were recovered and 68 (46%) gave easily readable maximum dive depths. All penguins were recaptured 1 ($n = 30$)–7 ($n = 3$) days after being equipped. There was no significant correlation between time spent at sea and maximum depth reached.

Forty-nine gauges indicated depths deeper than 10 m (Fig. 1). The 19 remaining gauges showed depths of less of 10 m with a mean value of 3.2 ± 0.5 m (0.8–7.8 m). Such low depths were probably reached while penguins bathed and preened at sea in the morning near shore. Two instrumented birds that reached depths of only 0.8 and 1.6 m had only accumulated items in their stomach, and very recent unpublished data using time-depth recorders indicated that maximum diving depths during foraging trips were always below 10 m. The diving depths shallower than 10 m were therefore discarded from the analysis.

The maximum diving depths reached by northern rockhopper penguins during chick rearing ranged from 12 to 168 m ($n = 49$) and averaged 66 ± 4 m. Thirteen birds (27%) dived between 60 and 70 m, six birds dived deeper than 100 m (12%), and one female reached 168 m (Fig. 1). In agreement with other studies using maximum depth recorders (Montague 1985; Whitehead 1989; Seddon and Van Heezik 1990; Scolaro and Suburo 1991; Bost et al. 1994), there was no difference between the overall mean dive depths of males (64 ± 5 m, $n = 26$) and females (66 ± 7 m, $n = 23$). Within the creche period, adult northern rockhopper penguins dived deeper ($P < 0.01$) in November (83 ± 7 m, $n = 17$) than in December (57 ± 4 m, $n = 32$).

Stomach samples collected in November did not differ significantly in mean mass from those collected in December (51 ± 9 g, $n = 9$, and 45 ± 12 g, $n = 12$, respectively). Three prey classes, crustaceans, squid and fish, were important by mass during the two periods (Fig. 2). By number, crustaceans formed the bulk of the prey both in November (98%) and December (94%), but, owing to their larger size, squid dominated the diet by mass in November (44%) and fish in December (64%) (Fig. 2).

There were major differences in the prey species eaten during the two periods. The euphausiids *Thysanoessa gregaria* and *Nematoscelis megalops* accounted for more than 99% of the crustaceans eaten in November and December, respectively. *Mendosoma lineatum* (Latrididae) was the main fish prey in

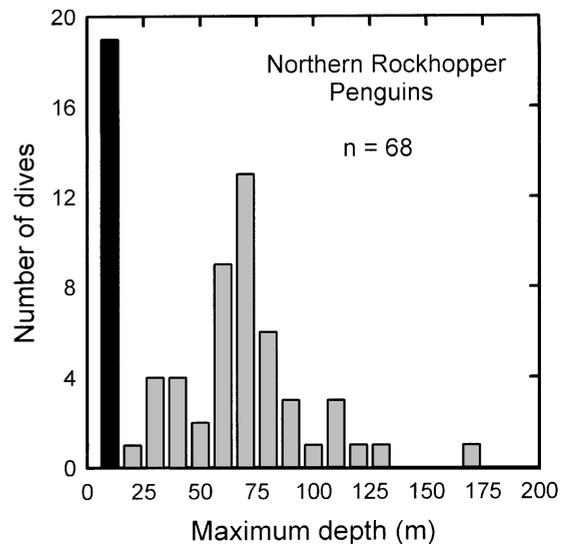


Fig. 1 Frequency distribution of 68 maximum dive depths by northern rockhopper penguins during chick rearing at Amsterdam Island in November/December 1994

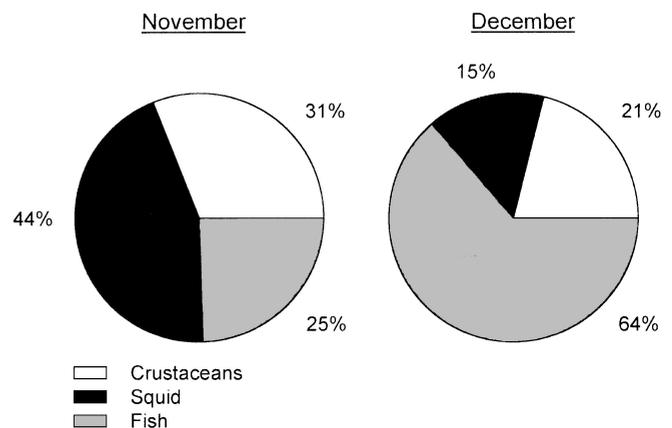


Fig. 2 Proportion by mass of crustacea, squid and fish in the diet of northern rockhopper penguins feeding chicks at Amsterdam Island in November and December 1994 ($n = 9$ and 12 samples, respectively)

November but it was replaced by *Scomberesox saurus* (Scomberesocidae) in December. Ommastrephid squid (probably *Todarodes filippovae*) was the only cephalopod prey identified in November, while numerous very small squids (probably *Brachioteuthis* sp.) dominated the cephalopods consumed by number (90%) in December.

Discussion

Though recorders used in this study only indicated the deepest dives of the foraging trips with no other information on underwater behaviour, they give a first

insight into the diving capabilities of northern rockhopper penguins. From an ecological point of view, the maximum dive depth recorded (168 m) demonstrates that northern rockhopper penguins are able to exploit deep water prey, even if it may represent a rare dive beyond the birds' normal foraging depths.

The diving abilities of penguins are generally related to body mass, larger animals being physiologically capable of longer and deeper dives (Kooyman and Kooyman 1995). Being the second smallest penguin species so far investigated, it is interesting to compare our data to the allometric equation of Wilson (1995), relating maximum diving depth (x) to body mass (y) for penguins ($y = 47.6 + 18.0x$). With a mean body mass of 2.66 kg for males and females combined, the predicted maximum dive is 95 m for northern rockhopper penguins. This value is much lower than maximum depths recorded in this study, where 6 birds (12%) dived deeper than 100 m. The maximum depth of dives is primarily determined by the anaerobic capabilities of swimming muscles (Baldwin 1988). Physiological evidence shows that rockhopper penguin muscles have lower anaerobic capacities than those of emperor, king, Adélie and gentoo penguins, similar capacities to those of the royal penguin (*Eudyptes schlegeli*) but higher capacities than those of the little penguin (Baldwin 1988). Muscle biochemistry appears to reflect, therefore, the maximum diving depths of free-living penguins (Table 1). We can thus predict that the maximum diving depths of some penguin species heavier than the rockhopper penguin are likely to be underestimated. Underestimation of the diving ability results probably from the scarcity of dives performed near the physiological limits. Diving depth is also usually related to prey location in the water column and/or to bottom topography, both commonly occurring at depths shallower than the maximum diving capacity of penguins.

Maximum depths for *Spheniscus* species and Adélie penguins change according to location and time of the year (Whitehead 1989; Wilson and Wilson 1990; Scolaro and Suburo 1991). The most likely explanation for such changes in diving behaviour is differences in the availability of prey. For example, gentoo penguins feeding on pelagic crustaceans or benthic fish exhibit shallow or deep dives, respectively (Croxall et al. 1988), and macaroni and king penguins follow the diel migration of their prey and/or are restricted in their dive depths by light availability (Croxall et al. 1988; Kooyman et al. 1992; Wilson et al. 1993). As demonstrated for Adélie penguins (Whitehead 1989), northern rockhopper penguins reached greater depths at the beginning than at the end of the creche period. Diet analysis indicated that this difference in foraging behaviour was concomitant with a marked shift in prey species.

In November 1994, the main prey of rockhopper penguins at Amsterdam Island were identical to those eaten at Gough Island during three successive November months (Klages et al. 1988). The proportion

Table 1 Maximum diving depths of penguins. (Abbreviations: ADG autoradiographic depth gauges; MDR maximum dive depth recorders; TDR time/depth recorders)

Species	Number of birds	Maximum diving depths (m)	Method	Locality	Reference
King penguin (<i>Aptenodytes patagonicus</i>)	?	323	TDR	Crozet Islands	Pütz in Wilson (1995)
Emperor penguin (<i>Aptenodytes forsteri</i>)	5	534	TDR	Ross Sea, Antarctica	Kooyman and Kooyman (1995)
Gentoo penguin (<i>Pygoscelis papua</i>)	15	210	MDR	Crozet Islands	Bost et al. (1994)
Adélie penguin (<i>Pygoscelis adeliae</i>)	58	175	MDR	Prydz Bay, Antarctica	Whitehead (1989)
Chinstrap penguin (<i>Pygoscelis antarctica</i>)	4	121	TDR	South Shetland Islands	Bengtson et al. (1993)
Southern rockhopper penguin (<i>Eudyptes chrysocome filholi</i>)	2	c100	MDR	Marion Island	Cooper and Brown (1990)
Northern rockhopper penguin (<i>Eudyptes chrysocome moseleyi</i>)	49	168	MDR	Amsterdam Island	This study
Macaroni penguin (<i>Eudyptes chrysolophus</i>)	4	115	TDR	South Georgia	Croxall et al. (1993)
Yellow-eyed penguin (<i>Megadyptes antipodes</i>)	43	56	MDR	New Zealand	Seddou and Van Heezik (1990)
Little penguin (<i>Eudyptula minor</i>)	32	69	MDR	Australia	Montague (1985)
African or jackass penguin (<i>Spheniscus demersus</i>)	15	130	ADG	South Africa	Wilson (1985)
Humboldt penguin (<i>Spheniscus humboldti</i>)	18	80	MDR	Chile	Duffy et al. in Wilson and Wilson (1990)
Magellanic penguin (<i>Spheniscus magellanicus</i>)	63	90	MDR	Argentina	Scolaro and Suburo (1991)

by mass of prey classes, however, differed greatly. Similar to most other localities (Cooper et al. 1990), crustaceans predominated at Gough Island (> 90% by mass), while they accounted for 31% of the diet at Amsterdam Island. The predominance of squid at that time is only comparable to the diet of rockhopper penguins at the Falkland Islands where cephalopods form the bulk of the food (53% by mass) during the brooding period (Croxall et al. 1985).

The complete shift in prey species between early and late creche stages in northern rockhopper penguins at Amsterdam Island appears unique among crested penguins and requires further investigation in subsequent years. With only minor exceptions, all prey eaten by rockhopper penguins are pelagic swarming species (Cooper et al. 1990). Our findings confirm this general trend. The euphausiids *Thysanoessa gregaria* and *Nematocelis megalops* occupy near-surface waters of the Indian Ocean, where they are abundant between 30 and 41°S, and 35 and 40°S, respectively (Brinton and Gopalakrishnan 1973; Casanova 1980), and *Scomberesox saurus* is an epipelagic fish found in the open ocean in cold- to warm-temperate waters between 25 and 40°S at the latitude of Amsterdam Island (Hubbs and Wisner 1980). However, and as previously noted at Macquarie Island (Hindell 1988), rockhopper penguins may also feed on inshore species, indicating that they spend some time foraging close to the breeding colony. The latridid *Mendosoma lineatum* is a typical example of this kind of prey since it is a coastal fish around both Gough and Amsterdam Islands (Duhamel 1989; Andrew et al. 1995).

The dietary shift from the inshore *M. lineatum* to the offshore *S. saurus*, together with the monthly difference in the mean maximum depth reached, are indicative of a change in food and feeding ecology between November and December. A better knowledge of this change necessitates the use of more sophisticated devices, which allow determination of foraging parameters such as the duration, depth and profile of each dive.

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