Antarctic Science 19 (1), 31–38 (2007) © Antarctic Science Ltd Printed in the UK DOI: 10.1017/S0954102007000065

Effects of giant icebergs on two emperor penguin colonies in the Ross Sea, Antarctica

GERALD L. KOOYMAN[1]*, DAVID G. AINLEY[2], GRANT BALLARD[3,4] and PAUL J. PONGANIS[1]

[1]*Scholander Hall, Scripps Institution of Oceanography, La Jolla, CA 92093-0204, USA*
[2] *H.T. Harvey & Associates, San Jose CA 95118, USA*
[3] *PRBO Conservation Science, Bolinas, CA 94924, USA*
4 Behaviour, School of Biological Sciences, University of Auckland, New Zealand
**gkooyman@ucsd.edu*

Abstract: The arrival in January 2001 in the south-west Ross Sea of two giant icebergs, C16 and B15A, subsequently had dramatic affects on two emperor penguin colonies. B15A collided with the north-west tongue of the Ross Ice Shelf at Cape Crozier, Ross Island, in the following months and destroyed the penguins' nesting habitat. The colony totally failed in 2001, and years after, with the icebergs still in place, exhibited reduced production that ranged from 0 to 40% of the 1201 chicks produced in 2000. At Beaufort Island, 70 km NW of Crozier, chick production declined to 6% of the 2000 count by 2004. Collisions with the Ross Ice Shelf at Cape Crozier caused incubating adults to be crushed, trapped in ravines, or to abandon the colony and, since 2001, to occupy poorer habitat. The icebergs separated Beaufort Island from the Ross Sea Polynya, formerly an easy route to feeding and wintering areas. This episode has provided a glimpse of events which have probably occurred infrequently since the West Antarctic Ice Sheet began to retreat 12 000 years ago. The results allow assessment of recovery rates for one colony decimated by both adult and chick mortality, and the other colony by adult abandonment and chick mortality.

Received 3 October 2005, accepted 11 August 2006

Keywords: *Aptenodytes forsteri*, Beaufort Island, B15A, Cape Crozier, Ross Ice Shelf

Introduction

In March, 2000, a giant piece of the Ross Ice Shelf calved and formed the largest iceberg ever recorded from Antarctica. This iceberg, 295 km long and 40 km wide, soon fragmented. The two major parts followed different trajectories. B15B drifted north-west and exited the Ross Sea by May 2001. B15A moved west along the Ross Sea Ice Shelf, and knocked another iceberg, C16, from the shelf; both then lodged near Ross Island (Perkins 2001). B15A was 165 km long, and C16 about 50 km long. Details of these icebergs' initial effects on sea ice distribution, chlorophyll *a* production, and Adélie penguin, *Pygoscelis adéliae* (Hombron & Jacquinot), behaviour are summarized in Arrigo *et al*. (2002). By January 2001, B15A, which had been parallel to the Ross Ice Shelf, began to pivot at its base with the eastern tip swinging to the north. By March the northern tip pointed NNE away from Cape Crozier (Fig. 1), and the southern base filled the embayment between the Ross Ice Shelf and Ross Island. In the process, the promontory of the ice shelf that contains the rifts in which emperor penguins, *Aptenodytes forsteri* (Gray), had established their colony (Kooyman 1993), was broken off (Fig. 2). In this position B15A may have hindered the autumn arrival of many emperor penguins coming from their traditional moulting area in the eastern Ross and Amundsen seas (Kooyman *et al*. 2000). From March onward, a huge collection of iceberg rubble was created by the collisions between berg and shelf. This area remained about the same through January 2005. In addition to the effects on the Cape Crozier habitat, the positions of C16 and B15A most probably blocked the penguins' usual access route to their colony at Beaufort Island, forcing the birds that breed there to approach from the north rather than the east when arriving after their moult, and later interfered with their foraging cycles (Fig. 3).

Here we report the trends in chick counts at Cape Crozier from 1961 to 2004, and for Beaufort Island from 1983–2004. In both cases there are many gaps in the record, especially in the case of Beaufort, because these sites were not part of a formal, long-term annual assessment. However, counts shortly before and after the B15A event help us to appreciate the possible, and, in some cases, unequivocal effects of B15A on the breeding population of emperor penguins in the south-western Ross Sea. These colonies must have dealt with similar events that occurred periodically as the West Antarctic Ice Sheet (which included the Ross Ice Shelf), which once covered most of the Ross Sea, retreated from the last glacial maximum, about 12 000 years ago (Stuiver *et al*. 1981). Only now we have had the opportunity to observe how the penguins respond.

Methods

Ground counts of the Cape Crozier colony were made

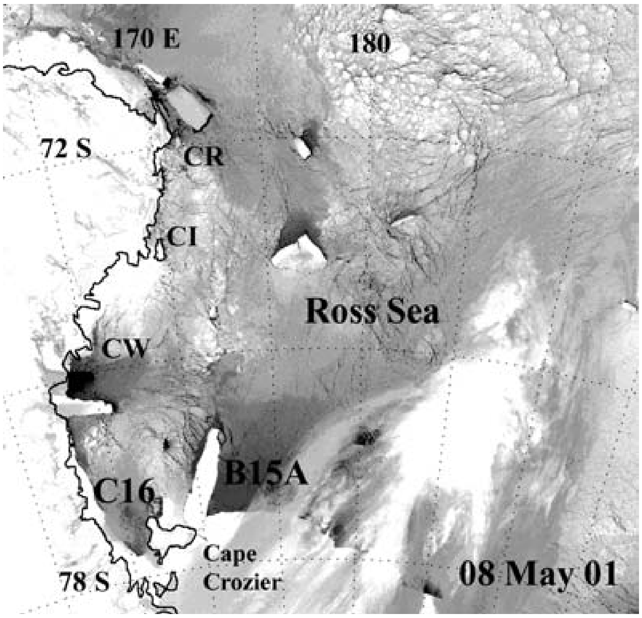

Fig. 1. Satellite image of the Ross Sea taken 8 May 2001. All images are Defense Meteorological Satellite Program (DMSP) 0.6 km resolution, optical line scanner (OLS), infrared imagery. Latitude and longitude lines and labels indicate the scale. Four of the emperor penguin colonies approximate positions are indicated by their abbreviations except Cape Crozier which is spelled out in full. The others are Cape Washington, Coulman Island, and Cape Roget. The major icebergs relevant to this report are B15A, the origin of which was in March 2000 from the Bay of Whales; a location at the northern edge of the Ross Ice Shelf just east of the image boundary. C16 a much smaller iceberg broke away from the ice shelf next to Cape Crozier, and rotated into the position that it still occupies as of May 2005.

during the crèche period, mostly in November or December, beginning in 1961(see Fig. 4 caption). Counts from 2002 to 2005 were made in mid-October, specifically to investigate

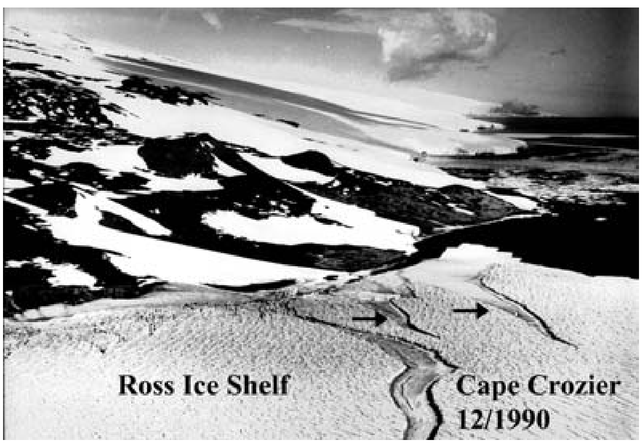

Fig. 2. An aerial photograph taken in December 1990 when the ice rifts were in the traditional configuration before B15A arrived. The arrows point to the usual positions in the rift where the emperor penguin colony resided.

iceberg effects. At this time of year adults would normally be guarding very small chicks. In 2002 ground counts were done in duplicate by two investigators. When there was agreement within 10%, the average was accepted as final. In 2003–2005 aerial photographs were taken and counts derived from both the aerial photographs and ground counts. At Beaufort Island, ground counts were made in 2000 and 2001; counts in 2002–2005 were based on aerial photographs.

In 2001, the first visit to Cape Crozier was on 3 November. Offshore conditions in the area of the usual emperor penguin colony were highly disrupted with numerous icebergs and considerable ice rubble piled as high as 15 m (Fig. 5). On top of some of the icebergs we found evidence of emperor penguin incubation sites. On 23 November, another visit was made to collect carcasses for more detailed analyses, and to search for other sites. In late November through December the largest incubation site was discovered near the more traditional breeding area. All adults were frozen into ice that had been pressured into a dome and cracked, trapping the birds. Only skin samples were collected for gender determination (Avian Biotech International).

Over the next four years annual visits were made. There was usually an early, short visit in October, and a more extended visit from mid-November to beyond the fledging time in late December.

Aerial photographs used to determine habitat, colony location, and bird counts were taken on 19 November 2000 and 22 November 2001 at Beaufort Island, and 23 November 2001 at Cape Crozier with a N90 Nikon, 35mm camera with a 80–200 mm, f2.8 zoom lens using Kodak TMY black and white film. The photographs were then scanned and counts were made using Adobe Photoshop 6.0. All aerial photographs were taken from an A-Star helicopter at an oblique angle and an altitude of 460 m. Digital aerial photographs were taken 26 August 2002 with a Nikon D1H and Nikkor 80–200 mm f2.8 zoom lens, and shot at a focal length of 200 mm. The images were near vertical taken at 3050 m from a Boeing C17 aircraft, at 1500 local time.

In 2002 the images taken at Beaufort Island were acquired with a Nikon D1X and Nikkor 80–400 mm f4.5~5.6 image stabilizing zoom lens from an A-Star helicopter at an altitude of 700 m. In 2003 a similar image was shot with a Canon EOS 10D, 100–400 mm IS f4.5~5.6 zoom lens, from a Twin Otter at an altitude of 460 m. In 2004 images were shot with a Nikon D70, Nikkor 80–200 mm f2.8 zoom lens from a Twin Otter at 610 m, and in the final year of 2005 images of both Cape Crozier and Beaufort Island were shot with the system used in 2003.

Results

Cape Crozier

The colony declined in size from the 1960s through the

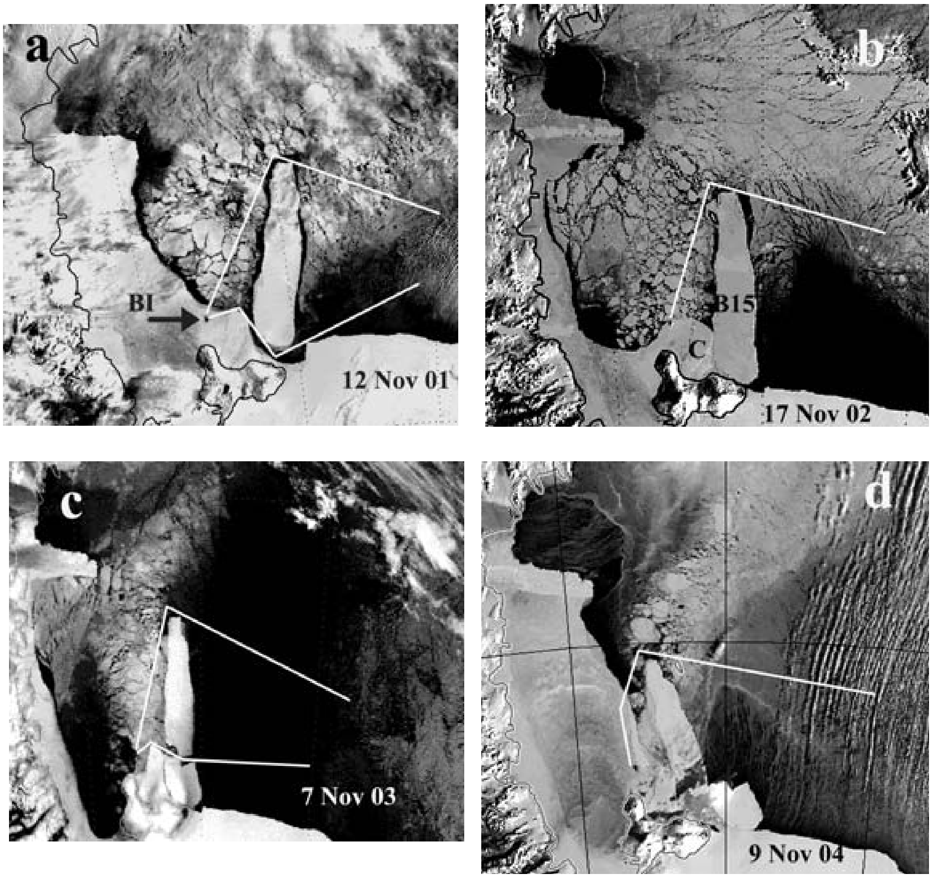

Fig. 3. Proposed foraging route to and from Beaufort Island by adult birds in October and November during the period of maximum growth rate of the chicks. **a.** proposes that there were two possible routes to reach eastern foraging areas. Also, in late March B15 was against Cape Crozier and there was probably no southern route to the east. **b.** Shows that C16 (C) and B15 were against the shoreline and blocked passage to the east from Beaufort Island. **c.** shows the widening separation between B15 and the newly formed iceberg B15J. The white lines indicate possible routes to the east of B15. Also, noteworthy is that the area to the east is free of pack ice. **d.** shows that again, the icebergs prevented a southern route to the east of the icebergs. In addition, there was extensive fast ice to the north that may have forced the birds to walk about 90 km before being able to enter the water.

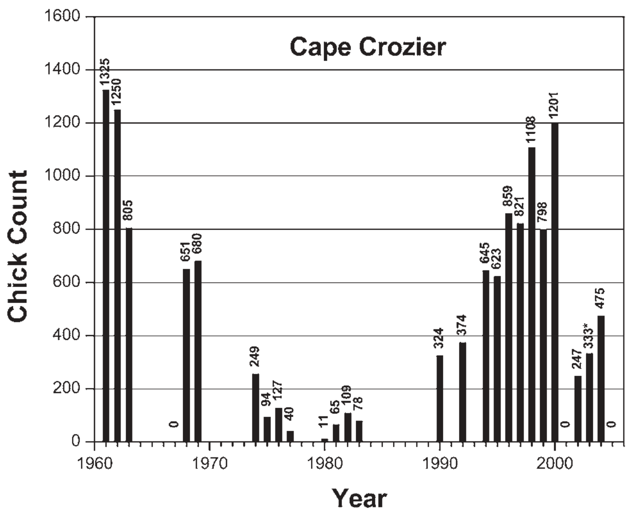

Fig. 4. Population histogram of Cape Crozier chick counts from 1961 to 2004. Numbers over each bar indicate the exact counts. Years with a zero indicate a total failure of any chicks to fledge. A count was not obtained for years with no numbers. Counts from 1961–1963 (Stonehouse 1964); counts from 1969–1975 (Ainley *et al*. 1978); counts for 1976 & 1977 (Todd 1980); counts for 1980–1983 were Ainley cited in Kooyman & Mullins (1990), counts for 1990–2004 this study. *Based on brooding adult count.

1980s. In the 1990s the colony began to increase in size, reaching a maximum fledging number of 1201 chicks in 2000 (Fig. 4). During the same period, owing to growth of the western portion of the Ross Ice Shelf (Keys *et al*. 1998), the colony location gradually shifted north-westward along the Crozier cliffs from south to north of the Cape, and also shifted offshore of the cliffs 100–200 m, owing to a broadening of the area covered by fast ice. In most years when there had been total failure or very low counts, mortality was limited mostly to chicks, and the causes usually related to uncompromising habitat, such as colony

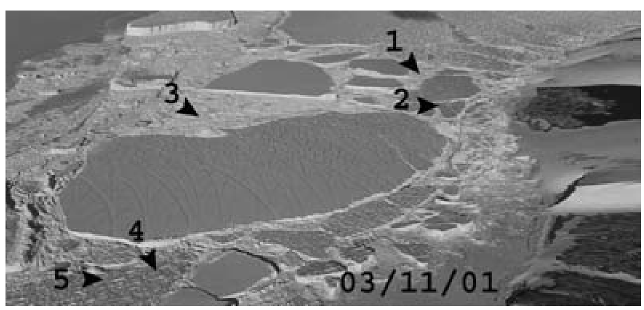

Fig. 5. This aerial photograph shows the breeding group distribution at Cape Crozier in 2001. Carcasses, chicks, and/or eggs indicated by darts with numbers were incubation sites. For scale site 1 was 408 m by GPS positioning from site 2.

Table I. Body and organ masses, and sex of emperor penguins found at Cape Crozier in 2001 compared to carcasses found at Cape Washington. Cause of death in the Cape Washington birds was unknown. Date of find indicated in adjacent column. Ratio bottom row.

Bird Identification		Sex	Remarks			
Cape Crozier (G1 and nearby; 12 eggs, 2 chicks)						
1		M	2001, emaciated			
2		M	2001, emaciated			
3		F	2001, emaciated			
4		M	2001, emaciated			
5		M	Adjacent to G1; present in 2001, found in 2002			
6		M	Between G1 and G2; present 2001, found in 2002			
7		M	Against 6, found in 2002			
Cape Crozier (G2–G4)			Body (kg)	Breast (kg)	Leg (kg)	Liver (kg)
(G2, 2 eggs, 2 chicks)						
A		F	10.5	1.27	0.54	0.17
B		F	12.5	2.28	0.66	0.28
C			13.0			
D		F	11.3	2.13	0.66	0.19
E		F	11.0	1.75	0.60	0.16
8		F	Next to G2; found in 2002			
9		F	Next to 8; found in 2002			
(G3, 2 eggs)		F	11.4			
(G4, 3 eggs)			11.0			
Average			11.5			
Cape Washington						
A	1986	M	22.0	5.2	0.41	
B	1986	F	23.5	6.5	1.22	
C	1989	?	21.9	5.1	1.42	
D	1990	M	21.5	5.8	1.54	0.46
E	1993	?	22.0	6.5	1.20	0.46
Cape Crozier/Cape Washington			.51	.32	.46	.45

sea ice disintegration before fledging. In 1976 there was high mortality of adults and chicks. Avalanches from the cliffs killed the adults, and the death of the chicks was from unknown causes (Todd 1980).

2001

Few eggs hatched and no chicks survived. Seven adult corpses (Table I), with two dead hatchlings and 12 frozen eggs were atop a 10 m high jumbled, sea ice pressure ridge (G1 in Fig. 5), or nearby the location at 77°27.597'S, 169°18.648'E which was in the conventional pre-2001 colony location within a rift of the Ross Ice Shelf. We noted that the frozen adult birds appeared to have been trapped in the cracks and were found in various postures from standing upright and waist deep in the crack, to prone and partially buried under plates of broken ice. The gender of these birds was one female and six males (Table I). The other carcasses were among three other small, guano-stained areas in the vicinity.

For all these sites there was a total of four small, dead chicks, 19 frozen eggs and 18 dead adults, for two of which there are no data and no entry in Table I. Five adult corpses, plus two dead hatchlings and two frozen eggs were on a single, 10 m diameter guano patch (G2) atop the largest iceberg (77°27.529'S; 169°17.687'E), which broke off from the adjacent Ross Ice Shelf (Fig. 5). Based on the size of the guano stain and presence of eggs, we assumed the area represented an incubation site. One adult corpse was found on top of a crushed egg.

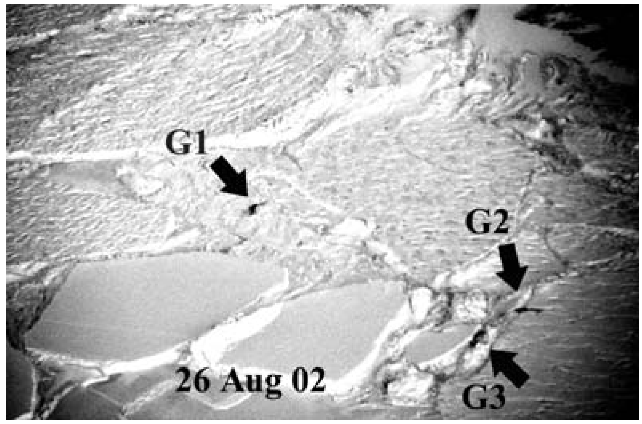

Fig. 6. Late winter aerial photograph taken on 26 August 2002. Emperor penguin groups are visible as dark spots on the ice. G1 is on multi-year ice near the pre-B15A breeding location. G2 is on shelf ice. G3 is between two plates of shelf ice in a canyon about 15 m deep. For scale G1 was 278 m from G2.

All dissected adult carcasses from G2 and G3 were female, and all were extremely emaciated. Seven birds, weighed in the field, ranged from 10.5 to 13 kg. The breast muscles of four ranged from 1.27 to 2.28 kg. In the lab, body masses of these birds agreed with their masses measured previously in the colony. None of these birds had any subcutaneous or other body fat. By comparison they were 51% of the body mass of carcasses found at Cape Washington, which had died of causes other than starvation (Table I). Breast and leg muscles were 32% and 46%, respectively, of the Cape Washington carcasses. Breastbone, hips and shoulders were clearly visible through their coats. Lyophilization of muscle samples (pectoralis and supracoracoideus) from the carcasses demonstrated water content of 74 to 79%. These values are greater than the 68% water content of breeding emperors (Groscolas 1990); therefore, there was no evidence of desiccation of the carcasses. The greater muscle water content of the carcasses may have been secondary to fat and protein depletion in muscle due to starvation; however, no lipid content analysis of muscle samples was conducted.

2002

Birds were again dispersed into four groups, and the main group (G2) was atop an iceberg 303 m from where G2 was the previous year (Figs 5 & 6). The chick count totalled 247, or 21% of the 1201 chicks that fledged in 2000 (Fig. 4).

From the aerial images taken 26 August 2002 (Fig. 5), the two largest groups appeared to be G2 and G3. G1 was on very rough multi-year sea ice. It was not far from G1 location in 2001 (Fig. 5). G1 had 82 chicks and 75 adults. There were 14 dead chicks. Although the chicks were small, many were without brooding adults. The condition of most of the chicks was poor compared to those at G2. On 18 October we estimated that there were 132 live chicks present and 312 adults. Most chicks were being brooded by an adult. G3 on 26 August was about 100 m seaward from G2 in a deep canyon (Fig. 6). The size of the stained ice suggests that it was about equal in size to G2. During 15–19 October, we were unable to locate this group, or the canyon in which it occurred. Iceberg movement had obliterated the canyon. By mid-October a remnant of G3 may have been represented by a small group on sea ice next to the berg occupied by G2. Here we found four chicks and 84 adults. If most of the birds were trapped, then the continued ice instability added to the presumed adult losses of 2001. Evidence of trapping was the presence of a dead adult near the top of ice rubble at the seam between the two icebergs. About 1 km north of G2, and beyond the tip of the large shelf plate, was G4 (not shown in Fig. 6). The birds were on smooth sea ice under cliffs that put them in the lee of any wind from the shelf, or katabatics from Mount Terror. At G4 there were 29 chicks, seven dead chicks, two eggs and 172 adults. Adults attended most of the chicks.

2003

The colony had coalesced into a single group occupying the same area as G2 of 2002. This site on top of the iceberg was exposed to strong winds. Considering the rough ice conditions throughout the area this was the only option for the birds. The group was inaccessible from the shore because of deep and unstable ice canyons. From ground photographs taken 19 October, about 100 m from the group, we were able to count 333 adults. We presume from the posture and close distribution of the adults that most were either brooding or standing next to chicks, but the chicks were obscured. We assume an estimate of 333 chicks, however, this results in a lower ratio of chicks to adults than observed in 2002. In December, the iceberg they occupied split in half and broke free from the fast ice, leaving most of the chicks isolated from their parents by a 10 m ice cliff. It is likely that few chicks successfully fledged this season; most chicks were probably smaller than average. Three chicks, which were accessible, weighed < 6 kg (range 4795–5750 g) on 16 December, far lighter than the 12 kg expected this close to fledging.

2004

By the end of the 2003–2004 season much of the ice rubble from the past three years had disappeared, providing relatively easy access to sheltered fast ice near the 1990 location (Fig. 2). By that time B15A had also split to form B15A and J, the former moving away. B15J, about a third the size of the former B15A, continued to rotate in place off Cape Crozier, occasionally colliding with the ice shelf and Ross Island, creating jumbled conditions on a smaller scale than 2001–2004. Total number of 475 chicks was 40% of the count in 2000 (Fig. 4).

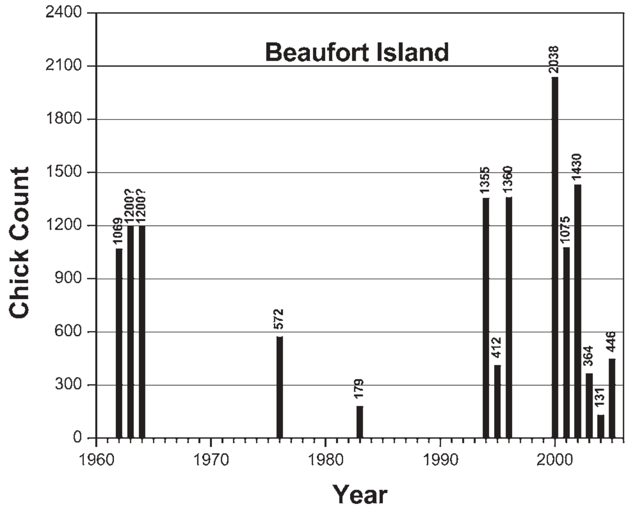

Fig. 7. Population histogram of Beaufort Island chick counts from 1983 to 2004. Counts for 1962 and estimates for 1963 & 1964 Stonehouse (1966), count for 1976 and >1115 carcasses from Todd (1980), count for 1983 Kooyman & Mullins (1990), counts from 1994–2004 ground or aerial surveys by GK & PP.

2005

On 17 October there were 147 adults in close assembly at the base of the Ross Ice Shelf on annual sea ice, and close to the position where they had bred in 2004. There was no sign of breeding; no abandoned eggs, no dead chicks, and no live chicks. The level of stain in the area indicated that birds had been present for some time. Along the route to the sea ice edge and adjacent to the shelf there were another 126 adults. The birds had failed to breed, and just over a month after our visit there were no adults present.

Beaufort Island

This colony was discovered 5 November 1956 by a passing ship, and Stonehouse summarized the early history (1966). On 6 December 1962 aerial photographs were taken, and used to estimate a chick population of 1069 (Fig. 7). Photographs taken in November 1963 and 1964 showed a similar size colony, indicating a breeding population of 1200–1500 pairs (Stonehouse 1966). The first ground visit was in 1976 by Frank Todd (1980), who counted 572 live chicks and > 1115 carcasses. No more aerial photographs were obtained until 1983 when USGS photographed all Ross Sea colonies except Cape Crozier (Kooyman & Mullins 1990). As a result of the unusual extent of fast ice, allowing helicopter flights to Beaufort Island, ground counts were obtained in 1994–1996. Such conditions in 2000–2004 also allowed aerial photography and sometimes ground counts as well.

2000
The colony on Beaufort Island was divided into three groups, each separated by about 300 m and running out from shore in a south-east direction. There were 2038 chicks counted from the aerial photographs of 19 November.

2001
On 22 November the colony was divided into three groups. There were a total 1065 chicks counted from the ground; 52% of 2000 (Fig. 7). There were also 410 dead chicks, all at an early age, spread across the original incubation site.

2002
On 24 October the single group was photographed from the air. There were 1430 chicks; 70% of the count in 2000. The chick count suggests that the birds persisted in breeding at the site, despite the possible extended detour around the iceberg to reach foraging areas (Fig. 3b). However, if the count had been made on 22 November, similar to the previous year, there may have been similar numbers of dead chicks.

2003
On 30 October a single group was photographed from the air. There was no surface visit. There were 364 chicks or 18% of the count in 2000 (Fig. 7). Noteworthy is the fact that B15A had broken to form B15A and B15J, and there was a possible channel to the east between the pieces (Fig. 3c).

2004
On 25 October the single group was several kilometres to the east of the island and in the lee of iceberg B15K, a recent calving product of B15A (Fig. 3d). There were 360 dead chicks that formed a trail from the island to the colony. In most cases the chicks were more developed than those dead chicks observed in 2001. The live chick count of only 131 was an all time low for this colony; 6% of the count in 2000 (Fig. 7).

2005
A ground visit was made on 12 October. Aerial photographs were used to obtain the count of 446 chicks. Surface conditions were ideal, with extensive smooth annual sea ice. The birds were in the lee of an iceberg due east about 1 km from the traditional breeding site next to the island. There were no large bergs blocking access to the eastern foraging area, and the ice edge was about 20 km to the east. Sixty dead chicks and four eggs were found.

Discussion

Historical trends in the Crozier colony

When the colony was first visited by Edward Wilson, Apsley Cherry-Garrard and Henry (Birdie) Bowers in the winter of 1911, these adventurers camped at what is now called Igloo Spur (Cherry-Garrard 1922). In 1911, as during the years from 1961 to 1996, the colony was situated on the fast ice that formed between rifts in the Ross Ice Shelf (West Antarctic Ice Sheet) (Fig.2). These rifts, hundreds of metres wide at the cliffs and a few kilometres long, formed as the moving ice shelf forced itself around Cape Crozier until it was released from the pressure of the collision, allowing cracks to expand. As a result of Ice Shelf growth (see Keys *et al*. 1998), its Ross Sea front gradually moved north during the late 20th century. The emperor penguin colony shifted with it. During the 1960s the colony was offshore from the Crozier cliffs, just north of Cape Crozier (as in 1911). By the early 1970s, the rifts had disappeared or diminished in size and the colony was close to or against the cliffs, about 3 km south of the portion of the Adélie penguin colony known as East Crozier (see figure 3.3B in Ainley 2002); by the 1980s and early 1990s it was within a few hundred metres of East Crozier. By the late 1990s it was located on the fast ice offshore and to the north of East Crozier. Thus, since 1911, the location of the colony has shifted about 7 km. Owing to the over-riding effect of the ice shelf on colony characteristics, the colony's recent history does not compare to that of other Antarctic colonies (Ainley *et al*. 2005). The 1970s and 1980s were bad times for the Crozier colony, mostly due to its dangerous location under the Ross Island cliffs, where rock avalanches are frequent and adult and chick mortality were high as described by Todd (1980). When access was particularly difficult the penguins nested on fast ice along the Ice Front, a position subjecting them to blow-out of the ice and colony long before chicks were ready to fledge. Probably owing to increased stability of the fast ice, due to the growing ice shelf, and resulting increased breeding success, the colony regained its 1960s numbers by 2000. What size it was in any year prior to 1960 is unknown.

Cape Crozier, the iceberg years

In January 2001 C16 and B15A arrived and grounded to the west of Cape Crozier. By March the long axis of the icebergs, rotated from an east to west orientation to a north to south orientation as they moved into the Lewis and Cape Crozier embayments, respectively. This was a month or so before emperor penguins arrived to begin their pre-nuptial pairing. For the following four years conditions created by these bergs have made life difficult for breeding emperor penguins. In 2003 B15J formed from a split of the lower third of B15A, and remained in the area until 2006. During the repeated collisions of B15A with Cape Crozier, especially in 2001, sea ice was ground to small bits and pushed ahead as a moraine-like wall. This continued through the winter, and what we found in October 2001 was a chaotic jumble of ice rubble, numerous smaller icebergs lining the shelf edge 200 m from shore, and B15A a few kilometres offshore. It is unusual to find more than one or two dead adults in an emperor penguin colony. We found 18, for 16 of which we obtained data (Table I), in this relatively small colony, with the likelihood that many more were buried under ice rubble, or in cracks between icebergs. The few adults that survived or remained probably formed small huddles, among the constantly shifting ice

Of the seven adult carcasses at or near G1 six were males, one was a female (Table I), and two were not identified by gender. The birds at G1 were emaciated, but may have been killed by trauma resulting from shifting and heaving of the sea ice. The nine carcasses found away from G1 (Fig. 5), the traditional breeding site, seven were females and the gender for two were not determined. All appeared to have starved to death (Table I). After laying the egg, the typical female departs the colony with a body mass of about 25 kg (Kirkwood & Robertson 1997, Wienecke & Robertson 1997). The critical body mass, that weight at which most if not all body fat is exhausted, occurs between 20 to 22.5 kg (Le Maho *et al*. 1976). After moult, another stressful fasting period for emperor penguins, their average body mass is 19.6 to 20.5 kg (Groscolas 1978, Kooyman *et al*. 2004), and the lowest weight recorded was 16.5 kg (Kooyman *et al*. 2004). All of these weights, from post-laying to post-moult hover around this critical body mass, but are seldom below the threshold where protein catabolism becomes the major source of energy. Yet, the dead females at Cape Crozier had reached a mass of nearly half that critical mass. The disruption near the time of laying may have flushed the males, which broke with the tradition of assuming all incubation responsibility, and deserted before the females laid the egg. With no male to take the egg, these few females may have remained to incubate their eggs. This is a common response in Adélie penguins, when males do not have the resources to incubate first (Ainley 2002). These exposed sites selected for laying, the lack of large groups in which to huddle for warmth, and the smaller fat store of the female resulted in starvation before or soon after hatching. Finding these starved females is especially noteworthy because death by starvation has never been observed in the Pointe Géologie colony (Groscolas & Robin 2001), which has been intensively and continuously studied throughout all seasons since the late 1950s. Only two dead adults out of 20 found in the spring seasons from 1986 to 1996 at the Cape Washington colony appeared to have died from starvation (GK, personal observation). One of these was trapped under a plate of ice that probably collapsed while it was sleeping beneath it. Trapped and unable to forage the bird died of starvation.

Over the four years since 2001 the number of chicks produced has ranged from 0 to 40% of the chick production in 2000. Despite the disturbance to the colony, and return of incubation habitat to the poor quality exhibited in the 1970s, some birds have shown determination to reproduce in this area. Perseverance was rewarded as the area returned not to ideal, but at least more suitable conditions in 2004. The large iceberg on which incubation had occurred for the largest group (G2) during 2002 and 2003 had disappeared, and once again the birds were nesting on fast ice near the snowdrifts and cliffs of Ross Island. Chick production was 475 chicks, or 40% of pre-berg year of 2000. However, on 16 October 2005, the year of our most recent survey, there were 273 adults present, but no sign of any attempt to breed. We conclude that there was high mortality of adults at Cape Crozier in 2001, and that is partly why the colony remains well below pre-2000 levels. Another reason is because habitat conditions remain marginal, and lack of an attempt to breed in 2005 highlights this situation. Indeed, many older birds and some recruits may be looking for better conditions before committing again to breeding at Cape Crozier.

Beaufort Island, the iceberg years

There are few historical data to describe the size or conditions of the Beaufort Island colony. In recent years, while Cape Crozier habitat was being destroyed by B15A, the extended northern body of that iceberg, along with C16, created a 150 km barrier between Beaufort Island and the Ross Sea Polynya to the east (see Massom *et al*. 1998, for correspondence of emperor penguin colonies and polynyas). For the next two years until late October 2003, these icebergs, and a fragment of B15A called B15K, formed an impassable barrier for birds returning from their moult area in the eastern Ross and Amundsen seas (Fig. 3). The course deviation caused by the presence of C16 and B15A, and later B15A and J, resulted in a substantial decrease in the number of breeding birds at this colony from 2001 to 2005. In addition, the confirmed large mortality of chicks in 2001 and 2004 indicate poor foraging conditions. We conclude that the low chick counts and the large number of dead chicks is evidence that many adults have chosen either not to breed or to go elsewhere.

Overall these large bergs changed current flow (Arrigo *et al*. 2002), sea ice and fast ice distribution, and routes of access to the colonies and the foraging areas. All seem to be negative effects, but in the face of this adversity the colonies have persisted. In the future Beaufort Island will continue as a moderate size colony, limited by the small space available on the fast ice plate next to the island (Kooyman & Mullins 1990). Cape Crozier will continue as a small colony marked by high variability in breeding success because of the frequently changing habitat. Even in the best of times the sea ice breeding area is very limited and offers little potential for population expansion.

Acknowledgements

This work was supported by NSF grants OPP 98-14794, 02-29638 and 02-24957 to PP, 0001450 to GK, and grants 9526865, 9814882 and 0125608 to DGA and GB. We are grateful to all those at NSF that helped make this work possible, those at Raytheon Antarctic Support Services for all the field support, Kenn Borek Air and Petroleum Helicopters International for air support. Those that assisted in the field were vital to the project. They were: L. Blight, J. Blum, R. Davis, M. Hester, G. Marshall, C. McCreedy, R. Orben, K. Ponganis, B. Saenz, P. Thorson, V. Toniolo and R. Van Dam. Mention of trade names does not indicate product endorsement. Finally, we are grateful for the reviews of Y. LeMaho and G. Robertson. PRBO contribution #1517.

References

Ainley, D.G. 2002. *The Adélie penguin: bellwether of climate change*. New York: Columbia University Press, 310 pp.

Ainley, D.G., Wood, R.C. & Sladen, W.J.L. 1978. Bird life at Cape Crozier, Ross Island. *The Wilson Bulletin*, **90**, 492–510.

Ainley, D.G., Clarke, E.D., Arrigo, K., Fraser, W.R., Kato, A., Barton, K.J. & Wilson, P.R. 2005. Decadal-scale changes in the climate and biota of the Pacific sector of the Southern Ocean, 1950s to the 1990s. *Antarctic Science*, **17**, 171–182.

Arrigo, K.R., van Dijken, G.L., Ainley, D.G., Fahenstock, M.A. & Markus, T. 2002. Ecological impact of a large Antarctic iceberg. *Geophysical Research Letters*, **29**, 10.1029/2001GL014160.

Cherry-Garrard, A. 1922. *The Worst Journey in the World, Antarctic 1910–1913*. London: Constable, 585 pp.

Groscolas, R. 1978. Study of moult fasting followed by an experimental forced fasting in the emperor penguin *Aptenodytes forsteri*: relationship between feather growth, body weight loss, body temperature and plasma fuel levels. *Comparative Biochemistry and Physiology*, **61A**, 287–295.

Groscolas, R. 1990. Metabolic adaptations to fasting in emperor and king penguins. *In* Davis, L.S. & Darby, J.T., *eds. Penguin biology*. San Diego, CA: Academic Press, 269–296.

Groscolas, R. & Robin, J.-P. 2001. Long-term fasting and re-feeding in penguins. *Comparative Biochemistry and Physiology*, **128**, 645–655.

Keys, H.J.R., Jacobs, S.S. & Brigham, L.W. 1998. Continued northward expansion of the Ross Ice Shelf, Antarctica. *Annals of Glaciology*, **27**, 93–98.

Kirkwood, R. & Robertson, G. 1997. The foraging ecology of female emperor penguins in winter. *Ecological Monographs*, **67**, 155–176.

Kooyman, G.L. 1993. Breeding habitats of emperor penguins in the western Ross Sea. *Antarctic Science*, **5**, 143–148.

Kooyman, G.L. & Mullins, J. 1990. Ross Sea emperor penguin breeding populations estimated by aerial photography. *In* Kerry, K.R. & Hempel, G., *eds*. *Antarctic ecosystems, ecological change and conservation*. Hobart: Springer, 169–176.

Kooyman, G., Hunke, E., Ackeley, S., van Dam, R. & Robertson, G. 2000. Moult of the emperor penguin: travel, location, and habitat selection. *Marine Ecology Progress Series*, **204**, 269–277.

Kooyman, G.L., Siniff, D., Stirling, I. & Bengtson, J. 2004. Moult habitat, pre- and post-moult diet and post-moult travel of Ross Sea emperor penguins. *Marine Ecology Progress Series*, **267**, 281–90.

Le Maho, Y., Delclitte, P. & Chatonnet, J. 1976. Thermoregulation in fasting emperor penguins under natural conditions. *American Journal of Physiology*, **231**, 913–922.

Massom, R.A., Harris, P.T., Michael, K.J. & Potter, M.J. 1998. The distribution and formative processes of latent-heat polynyas in East Antarctica. *Annals of Glaciology*, **27**, 420–426.

Perkins, S. 2001. Big bergs ahoy! An armada of ice sets sail for the new millennium. *Science News*, **159**, 298–300.

Stonehouse, B. 1964. Emperor penguins at Cape Crozier. *Nature*, **203**, 849–851.

Stonehouse, B. 1966. Emperor penguin colony at Beaufort Island, Ross Sea, Antarctica. *Nature*, **216**, 925–926.

Stuiver, M., Denton, G.H., Hughes, T. & Fastook, J.L. 1981. History of the marine ice sheet in West Antarctica during the last glaciation: a working hypothesis. *In* Denton, G.H. & Hughes, T., *eds*. *The last great ice sheets*. New York: Wiley, 319–369.

Todd, F.S. 1980. Factors influencing emperor penguin mortality at Cape Crozier and Beaufort Island, Antarctica. *Gerfaut*, **70**, 37–49.

Wienecke, B.C. & Robertson, G. 1997. Foraging space of emperor penguins *Aptenodytes forsteri* in Antarctic shelf waters in winter. *Marine Ecology Progress Series*, **159**, 249–263.