

Trends in western Ross Sea emperor penguin chick abundances and their relationships to climate

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Abstract: The emperor penguin (*Aptenodytes forsteri*) is extremely dependent on the extent and stability of sea ice, which may make the species particularly susceptible to environmental change. In order to appraise the stability of the emperor penguin populations at six colonies in the western Ross Sea, we used linear regression analysis to evaluate chick abundance trends (1983–2005) and Pearson's r correlation to assess their relation to two local and two large-scale climate variables. We detected only one significant abundance trend; the Cape Roget colony increased from 1983 to 1996 ($n = 6$). Higher coefficients of variation in chick abundances at smaller colonies (Cape Crozier, Beaufort Island, Franklin Island) suggest that such colonies occupy marginal habitat, and are more susceptible to environmental change. We determined chick abundance to be most often correlated with local Ross Sea climate variables (sea ice extent and sea surface temperature), but not in consistent patterns across the colonies. We propose that chick abundance is most impacted by fine scale sea ice extent and local weather events, which are best evaluated by on-site assessments. We did not find sufficient evidence to reject the hypothesis that the overall emperor penguin population in the Ross Sea was stable during this period.

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Introduction

Understanding the relationship between climate variables and emperor penguin (*Aptenodytes forsteri*, Gray 1844) biology may help predict the consequences of environmental shifts for emperor penguin breeding populations. Because emperor penguins are dispersed throughout the Antarctic seasonal pack ice zone, are colonial, probably have high site fidelity, and are long-lived animals, their breeding success as well as adult mortality may be susceptible to both short and long-term changes in pack ice, fast ice, and prey species distribution and abundance (Ainley 1983, Ancel *et al.* 1992). All of these factors may be influenced by global climate change (Barbraud & Weimerskirch 2001, Croxall *et al.* 2002, Weimerskirch *et al.* 2003, Kato *et al.* 2004).

Several studies have shown emperor penguin population parameters are related to both local and large-scale climate variables (Barbraud & Weimerskirch 2001, Jenouvrier *et al.* 2005a, 2005b). However, these studies were conducted in an Antarctic region (Pointe Géologie, Terre Adélie) subject to different weather patterns from those in the Ross Sea (Stammerjohn & Smith 1997, Yuan & Martinson 2000, Doran *et al.* 2002, Kwok & Comiso 2002, Zwally *et al.* 2002, Parkinson 2004). Therefore, dissimilar population trends may be occurring in the Ross Sea emperor penguin colonies. In fact, regions of the Ross Sea appear to be slightly cooling and sea ice extent increasing (Stammerjohn & Smith 1997, Yuan &

Martinson 2000, Doran *et al.* 2002, Kwok & Comiso 2002, Zwally *et al.* 2002, Parkinson 2004), while large increases in ice shelf melting, surface air temperature, and winter troposphere temperatures have been observed elsewhere in Antarctica (Murphy *et al.* 1995, Smith *et al.* 1998, Vaughan *et al.* 2001, Curran *et al.* 2003, Turner *et al.* 2006). In addition, the Pointe Géologie (Terre Adélie) colony is both small and relatively isolated with no other colonies nearby. In contrast, the colonies of the western Ross Sea occur on average about 100 km from each other in a region with one of the highest densities of emperor penguins in Antarctica, and represent the largest, smallest, and most southerly of all emperor penguin colonies. For present and future comparisons we investigated trends in western Ross Sea chick abundances, and evaluated their relationship to two local and two large-scale climate variables.

Methods

Our study area included six emperor penguin colonies located in the western Ross Sea at $c.$ 165–171°E, 71–78°S. From south to north the colonies were: Cape Crozier, Beaufort Island, Franklin Island, Cape Washington, Coulman Island, and Cape Roget (Fig. 1). Aerial photos from fixed wing aircraft and/or ground counts were used to determine live chick abundance during October–December

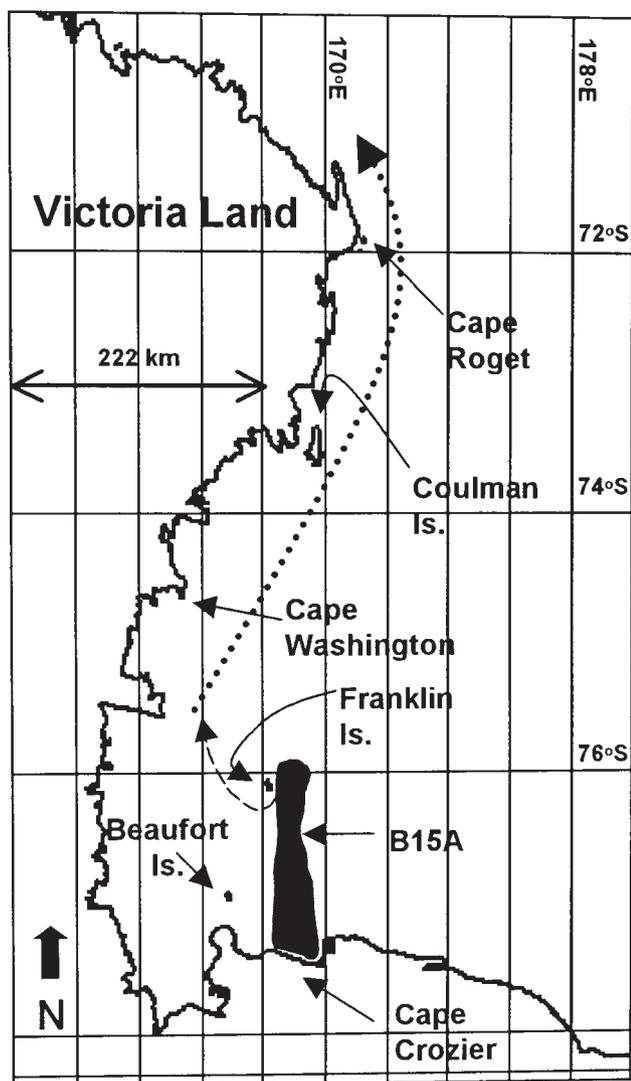


Fig. 1. Locations of six emperor penguin colonies in the western Ross Sea. Arrows represent the approximate location of each colony. Iceberg B15A is shown as solid black in its 2001–03 location. Subsequently, the lower third of the iceberg broke off and the rest travelled (dashed line) just south of Franklin Island and then north during 2004 and continued north (dotted line) during 2005.

from 1983–2005 (see Kooyman & Mullins 1990, Kooyman 1993, Kooyman *et al.* 2007 for census details). During ground counts we generally used two observers to count each group and used the mean of the two counts. If the counts differed by more than 10% we repeated the counts whenever possible. We elevated our observation point when possible by using existing topographic relief such as the large bluff at Cape Washington or by standing on our snowmachines while they were parked on hummocks. With the exception of Cape Washington during 2001, 2003 and 2005, and Cape Crozier, we obtained all counts after 2000 from aerial photographs. We did not conduct surveys every

year and we did not survey all colonies equally because of limitations of air support and weather. We used simple linear regression to examine chick abundance trends over time (Micol & Jouventin 2001, Kato *et al.* 2004). We analysed each colony separately because of unequal survey effort.

We investigated the relationship between chick abundance during 1983–2005 and climate variables using Pearson's coefficient r . We used two local Ross Sea (sea ice extent, SIE and sea surface temperature, SST) and two large-scale (Southern Oscillation Index, SOI and Southern Hemisphere Annular Mode, SAM) climate variables (Fig. 2). With respect to SIE and SST, we considered the Ross Sea as the sector enclosing 160°E to 130°W from 50°S to the Antarctic continent, approximately 78°S (Zwally *et al.* 1983). We obtained all climate data online in January 2007 (SIE from the National Snow and Ice Data Center, SST from the Jet Propulsion Laboratory, SOI from the Climate Research Unit, and SAM from the National Weather Service Climate Prediction Center). Because only SOI data were available prior to 1978, we were unable to assess if the values of the remaining climate variables were typical during our study period (1983–2005) relative to the rest of the 20th century (Fig. 2).

We used three month averages across January–March, April–June, and July–September for SIE and SST climate variables. We hypothesized that chick abundance during October–December would be influenced by SIE positively and SST negatively: 1) during January–March when adults require ice to moult and are foraging prior to their return to the colony for breeding (Kooyman *et al.* 2004), 2) during April–June when breeding, laying, and incubation occurs, and 3) during July–September when chicks are reared and parents make repeated foraging trips to feed the chicks. Notably, July–September was the period of greatest chick mortality in other emperor penguin research (Mougin 1966). Previously, SIE and SST have been correlated with emperor penguin population parameters in other research (Jenouvrier *et al.* 2005a, 2005b). We hypothesized the positive and negative relationships between chick abundances and SIE and SST would be dampened because reduced chick abundance might result from extensive sea ice increasing the foraging distance for adults rearing chicks (Barbraud & Weimerskirch 2001, Croxall *et al.* 2002) and severely cold temperatures might increase mortality of chicks (G.L. Kooyman, personal communication 2007).

We also evaluated annual SOI because this was correlated with emperor penguin breeding pairs and breeding success in studies conducted at Pointe Géologie (Jenouvrier *et al.* 2005a, 2005b). SOI, which is calculated as the difference in sea level pressures from Tahiti and Darwin, is related to the magnitude of an El Niño Southern Oscillation event (Kwok & Comiso 2002). While SOI values have been correlated with SST and SIE, the relationships are complex (Simmonds & Martinson

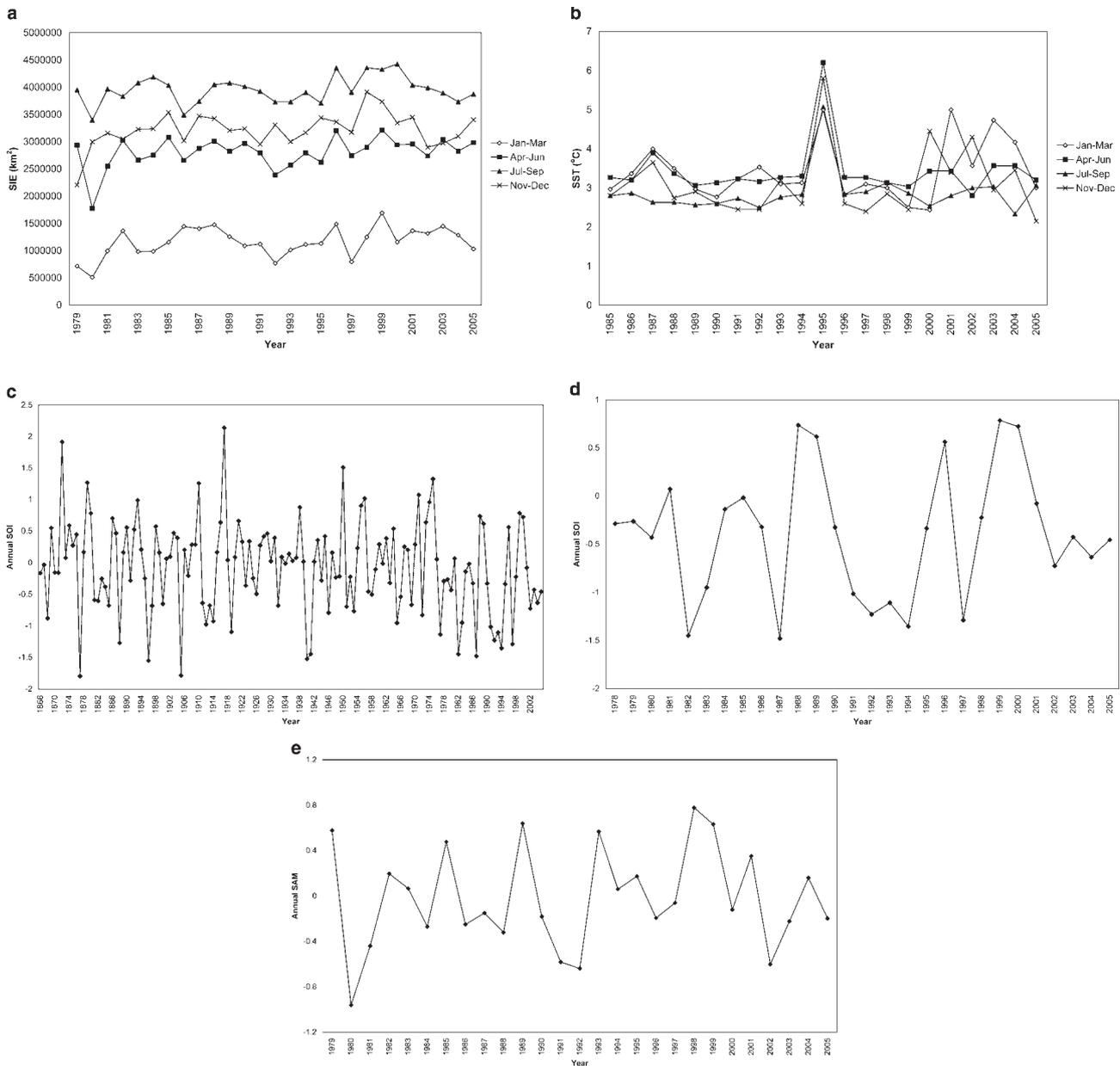


Fig. 2a–e. Sea ice extent (SIE), sea surface temperature (SST), Southern Oscillation Index (SOI), and Southern Hemisphere Annular Mode (SAM) data used in correlations with western Ross Sea emperor penguin live chick counts from 1983–2005.

1995, Gloersen & Mermicky 1998, Petersen & White 1998, Kwok & Comiso 2002). Nevertheless, this may explain the correlation of SOI with emperor penguin breeding success in other research (Jenouvrier *et al.* 2005a, 2005b). We examined SAM (also known as the Antarctic Oscillation, AAO) because, like SOI, it has been implicated as an important Antarctic climate variable related to SIE and ocean circulation (Kwok & Comiso 2002, Lefebvre *et al.* 2004), yet remained untested as to its relationship with emperor penguin population characteristics. High SAM values were associated with increased SIE in the Ross Sea area (Lefebvre *et al.* 2004).

We also examined time-lagged forms for all of the climate variables for five years prior because the average time for fledglings to return as breeding adults is five years (Mougin & van Beveren 1979, Jenouvrier *et al.* 2005a). Because our samples were small, we did not examine correlations with running means of various lengths (e.g. 3–20 years). While that type of analysis would be useful in detecting other signals, our data are not yet sufficient for such tests. Further, we examined the influence of SIE and SST averaged across November–December five years prior because we hypothesized that if the sea ice went out too early before chicks were ready to fledge this would result

Table I. Western Ross Sea emperor penguin live chick counts from 1983–2005, summary statistics, and linear regression parameters for abundance trends. Note that the sampling years are not continuous.

	Colony					
	Cape Crozier (169°25'E, 77°30'S)	Beaufort Island (167°03'E, 76°56'S)	Franklin Island (168°15'E, 76°07'S)	Cape Washington (165°22'E, 74°39'S)	Coulman Island (169°38'E, 73°20'S)	Cape Roget (170°31'E, 71°59'S)
Chick counts						
1983	78	175	4893	16384	21708	3777
1986	?	?	?	19364	?	?
1989	?	?	?	22819	?	?
1990	324	?	?	23502	27920	6921
1992	374	?	?	26511	34735	6478
1993	?	?	?	23920	18767	6551
1994	645	1356	1548	23780	20204	6358
1995	623	412	1785	22354	?	?
1996	859	1360	3241	17896	19471	7207
1997	821	?	?	?	?	?
1998	1108	?	?	?	?	?
1999	798	?	?	?	?	?
2000	1201	2038	2915	17397	?	?
2001	0	1065	1496	18734	?	?
2002	247	1430	?	11093	?	?
2003	333 ^a	364	2598	13163	?	?
2004	475	131	5145	16700	?	?
2005	0	628	1966	23021	24207	?
Summary statistics						
N	15	10	9	15	7	6
Mean	526	896	2843	19776	23859	6215
SE	98	204	458	1133	2172	504
CV	72.3%	71.9%	48.3%	22.2%	24.1%	19.9%
Range	0–1201	131–2038	1496–5145	11093–26511	18767–34735	3777–7207
Regression parameters ^b						
y0	-5594	-26117	112 261	491 055	131 243	-477 897
a	3.06	13.52	-54.77	-236.17	-53.87	243.11
R ²	<0.01	0.02	0.07	0.13	<0.01	0.80
P	0.87	0.70	0.48	0.18	0.89	0.02
F	0.03 (1, 13)	0.16 (1, 8)	0.57 (1, 7)	2.03 (1, 13)	0.02 (1, 5)	16.05 (1, 4)

^a We were unable to view all chicks due to rugged ice conditions and thus, we assumed one chick per adult counted.

^b $f = y_0 + a \cdot x$ and $F = F(df_{\text{regression}}, df_{\text{residual}})$.

Table II. Pearson correlation coefficients (n) between Ross Sea emperor penguin live chick counts from 1983–2005 and climate variables averaged across varying months evaluated at t and a lag of five years.

Variable	Colony					
	Cape Crozier	Beaufort Island	Franklin Island	Cape Washington	Coulman Island	Cape Roget
SIE, sea ice extent						
Jan–Mar	0.15 (15)	0.17 (10)	-0.05 (9)	-0.63 ^a (15)	-0.64 (7)	0.38 (6)
Apr–Jun	0.21 (15)	0.31 (10)	-0.14 (9)	-0.37 (15)	-0.41 (7)	0.37 (6)
Jul–Sep	0.56 ^a (15)	0.72 ^a (10)	0.09 (9)	-0.29 (15)	-0.39 (7)	-0.01 (6)
LSIE, sea ice extent five years prior						
Jan–Mar	-0.33 (14)	-0.48 (9)	0.52 (8)	0.24 (14)	0.14 (6)	-0.73 (5)
Apr–Jun	-0.68 ^a (14)	-0.73 ^a (9)	0.18 (8)	0.14 (14)	0.19 (6)	0.01 (5)
Jul–Sep	-0.73 ^a (14)	-0.73 ^a (9)	-0.02 (8)	-0.11 (14)	-0.41 (6)	-0.03 (5)
Nov–Dec	-0.39 (14)	-0.54 (9)	0.38 (8)	-0.16 (14)	0.60 (6)	-0.44 (5)
SST, sea surface temperature						
Jan–Mar	-0.50 ^b (14)	-0.67 ^a (9)	-0.14 (8)	-0.28 (14)	0.53 (6)	-0.74 (5)
Apr–Jun	0.06 (14)	-0.42 (9)	-0.20 (8)	0.12 (14)	-0.83 ^a (6)	-0.18 (5)
Jul–Sep	0.03 (14)	-0.32 (9)	-0.45 (8)	0.04 (14)	-0.65 (6)	0.16 (5)
LSST, sea surface temperature five years prior						
Jan–Mar	0.57 ^a (14)	0.78 ^a (9)	0.04 (8)	0.04 (12)	0.40 (6)	-0.29 (5)
Apr–Jun	0.42 (14)	0.66 ^b (9)	0.06 (8)	-0.03 (12)	0.80 ^b (6)	-0.24 (5)
Jul–Sep	0.44 (14)	0.58 ^b (9)	0.20 (8)	-0.35 (12)	0.13 (6)	0.84 ^b (5)
Nov–Dec	0.23 (14)	0.46 (9)	-0.09 (8)	0.16 (12)	0.45 (6)	-0.63 (5)
SOI, Southern Oscillation Index						
Jan–Dec	0.40 (15)	0.47 (10)	-0.06 (9)	-0.21 (15)	-0.20 (7)	0.39 (6)
LSOI, Southern Oscillation Index five years prior						
Jan–Dec	-0.43 (15)	-0.34 (10)	-0.14 (9)	0.22 (15)	-0.56 (7)	-0.07 (6)
SAM, Southern Hemisphere Annular Mode						
Jan–Dec	0.34 (15)	-0.35 (10)	-0.04 (9)	0.25 (15)	-0.80 ^a (7)	-0.18 (6)
LSAM, Southern Hemisphere Annular Mode five years prior						
Jan–Dec	0.01 (14)	-0.30 (9)	0.25 (8)	-0.21 (14)	0.15 (6)	-0.44 (5)

^a $P \leq 0.05$.^b $P \leq 0.10$.

in a decreased number of breeders at the colony five years later.

We estimated egg loss, early chick mortality, and breeding success among birds producing eggs from Cape Washington (six years) data (obtained by counting dead chicks and unhatched eggs) using the following formulas:

$$\% \text{ egg loss} = \frac{\text{unhatched eggs}}{(\text{unhatched eggs} + \text{live chicks} + \text{dead chicks})}$$

$$\% \text{ early chick mortality} = \frac{\text{dead chicks}}{(\text{live chicks} + \text{dead chicks})}$$

$$\text{breeding success} = \frac{\text{live chicks}}{(\text{unhatched eggs} + \text{live chicks} + \text{dead chicks})}$$

We also collected data from Beaufort Island (four years) on egg loss and early chick mortality but because the surveys were less rigorous than those conducted at Cape Washington because of weather and time constraints, we did not estimate egg loss, early chick mortality, or breeding success.

We conducted regressions using Arc v.1.06 (Cook & Weisberg 1999) and Pearson's r correlations with Statistica v.6 (StatSoft, Tulsa, Oklahoma, USA). We calculated basic statistical descriptions of the chick counts using Microsoft Office Excel (2003).

Results

Western Ross Sea emperor penguin chick counts showed high variability through time (Table I). We counted chicks most easily from aerial photographs during October because the chicks were more tightly grouped, whereas ground counts were easiest during December when the chicks were spread out. We did not distinguish between counts obtained aerially or by ground because we observed minimal chick mortality between October and December (G. L. Kooyman, personal communication 2007). As an example of inter-observer variation 22 groups of live chicks at Cape Washington during 1992 were counted by G. Kooyman and P. Ponganis, and the difference averaged 10.0% (range = 0–22.7%). As an example of intra-observer variation, once-repeated counts by P. Ponganis of three groups at Cape Roget during 1990 varied by an average of 5.6% (range = 5.0–6.3%). The smallest and most southerly colonies (i.e. Cape Crozier, Beaufort Island, Franklin Island) had the highest coefficients of variation in chick counts (Table I). Only one colony showed a significant abundance trend, Cape Roget (slope = 243.11, $r^2 = 0.80$, $F_{1,4} = 16.05$, $P = 0.02$) (Table I). This colony increased during 1983–1996, though the trend is dependent upon the low count during 1983 (3777). Removal of this year results in a relatively stable population during 1990–96 with counts fluctuating from a low of 6358 during 1994 to a high of 7207 during 1996.

We detected notable features in chick counts at five colonies (Table I). During 1992 Coulman Island live chick counts reached a record high of 34 735. The following year the counts declined by 46% to their lowest abundance on record (18 767). During 2002 Cape Washington live chick counts declined by 41% from the previous year and reached a record low (11 093). Over the next three years chick abundance steadily increased and by 2005 live chick counts had more than doubled and reached the high levels observed during the early 1990s. During 2001 and 2005 we counted no live chicks at Cape Crozier and chick counts during 2003–05 at Beaufort Island were greatly reduced from the three previous years. Both the Cape Crozier and Beaufort Island anomalies occurred either during or just after iceberg B15A's residence in the immediate area (Kooyman *et al.* 2007). The situation during 2005 at Cape Crozier is especially unusual because although there were 437 adults at the colony in mid-October, there were no signs of breeding (e.g. no eggs and no chicks). The reason for this failure was not apparent. Preliminary data suggested the breeding success was much improved during 2006 (i.e. *c.* 340 live chicks). During 2005 chick abundance at Franklin Island declined 62% from the previous year. Interestingly, we observed during an aerial flight five years prior that the sea ice went out early (i.e. prior to December 15) and we suspect that none of the 2915 chicks survived because they were not ready to fledge. The loss of that year's chicks may have partially contributed to the decline observed in 2005.

We found no consistent correlation with any of the climate variables across all colonies, possibly in part due to small samples (Tables I & II). However, local climate variables appeared to be most important to chick abundance, although in disparate magnitude, direction, and season across colonies. Two colonies in close proximity (Cape Crozier and Beaufort Island), which were both greatly impacted by iceberg B15A (Kooyman *et al.* 2007), showed similar significant responses to SIE (during July–September [positive correlation] of the current year and five years prior [negative correlation] and during April–June five years prior [negative correlation]) and to SST (during January–March [negative correlation] of the current year and five years prior [positive correlation]) (Table II). We only detected one significant correlation between chick abundances and a large-scale climate variable. Chick counts at Coulman Island were negatively correlated with SAM (Table II).

We estimated the egg loss, early chick mortality, and breeding success at one large colony (Cape Washington). Percent egg loss averaged 0.64% ($n = 6$, $SE = 0.17$, range = 0.34–1.40%) and percent early chick mortality averaged 4.80% ($n = 6$, $SE = 1.13$, range = 2.63–10.24%). Breeding success averaged 94.60% ($n = 6$, $SE = 1.21$, range = 88.96–96.99%). Also, during four years (1994,

2001, 2004, and 2005) at Beaufort Island we found 82, 400, 360, and 54 dead chicks and 10, 10, 1, and 4 eggs, respectively at this colony.

Discussion

Because emperor penguins breed each year once they reach breeding age (about five years; Mougin & van Beveren 1979, Jenouvrier *et al.* 2005a) and lay only one egg, chick counts minimally represent half of the breeding population. Therefore, in the absence of direct measurements of breeding adults, chick count trends may be used to detect large changes in the breeding populations of emperor penguins. We only detected one significant trend in our study (positive trend, Cape Roget). The two largest colonies (Cape Washington, Coulman Island) appeared more or less stable. The reason for the remarkable 1992 spike in Coulman Island chick abundance, followed by the lowest count ever for the colony, remains unknown. During the early 1990s Cape Washington chick abundance was at its highest levels and then declined to low numbers that persisted until 2004. The lowest counts were from 2002–04, which coincided with the period when the giant iceberg B15A was in the area (Fig. 1) (Kooyman *et al.* 2007). The presence of the iceberg possibly modified breeding behaviour and chick nurturing in some way. Both Beaufort Island and Cape Crozier were heavily impacted by B15A from 2001–04 (Kooyman *et al.* 2007). In our study the ability to detect trends appears to vary, in part, by colony size, with smaller colonies exhibiting greater variation in chick counts and thus, reduced utility in detecting a pattern of change.

Smaller colonies like Cape Crozier and Beaufort Island may represent populations in marginal habitat (Todd 1980), which are more susceptible to disturbance than larger colonies in relatively ideal habitat such as Cape Washington and Coulman Island (Kooyman 1993). The rapid increase we observed following the 2002 decline in Cape Washington live chick counts also suggests larger colonies are more resilient than smaller colonies. At first glance it seems the size differential among colonies may be explained by the smaller colonies being farther south where they are exposed to less daylight and colder temperatures. However, there is a notable exception to this, Cape Colbeck, a relatively large colony (6358 live chicks counted in 1994; G. L. Kooyman, personal observations) in the eastern Ross Sea at approximately the same latitude as Cape Crozier. Therefore, habitat assessments must also include features such as those described by Kooyman (1993, p. 143), “stable fast ice, nearby open water, access to fresh snow, and shelter from the wind”, as well as distance to foraging areas and prey distribution.

Ice anomalies such as iceberg B15A, which negatively affected the Cape Crozier and Beaufort Island colonies (Kooyman *et al.* 2007), appear to have some of the greatest

impact on chick abundances. Large-impact ice anomalies may mask the effects of subtle relationships with local (SIE and SST) and large-scale climate (SOI and SAM) variables.

In our study western Ross Sea chick abundances were positively correlated with SIE during July–September (two colonies) and negatively correlated with SST during January–March (two colonies). If SIE is reduced during July–September, adults may be challenged to find sufficient food to feed their chicks (Jenouvrier *et al.* 2005a) because of the relationships between SIE and prey distribution and abundance (Loeb *et al.* 1997, Nicol *et al.* 2000), however, chick needs are very low so soon after hatching and adult foraging behaviour and prey type at this time of year are unknown. During January–March higher SST may lead to reduced ice floes suitable for moulting and reduced foraging opportunities (Jenouvrier *et al.* 2005a). Both conditions would affect the number of adults prepared to breed the following season. We also found chick abundances were negatively correlated with SIE five years prior during April–June and July–September. Because all of these correlations were only detected at Cape Crozier and Beaufort Island, we suspect that the effects from iceberg B15A (present from 2001–04) may have influenced our results (Kooyman *et al.* 2007).

With the exception of Coulman Island, we did not find any significant correlations between emperor penguin chick counts and large-scale climate variables (SOI and SAM). This may have been in part due to small samples. Linkages between the variability of sea ice and the SOI (White & Peterson 1996) may explain why SOI was positively correlated with the number of breeding emperor penguin pairs and their breeding success at Pointe Géologie (Jenouvrier *et al.* 2005a, 2005b). However, research on Adélie penguins (*Pygoscelis adeliae*, Hombron & Jacquinot 1841) in the Ross Sea showed that SOI was related to SIE in the eastern but not the western portion of the Ross Sea (Wilson *et al.* 2001). Wilson *et al.* (2001) proposed, “this may be related to observations that the sea ice edge in the central-eastern Pacific sector is more responsive to extrapolar climate variability (e.g. Yuan & Martinson 2000)”. If this hypothesis is correct, it is not surprising that we did not find correlations between the western Ross Sea emperor penguin chick counts and SOI. This may be further evidence for the complexities involved in climate interactions with emperor penguin populations. Also, because we limited our correlation analyses (rather than, for example, using running means from 3–20 years) we may have missed other signals that with a larger and longer dataset we might have detected. Ultimately, we expect emperor penguin populations are most responsive to local sea ice conditions in the moult area, and at the colony. The high chick mortality mentioned in the results for Beaufort Island provides evidence for the latter (Kooyman *et al.* 2007). However, colonies will be indirectly influenced by large-scale climate variables as

they relate to sea ice conditions in the long term making them especially vulnerable to climate change (Barbraud & Weimerskirch 2001, Croxall *et al.* 2002, Jenouvrier *et al.* 2005a). Thus far, behavioural responses to climate change such as shifts in the dates of breeding and egg laying have not yet been observed in emperor penguins as they have in other Antarctic birds (Barbraud & Weimerskirch 2006).

We could only find two other long-term studies (Pointe Géologie, and Taylor Glacier and Auster) with which to compare our estimates of egg loss and breeding success (Robertson 1992, Williams 1995). Our estimates indicated Cape Washington emperor penguins during our study had lower egg loss and higher breeding success than those at Pointe Géologie (egg loss 22.4% and breeding success 62.9%; Williams 1995, pp. 158–159) and Taylor Glacier (breeding success 61%; Robertson 1992, p. 68) and Auster (egg loss 3.6% and breeding success between 58–73%; Robertson 1992, pp. 67–68). Although we probably missed eggs and chicks that were buried by snow, we expect this was a trivial amount based on the trampled condition and the thinness of the snow cover in the incubation and brooding areas.

Conclusions

Although adult survival, breeding success, and total breeding adults are more useful parameters in detecting population trends (Micol & Jouventin 2001), these are impossible to determine at most Antarctic emperor penguin colonies, including those in the Ross and Weddell seas where the largest numbers of breeding emperor penguins occur. Only Pointe Géologie, Taylor Glacier, Auster, Haswell Island, and Halley Bay are accessible year round (Woehler 1993). Of these, only Pointe Géologie (Barbraud & Weimerskirch 2001, Micol & Jouventin 2001) and Taylor Glacier are currently being studied. Furthermore, adult survival via mark-recapture analyses are not currently practical because radio frequency identification (RFID) tags are not logistically feasible for most study areas (Dugger *et al.* 2006) and flipper banding may cause significant mortality in penguins (Jackson & Wilson 2002, Gauthier-Clerc *et al.* 2004, Dugger *et al.* 2006). Genetic mark-recapture studies are not feasible because they are cost prohibitive and the probability of getting a recapture at mid-size to large colonies is very low.

The only other long-term emperor penguin studies are located at Terre Adélie (Barbraud & Weimerskirch 2001), the Mawson Coast (Robertson 1992), and the Prince Olav Coast / Riiser-Larsen Peninsula (Kato *et al.* 2004). The Pointe Géologie population at Terre Adélie appears to have stabilized following a significant decline in the 1970s (Barbraud & Weimerskirch 2001) and both the Taylor Glacier and Auster colonies along the Mawson Coast appeared stable during 1988–99 (Woehler & Croxall 1997, Woehler *et al.* 2001). In contrast, the Prince Olav Coast / Riiser-Larsen Peninsula populations have recently declined

in 2000 (Kato *et al.* 2004). Compared to these colonies, the Ross Sea population represents a more substantial component of the total population of emperor penguins (about 25% of the worldwide population; Kooyman 1994) and is located in an area of Antarctica subject to different climate patterns. While the Ross Sea population appeared stable (i.e. we did not find evidence suggesting an overall increase or decrease) during 1983–2005, continued research is warranted, especially in light of global climate change and the recent effects of B15A on the Cape Crozier and Beaufort Island colonies (Kooyman *et al.* 2007).

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