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ORIGINAL PAPER

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Changes in Adélie penguin breeding populations in Lützow-Holm Bay, Antarctica, in relation to sea-ice conditions

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Abstract The Adélie penguin, *Pygoscelis adeliae*, an important component of the Antarctic marine ecosystem, is closely associated with sea ice. Using data collected by Japanese Antarctic Research Expeditions since the 1960s, we examined trends in breeding populations of this species around Lützow-Holm Bay. Ten colonies ranging in size from 10 to 2,500 individuals were counted along the Soya Coast. Populations fluctuated synchronously, and overall increased at most colonies, except for two: one located deep inside the bay and another where human disturbance was substantial. Populations tended to increase during, or after, periods of sparse sea ice in summer, a condition that occurred once every decade. An increase in population size also occurred 5 years after a winter of extensive sea ice and after a winter of especially reduced sea ice.

Introduction

The trends of seabird populations, especially those of penguins, have long been thought to be reliable indicators of important ecosystem changes in the Southern Ocean (e.g. Jouventin and Weimerskirch 1990; Croxall 1992; Micol and Jouventin 2001). Consequently, birds have been used over the last decade as bio-indicators of the resource variability, particularly in relation to commercial harvesting and its effect on the Southern Ocean ecosystem (Trivelpiece et al. 1990; Ichii et al. 1996; Croll and Tershy 1998). The status of the Adélie penguin has received attention because it is an important component of upper trophic levels (CCAMLR 1997). It breeds in dense colonies in ice-free areas on continental and insular coasts, mainly south of 60°S (Marchant and Higgins 1993), where it forages mainly on fish and euphausiids (Williams 1995).

Several factors may affect this species' population trends. Recently, human disturbance related to increased tourism and research has become a non-negligible factor that can induce declines in local populations (Wilson et al. 1990; Woehler et al. 1994; Micol and Jouventin 2001). However, physical factors, including sea-ice conditions, are certainly the main sources of variation at a greater spatial scale. Indeed, sea-ice extent has been studied in relation to the change in population size of top predators in several instances (Fraser et al. 1992; Trathan et al. 1996; Barbraud et al. 2000; Wilson et al. 2001). The trends of Adélie penguin populations are closely related to sea-ice characteristics, which can affect foraging behavior (Watanuki et al. 1997; Rodary et al. 2000) and breeding success (Ainley and Le Resche 1973; Ainley et al. 1998; Irvine et al. 2000). Changes in the Antarctic climate that modify sea-ice conditions over time will, therefore, affect Adélie penguin populations. For instance, Adélie populations in the Antarctic Peninsula region have been declining over the last century (Fraser and Patterson 1997), whereas those in the Ross Sea area increased rapidly in the 1980s and have remained relatively stable since then (Taylor et al. 1990; Wilson et al. 2001). While the decline in the peninsula is related to loss of sea ice induced by climate warming (Fraser et al. 1992; Fraser and Patterson 1997; Smith et al. 1999), causes for increases in the Ross Sea have yet to be determined (Wilson et al. 2001).

Several studies have investigated the sea ice/penguin relationship, but not in East Antarctica. Long-term monitoring of Adélie penguin populations has been conducted by the Japanese Antarctic Research Expeditions (JARE); at some localities in Lützow-Holm Bay, records date from the 1960s, but they are mostly from the 1980s (Hoshiai and Matsuda 1979; Hoshiai et al. 1981, 1984; Kanda et al. 1986; Watanuki and Naito 1992). In order to better understand the factors affecting trends in Adélie penguin populations, we examined changes in population size of each Adélie penguin

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colony of Lützow-Holm Bay in relation to sea-ice conditions at different temporal and spatial scales.

Materials and methods

Colonies of Adélie penguins breeding around Syowa Station were censused occasionally during the 1960s and 1970s and systematically from the 1980s. In the Lützow-Holm Bay area, penguins start to arrive at the colonies around mid-October. Numbers peak in mid-November before decreasing through late November and finally stabilizing in early December (Watanuki and Naito 1992). We compiled and analyzed the available population data collected in mid-November from 1961 to 2001. Usually the number of penguins was counted directly three times by three people from the ground or from photographs taken from the ground. Average values were used for the analysis.

Regional sea-ice distribution was defined by the sea-ice extent along 40°E: (1) in winter (maximum in August/October); (2) in spring, which corresponds to the arrival of penguins at the colony (24 October to 4 November); and (3) in summer (minimum in February/April). These values were extracted from the Antarctic Ice Chart 1973–2001 (US Ice Center). We also used data collected by icebreakers that serve Syowa Station for the JARE once a year. These icebreakers break the ice near the station in December in order to allow access by ship. The icebreaker "Fuji" was used from 1966 to 1982; it reached Syowa Station, East Ongul Island 5 times and failed 12 times, depending on sea-ice conditions. The icebreaker "Shirase", operating from 1983 to the present, is much more powerful and has failed to reach Syowa only once. In our analysis, we used the minimum distance (in kilometers) between Syowa and the anchor point of the "Fuji", as well as the number of rammings needed by "Shirase" to complete its approach in December of each year. We defined the severity of ice conditions on the basis of the distance and the number of rammings.

Population trends and relationships between population changes and sea-ice parameters were tested by ANOVA. Correlations of annual populations between colonies were tested by Fisher's *r-z* conversion. All tests were carried out using Statview (SAS Institute, USA), and for all statistical tests, the threshold was 5%.

Results

Ten Adélie penguin colonies occur along the Soya Coast: three on the continent and seven on islands (Fig. 1). The largest colony was Rumpa with 1,000–2,500 individuals; the smallest was Benten I. with 2–15 individuals. A colony of 13 individuals was discovered on Sigaren in 2000; it increased to 28 individuals in 2001. A colony reported on Padda in 1975 has not been found since 1989. At the broadest temporal scale, Adélie penguin populations have increased linearly on Mame I. (6.4% annually), Ongulkalven (1.4%), Rumpa (2.1%), Muzukuguri Cove (6.4%), and Ytre Hovdeholmen (3.8%). They have decreased at Hukuro Cove (–2.2%) and Torinosu Cove (–2.5%) (Fig. 2). No significant trends were observed for the populations on Benten I. and Nøkkelholmane. At decadal scale, Ongulkalven data show that the population decreased during the 1970s (–14%) and then began to increase (3.8%). Fluctuations among five increasing colonies (Mame I., Ongulkalven, Rumpa, Muzukuguri Cove, Ytre Hovdeholmen) were correlated, as were those between the two decreasing colonies (Hukuro Cove and Torinosu Cove)

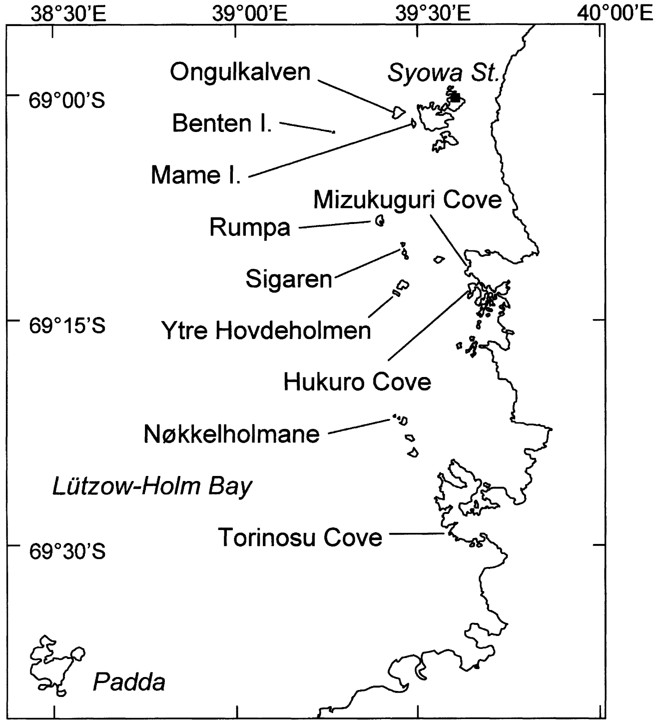

Fig. 1 Locations of Adélie penguin colonies along the Soya Coast of Lützow-Holm Bay

(Table 1). Dramatic increases (> +100%) were observed in 1981, 1986, 1988, and 1997 (Fig. 3), occurring simultaneously in several colonies.

Over the last 40 years, sea-ice extent has fluctuated substantially, especially in winter, but no significant tendency, either towards an increase or a decrease, was evident for this area between 1971 and 2001 (Fig. 4a). Winter sea ice was extensive (to 57°S) in 1976, 1989, and 1992, and was minimal (within 60°S) in 1980, 1981, and 1996. Maximum winter sea-ice extent was well synchronized with that in spring ($r=0.63$, $n=29$, $P=0.0002$). The distances between Syowa Station and the "Fuji" anchor point increased between 1966 and 1982 ($r=0.51$, $n=17$, $P=0.036$), indicating that sea-ice conditions became more severe during this period (Fig. 4b). However, the number of rammings by the icebreaker "Shirase" varied from 0 to 3,000 but did not increase or decrease between 1983 and 2001 (Fig. 4c). According to these parameters, light sea-ice conditions were observed in the late 1960s, late 1970s, late 1980s and late 1990s. However, these indices were not statistically correlated with the regional sea-ice extent.

For every year *t*, percent change of population from the previous observation was related to the sea-ice extents in summer and winter observed in year *t* and the preceding years, up to *t*-5. Population changes were not significantly related to the summer sea-ice extent, except in year *t*-2 at Ongulkalven ($r=0.46$, $P=0.04$, $n=21$), Mizukuguri Cove ($r=0.60$, $P=0.02$, $n=14$), and Hukuro Cove ($r=0.73$, $P=0.01$, $n=11$) and in year *t*-3 at Torinosu Cove ($r=-0.89$, $P=0.04$, $n=5$). Population changes were not significantly related to the winter sea-ice extent, except in year t-5 at Ytre Hovdeholmen ($r = -0.85$, $P = 0.03$, $n = 6$).

Discussion

Overall, in accord with the general trend observed in East Antarctica (Jouventin and Weimerskirch 1990; Woehler et al. 2001), Adélie penguin populations have increased in the Lützow-Holm Bay area. Smith et al. (1999) suggested a model to explain the relationship between sea-ice conditions and a penguin population change, indicating an ideal level of sea-ice conditions. As the severity of sea ice decreases, populations will increase, but if severity continues to decrease, the penguin populations will begin to decrease. Where sea-ice conditions are very severe, or there is no sea ice, there are no Adélie penguin colonies. In East Antarctica, the patterns seem to be similar to those of the Ross Sea (cf. Wilson et al. 2001).

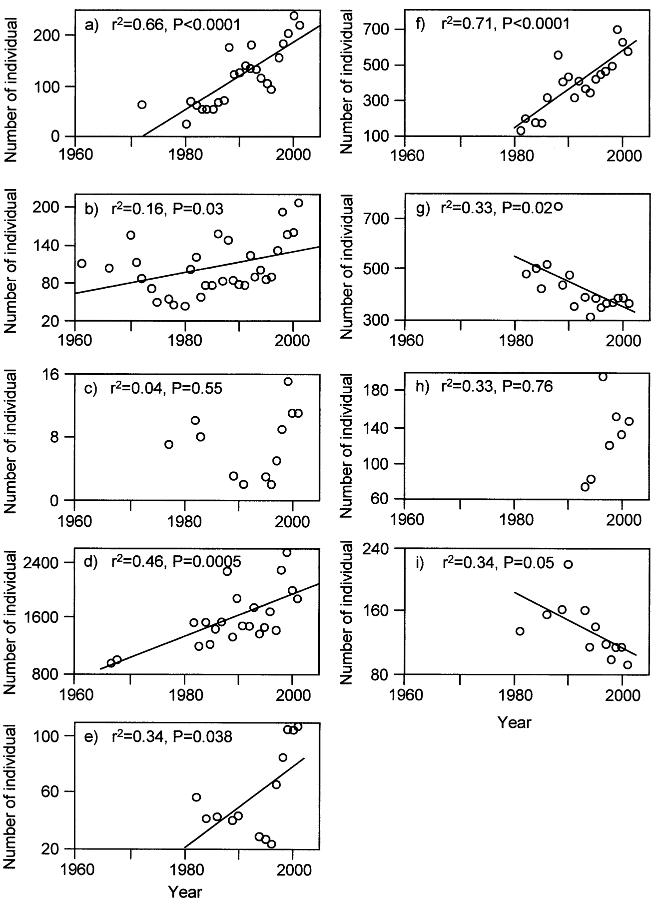

Fig. 2 Population changes in Adélie penguin breeding at **a** Mame I., $n = 23$, **b** Ongulkalven, $n = 31$, **c** Benten I., $n = 12$, **d** Rumpa, $n = 22$, **e** Ytre Hovdeholmen, $n = 13$, **f** Muzukuguri Cove, $n = 19$, **g** Hukuro Cove, $n = 17$, **h** Nøkkelholmane, $n = 7$, **i** Torinosu Cove, $n = 12$. Coefficients of determination (r^2) and statistical probabilities (P) are shown

Although increasing, the population size of Adélie penguin colonies in the study area remains relatively small compared to colonies elsewhere. This is especially the case for the colonies located deep inside the bay. In addition to the 10 colonies investigated in the present study, a very small colony (20–40 pairs) was present at Kuzira Point on Padda Island (69°36′S, 38°18′E) (Hoshiai and Matsuda 1979), but it disappeared during the 1990s. This colony was the farthest into the bay, where sea ice is especially severe. Penguins breeding there would have had to travel great distances between their nests and open water. On the basis of our results, colony size seems to be limited by increasing distances between foraging and breeding zones. Otherwise, the decline of the Hukuro Cove colony may be related to research activities conducted during 1989/1991 (Watanuki et al. 1993) and 1995/2001 (Takahashi 2001). During these summer campaigns, 40–120 birds were captured inside the colony, manipulated, equipped with externally attached loggers and/or had their stomachs flushed each year. Therefore, a series of detrimental factors may have contributed to a reduction in breeding success and consequently the size of the colony. Indeed, externally attached loggers may compromise swimming ability, greatly reducing normal swim speeds (Wilson et al. 1986) and modifying the diving behavior (Ropert-Coudert et al. 2000). These alterations to foraging ability in turn reduce chick growth (Watanuki et al. 1992). Furthermore, frequent human visits can reduce the breeding success and colony size (Woehler et al. 1994; Giese 1996). As a possible consequence of the decrease of the Hukuro Cove population, that of the neighboring Muzukuguri Cove increased, some individuals probably

Table 1 Correlation matrix of Adélie penguin populations from nine colonies along the Soya Coast. Values are correlation coefficients between populations of two colonies and sample size (*NS* no significant correlation)

	Mame I.	Onglkalven	Benten I.	Rumpa	Muzukuguri Cove	Hukuro Cove	Ytre Hovdeholmen	Nøkkelholmane
Onglkalven	0.65, 21**	–	–	–	–	–	–	–
Benten I.	NS	NS	–	–	–	–	–	–
Rumpa	0.69, 18**	0.65, 18**	NS	–	–	–	–	–
Muzukuguri Cove	0.86, 17**	0.50, 17*	NS	0.75, 16**	–	–	–	–
Hukuro Cove	NS	NS	NS	NS	NS	–	–	–
Ytre Hovdeholmen	0.73, 11**	0.76, 11**	0.89, 7**	0.79, 11**	NS	NS	–	–
Nøkkelholmane	NS	NS	NS	NS	NS	NS	NS	–
Torinosu Cove	NS	NS	NS	NS	NS	0.71, 9*	NS	NS

*$P < 0.05$; **$P < 0.01$

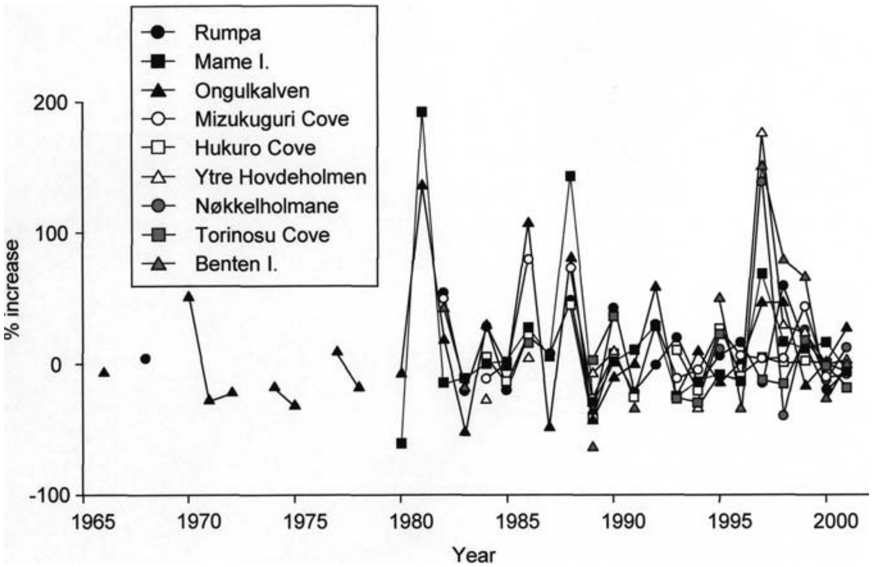

Fig. 3 Percent change of Adélie penguin population from the previous observation

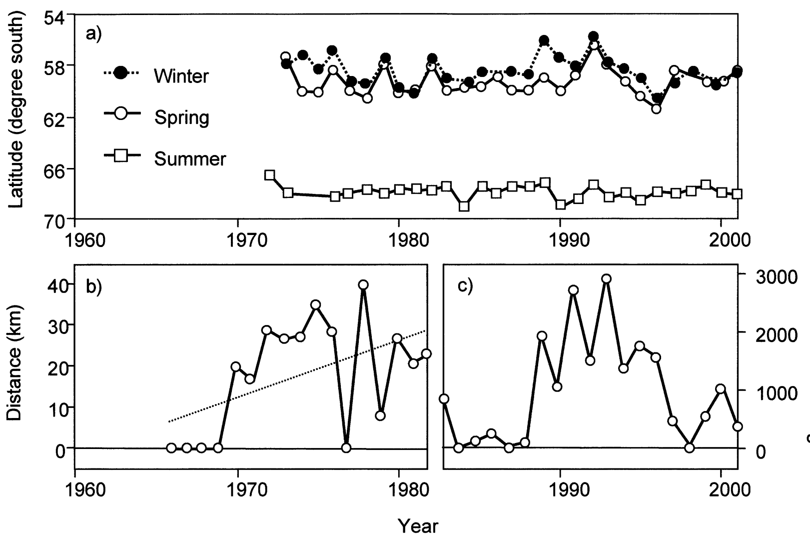

Fig. 4 **a** Annual variation of sea-ice extent in winter, spring and summer along 40°E; **b** minimum distance between Syowa Station and the anchor point of the icebreaker "Fuji"; **c** the number of rammings by the icebreaker "Shirase" approaching Syowa Station

changing their breeding site in order to escape the disturbance.

Synchronous increases in population size, as observed for the five colonies of the Lützow-Holm Bay area, may be the result of a combination of factors that enhanced the breeding success of Adélie penguins. The present study allows us to highlight some of these factors; increases in population were observed during, or just after, periods of light sea-ice conditions in summer, which occurred at the end of almost every decade. Hoshiai et al. (1981) reported that populations of Ongulkalven and Mame I. decreased after 1971 because of the severe sea-ice condition experienced by birds during the breeding season. Since local sea-ice condition in summer affects accessibility to the foraging areas, light ice conditions may improve prey accessibility and breeding success, and increase the number of birds attempting to breed (Ainley and Le Resche 1973; Ainley et al. 1998). Conversely, extensive sea ice in winter was observed in 1976 and 1992, with an increase in penguin populations 5 years later, in 1981 and 1997. Interestingly, small sea-ice extents in winter were observed just before an increase in the bird population during the two reproductive seasons of 1981 and 1996. These results accord well with those of Wilson et al. (2001), who hypothesized a reduced sub-adult survival during years of extensive winter sea-ice extent, with a subsequent decrease in the breeding population size 5 years later. Thus, we can postulate that reduced sea-ice extents not only induce a high sub-adult survival but also a high adult survival, which leads to a high number of breeding attempts in the following season.

In conclusion, sea ice is definitely one of the primary factors that affect the population of Adélie penguins breeding in areas of severe sea-ice condition, although the mechanisms are not fully known. The size of the annual breeding population is under the control of several interacting parameters, such as adult survival, recruitment, and number of breeding attempts, which are themselves driven by local sea-ice conditions. In order to understand the underlying processes that control this intricate web, a wide range of biological and physical parameters have to be monitored simultaneously.

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