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Historical population changes of Adélie penguins in the Ross Sea region, Antarctica, and its climatic forcings

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Highlights

- As, Cd, P, Cu, Zn are bio-elements in ornithogenic sediments at Inexpressible Island.
- Adélie penguin populations in the Ross Sea peaked during the Medieval Climate Anomaly (MCA; 750–1300 AD).
- The warmer climate during the MCA led to expansion of penguin habitats.
- The activities of SAM and ENSO impacted penguin communities possibly via nutrient delivery.

Abstract

The atmospheric-oceanic circulation patterns, especially for the Southern Annular Mode (SAM) and El Niño-Southern Oscillation (ENSO), two major atmospheric circulation patterns in the Ross Sea region, have been reported to greatly affect climate and marine ecosystems. However, from a historical perspective, the influence of atmospheric-oceanic circulation patterns on penguin populations remains unclear in this region. Here, we analyzed two lacustrine sediment cores collected from abandoned penguin colonies at Inexpressible Island, Ross Sea, Antarctica, and by applying alternative geochemical indices, successfully reconstructed the populations of the Adélie penguins (Pygoscelis adeliae) over the past~1500 years. We found that penguin population peaked during 750–1350 AD at Inexpressible Island, potentially due to habitat expansion in the warmer climate. After comparing with historical records of penguin populations at Cape Bird, Dunlop Island, and Cape Adare, all were found to have a common increase during the 750-1350 AD period in the Ross Sea. The population trend also coincided with extreme activities of El Niño and SAM (+). We inferred that the SAM-ENSO might promote influxes of Circumpolar and Modified Circumpolar Deep Waters into the Ross Sea. The enhanced influx of nutrient-rich deep water, together with a warmer climate may jointly enhance polynya efficiency and population increase of Adélie penguins. Our study indicates the potentially significant roles of ENSO and SAM in the regulation of Antarctic ecosystems.

Introduction

The Ross Sea region, Antarctica, is a hot spot for research on climate change and ecological responses by both marine and terrestrial species. There are several submarine banks (Mawson Bank, Pennell Bank, and Ross Bank; Smith et al., 2012) and coastal polynyas (Terra Nova Bay polynya, and the Ross Shelf polynya), hosting rich benthic invertebrate assemblages (Barry et al., 2003; Kooyman et al., 2020), Antarctic silverfish (*Pleurogramma antarctica*; O'Driscoll et al., 2011), and krill (*Euphausia* spp.) depredated by carnivores, such as penguins and seals (Davis et al., 2017). This region represents one of the most productive areas in Antarctica. Its weather is mainly affected by three air masses from the Ross Sea, the Ross Ice Shelf, and Victoria Land, and the region is highly sensitive to climate change (Monaghan et al., 2005). Meanwhile, the high productivity in the Ross Sea is largely sustained by regional atmospheric-oceanic circulations and their interactions. Particularly, the Antarctic Circumpolar Current (ACC), dominated by a thick layer of warm and nutrient-rich water from low latitudes (Tynan, 1998), allows the inflow of Circumpolar Deep Water (CDW) and Modified Circumpolar Deep Water (MCDW) by the Ross Gyre, which replenishes

heat and nutrients to the polynya and banks (Smith et al., 2007, Smith et al., 2012, Smith et al., 2014; Fig. 1a and b). In addition, the atmospheric-oceanic circulations, including El Niño-Southern Oscillation (ENSO) and the Southern Annular Mode (SAM), lead to changes in the ACC, wind strength, and Sea Surface Temperature (SST), exerting a great impact on the size of polynyas, the formation of sea ice, and marine productivity (La et al., 2019; Murphy et al., 2007; Wilson et al., 2001; Yuan, 2004). These atmospheric-oceanic circulations are highly sensitive to climatic events, making the Ross Sea region an ideal place for investigating ecological responses to regional and global climate change.

As one of the most important 'sentinel species' in the Antarctic ecosystem, the Adélie penguin (*Pygoscelis adeliae*) is widely distributed in the Ross Sea region and its population is extremely sensitive to climate change (Ainley, 2002; Ainley et al., 2010). Since the International Geophysical Year in 1957, researchers have conducted extensive field investigations on climate change (including temperature, SST, sea ice, and polynyas) and Adélie penguin populations in Antarctica. Modern monitoring data also show that Adélie penguin breeding is closely linked to temperature (Croxall et al., 2002; Riaz et al., 2020; Watanabe et al., 2020), sea ice extent/concentration (Iles et al., 2020; Smith et al., 1999), and polynya size (Mezgec et al., 2017; Thatje et al., 2008). As crucial atmospheric-oceanic circulation patterns in Antarctica, ENSO and SAM also produce indispensably direct (e.g., winds) or indirect (e.g., polynya, ice cover, and SST) impacts on penguin ecology (i.e., survival rate and breeding; Croxall et al., 2002; Forcada and Trathan, 2009; Krüger et al., 2021; Wilson et al., 2001), especially in the Antarctic Peninsula (Barbraud et al., 2012; Henley et al., 2019; Hinke et al., 2014). Although previous studies have discussed the potential impacts of ENSO and SAM on modern penguin ecology based on observation data in Antarctica Peninsula and east Antarctica, they rarely cover the long-term influences of these circulations on penguin populations using geological proxies from sediments, particularly in the Ross Sea region (Forcada and Trathan, 2009).

Several recent studies have provided some historical data, enabling a discussion on the response of penguin populations to climatic events in the Ross Sea region (Hu et al., 2013; Yang et al., 2018). More recently, Zheng et al. (2022b) pointed out that atmospheric-oceanic circulation coupled with sea ice extent and polynya size impacted the penguin population at Beaufort Island since ~1650 AD. However, there is a lack of widely accepted mechanisms to explain the changes in the penguin population since the Holocene in the Ross Sea region.

Here, we systematically studied two lacustrine sediment profiles collected from abandoned Adélie penguin colonies at Inexpressible Island, Ross Sea. Our main objectives are to: 1) reconstruct penguin populations over the past 1500 years by generalized additive models

(GAMs) based on multiple geochemical proxies, 2) explore the characteristics of penguin population change, and 3) test if there is an influence of atmospheric circulation (SAM and ENSO) on historical change of penguin ecology.

Section snippets

Sampling sites

Inexpressible Island (74° 54′S, 163° 43′E) is a rocky island located near Terra Nova Bay in Northern Victoria Land, Ross Sea, Antarctica (Baroni and Orombelli, 1994, Fig. 1c). Numerous abandoned Adélie penguin colonies and some currently active colonies exist on raised beaches. Approximately 25,000 breeding pairs colonize the ice-free area around Seaview Bay (Lynch and LaRue, 2014; Park et al., 2021). The annual average temperature is between −18.7 °C and −15.3 °C. The anomalously strong…

Organic matter source and element distribution in the two sediment profiles

The geochemical characteristics of sediment cores IIL1 and IIL4 have been reported in our previous studies (Jin et al., 2021, Wei et al., 2016, Zheng et al., 2022b). The average $\delta^{13}C_{org}$ and TOC/N values in IIL1 (−21.80±0.40‰, n=55; 1.15±0.17, n=55) are significantly lower than IIL4 (-16.70±1.50‰, n=23; 12.24±2.19, n=23). The guano-contributed proportion calculated by the two-endmember mixing model reveals that both sediment profiles are influenced by guano input (Fig. S1). All…

Reconstruction of the penguin population at Inexpressible Island

The accuracy of penguin population reconstruction is a key factor in understanding their ecological responses to climate change. In previous studies, bio-elements (Liu et al., 2013, Nie et al., 2022, Sun et al., 2000, Yang et al., 2018, Yang et al., 2021), and organic geochemical

proxies (carbon isotope, lipid biomolecules, diatoms, pigments; Duda et al., 2021, Nie et al., 2014) have been used to reconstruct long-term changes in seabird populations from lake sediments. Considering that there…

Conclusions

In this study, we identified the bio-elements in the ornithogenic sediments brought by penguin activities and also used multiple geochemical proxies to reconstruct Adélie penguin populations since 300 AD at Inexpressible Island (IIL1 and IIL4), then systematically explored the impacts of atmospheric and marine conditions on penguin habitability. Our results suggest that the most likely bio-elements that reflect penguin activities at Inexpressible Island are P, As, Cu, Cd, and Zn. The penguin…

Credit author statement

Zhangqin Zheng: Formal analysis, Writing – original draft, Writing – review & editing, Methodology, Conceptualization, Software. **Jing Jin:** Writing – review & editing, Methodology, Formal analysis, Software. **Yaguang Nie:** Writing – original draft, Writing – review & editing, Methodology, Formal analysis. **Jihua Hao:** Writing – review & editing, Formal analysis. **Yulu Xue:** Formal analysis, Writing – review & editing. **Can Liu:** Formal analysis, Writing – review & editing. Yongyan Chen: Software,…

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.…

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