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Oceanographic mechanisms and penguin population increases during the Little Ice Age in the southern Ross Sea, Antarctica

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ABSTRACT

The Adélie penguin is a well-known indicator for climate and environmental changes. Exploring how large-scale climate variability affects penguin ecology in the past is essential for understanding the responses of Southern Ocean ecosystems to future global change. Using ornithogenic sediments at Cape Bird, Ross Island, Antarctica, we inferred relative population changes of Adélie penguins in the southern Ross Sea over the past 500 yr, and observed an increase in penguin populations during the Little Ice Age (LIA; 1500–1850 AD). We used cadmium content in ancient penguin guano as a proxy of ocean upwelling and identified a close linkage between penguin dynamics and atmospheric circulation and oceanic conditions. During the cold period of ∼1600–1825 AD, a deepened Amundsen Sea Low (ASL) led to stronger winds, intensified ocean upwelling, enlarged Ross Sea and McMurdo Sound polynyas, and thus higher food abundance and penguin populations. We propose a mechanism linking Antarctic marine ecology and atmospheric/oceanic dynamics which can help explain and predict responses of Antarctic high latitudes ecosystems to climate change.

1. Introduction

Understanding the mechanisms for Southern Ocean ecosystem responses to climate variability is challenging, and up to now there has been little research on the coupling of atmospheric circulation, ocean conditions, and Antarctic marine ecology over geologic time scale. The Ross Sea is the conjunction point of three different air masses from Victoria Land, the Ross Sea and the Ross Ice Shelf (Monaghan et al., 2005) and is highly sensitive to climate change. Climate in this region is mainly controlled by large-scale atmospheric circulation via changes in winds and temperature that further influence sea ice extent (Coggins and McDonald, 2015; Holland and Kwok, 2012; Hosking et al., 2013), and has been so over the last millennium, especially during the Little Ice Age (LIA; 1500–1850 AD). Records from Siple Dome ice cores show strengthened meridional atmospheric circulation since ∼1400 AD, coincident with the initiation of the LIA (Kreutz et al., 1997). Records from Talos Dome ice cores suggest a prolonged, cooler climate from the 16th to the beginning of the 19th centuries (Stenni et al., 2002). Marine sediments from McMurdo Sound exhibit higher open water diatom abundance, a more persistent Ross Sea polynya, and enhanced primary production in the southwestern Ross Sea from ∼1600–1875 AD (Leventer and Dunbar, 1988). All these data indicate that during the LIA, the Ross Sea experienced cooler and drier conditions, characterized by stronger katabatic winds, cooler sea surface temperatures, and larger polynyas than today (Bertler et al., 2011).

Changes in the oceanic conditions associated with large-scale atmospheric forcing are expected to have cascading effects on marine food webs, from phytoplankton to krill and to upper trophic level predators (Montes-Hugo et al., 2009; Saba et al., 2014; Trivelpiece et al., 2011). The Ross Sea currently supports over two million Adélie penguins (*Pygoscelis adeliae*) and this species is widely used as bio-indicator for climate and environmental changes (Ainley, 2002; Lynch and LaRue, 2014). The ecological history of Adélie penguins in the Ross Sea region, including occupation history (Emslie et al., 2003, 2007), population dynamics (Ainley et al., 2005; Wilson et al., 2001), and dietary changes (Ainley et al., 1998; Lorenzini et al., 2014; Polito et al., 2002) has been extensively examined. The population dynamics of penguins,

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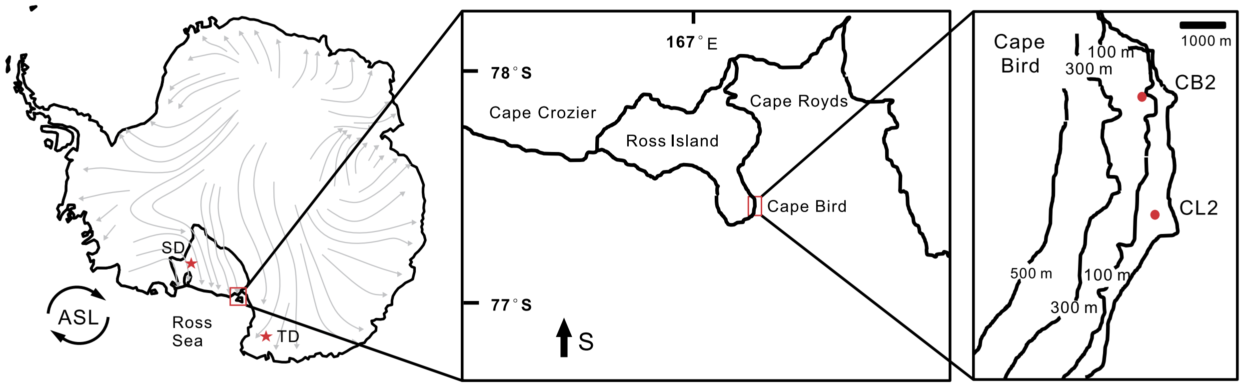

Fig. 1. Location of sampling sites of ornithogenic sediments (represented by red dots) at Cape Bird, Ross Island, as well as ice core sites (represented by red stars) in the Ross Sea, Antarctica. The grey arrows indicate katabatic wind flow (modified from Bertler, 2004). ASL: Amundsen Sea Low; CB2: this study; CL2: referring to Nie et al. (2015); SD: Siple Dome ice core, referring to Mayewski et al. (2004); TD: Talos Dome ice core, referring to Stenni et al. (2002). (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

seals and krill during the Holocene from studies in the Antarctic Peninsula and East Antarctica are tightly associated with climatic conditions (Huang et al., 2009, 2013; Sun et al., 2000, 2004, 2013) and likely so in the Ross Sea as well. For example, evidence suggests that Adélie penguin populations at Cape Bird, Ross Island, shifted locations of breeding sites there due to coastline variations and frequent storms under the colder climatic conditions of the LIA (Hu et al., 2013; Nie et al., 2015).

Here, we analyzed geochemical records in ornithogenic sediments from Cape Bird, Ross Island (Fig. 1), and used phosphorus (P) to reconstruct historic changes of Adélie penguin populations and cadmium (Cd) as a proxy for ocean upwelling intensity; stable nitrogen isotopes (δ^{15}N) in penguin feathers were used to infer penguin dietary changes for the past 500 yr. We also investigated the connection between atmospheric circulation, oceanic conditions and the impact of large-scale climate forcing on marine ecosystem along the southwestern Ross Sea.

2. Material and methods

2.1. Sampling site

The sediment core CB2 in this study was collected at Ross Island, southwestern Ross Sea, during the 2012 austral summer (Fig. 1). This 15-cm deep core was collected from a catchment on an elevated hillside at southern Cape Bird, with an active Adélie penguin colony nearby, indicating possibly high impact of penguin guano on the sediment. The profile was sectioned at 0.5 cm intervals, and a total of 30 subsamples were obtained and stored in a freezer at −20 °C prior to analysis. The CB2 profile contained numerous penguin feather fragments, but sample sizes per 0.5 cm section were small (fragments representing 3–5 individual feathers). Fragments were pooled into one sample per 0.5 cm section for δ^{15}N analysis.

2.2. Chronology

Two penguin feathers were selected from the CB2 profile (at depths of 9 cm and 15 cm) for AMS ^{14}C dating (Table 1). These two conventional radiocarbon dates were calibrated using the CALIB 7.0.2 computer program and the dataset of Marine13 (Reimer et al., 2013), and corrected using a $\Delta R = 750 \pm 50$ yr for the marine carbon reservoir effect in the Ross Sea region (Emslie et al., 2007). As a result, CB2 profile has a bottom age of ∼1471–1695 AD (2σ range).

To obtain the chronology of the CB2 profile, the levels of bio-elements mercury (Hg) and phosphorus (P) were compared with those in another ornithogenic sediment profile (CL2) from the middle Cape Bird (Nie et al., 2015). The CL2 profile was taken from a small pond that is located on the fifth beach ridge above sea level with abandoned penguin colonies nearby. CB2 and CL2 are geographically close (∼1 km apart), have similar ornithogenic influence on the two sediment cores from penguin guano, and thus the typical bio-elements Hg and P in the two cores are comparable. Based upon these comparisons, we established the age-depth model for CB2 by matching the two cores' bio-elemental characteristics (Fig. 2), with the bottom age calculated as ∼1450 AD, consistent with the ^{14}C age (Table 1). Therefore, we established the complete and accurate chronology of CB2, which represents about 500 yr of deposition at the sampling site.

Table 1
^{14}C dates and calibrated ages for the CB2 profile.

Sample	Depth (cm)	Material	Conventional ^{14}C age (BP)	Calibrated age (AD)
CB2-18	9	Feather	1065 ± 36	/
CB2-30	15	Feather	1463 ± 38	1471∼1695 (2σ)

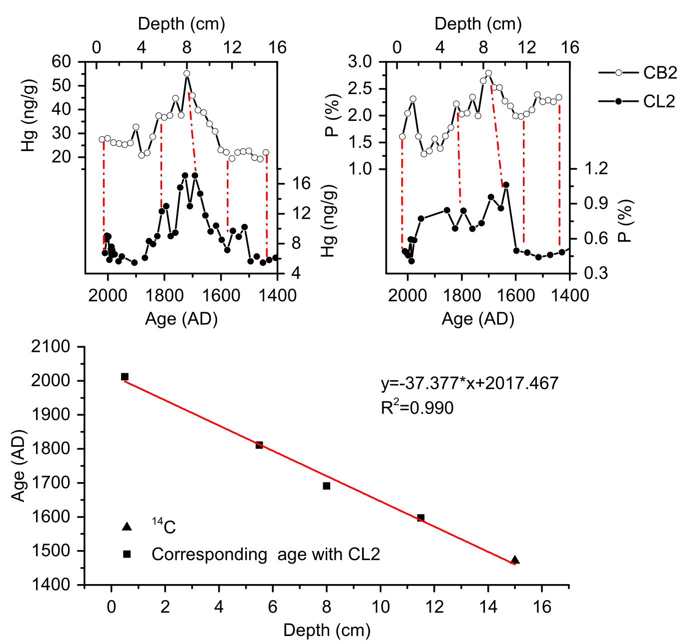

Fig. 2. Chronology of the profile CB2. Upper panel: comparison of mercury (Hg) and phosphorus (P) concentrations in profile CB2 and CL2, respectively; bottom panel: age-depth model for profile CB2, with a linear fitting.