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The application of inverse-dispersion and gradient methods to estimate ammonia emissions from a penguin colony

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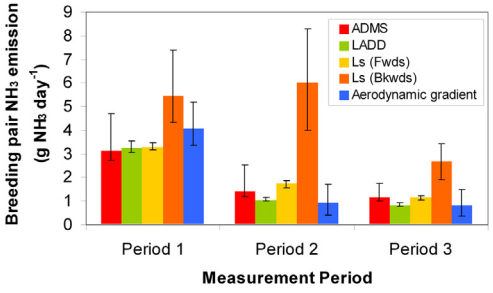
HIGHLIGHTS

- We measure atmospheric ammonia concentrations at locations around a penguin colony.
- We estimate ammonia emission rates using inverse modelling and gradient methods.
- Mean ammonia emissions are estimated to be 1.1 g ammonia per breeding pair per day.
- We estimate that 2% of the nitrogen excreted by the penguins is emitted as ammonia.

GRAPHICAL ABSTRACT



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ABSTRACT

Penguin colonies represent some of the most concentrated sources of ammonia emissions to the atmosphere in the world. The ammonia emitted into the atmosphere can have a large influence on the nitrogen cycling of ecosystems near the colonies. However, despite the ecological importance of the emissions, no measurements of ammonia emissions from penguin colonies have been made. The objective of this work was to determine the ammonia emission rate of a penguin colony using inverse-dispersion modelling and gradient methods. We measured meteorological variables and mean atmospheric concentrations of ammonia at seven locations near a colony of Adélie penguins in Antarctica to provide input data for inverse-dispersion modelling. Three different atmospheric dispersion models (ADMS, LADD and a Lagrangian stochastic model) were used to provide a robust emission estimate. The Lagrangian stochastic model was applied both in 'forwards' and 'backwards' mode to compare the difference between the two approaches. In addition, the aerodynamic gradient method was applied using vertical profiles of mean ammonia concentrations measured near the centre of the colony. The emission estimates derived from the simulations of the three dispersion models and the aerodynamic gradient method agreed quite well, giving a mean emission of 1.1 g ammonia per breeding pair per day (95% confidence interval: 0.4–2.5 g ammonia per breeding pair per day). This emission rate represents a volatilisation of 1.9% of the estimated nitrogen excretion of the penguins, which agrees well with that estimated from a temperature-dependent bioenergetics model. We found that, in this study, the Lagrangian stochastic model seemed to give more reliable emission estimates in 'forwards' mode than in 'backwards' mode due to the assumptions made.

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1. Introduction

Large colonies of wild animals can emit substantial quantities of ammonia (NH_3) into the atmosphere. This is especially true for colonies of seabirds such as penguins, which represent some of the most concentrated natural sources of atmospheric ammonia in the world (Wilson et al., 2004; Riddick et al., 2012). Most penguin colonies are situated in remote locations and hence the emitted ammonia can represent the principal source of atmospheric nitrogen (N) input into nearby ecosystems, making them interesting case studies of ecosystem N-cycling (Lindeboom, 1984; Crittenden et al., unpublished results). Although penguins and other seabirds contribute less than 2% of global NH_3 emissions (Riddick et al., 2012), the concentrated nature of seabird colony emissions can have important local ecological effects, the understanding of which is aided by knowing how much NH_3 is emitted. At the same time, seabird colonies provide a model system for studying NH_3 emission processes that largely excludes human management of the excreta, allowing the effects of climatic differences to be examined (Sutton et al., 2013).

Initial estimates of penguin ammonia emissions on a global scale were made by Blackall et al. (2007), who estimated total NH_3 emissions from all seabird species of 242 Gg NH_3 $year^{-1}$ using a simple bioenergetics model. Penguin species contributed most, accounting for around half of this total. This approach was subsequently modified by Riddick et al. (2012) to include an estimated temperature dependency and updated database of seabird colonies to produce a spatial emission inventory for seabird NH_3 emissions. Laboratory studies have also been carried out to estimate the potential of penguin colonies to emit NH_3 into the atmosphere. For example, Zhu et al. (2011) studied the NH_3 emission potential of guano and ornithogenic soils from penguin colonies and their dependence on temperature, pH and total nitrogen content. However, despite these advances in emission inventories and laboratory studies, no field-based estimates of NH_3 emissions from penguin colonies have been published.

The objective of this paper is to derive the first field-based emission estimates (and their uncertainty) of a penguin colony using different dispersion models and micro-meteorological methods.

2. Materials and methods

2.1. Colony location

Cape Hallett is situated at the southern end of Moubray Bay, northern Victoria Land, in the western Ross Sea (Fig. 1a) at the northern tip of the Hallett Peninsula (72° 19′ S, 170° 16′ E; Fig. 1b). At the northern tip of the Cape is the small spit of Seabee Hook (Fig. 1c), where a colony of Adélie penguins (*Pygoscelis adeliae*) is located.

The most recent estimate of the colony size is 39 000 breeding pairs, recorded in the breeding season 1998–1999 (Landcare Research, 2000). In addition to the breeding pairs, the colony also contains non-breeding adults and chicks. The colony occupies an area of approximately 33.2 ha covering most of the spit and part of the slopes of the Cape (Fig. 1c). During summer, the sea surrounding the spit partly melts, while to the east rise the steep slopes of the Hallett peninsula (Fig. 1b).

2.2. Measurements

During the experimental period (December 2005–January 2006), which was coincident with the penguin breeding season, mean atmospheric ammonia concentrations were measured at seven locations (Fig. 1c) using ALPHA passive diffusion samplers (Tang et al. 2001) mounted at a height of 1.5 m above ground. The height of 1.5 m was used so that the measurements were made close to the emitting surface but out of reach of the penguins. Samplers were exposed in triplicate at each site for three periods: 26th December 2005 to 10th January 2006, 11th to 17th and 17th to 23rd January 2006. Measurements at additional heights of 0.25,

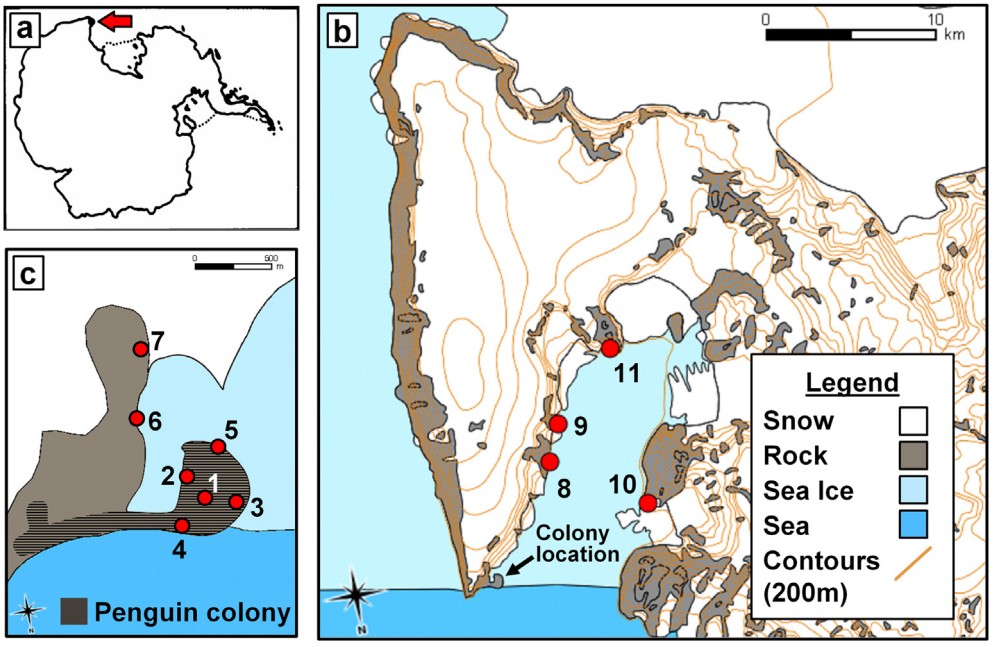

Fig. 1. Maps showing the locations of: a) the study site relative to the Antarctic continent; b) the Cape Hallett peninsula and c) the penguin colony. The numbered circles indicate the locations and site numbers of the ammonia concentration measurements. Note the rotated north directions in maps b and c. Land cover and contour data courtesy of the Antarctic Digital Database (ADD Consortium, 2000). Extent of sea ice and shape of Seabee Hook modified based on personal observations and aerial photographs, respectively.