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Nature of the Antarctic Peninsula Ice Sheet during the Pliocene: Geological evidence and modelling results compared

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ABSTRACT

In this paper, we examine the nature of the Pliocene Antarctic Peninsula Ice Sheet by comparing the terrestrial and marine geological records of the Antarctic Peninsula and surrounding sea floor with estimated net snow accumulation in the region derived from numerical palaeoclimate model experiments. Pliocene geological data and our new modelling results are consistent and mutually supportive in suggesting that an ice sheet was present even during the warmest episodes of the Pliocene. The combined results suggest that the ice sheet in the Antarctic Peninsula is more robust to globally warmer conditions than is generally assumed, at least up to the climatic limits examined in our study.

Contents

1. Introduction

Antarctica and the high southern latitudes have played a critical role in determining global climate change over much of the last 100 million years (Barker et al., 1998; Gersonde et al., 1999). Paradoxically, the intricate relationships and responses of Antarctic ice volume, eustatic sea level and ocean circulation to climatic change over geological timescales are poorly resolved. Due to anthropogenic modification of climate, determination of the scale and rapidity of changes affecting the Antarctic ice mass and the links with global climate change is vital (IPCC, 2007). Numerical models of the global

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atmosphere–ocean–biosphere and cryosphere are now sufficiently mature to test hypotheses derived from geological data, as well as providing mechanistic explanations for environmental change recognised in Antarctic geological records (e.g. Florindo and Siegert, 2008, and papers therein; Francis et al., 2008). In order to evaluate such models, we must examine archives of climatic change preserved in the geological record (on the million-year timescale) to determine the relationship between ice-sheet fluctuations and climatic change.

When planning to investigate past climates, regions in which large climate changes take place are generally more informative because the large signal to noise ratio means that the geological proxies used can more easily detect such changes. New proxy data acquired from these regions can enable us to carry out more rigorous tests of model simulations, resulting in better constraints on the various boundary conditions used to force the models (Lunt et al., 2008). The Antarctic Peninsula region and its ice sheet are believed to be particularly sensitive to climatic change (Barker et al., 2002). Observational records clearly demonstrate that over the last 50 years the Antarctic Peninsula has warmed substantially faster than the rest of Antarctica (Vaughan et al., 2001; Turner et al., 2002a; Vaughan et al., 2003). Thus, it seems likely that a similar climatic sensitivity probably affected the region in times past and, consequently, we might expect a more easily detectable signal in the geological proxies compared to regions characterised by greater climatic inertia. With this in mind, we have targeted the Antarctic Peninsula and, specifically, its climatically sensitive ice sheet, as an important test of modelling behaviour.

Although much is known about the modern Antarctic Peninsula Ice Sheet (APIS) and its behaviour during the Quaternary, particularly since the Last Glacial Maximum (LGM) (e.g. Lucchi et al., 2002; Heroy and Anderson, 2005; Bentley et al., 2006; Domack et al., 2006; Pudsey et al., 2006; Sugden et al., 2006 and references therein), what was the nature of the APIS during pre-Quaternary warm periods? In particular what was the nature of the APIS during the last period of significantly greater sustained global warmth, i.e. the Pliocene? Existing palaeoclimate modelling experiments for the Pliocene have not been prescribed with an Antarctic Peninsula Ice Sheet. Yet the melting APIS may contribute disproportionately to global sea levels (Nakada et al., 2000; Vaughan, 2006) and we may anticipate a similar response as global warmth climbs steadily in future decades.

The premise behind the configuration of land ice cover in published Pliocene climate models is that any sea-level rise sufficiently large to require a substantial reduction in the relatively ‘stable’ East Antarctic Ice Sheet must have had a more dramatic effect on the smaller and ‘less stable’ Greenland, West Antarctic and Antarctic Peninsula ice sheets. But how realistic is that configuration in reality? Haywood and Valdes (2004) identified that the principal forcing mechanism driving globally-warmer climates during the mid Pliocene may have been reduced terrestrial ice cover combined with feedbacks from clouds and a modest increase in concentration of CO_2 in the atmosphere. However, that result hinges on a realistic representation of global ice cover within the models. In addition, because of important variations in configuration of the individual interior drainage basins (e.g. Vaughan et al., 1999), the different parts of the Antarctic Ice Sheet might respond very differently to climate changes (e.g. Smellie et al., 2006b; Hill et al., 2007). In this paper, we examine the nature of the APIS during the Pliocene via examination of the geological record of the Antarctic Peninsula and offshore areas, together with snow accumulation estimates derived from numerical palaeoclimate model experiments. A particular focus is on the geological data derived from recent studies of the terrestrial outcrops, which we review in depth since they are not yet widely known but are uniquely capable of yielding otherwise unobtainable information on the thickness of past ice sheets. From our study, we are able to show that the geological proxy data and our modelling results are consistent and converge in suggesting that an APIS existed during the Pliocene warm period.

2. The Antarctic Peninsula and its ice sheet

The Antarctic Peninsula is a north–south-orientated, narrow sliver of continental crust extending over approximately 12° of latitude (1700 km) and a height that decreases from about 2500 to 1000 m a.s.l. in a northerly direction (Figs. 1 and 3). The local climate is relatively warm and wet in the west but is colder and drier in the east (Martin and Peel, 1978; Morris and Vaughan, 2003). Precipitation mainly by snow is particularly high along the crest and west side of the Peninsula, where it is about 3–4 times higher than other parts of Antarctica (Turner et al., 2002b; van Lipzig et al., 2004).

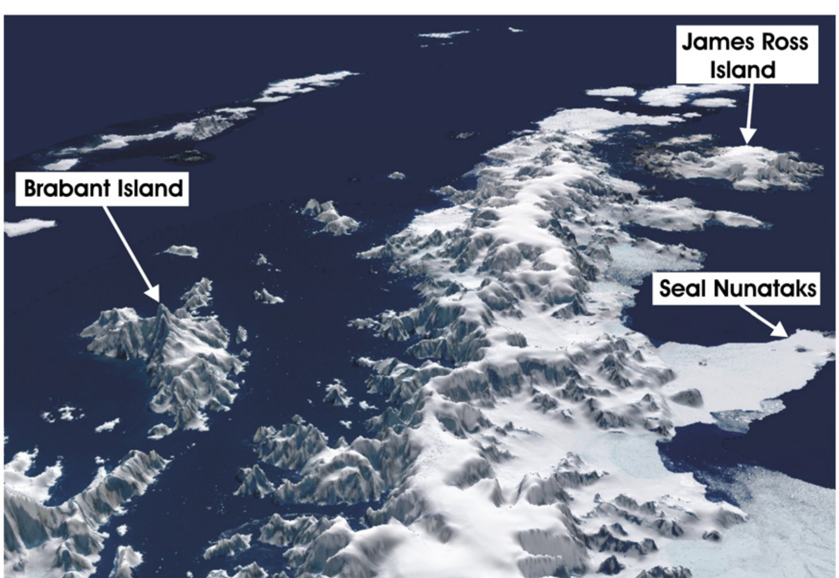

Fig. 1. Synthetic oblique aerial view of the northern tip of the Antarctic Peninsula, looking northeast, showing the locations of some of the terrestrial outcrops described (Brabant Island, James Ross Island and Seal Nunataks). The tall narrow spine of the Antarctic Peninsula and its draping ice sheet are evident, as is the prominent ice-capped Graham Land plateau (see Section 5). Four times vertical exaggeration.