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Exploring the MIS M2 glaciation occurring during a warm and high atmospheric CO_2 Pliocene background climate

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ABSTRACT

Prior to the Northern Hemisphere glaciation around ∼2.7 Ma, a large global glaciation corresponding to a 20 to 60 m sea-level drop occurred during Marine Isotope Stage (MIS) M2 (3.312–3.264 Ma), interrupted the period of global warmth and high CO_2 concentration (350–450 ppmv) of the mid Piacenzian. Unlike the late Quaternary glaciations, the M2 glaciation only lasted 50 kyrs and occurred under uncertain CO_2 concentration (220–390 ppmv). The mechanisms causing the onset and termination of the M2 glaciation remain enigmatic, but a recent geological hypothesis suggests that the re-opening and closing of the shallow Central American Seaway (CAS) might have played a key role. In this article, thanks to a series of climate simulations carried out using a fully coupled Atmosphere Ocean General Circulation Model (GCM) and a dynamic ice sheet model, we show that re-opening of the shallow CAS helps precondition the low-latitude oceanic circulation and affects the related northward energy transport, but cannot alone explain the onset of the M2 glaciation. The presence of a shallow open CAS, together with favourable orbital parameters, 220 ppmv of CO_2 concentration, and the related vegetation and ice sheet feedback, led to a global ice sheet build-up producing a global sea-level drop in the lowest range of proxy-derived estimates. More importantly, our results show that the simulated closure of the CAS has a negligible impact on the NH ice sheet melt and cannot explain the MIS M2 termination.

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1. Introduction

Despite absolute differences, most atmospheric carbon dioxide proxies point towards a drastic decrease associated with large cooling from the Late Eocene to the Quaternary (Pagani et al., 2005; Zachos et al., 2001). The first major atmospheric CO_2 threshold for ice sheet build-up is reached around 34 Ma, when the Antarctic glaciation began under CO_2 levels equivalent to about three times those of the preindustrial concentrations (DeConto and Pollard, 2003; Ladant et al., 2014; Gasson et al., 2014). The onset of extensive Northern Hemisphere glaciation occurred approximately 30 million years later around 3.0–2.7 Ma (Lunt et al., 2008), ultimately leading to the glacial–interglacial cycles of the Quaternary (e.g. Ganopolski and Calov, 2011). However, prior to this glaciation, a major ephemeral glacial event took place, the Marine Isotope Stage (MIS) M2 (3.312–3.264 Ma), producing a ∼0.5‰ shift of benthic foraminiferal $\delta^{18}O$ (Lisiecki and Raymo, 2005). The sea-level drop produced by this glacial event has been estimated at 20 to 60 m by different proxy estimates (Dwyer and Chandler, 2009; Miller et al., 2012; Naish and Wilson, 2009). As a comparison, 20–60 m sea level drop represents between one sixth and nearly half of the sea level drop during the Last Glacial Maximum. Therefore, the M2 ice sheets were not only confined to Greenland but must have spread over the Northern Hemisphere continents. Also, a contribution from an expanded Antarctic ice sheets is likely (detailed evidence for ice sheets during MIS M2 are summarised by De Schepper et al., 2014). Nevertheless, the M2 glaciation has some very peculiar characteristics with respect to Quaternary glaciations: first, this glacial event occurred in the interval of two long and stable warm periods and only lasted for ∼50 kyr, which is half the duration of recent Quaternary glacial cycles (e.g. Ganopolski and Calov, 2011). In the southern Hemisphere, the East Antarctic ice sheets were present and lasted during the mid-Piacenzian warm period (Hill et al., 2007), whereas the West Antarctic ice

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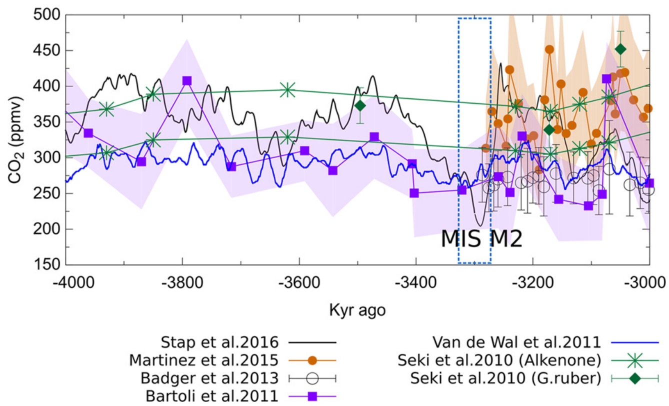

Fig. 1. Syntheses of reconstructed atmospheric CO_2 concentration from 4.0 to 3.0 Ma from different studies. The proxies from Martinez et al. (2015), Bartoli et al. (2011) and Seki et al. (2010) (green rhombus symbol) are boron-based data; The proxies from Badger et al. (2013) and Seki et al. (2010) (green asterisk symbol) are alkenone-based data. The reconstruction of Stap et al. (2016) and Van de Wal et al. (2011) are obtained by inversing benthic $\delta^{18}O$ routine with the climate and ice sheet model. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

sheets experienced waning and waxing during and after M2 period, since it is much more sensitive to the change of climate in the adjacent ocean margin (Riesselman and Dunbar, 2013); second, the proxy records show that the M2 event might occur under CO_2 concentrations ranging between 220 and 390 ppmv (Fig. 1); third, the summer insolation over the high-latitudes of the Northern Hemisphere is not particularly favourable for ice sheet inception during the M2 period (Laskar et al., 2004) (Fig. A.1). Together, these three characteristics raise the question whether the classical forcing factors of low CO_2 concentrations and/or low high-latitude insolation are sufficient to explain the MIS M2 glaciation or whether other additional driving factors are needed.

The role of the closure of the CAS on changes in ocean circulation and climate change during the Pliocene remains heavily debated (e.g. Brierley and Fedorov, 2016; Lunt et al., 2008). Although restriction of surface waters through the Central American Seaway might occur during the Early Pliocene (4.5–4.3 Ma) based on planktonic foraminifera data (e.g. Haug and Tiedemann, 1998), the final tectonic closure of the Central American Seaway might not occur until ~2 Ma (Jackson et al., 1993). During this long interval, the exchange of surface waters was probably constrained up to a 100-meters sill depth and dynamically affected by the glacial induced sea-level change (Groeneveld et al., 2014). Even such shallow water exchange might have had influenced the Northern Hemisphere climate. A study of De Schepper et al. (2013) put forward the hypothesis that a re-opening and closing of the shallow CAS may have triggered the onset and the termination of the M2 glaciation. This hypothesis provides for the first time an explanation for the formation and decay of the NH ice sheets during M2 in relation to tectonic and glacio-eustatic change. Based on dinoflagellate cysts and geochemical proxy data from different Ocean Drilling Project sites, they conjecture that a re-opening of the shallow CAS occurring before and during the M2 event allowed seawaters flowing from the Pacific to the Atlantic. The fresh and cold inflow seawater helped to weaken the North Atlantic circulation and to cool the northern high latitudes. Then the cooling was gradually amplified by the positive sea ice albedo feedback, the adaptation of vegetation to colder climates and pCO_2 changes, finally leading to substantial ice sheet growth in NH high latitudes De Schepper et al. (2013). Inversely, the large ice volume accumulated over land would then produce a sea-level drop large enough to close the CAS. Following this glacio-eustatic closure, the ocean circulation shifted to its modern state and warmed the northern high latitudes, triggering the deglaciation. This hypothesis has gained a lot of attention because it provides an explanation both for the onset and the termination of the M2 glaciation. Moreover, this seaway hypothesis would better fit the short duration of the M2 glaciation comparing to other long-term geological processes and the glacio-eustatic closure corresponds well to the sea-level drop estimates (20–60 m).

Unlike the mid-Pliocene Warm Period (ca. 3.3 to 3.0 Ma, mPWP), which is well documented in marine data (Dowsett et al., 2012), continental records (Salzmann et al., 2008) and model studies (Haywood et al., 2016 and reference therein), the M2 event is very poorly understood and suffers from a lack of modelling studies. Only the recent work of Dolan et al. (2015) study the M2 glaciation in a modelling framework. In their study, they implement plausible ice sheet configurations into a coupled atmosphere–ocean climate model to test whether larger-than-modern ice sheets in both hemispheres might exist during M2. They demonstrate that a larger-than-modern imposed ice sheets during the M2 period is more compatible with the marine proxy records, but they do not attempt to study the underlying mechanisms for M2 glaciation.

In this contribution, we performed a series of simulations using the IPSL-CM5A ocean/atmosphere GCM (Dufresne et al., 2013) and ice sheet model GRISLI (Ritz et al., 2001) (see Methods) first to explore whether the sole geological hypothesis of the re-opening and closure of the CAS can fully explain the M2 event, and second to quantify the maximum ice sheet scenario that our model can simulate for the M2 glaciation.

2. Method

2.1. Models

The climate model used in this study is the IPSL-CM5A atmosphere–ocean general circulation model (AOGCM). The atmosphere component is the LMDZ5A version of the LMDz model (including the ORCHIDEE land-surface model) with a resolution of 3.75° × 1.875° and 39 vertical layers. More details about the physical parameterisation can be found in Hourdin et al. (2006). The ocean model is NEMOv3.2 including the ORCA2.3 ocean configuration (Madec, 2008), which uses a tri-polar global grid. There are 31 unequally spaced vertical levels and a nominal resolution of 2° that is refined up to 0.5° in the equatorial area. The atmosphere and ocean models are linked through the coupler OASIS, ensuring energy and water conservation. Additional details about the IPSL-CM5A model can be found in Dufresne et al. (2013). The IPSL-CM5A model has been used in the framework of CMIP5 for historical and future simulations (Dufresne et al., 2013) as well as for paleo-climate studies, like Quaternary (Kageyama et al., 2013) and Pliocene (Contoux et al., 2012) simulations.

The ice sheet model used in this study is the GRenoble Ice-Shelf and Land-Ice model (GRISLI). GRISLI is a three-dimensional thermo-mechanical model, which simulates the evolution of ice sheet geometry (extension and thickness) and the coupled temperature–velocity fields in response to climate forcing. A comprehensive description of the model can be found in Ritz et al. (2001). The equations are solved on a Cartesian grid (40 km × 40 km) and solved with a semi-implicit temporal scheme and a point relaxation method. The principle time step is 5 years, a short time step utilised for the mass-conservation equation is between 0.002 year and 1 year, which is adjustable and depends on the maximum velocity found over the whole domain. Over the grounded part of the ice sheet, the ice flow resulting from internal deformation is governed by the shallow-ice approximation. The model also deals with ice flow through ice shelves using the shallow-shelf approximation and predicts the large-scale characteristics of ice streams

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