Earth and Planetary Science Letters 424 (2015) 295–305

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

Modelling Greenland ice sheet inception and sustainability during the Late Pliocene

C. Contoux [a,*], C. Dumas [b], G. Ramstein [b], A. Jost [c,d], A.M. Dolan [e]

[a] Aix-Marseille Université, CNRS, IRD, CEREGE UM34, Aix-en-Provence, France
[b] Laboratoire des Sciences du Climat et de l'Environnement/IPSL, CEA/CNRS/UVSQ, Gif-sur-Yvette Cedex, France
[c] Sorbonne Universités, UPMC Université Paris 06, UMR 7619, Metis, 75005 Paris, France
[d] CNRS, UMR 7619, Metis, 75005 Paris, France
[e] School of Earth and Environment, University of Leeds, Woodhouse Lane, Leeds LS29JT, UK

ARTICLE INFO

Article history:
Received 15 September 2014
Received in revised form 7 May 2015
Accepted 11 May 2015
Available online 2 June 2015
Editor: J. Lynch-Stieglitz

Keywords:
Greenland ice sheet
Pliocene
paleoclimate modelling
ice sheet modelling

ABSTRACT

Understanding the evolution and dynamics of ice sheet growth during past warm periods is a very important topic considering the potential total removal of the Greenland ice sheet. In this regard, one key event is the full glaciation of Greenland that occurred at the end of the Pliocene warm period, which remains partially unexplained. Previous modelling studies succeeded in reproducing this full glaciation either by imposing an unrealistically low CO_2 value or by imposing a partial ice sheet over the surface of Greenland. Although they highlight some fundamental mechanisms, none of these studies are fully satisfactory because they do not reflect realistic conditions occurring during the Late Pliocene. Through a series of simulations with the IPSL-CM5A coupled climate model used to force the GRISLI ice sheet model, we show that a drop in CO_2 levels does not lead to an abrupt inception of the Greenland ice sheet. High ablation rates in central and northern Greenland combined with low accumulation prevent such an abrupt inception. Ice sheet inception occurs when low summer insolation and CO_2 levels below modern values are combined, the Greenland ice sheet being restricted to the southeast region, where high topography favours this build-up. This ice sheet experiences only partial melting during summer insolation maxima combined with high CO_2 levels. Further growth of the ice sheet with recoupling experiments is important at 360 and 280 ppm during insolation minima. Thus, the full glaciation at 2.6 Ma could be the result of a cumulative build-up of the Greenland ice sheet over several orbital cycles, leading to progressively more intense glaciations during low summer insolation periods. Although this result could be a shortcoming of the modelling framework itself, the gradual glacial inception interpreted from the oxygen isotope record could support our scenario.

1. Introduction

1.1. The story of the Greenland ice sheet from the Miocene to the Pleistocene

The very beginning of ice cover on Greenland is thought to date back to the late Miocene, with the build-up of an ice sheet on southern Greenland (e.g. Wolf and Thiede, 1991), which was made possible by the mountain uplift in southern and eastern Greenland (e.g. Japsen et al., 2006; Solgaard et al., 2013). This was followed by a gradual intensification of glaciation starting in the Late Pliocene, at around 3.6 Ma (Mudelsee and Raymo, 2005), peaking during Marine Isotope Stage (MIS) M2 around 3.3 Ma, and much lower ice volume during the mid-Piacenzian warm period, between 3.3 and 3 Ma (see De Schepper et al., 2014, for a review), central Greenland being most probably deglaciated after MIS M2 (Bierman et al., 2014). Ice-rafted debris in the North Atlantic (Ocean Drilling Program site 907) depicts an intensification of glacial intervals on Greenland at 3.3 Ma and at 3.1–2.9 Ma (Jansen et al., 2000; Kleiven et al., 2002). The first ice-rafted debris peak at 3.3 Ma is well correlated to the peak increase in $\delta^{18}O$ of benthic foraminifera at MIS M2 (Lisiecki and Raymo, 2005; Mudelsee and Raymo, 2005). MIS M2 was accompanied by mean sea levels estimated to be lower than the present-day value (De Schepper et al., 2014), and is sometimes called a 'failed glaciation', which could be due to a southward shift of the North Atlantic Current driven by reduction of Pacific to Atlantic water flow through the Central American Seaway (De Schepper et al., 2009, 2013). After MIS M2, during the mid-Piacenzian warm period,

* Corresponding author.
E-mail address: contoux@cerege.fr (C. Contoux).

http://dx.doi.org/10.1016/j.epsl.2015.05.018

global ice volume was much reduced, as shown by sea level estimates of around +10 to +40 m (Raymo et al., 2011), with a most probable mean value of 25 ± 5 m (Dwyer and Chandler, 2009; Miller et al., 2012; Rovere et al., 2014). The Greenland ice sheet (GrIS) inception was thus not a short-term, single event, but rather followed a gradual long-term trend from 3.6 to 2.4 Ma (Mudelsee and Raymo, 2005), and with an anomalous event, the MIS M2 glaciation. Large-scale Northern Hemisphere glaciation then occurred around 2.7–2.5 Ma (Lisiecki and Raymo, 2005), or potentially later around 2.15 Ma (Rohling et al., 2014). This event determines the transition from the globally warm Neogene to the Quaternary climate oscillations of the glacial/interglacial cycles.

1.2. Assessing the GrIS during the Late Pliocene

Assessing the extent, volume and location of the GrIS during the Late Pliocene is important for two reasons. First, because of the multistability of ice sheets (e.g. Solgaard and Langen, 2012), the initial state of the cryosphere on Greenland would modify the conditions necessary to form a large Greenland glaciation around 2.6 Ma. In other words, if Greenland was completely deglaciated during the Late Pliocene, the CO_2 level necessary to fully glaciate it at 2.6 Ma would be lower than if Greenland was partially glaciated. Second, a more accurate extent of the GrIS is needed to be used as a boundary condition in climate modelling studies of the Late Pliocene, in particular for the second phase of the Pliocene Model Intercomparison Project (PlioMIP), which will focus on a narrower time slice (Haywood et al., 2013b).

Most previous studies investigating Plio-Pleistocene Greenland glaciation or sensitivity of the Pliocene GrIS assumed that Greenland was already partially glaciated. They used the PRISM2 (e.g. Lunt et al., 2008; Hill et al., 2010; Dolan et al., 2011) or PRISM3 (Yan et al., 2014) boundary conditions, for which GrIS volume is fixed to almost 50% of its present-day volume and covers about a third of Greenland, including its centre. Notably, using the PRISM2 boundary conditions, Lunt et al. (2008) demonstrated that a CO_2 decline to 280 ppm was causing Greenland to be fully glaciated. The same experimental design was used by Dolan et al. (2011) to study GrIS extent changes related to insolation variations during the mid-Piacenzian warm period with the BASISM ice sheet model. Dolan et al. (2011) found that during periods of high summer insolation, the GrIS vanishes, while its volume is around 35% of the present-day volume during periods of low summer insolation at 65°N. The PRISM2 ice sheet used as a boundary condition in the coupled climate model HadCM3 in Lunt et al. (2008) and Dolan et al. (2011), should help to further glaciate Greenland in the ice sheet model during low summer insolation periods. In contrast, the Dolan et al. (2011) simulated ice sheet is smaller than the PRISM2 and PRISM3 ice sheets, revealing that neither the PRISM2 ice sheet nor the PRISM3 ice sheet could survive in the Pliocene simulated climate. The same applies to the work of Lunt et al. (2008), where the simulated ice sheet in Pliocene control conditions is much smaller than the imposed PRISM2 GrIS boundary condition. The PRISM2 reconstruction was based initially on sea level estimates and the estimated contribution of the Antarctic ice sheet to the sea level rise (Dowsett et al., 1999), providing a pioneering estimate of Greenland ice volume during the Late Pliocene. It was later refined for PRISM3, by modelling the GrIS with the BASISM ice sheet model forced with the Pliocene climate simulated by the atmospheric model HadAM3, which was itself forced with the PRISM2 sea surface temperatures, topography and GrIS reconstruction (Hill, 2009). These reconstructions assume the presence of an ice sheet over central Greenland during the mid-Piacenzian warm period, which is highly uncertain in the light of recent results (Bierman et al., 2014; Koenig et al., 2015). In particular, using the PlioMIP climate ensemble, Koenig et al. (2015) have demonstrated that the presence of ice during the warm Pliocene must have been restricted to high-topography regions in eastern and southern Greenland.

Thanks to a large climate modelling effort followed by data–model comparisons, the PlioMIP showed that the mid-Piacenzian time period was globally warmer than today, with important warming in the high latitudes, and warming of more than 10 °C on the deglaciated parts of Greenland (Haywood et al., 2013a; Dowsett et al., 2013). The vegetation reconstructions compiled by Salzmann et al. (2008, 2013) describe evergreen taiga on the northeastern tip of Greenland, and alternating evergreen taiga/cool conifer forest off the southern tip of Greenland, attesting of a much warmer climate than at present in these areas. In addition, a recent study of lacustrine sediments of Lake El'gygytgyn, which is situated in northeastern Russia, provides temperature estimates around 7–8 °C warmer than today between 3.6 and 3.4 Ma, and around 3–6 °C warmer between 3.26 and 2.2 Ma (Brigham-Grette et al., 2013). Although PRISM2 and PRISM3 reconstructions assumed that a subsequent ice sheet was already covering Greenland during the Pliocene, such elevated temperatures in the high latitudes seem unfavourable for the build-up of a sustainable ice sheet over Greenland. This view is supported by a transient modelling study by Berger et al. (1999) combining insolation variations and a linear decrease of CO_2 atmospheric concentration during the Plio-Pleistocene. Their study shows that between 3 and 2 Ma, Northern Hemisphere ice sheets could not develop during small eccentricity periods, during which insolation is never low enough to allow ice to grow. They show that during the Pliocene, ice sheets could be created only during high-eccentricity insolation minima and should melt during the following high-eccentricity insolation maxima. More recently, Koenig et al. (2011) showed that the growth of a GrIS during the Late Pliocene depended on the orbital configuration and CO_2 level, full glacial conditions being obtained with 200 ppm of CO_2 combined with low summer insolation. Reconstructions of pCO_2 for the Pliocene differ greatly among studies, from low values around 280 ppm (Bartoli et al., 2011; Badger et al., 2013) to high values around 410 ppm (Bartoli et al., 2011; Seki et al., 2010), while glacial–interglacial cycles during the Pliocene might be accompanied by atmospheric CO_2 variations with amplitude of 50–100 ppm (Bartoli et al., 2011; Badger et al., 2013).

These studies demonstrate the need to further investigate what conditions would have been able to initiate the GrIS inception during the Late Pliocene, as well as its sustainability through the climate variability of this period, in order to understand what conditions could have finally led to the full glaciation of Greenland at the Pliocene–Pleistocene boundary. To answer these questions, we chose to test the impact on GrIS inception of imposing three different CO_2 levels in the range of the reconstructions (405, 360 and 280 ppm), combined with a preindustrial, favourable or unfavourable orbit in our climate model starting first from deglaciated conditions. Second, we tested the sustainability of the ice sheet in warmer conditions. Finally, we tested the possibility of further growth of the ice sheet using cold conditions. These experiments allow us to characterise the conditions leading to a full glaciation over Greenland.

2. Method

We used a set of Pliocene climates simulated with a fully coupled atmosphere–ocean general circulation model, IPSL-CM5A (Marti et al., 2010; Dufresne et al., 2013), to force the GRISLI ice sheet model (Ritz et al., 2001). CO_2 levels, insolation and ice sheet boundary conditions were modified in the various Pliocene climate simulations, and all simulations (climate and ice sheets) were