Earth and Planetary Science Letters 466 (2017) 129–138

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

Amplified Late Pliocene terrestrial warmth in northern high latitudes from greater radiative forcing and closed Arctic Ocean gateways

Ran Feng[a,*], Bette L. Otto-Bliesner[a], Tamara L. Fletcher[b], Clay R. Tabor[a], Ashley P. Ballantyne[b], Esther C. Brady[a]

[a] National Center for Atmospheric Research, 1850 Table Mesa Drive, Boulder, CO, 80305, USA
[b] University of Montana, Missoula, MT, 59812, USA

ARTICLE INFO

Article history:
Received 15 September 2016
Received in revised form 31 January 2017
Accepted 5 March 2017
Available online xxxx
Editor: H. Stoll

Keywords:
Late Pliocene climate
glacial–interglacial variation in insolation
cluster analysis
terrestrial temperature reconstructions
polar amplification

ABSTRACT

Proxy reconstructions of the mid-Piacenzian warm period (mPWP, between 3.264 and 3.025 Ma) suggest terrestrial temperatures were much warmer in the northern high latitudes (55°–90°N, referred to as NHL) than present-day. Climate models participating in the Pliocene Model Intercomparison Project Phase 1 (PlioMIP1) tend to underestimate this warmth. For instance, the underestimate is ∼10 °C on average across NHL and up to 17 °C in the Canadian Arctic region in the Community Climate System Model version 4 (CCSM4). Here, we explore potential mPWP climate forcings that might contribute to this mPWP mismatch. We carry out seven experiments to assess terrestrial temperature responses to Pliocene Arctic gateway closure, variations in CO_2 level, and orbital forcing at millennial time scale.

To better compare the full range of simulated terrestrial temperatures with sparse proxy data, we introduce a pattern recognition technique that simplifies the model surface temperatures to a few representative patterns that can be validate with the limited terrestrial proxy data. The pattern recognition technique reveals two prominent features of simulated Pliocene surface temperature responses. First, distinctive patterns of amplified warming occur in the NHL, which can be explained by lowered surface elevation of Greenland, pattern and amount of Arctic sea ice loss, and changing strength of Atlantic meridional overturning circulation. Second, patterns of surface temperature response are similar among experiments with different forcing mechanisms. This similarity is due to strong feedbacks from responses in surface albedo and troposphere water vapor content to sea ice changes, which overwhelm distinctions in forcings from changes in insolation, CO_2 forcing, and Arctic gateway closure.

By comparing CCSM4 simulations with proxy records, we demonstrate that both model and proxy records show similar patterns of mPWP NHL terrestrial warmth, but the model underestimates the magnitude. High insolation, greater CO_2 forcing, and Arctic gateways closure each contributes to reduce the underestimate by enhancing the Arctic warmth of 1–2 °C. These results highlight the importance of considering proxy NHL warmth in the context of Pliocene Arctic gateway changes, and variations in insolation and CO_2 forcing.

1. Introduction

The mid-Piacenzian warm period (mPWP, between 3.264 and 3.025 Ma, Dowsett et al., 2010) features a distinctive climate state. Global geography and surface elevations are similar to present-day, yet climate as a whole is warmer by 1.9–3.6 °C based on combined proxy and model estimates (e.g. Haywood and Valdes, 2004; Masson-Delmotte et al., 2013). One remarkable feature of the mPWP is the strongly amplified arctic warming despite moderate CO_2 levels. The reconstructed CO_2 levels for mPWP range from pre-industrial to 500 ppm, with a best estimate of 350 to 450 ppm (e.g. Masson-Delmotte et al., 2013; Haywood et al., 2016a). Fossil pollen, plant records, and insect assemblages suggest boreal forests and warm conditions across the Canadian Arctic and Eastern Russia during the Pliocene (5.33–2.58 Ma) (Ballantyne et al., 2010, 2013; Elias and Matthews, 2002; Salzmann et al., 2008, 2013), which are currently occupied by tundra and permafrost. Quantitative reconstructions further suggest mean annual temperatures of northern high latitudes are above freezing (Salzmann et al., 2013; Ballantyne et al., 2010, 2013). While inde-

---

* Corresponding author.
E-mail address: rfeng@umich.edu (R. Feng).

http://dx.doi.org/10.1016/j.epsl.2017.03.006

pendent proxy estimates converge on the strong Arctic warming, much greater than the global mean warming during the mPWP, coupled atmosphere–ocean climate simulations reproduce only a small amount of this amplified warming (Haywood et al., 2013). Temperature underestimates range from a few to up to 18 °C across northern high latitudes in model simulations with PlioMIP1 boundary conditions (Dowsett et al., 2010; Haywood et al., 2010), including HadCM3, MIROC, and CCSM4 (Haywood et al., 2013; Salzmann et al., 2013). This large discrepancy between model results and proxy data may limit confidence in model predictions of future warming across northern high latitudes.

Uncertainties in geological reconstructions of boundary and forcing conditions used by climate models have been proposed to resolve the underestimates of Pliocene circum-Arctic warming in the coupled models. Reported terrestrial biomes for the mPWP represent a time slab that overlaps, but is much longer than, the targeted mPWP. As a result, these records could correspond to a variety of insolation and CO_2 forcings that are not represented by the prescribed orbital parameters (modern) and CO_2 level (405 ppm) in PlioMIP1 (Haywood et al., 2010). Within the mPWP time slab, the summer insolation varies by up to 89 W/m^2 and the annual insolation varies by 1.6 W/m^2 at 65°N (Laskar et al., 2004). Variation of summer and annual insolation at millennial time scale is known to be important for high latitude climates (e.g. Tabor et al., 2015; Prescott et al., 2014). This insolation variation may account for some of the proxy warming in the northern high latitudes, especially if terrestrial proxies are sampling towards high productivity periods (Prescott et al., 2014; Salzmann et al., 2013). The CO_2 level declines from over 500 ppm to pre-industrial levels through the Pliocene and varies by reconstruction methods (Martínez-Botí et al., 2015). The uncertainty range is over 100 ppm at almost any given Pliocene time period (See discussion of records by Haywood et al., 2016a).

Variations in both CO_2 and orbital forcing have been shown to be important for explaining the PlioMIP1 model-proxy data mismatches. Salzmann et al. (2013) and Howell et al. (2016b) investigated terrestrial surface temperature sensitivity to extremes of mPWP insolation and CO_2 forcing of northern high latitudes; their results highlight the importance of these forcings in improving the model-proxy data comparison. Further, Prescott et al. (2014) performed a series of simulations using HadCM3 to simulate interglacial periods of mPWP climate. The results show high sensitivity of Arctic surface temperatures to orbitally-driven insolation variations, especially at seasonal time scale (up to 20 °C). Finally, Willeit et al. (2013) investigated variability of Pliocene climate to orbital forcing in a transient simulation with dynamical ice sheet and vegetation using an intermediate complexity model. In their results, simulated summer temperatures in the high latitudes approach proxy temperatures only during the interglacial periods of Pliocene.

Uncertainties in mPWP geography, in particular whether Arctic Ocean gateways are open or closed, can have strong effects on mPWP climate by changing ocean circulation and freshwater transport (Otto-Bliesner et al., 2016). Published simulations from PlioMIP1 use boundary conditions that were derived from Pliocene Research, Interpretation and Synoptic Mapping paleoenvironmental reconstructions (PRISM3D, Dowsett et al., 2010). Many modeling groups adopted modern geography and bathymetry since it is difficult for some complex climate models to alter the land/sea mask. During the second phase of PlioMIP (PlioMIP2), two ocean gateway changes around the Arctic are highlighted (i.e. closure of both the Bering Strait and Straits in the Canadian Arctic Archipelago) (Dowsett et al., 2016). Additional, but less constrained changes to Pliocene paleogeography may come from replacing the Barents Sea with land (Butt et al., 2002; Knies et al., 2009), a deeper undersea Greenland–Scotland–Iceland ridge (Robinson et al., 2011), and an extended drainage basin of the Hudson Bay (Duk-Rodkin and Hughes, 1994). Individual or a combination of these paleogeographic changes are shown to strengthen the Atlantic Meridional Overturning Circulation (AMOC) and/or redirect the north Atlantic currents, which subsequently warm the northern North Atlantic in excess of 5 °C (Robinson et al., 2011; Hill, 2015).

In this study, we provide a systematic evaluation of northern high latitude (NHL, stands for 55°–90°N region) terrestrial climate responses to mPWP variations in orbital and CO_2 forcing, and Pliocene Arctic gateway changes using the CCSM4 model. A separate study by Otto-Bliesner et al. (2016) evaluates oceanic responses to Pliocene Arctic gateway closure. Although climate responses to some of these forcings have been reported for the HadCM3 model, a systematic synthesis and comparison is lacking, and model-proxy data comparison is mainly based on individual sites (Salzmann et al., 2013; Hill, 2015; Howell et al., 2016b). The use of CCSM4 and our new approach of model-proxy data comparison utilizing pattern recognition techniques provide independent and comprehensive evaluations of the gap between model and proxy data for the NHL terrestrial temperatures. We conduct a series of model experiments to quantify terrestrial temperature and sea ice responses to individual forcing mechanisms. We have also compiled NHL terrestrial proxy temperatures to provide a benchmark for our CCSM4 experiments by integrating previous compilations of Salzmann et al. (2013), Ballantyne et al. (2010, 2013), and more recent records (Pound et al., 2015; Panitz et al., 2016; Fletcher et al., 2017, personal communication). Large-scale results, patterns of simulated changes in surface temperature responses, comparison with terrestrial proxy data, and responses of NHL energy budget to these imposed Pliocene climate forcings are further analyzed and discussed.

2. Methods

2.1. Experiments

Seven experiments are conducted with the coupled CCSM4 model, including the upper end of Pliocene variations in CO_2 level (450 ppm: PlioHCO2) (Seki et al., 2010; Haywood et al., 2016a), extremes in orbital forcing (65°N July maximum: $\mathrm{PlioMaxInso_{July}}$; 65°N July minimum: $\mathrm{PlioMinInso_{July}}$; 65°N annual maximum: $\mathrm{PlioMaxInso_{ann}}$) (Laskar et al., 2004), and closure of the Bering Strait (PlioBSC), the Canadian Arctic Archipelago Straits (PlioCAA), and combined closure of both gateways (PlioCAA+BSC) (Otto-Bliesner et al., 2016). Changes in boundary conditions and abbreviations for individual experiments are listed in Table 1. CCSM4 (Gent et al., 2011) is comprised of four dynamical model components: Community Atmospheric Model version 4 (CAM4), the Community Land Model version 4 (CLM4), Community Ice CodE version 4 (CICE4), and Parallel Ocean Program version 2 (POP2). As in Rosenbloom et al. (2013), all model components are coupled. Pliocene vegetation types are prescribed based on the Salzmann et al. (2008) compilation. The carbon–nitrogen biogeochemistry component of CLM4 allows the vegetation phenology to be impacted by the modeled climate conditions.

We run CCSM4 with a finite volume dynamical core at 0.9 × 1.25° horizontal resolution of the atmosphere and the displaced Greenland pole grid with an average ~1.11 × 0.54° horizontal resolution of the ocean (Gent et al., 2011). The model features 26 (surface to 3.5 hPa) and 60 vertical levels of the atmosphere and ocean, respectively. The model resolution is the highest among all the participating models in PlioMIP1 (Haywood et al., 2013). The experiments are branched from CCSM4 PlioMIP1 simulations (Rosenbloom et al., 2013) and run for at least 200 model years each, until the experiments reach near equilibrium with top of the atmosphere energy imbalance below 0.1 W/m^2 and trends of