Earth and Planetary Science Letters 461 (2017) 96–104

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

The influence of true polar wander on glacial inception in North America

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ARTICLE INFO

Article history:
Received 6 March 2016
Received in revised form 16 October 2016
Accepted 22 December 2016
Available online 12 January 2017
Editor: B. Buffett

Keywords:
glacial inception
polar wander
Cenozoic
climate

ABSTRACT

The impact that long-term changes in Earth's rotation axis relative to the surface geography, or true polar wander (TPW), and continental drift have had in driving cooling of high-latitude North America since the Eocene is explored. Recent reanalyses of paleomagnetic pole positions suggest a secular drift in Earth's rotation axis of ∼8° over the last 40 Myr, in a direction that has brought North America to increasingly higher latitudes. Using modern temperature data in tandem with a simple model, a reduction in the annual sum of positive degree days (PDDs) driven by this polar and plate motion over the last 20 Myr is quantified. At sites in Baffin Island, the TPW- and continental drift-driven decrease in insolation forcing over the last 20 Myr rivals changes in insolation forcing caused by variations in Earth's obliquity and precession. Using conservative PDD scaling factors and an annual snowfall equal to modern station observations, the snowiest location in Baffin Island 20 Myr ago had a mass balance deficit of $\sim 0.75–2\ \mathrm{m\,yr^{-1}}$ (water equivalent thickness) relative to its projected mass balance at 2.7 Ma. This mass balance deficit would have continued to increase as one goes back in time until ∼40 Myr ago based on adopted paleopole locations. TPW and continental drift that moved Arctic North America poleward would have strongly promoted glacial inception in Baffin Island at ∼3 Ma, a location where the proto-Laurentide Ice Sheet is thought to have originated.

1. Introduction

The fossil record in North America shows evidence of a long-term secular cooling over the past 65 Myr. This cooling began at a time when much of Earth's climate was relatively warm and culminated in the glacial cycles of the Pleistocene. In contrast to the polar desert with sparse vegetation that exists today, 50 Myr ago flora and fauna in the northernmost islands of the Canadian Arctic Archipelago reflected the presence of a temperate climate with high rainfall (e.g., Francis, 1988; McKenna, 1980; Basinger et al., 1994). Compilations of oxygen isotope (δ^{18}O) values from benthic foraminerfera found in globally-distributed deep-sea cores also provide evidence of a global secular cooling trend throughout the Cenozoic (e.g., Zachos et al., 2001). Oxygen isotope values record changes in both deep-sea temperatures and ice volume (e.g., Shackleton, 1987), and show variability over a range of timescales. In addition to an observed long-term trend, oxygen isotope values show higher frequency variability (10^4–10^6 yr) that is related to changes in Earth's orbital parameters, i.e., precession, obliquity, eccentricity (e.g., Hays et al., 1976; Imbrie et al., 1992). While changes in the amount and distribution of insolation driven by variations in Earth's orbital parameters have been correlated with glacial and interglacial cycles (Milankovitch, 1941; Imbrie et al., 1992; Huybers and Wunsch, 2005), these changes in insolation alone appear not to have been responsible for glacial inception in North America ∼3 Ma (Shackleton and Opdyke, 1977). In particular, orbital solutions indicate generally consistent insolation variability over the last 30 Myr (Laskar et al., 2004), and minimum values for Northern Hemisphere insolation during the Pleistocene are comparable to those seen at earlier times during the Cenozoic.

Other mechanisms thought to have played a role in shaping Cenozoic climate include changes in the concentration of atmospheric greenhouse gases, and a number of slow processes that are tectonic in origin. Long-term records show a large (>500 ppm) and variable decline in atmospheric CO_2 concentrations since 50 Ma, reaching values below 500 ppm after ∼25 Ma that have been

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http://dx.doi.org/10.1016/j.epsl.2016.12.036

relatively stable in comparison to the aforementioned decline (Pearson and Palmer, 2000; Pagani et al., 2005; Beerling and Royer, 2011; Zhang et al., 2013; Martínez-Botí et al., 2015). Numerical modeling suggests that declining levels of atmospheric CO_2 could have been an important driving mechanism for Cenozoic glaciation of Antarctica ~34 Ma (DeConto and Pollard, 2003), and an intensification of Northern Hemisphere glaciation during the Plio-Pleistocene Transition (Lunt et al., 2008; Willeit et al., 2015). A sharp decline in atmospheric CO_2 on the order of 100 ppm could have led to conditions favorable for glacial inception in North America through reduced radiative forcing during the Plio-Pleistocene Transition (PPT). However, whether such a decline occurred is difficult to establish with confidence given that different estimates of CO_2 spanning the same time period are uncertain to within at least 200 ppm (e.g., Pagani et al., 2010; Seki et al., 2010; Willeit et al., 2015). As for the role of CO_2 in driving long-term Cenozoic climate change, a clearer link exists during the early Cenozoic when declining levels of atmospheric CO_2 were coincident with a long-term secular cooling trend. However, during the late Oligocene and Miocene, atmospheric pCO_2 was relatively low and stable during periods of both high-latitude cooling and global warming (Pagani et al., 2005; Zhang et al., 2013).

Tectonic processes are plausible candidates as drivers for climate change over long timescales, since these are inherently linked to mantle convection, a process that evolves over millions of years. Movement of the Earth's tectonic plates drives continental drift and sea-floor spreading, which reflect horizontal motions, as well as vertical displacements caused by rifting and orogeny. Mantle flow can also drive large-scale vertical displacements of the Earth's tectonic plates, known as dynamic topography (Hager, 1984; Mitrovica et al., 1989; Gurnis, 1992). Changes in paleogeography could have had an important effect on the observed global cooling of Cenozoic climate by altering oceanic and atmospheric circulation (e.g., Raymo, 1994). Tectonically driven events thought to be responsible for such changes include the opening of a circum-Antarctic seaway (Kennett, 1977; Lawver and Gahagan, 2003) and elevation of both the Tibetan–Himalayan and Sierra–Coloradan regions (Ruddiman and Raymo, 1988). In addition, uplift of the Tibetan plateau could have led to higher erosion rates, resulting in increased carbon sequestration and subsequent cooling of global climate (Raymo and Ruddiman, 1992). Prior to the closure of the Indonesian seaway 3–4 Myr ago, a warmer eastern tropical Pacific and permanent El Niño state could have increased heat transport to North America through atmospheric teleconnections, inhibiting glaciation (Cane and Molnar, 2001; Huybers and Molnar, 2007). The creation of the Isthmus of Panama during the Pliocene, and its impact on ocean circulation, have also been cited as a mechanism for Northern Hemisphere cooling and glaciation (Driscoll and Haug, 1998; Haug and Tiedemann, 1998), however the significance and precise timing of these events remain highly contentious (Molnar, 2008).

The mechanisms described above may have acted together to drive Cenozoic cooling, and numerical modeling has provided some insight into their relative importance. For example, Bradshaw et al. (2012) used a fully coupled atmosphere–ocean–vegetation simulation to examine the effect of changing paleogeography and atmospheric CO_2 concentrations in reproducing late Miocene climate. They found that while changing paleogeography did impact their results, atmospheric CO_2 concentrations at the higher end of the range of estimates were required to explain a warmer late Miocene climate relative to present-day.

In this paper we consider another process that has the potential to significantly alter climate, namely true polar wander (TPW), and focus on its possible role in the inception of North American glaciation. TPW refers to a motion of the rotation axis relative to the Earth's surface and it has a direct impact on climate by changing the latitude (and thus insolation history) of all points on the surface. This process has previously been proposed as a mechanism for secular cooling of North America during the Cenozoic (Donn and Shaw, 1977), however paleomagnetic inferences of TPW from the 1970s (Jurdy and Van der Voo, 1975) suggested that polar motion, and its effect on climate, would have been minor since the beginning of the Cenozoic. In this paper we revisit this possible connection using a recently updated estimate of TPW since the Late Cretaceous and simple models of North American climate.

2. True polar wander and climate

In addition to changes in a planet's rotation axis in space (e.g., obliquity, precession), large excursions of the rotation axis relative to the surface geography are possible (Gold, 1955; Goldreich and Toomre, 1969). This reorientation of the rotation pole, or TPW, results from any mass redistribution within the Earth system, and it occurs over a wide range of time scales. For example, ice age surface mass (ice plus ocean) flux, and the associated glacial isostatic adjustment of the solid Earth, drives TPW with time scales of 10^3–10^5 yr (e.g., Sabadini and Peltier, 1981; Wu and Peltier, 1984). This ice-age-induced polar motion is characterized by relatively small (~0.1°) oscillatory changes in Earth's rotation axis, with no secular component (Chan et al., 2015). In contrast, the redistribution of density heterogeneities within the Earth's mantle by thermo-chemical convection can drive large amplitude ($>10°$) oscillatory (Creveling et al., 2012) and secular (e.g., Spada et al., 1992; Ricard et al., 1993; Steinberger and O'Connell, 1997; Doubrovine et al., 2012) TPW with time scales of order 10^6–10^9 yr. These excursions of the rotation axis have been inferred from paleomagnetic measurements and they have occurred throughout geological time (e.g., Van der Voo, 1994; Evans, 1998; Maloof et al., 2006; Mitchell et al., 2010). Moreover, they have been linked to major changes in global climate and geochemical cycles (Hoffman, 1999; Li et al., 2004; Maloof et al., 2006).

Changes in the position of North America relative to the Earth's rotation axis through the Cenozoic result from both TPW and continental drift. The net direction of this motion brings North America increasingly poleward (e.g., Jurdy and Van der Voo, 1975; Besse and Courtillot, 2002; O'Neill et al., 2005; Torsvik et al., 2012; Doubrovine et al., 2012). Early studies using climate models of varying sophistication (e.g., Donn and Shaw, 1977; Barron, 1985) concluded that the observed cooling of North American climate during the Cenozoic could not be explained by net changes in paleogeography alone. This result led Donn and Shaw (1977) to speculate that a larger contribution from TPW was required in order to explain the observed cooling trend. At the time of these studies, paleomagnetically inferred pole positions suggested TPW of less than a few degrees since 65 Ma (Jurdy and Van der Voo, 1975).

In order to simultaneously estimate plate motions and TPW from paleomagnetic data, these data must be evaluated relative to a specific frame of reference. The analysis by Jurdy and Van der Voo (1975) adopted the hotspot reference frame which assumes that hotspots are relatively stationary with respect to the Earth's mantle (Morgan, 1972). Using a recent compilation of paleomagnetic data that significantly increases the number of constraints on TPW (Torsvik et al., 2012), and an iterative analysis procedure that permits the drift of hotspots, Doubrovine et al. (2012) have inferred a secular drift in Earth's rotation axis of ~8° since 40 Ma in the so-called global moving hotspot reference frame (GMHRF; Fig. 1). Their estimated TPW path indicates a progressive displacement of the Earth's rotation axis toward Greenland over the last 40 Myr.

To better illustrate North America's changing location during the Cenozoic, paleogeography at 30 Ma in the GMHRF (including