Earth and Planetary Science Letters 444 (2016) 116–130

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

Comparing the impacts of Miocene–Pliocene changes in inter-ocean gateways on climate: Central American Seaway, Bering Strait, and Indonesia

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ARTICLE INFO

Article history:
Received 1 September 2015
Received in revised form 3 March 2016
Accepted 5 March 2016
Available online xxxx
Editor: D. Vance

Keywords:
gateways
Bering
Panama
onset glaciation
paleoclimate

ABSTRACT

Changes in inter-ocean gateways caused by tectonic processes have been long considered an important factor in climate evolution on geological timescales. Three major gateway changes that occurred during the Late Miocene and Pliocene epochs are the closing of the Central American Seaway (CAS) by the uplift of the Isthmus of Panama, the opening of the Bering Strait, and the closing of a deep channel between New Guinea and the Equator. This study compares the global climatic effects of these changes within the same climate model framework. We find that the closure of the CAS and the opening of the Bering Strait induce the strongest effects on the Atlantic meridional overturning circulation (AMOC). However, these effects potentially compensate, as the closure of the CAS and the opening of the Bering Strait cause similar AMOC changes of around 2 Sv (strengthening and weakening respectively). Previous simulations with an open CAS consistently simulated colder oceanic conditions in the Northern Hemisphere – contrasting with the evidence for warmer sea surface temperatures 10–3 million years ago. Here we argue that this cooling is overestimated because (a) the models typically simulated too strong an AMOC change not yet in equilibrium, (b) used a channel too deep and (c) lacked the compensating effect of the closed Bering Strait – a factor frequently ignored despite its potential influence on northern high latitudes and ice-sheet growth. Further, we discuss how these gateway changes affect various climatic variables from surface temperature and precipitation to ENSO characteristics.

1. Introduction

The ultimate driving forces behind the global climate cooling from the late Miocene through the mid-Pliocene and culminating in the onset of modern glacial cycles remain enigmatic. The general consensus is that atmospheric CO_2 concentration was a major factor (DeConto et al., 2008; Lunt et al., 2008). Yet uncertainties in its values (Fedorov et al., 2013) and examples of divergent trends in CO_2 and temperature (LaRiviere et al., 2012) necessitate considering additional factors, such as the effects of tectonic changes on the climate evolution. The climate system is especially sensitive to tectonic changes of its inter-ocean flows (gateways). Numerical modelling of the role of gateways has been performed for over two decades (Hirst and Godfrey, 1993; Maier Reimer et al., 1990).

The closure of the Central American Seaway (CAS) that linked the tropical Atlantic to the Pacific has been the predominant focus of research on Plio–Pleistocene gateway changes, as it was suggested that the closure might have acted as a trigger for the onset of Northern Hemisphere glaciation (Haug and Tiedemann, 1998). The opening of the Bering Strait created a high latitude connection between the Pacific and the Arctic. This has previously thought to have occurred prior to 4.8 million years ago (Ma) (Marincovich and Gladenkov, 1999), yet recent boundary conditions provided for the Pliocene Model Intercomparison Project still have it closed at ~3 Ma (Haywood et al., 2016). This work builds on that of Fedorov et al. (2013), where several proposed explanations for the Early Pliocene's weakened temperature gradient in the tropical Pacific were compared. These included two proposed gateway changes: the closing of the Central American Seaway and alterations of the Indonesian passages, to which we add the opening of the Bering Strait.

Previous studies that have looked at the impact of multiple ocean gateways have included the Southern Ocean (e.g. Mikolajewicz et al., 1993), which was closed long before the Pliocene. As far as we know, no one has previously compared the impacts of opening the Bering Strait, closing the Central Ameri-

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http://dx.doi.org/10.1016/j.epsl.2016.03.010

can Seaway and altering the Indonesian passages within the same model framework. As such, we will first briefly review each separately below. The model setup will then be presented, along with our altered boundary conditions. The climate impacts will be investigated; first locally; then globally and finally we will explore the changes in the El Niño Southern Oscillation. The conclusions of the intercomparison will then be summarized and its implications for Plio–Pleistocene climate evolution discussed.

1.1. Central American Seaway

The established view of the closure of the Central American Seaway and creation of the Isthmus of Panama is of a slow process taking many millions of years. The first step was the creation of a volcanic arc around 17 Ma leading to the creation of an archipelago by 12 Ma (Coates et al., 1992). The critical condition from an oceanographic perspective is the extent of constriction of deep and shallow water flow. The deep water connection was already cut by the Pliocene. The upper-ocean flow through the CAS curtailed between 4.7 and 4.2 Ma; as evidenced by the developing contrast in ocean surface δ^{18}O values between the Caribbean Sea and the Pacific (Haug et al., 2001). Finally, the shallow link is commonly thought to have been severed around 3.5 Ma (Coates et al., 1992). The similarity of this date to that of the onset of Northern Hemisphere Glaciation has led to much discussion of the closing of the seaway as preconditioning the glaciation (Haug and Tiedemann, 1998). However, debate continues on the timing of closure (Molnar, 2008, provides a comprehensive review of the problems of determining this timing). Recent suggestions of a much earlier closure in the middle Miocene (e.g. Montes et al., 2015) have further complicated matters.

Numerical modeling experiments looking at the role of the Isthmus of Panama on the global circulations have been performed by many authors over the past two decades (many compiled by Zhang et al., 2012). From the outset, it was recognized that the Atlantic meridional overturning circulation (AMOC) is weaker with an open seaway (Maier Reimer et al., 1990). How much weaker depends on both the details of the seaway changes and the climate model used (Zhang et al., 2012) as these factors affect the salinity contrast between the North Pacific and Atlantic, which in turn influences the strength of the AMOC. This salinity contrast is maintained largely by atmospheric freshwater transport from the Caribbean into the Eastern Pacific. However, the Central American Seaway provides an oceanic counterbalance to this freshwater flux, weakening the salinity difference and hence the AMOC. Mestas Nuñez and Molnar (2014) note this salinity contrast can also be influenced by other climate changes, such as long-term trends in Pacific sea surface temperatures (SSTs; Fedorov et al., 2013), so salinity changes may not relate solely to tectonic movement.

Haug and Tiedemann (1998) hypothesize that a strong AMOC (caused by a recent closure of the CAS) was a primer for the onset of Northern Hemisphere glaciation. The consequences of a CAS closure at ∼3.5 Ma would be a coeval warming of the North Atlantic. The warmer Atlantic SSTs would have led to increases in precipitation and presumably ice accumulation (Haug and Tiedemann, 1998). However, this idea contradicts more recent paleoclimate reconstructions (Lawrence et al., 2010) that suggest gradual cooling in northern high latitudes over the same time period. It is indicative that this cooling had a similar magnitude in northern and southern high latitudes (Fedorov et al., 2013), whereas an AMOC change would typically produce a seesaw SST anomaly about the Equator. Furthermore, climate model experiments with interactive continental-ice sheets suggest the increased precipitation does not lead to greater ice cover over Greenland (Lunt et al., 2008), implying the role of CAS closure for Northern Hemisphere glaciation may be overstated.

Indications of an earlier closure of the CAS (∼4.4 Ma) have led to suggestions that it caused a shoaling of the tropical thermocline (Steph et al., 2010), which is tentatively supported by model simulations (Zhang et al., 2012). However, for realistic depths of the CAS (a few hundred meters or less) this effect is moderate, shows both thermocline deepening and shoaling along the equator, and has only weak manifestation in SST (Zhang et al., 2012; Fedorov et al., 2013, and Section 3 of the present study).

1.2. Bering Strait

The Pacific ocean was connected to the Arctic through the Bering Strait in the late Miocene or early Pliocene (Marincovich and Gladenkov, 1999). The Bering Strait is shallow (about 50 m) yet plays an interesting role in the Arctic Ocean circulation as a conduit for fresh water (Woodgate, 2005).

The timing of the opening of the Bering Strait is not well known. Marincovich and Gladenkov (1999) find that the Bering Strait was permanently closed prior to 4.8 Ma from biogeographic evidence. Ocean-only experiments also suggest the closure of the CAS reverses the flow in the Bering Strait (Maier Reimer et al., 1990). The Pliocene Model Intercomparison Project (PlioMIP) provides global land-sea mask reconstructions for the period 3.2–3.0 Ma. The Bering Strait was considered open in the first set of PlioMIP experiments (Dowsett et al., 2012), but is closed in the recent reconstruction (Haywood et al., 2016). As the Bering Strait is/was so shallow, the timing and nature of its opening is also contingent on global sea level changes (Hu et al., 2010). The uncertainty in Pliocene sea levels has a significant impact in this instance, with the observational error of ±10 m probably being overly optimistic (Dutton et al., 2015).

Numerical and theoretical studies have shown a role for the Bering Strait in controlling the strength and stability of the AMOC (Shaffer, 1994; Wadley and Bigg, 2002; De Boer and Nof, 2004). This occurs as the Bering Strait helps determine the salinity of the Arctic and hence the North Atlantic, by regulating the flow of relatively fresh water from the North Pacific. Simulations by Hu et al. (2010) looked at the impact of rapid changes in the Bering Strait controlled by sea level changes during a glacial cycle. They posited a feedback involving the Laurentide ice sheet, the AMOC and the Bering Strait – suggesting a role in glacial climate variability. Here we are thinking more about its impacts in the Late-Miocene/Pliocene and so do not use a glacial baseline for our experiments.

1.3. Indonesian Throughflow

Since detaching from Antarctica in the Early Eocene, the continent of Australasia has been moving slowly northwards towards the Equator (Hall, 2002). The most northerly tip of Australasia, namely the Bird's Head of Papua New Guinea, is now within 1° of the Equator. It is so close to the island of Halamahera to the north of the Equator that there are no channels through which deep water may pass between them. It is assumed that this deep channel closed during the Pliocene (Hall, 2002); however more precise, direct dates are not available.

One effect of this deep channel closing may have been to shift the source of the Indonesian Throughflow from Southern to Northern Pacific subtropical waters (Rodgers et al., 2000). Potential traces of such behavior has been observed in the paleoclimate record (Karas et al., 2009), who find a cooling and freshening of the subsurface waters entering the Indian ocean from the Pacific after 3.5 Ma. It has been suggested that such a change could have had global climate consequences, including the aridification of East Africa during the Pliocene (Cane and Molnar, 2001), but subse-