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

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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.

Keywords: gateways, Bering, Panama, onset glaciation, palaeoclimate

Highlights:

- Opening of Bering Strait cooled North Atlantic
- Overturning response to Central American Seaway (CAS) previously overestimated
- Opening of Bering Strait could compensate for CAS overturning changes
- New Guinea crossing Equator appears climatically less important

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., 2014). 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 American 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 summarised 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 $\delta^{18}O$ values between the Caribbean Sea and the Pacific (Haug et al. 2001). Finally, the shallow link is commonly thought to have been severed around 3.5Ma (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 Teidemann, 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., 2014). 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 have 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 subsequent model simulations did not support that idea (Jochum et al., 2009; Krebs et al., 2011).

Krebs et al. (2011) found that Indonesian changes could explain some of the large ecological changes observed in Australia during the Plio-Pleistocene. Jochum et al. (2009) found little global climate impact with both coupled and ocean-only mode of CCSM3 (an earlier version of the model used here). They saw a small warming of the Central Equatorial Pacific and alterations in the statistical properties of ENSO. Modeling results of Fedorov et al. (2013) also did not support Indonesian constriction as an explanation for the changes in patterns of tropical Pacific SSTs they had diagnosed. Here, we expand upon that analysis.

Changes in the pathways of the Indonesian Throughflow are not the only method by which changes in topography in this region may affect global climate. Recent work on dynamic topography (Rowley et al., 2013) allows for the exposure of shallow shelves in the region due to mantle convection (Haywood et al., 2014). Exposure of the Sunda and Sahul shelves at the Last Glacial Maximum are thought to have affected the atmospheric Walker circulation (DiNezio et al., 2011). Likewise, Molnar and Cronin (2015) suggest a gradual increase in the exposed landmass of the Maritime Continent since 5 Ma played a role both in the CO_2 drop seen during the Plio-Pleistocene and the evolution of the Walker circulation. Brierley and Fedorov (2011) show changes in tidal mixing in the Banda Sea (arising from changes in bathymetric roughness) could be sufficient to drive changes in throughflow properties, yet hard to constrain from the geologic record.

2. Method

2.1 Community Earth System Model

All the simulations presented in this comparison study use the Community Earth System Model (CESM; Gent et al., 2011). This is the most recent generation of the coupled general circulation model developed by the National Center for Atmospheric Research (NCAR). This model involves fully dynamical atmosphere and ocean components with representations of the land surface and sea ice. These simulations are performed with the (relatively) low resolution version developed for paleoclimate studies (Shields et al., 2012). The atmosphere and land models have a horizontal resolution of T31 (3.75° x 3.75°) with 26 atmospheric vertical levels. The land model involves biochemistry and semi-dynamical vegetation that grows and dies-back with the seasons, however the land-cover proportions are prescribed throughout the simulations. The ocean has a rotated grid with a pole under Greenland. It has a nominal resolution of 3° and 60 vertical levels, along with suitable parameter settings (Shields et al., 2012). More precisely, we use CESM version 1.0.2 at T31_gx3 resolution with component setting B1850_CN.

The treatment of the sub-grid scale mixing has become significantly more sophisticated than previous model generations, which relied predominantly on the Gent-McWilliams parameterization (Gent et al., 2011). Of relevance to this study are parameterizations of Nordic overflows (Danabasoglu et al., 2010), sub-mesoscale mixed layer eddies (Fox-Kemper et al, 2010) and abyssal tidal mixing (Jayne, 2009). The overflow parameterization improves the representation of dense water crossing a sill and entraining water as it sinks. It would only be relevant for the sill in the newly-created Central American Seaway, yet the density gradient here is not sufficient to necessitate its implementation.

The simulation used as a control is a 500 year extension from the preindustrial run described in Shields et al. (2012). The simulation with an altered New Guinea, "Indonesia", is also 500 years long starting from the same initial conditions. Assessment of the degree of equilibration was made through inspection of the global average top of the atmosphere heat flux imbalance, and surface and deep ocean temperature trends (Supplementary Figure 1). The simulations involving the closing of the Bering Strait, "Bering", and the opening of the Central American Seaway, "Panama", showed trends in the deep ocean and so were integrated for 1500 and 2400 years respectively. Even after such long times neither simulation is fully equilibrated throughout the ocean, yet the trends in the AMOC are hard to distinguish from internal variability at this point (sect. 4.5). The results shown here are the difference in the final 200 years of each simulation compared to the Control.

2.2 Application of boundary condition changes

All of the simulations described here are sensitivity studies: meaning that the gateway change is the only imposed difference from the control simulation. To alter the Central American Seaway and the Indonesian Archipelago, we have converted land grid points into ocean. This requires some assumptions to be made about the ocean bathymetry (Figure 1). The new ocean grid points in Indonesia were set at the average depth of the neighboring locations, leading to a depth of 500m. For the open Central American Seaway, a value of 150m was chosen for the sensitivity test (Fig. 1). This sill depth is shallower than some of the simulations in the multi-model comparison of Zhang et al. (2012), but still three times the depth of the present Bering Strait. The suggestion by De Schepper et al. (2013) that the CAS was temporally closed by the sea level fall during MIS M2 glaciation at ~3.3 Ma implies a sill depth of at most 65 m.

Previous work has suggested that changes in tidal mixing may have been important in Indonesia during the Pliocene (Brierley and Fedorov, 2011). Therefore, rather than turning off the abyssal tidal mixing (as proposed by Paleoclimate Working Group, 2015, for palaeoclimate simulations), the prescribed energy flux field was interpolated over new ocean locations, although this is probably second-order to the bathymetric changes. Appropriate river routings and other ancillary files were created using the altered bathymetry (Paleoclimate Working Group, 2015). The potential land dataset used to create CESM boundary conditions at finer resolutions has sufficient island data that realistic preindustrial values were prescribed for the new land points after the closing of the Bering Strait (Fig. 1). This prevented arbitrary choices of the new land cover, and results in roughly 40% deciduous broadleaf boreal shrub, 30% bare ground and 30% Arctic C3 grass.

2.3 Statistical Significance

The importance of any changes observed in this article is assessed by comparing to the model's internal variability. Reliably estimating the model's multi-centennial internal variability is problematic and therefore we adopt a conservative approach and use the control run to estimate the internal variability on a shorter timescale. The 500 year long preindustrial run has been subdivided into twenty different segments, each 25 years long. Differences are considered statistically significant if they fall outside the two-tailed 95% confidence range assuming the segments are independent samples of a normally distributed noise caused by internal variability. In the following figures, stippling indicates significant anomalies (in spatial maps) whilst diagonal hatching indicates non-significant anomalies (in the plots of overturning streamfunction).

3. Local impacts

Unsurprisingly, altering each gateway leads to changes in the local oceanographic conditions that are significantly different from the model's internal variability. We present the transports of mass, heat and salt (Table 1) along with velocities of the upper 150 m of the ocean near the gateways (Figures 2 & 3).

3.1 The Central American Seaway

Opening the Central American Seaway leads to a net flow from the Pacific to Atlantic with a volume of 3.7 Sv (Table 1). This flow is at the lower end of the range in Zhang et al. (2012), but is to be expected as its cross-sectional area is substantially less than those with deeper sill-depths. The flow is achieved by a northward current flowing up the Colombia's Pacific coast partly balanced by a westward flow through what is presently Costa Rica (Fig. 2e). In fact, there is some recirculation occurring, as water flowing along the Colombian coast is entrained into the larger Atlantic western boundary current within the Caribbean. In the Pacific, there is an extension of the southward current flowing along the Mexican coast. When this newly strengthened current reaches the mouth of the Central American Seaway, it in turn leads to greater recirculation.

3.2 The Bering Strait

The Bering Strait is presently open, but only reaches depths of up to 40m in the model (Fig. 1) and so does not support as large a flow as the other gateways. Closing the Bering Strait deprives the Arctic Ocean of this inflow, which is a source of freshwater because of the low salinity of the northern Pacific (Woodgate, 2005). The salt transport is provided in Table 1, yet the virtual freshwater transport is perhaps more enlightening. The average density of water flowing through the Bering Strait is 1026.5 kg/m^2 meaning that the salt transport is equivalent to a mass transport of 0.869 Sv of 34.8 psu sea water. The Bering Strait in CESM therefore transports approximately 0.037 Sv of freshwater, about half the observational estimate (Woodgate, 2005). Surprisingly the strong changes in upper-ocean flow (Fig. 2c) do not extend past the Aleutian Islands into the North Pacific. There are significant changes in the Arctic Ocean that are more widely felt, primarily downstream of the Strait in the Beaufort Gyre.

Recent palaeoceanographic work has found evidence of a progressive Pliocene cooling south of the Strait (Horikawa et al., 2015). This cooling has been interpreted as a consequence of a flow reversal in the Strait caused by the closing of the Central American Seaway (Maier Reimer et al., 1990). There is a Northward flow of both heat and salt in all the simulations (Tab. 1) suggesting an alternate paleoclimatic interpretation is required – perhaps revolving around changes to the Bering Strait itself.

3.3 Indonesian Throughflow

Observational estimates of the Indonesian Throughflow are 15 Sv emerging into the Indian Ocean, with 13 Sv entering the region directly from the Pacific Ocean (Gordon et al., 2010). The model underestimates the net outflow slightly (13.8 Sv, Tab. 1), but considering its coarser resolution in relation to other recent studies (Jochum et al., 2009; Krebs et al., 2011), it is reasonable.

In the simulation without the northern extension of New Guinea, there is a significant reduction in throughflow (Tab. 1). There is a strong increase in flow entering the Makassar Strait/Molucca Sea (Fig 3b; the model does not resolve Sulawesi so they form a single entity). However, this is negated by an even greater increase in the flow around the northern edge of New Guinea into the Pacific. There is a weakened outflow resulting from this, although the flow through the Tasman Sea has been somewhat strengthened.

Interestingly, changes in all three gateways investigated have significant impacts on the Indonesian Throughflow (Tab. 1). The closing of Bering Strait increases the mass transport by just over 1.5 Sv. The opening of the Central American Seaway causes the throughflow to reduce by 35%. Both of these changes are consistent in sign and relative magnitude with changes to the AMOC (section 4.5) driving a global ocean conveyor.

4. Global climate impacts

The majority of the discussion of gateways in the paleoceanographic literature centres on the role they may play in long-term climate evolution. This assumes that the gateways have remote impacts, leading to either global changes (Haug and Tiedemann, 1998) or at least changes elsewhere (Cane and Molnar, 2001). In this section, we compare several global diagnostics between the simulations. We present these diagnostics in the conventional sense for sensitivity studies (i.e. *perturbed – control*). This is opposite to the chronological sense of the changes, which would be *control – perturbed* (i.e. *after – before*).

4.1 Poleward heat transports

The opening of the Central American Seaway causes the largest alterations in the poleward heat budgets (Fig. 4). It reduces northward ocean heat transports at most latitudes and increases the atmospheric transports at all latitudes. The two changes do not compensate completely leaving a net alteration in the Tropics (Fig. 4b). The anomalous northward atmosphere heat transports is associated with a southward movement of the inter-tropical convergence zone (ITCZ) and reduced temperature gradient between the Northern and Southern hemispheres. This southward ITCZ shift leads to a reduced dominance of the Southern Hadley cell (not shown). The relative strengthening of the Northern Hadley Cell allows it to transport more heat northwards. The reduced ocean heat transport is associated with both AMOC changes (sect 4.2) and changes in the subtropical cells.

Shifting Indonesia causes a marginally significant increase in the atmospheric heat transport near the Equator. The closing of the Bering Strait causes no significant changes in the combined heat transport (Fig. 4b). There is an increase in the ocean heat transport with a maximum at 35 °N, likely associated with changes in the AMOC.

4.2 Meridional overturning circulation

The preindustrial control simulation shows a peak in the zonal mean meridional overturning streamfunction in the Atlantic occurring at a depth of 1 km around 35 °N (Figure 5b). The Antarctic bottom water cell is weak - a feature of all resolutions of CESM (Danabasoglu et al., 2012). A pair of shallow subtropical overturning cells exists in the upper 250 m, with upwelling occurring on the equator.

The temporal evolution of the maximum of the meridional overturning streamfunction in the North Atlantic shows little evidence of secular trends beyond 100 years in either the control or Indonesian simulations (Fig. 5a). There are AMOC changes in both the Bering Strait and Central American Seaway simulations emerging over the first 500 years. These simulations were integrated for a further 1000 and 1900 years respectively, allowing any recovery to occur. The recovery is most notable in the CAS simulation (Fig. 5a) and is predominantly complete after 1500 years (though there is still drift in the deep ocean, Supplementary Fig 1). The AMOC continues to exhibit a strong centennial to multi-centennial internal variability (to be discussed elsewhere). Only changes in the mean state are discussed here.

A closed Bering Strait causes an increase in the deep overturning cell throughout the Atlantic (Fig. 5d). This reaches a maximum of 2.5 Sv and is statistically distinguishable down to 4 km. An open Central American Seaway has the reverse response (Fig. 5e) and leads to significant weakening and shoaling of the AMOC (as observed by previous authors e.g. Maier Reimer et al., 1990; Zhang et al., 2012). The weakening seen here is among the lowest of the results complied by Zhang et al. (2012), but it also has one of the shallowest sill depths of their simulations. Interestingly with this shallower sill depth (more appropriate for the Pliocene) the impact of the CAS on the AMOC has a very similar magnitude as that of the Bering Strait. This was not foreseen in the first 500 years of simulation. The recovery means that if the AMOC response to the opening of the CAS was taken after, say, only 500 years (as in Lunt et al., 2007) it would be over-estimated by factor of two (Fig. 5a). Alterations in the Indonesia bathymetry have no significant impacts on the AMOC (Fig. 5c). In general, the changes in AMOC are accompanied by changes in the North-South surface salinity gradient in the Atlantic of roughly 1 psu (see sect 4.5).

4.3 Surface Temperature Changes

All three simulations show statistically significant changes in surface air temperature at different regions (Fig. 6). These surface air temperature changes are very similar to the underlying SST changes, so the SSTs are not shown here.

In the Indonesia simulation, there are no significant temperature changes directly overlying the boundary alterations (Fig. 6a). There is a cooling over the Yellow Sea and a warming of the Eastern Equatorial Pacific. It is not clear why the Arctic warms just north of the Bering Strait, especially given the lack of significant changes in the flow through the Bering Strait itself (Tab. 1). We suspect this may be part of internal variability in the model or atmospheric teleconnections.

A closed Bering Strait leads to a local cooling, yet the largest region of significant changes is a warming in the North Atlantic (Fig 6b). The impacts of closing the Bering Strait on Pacific surface temperatures appear marginal. The warming in the Southern Ocean is counter to a bipolar seesaw response to a strengthened AMOC, and is instead collocated with weakened surface wind stresses (not shown).

The opening of the Central American Seaway demonstrably had a global impact (Fig. 6c). It alters the inter-hemispheric temperature gradient, by cooling the Northern Hemisphere and warming the Southern. Interestingly the changes in the higher latitudes of the North Atlantic (the sinking region of the AMOC) are not statistically significant according to the metric used here (sect. 2.3). The lack of statistical significance may be influenced by the sea ice edge of the pre-industrial control simulation, which has a southward bias into the region (Shields et al., 2012). Intriguingly, a strong cooling occurs in the Subarctic North Pacific. While it is insufficient to activate a Pacific MOC, it may indicate a tendency towards a modified version of the ocean global conveyor that is known to be impacted by tropical gateways (von der Heydt and Dijkstra, 2008).

4.4 Precipitation

The changes in annual average precipitation caused by the gateway changes are generally less than those for temperature (Fig. 6). In general, changes in either the Bering Strait or Indonesia do not show systematic changes in precipitation of local or global extent. Specifically, the simulation with alterations to Indonesia (Fig. 6d) does not show either the rainfall changes over Africa hypothesized by Cane and Molnar (2001) or over Australia as modeled by Krebs et al. (2011). The Indonesian simulation does show increased precipitation over the Eastern Equatorial Pacific, probably associated with its altered ENSO properties (see section 4.7). The warming in the North Atlantic caused by the closing of the Bering Strait is also associated with increased precipitation there (Fig. 6e).

Opening the Central American Seaway causes significant regional precipitation changes in the Eastern Tropical Pacific and Tropical Atlantic (fig. 6f). These show the southward shift in the ITCZ associated with the reduction in the inter-hemispheric temperature gradient discussed above. The reduction in rainfall on either side of the Isthmus of Panama shows a further alteration of the inter-ocean freshwater flux. Not only is there a freshwater flux transport through the opened seaway from the Pacific to the Atlantic (Tab. 1), there is also a weakened freshwater transport going the other direction in the atmosphere.

4.5 Surface salinity

The changes in salt transport through the ocean gateways (Tab. 1) and their impact on the freshwater budget of the ocean would be expected to alter the ocean's surface salinity structure (Fig. 7). The impact of altering the Indonesian gateway leads to changes in the tropical Pacific salinities (Fig. 7a). These changes are not collocated with the temperature (Fig. 6a) and precipitation changes (Fig. 6d), but are presumably related. Preventing the flow of relatively fresher water in the Arctic Ocean by closing the Bering Strait, leads to the Arctic becoming significantly saltier (Fig 7b). This signal is able to propagate into the North Atlantic, causing the Labrador Sea to become 0.5 psu saltier. The rest of the ocean becomes fresher as a consequence, leading to an increased salinity gradient between the North and South Atlantic. The initially counter-intuitive freshening north of the Bering Strait is caused by weaker circulation in region (Fig. 2; Wadley and Bigg, 2002).

Globally the impact of opening the Central American Seaway makes the ocean surface significantly saltier. Intriguingly the salinity reduction in the North Atlantic is relatively weak (Fig. 7c), but joined with the saltier South Atlantic leads to a robust decrease in the salinity gradient consistent with the weakened AMOC (Fig. 5e). The increased surface salinity in the Arctic may arise from increased sea ice formation due to the colder temperatures.

4.6 Thermocline changes in the tropics

Steph et al. (2010) suggest that the closure of the Central American Seaway resulted in the end of the weak SSTs characteristic of the equatorial Pacific in the Pliocene (Fedorov et al., 2013). Zhang et al. (2012) found support for this hypothesis from a model compilation. The thermocline changes in the simulation here are qualitatively similar, but with a reduced magnitude as befits the shallower sill depth (Supplementary Figure 2). Minimal changes to the tropical thermocline are caused by the closure of the Bering Strait (despite its AMOC intensification). However, in all of these experiments surface temperature manifestation of these changes in the equatorial band is weak, on the order of 0.25 °C (Fig. 6).

4.7 El Niño Southern Oscillation

It has previously been observed that changing ocean gateways can significantly alter the modes of interannual variability of a climate model, even with weak changes in the mean climate (von der Heydt et al., 2011; Jochum et al., 2009). We focus our attention on the El Niño Southern Oscillation (ENSO) as it is the dominant mode of climate variability globally. Jochum et al. (2009) found that altering the Indonesia bathymetry led to a more irregular and weaker ENSO. Analysis of 200 years of SST anomaly in the Niño 3.4 region (5°S–5°N, 190-240°E) does not confirm the weakening of ENSO (Table 2), which is instead stronger in this study.

The low-resolution version of CESM used here has a power spectrum of ENSO that is not unreasonable (Shields et al., 2012). There is too little power at periods above 4 years (Figure 8) compared to observations (Smith et al., 2008), with a slight concentration at 2.5 years. The Indonesian alterations tend to smear this concentration out to longer periods (Tab. 2) in agreement with Jochum et al. (2009).

An open Central American Seaway leads to marginally stronger ENSO, but with dominant period stretching towards ~3 years instead of ~2.5 years (Table 2). It is likely that this is caused by changes in the seasonal cycle in the Eastern Equatorial Pacific as hinted at by the alterations in the annual mean flow patterns (Fig. 2). There may also be a contribution from a shoaling of the thermocline (Supplementary Figure 2), but that is unlikely to be the dominant cause (Steph et al., 2010; Zhang et al., 2012). Previous work with a simple model suggested an open Central American Seaway reduces ENSO amplitudes and shortens its period (Heydt et al., 2011): the opposite to the effects observed here. Interestingly the existence of the Central American Seaway removes the skew in ENSO – making La Niña deviations as strong as El Niño ones (Table 2). The correlation patterns associated with El Niño appear substantively similar in all four integrations (not shown). The opening of the Central American Seaway leads to only a slightly stronger link to ENSO in the Caribbean, despite the new ocean connection.

5. Discussion

We have compared the impacts of three gateway changes that potentially occurred during the late Miocene-Pliocene within the same model framework. In a global sense, the closing of the Central American Seaway through the creation of the Isthmus of Panama has the largest effects. The opening of the Bering Strait, thereby connecting the North Pacific to the Arctic, also had global consequences.

Our simulation with a closed Central American Seaway show changes in SST and SSS over the North Atlantic, but statistically significant only in some regions. There is a ~1 °C cooling over the North Atlantic, while surface salinity in the North Atlantic increases in the subtopics, but decreases slightly in higher latitudes. The model does show a reduction in the Atlantic Meridional Overturning Circulation of ~2 Sv, but a recovery with a timescale longer than one thousand years means this reduction is much smaller than seen after the first 500 years (~5 Sv). The impact of the closed Bering Strait on the AMOC is opposite and approximately equal to that of an open CAS, yet causes significant changes to the surface climate of the North Atlantic (with surface temperature changes in the North Atlantic exceeding 1 °C). The global climate impacts of altering the land/ocean configuration of Indonesia appear insignificant. The weakening of the AMOC in the opened CAS experiment and the strengthening of the AMOC in the closed Bering Strait experiments are paralleled by the increase and decrease of the ocean vertical stratification, respectively (Supplementary Fig. 1).

The changes around Indonesia represent only a gateway constriction, not a complete opening or closing like in the other two simulations. This may explain their small impacts, but the imposed alterations are representative of changes seen over the past several million years. Nevertheless, one could ask whether sufficient land mass has been removed from the model to truly test the hypothesis of Cane and Molnar (2001) that Indonesia change were responsible for African aridification. The western boundary current in the South Pacific that runs along the coast of New Guinea has not been given an opportunity to flow unimpeded into the Banda Sea (as the resolution is too course). The two prior studies with coupled climate models are equivocal: Krebs et al. (2011) show an increased throughflow, whilst Jochum et al. (2009) show little change. Nonetheless neither previous studies, nor this one, show substantial remote impacts to the mean climate to support the African aridification hypothesis.

As the exact bathymetry of the Indonesian Archipelago several million years ago is not known, other alterations may have driven climate changes. An increased tidal mixing is one such possible alteration (Brierley and Fedorov, 2011), although even that does not have strong non-local consequences to the mean climate. A gradual increase in the areal extent of Indonesia can be potentially important for climate evolution (Molnar and Cronin, 2015), but is not tested here.

Previously the El Niño-Southern Oscillation (ENSO) has been suggested to alter in response to both tropical gateways changes: an open Central American Seaway to make ENSO weaker but more frequent (Heydt et al., 2011) and Indonesian alterations to make ENSO again weaker but less frequent (Jochum et al., 2009). Our simulations show some ENSO changes from the tropical gateway changes, although not those anticipated previously. We find both tropical gateways generally decrease the frequency of ENSO and increase its amplitude. However, the Bering and Indonesia simulations also develop a secondary, biennial peak in the ENSO spectrum. The most notable response to an open CAS appears to be an absence in skew of ENSO. We would be cautious in interpreting these ENSO changes, since their statistical significance is hard to estimate and some may be model dependent.

This study has treated each gateway change in isolation. It is possible that there could be non-linear interactions between gateway changes and broader changes in climate. Examples of these non-linearities have been documented by several studies in other contexts. For example, von der Heydt and Dijkstra (2008; 2006) found the combined impacts of the Central American Seaway and the Drake Passage cause different circulation regimes depending on their configuration. Hu et al. (2010) have found that the closing of the Bering Strait during glacial intervals can lead to greater impacts in the North Atlantic than during an interglacials. In this study, an attempt was made to combine the multiple gateway changes, but this led to unrealistic drifts in the salt budget culminating in numerical errors. However, given the potentially compensating character of the Bering Strait opening and the CAS closure, and a weak effect of Indonesia drift on climate, we anticipate that such non-linear interaction are not a major factor in Miocene-Pliocene climate evolution. Uncertainties in the depth of gateways appear to be much more important.

The three gateways investigated here had not previously been investigated in a single model. The present model, a CESM version with a relatively low resolution, was chosen for computational efficiency, but potentially these results could be model dependent. However, the responses are qualitatively similar to prior simulations (Zhang et al., 2012; Kerbs et al, 2011; Wadley and Bigg, 2002). Another issue is systematic cold biases in the present and other climate models. However, the relatively small climatic impacts of the imposed gateway alteration (e.g. ~10% change in the AMOC, SST changes on the order of 1^{o}C or less in our experiments) suggest a linear regime, which should not be strongly affected by these biases.

A number of processes that are missing or under-resolved in climate models can be also relevant in a Pliocene and/or Gateway context, including tidal mixing (Brierley and Fedorov, 2011), tropical cyclone feedbacks (Fedorov et al, 2010), changes in tropical convection (Arnold et al., 2015), cloud properties (Burls and Fedorov, 2014), atmospheric chemistry (Unger and Yue, 2014), stratospheric connections (Joshi and Brierley, 2013) and ocean eddies (Viebahn et al., 2015).

6. Conclusions

It is widely thought that changes in the inter-ocean gateways played a role in the development of Northern Hemisphere glaciation during the Plio-Pleistocene (e.g. Haug and Tiedemann, 1998). The onset of glaciation was probably a threshold response to a gradual reduction in atmospheric greenhouse gases (DeConto et al., 2008; Lunt et al., 2008), whose precise timing was controlled by variations in Earth's orbital parameters favorable for ice accumulation. Inter-ocean gateway changes may have altered the Earth system's response to (orbital) forcing and so helped set the level of that threshold. Specifically, the closing of the Central American Seaway (CAS) has been suggested as preconditioning glaciation through its impact on the North Atlantic (Haug and Tiedemann, 1998). Subsequently, the climate role of the CAS closure has received substantial discussion (e.g. Steph et al., 2010; Zhang et al., 2012; Horikawa et al., 2015), but was questioned by some studies (Molnar, 2008).

Here, for the first time, we have compared the climate impacts of three inter-ocean gateway changes that potentially occurred in the Late Miocene or early Pliocene within a single coupled model. Whilst the impacts of the Bering Strait are not as globally pervasive as those of the Central American Seaway, they have a stronger signature in the high northern latitudes pertinent for glacial inception (Fig. 6). It is uncertain when exactly the Bering Strait opened, although a Pliocene date seems probable. A recent global topography for 3.2 Ma (Haywood et al., 2014) reconstructs a Bering Strait that has not yet opened, although the Central American Seaway has already closed. De Schepper et al. (2013) suggest a shallow CAS was critical in aborting an early attempt at initiating glacial cycles at 3.3 Ma. Yet perhaps the closed Bering Strait is a more likely culprit: it has a greater impact in the North Atlantic and is now reconstructed to have changed after 3.3 Ma.

We hope that this work will provoke further consideration of changes in the Bering Strait - especially given its nearly equal and opposite impact on the deep ocean circulation as that of the CAS closure. The simulations presented here are individual sensitivity studies. Further work is required to test whether the relative impacts of the gateways remain the same with other climate models and with more representative boundary conditions. The role of non-linear interactions between inter-ocean gateways (e.g. von der Heydt and Dijkstra, 2008) and systematic biases in model simulations (e.g.

Burls and Fedorov, 2014) also need investigation. Yet, if indeed the two effects (the CAS closure and the Bering strait opening) were nearly compensating as suggested by these results, one must consider other mechanisms that led to global cooling since the late Miocene. A likely mismatch in the timing of the opening of the Bering Strait and the closure of the CAS is another factor to consider.

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Tables

Gateway	Simulation	Mass (Sv)	Heat (TW)	Salt (10^6 kg/s)
Bering	Control	0.906 ± 0.017	-1.367 ± 0.356	29.4 ± 0.6
	Indonesia	*0.922*	*-0.935*	*29.7*
	Bering	0[†]	0[†]	0[†]
	Panama	0.588	*-1.903*	18.7
Indonesia	Control	13.8 ± 0.2	891 ± 14	486 ± 7
	Indonesia	12.0	749	424
	Bering	15.5	959	544
	Panama	9.23	698	325
Panama	Control	0[†]	0[†]	0[†]
	Indonesia	0[†]	0[†]	0[†]
	Bering	0[†]	0[†]	0[†]
	Panama	3.69	116*	151*

Table 1. Transport through the gateways. The total mass, heat and salt transported through each gateway in each simulation (positive is defined as flow out of the Pacific). The error on the preindustrial control simulation represents the standard deviation of 25-year segments during the integration (sect. 2.3). Values in italics do not have statistically significant differences from the control simulation. [†]There must be no transport through closed gateways. *Unfortunately, the diagnostics for the eastward component of heat and salt fluxes caused by isopycnal diffusion nor the sub-mesoscale eddy pararmeterization were stored during the simulation, so their contributions are assumed to be zero.

	Niño 3.4 SST Anomaly		
Simulation	**Amplitude (°C)**	**Skew (°C^2)**	**Dominant Period (years)**
Control	0.75	0.45	2.4
Indonesia	0.84	0.40	4.0
Bering	0.74	0.47	3.4
Panama	0.81	0.24	3.1
Observations	0.85	0.27	3.3

Table 2. ENSO metrics in the simulations. The standard deviation and skew of the time series of Niño 3.4 sea surface temperature anomalies. The dominant period is computed as the frequency with the most spectral power between 1.2 and 8 years (computed before smoothing as in Fig 8).

Figure Captions

Figure 1. The model bathymetry on the temperature (left) and velocity (right) grids surrounding the three gateways under investigation: Indonesia (top), the Bering Strait (middle) and the Central American Seaway (bottom). Green indicates land points. The red crosshatched area shows the land points that have been removed or created in the each sensitivity study.

Figure 2. The upper ocean (top 150m) average velocities around the Bering Strait and Central American Seaway. The difference between the control (top) and perturbed (middle) simulations is shown at the bottom. The arrows represent the ocean velocity, whilst the color indicates its magnitude. The solid black line delineates the land points (Fig. 1) and the crosshatched area also incorporates the grid points whose velocity is zero (through the non-slip boundary conditions). Only statistically significant velocity changes are show in the lower panels. *Note color scales differ between the left and right panels.*

Figure 3. The upper ocean (top 150m) average velocities around Indonesia. The flow regime in the control simulations in shown at the top. The flows in the various sensitivity simulations (left) and its difference from the control (right) are shown below. The arrows represent the upper ocean velocity, whilst the color indicates its magnitude. The solid black line delineates the land points (Fig. 1) and the crosshatched area also incorporates the grid points whose velocity is zero (through the non-slip boundary conditions). Only statistically significant velocity changes are show in the right panels. *Note the magnitude of the change in velocity arrows differs (although the color scales do not).*

Figure 4. The poleward heat transports in the control simulation (a) are shown along with the changes in each sensitivity experiment of total (b), atmospheric (c) and oceanic (d) heat transports. The blue envelope indicates the 5-95% range of internal variability estimated from 25 year segments of the control simulation. The atmospheric term is calculated as a residual.

Figure 5. The Atlantic Meridional Overturning Circulation (AMOC). (a) Maximum of the Atlantic meridional overturning streamfunction in the control (blue), Indonesia (orange), Panama (purple) and Bering (green) simulations. Decadal smoothing has been applied. The mean in the control simulation (dashed) and the 5-95% range (dotted) are shown as horizontal lines. (b) Atlantic meridional overturning streamfunction in the final 200 years of the control simulation. (c-e) Changes in the streamfunction observed in the final 200 years of the sensitivity experiments. Those changes covered with diagonal lines are not statistically significant with respect to the 25-year internal variability in the control simulation.

Figure 6. Global impacts of the gateway changes on annual average surface air temperature (left in °C) and annual average precipitation rates (right as %). The stippling indicates a 200 year average change that is statistically different from the 25-year internal variability in the control simulation. *Note: chronologically the patterns would be reversed, so an opening of the Bering Strait would lead to a* cooling *of the North Atlantic.*

Figure 7. The impact of the gateway changes on the sea surface salinity (psu). The stippling indicates a 200 year average change that is statistically different from the 25-year internal variability in the control simulation (sect. 2.3).

Figure 8. El Niño Southern Oscillation (ENSO). (a-d) Progression of the Niño 3.4 sea surface temperature anomalies in the four simulations. (e) Power spectra for the Niño 3.4 sea surface temperature anomalies from the ERSST observations (Smith et al., 2008) and in each simulation (following Phillips et al., 2014, but with a five-point smoothing). The area under each line integrates across all periods to give the total variance. *Note: whilst the time series are shown for only the final fifty years of each simulation (for legibility), the spectra and the statistics quoted in Table 2 are taken over the whole two hundred years of the intercomparison.*

Supplementary Figure 1. Development of pertinent global mean features throughout the simulations. (a) The 25 year running mean of the global mean surface air temperature and (b) the top of atmosphere heat flux imbalance for all the simulations. All simulations including the control show a slight warming trend of roughly 0.01 °C per century, which for most of the runs is consistent with the net gain of heat through the top of the atmosphere. (c-f) The depth profile of global mean ocean temperatures in each simulation. The ocean temperatures are shown as anomalies from the time average of the control simulation. The temperature of the abyssal ocean is still not in equilibrium in neither the Bering nor Panama simulations.

Supplementary Figure 2. The change in depth of the 20 °C isotherm in comparison with the control run. The response to the opening of the Central American Seaway (c) is relatively muted with respect to the collection presented in the Zhang et al. (2012) intercomparison, but shows a similar pattern to the other coupled simulations. It should be noted that at 150 m deep, the Central American Seaway is among the shallowest tested.