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The non-analogue nature of Pliocene temperature gradients

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A B S T R A C T

The strong warming of the North Atlantic and high latitudes in the Pliocene (5.3–2.6 million years ago) continually fails to be simulated in climate model simulations. Being the last period of Earth history with higher global temperatures and carbon dioxide levels similar to today, it is an important target period for palaeoclimate models. One of the key features of the Pliocene climate is the reduced meridional gradients, particularly in the high latitudes of the Northern Hemisphere. Here we show that previously unconsidered palaeogeographic changes (river routing, ocean bathymetry and additional landmass in the modern Barents Sea), in the North Atlantic region can produce significant temperature responses at high latitudes. Along with orbital forcing, this can significantly decrease equator to pole temperature gradients in the Atlantic Ocean. These additional forcings show that the large Arctic warming and significantly reduced temperature gradients in the Pliocene are not analogous to future warming and that careful consideration of all the possible climatic forcings is required to accurately simulate Pliocene climate.

1. Introduction

1.1. Palaeoclimates as future climate analogues?

Past climates provide the opportunity to test both our understanding of the Earth system and the models used to simulate climate changes. Warm periods, with atmospheric carbon dioxide levels above pre-industrial levels, have previously been used as an analogue to future warming (Zachos et al., 2008; Haywood et al., 2009). However, it has been shown that geological and palaeogeographic changes can cause significant changes to the sensitivity of the climate. Haywood et al. (2011a) suggested that the last major change in Earth history to significantly bias climate away from its modern sensitivity to CO_2 changes was the closure of the Isthmus of Panama, which occurred during the early Pliocene (Coates et al., 1992). This assertion has been supported by the palaeoenvironmental reconstructions of the mid-Pliocene, created by the PRISM (Pliocene Research, Interpretation and Synoptic Mapping) group of the US Geological Survey. These reconstructions, which form the basis of the climate model boundary conditions used in the Pliocene Model Intercomparison Project (PlioMIP), include few non-analogue changes (those that would not be expected under future climate change). Those that are included are the infill of the Hudson Bay, small changes in Rocky Mountain and East African orography and some minor tectonic plate rotations. As such, the Pliocene has been used to estimate the long term sensitivity of the climate to increased atmospheric carbon dioxide (Lunt et al., 2010; Pagani et al., 2010; Haywood et al., 2013a). However, there are many changes that have occurred since the Pliocene that have not been incorporated into climate model simulations and hence have been implicitly assumed to have no significant impact on climate and climate sensitivity.

1.2. The Pliocene North Atlantic

In this study we focus on changes in the North Atlantic region, as this is the most extensively studied region in the Pliocene and provides the greatest evidence for warming and a reduction in temperature gradients (Dowsett et al., 1992, 2010; Ballantyne et al., 2010). There is evidence for warming and change in temperature gradients in the North Pacific (Fedorov et al., 2013), but the available data is focused in upwelling regions (California margin and Kuroshio Current). Although these areas warm strongly, it is difficult to characterise the temperature gradients with so little data and the strong clustering of sites in upwelling regions. By contrast, in the North Atlantic there are more sites in a multitude of different oceanographic settings, all showing a significant reduction in the meridional temperature gradient (Dowsett et al., 1992, 2010). Despite having the most data and the highest quality data (Dowsett et al., 2012), the North Atlantic also shows the greatest discrepancies between climate model simulations and data. The range of models incorporated into the Pliocene Model Intercomparison Project (PlioMIP) fail to produce the strength of warming seen in the reconstructions, particularly at the highest

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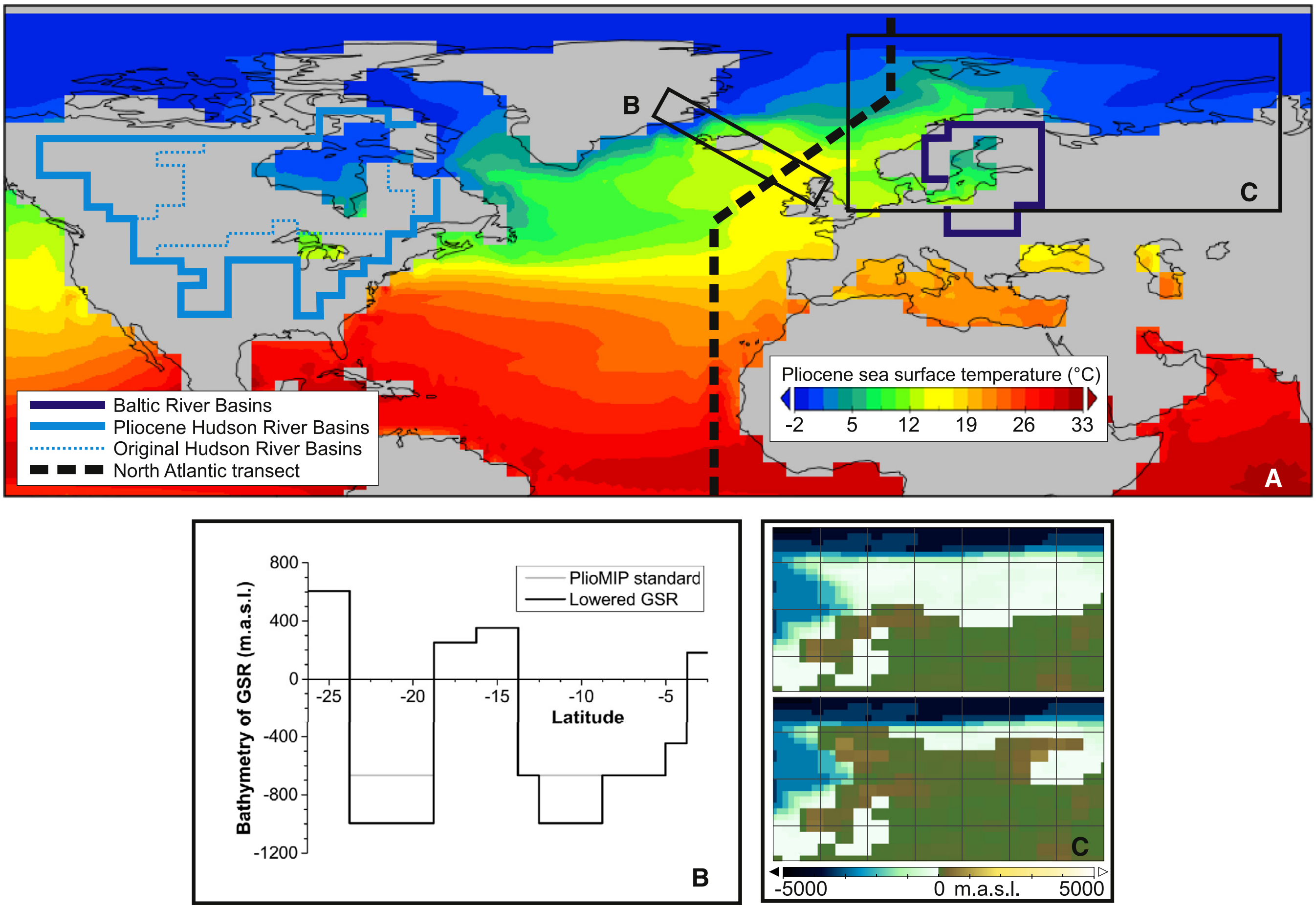

Fig. 1. Novel Pliocene palaeogeographic changes, as incorporated into the HadCM3 simulations. Panel A shows changes in North American rivers flowing out through the Hudson Bay river basins (Pliocene in solid cyan line, pre-industrial in dashed cyan line) and the Baltic river basins (dark blue), whose outflow has been diverted to the southern North Sea. Sea surface temperatures shown in the oceans are from the standard PlioMIP HadCM3 simulation. Panel B shows changes in the Greenland–Scotland ridge implemented in the model and Panel C shows the area raised above sea level in the Barents Sea simulations. Dashed black line through the North Atlantic and Nordic Seas in Panel A is the transect used for plotting sea surface temperature gradients in Figs. 6 and 7. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

latitudes (Dowsett et al., 2012; Haywood et al., 2013a), although further work is required to quantify the exact magnitude and causes of the mismatches (Haywood et al., 2013b).

1.3. Pliocene North Atlantic palaeogeography

There are a number of regional palaeogeographic changes that could have a significant impact on either the simulated warming or on the strength of AMOC and its northward ocean heat transport. Some are already incorporated into the PRISM3 reconstruction and PlioMIP boundary conditions, e.g. Greenland Ice Sheet retreat, northward Arctic treeline migration, etc. Many more potential factors are poorly constrained or completely unknown, e.g. Arctic palaeobathymetry, iceberg freshwater forcing, etc. In this study a number of palaeogeographic changes are selected based on proximity to the North Atlantic and Nordic Seas, the fact that they have not been incorporated into previous standard Pliocene model boundary conditions, that there are published reconstructions detailing their state in the Pliocene and on their non-analogue nature. This final criterion is important as the Pliocene has been used to estimate the long term sensitivity of the Earth system to changes in carbon dioxide forcing, commonly referred to as Earth System Sensitivity or ESS (Pagani et al., 2010; Lunt et al., 2010). Such calculations may be skewed by incorporating non-analogue palaeoclimate changes into these estimates, which would not be reflected in future climate change (Lunt et al., 2010). These criteria lead this study to focus on the impact of changes in the rivers of North America and Europe, a landmass in what is now the Barents Sea, and the depth of the Greenland–Scotland ridge (Fig. 1) and additionally the orbital impact on the results.

North American river routing has been altered across much of the continent by the Pleistocene glaciations and especially the emplacement of glacial moraines. The Mississippi River has captured the Ohio and Missouri rivers, areas that previously flowed northwards (Prather, 2000). The MacKenzie River has greatly expanded, capturing large areas south of its Pliocene drainage basin, which previously flowed into the Hudson Bay region (Duk-Rodkin and Hughes, 1994). Similarly the St. Lawrence River had only a relatively small coastal drainage basin during the Pliocene (Duk-Rodkin and Hughes, 1994). Small changes in the Rio Grande flow (Mack et al., 2006) have been included for completeness.

In Europe, the formation of the Baltic Sea inundated land that in the Pliocene formed the main trunk of the Eridanos River, capturing the flow of its tributaries that previously flowed into the North Sea (Overeem et al., 2002). The modern Barents Sea is an important control on poleward ocean circulation (Moat et al., 2014), but was the location for a large marine ice sheet during the Last Glacial Maximum. Sedimentation records suggest that glaciation reached the edge of the continental shelf by 2.4 million years ago (Knies et al., 2009). Backstripping of these Pleistocene sediment packages shows that prior to glacial erosion the Barents Sea was an extensive, if low lying, landmass (Butt et al., 2002).

The Greenland–Scotland ridge, a major feature of AMOC and barrier to northward heat transport, sits on top of the active Icelandic mantle plume (Wright and Miller, 1996). The upward force of the plume causes the crust on and around Iceland to bulge outwards (Sleep, 1990). As the intensity of the Icelandic plume varies, so does the bulging of the crust and hence the depth of the Greenland–Scotland ridge. Evidence of surface elevation change over the late Cenozoic, suggests that Iceland was around 300 m lower in the mid-Pliocene (Wright and Miller, 1996). Climate model simulations using a 1000 m lower Greenland–Scotland ridge suggest that there is a large climate signal associated with variations in the height of the ridge (Robinson et al., 2011).

2. Methodology

2.1. Model boundary conditions

All the new climate simulations presented here are based on the PlioMIP experimental design for coupled ocean–atmosphere models (Haywood et al., 2011b), which uses the PRISM3 palaeoenvironmental reconstructions of the mid-Pliocene (3.264–3.025 Ma; Dowsett et al., 2010) and incorporates an atmospheric CO_2 concentration of 405 parts per million (ppmv). This interval is typified by heavier than modern benthic oxygen isotopes (Lisiecki and Raymo, 2005), suggesting less global ice volume and warmer temperatures. It is bounded by significant isotope excursions, the M2 and G20 glacial periods (Dowsett et al., 2012), enabling easy identification in global marine records. As all of these simulations utilise a coupled ocean–atmosphere General Circulation Model (GCM) the PRISM3 fields used are topography (Sohl et al., 2009), ice sheets (Hill et al., 2007, 2010) and vegetation (Salzmann et al., 2008). The topography and vegetation fields were modified in simulations with an aerially exposed Barents Sea, based on the reconstructions of Butt et al. (2002) and regional climate factors, to reflect these changes. Apart from simulations where changes were specified both ocean bathymetry and river routing are kept at modern, as specified in the PlioMIP Experiment 2 design (Haywood et al., 2011b).

The HadCM3 river routing scheme specifies the oceanic outlet for each terrestrial grid box, where the simulated freshwater runoff is put into the ocean. For the North American river basin changes the grid boxes representing the Ohio and Missouri Rivers, the upper MacKenzie and St. Lawrence Rivers and the rivers that flow to the modern Hudson Bay are all altered to flow out into the Labrador Sea at the Hudson Strait. These alterations to North American rivers would represent similar to 30,000 $m^3\,s^{-1}$ additional riverine inputs to the Labrador Sea, rerouted from the Atlantic Ocean, Gulf of Mexico and Arctic Ocean, under a modern climatic regime. For the European river changes all the rivers that currently flow into the Baltic Sea where rerouted to flow out into the southern North Sea, representing roughly 7000 $m^3\,s^{-1}$ of modern freshwater input. In order to change the Greenland–Scotland ridge the depth of the sill below sea level was reduced from the modern standard of 666 m to 996 m at all of the shallowest points, except those between Scotland and the Faeroe Islands (Andersen et al., 2000).

Creating land over the Barents Sea involves significant changes to the model boundary conditions. The land–sea mask and topography are based on the reconstruction of Butt et al. (2002), taking the islands of Svalbard, Franz Josef Land and Novaya Zemlya as furthest extent of the Pliocene landmass. The vegetation on the new landmass was extrapolated from the PRISM3 reconstruction (Salzmann et al., 2008), taking into account the meridional and zonal temperature gradients. The meridional gradients are primarily constrained by the reconstruction of Svalbard vegetation, while there is a significant zonal gradient due to the distance from the warm waters of the Nordic Seas.

2.2. HadCM3 climate model

All the climate simulations used in this study were performed with the coupled ocean–atmosphere HadCM3 GCM (Gordon et al., 2000), a component of the UK Met Office Unified Model. The atmosphere has a resolution of 3.75° in longitude and 2.5° in latitude, with 19 levels in the vertical. The ocean has a resolution of 1.25° by 1.25°, with 20 vertical levels. The ocean model uses the Gent and McWilliams (1990) mixing scheme, coupled to a thermodynamic sea ice model with parameterised ice drift and sea ice leads (Cattle and Crossley, 1995). Modern climate simulations have been shown to simulate SST in good agreement with observation, without requiring flux corrections (Gregory and Mitchell, 1997). HadCM3 has been used extensively for simulating Pliocene climate (Haywood and Valdes, 2004; Lunt et al., 2008a; Bragg et al., 2012) and, despite problematic regions, has been shown over a number of dataset iterations to perform generally very well against Pliocene temperature data (Haywood and Valdes, 2004; Dowsett et al., 2011, 2012; Haywood et al., 2013a; Salzmann et al., 2013).

2.3. Modelling strategy

The standard mid-Pliocene simulation presented here (Fig. 2) is a 500 year continuation of the original HadCM3 PRISM2 simulation, under altered PRISM3 boundary conditions (Bragg et al., 2012), following the PlioMIP Experiment 2 protocol (Haywood et al., 2011b). The other Pliocene simulations branch off this standard at the beginning of the continuation and also run for a further 500 years. In each of four sensitivity experiments a single palaeogeographic factor is changed from North American rivers, European rivers, Greenland–Scotland ridge and Barents Sea. Two simulations are run with all four factors changed, one with just these changes and one with additional orbital forcing (Table 1). The chosen orbit, with parameters from 3.037 Ma, represents a time point when Northern Hemisphere summer insolation at 65°N was at a maximum (Dolan et al., 2011). In all the other simulations orbits are kept at the present day standard configuration.

3. Results

3.1. Impact of individual palaeogeographic changes on simulated sea surface temperature and Atlantic Meridional Overturning Circulation

Each of these factors produces a unique pattern of warming and changes in ocean circulation. The impact of rerouting North American rivers on SSTs is relatively small (Fig. 3(a)). The largest changes, which only amount to between 1 and 2 °C, are the response to the freshwater injection into the Labrador Sea, at the mouth of the present Hudson Strait. In the Labrador Sea itself SST warm, as the increased riverine input leads to a reduction in local sea ice (cf. Nghiem et al., 2014). In the North Atlantic, where the freshwater is transported, the warm currents of the North Atlantic Drift are weakened, reducing overturning (Fig. 4(a)) and therefore cooling SST by nearly 2 °C. Outside of these regions there are few significant changes (Fig. 3(a)).

The introduction of the Eridanos River freshens the Norwegian Current, the northernmost extension of the Atlantic thermohaline circulation and invigorates the northward heat transport in the Nordic Seas (Fig. 4(b)). This freshening and increased export acts to

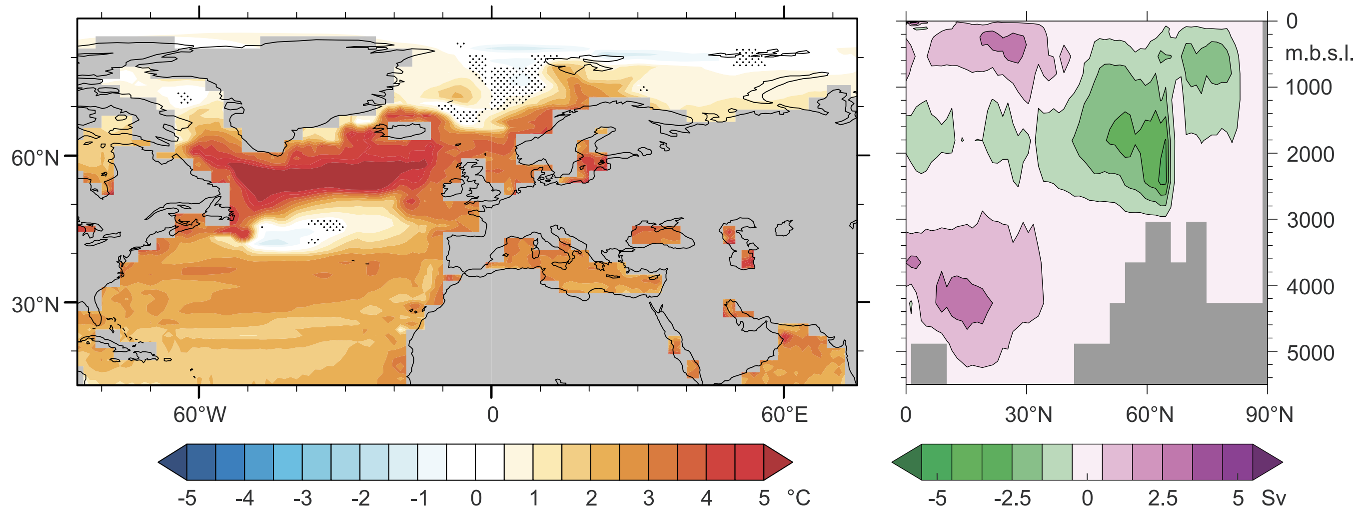

Fig. 2. Sea surface temperature (left) and AMOC (right) changes between the standard Pliocene and pre-industrial HadCM3 simulations. These simulations are based on the PlioMIP alternate experimental design (Haywood et al., 2011b; Bragg et al., 2012). Stippling indicates areas where sea surface temperature changes are not significant to a 95% confidence level according to the Student's t-test.

Table 1
Changes implemented in the various simulations used in this study and their impact on Pliocene warming along the transect plotted in Fig. 1. Stated palaeogeographic changes are from standard PlioMIP simulation, except for that simulation, which is compared to a standard pre-industrial simulation.

Simulation	Palaeogeographic change	Peak SST warming along transect in North Atlantic, Nordic Seas (°C)	Latitude of peak warming along transect (°N)
PlioMIP	CO_2, vegetation, ice sheets, orography	**4.57, 0.59**	**58.1**
North American rivers	Rerouting of Mackenzie, St. Lawrence and Mississippi rivers	3.95, 0.42	55.6
Baltic rivers	Reinstatement of Eridanos River	3.19, 2.03	58.9
Greenland–Scotland ridge	Lowering of ridge (∼300 m)	3.65, 1.89	58.1
Barents Sea	Above sea level	3.18, 2.89	58.1
Altered palaeogeography	All the above	**4.05, 4.70**	**83.1**
Altered palaeogeography + orbital forcing	All the above	**5.06, 6.34**	**78.1**

cool the Norwegian Current itself, but the SSTs warm in the Barents Sea (and the waters being transported into the Fram Strait) by more than 5 °C (Fig. 3(b)). These changes also have a far-field effect in the North Atlantic, as freshening the Norwegian current affects the salinity balance over the Greenland–Scotland ridge.

In a previous sensitivity study, lowering of the Greenland–Scotland ridge has been shown to cause large warming in the Nordic Seas, as the barrier to northward heat transport is reduced. Lowering the ridge by ∼1000 m increased simulated high latitude SSTs within HadCM3 by up to 5 °C under the previous iteration of boundary conditions from PRISM (Robinson et al., 2011). However, the large magnitude of this implemented change represents a particularly extreme scenario of Icelandic crustal movements. Evidence suggests a more modest lowering of around 300 m during the Pliocene (Wright and Miller, 1996), which we incorporate into the altered PlioMIP HadCM3 boundary conditions (Fig. 1). Although the pattern of warming is similar to previous studies, the magnitude is much reduced (Fig. 3(c)), approximately in line with expectations should a linear relationship between ridge depth and high latitude warming be assumed. The AMOC shows a strong increase in northward heat transport on both sides of the ridge (Fig. 4(c)), showing just how significant a restriction the Greenland–Scotland ridge is to Atlantic overturning.

Introducing a land mass in the Barents Sea blocks off one of the two currents that extend the Norwegian Current from northernmost Norway into the Arctic. Thus, the relatively warm and saline waters of the Norwegian Current are all deflected northwards towards the Fram Strait. This increase in regional heat transport, combined with a significant sea ice feedback (Table 2) leads to a large warming in the region between the Fram Strait and Norway and spilling over into the European sector of the Arctic Ocean (Fig. 3(d)). Despite this high latitude warming the AMOC is significantly reduced in this simulation (Fig. 4(d)). This reflects the fact that the warming is due to a change in the geometry of the Nordic Seas and probably also the reduced thermohaline forcing due to strong high latitude warming. This clearly shows that changes in SST and AMOC need not necessarily be positively correlated when other factors are also changing (Zhang et al., 2013, cf. Raymo et al., 1996).

3.2. *Overall impact on simulated Pliocene climate*

In the North Atlantic, small shifts in the North Atlantic Drift current cause relatively large temperature signals, but these largely cancel out when all of the factors are incorporated (Fig. 5(a)). Significant impacts on AMOC (up to 5 Sv) are produced by changes in North American rivers, introducing significant volumes of freshwater into the Labrador Sea, which is exported directly into the key latitudes for AMOC. Despite strong competing impacts from the Greenland–Scotland ridge, overturning is significantly weaker when all the palaeogeographic changes are incorporated. This causes the North Atlantic to cool compared to PlioMIP simulations, although this cooling is small when all the factors are included (Fig. 5(a)).

Large portions of the Nordic Seas (Iceland Sea, Greenland Sea and the Norwegian Sea) are warmed by a number of palaeogeographic factors (Baltic Rivers, Barents Sea and Greenland–Scotland ridge) and the overall warming seems to be largely cumulative (Fig. 6). Local impacts from the introduction of the Eridanos River

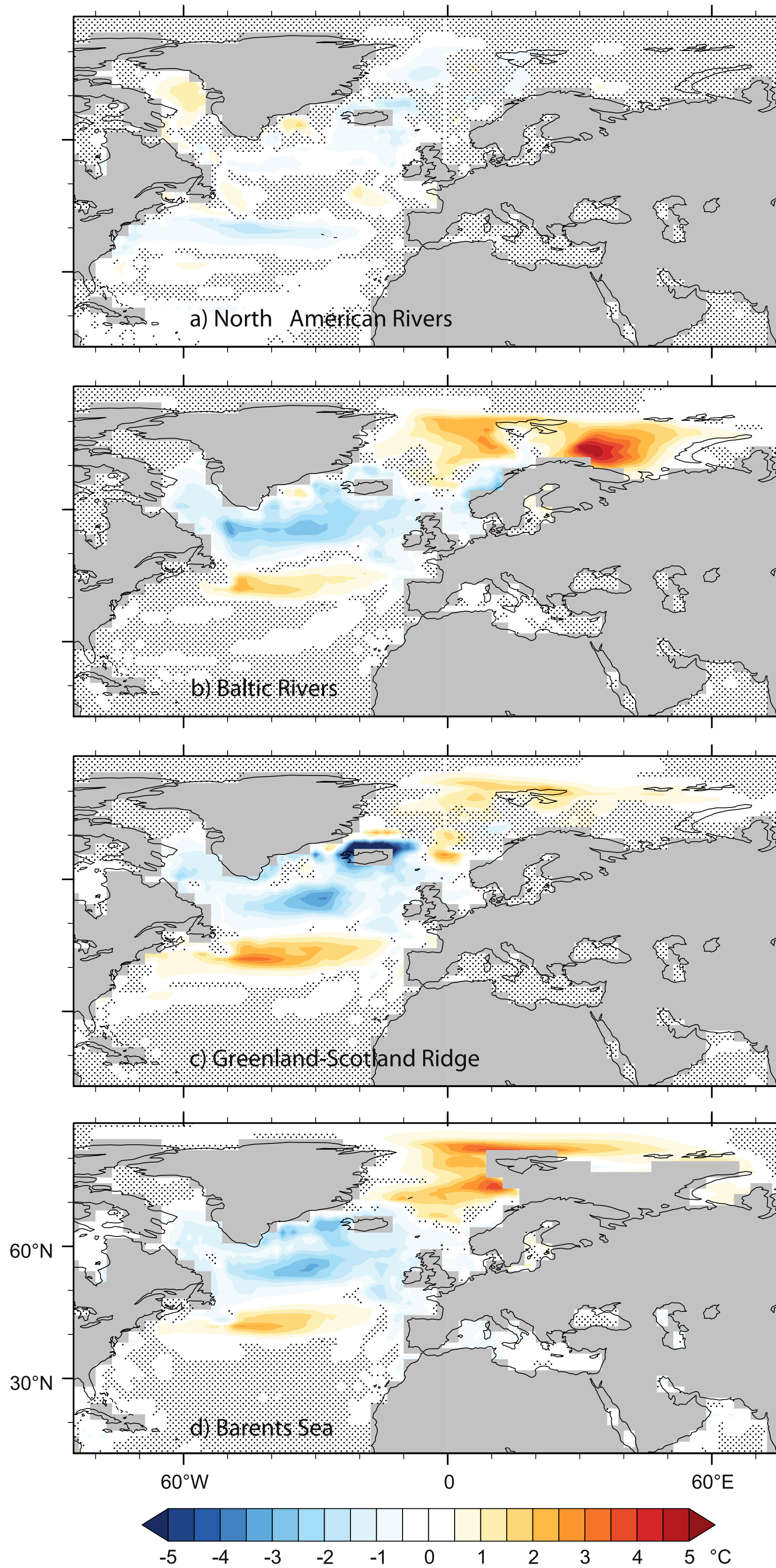

Fig. 3. North Atlantic sea surface temperature warming. Fields shown are relative to the PlioMIP standard simulation. Each of the simulations incorporates a single palaeogeographic change, (a) North American rivers, (b) Baltic rivers, (c) Greenland–Scotland ridge and (d) Barents Sea. Stippling indicates areas where changes are not significant to a 95% confidence level according to the Student's t-test.

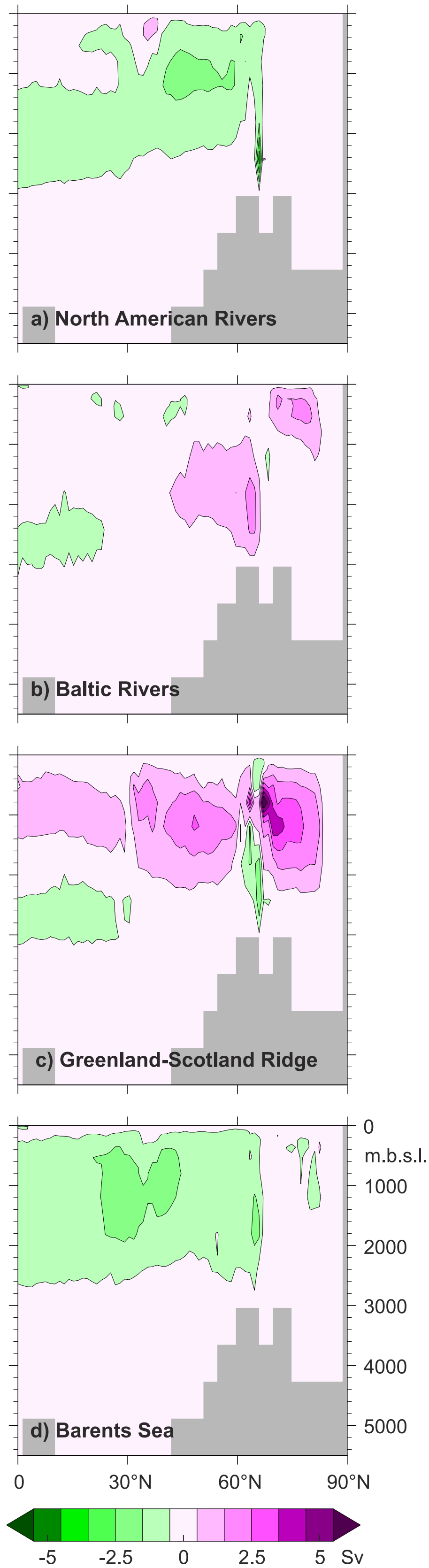

Fig. 4. Changes in Atlantic Meridional Overturning Circulation in response to individual changes in palaeogeographic boundary conditions. Fields shown are relative to the PlioMIP standard simulation. Each of the simulations incorporates a single palaeogeographic change, (a) North American rivers, (b) Baltic rivers, (c) Greenland–Scotland ridge and (d) Barents Sea.

mean that coastal regions of the Norwegian Sea are cooler than the standard Pliocene simulations (Fig. 5(a)). For Baltic rivers and Greenland–Scotland ridge changes the increased temperatures in the Nordic Seas are due to increased overall overturning north of the Greenland–Scotland ridge. This is especially strong when the depth of the ridge is increased, driving warmer waters further into the Nordic Seas (Fig. 5(a)). The warming is further enhanced by the introduction of land over the Barents Sea, which prevents the North Atlantic sourced waters from spreading eastwards and concentrates the warming around Svalbard and through the Fram Strait into the Arctic (Fig. 5(a)).

3.3. Impact of palaeogeographic changes on Atlantic temperature gradients

The combined effect of all these palaeogeographic changes is to introduce a strong warming to the Nordic Seas (Fig. 5(a)), where the original PlioMIP simulation showed little change or a slight cooling (Fig. 2). This has the effect to completely alter the gradient of Pliocene warming (Fig. 6), to the point where the latitude of maximum warming is no longer in the North Atlantic, but in the Nordic Seas, 25° latitude northwards (Table 1). Although all the individual simulations showed some change, this dramatic change is not seen in any of the simulations where the individual palaeogeographic changes were implemented. This shows the importance of incorporating all of the changes in model boundary conditions when modelling past climates. However, the pattern is far from uniform, even in the Nordic Seas. The Norwegian Current is actually cooler in the simulations with altered palaeogeography compared to both the standard PlioMIP and pre-industrial simulations. The largest cooling in the simulation with altered palaeogeography is in the waters around Iceland (Fig. 5(a)), which is associated with greater flow over the Iceland–Scotland ridge and a significant northward shift in North Atlantic Deep Water production.

The SSTs in the North Atlantic are reduced by these palaeogeographic changes (Fig. 5(a)), not helping previously documented data–model mismatches (Dowsett et al., 2012), but the effect is an order of magnitude less than the Nordic Sea warming (and the data–model mismatches). The individual sensitivity simulations presented here show how previously unconsidered forcings can have a significant impact on the SSTs (Fig. 3) and ocean circulation (Fig. 4) of the North Atlantic and also how these different forcings can interact to enhance or reduce the magnitude of change. The reconstructed strong warming in the North Atlantic occurs in one of the regions of strongest variability in both the observed modern climate (Hurrell, 1995) and Pliocene palaeoceanographic records (Lawrence et al., 2009). There may be further palaeogeographic changes that could have a large impact on the North Atlantic, perhaps via significant changes in global thermohaline circulation. For example changes in the Bering Strait (Hopkins, 1967; Marincovich and Gladenkov, 2001), Isthmus of Panama (Lunt et al., 2008b) or the Canadian Archipelago (Rybczynski et al., 2013). Despite the different responses in different regions, the overall effect of these changes in palaeogeography is a warming, particularly strong in the Nordic Seas.

3.4. Additional warming from orbital forcing

There are times during the Pliocene when orbital forcing was very similar to present day, atmospheric carbon dioxide was similar to modern and the climate was warmer (Haywood et al., 2013b). However, there are also intervals of significant increases in incoming solar radiation in both the Northern and Southern Hemisphere (Dolan et al., 2011; Prescott et al., 2014). This additional forcing is, in some way, incorporated into Pliocene tem-

Table 2
Modelled Pliocene Arctic September sea ice area.

Simulation	September Arctic sea ice area (million km^2)
Pre-industrial	**7.84**
PlioMIP	**1.95**
North American rivers	2.08
Baltic rivers	2.06
Greenland–Scotland ridge	1.58
Barents Sea	1.74
Altered palaeogeography	**1.82**
Altered palaeogeography + orbital forcing	**0.13**

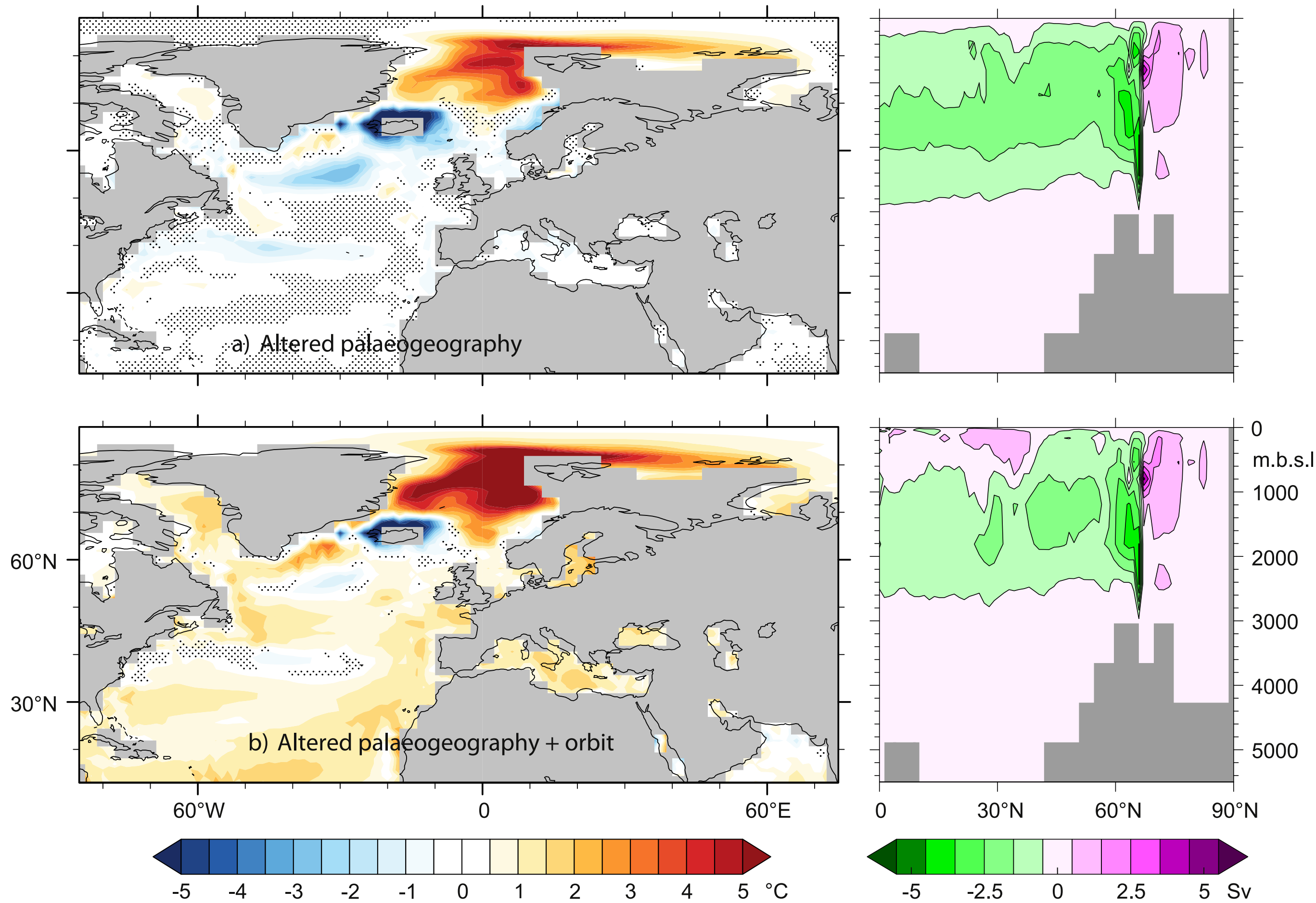

Fig. 5. Sea surface temperature and AMOC results of simulations with all four palaeogeographic changes. (a) Under modern orbital forcing and (b) including Northern Hemisphere maximum orbital forcing, both relative to the PlioMIP standard simulation. Stippling indicates insignificant temperature changes according to the Student's t-test.

perature records, but the magnitude of this effect has yet to be resolved (Haywood et al., 2013b). In order to test how much additional orbital forcing could decrease the North Atlantic temperature gradient, a further simulation was run with the maximum mid-Pliocene incoming summer solar radiation (Dolan et al., 2011) on top of changes in palaeogeography. This additional forcing increases SSTs throughout the Northern Hemisphere, with particularly strong overall warming of up to 10 °C in the high latitudes (Fig. 5(b)). This is seen particularly in the simulation of summer sea ice in the Pliocene, which all but completely disappears when orbital forcing is added to the palaeogeographic changes (Table 2). Although the strong orbital forcing during periods of the Pliocene acts to further enhance the reduction in North Atlantic temperature gradients, the basic structure of the warming, which peaks in the high latitude Nordic Seas, does not change (Fig. 7).

3.5. Comparison to Pliocene temperature records

Due to polar amplification the high latitude sites are generally the drivers of reconstructed reductions in temperature gradients. In the marine realm, high latitude sites are rare and often the measurements made in this region are of lowest confidence (Dowsett et al., 2012). Even if we restrict ourselves to the higher confidence sites in the PRISM3 SST reconstruction, the addition of the non-analogue palaeogeographic and orbital forcing clearly improves the data–model comparison, both in magnitude of warming and the profile of warming (Fig. 7). The problems of overestimating modelled warming in the tropics are made marginally worse, but are more than compensated for by improvements in the higher latitudes.

Although high Arctic terrestrial records are rare and often poorly dated, the Pliocene sediments at Beaver Pond on Ellesmere

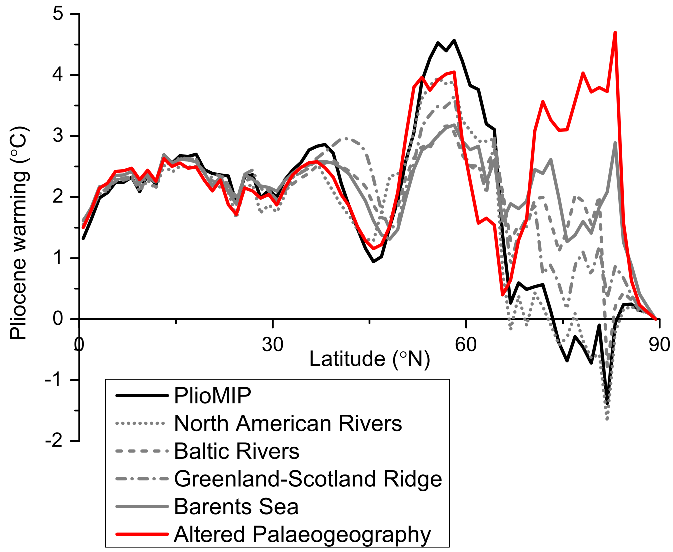

Fig. 6. Pliocene North Atlantic mean annual sea surface temperature gradient. Values shown are relative to a standard pre-industrial simulation, along a 5° wide transect centred on the line shown in Fig. 1. Each of the simulations with a single altered palaeogeographic factor are shown, as well as the PlioMIP standard and the simulation with all the palaeogeographic changes.

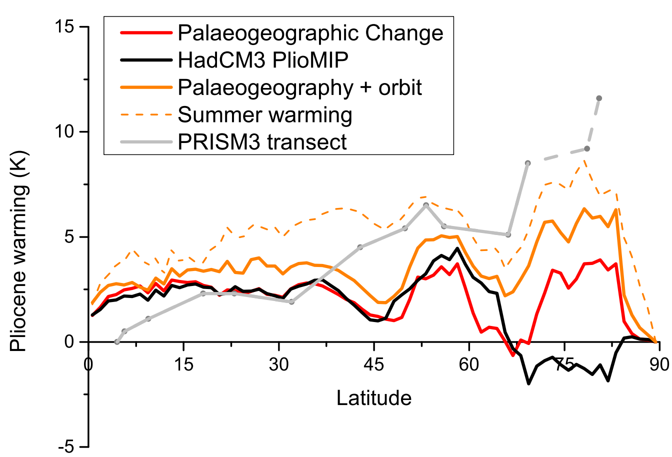

Fig. 7. Pliocene North Atlantic mean annual sea surface temperature warming transects, as shown in Fig. 6. Dashed line is the August warming in the simulation with altered palaeogeographical and orbital forcings. Points are the Pliocene warming at the PRISM3 sites in close proximity to the transect (Dowsett et al., 2010), with the dashed portion showing where the gradient is defined by lower confidence (and potentially summer biased; Robinson, 2009) sites (Dowsett et al., 2012). Although the PRISM3 data is not directly comparable to the model simulations, as they represent very different reconstruction techniques (Haywood et al., 2013b), the change in the modelled profile shows that the additional palaeogeographic changes and orbital forcing produces a Pliocene temperature gradient much closer to the SST reconstructions.

Island have been extensively studied and multi-proxy analysis means it has well constrained temperature estimates (Ballantyne et al., 2010). The strong warming shown in these temperature reconstructions is not reproduced by Pliocene climate models and can only be reconciled when the most conservative and uncertain reconstruction techniques are considered (Salzmann et al., 2013). The standard PlioMIP simulation underestimates surface air temperature warming by 4–10 °C at the Beaver Pond site. Including the additional palaeogeographic forcing does not improve the data–model comparison, although the incorporated changes were chosen for their potential impact on the North Atlantic and there could be local changes in the Canadian Arctic that we have not considered here (Rybczynski et al., 2013). However, including the orbital forcing reduces the mismatch by at least 2 °C. It is possible that these temperature reconstructions are biased towards the summer months, as the chemical proxies are the result of summer biased biological productivity (Ballantyne et al., 2010). The additional summer orbital warming increases the estimates of Pliocene warming at Beaver Pond to the levels suggested by the proxy reconstructions (Table 3).

4. Discussion

4.1. Pliocene temperature gradients

The large reduction in meridional temperature gradients has been suggested as one of the key factors in Pliocene warming (Dowsett et al., 1992, 2010; Fedorov et al., 2013) and is also a major concern for future climate change (Simon et al., 2005; Anisimov et al., 2007). Pliocene climate models have been shown to poorly reproduce evidence for large high latitude warming and reduced temperature gradients (Ballantyne et al., 2010; Dowsett et al., 2012; Salzmann et al., 2013). However, the simulations presented here show that previously unconsidered non-analogue palaeogeographic changes can drive significant changes in the meridional temperature gradient in the Pliocene North Atlantic (Fig. 6). There remain significant data–model mismatches, although this study suggests that a more thorough treatment of the palaeogeographic uncertainties, as well as planned improvements in the treatment of palaeoclimatic variability (Haywood et al., 2013b), could resolve these discrepancies (Fig. 7).

The meridional gradients in the North Pacific are less well constrained, although strong warming occurs in the records from the California margin and the Kuroshio Current (Dekens et al., 2007; Dowsett et al., 2012; Fedorov et al., 2013). Any data–model mismatch in these areas is going to be complicated by the fact that they are major upwelling zones, a process not well simulated with the current range of models used for Pliocene climate studies. However, the models do a reasonable job of simulating mid-Pliocene warming in these regions (Haywood et al., 2013a). The records suggest that the early Pliocene is slightly warmer than the simulated mid-Pliocene (Fedorov et al., 2013), although this is probably in a period with an open Isthmus of Panama (Coates et al., 1992). There are, however, further palaeogeographic changes that could have occurred in the Pliocene North Pacific. The history of changes in the geography of the Indonesian Throughflow (ITF) over the last 3 million years is not well constrained. We know that there have not been large movements in the relative position of the tectonic plates, but the ITF flows through narrow channels

Table 3
Modelled Pliocene surface air temperature warming for the high latitude terrestrial site at Beaver Pond, located at 78°N, 82°W. The proxy record suggests Pliocene warming of +19 ± 1.9 °C, although this may reflect summer warming due to proxy biases (Ballantyne et al., 2010).

Reconstruction	Annual mean Pliocene warming at Beaver Pond (°C)	July mean Pliocene warming at Beaver Pond (°C)
PlioMIP	+11.1	+13.3
Altered palaeogeography	+10.7	+13.0
Altered palaeogeography + orbital forcing	+13.2	+19.3

between Asia, Australia and the Indonesian Archipelago. Relatively small changes in the depth of these channels or the configuration of the islands could have large impacts on the Pliocene climate (Karas et al., 2009). There is some geological evidence for changes in water depth and the islands of the Indonesian archipelago (van Marle, 1991; Roosmawati and Harris, 2009), suggesting potential impacts on Pliocene climate. More proximal to the North Pacific are changes in the North American Pacific watershed (Mack et al., 2006), the heights of the Rocky Mountains (Thompson and Fleming, 1996; Moucha et al., 2008), the marginal seas of the Asian Pacific (Jolivet et al., 1994) and possibly the closure of the Bering Strait (Hopkins, 1967).

4.2. Palaeogeography in palaeoclimate models

Previous research into the impact of palaeogeography on past climates has focused on the role of ocean gateways on climate (Zhang et al., 2011; Lefebvre et al., 2012). While this has a large potential for shifting global circulation patterns and impacting global heat transports, it is far from the only important climate model boundary condition that can significantly alter past climates. This is especially true of climatically sensitive regions, such as the North Atlantic, where this study has shown boundary condition changes can have significant impacts. While altering key gateways within modelling studies has great value in understanding the impacts of changes in the Earth system, comparing to palaeoenvironmental data without reference to the potential uncertainties due to underrepresented palaeogeographic change, leaves any mismatch with multiple possible explanations.

4.3. The Pliocene as a future climate analogue

The Pliocene remains the best palaeoclimate for understanding the workings of the Earth system at ∼400 parts per million concentrations of carbon dioxide. In no other past climate was the Earth in as similar a condition to today, with carbon dioxide significantly raised from pre-industrial levels. However, if the Pliocene is to provide us with lessons for the future of the Earth, then a more thorough understanding of the climatic impact of non-analogue changes in the Earth system is required. If this can be properly quantified then there is the potential that the Pliocene could provide a good example of the climatic changes and impacts that would be expected under sustained present-day levels of atmospheric carbon dioxide.

Lunt et al. (2010) provide the sort of framework that is required for any study that wishes to use palaeoclimates as a future climate analogue. In this study, the modelled impact of orographic changes on the climate of the Pliocene was removed from the calculations of Earth System Sensitivity. Although the changes implemented in that study were less than those that would be required to do a complete analysis of non-analogue changes, it provides a simple framework to incorporate these changes into our understanding of the Pliocene in the context of future climate change. This study suggests that there are further non-analogue components to Pliocene warming, which need to be removed from considerations of Earth System Sensitivity.

5. Conclusion

Palaeogeographic changes since the Pliocene significantly alter the modelled temperature gradients in the North Atlantic, suggesting a role for them in producing the much warmer than modern high latitude temperatures. None of these additional forcings will be a factor in the future, calling into question the use of the Pliocene as a climate change analogue. However, if we are to look for potential climates to understand the working of climate at modern concentrations of atmospheric CO_2, then the mid-Pliocene remains the best palaeoclimate. Lunt et al. (2010) provides a framework for incorporating these changes within the context of using the Pliocene to understand the potential future response to anthropogenic CO_2 increases. These results also show the importance of incorporating all the palaeogeographic changes into palaeoclimate models, particularly when investigating regional climate or doing data–model comparisons.

6. Conflict of interest statement

Climate model results are archived at the University of Leeds and are available upon request. The author declares no competing financial interests. Correspondence and requests for materials should be addressed to D.J.H. (eardjh@leeds.ac.uk).

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