***Highlights (for review)**

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- Neogene thermal latitudinal gradients are reconstructed for N America and W Eurasia
- Proxy-based, continental temperature gradients are evaluated against model data
- Thermal gradients were flat throughout the Miocene and strongly steepened in the Pliocene
- The thermal anomaly between North America and Europe first appeared in the Pliocene
- AMOC intensified after the final closure of the CAS during the early Pliocene

Continental Climate Gradients in North America and Western Eurasia before and after the Closure of the Central American Seaway

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Abstract

The Gulf Stream, as part of the Atlantic Meridional Overturning Circulation (AMOC), is known as a major driver of latitudinal energy transport in the North Atlantic presently causing mild winters over northwestern Eurasia. The intensity of the AMOC throughout the Neogene, prior to the final closure of the Central American Seaway (CAS) in the early Pliocene, is still poorly known, but most authors assume that the circulation was considerably weaker than present. Here we address this issue from a continental point of view. We studied the past AMOC intensity by analyzing Neogene continental climate patterns along North American and Western Eurasian transects. Based on a total of 317 palaeofloras thermal latitudinal gradients are reconstructed for three Neogene time slices, namely the middle Miocene, late Miocene, and late Pliocene using the Coexistence Approach to obtain quantitative climate data. The obtained proxy-based, continental temperature gradients are evaluated against data from a selection of published General Circulation Model (GCM) simulations for the three time slices studied.

Our study suggests that shallow thermal latitudinal gradients existed in North America and Western Eurasia throughout the Miocene but became strongly steepened in the late Pliocene. In both Miocene time slices studied, the higher latitudes were by up to 30 °C warmer than present (cold month mean), also at times with presumed pre-industrial CO_2 such as the late Miocene. In the late Pliocene high-latitude, the temperature difference with respect to the present had decreased by up to 10 °C (cold month mean). Both mean annual temperatures and cold month means of the lower mid and low latitudes were at the present-day level throughout all three time slices, or even slightly below. In both Miocene time slices, zonal temperature means at both continental transects were similar in the mid and higher latitudes. However, several northwest European sites reveal very mild winter condition suggesting the early existence of a probably less intense Palaeo-Gulf Stream. The distinct thermal anomaly (annual and cold month means) today existing between North America and Western Eurasia appeared for the first time in the late Pliocene, attaining about 50 % of the present-day magnitude. This supports the assumption that the AMOC intensified after the final closure of the

CAS during the early Pliocene. The results obtained from the palaeobotanical proxies are in line with data from coeval marine archives, particularly with North Atlantic sea surface temperatures (SSTs) inferred from oxygen isotopes. However, the proxy-based thermal gradients are not well reproduced by a selection of GCM simulations, due to a well-known systematic underestimation of high latitude warming by GCMs for the Miocene and Pliocene time slices.

Key words: Climate gradients, Northern Hemisphere, Neogene, North Atlantic Circulation, Gulf Stream, palaeobotanical record, Coexistence Approach

1. Introduction

The Gulf Stream, as part of the Atlantic Meridional Overturning Circulation (AMOC), is known as a "Heat Conveyor" and a major driver of latitudinal energy transport. The ocean current results from a combination of two systems - the wind-driven circulation and thermohaline circulation (THC) (e.g., Manabe and Stouffer, 1995). Although the relevance of atmospheric versus oceanic heat transport to northwestern Eurasia is controversial (e.g., Seager et al., 2002) it is clear that the Gulf Stream allows "the maritime effect to operate in the northern North Atlantic and creates a milder European climate than in North America and that without the heat transport, ice would likely extend over much greater areas of ocean and land" (Rhines and Hakinnen, 2003). This effect is most pronounced in winter. Reduced salinity of surface waters related to higher precipitation rates and melting of the Greenland ice might disrupt this circulation (e.g., Johannessen et al., 2005). A slowing-down or cessation of the THC in the Northern Atlantic under future global warming may be possible and its consequences for Western Europe would be significant (e.g., Bryden et al., 2005; Rhein et al., 2013).

The Neogene AMOC and its varying intensity - prior to the closing of the Central American Seaway (CAS) in the early Pliocene - is still a matter of debate. Most authors state that both the circulation and associated heat transport were considerably reduced when compared to present-day conditions, the decrease of volumetric rate of transport of AMOC with an open CAS being estimated between 2 to 16 Sv (e.g., Maier-Reimer et al., 1990; Lunt et al., 2007; Steppuhn et al., 2007; Sepulchre et al., 2014). However, tectonism in the Caribbean realm (Kirby et al., 2008) might have intermittently affected deep-water exchange across the CAS since middle Miocene times (Sepulchre et al., 2014; Montes et al, 2015). Considerable increases in North Atlantic Sea Surface Temperatures (SSTs) over those of the present (Lutz et al., 2008) and primary production peaks within the Northern Component Water (Poore et al., 2006; Newkirk and Martin, 2009) are already documented for the late middle to late Miocene.

After the closure of the CAS, both the AMOC and associated heat transport to the North Atlantic increased during the early Pliocene, due to enhanced transport of saline surface waters via an intensified Gulf Stream, and intensification of the upper North Atlantic Deep Water (NADW) formation in the Labrador Sea (Steph et al., 2006). The relative flux of deep water forming in the North Atlantic was enhanced between 4.3 and 3.7 Ma, and was warmer and more saline than today (Billups et al., 1999). The warm conditions in the late Pliocene were referred to as a stronger greenhouse and stronger conveyor (Raymo et al., 1996). The appearance of large-scale, Arctic glaciation in the Pleistocene caused a southward displacement of NADW formation or even collapse at times of fresh water pulses (Clark et al., 1999). The final establishment of the Panama land-bridge is also reflected in a decoupling of the Pacific and Atlantic $\delta^{13}C$ records, which diverge from ca. 4.4 Ma onwards (Steph et al., 2006). The Northern Atlantic circulation has and had a strong impact on the continental climate of Western Eurasia, also in times prior to the closure of the CAS (e.g., NAO-induces patterns in Tortonian records of Greece (Brachert et al., 2006), however, this impact is difficult to assess from marine proxies only.

In the last decade, quantitative studies of continental climate data have considerably increased in both quality and quantity. Most studies focus on the analysis of time series and therefore document climate evolution on a regional scale. Comparatively few studies exist on global or continental scale spatial palaeoclimate patterns, mainly focusing on the Paleogene (e.g., Greenwood and Wing, 1995; Fricke and Wing, 2004). For the Neogene, few studies have been carried out at a global scale. Pound et al. (2012) reconstructed the relative steepness of thermal latitudinal gradients inferred from latitudinal biome distribution in two east coast transects (the Americas / Pacific coast of Eurasia and Australia) for four time slices (Langhian, Serravallian, Tortonian, Messinian). For the late Pliocene Salzmann et al. (2008; 2013) provided global biome and climate reconstructions (mainly mean annual temperatures) for data model comparison as part of PRISM (Pliocene Research, Interpretation and Synoptic Mapping) and the Pliocene Model Inter-comparison Project (PlioMIP) (Haywood et al., 2016; Dowsett et al., 2016). However, both the Miocene and late Pliocene global vegetation reconstructions use the published authors´ original climate interpretations and therefore lack an internally consistent approach to derive global quantitative climate estimates from palaeobotanical proxies.

The study of Neogene climate patterns of Western Eurasia is the focus of the NECLIME research consortium (Bruch et al., 2007; Utescher et al., 2011). Data reconstructed for the Miocene point to shallow gradients in general, of e.g. 0.48 °C per degree latitude in the middle Miocene Western Europe, between 36 and 47 °N (Fauquette et al., 2007; Jimenez-Moreno et al., 2010), and considerably higher than present temperatures at higher mid- and higher latitudes (e.g., Bruch et al., 2011; Utescher et al., 2011). These studies represent an important knowledge base but they do not cover the required spatial range and time-frame.

In the present study, continental temperatures and thermal latitudinal gradients for North American and Western Eurasian transects (Fig. 1) are reconstructed from the palaeobotanical record, for a total of three Neogene time slices, namely middle Miocene, late Miocene, and late Pliocene, revealing details on Neogene cooling of the Northern Hemisphere and highlighting the apparent evolution of the effect of North Atlantic ocean circulation on Western Eurasia. Proxy-based temperature gradients are evaluated against temperature gradients obtained from a selection of published General Circulation Model (GCM) simulations. Generally, GCM simulations for Cenozoic time slices fail to reproduce the equator-to-pole temperature gradients inferred from terrestrial and marine proxy-data (Herold et al., 2010; Stephanek and Lohmann, 2012; Goldner et al., 2014) and therefore might underestimate future warming (Spicer et al., 2014). The comparison performed here allows for a first attempt to quantify the data-model mismatches for the two continental transects in the Miocene and Pliocene.

2. Materials and methods

To compare continental patterns on both sides of the Atlantic two transects are defined within the Northern Hemisphere. The North American transect ranges from 120 ° to 25 °W, the Western Eurasian transect from 25 °W to 35 °E. For both transects, published floral lists for a total of 317 sites were analyzed with respect to palaeoclimate. The sites were compiled to study conditions in three time intervals, the middle Miocene (15.97 – 11.63 Ma), late Miocene (11.63 – 5.33 Ma), and late Pliocene (3.6 – 2.58 Ma), and comprise micro- (pollen and spores) and macrofloras (leaves, fruits and seeds). The sites selected for both Miocene time slices in each case represent extended NECLIME data sets (records partly published in Pangaea, www.pangaea.de), complemented by North and Central American localities (this study). Our late Pliocene time slice includes sites compiled by Salzmann et al. (2013) from palaeobotanical literature. The palaeofloras considered here have varying quality and age control. These uncertainties are accepted here in favour of spatio-temporal data cover. While the Miocene climate can be characterized as comparatively stable, a higher variability can be assumed for the late Pliocene, already having distinct glacial-interglacial cycles (e.g., Mosbrugger et al., 2005; Zachos et al., 2008; Utescher et al., 2012; Jimenez-Moreno et al., 2013; Prescott et al., 2014; Panitz et al., 2016; Andreev et al., 2014). Details on the sites included in this study are given in the electronic supplement.

To reconstruct quantitative temperature data from the palaeobotanical record we use the Coexistence Approach (CA) (cf. Utescher et al., 2014 for more details on the method), together with a calibration procedure enhancing the climatic resolution (Utescher et al., 2009). Climate data for extant taxa were retrieved from the Palaeoflora Database (Utescher and Mosbrugger, 2015). As a taxonomy-dependant approach, the CA is based on climatic requirements of Nearest Living Relatives (NLRs) identified for the plant fossils. In the CA an interval is identified for a given climate variable and NLR association in a fossil flora in which a maximum number of taxa could coexist. This interval is denoted as coexistence interval representing the most probable estimation for the past climatic condition. The CA can be applied on all types of fossil floras as long as at least 10 NLRs having climate data are known. The CA is a well-established method for reconstructing Cenozoic continental spatial climate patterns and time series (e.g., Mosbrugger et al., 2005; Bruch et al., 2007; 2011; Utescher et al., 2011; Popova et al., 2012; Utescher et al., 2015). The temperature resolution of the CA may attain the range of a few degrees, but depends on a variety of factors (Utescher et al., 2014).

Here we focus on the reconstruction of two temperature variables, cold month mean temperature (CMT) considered most sensitive to the impact of the AMOC on continental climate (e.g., Palter, 2015), and mean annual temperature (MAT), a variable commonly used in model - proxy data comparisons. For the calibration procedure, we also reconstructed warm month mean temperature (WMT), in addition to MAT and CMT, as well as four precipitation variables (mean annual precipitation, MAP; precipitation of the wettest, driest and warmest month, MPwet, MPdry, MPwarm) in order to identify equivalents in modern global climate space using the 0.5° gridded climate means of New et al. (2002). The climatic sub-spaces identified for the variable combination of each palaeoflora were then used to extract calibrated MAT and CMT coexistence intervals, commonly more restricted compared to the primary CA data (Utescher et al., 2009) and therefore used in this study.

On average, 28 taxa (SD = 15) contribute with climate data in the analysis, for MAT a mean resolution of 2.7 °C (SD = 2.4 °C) is obtained corresponding with the average width of the coexistence intervals. For CMT the mean resolution amounts to 4.4 °C (SD = 4.0 °C). This comparatively low resolution is due to the high proportion of microfloras in the record (Utescher et al., 2014). All floras included in this study are provided in the electronic supplement, including references, diversity, and climatic results encompassing both primary and calibrated data for MAT and CMT.

The proxy-based temperature gradients for the three periods of interest were compared to near surface air temperature gradients derived from published climate model simulations with different versions of the atmospheric model ECHAM5 (Roeckner et al., 2003). We selected available simulations of ECHAM5 with prescribed oceanic conditions or fully-coupled ocean model. The model setup follows the PLIOMIP protocol for the Pliocene simulations (Haywood et al., 2013). For Miocene time slices, we selected simulations with middle-range boundary conditions, excluding e. g. extreme values of CO_2 concentrations or singular palaeogeography. The model simulation selection applied here allows for a first estimation of data-model mismatches for the two continental transects. Future analysis should be based on extended data-model comparison including several GCMs with various boundary conditions. We use the MPI-ESM (Krapp and Jungclaus, 2011) and the Planet Simulator (Henrot et al., 2010) simulations for the middle Miocene. MPI-ESM is a comprehensive Earth-System Model including the spectral atmospheric model ECHAM5 (Roeckner et al., 2003), used here at a resolution of T42 (i.e., a resolution of 2.81°×2.81° in longitude-latitude), the land surface model (Raddatz et al., 2007; Brovkin et al., 2009), and the ocean model MPI-OM (Marsland et al., 2003). Planet Simulator is a spectral Atmospheric General Circulation Model (AGCM) derived from ECHAM5, based upon the Portable University Model of the Atmosphere, PUMA (Fraedrich et al., 1998), with a T42 resolution, and including a slab ocean model. The middle Miocene simulations assume an atmospheric CO_2 concentration of respectively 480 ppmv for MPI-ESM and 500 ppmv for Planet Simulator. For the late Miocene, temperature gradients are calculated from a simulation performed with the COSMOS atmosphere-ocean general circulation model (AOGCM) (Micheels et al., 2011), forced with an atmospheric CO_2 concentration of 360 ppmv. The atmospheric component of the model is ECHAM5 at a resolution of T31 (i.e., a resolution of 3.75°×3.75° in longitude-latitude) and the oceanic component is MPI-OM. For the late Pliocene we use two COSMOS simulations (Stepanek and Lohmann, 2012) performed in the frame of the PlioMIP project (Haywood et al., 2013). For the first simulation COSMOS 1, ECHAM5 is run in standalone mode and forced by climatological monthly means of SSTs and sea ice concentration. For the second simulation COSMOS 2, ECHAM5 is coupled to the MPI-OM ocean model. Both COSMOS late Pliocene simulations assume a CO_2 concentration of 400 ppmv and have a T31 resolution. A summary of model setups and configurations for Miocene and Pliocene simulations is given in Table 1. More detail on the models and the designs of the climate simulations can be found in the reference publications mentioned above (Krapp and Junglaus, 2011; Henrot et al., 2010; Micheels et al., 2011; Stepanek and Lohmann, 2012).

To display thermal latitudinal gradients for both continental transects we calculated zonal means for MAT and CMT in steps of 5 ° latitude. For modern values we use 0.5° gridded climatological data (New et al., 2002). The model zonal and continental mean MATs and CMTs were calculated at the respective model resolutions. Only continental grid-cells (grid-cells with a land fraction greater than 50 %) of the model land masks included in both transects were used to calculate the model zonal means. The visualization of the fossil gradients is also based on zonal means calculated from the means of coexistence intervals obtained from the floras in both continental transects. The mode of comparison of past and present temperature fields does not account for past elevation changes in the continental transects studied.

3. Results

3.1 Latitudinal temperature gradients – palaeobotanical proxies

The spatial distribution of the fossil sites within the studied continental transects (Fig. 1) is fragmentary. While continental areas between 35 and 55 °N are well represented by data, records from the low and high latitudes are scarce, thus hampering clear identification of gradients and their inter-comparison. Today, MAT ranges from 24 to 28 °C in the low latitudes (ca. 0 – 20 °N) of both key regions (New et al., 2002). In North America, zonal MAT means in the transect decline by about 46 °C to -20 °C, at 80 °N, but in Western Eurasia by only about 33 °C, thus leading to a marked difference between both thermal gradients. This divergence is even more distinct in CMT, with North American values declining by ca. 55 °C to -32 °C at 80 °N, but in Western Eurasia by ca. 43 °C to only -18 °C at the same latitude (Fig. 1).

For reconstructing past climates in the low latitudes between 0 and 25 °N data from 10 palaeofloras are available. Almost all inferred temperatures are at the present-day level or even slightly lower (Chilga, Ethiopia at 12.6 °N, late Miocene; ODP Site 658, off West Africa at 21 °N, late Pliocene: by ca. 2 °C for MAT) (Fig. 2). A higher value compared to the modern zonal mean is obtained only for one site (Herrería flora at 17 °N, late Pliocene: by ca. 2 °C for CMT). When considering the fact that in CA reconstructions of low latitude floras the actual values are expected to be close to the warm end of the coexistence intervals we assume for the tropics a temperature level close to modern across all time slices. In both transects, the latitudinal sector from ca. 25 ° to 33 °N represents a gap in our records, except for the late Pliocene Peace Creek microflora located at ca. 28 °N on the American East Coast, providing MAT and CMT values within the range of modern conditions (Fig. 2). Overall, the mid-latitudes of our continental transects show the best data coverage although comparatively few sites are available for the eastern part of the American continent (cf. Chapter 2). For the middle Miocene high latitude sites reach 66 °N in Western Eurasia (floras on Iceland), and 72 °N in North America (Mary Sachs Gravel). Late Miocene high-latitude sites include Iceland for Western Eurasia, while data for North America are only available south of 45 °N. The late Pliocene time slice allows a comparison of both continental transects up to ca. 70 °N. Regarding the High Arctic, climate conditions can only be documented for North America (Meighen, Ellesmere Islands).

In both Miocene time slices, latitudinal thermal gradients were considerably shallower compared to present. Based on zonal means calculated for the palaeoclimate data by using means of coexistence intervals, a latitudinal MAT gradient of 0.23 °C/°lat (R^2=0.95; SE=3.8) is obtained for Western Eurasia, based on middle and late Miocene floras (modern: 0.56), for North America 0.27 °C/°lat (R^2=0.92; SE=5.4) are obtained (modern: 0.69). For the middle and late Miocene a CMT gradient of 0.36 °C/ °N (R^2=0.93; SE=3.6) results for Western Eurasia, for North America 0.46 °C/°lat (R^2=0.91; SE=5.6; modern: 0.67; 0.92). In the lower mid-latitudes the inferred Miocene temperature plots within the range of the modern values, while almost all floras north of 40 °N indicate warmer than present conditions, with temperature anomalies (with respect to present) increasing with the latitude of the flora. The highest Miocene temperature, compared to the present zonal mean, can be found at the middle Miocene Mary Sachs Gravel megaflora located at ca. 72 °N (ca. 25 °C for MAT, ca. 30 °C for CMT), while the Western Eurasian floras on Iceland, at ca. 66 °N, indicate MAT and CMT means warmer by ca. 10 °C than today. The zonal means calculated from our Miocene floras do not show the same temperature divergence between both continental regions as we see today. For both Miocene time slices the inferred temperatures and zonal means are very similar, with the late Miocene data being slightly cooler on average. At 50 – 55 °N our reconstruction reveals differences in middle and late Miocene CMTs. The middle Miocene data includes floras with exceptionally warm CMT coexistence intervals in the order of 10-12 °C. All these refer to floras from coastal settings adjacent to the Cenozoic North Sea (Lower Rhine Basin, Lusatian Basin, Eastern North Sea Basin). In the late Miocene, such warm environmental conditions were less common by far.

The latitudinal thermal gradients obtained for the late Pliocene are steeper when compared to both Miocene time slices (Fig. 3). Western Eurasia shows a Pliocene MAT gradient of 0.33 °C/°lat (R^2=0.99; SE=1.8) (CMT: 0.40; R^2=0.97; SE=2.5), North America has the same gradient for MAT (R^2=0.97; SE=4.6), but a steeper CMT gradient (0.56/°lat (R^2=0.98; SE=3.9)). The lower latitudes up to 40 °N of both transects indicate palaeotemperatures close to modern. For three sites located between 0 and 25 °N temperatures were cooler than present in the order of 2 °C (eastern transect: ODP site 658 (MAT); western transect: Facatativá 13 Site, Columbia, Bogotá; Bogotá B (MAT, CMT)). For Herrería (Guatemala) a warmer than present CMT (by ca. 2 °C) is reconstructed. Most of the palaeotemperatures obtained for mid-latitudinal sites north of 40 °N are clearly above the modern zonal means. However, with differences from present ranging from 2 to 5 °C, Pliocene temperatures were significantly cooler when compared to both Miocene time slices. At the high latitudes of North America both late Pliocene sites (Meighen Island, Ellesmere Island) indicate warmer than present MAT and CMT by ca. 14 °C and 20 °C, respectively. However, the temperatures are well below the Miocene estimates suggesting that late Pliocene polar temperature amplification was not as extreme as during the middle Miocene.

Another feature of the late Pliocene thermal gradient pattern is the appearance of the present day characteristic divergence of the gradients across both continental areas. The difference can be seen in both temperature variables studied but is more evident in CMT, attaining at least 4 °C when regarding the extremes of coexistence intervals. Although our result is based on relatively few sites we assume that in the late Pliocene, the thermal difference between both continental areas attained about 50% of the present values.

3.2 Latitudinal temperature gradients – model data

Climate model simulations for the Miocene time slices show much steeper MAT and CMT gradients in both transects in comparison to data-based reconstructions. Middle and late Miocene simulations support warmer temperatures at low latitudes, and colder temperatures northwards to 50 °N, by more than 20 °C for both MAT and CMT, in comparison to the data. Between 30° and 50 °N means of model and data-based MAT and CMT fairly well agree. We calculate middle and late Miocene MAT latitudinal gradients for Western Eurasia of respectively 0.51, 0.52 and 0.54 °C/°lat for the MPI-ESM, Planet Simulator and COSMOS simulations (North America 0.59, 0.6 and 0.6). For CMT, the latitudinal gradients in Western Eurasia are respectively 0.57, 0.66 and 0.61 (North America 0.81, 0.89 and 0.77). The gradients calculated from the Miocene simulations are closer to the modern ones than to the latitudinal gradients derived from the palaeobotanical data. Moreover, the modelled temperature gradients for Western Eurasia, particularly for CMT, are flatter than for North America in the middle and late Miocene simulations, suggesting a divergence of both continental regions in the Miocene simulations.

The temperature gradients derived from the COSMOS Pliocene simulations show a better agreement with proxy-based temperature reconstructions at mid- and high latitudes than the Miocene simulations. The latitudinal gradients calculated for Western Eurasia for MAT are respectively 0.41 and 0.49°C/°lat for the COSMOS 1 and COSMOS 2 simulations (North America 0.53 and 0.59), and for CMT 0.44 and 0.51°C/°lat (North America 0.67 and 0.75). The latitudinal gradients are flatter for both continental regions in the Pliocene than in the Miocene simulations. However, as observed in the data-based temperature reconstructions, the divergence of the temperature gradients of North

America and Western Eurasia is more pronounced than in the Miocene runs, particularly for CMT (Fig. 3).

4. Discussion

4.1 Temperature gradients and patterns based on palaeobotanical proxies

Our reconstruction based on a total of 317 palaeobotanical records from continental areas on both sides of the Atlantic provides for the first time a coherent picture of the temperature patterns and their evolution using three selected Neogene time slices. Our data indicate that the latitudinal thermal gradients were considerably flatter than present throughout the Miocene, and steeper in the Pliocene, thus getting closer to present-day conditions. Our data also suggest the evolution of the temperature offset between North America and Western Eurasia. Partially, this offset can be related to a strengthening of the Gulf Stream causing a relative winter warming in the Eurasian continental part, combined with temperature decline in the continental interior of North America causing a relative cooling.

The very flat latitudinal MAT gradient we reconstruct for both Miocene time slices (ca. 0.23 °C/°lat for Western Eurasia and 0.27 °C for North America) results from the combination of near present-day low latitude temperatures and a considerable thermal anomaly at the high latitudes. The shallow inclination of both Miocene gradients resembles conditions reported for the Palaeogene (e.g., Greenwood and Wing, 1995; Fricke and Wing, 2004) and traditionally has been related to a high atmospheric CO_2 level (e.g., Shellito et al., 2009). This is especially noteworthy when considering the fact that during the middle Miocene the CO_2 level was only moderately raised (Foster et al., 2012) while for the late Miocene most author assume a pre-industrial level (e.g., Pagani et al., 1999; Forrest et al., 2015). Recent studies suggest therefore other mechanisms for temperature increase such as a reduction in the planetary albedo and a positive water vapor feedback in a warmer atmosphere (Knorr et al., 2011).

The existence of shallow latitudinal thermal gradients over most of the Miocene, combined with significantly raised temperature in the high latitudes basically coincides with results obtained in various previous studies. For Western Eurasia several studies by the NECLIME network suggest a weak Miocene climatic gradient (e.g., Bruch et al., 2007; Jimenez-Moreno et al., 2010; Utescher et al., 2011; Bruch et al., 2011; Popova et al., 2012). Pound et al. (2012) concluded from the distribution of major biomes in various Neogene time slices that the Northern Hemisphere bioclimatic zonal gradient continued to be shallower than modern throughout the Miocene and slowly became closer to modern by the Messinian. Also qualitative interpretations of the floral record in the higher latitudes (e.g. Iceland) come to the conclusion that at the onset of the late Miocene, warm temperate climate prevailed (mostly Cfa climate sensu Köppen-Geiger), supporting a vegetation with numerous thermophilous elements (Grimmson et al., 2007). In Iceland, warmth-loving taxa including *Magnolia*, *Liriodendron*, *Sassafras* and *Comptonia* went extinct between 12 and 10 Ma, following the cooling after the Mid-Miocene Climatic Optimum (MMCO). However, this association was replaced by another set of thermophilous taxa (Juglandaceae aff. *Pterocarya*/*Cyclocarya*, *Rhododendron ponticum* type; cf. Denk et al., 2005) at 10 Ma. More evidence for the exceptionally warm higher latitudes comes from the middle Miocene fossil record of Jutland where palms are reported among other thermophilous floral elements (Friijs, 1975; Larsson et al., 2011). The presence of crocodiles and apes in the Langhian of the Lower Rhine Basin (Mörs et al., 2000) and a very warm climatic phase in the late Tortonian (Lower Rhine Basin, 7 F horizon containing fossil taxa referred to the *Mastixia* genus, and other thermophilous components (see van der Burgh, 1988) provide another line of evidence.

Temperatures similar to those of the present level in the lower latitude Miocene sites, namely localities of the Tethyan realm, were previously described in other studies using the CA to quantify palaeoclimate (e.g. Mantzouka et al., 2015). In our reconstruction, the Miocene temperature gradients form a plateau in the latitudinal range of the Tethyan realm (Fig. 2), pointing to equable conditions in this region and to temperatures close to modern. Other studies carried out on middle to late Miocene floras of Western Europe located between 36 and 47 °N came to somewhat differing conclusion. Based on the Climate Amplitude Method (Fauquette et al., 1998), a MAT level in the western Mediterranean realm consistently warmer by 4 °C compared to modern values and a steeper gradient (0.48; 0.6 °C /°lat) were reconstructed (Fauquette et al., 2007; Jimenez-Moreno et al., 2010).

No comprehensive quantitative data on latitudinal temperature gradients currently exist for North American Miocene floras. This lack of information might result from the scarcity of coeval sites in the eastern half of the continent, a fact that also compromises the present analysis. Moreover, climatic analyses for the sites located in western North America are complicated by uncertainties concerning the palaeoaltitude of the different basin complexes (e.g., McMillan et al., 2006). Based on the occurrence of thermophilous taxa in mid-Miocene Pacific floras located between 35 and 65 °N, a latitudinal gradient of 0.3 °C per degree of latitude has been estimated by Liu and Leopold (1994), a value close to our reconstruction. Although being based on few northerly sites only, our gradient points to conditions comparable with Western Eurasia. For the low latitudes between 10 and 20 ° data for both Miocene time slices indicate temperatures close to the modern ones. However, it is important to note that the NLR-based CA does not allow for reconstructing warmer conditions than the present global maximum (Utescher et al., 2014).

For the late Pliocene our data suggest warmer than present conditions for the higher mid- and higher latitudes. This coincides with a raised CO_2 level (Martínez-Botí et al., 2015; Pagani et al., 2010). For Western Europe our reconstruction partly agrees with the data provided by Fauquette et al. (2007) suggesting MATs at 45 – 50 °N ca. 2 – 3 °C higher than present while in our reconstruction, MATs for the more southerly sites (e.g., the Andalucia G1 site) were near the modern level, thus indicating a shallower thermal gradient. Accordingly, palaeobotanical data for the tropical zone suggest that the evergreen rain forest belt was nearly in the same latitudinal position as today (e.g., Kershaw and Sluiter, 1982; Suc et al., 1995). At high latitudes, the late Pliocene warm climate resulted in taiga forest, and positioned the taiga – tundra transition zone 2,500 km (Canadian Arctic) further north compared to present (e.g,. DeVernal and Mudie, 1989; Salzmann et al. 2008). For the Canadian high Arctic, a multi-proxy study suggests Pliocene MATs were approximately 19 °C warmer than at present (Ballantyne et al., 2010; according to our data: 20 – 23 °C). However, with zonal CMT means in the order of -10 to -18 °C, as calculated for the sites at 70 - 80 °N, our results accommodate Arctic sea ice forming during the Pliocene (e.g., Lunt et al., 2008; Meyers and Hinnov, 2010).

4.2 Evolving offset between the latitudinal gradients

The temperature difference between both continental areas reflected in modern climatology (Fig. 1; New et al., 2002) can be related to the oceanic circulation in the North Atlantic and its intensity, being an important trigger for the observed offset of the temperature gradients. The present-day very effective Gulf Stream, with a capacity of up to 150 sv adds to the shallow modern gradient in Western Eurasia and causes winter temperatures allowing palm growth on the Kerry coast of Ireland, at a northern latitude of 53 °N. Since palaeogeography has not substantially changed in our selected transects throughout the Neogene, the evolving differences can be interpreted to reflect past changes in the Gulf Stream intensity.

According to our present results, there is first clear evidence for the offset of latitudinal thermal gradients between both transects in the late Pliocene (fig. 2). This points to a Pliocene intensification of the Gulf Stream postdating the final closure of the CAS between 4.3 and 3.7 Ma (Kirby et al., 2008) as is suggested based on marine proxies (increased Atlantic THC, intensified Upper NADW formation in the Labrador Sea, and decoupling of the Pacific and Atlantic $\delta^{13}C$; cf. Steph et al., 2006). Considering the fact that this offset is about 50 % of the present, our data do not support a stronger-than-present conveyor as proposed for the time of the late Pliocene warmth (Raymo et al., 1996; Billups et al., 1999).

When comparing CMT data obtained for the middle Miocene Pyramid Lake flora (CMT 5.0 – 5.1 °C) with Western European floras at the same latitude (e.g., several of the LRB and WB floras: CMT ca. 9

– 12 °C) the temporary existence of a Palaeo-Gulf Stream, already in the late early to middle Miocene appears possible. Similar observations were made by Bruch et al. (2011) reporting low seasonality for Western Europe during the Burdigalian and Langhian. Moreover, there is evidence for milder conditions in Western Eurasia and a more thermophilous aspect of the vegetation compared to the eastern part of North America at the same latitude (Utescher et al., 2013). Recent studies comparing mid-latitude Eurasian records of the Atlantic and Pacific sides of Eurasia came to the conclusion that a marked temperature difference (mainly CMT) between both regions began to evolve during the Aquitanian, attaining more than 5 °C for CMT during the Mid Miocene Climatic Optimum (Utescher et al., 2015). This temperature difference between East and West suggests the existence of a Palaeo-Gulf Stream, already operational from the late early Miocene on. This agrees with evidence for an earlier, at least intermittent, disappearance of the CAS, at ca. 15 Ma (Montes et al., 2015; Bacon et al., 2013).

4.3 Proxy-based gradients and palaeoclimate modelling

As is shown by our proxy-model data comparison at the level of zonal means, middle and late Miocene simulations do not reproduce the latitudinal thermal gradients reconstructed from palaeobotanical data both in North America and Western Eurasia. The model gradients are closer to the modern ones, due to slightly warmer temperature at low latitudes and much colder temperatures at high latitudes compared to the data-based reconstructions. Previous studies already pointed out that the models underestimate proxy-derived mean annual temperatures for the middle Miocene and overestimate the equator-to-pole temperature gradient (Herold et al., 2010; Goldner et al., 2014; Henrot et al., 2016). Goldner et al. (2014) reported that most of the models simulate only one third of the expected middle Miocene warming, suggesting that GCMs are either not sensitive enough or additional feedbacks remain missing to simulate the Miocene warmth. The inability of models to reproduce Cenozoic climates in general can also be attributed to the calibration of the models to present-day climate, using various forms of often simplifying parameterizations (Stainforth et al., 2005; Spicer et al., 2013). However, some model-data mismatches can also be due to feedback mechanisms in the climate system of the models. For example, the MPI-ESM and COSMOS Miocene simulations produce temperatures close to the modern ones or even slightly cooler in Northwestern Europe, in response to a weakening of the meridional heat transport in the North Atlantic resulting from a reduction of NADW production caused by sea-ice melting under higher pCO_2 (Krapp and Jungclaus, 2011; Butzin et al., 2011).

All the selected Miocene simulations show a steeper thermal gradient in North America in comparison to Western Eurasia, reflecting the continental influence on temperature in North America (Henrot et al., 2010; Krapp and Jungclaus, 2011).

The late Pliocene experiments are in better agreement with the proxy data reconstructions, but e.g. for the high latitudes of North America, model estimates are still too cold by ca. 8 °C compared to the proxy-based zonal mean. In the Pliocene simulations, the difference in temperature gradients between North America and Western Eurasia is well marked. The thermal gradient is close to the Miocene ones in North America, but is much flatter in Western Eurasia, in response to the enhancing of the Gulf Stream effect with a closed CAS (Haywood et al., 2013; Stepanek and Lohmann, 2012). The gradient is steeper in the fully coupled ocean-atmosphere simulation COSMOS 2, because the oceanic model cannot reproduce the warming in the northern North Atlantic Ocean and neighbouring areas of the Arctic suggested by sea surface temperature proxy-based reconstructions (Dowsett et al., 2013), which are prescribed in the atmosphere-only COMSOS 1 simulation (Stepanek and Lohmann, 2012). This leads to a better agreement of the atmosphere-only COSMOS 1 simulation with proxy data reconstructions.

4.4 Marine proxies

Marine data represent important independent proxies to assess the reliability of the palaeobotany based reconstruction of thermal gradients although they are as well subject to various uncertainties (e.g., cf. Crowley and Zachos (2000) for planctonic forams). From various studies on Cenozoic continental climate evolution, a close correlation with marine archives could be demonstrated at different scales (e.g., Mosbrugger et al., 2005; Donders et al., 2009; Utescher et al., 2012). Also the shallow latitudinal gradients evidenced by continental data, including the warmer-than-present high latitudes for all the time slices, are largely supported by proxy-based sea surface temperature data (SSTs) available from boreholes in the North Atlantic.

For the middle Miocene between 14 and 17 Ma, including the MMCO, several studies indicate warm SSTs for the North Atlantic ranging between 15° and 22 °C at ca 50 °N (e.g., Pagani et al., 1999; Shevenell et al., 2004; Raddatz et al., 2011). These estimates are in perfect agreement with our reconstruction of continental Western European MATs of 15.9 °C (SD = 1.3 °C) as an average obtained for that latitude. At high northern latitudes there is evidence for high SST anomalies increasing with latitude (Robinson et al., 2008; Oleinik et al., 2008; Pohlmann et al., 2009), supporting our data.

Multi-proxy SST estimates document warm surface water conditions in the higher mid- and high latitudes of the North Atlantic during the late Pliocene (cf. Lawrence et al., 2009; DSDP sites 606, 607, 609, 552). At site 552, ca. 58 °N, south of Iceland, a ΔSST of ca. 5 – 7 °C with respect to present is reported, similar to the continental ΔMAT of >6 °C we reconstruct for the Sleipner well. Strong, sustained cooling of North Atlantic SSTs, e.g. by ~4.5 °C at around 3.5 Ma (Site 982; Lawrence et al., 2009) postdates most of our proxy data records.

5. Conclusions

Our study shows that the shallow thermal gradients that existed in North America and Western Eurasia throughout the Miocene strongly steepened in the late Pliocene. In both the middle and late

Miocene time slice, the higher mid and high latitudes were considerably warmer than present, independent of prevailing atmospheric pCO_2 conditions, including pre-industrial concentrations suggested for the late Miocene, or under raised atmospheric CO_2 reconstructed by most of the authors for the time of the MMCO. The MAT anomaly at high northern latitudes with respect to present (at 75 – 80 °N) declined from about 30 °C in the Miocene to about 20 °C in the late Pliocene. Hence, very warm high latitudes persisted in the study area throughout most of the Neogene.

According to our continental data, temperatures of the lower mid and low latitudes were at the present-day level, or even a few degrees below. Thus, the thermal gradients reconstructed based on zonal means of the palaeobotany-based proxies asymptotically approximate modern continental gradients at northern latitudes between 34 to 40 °.

Our reconstruction is basically in line with other estimates of continental temperatures for the studied time slices based on the palaeobotanical record such as the distribution of major zonal biomes. Past scenarios with generally raised continental temperatures under higher atmospheric pCO_2, including the lower latitudes, are not supported by our reconstruction. Moreover, the continental temperature patterns inferred from palaeobotanical data largely agree with results obtained from coeval marine archives, particularly with North Atlantic SSTs inferred from oxygen isotopes. However, the proxy-based thermal gradients are not well reproduced by a selection of GCM simulations for the studied time slices. Model simulations show steeper temperature gradients, particularly for the Miocene, mainly due to an underestimation of high latitude warming in comparison to data-based reconstructions.

According to our results there is evidence that the distinct thermal anomaly presently existing between North America and Western Eurasia evolved after the late Miocene, attaining about 50 % of the present-day magnitude in the late Pliocene. The difference between both continental regions is most expressed in winter temperature and is considered to reflect both the degree of winter cooling in the high latitude continental interior of North America as well as the effect of the Gulf Stream creating mild winter conditions in northwestern Eurasia. Thus, the first appearance of the difference in the late Pliocene continental proxies supports the assumption that AMOC intensified after the final closure of the CAS during the early Pliocene. However, very warm CMTs reconstructed for several northwest European Miocene sites suggest that there existed a Miocene Palaeo-Gulf Stream circulation that caused mild winter in coastal areas of the Cenozoic North Sea.

Although a large number of sites was compiled to analyse past continental climate patterns our study reveals distinct gaps in the palaeobotanical record of both transects. Future works will mainly focus on the palaeobotanical record of the North American continental transect in order to enhance data cover and taxonomic resolution in the available palaeofloras.

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Figure 1

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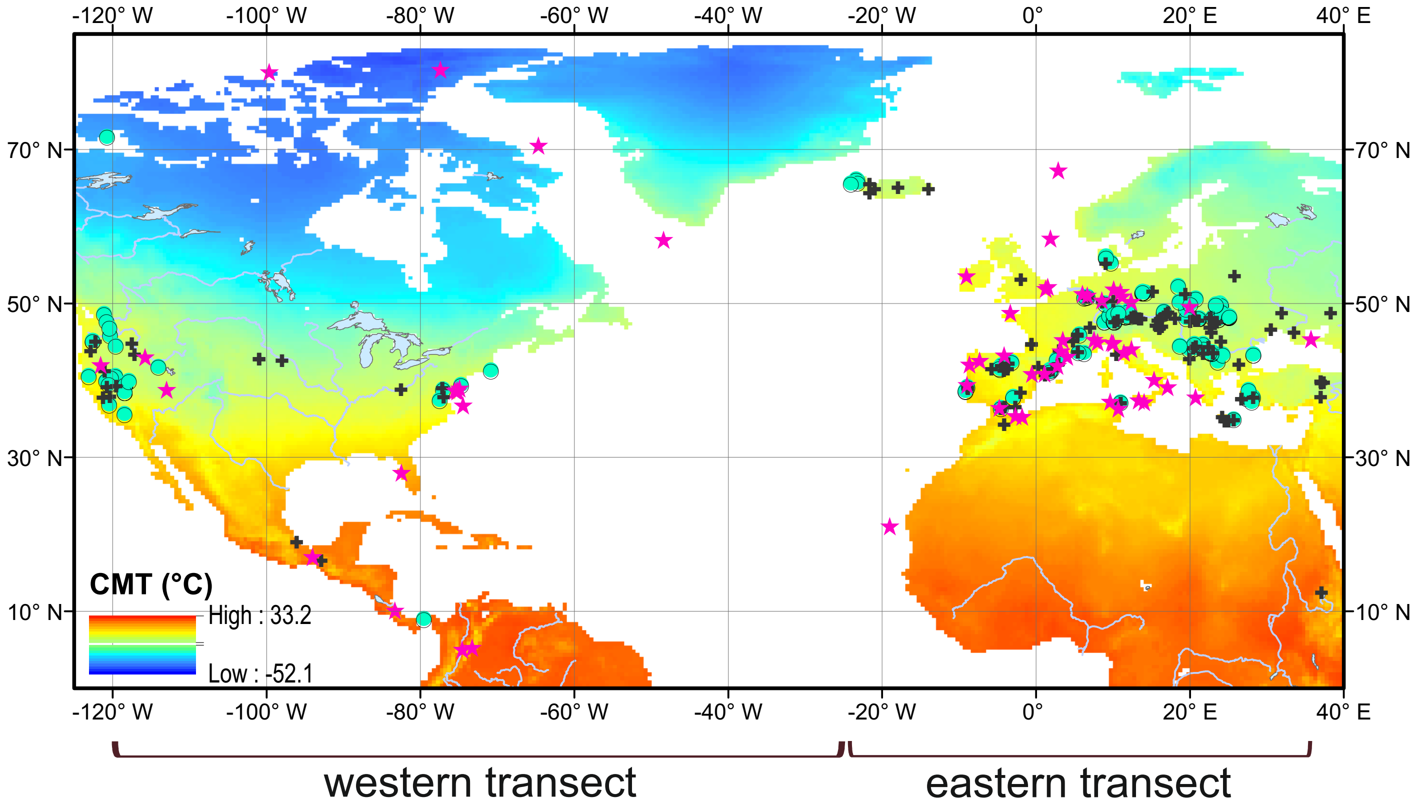

Figure 2

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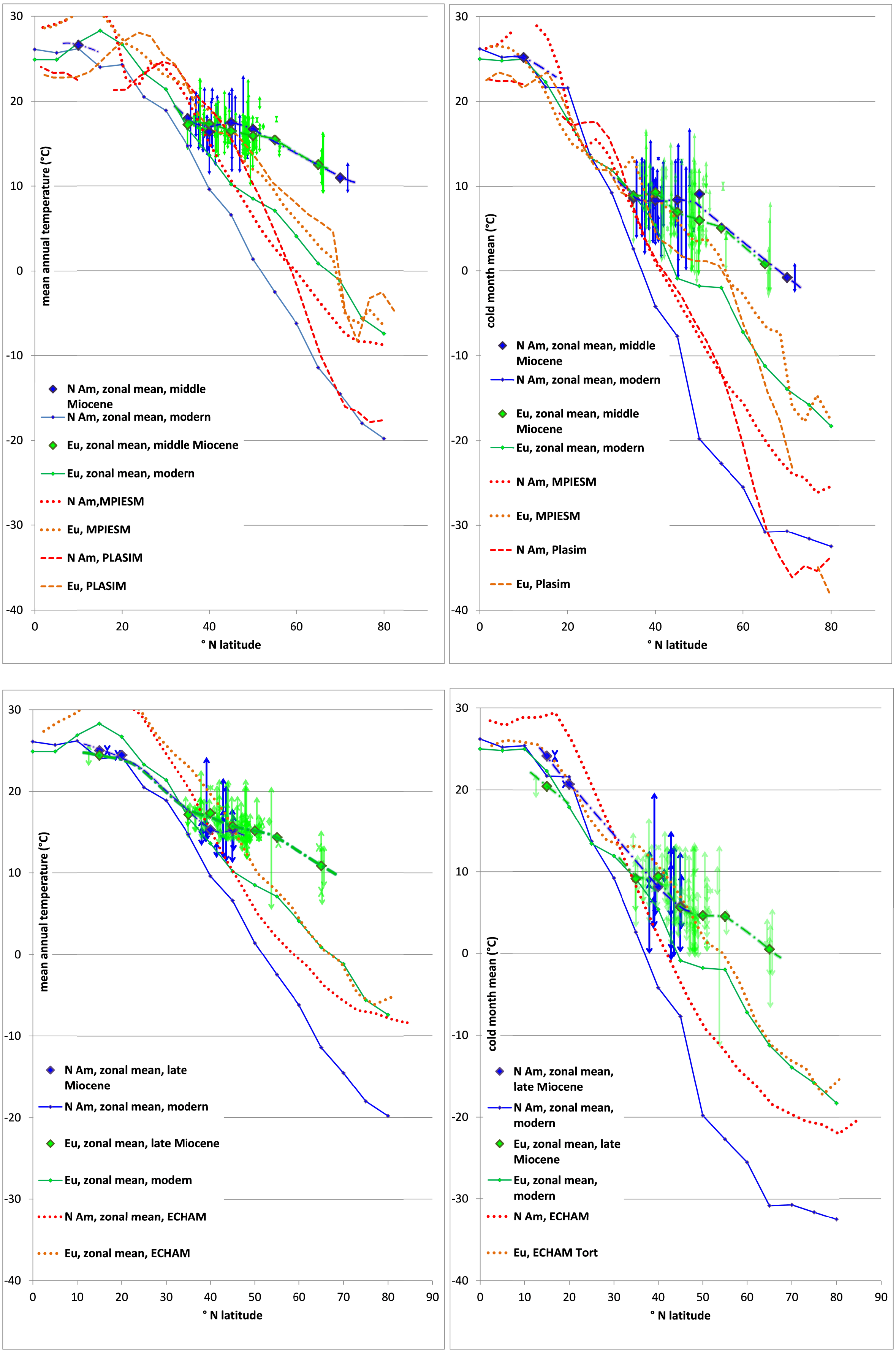

Figure 3

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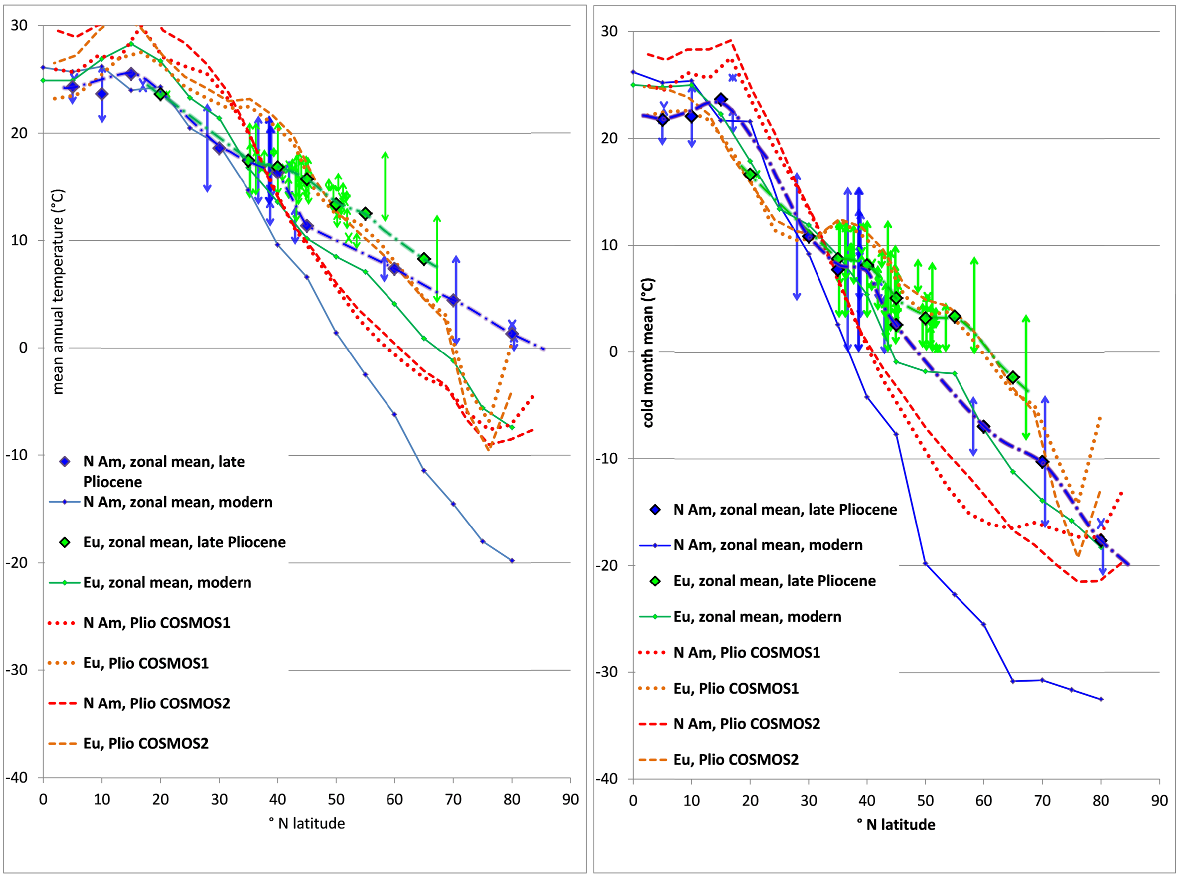

Table 1
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Table 1: Selected GCM simulations and setup details

Models	Atmosphere	Ocean	Land surface	Palaeogeography	pCO_2
middle Miocene					
MPI-ESM (Krapp and Jungclaus, 2011)	ECHAM5 (T42)	MPI-OM (fully coupled)	JSBACH (fully coupled)	from Herold et al. (2008)*	480 ppmv
Planet Simulator (Henrot et al., 2010)	PUMA-2 (T42)	SSTs and SICs prescribed from Butzin et al. (2011)	fixed vegetation from CARAIB run (Henrot et al., 2010)	from Butzin et al. (2011)*	500 ppmv
late Miocene					
COSMOS (Micheels et al., 2011)	ECHAM5 (T31)	MPI-OM (fully coupled)	fixed vegetation from proxy-based reconstruction (Micheels et al., 2007)	present-day based with adaptation to late Miocene (Micheels et al., 2011)**	360 ppmv
late Pliocene					
COSMOS 1 (Stephanek and Lohmann, 2012)	ECHAM5 (T31)	SSTs and SICs prescribed from Dowsett et al. (2009)	fixed vegetation derived from the PLIOMIP protocol (Haywood et al., 2011)	derived from the PLIOMIP protocol (Haywood et al., 2011) ***	400 ppmv
COSMOS 2 (Stephanek and Lohmann, 2012)	ECHAM5 (T31)	MPI-OM (fully coupled)	fixed vegetation derived from the PLIOMIP protocol (Haywood et al., 2011)	derived from the PLIOMIP protocol (Haywood et al., 2011) ***	400 ppmv

* Middle Miocene configurations both include open Central American and Tethys Seaways, a closed Bering Strait and a filled Hudson Bay.
** Late Miocene configuration includes an open Central American Seaway, the Paratethys and Pannonian Lake and a closed Hudson Bay.
*** Late Pliocene configuration includes closed Central American and Tethys Seaways, an open Bering Strait and a closed Hudson Bay.