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# 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.



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## 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 Häkinnen, 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 Maonwards (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 palaebotanical 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; Jiménez-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; Stepanek and Lohmann, 2012; Goldner et al., 2014) and therefore might underestimate future warming (Spicer et al., 2013). 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 favor 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; Jiménez-Moreno et al., 2010; Panitz et al., 2016; Andreev et al., 2014). Details on the sites included in this study are given in the electronic supplement.