



The Cenozoic Cooling – continental signals from the Atlantic and Pacific side of Eurasia



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ABSTRACT

The evolution of Cenozoic continental climate signals from the Atlantic and Pacific side of Eurasia can be assessed for the first time by comparing climate records obtained for two mid-latitude regions. For the West, a detailed climate record over the past 45 Ma, based on palaeofloras from two Northern German Cenozoic basins (Mosbrugger et al., 2005) revealed major trends and shorter-term events throughout the Cenozoic Cooling, thus testifying the close correlation of continental and marine temperature evolution as derived from oxygen isotopes (Zachos et al., 2008). Using the same methodology, we analyze a total of 14 floral horizons originating from continental strata of Southern Primory'e (Russia) in order to study the evolution at the eastern side of the continent. The Primory'e record spans the middle Eocene to early Pleistocene. As the coeval record for the Atlantic side, it reflects major global signals of Cenozoic climate change such as the temperature decline throughout the late Eocene, coinciding with the growth of Antarctic Ice-sheets, warming during the Mid-Miocene Climatic Optimum, and step-wise cooling throughout the later Neogene. The comparison of both records reveals differing regional patterns. The considerable longitudinal temperature gradient, currently existing between both study areas, already began to evolve during the Aquitanian, and was very significant during the Mid-Miocene Climatic Optimum. The temperature offset between East and West is likely attributable to an effective North Atlantic Current, already operational from the late early Miocene onwards bringing about mild winters and low seasonality in Western Europe, while in Primory'e, seasonality steadily increased from the late Oligocene on. The strong late Pliocene decline of cold month mean temperatures recorded in Primory'e is supposed to coincide with the establishment of the Siberian High as semi-permanent structure of the Northern Hemisphere circulation pattern. When comparing the precipitation records obtained for both study areas, an unexpected co-variability at the longer-term (in the order of 5–20 Ma) is noted, pointing to continent-wide hydrological changes. The steady decline of mean annual precipitation in the Primory'e record, beginning in the Bartonian and culminating in the Aquitanian, coincides with an aridity increase reported from coeval Chinese inland localities of the mid-latitudes. The seasonality patterns of rainfall point to progressive intensification of the East Asian Summer Monsoon in Primory'e since the later Tortonian while the post-Zanclean decline of the precipitation of the dry season can be related to an increasing impact of the winter monsoon.

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1. Introduction

Eurasian climate is characterized today by a distinct contrast between the western (Atlantic) side and the eastern (Pacific) side with a central region marked by strong seasonality typical of con-

tinental interiors (Rhines and Hakinen, 2003; Takaya and Nakamura, 2005). The presently observed gradients largely result from prevailing global and regional circulation patterns of the atmosphere and oceans and their variability. On the Atlantic side, the presently effective Gulf Stream, including its eastern extension, the North Atlantic Current (NAC), bring about oceanic climate conditions in northwestern Europe. The northward energy transport by ocean and atmosphere causes a displacement of the January isotherms by up to 20° northern latitude when compared to the Pacific side as evident from climatological data (New et al., 2002),

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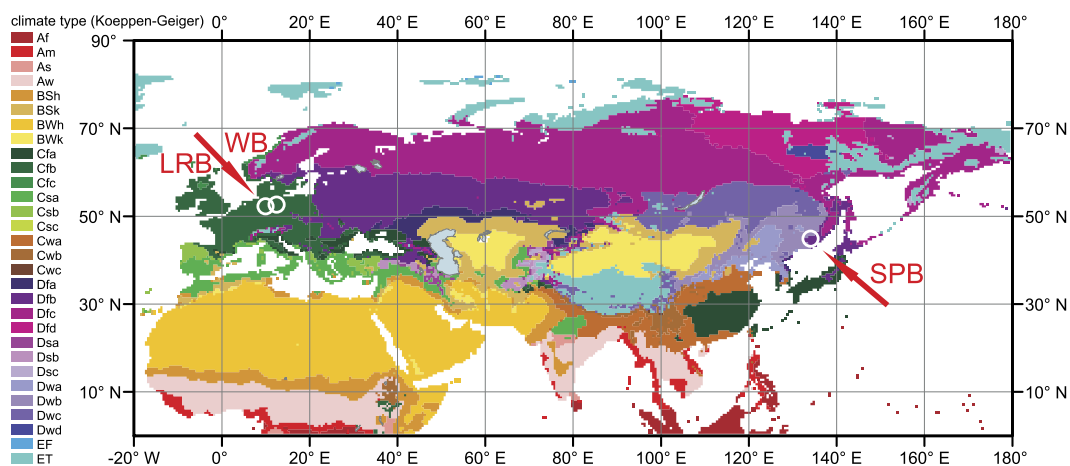


Fig. 1. Study areas at the Atlantic and Pacific sides of Eurasia in the context of modern Koeppen–Geiger type climates. A: tropical; B: dry; C: megathermal; D: microthermal; E: polar; w: winterdry; s: summerdry; f: fully humid; m: monsoon. White circles mark the approximate position of the studied Cenozoic basins. LRB: Lower Rhine Basin; WB: Weisselster Basin; SPB: Cenozoic basins of southern Primory'e.

and the asymmetric distribution of Koeppen–Geiger climate types over Eurasia (Fig. 1). Past climates of Eurasia are supposed to reflect various states of the North Atlantic ocean circulation system in the West (e.g., Via and Thomas, 2006; Steppuhn et al., 2007; Krapp and Jungclauss, 2011) and the varying intensity of the warm Kuroshio and cold, subarctic currents in the eastern coastal regions (e.g., Gallagher et al., 2009; Matthiessen et al., 2009). Moreover, the climatic evolution in eastern Eurasia is tied to the history of the East Asian Monsoon System and is complicated by tectonic events such as uplift of the Tibetan Plateau, and the Japan Sea back-arc opening (e.g., An et al., 2001; Liu and Yin, 2002; Sato et al., 2006; Yamamoto and Hoang, 2009). Thus, the comparison of continental climate records from both sides of the continent can provide valuable insights into the evolution of past continental climate anomalies throughout the Cenozoic cooling, and their underlying processes.

For the Atlantic side of Eurasia, detailed, quantitative climate records for Cenozoic time-spans were reconstructed based on palaeobotanical records from various, mid-latitude regions such as the Central Paratethys (Mosbrugger et al., 2005), Eastern Paratethys (Syabryaj et al., 2007; Bozukov et al., 2009; Ivanov et al., 2011), and Cenozoic North Sea realm (Mosbrugger et al., 2005; Utescher et al., 2009). This last area provided the most comprehensive record, reconstructed based on megaflores from two continental to marginal marine Cenozoic basins, the Lower Rhine Basin and the Weisselster Basin, both located in Northern Germany, which together document Cenozoic climate history throughout the past 45 Ma. This record reflects global climatic trends and events such as the late Eocene temperature decline during the buildup of the Antarctic ice-sheets, the Mid-Miocene Climatic Optimum (MMCO), and the Late Neogene Cooling, and testifies the close correlation of continental and marine temperature evolution as evident from benthic foraminiferal oxygen isotopes on million-year time scales (Mosbrugger et al., 2005; Zachos et al., 2001, 2008), and even at orbital time-scales (Utescher et al., 2012).

As regards the Cenozoic climate evolution on the Pacific side of Eurasia, our knowledge is still more fragmentary. Palaeoclimate studies based on Miocene sites in several regions of Northern China considering three different Miocene levels show a general cooling trend (Liu et al., 2011). For the earlier part of the Paleogene, Quan et al. (2012) present a more detailed record for Liaoning Province, Northern China, based on palynofloras from the Fushun Mine (coordinates: 41.84°N; 123.88°E) that partly correlates with the benthic foraminiferal oxygen-isotope curve (Zachos et al., 2008). Although these studies give valuable de-

tails there is still no comprehensive, quantitative record showing Cenozoic climate evolution of a region in a typical “East Coast Setting”.

In order to obtain a longer, quantitative climate record for the mid-latitudes of the Pacific side of Eurasia, we selected the rich palaeobotanical record of Primory'e, Russian Federation, located at ca. 43°N and thus about comparable with the German study area (ca. 50°N) addressed in Mosbrugger et al. (2005). The Cenozoic continental deposits of Primory'e are well exposed in open cast mines exploiting browncoal in several basins, and have a reasonable time control based on regional stratigraphy (see Section 2.1). The current state of taxonomic resolution in the palaeobotanical record allows for the analysis of 14 different floral horizons in total, representing warm temperate broadleaved forests with evergreens to temperate mixed deciduous-conifer forests (cf. Table 1 for references), and covering the time-span from the middle Eocene to the early Pleistocene. The climate records of Primory'e presented in this study for the first time allows for direct comparison of two mid-latitude regions of the Atlantic and Pacific side of Eurasia representing the characteristic west and east coast climate situation. All the climate data for the 14 floral assemblages considered are reconstructed using the Coexistence Approach, a method of quantitative palaeoclimate reconstruction applicable on Cenozoic floras of every organ type (Mosbrugger and Utescher, 1997; Utescher et al., 2014), and thus are directly comparable with published records from the Atlantic side (Mosbrugger et al., 2005; Utescher et al., 2009).

2. Materials and methods

2.1. Study areas and floral records

2.1.1. Primory'e

The palaeobotanical record of Primory'e studied here with respect to palaeoclimate originates from 6 Cenozoic basins, all located in Southern Primory'e, within a distance of ca. 100–200 km from Vladivostok, except the Turérogskii Basin west of Khanka Lake, which is situated ca. 600 km to the north of the city (Fig. 2). Because of the closeness of the sites we consider spatial gradients as negligible. The Cenozoic of South Primory'e is represented by a series of volcanic and sedimentary deposits, unconformably lying on Mesozoic strata. The sedimentary facies includes fine to coarse-grained continental clastics and intercalated lignites excavated in several active open cast mines. For some of the basins, mainly generated by extensional tectonics (Pavlovskoe,

Table 1

Palaeofloras studied. P: palynoflora; L: leaf flora; C: carpoflora. References and complete flora lists with NLRs used for climate calculations are given in Electronic Supplement 1. Modern climate data (Vladivostok) are taken from Müller and Hennings (2000).

Locality name	Code/taxa with climate data	Type of flora	Basin, formation	Lon	Lat	Age, method of dating	References
Suifunskaya_CF2	1/18	C	Pavlovskoe, Suifunskaya	132.08	40.08	Calabrian (~0.8 Ma), magnetostratigraphy	Pavlutkin (1997, 1998); Pavlutkin et al., (1988, 1991)
Shufunskaya_late_Pliocene	2/13	P	Pushkinskii, Shufunskaya	131.52	43.2	Late Pliocene (>3.0 Ma), radiometric dating	Pavlutkin and Petrenko (2010); Martynov (1999); Rasskazov et al. (2003)
Shufunskaya_early_Pliocene	3/21	P	Pushkinskii, Shufunskaya	131.52	43.2	Early Pliocene, palynology, younger than code 4	Pavlutkin and Petrenko (2010)
Ust'-Suifunskaya_Messinian	4/32	P	Pushkinskii, Shufunskaya	131.91	43.64	late Late Miocene (< 7.0 Ma), radiometric dating	Pavlutkin and Petrenko (2010); Pavlutkin et al. (1999); Martynov (1999); Rasskazov et al. (2003)
Ust'-Suifunskaya_9017	5/66	L	Pavlovskoe, Ust'-suifunskaya	132.63	44.05	Tortonian (10.8 ± 1.1 Ma), K/Ar dating	Pavlutkin (1997, 1998, 2002); Pavlutkin et al. (1988)
Ust'-Suifunskaya_4130	6/55	L	Pushkinskii, Ust'-suifunskaya	131.91	43.64	Serravallian (11.8 ± 0.9 Ma), K/Ar dating	Pavlutkin et al. (1985); Pavlutkin (2001); Pavlutkin and Petrenko (2010)
Novokachalinskaya_9151	7/124	L	Tur'erogskii, Novokachalinskaya	132	45.1	Middle Miocene, palaeobotany (inter-regional correlation)	Pavlutkin (2004, 2005); Pavlutkin and Petrenko (2010); Pavlutkin et al. (2004)
Nezhinskaya_9180	8/65	L	Pushkinskii, Nezhinskaya	131.47	43.29	Burdigalian (17.1 ± 1.3 Ma), fission track dating	Pavlutkin and Petrenko (2010); Pavlutkin et al. (2012)
Sineutesovskaya_9200/1_9200/2	9/44	L	Sineutesovskii, Sineutesovskaya	131.15	43.08	Aquitanian (22.0 ± 1.0 Ma), K/Ar dating	Klimova (1977); Kryshchovoch (1939); Pavlutkin and Petrenko (2010)
Upper_Pavlovskaya	10/26	L	Pushkinskii, Pavlovskaya	131.47	43.29	Chattian, regional geology, palaeobotany	Pavlutkin et al. (2012)
Lower_Fatashinskaya_655_703	11/81	L	Khasanskii, lower Fatashinskaya	130.5	42.4	Rupelian, inter-regional correlation, palaeobotany	Ablaev and Vasiliev (1998); Pavlutkin and Petrenko (2010)
Artemo_Tavnchanskaya_9142	12/61	L	Artemo-Tavrichanskii Ust'-davydovskaya	131.5	43.2	Priabonian, vertebrate fauna, palaeobotany	Flerov et al. (1974); Pavlutkin (2007a, 2007b); Pavlutkin and Petrenko (1993, 2010); Pavlutkin et al. (2006); Yanovskaya (1954)
Artemo_Tavnchanskaya_Bartonian	13/23	L	Artemo-Tavrichanskii Nadezhdinskaya	131.5	43.2	Bartonian, palaeobotany, younger than code 14	Pavlutkin (2007a); Pavlutkin and Petrenko (1993, 2010)
Artemo_Tavnchanskaya_Lutetian	14/60	L	Artemo-Tavrichanskii Nadezhdinskaya	132.02	43.18	Lutetian, inter-regional correlation, palaeobotany	Ablaev (2000); Kundyshev and Petrenko (1987); Pavlutkin (2007a); Pavlutkin and Petrenko (2010)

Pushkinskii, Sineutesovskii Basins), intercalated volcanoclastic layers and tholeiitic lava flows (Pushkinskii Basin, Shufunskaya Fm.) allow for radiometric dating of the strata (Table 1; Fig. 3). The sedimentary successions in the individual basins are characterized by numerous unconformities related to regional tectonics and phases of rifting and subsidence (Pavlutkin and Petrenko, 2010). To overcome these gaps in the geological record, data from several basins are combined here in order to cover the time span of the last 45 Ma. The regional stratigraphical correlation chart for the basins is adapted from Pavlutkin and Petrenko (2010) (Fig. 3). The framework of this chart is based on a variety of stratigraphical data obtained from radiometric dating (volcanites), magnetostratigraphy, regional and inter-regional pollen zonation, as well as lithological correlations (Pavlutkin et al., 1984, 1985, 2004; Martynov, 1999; Rasskazov et al., 2003; Popov et al., 2005; Pavlutkin and Petrenko, 2010). The stratigraphical scheme has been tied to the International standard (Pavlutkin and Petrenko, 2010; Cohen et al., 2013) and at least allows for dating the flora-bearing horizons at the stage level. For some of the floras stratigraphical ages are better constrained (cf. Table 1: magneto-stratigraphy

for the Suifunskaya CF2 flora and radiometric datings for the Shufunskaya floral levels, and the floras Ust'-Suifunskaya 9017, 4130 and Sineutesovskaya 9200/1, 9200/2). Overall the ages of the floral horizons afford a time resolution of the climate record of ca. 2.5 Ma.

The overall palaeobotanical record of Primory'e is diverse and has been the subject of extensive taxonomic studies (cf. Table 1 for references). For all that, all palaeofloras considered were carefully re-evaluated regarding the validity of taxonomic identifications and the Nearest Living Relatives (NLRs) of the fossil taxa. In the present study, a total of 3 microfloras and 11 leaf floras are studied with respect to palaeoclimate at 14 stratigraphic levels. Climate data for the Calabrian stage of Primory'e were taken from Bondarenko et al. (2013). The floras cover a total time-span of ca. 45 Ma, ranging from the middle Eocene (Lutetian) to early Pleistocene (Calabrian). The single floras are listed in Table 1, together with information on basin provenience, type of flora, stratigraphic age, method of dating, and references. The complete floral lists, assigned NLRs and their climatic requirements are given in Electronic Supplement 1.

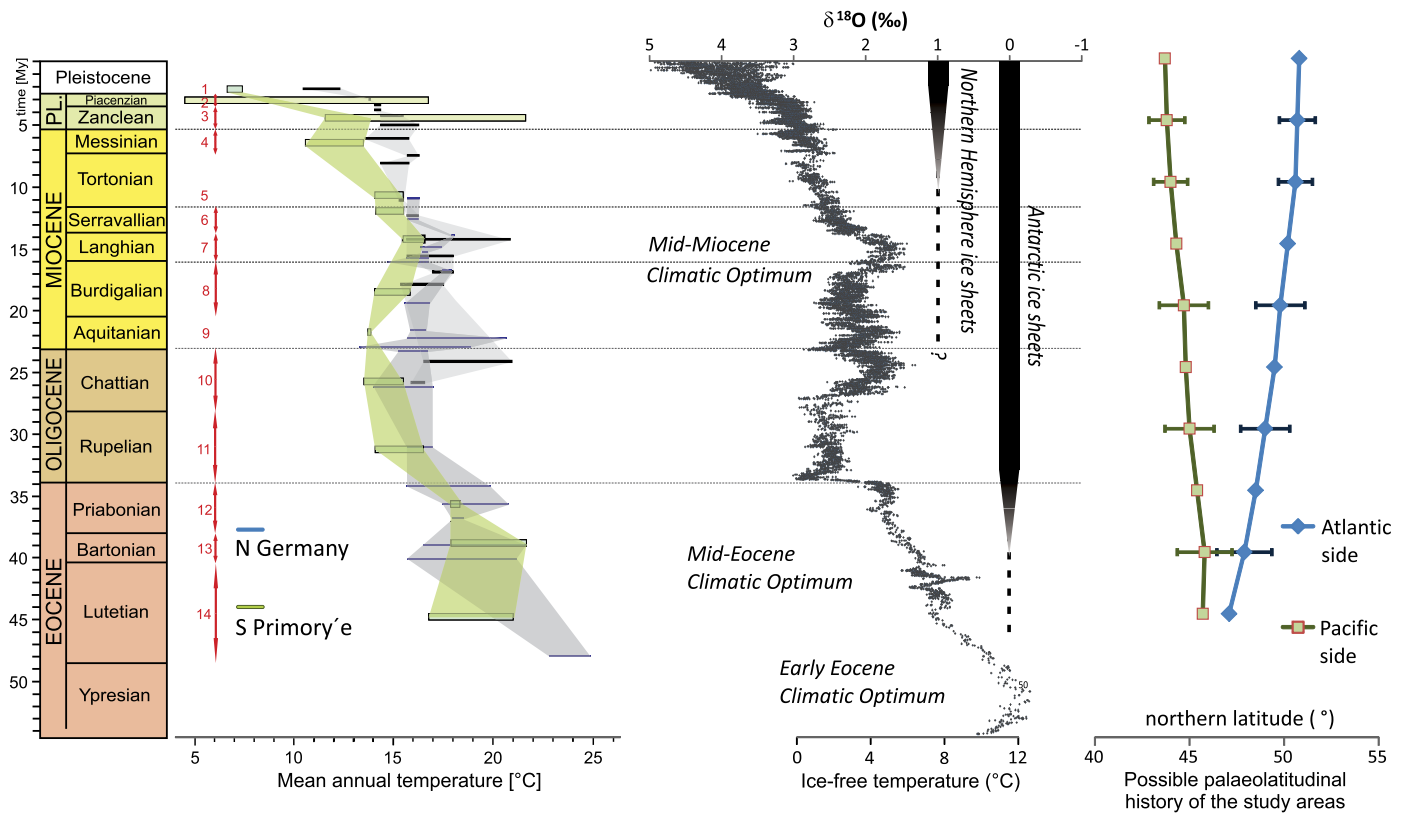


Fig. 4. MAT records for the Atlantic (in blue, Lower Rhine and Weiselster Basins, data from Mosbrugger et al., 2005, lowermost Geiselstal site newly positioned) and the Pacific side (in green, basins of the Primory'e, this study) of Eurasia next to the composite deep-sea benthic foraminiferal oxygen isotope record after Zachos et al. (2008) (ages based on GTS 2004; using 5 point running average for O-isotope data) and possible palaeolatitudinal history of both study areas (palaeolatitudes calculated using the Geomar plate reconstruction service, Ocean Drilling Stratigraphic Network, hotspot 2 reference frame; errors indicated for 5, 10, 20, 30, 40 Ma refer to A95 ovals of recommended APWP according to Torsvik et al., 2012). The bars show MAT intervals obtained with the CA. All data are given in Electronic Supplement 2. Red double arrows: errors regarding the stratigraphical position of the sites; for red code numbers see Table 1.

2.1.2. Northern Germany

The Northern German climate records exemplifying the conditions at the Atlantic side of Eurasia are taken from Mosbrugger et al. (2005), curves for monthly precipitation were produced from data published by Utescher et al. (2009). The records are based on the analysis of a total of 39 macrofloras originating from continental strata of two marginal basins of the southern Cenozoic North Sea, Lower Rhine Basin, exposing Chattian to early Pleistocene (Tiglian) strata, and Weiselster Basin providing palaeobotanical records from the early Lutetian to late Serravallian. The data record for the “Lower Coal” of the Geiselstal section (“Geiselstal, base of section” in Mosbrugger et al., 2005) was newly adjusted to 48 Ma, in following Standke et al. (2011).

2.2. Palaeogeographical aspects

The Northern German basins both are located in the headlands of peneplained Palaeozoic basement (Schäfer and Utescher, 2014) and are part of the Western Eurasian Plate. Hence, an altitudinal factor in palaeoclimate reconstruction can be excluded. During the last 45 Ma, a northward displacement by ca. 4° latitude is probable for the area (Ocean Drilling Stratigraphic Network, GEOMAR plate reconstruction service using hotspot reference frame). When roughly assuming a zonal gradient of 0.4°C per degree of latitude for mean annual temperature (MAT), plate tectonic movement may account for ca. 11% of the overall decline of MAT recorded (Mosbrugger et al., 2005). However, due to uncertainties concerning the reconstruction of palaeolatitudes and slope of the zonal gradient applicable in each time-slice, temperature estimates have not been corrected by this factor.

The basins of Southern Primory'e are related to Cenozoic rifting and extensional tectonics. The Sikhote-Alin Range, located to the NE of the study area represents a continental-margin arc including late Cretaceous to Paleogene volcanites and intrusives (Parfenov et al., 2009). From this area, palaeofloras from volcanic complexes, possibly existing at an elevation of several hundred meters were reported (Akhmetiev et al., 2009), while for the localities in the extensional basins of Southern Primory'e considered here we assume near sea-level elevation. As regards plate tectonic movement, a southward displacement of the Pacific study area by ca. 2° latitude occurred since the middle Eocene (Ocean Drilling Stratigraphic Network, GEOMAR plate reconstruction service using hotspot reference frame), thus decreasing the measured cooling signal. The possible latitudinal history of both study areas is illustrated in Fig. 4.

2.3. Quantitative palaeoclimate reconstruction – application of the Coexistence Approach (CA)

To reconstruct climate from the plant fossil record of Primory'e we use the Coexistence Approach (CA) (Mosbrugger and Utescher, 1997; Utescher et al., 2014) in order to obtain a data set fully compatible with the European records (Lower Rhine Basin, Weiselster Basin; Mosbrugger et al., 2005; Utescher et al., 2009). The CA is a widely used tool to reconstruct palaeoenvironment based on a fossil plant assemblage and has yielded results in various applications from late Cretaceous to Pleistocene, well interpretable in the context of data obtained from other proxies. Validations of the CA have been performed by the application on different organ types of fossil plants from the same stratigraphic level, the

comparison of CA results with other proxies and with data obtained with the two most common leaf-based physiognomic methods, the LMA (Leave Margin Analysis) as well as CLAMP (Climate Leaf Analysis Multivariate Program), showing consistent data in general (for details cf. Utescher et al., 2014). The CA is a technique based on overlapping climate requirements of the NLRs known for the fossil taxa occurring in a palaeoflora. The range of a given climate variable in which a maximum number of NLRs can coexist is denoted the coexistence interval and interpreted to represent the palaeo-conditions. The accuracy of the method is likely to vary according to various factors such as regional and stratigraphical representativeness of the considered flora, diversity, floristic composition, taxonomic level, and quality of climate data. A high diversity of the analyzed record generally enhances the climatic resolution of CA reconstructions and, as a function of the grade of overlapping, accounts for a higher statistical significance of the results (Mosbrugger and Utescher, 1997). Recently, the accuracy of NLR climate data provided in the Palaeoflora database was challenged (Grimm and Denk, 2012). However, probability considerations for a high number of taxa overlapping, successful tests with modern floras, and numerous comparisons with other, complementary, proxy-data-based climate reconstruction methods such as LMA and CLAMP underline the suitability of Palaeoflora climate data for palaeoclimate reconstructions. For a detailed description of the method the reader is referred to the original papers describing the procedure (Mosbrugger and Utescher, 1997; Utescher et al., 2014).

In this study, 3 temperature and 4 precipitation variables are reconstructed: MAT, warm and cold month means (WMMT, CMMT), mean annual precipitation (MAP), and mean monthly precipitation of the wettest, warmest, and driest month (MPwet, MPwarm, MPdry). In the CA, at least 10 NLR taxa contributing with climate data are required to obtain reliable results (Mosbrugger and Utescher, 1997). Here, 13 to 124 taxa (52 at a mean) contribute to determining the climate data. The precision of CA results also depends on the taxonomical level of NLR identification (Mosbrugger and Utescher, 1997). In order to optimize the climatic resolution of our records the NLRs of fossil taxa are identified at the species level, as far as taxonomical evidence is considered as sufficient. Following Utescher et al. (2014), *Sciadopitys* is excluded from the analysis. In addition, we do not consider *Keteleeria*, *Cercidiphyllum* and *Parrotia* in the calculations, because of their present endemic or relict status (cf. Electronic Supplement 1). Climate data for modern taxa were retrieved from the recently updated Palaeoflora database (Utescher and Mosbrugger, 2014), or were newly compiled where records did not already exist in the database. For chorological information we used plant distribution maps from Fang et al. (2009, 2011) and Sokolov et al. (1977, 1980, 1986) and overlapped them with data from meteorological stations, supplemented by information from climatological grids where necessary (Müller and Hennings, 2000; New et al., 2002). Floral lists with corresponding NLRs employed in this study and their climatic requirements are made available in Electronic Supplement 1.

2.4. Monsoon intensity

Today, Primory'e is under the influence of the East Asian Summer Monsoon (EASM) (Zhang and Wang, 2008) and hence is characterized by wet summers and dry winters, leading to water shortage in the soil in the early part of the growing season (Lau and Chan, 1983). In modern climate studies, various indices are in use quantifying monsoon intensity. Because monsoon circulation is characterized mainly by seasonal reversals of surface winds (Zhang and Wang, 2008) most of these indices require parameters such as wind speed and data on atmospheric pressure that are commonly

not provided by palaeobotanical proxies. Therefore, various indices based on monthly precipitation rates have been introduced. These do not in each case allow a clear distinction of monsoonal and non-monsoonal climates, but are useful for measuring monsoon intensity in a potentially monsoonal regime (Jacques et al., 2013). In this study we use the ratio of MPwet on MAP (RMPwet) according to Jacques et al. (2011) that can provide an indication of past monsoon intensity. Data for both MPwet and MAP are available for all floras presently studied.

3. Results

Climate data calculated for the 14 floras are given in Electronic Supplement 2, complete lists of taxa for the localities, including their NLRs with climatic requirements, are provided in Electronic Supplement 1. Climatic requirements of over 94% of identified NLRs of the fossil taxa in each case show overlapping, indicating a high significance level for the results (Mosbrugger and Utescher, 1997). Occasionally occurring multiple coexistence intervals at a close climatic range, possibly related to integration over differing floral horizons or caused by taphonomic effects (Utescher et al., 2014), were combined to one single interval (cf. Electronic Supplement 1). As regards the MAT, the mean precision of the results, i.e. the mean width of the coexistence intervals amounts to 1.7°C (std. 1.3°C), and to 143 mm (std. 75 mm) for the MAP, respectively. Thus, data obtained for the megaflores of Primory'e are well within the usual uncertainty range of CA data (Utescher et al., 2014). Two out of three studied microfloras provide a poorer climatic resolution. Both floras originate from two different Pliocene levels of the Shufunskaya Formation, Pushkinskii Basin (with only 13 and 21 taxa with climate data sets). Regardless, both microfloras were included because they provide valuable information on minimum values.

Climate records for MAT, CMMT, WMMT, and MAP reconstructed for the Primory'e sites, including published climate data for Calabrian flora from the Pavlovskoe brown coal field (Bondarenko et al., 2013), are plotted together with the climate curves from Mosbrugger et al. (2005), and the benthic oxygen isotope record after Zachos et al. (2008) (Figs. 4, 5 and 7). Records for seasonality of temperature (MART, see Fig. 6) and monthly precipitation values (Fig. 8) are provided for both key regions. For the Northern German basins, these data are shown for the first time. In the latter climate curves, means of coexistence intervals are connected in order to improve legibility of the graphs. The complete data with lower and upper limits of coexistence intervals are given in Electronic Supplement 1.

The proportion of MPwet on MAP (RMPwet) is taken as a measure of monsoon intensity and is shown in Fig. 9. For the Northern German basins, presently not under monsoonal impact, RMPwet tends to be overall lower compared to Primory'e. In the Weissenster Basin record, very low values near 10% are obtained for the early middle Eocene. Towards the early late Eocene, RMPwet distinctly increased to ca. 19%, then declined again to ca. 12% towards the end of the Eocene. During the Oligocene and earlier part of the Miocene, the RMPwet increased again to ca. 16%, and converged to modern values (12%) throughout the Plio-Pleistocene. The RMPwet record of Primory'e co-varies with the Northern German curves until ca. 10 Ma, with RMPwet being at the same or slightly higher level, while since ca. 6 Ma, the records diverge. Data obtained for the Messinian level (Ust'-Suifunskaya flora; RMPwet ca. 24%) and the modern value (20%) are among the highest.

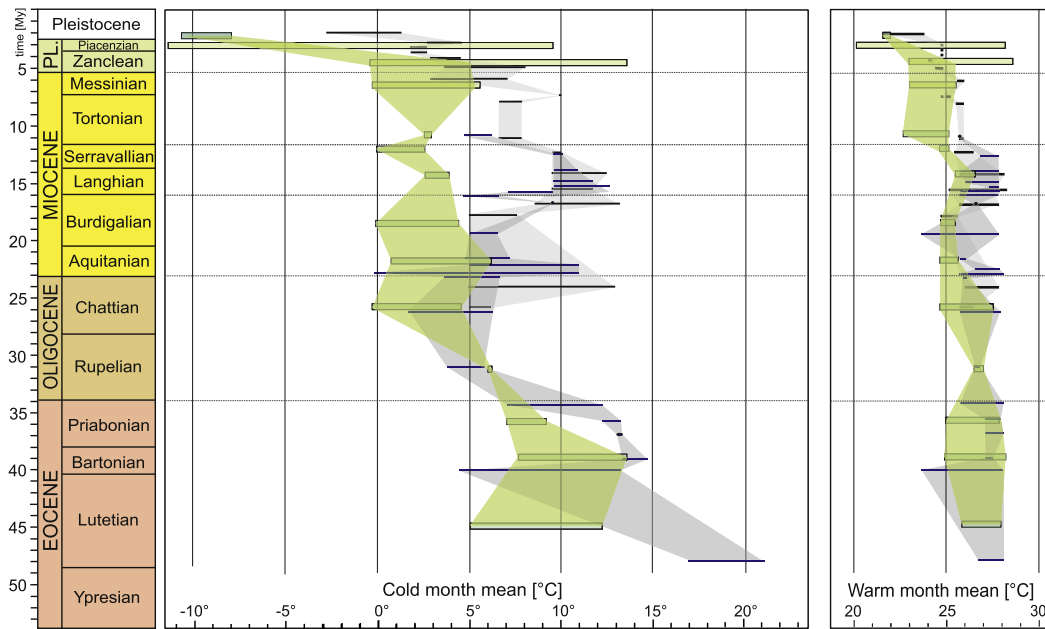


Fig. 5. CMMT and WMMT records for the Atlantic (in blue, Lower Rhine and Weissester Basins, data from Mosbrugger et al., 2005, lowermost Geiselstal site newly positioned) and the Pacific side (in green, basins of the Primory'e, this study) of Eurasia. Other details as in Fig. 4.

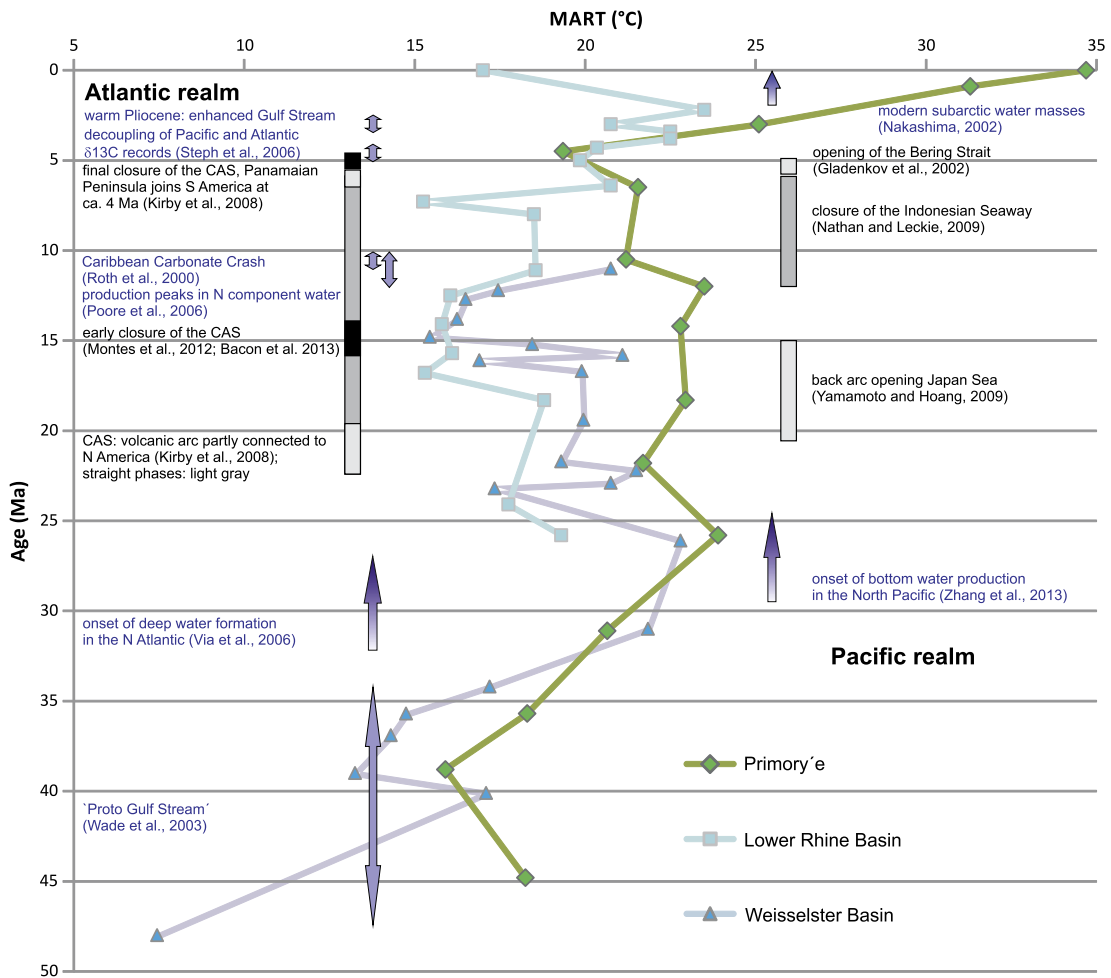


Fig. 6. MART records for the Atlantic (in blue, Lower Rhine and Weissester Basins, data from Mosbrugger et al., 2005, lowermost Geiselstal site newly positioned) and the Pacific side (in green, basins of the Primory'e, this study) of Eurasia shown next to important events concerning gateways (bars) and oceanographic data (blue arrows; data from Roth et al., 2000; Nakashima, 2002; Wade et al., 2003; Poore et al., 2006; Steph et al., 2006; Via and Thomas, 2006; Zhang et al., 2013). For all continental records means of CA intervals are plotted. All mean values and complete CA ranges are given in Electronic Supplement 2. Modern values: stations Cologne–Bonn airport and Vladivostok (Müller and Hennings, 2000).

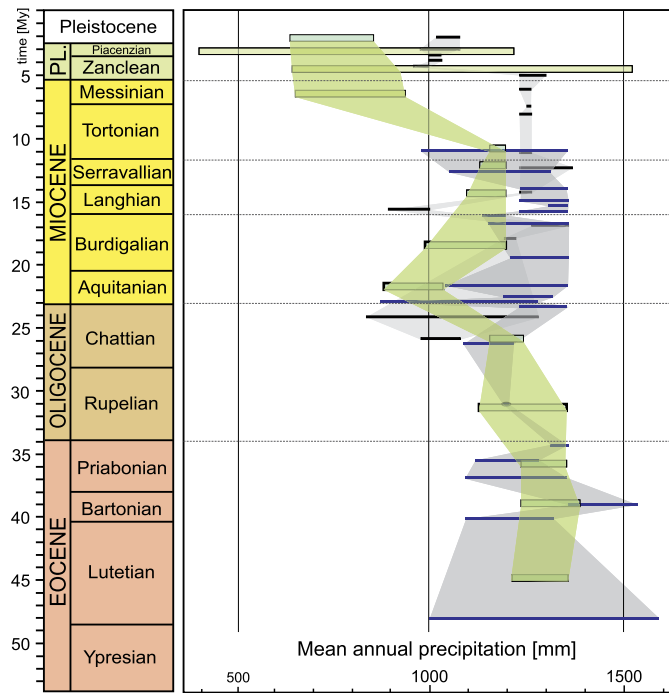


Fig. 7. MAP records for the Atlantic (in blue, Lower Rhine and Weissenster Basins, data from Mosbrugger et al., 2005, lowermost Geiselal site newly positioned) and the Pacific side (in green, basins of the Primory'e, this study) of Eurasia. Other details as in Fig. 4.

4. Discussion

4.1. Temperature evolution

As with the continental temperature records from Europe (Mosbrugger et al., 2005; Figs. 4–5) the fossil floras of Primory'e reflect major global Cenozoic climate change (Zachos et al., 2008). The highest MATs recorded in the Lutetian (~17–21 °C) and Bartonian (~18–22 °C) are succeeded by the cooling in the late Eocene

coinciding with the buildup of Antarctic ice sheets (Zachos et al., 2008). MATs reconstructed for the Chattian and Aquitanian (~13.5–15.5 °C) are among the lowest observed in the Paleogene and early Neogene, respectively. The MMCO is mainly evident from MAT and WMMT in the Primory'e record. The data obtained for the Langhian Novokachalinskaya 9151 flora indicate a moderate warming by 1–2 °C (MAT, WMMT). The precise timing of the onset of the Late Miocene Cooling is not resolved in the Primory'e record, but the floras designated Ust'-Suifunskaya 9017 and Ust'-Suifunskaya 4130, dating the late Serravallian to early Tortonian (~10.8–12.5 Ma), point to a minor temperature decline, post-dating the Langhian. Unfortunately, the Messinian to Pliocene data of our reconstruction are not well resolved, in particular the Pliocene, due to the low diversity and taxonomic resolution of the microfloras. Yet our data indicate that the Messinian and Zanclean climate of Primory'e was still warm temperate, with MAT >~12 °C and CMMT >~0 °C (C type Koeppen climate). The marked increase in the mean annual range of temperature (MART) observed in the Primory'e record, starting in the Zanclean (Fig. 6), directly succeeds the opening of the Bering Straits at ca. 5.1 Ma (Gladenkov et al., 2002) and therefore is likely to reflect an enhanced flow of Arctic water masses (Nakashima, 2002). Temperature estimates obtained for the late Pliocene microflora (Shufunskaya Fm.) point to subsequent cooling as testified by the absence of any thermophilous elements. The temperature decline occurring in Primory'e towards the early Pleistocene (Calabrian), however, was drastic and accounted for at least 5 °C for MAT and 8 °C for CMMT (Figs. 4–5), and brought about a D type Koeppen climate (Bondarenko et al., 2013). The coeval, pointed MART increase mirrors extreme winter cooling in Eastern Siberia, probably related to the establishment of the modern pattern of atmospheric pressure over the continent during the cold season (Popova et al., 2012; Bondarenko et al., 2013). Nevertheless, the Calabrian climate was significantly warmer compared to today (by ~3 °C for MAT, ~5 °C for CMMT) (Bondarenko et al., 2013; cf. Figs. 4–5).

When comparing the temperature records reconstructed for the Atlantic side of Eurasia (Mosbrugger et al., 2005) and the Pacific side, respectively, our data predominantly show overlapping temperature ranges for the Paleogene (Figs. 4–5). Throughout

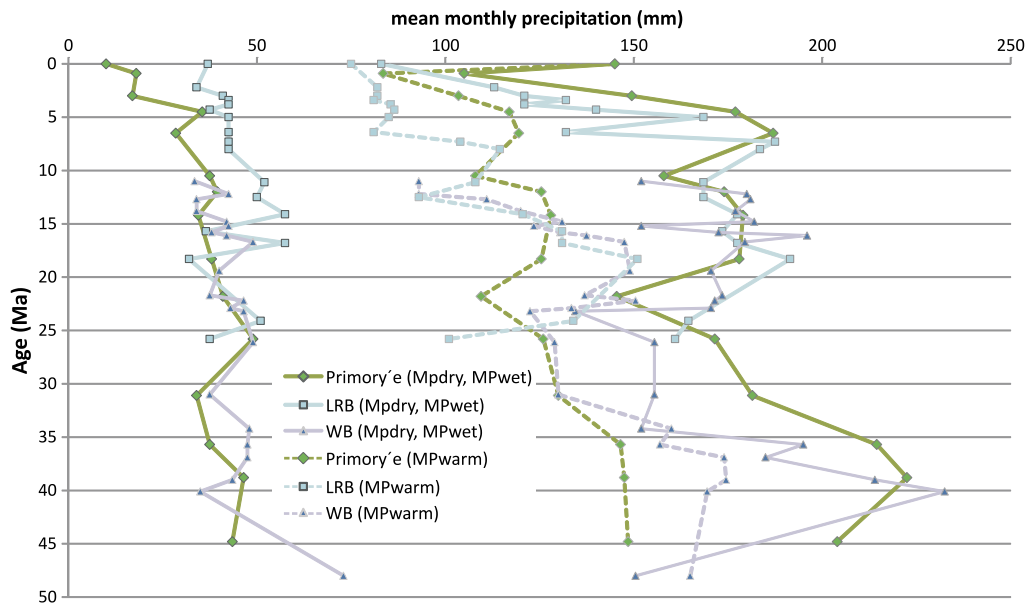


Fig. 8. Monthly precipitation records for MPdry, MPwarm and MPwet for the Atlantic (in blue, MPdry and MPwet data from Utescher et al., 2009; MPwarm: this study; lowermost Geiselal site newly positioned) and the Pacific side (in green, basins of the Primory'e, this study) of Eurasia. LRB: Lower Rhine Basin; WB: Weissenster Basin. For all records means of CA intervals are plotted. Coexistence intervals are given in Electronic Supplement 2. Modern values: stations Cologne-Bonn airport and Vladivostok (Müller and Hennings, 2000).

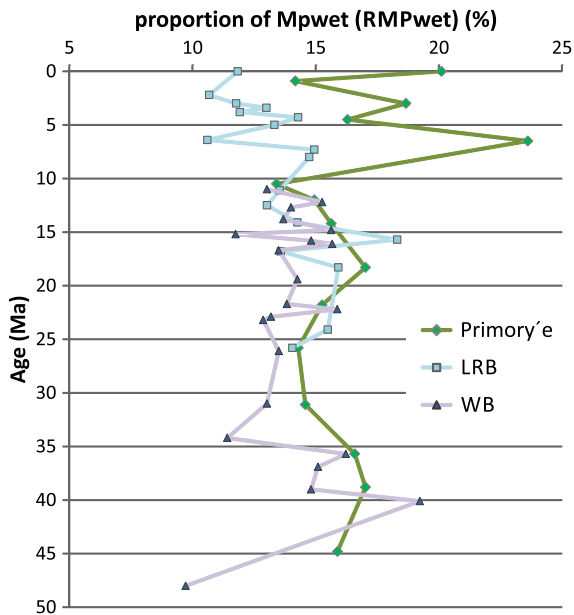


Fig. 9. Ratios of MPwet (RMPwet) for the Atlantic (in blue, Lower Rhine and Weissester Basins, MPwet data from Utescher et al., 2009, lowermost Geiselal site newly positioned) and the Pacific side (in gray, basins of the Primory'e, this study) of Eurasia. LRB: Lower Rhine Basin; WB: Weissester Basin. The calculation of RMPwet is based on means of coexistence intervals. All RMPwet data are given in Electronic Supplement 2. Modern values are calculated using station data of Cologne-Bonn airport and Vladivostok (Müller and Hennings, 2000).

the Neogene, however, temperatures recorded for Primory'e tend to be lower compared to the North Sea Basin records. Hence, the evolution towards the present-day longitudinal anomaly between Atlantic and Pacific study area, accounting ca. 6 °C for MAT and ca. 16 °C for CMMT, respectively (station data for Cologne-Bonn Airport and Vladivostok; Müller and Hennings, 2000), already had started to evolve at the onset of the Neogene (in the Aquitanian), and is most striking regarding CMMT. The divergence of CMMT records of both key regions even increased towards the MMCO where, compared to Primory'e, Northern Germany experienced winter temperatures warmer by up to ~13 °C. This anomaly, in principle, persisted over the younger Neogene, being probably slightly weaker in the Zanclean (<7 °C). The same effect is evident from the MAT records as well but far less distinct, outlining the importance of the temperature of the cold season in this continental, longitudinal anomaly. Regarding the warm season, the Primory'e record overlaps with both Atlantic records until the Langhian, thereafter, the eastern study area tends to be slightly cooler, with WMMT at the lower limit of the Atlantic data while today, the WMMT of Primory'e is higher in by ~2 °C, compared to Northwest Germany (Fig. 5).

Longitudinal gradients of temperature in Eurasia, in particular of the CMMT, and their intensification since the later Neogene have already been reported, based on palaeobotanical records (Bruch et al., 2011; Popova et al., 2012). It can be assumed that intensification was linked to coeval steepening of latitudinal gradients in the Northern Hemisphere (Utescher et al., 2011). These data, however, do not provide any details on the evolution of the continental West–East anomaly. In order to display the signal of continentality of climate in our records, the mean annual range of temperature (MART) is plotted for all floras, using means of CA intervals (Fig. 6). The MART records display two different signals: a global signal reflects the increase of temperature seasonality in general, associated with Cenozoic cooling, earlier identified as characteristic of Neogene cooling in the mid- and higher latitudes (Mosbrugger et al., 2005; Utescher et al., 2007). Regional signals, becoming manifest in

diverging records, are most evident in the time-span from the Burdigalian to late Tortonian, and then from the early Pleistocene on. At present, the maritime climate in Western Europe is characterized by low MART, primarily related to the NAC (Via and Thomas, 2006). Our data could be interpreted to suggest the early presence of an effective Gulf Stream, already operational from the late early Miocene onwards.

The Neogene Gulf Stream and its varying intensity, prior to the closing of the Panama Seaway in the early Pliocene as evidenced by the decoupling of the Pacific and Atlantic $\delta^{13}\text{C}$ records diverging from ca. 4.4 Ma on Steph et al. (2006), is still a matter of debate. Many studies come to the conclusion that prior to the final closure of the Central American Seaway (CAS) at ca. 4 Ma (Kirby et al., 2008), the circulation was considerably reduced (e.g., Steppuhn et al., 2007; Micheels et al., 2011). However, Nd isotope studies evidence the onset of deep-water production in the North Atlantic by the early Oligocene, at ca. 33 Ma, and thus the transition to a bipolar mode of deep-water circulation (Via and Thomas, 2006). As regards the CAS and its effectiveness in water mass exchange between Atlantic and Pacific, it is now assumed that the main axis of the volcanic arc in southern Central America existed as a peninsula connected to northern Central America and North America for much of the Miocene (Kirby et al., 2008). Recent data regarding plate tectonics, exhumation history, and phylogenetic studies point to an even earlier, at least intermittent, disappearance of the CAS, at ca. 15 Ma (Montes et al., 2012; Bacon et al., 2013; cf. Fig. 6). The anomaly we observe supports the existence of an effective Palaeo-Gulf Stream, already in the late early to middle Miocene. 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). Based on the analysis of a floral record from Greenland, comprising several late Miocene levels, Denk et al. (2013) assume the existence of an effective Gulf Stream throughout the Tortonian. Although our data support the existence of an effective Miocene Gulf Stream they do not corroborate a higher than present intensity during the Pliocene, as is assumed from Piacenzian marine data and modeling studies (PRISM) (for a summary cf. Dowsett et al., 2013). The distinctly higher than present seasonality of temperature we reconstruct for the Pliocene of Northwest Germany (Fig. 6) rather points to a weaker oceanic effect on continental climate at that time, on the other hand, the high Pliocene MART can be referred to the high Pliocene level of summer temperature (ca. 5 °C above modern value). The prevalence of high temperature in the warm season is not necessarily related to the intensity of the NAC but may primarily reflect atmospheric circulation patterns prevailing in the warm season over Western Eurasia.

Apart from the past state of the CAS and its effect on the North Atlantic circulation system, other factors may have played a role. According to modeling studies, the existence of a landbridge between the Far East and Alaska, prior to the opening of the Bering Strait at ca. 5.1 Ma (Gladnikov et al., 2002; cf. Fig. 6), may cause seesaw-like climate changes between the North Atlantic and the North Pacific, associated with the varying intensity of the Atlantic meridional overturning circulation (AMOC) (Hu et al., 2014). The study suggests that a strengthened AMOC and increased northward meridional heat transport in the Atlantic is connected with a weak Pacific meridional overturning circulation and lower SSTs in the North Pacific. This mechanism could have contributed to the high temperature anomaly we observe between our study areas throughout the Miocene. Moreover, it was demonstrated by Tortonian model runs that effects induced by the palaeovegetation (e.g. forested high latitudes) or increased sensible and latent

heat fluxes in the atmosphere can partly compensate a potentially weaker oceanic heat transport in the North Atlantic under a closed CAS (Micheels et al., 2007, 2011). Hence, there remains some uncertainty about the thermal transfer processes when attempting to explain the observed pattern.

When quantifying the longitudinal temperature anomalies observed between both study areas, and their evolution throughout the Cenozoic, plate-tectonic movements occurring in the studied time-span have to be considered. While the northward movement of Western Europe by ca. 4° latitude since 45 Ma may explain ca. 10% of the cooling there (MAT), the southward drift of the eastern study area since ~40 Ma could have slightly attenuated the effect of global cooling (Fig. 4). Without these opposing displacements of the study areas, attributed to plate tectonics, the divergence of western and eastern climate records, expressing the continental anomaly, would have been even more pronounced (Fig. 6). The comparatively moderate temperature level reconstructed for the Lutetian flora from the Artemo-Tavrichanskii Basin, the relatively high MART combined with a rather temperate aspect of the vegetation may be well attributable to a higher than present palaeolatitude of Southern Primory'e at that time.

4.2. Precipitation patterns

When comparing precipitation of the Atlantic and Pacific regions the Paleogene MAP of Primory'e is within the range of the German data and likewise shows the slight declining trend from the Lutetian to Chattian (~1300 mm to ~1200 mm; cf. Fig. 7). Since the Aquitanian, the MAP of Primory'e was consistently lower by ~100–200 mm compared to the West. Today, Primory'e and Lower Rhine Basins are about equally wet (721 mm and 701 mm, respectively), the more continental Weissenlöhler Basin presently has somewhat lower annual rates. At present, the western study area is mainly under the influence of Atlantic storm tracks and receives most rainfall from the Westerlies (Jones and Lister, 2009) while Primory'e, being located at the margin of the EASM, receives rainfall mainly during the warm season (Liu and Yin, 2002). Considering these differing settings it is surprising that the records share longer-term patterns of change. Obviously, the generally shallow Paleogene climatic gradients, combined with a high temperature level and the northward extended warm tropical pools (e.g., Zachos et al., 1994) brought about consistently high precipitation rates in the mid-latitudes. According to our results, the first decrease in overall high precipitation rates occurred in both study areas near the Oligocene–Miocene transition, and was possibly connected to the Mi 1 event. Thereafter, rainfall increased again throughout the early and middle Miocene. Being located in the Central European Wet Zone (van Dam, 2006), the MAPs of both German records stay at a high level until the early Pliocene (Zanclean). In Primory'e, the MAP declined by at least 250 mm during the later Tortonian, coevally with a temperature decline (Figs. 4, 7) and the closure of the Indonesian Seaway (Fig. 6; Nathan and Leckie, 2009). The low climatic resolution of the late Miocene to Pliocene floras does not resolve this evolution in very detail, however, the Calabrian MAP (631–850 mm) was close to that of the modern (station Vladivostok: 721 mm; Müller and Hennings, 2000). The low MAP calculated from the Aquitanian of Primory'e (Sineutesovskaya_9200/1_9200/2 flora; ca. 22 Ma; Fig. 7) coincides approximately with the onset of loess formation in the middle reaches of the Yellow River and increased aridity is assumed for inland regions of China (Guo et al., 2008). This has been related to a reorganization of the climate system resulting in a change from dominantly zonal circulation to monsoonal regime (Guo et al., 2008). Other precipitation data obtained from inland locations in northwest China, however, point to overall humid conditions at that time (Liu et al., 2011).

The study of seasonal rainfall patterns provides a further perspective on regional peculiarities of the eastern and western sides of Eurasia (Fig. 8). In the earlier Paleogene, monthly precipitation values in general are high when compared to modern conditions, broadly in accordance with the high temperatures (see above), and consistent with the general trend observed elsewhere in Eurasia from coeval records (e.g., Utescher et al., 2009; Bruch et al., 2011; Liu et al., 2011; Quan et al., 2011). The stable declining trend of MPwet and MPwarm in the Primory'e record, beginning at ca. 40 Ma and persisting to the Aquitanian, coincides with cooling (see above) and the coeval drying trend reported from Chinese mid-latitude inland localities (Bosboom et al., 2014; Quan et al., 2014). For Primory'e, data indicate that from the Messinian on, the warmest month progressively became the wettest month. The MPwet records of both key regions display a striking co-variation over most of the Neogene that might partly be related to the global temperature (high rates during the MMCO), but could as well point to the existence of larger scale patterns on the Northern Hemisphere as proposed by Böhme et al. (2011). The striking divergence of the Atlantic and Pacific records, post-dating the early Pleistocene (cf. Fig. 8), is expressed by a further decline of MPwet in the western study area and significant increases of MPwarm/MPwet in Primory'e, possibly related to an intensified regional effect of the EASM (Bondarenko et al., 2013).

The driest month of both study areas is presently in the cold season (Lower Rhine Basin: March; Southern Primory'e: January). The MPdry records obtained for Primory'e and Northern Germany separate in the early Miocene (Fig. 8), coevally with the assumed intensification of the Palaeo-Gulf Stream (see above). While in the Atlantic key region rates slightly declined from values around ~50 mm in the Langhian to ~35 mm recorded today, the Primory'e record first shows a moderate declining trend followed by a significant drop in the Zanclean. This signal probably is explained by an intensification of the Siberian high pressure during the cold season and the related impact of the East Asian Winter Monsoon.

4.3. Ratio of MPwet – monsoon intensity

The comparison of the RMPwet records obtained for the Atlantic and Pacific study areas shows that the ratios vary roughly in parallel throughout the Paleogene and earlier Neogene (Fig. 9), from the late Miocene on, the evolution of both continental regions diverges. While the record for the Lower Rhine Basin shows a stable declining trend in RMPwet, the RMPwet increased in Primory'e. Though most of the RMPwet data calculated for the sites of the northern German basins are above the present-day value, the existence of monsoon type climates in our Atlantic study area, also in deeper time, is not assumed here, in view of its geographical position and the absence of evidence from palaeoclimate modeling studies (e.g., Micheels et al., 2011). However, some sites reveal a distinct seasonal control of precipitation (Bartonian Scheiplitz flora; Langhian Hambach 6C flora; cf. Utescher et al., 2009 and Fig. 9). For Primory'e, presently under the influence of the East Asian monsoon system, our data suggest a stronger seasonal control of precipitation in general, when compared to northern Germany, but until the earlier part of the late Miocene the RMPwet stays well below the modern value. The high RMPwet obtained for the Messinian and Piacenzian levels point to an increasing impact of the EASM on the region throughout the late Neogene, with the Calabrian date being an outlier in this trend, indicating lower monsoon intensity at that time (Bondarenko et al., 2013).

5. Conclusions

The palaeobotanical record of Primory'e holds the key for reconstructing detailed climate curves for the mid-latitudes of the

Pacific side of Eurasia. The high diversity of the palaeofloras and up-to-date taxonomy result in useful climatic interpretations. Our climate curves for the first time allow quantifying climate change in a mid-latitude region on the Pacific side of Eurasia over the past 45 Ma. As the coeval records available from the Atlantic side of Eurasia, the climate curves of Primory'e are consistent with major global trends occurring during the Cenozoic Cooling, thus highlighting the potential of continental archives and the reliability of palaeobotanical proxies in the reconstruction of palaeoclimate. Moreover, the comparison of both records allows tracing Cenozoic history of the very conspicuous anomaly that exists today between both sides of the continent and sheds light on the underlying causes of those differences. The climatic divergence between the two sides of the continent began in the Aquitanian and most probably is attributable to an increase in northward energy transport in the North Atlantic realm likely related to an effective Gulf Stream, which was already established by the late early Miocene, bringing about mild winter temperatures and a low seasonality in Western Europe. In the East, post-Serravallian, Neogene Cooling was by far more pronounced, especially when taking into account the clockwise rotation of the Eurasian plate and hence, additional displacement of the eastern part to the South. Moreover, the early Pleistocene cooling was more strongly expressed in the East, pointing to the establishment of the Siberian High as semi-permanent structure of the Northern Hemisphere circulation pattern, forcing the climate system to present-day conditions.

The evolution of precipitation in both study areas reveals unexpected co-variability of the records over the longer-term pointing to continent-wide hydrological changes. In Primory'e, a stable drying trend beginning in the Bartonian (MPwet) approximately coincides with persistent global cooling throughout the late Eocene, preceding the onset of large-scale Antarctic glaciation at the Eocene–Oligocene transition (Zachos et al., 2008), and with relatively dry climate conditions reported from Chinese inland localities of the mid-latitudes from the late Eocene on (Quan et al., 2014). In Primory'e, the drying trend culminated in the Aquitanian, when major loess deposits formed in the middle reaches of the Yellow River evidencing increased aridity of the continental interior. As regards the existence and intensity of the palaeomonsoon system our data point to progressive intensification of the EASM in the Pacific study area since the later part of the late Miocene. Decline of MPdry since the Zanclean probably mirrors the increasing impact of winter monsoon on the region related to coeval amplification of a Siberian anticyclone.

Currently work is in progress to refine stratigraphy and time control in the Cenozoic basins of Southern Primory'e, and newly recovered palaeofloras are taxonomically studied. These advances in research will enable us to condense the climate record for the mid-latitudes of the Pacific side of Eurasia by including additional floral levels, and to improve the climatic resolution of the Pliocene part of our record.

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Appendix A. Supplementary material

Supplementary material related to this article can be found online at <http://dx.doi.org/10.1016/j.epsl.2015.01.019>.

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