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Preface

The Neogene of Eurasia: Spatial gradients and temporal trends — The second synthesis of NECLIME

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ABSTRACT

This volume represents the second synthesis of the international open research network NECLIME (Neogene Climate Evolution in Eurasia) that was established in 2000 to study climate change in Eurasia during the Neogene and its impact on ecosystems. The main objectives of NECLIME research are (1) proxy data-based quantitative reconstructions of Neogene climate in Eurasia by means of standardised techniques, (2) the modelling of atmospheric and oceanic circulation and of biomes using Neogene boundary conditions, and (3) the analysis of the interaction between palaeogeography, vegetation and climate. Presently, 94 scientists from 34 countries are NECLIME members, contributing with their published data to a collective data base.
Integrating proxies from various sources such as palaeobotany, vertebrate palaeontology, and geology, the following core topics are addressed in the volume: precipitation patterns and landscape opening, the Asian Monsoon Systems, the potential of past climates for the evaluation of future climate change scenarios, as well as short-term change and variability of climate. Highlights of the single contributions are summarised in a proxy data section, and in a modelling section, respectively. It is shown that the integrative approach presented in this volume brings about a much better and much more detailed understanding of Neogene climate dynamics in Eurasia than previously achieved. Even though Neogene climate changes may have regional aspects differing considerably from each other and from the general, global trend, the results from the various proxy and modelling studies consistently show that later Neogene cooling implicated more pronounced latitudinal and longitudinal gradients. On the other hand, the issue reveals a number of problems and questions, resulting from the contrary nature of palaeozoological and palaeobotanical palaeoclimate proxies and modelling results, mainly at a more regional level. The models can not yet explain the relatively warm high latitudes during the Neogene and we still do not sufficiently understand the role of the various boundary conditions such as CO_2, palaeogeography, and palaeovegetation in the observed Neogene climate change and its regional differentiation. These apparent uncertainties underline the importance of the study of palaeo-scenarios in order to enhance the reliability of future climate projections.

1. Introduction

The international open research network NECLIME – Neogene[1] Climate Evolution in Eurasia – was established in the year 2000 to study climate change in Eurasia during the Neogene and its impact on ecosystems. The main objectives of NECLIME research in the past ten years have been: (1) the quantitative reconstruction of Neogene climate in Eurasia in time and space based on proxy-data and its interpretation using standardised techniques, (2) the reconstruction of Neogene regional and global atmospheric and oceanic circulation patterns via climate modelling including modelling of the biosphere, and (3) the analysis of the interaction between palaeogeography, vegetation and climate. Presently, 94 scientists from 34 countries are NECLIME members. With their published data, they all contribute to a common data base and have access to this database for comprehensive and integrative analyses. For details about the concept, structure and current projects of NECLIME and its members, the reader is referred to the NECLIME web pages (http://www.neclime.de).

A first synthesis of NECLIME was published in 2007 (Bruch et al., 2007), focussing on studies on the Miocene of Europe and giving a summary for the area of climate and vegetation evolution in time and space. The present volume represents the second synthesis of NECLIME and again comprises proxy data-based climate interpretations of past ecosystems (fauna and flora) and modelling studies of the atmosphere and biosphere. The studies presented herein include

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[1] In this volume Neogene is regarded as comprising the Miocene to Pliocene Series.

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data from central and east Asia as well as Europe, thus allowing – together with the first synthesis volume – for a Eurasia-wide perspective and the analysis of large scale patterns and teleconnections in the Northern Hemisphere.

2. Core topics of the second NECLIME synthesis volume

Integrating proxies from various sources such as palaeobotany, vertebrate palaeontology, and geology, and results obtained from numerical modelling, the volume focuses on the following topics.

2.1. Precipitation patterns, landscape opening

For some regions of Eurasia, it is well known that Late Neogene cooling was connected to drying and to the expansion of open landscapes (e.g., Molnar, 2005; Fortelius et al., 2006; Strömberg et al., 2007; Utescher et al., 2007; Kovar-Eder et al., 2008; van Dam and Reichert, 2009). However, the timing of this process and the mechanisms involved are not yet clearly understood. When quantifying precipitation rates, it has been shown that plant and animal proxies may contradict each other to some extent (for discussion cf. Bruch et al., 2011). To analyse the response of terrestrial ecosystems to climatic and environmental changes, we have studied palaeoprecipitation patterns in time and space, as well as seasonal distribution of rainfall and amplitudes of change. The key regions considered here are the Western and Eastern Mediterranean (Akkiraz et al., Bertini and Martinetto; Böhme et al., 2011; Bruch et al. 2011; Furio et al., 2011), the Eastern Paratethys (Akkiraz et al., 2011; Bruch et al., 2011; Ivanov et al., 2011) and southeast Asia (Jaques et al., 2011; Liu et al., 2011; Sun et al., 2011; Yao et al., 2011). Vegetation and faunal data are compared in detail and discussed in the context of modelling results (François et al., 2011; Micheels et al., 2011). It is shown that faunal data can fill gaps in the environmental information provided by the palaeobotanical record. All in all, it can be stated that in many areas of Eurasia, Late Neogene cooling was directly linked to landscape opening and went along with an increasing seasonality of precipitation and continentality of the palaeoclimate.

2.2. Asian monsoon systems

The evolution of the Asian Monsoon Systems during the Neogene is still a matter of debate. Here, a new, comprehensive record is presented for East Asia, comprising palaeoclimate and vegetation data (Jaques et al., 2011; Liu et al., 2011; Sun et al., 2011; Yao et al., 2011). This data set allows the study of potential imprints of the monsoon on Neogene ecosystems in the context of tectonic activities, such as uplift of the Himalayas. Overall, studies come to the conclusion that the South and East Asian Summer Monsoon had already been established in the Late Miocene, with intensity close to present, while the East Asian Winter Monsoon may have been weaker in pre-Pliocene times. This can possibly be related to a late uplift of parts of the eastern Tibetan Plateau.

2.3. Potential of past climates for the evaluation of future climate change scenarios

According to the 4th Assessment Report of the International Panel on Climate Change (IPCC-4.AR), a significant global warming due to the increase of atmospheric greenhouse gases is predicted by climate models to occur over the next 100 years. It is known that the models are very capable of modelling the well-documented climate change that occurred over the last 150 years, but have flaws when boundary conditions differ significantly from today due to presently insufficient representations of physical processes and interactions. The comprehensive data set presented here provides climate states for various Cenozoic time slices of Eurasia that are similar or analogous to the predicted future climate. It is shown that the study of past climatic patterns provides important clues when evaluating modelling results for future scenarios (Utescher et al., 2011). Anomalies prognosticated for the future, such as the warming of continental interiors, are not only similar to palaeo-patterns we observe in time slices with a raised atmospheric CO_2 level. In the Tortonian, where pre-industrial CO_2 is usually assumed, data reveal related patterns. This generates new discussions about major drivers in global warming. Regarding continental areas, it can be speculated that a high degree of vegetation cover supports globally warm conditions, even under a moderate atmospheric CO_2. Overall, more humid conditions that are reconstructed for fossil examples, e.g., for the lower latitudes of Western Eurasia, are in a sense contradictory to the significant drying prognosticated in the future scenarios for the same area. This area, however, underwent several millennia of anthropogenic deforestation causing hydrological properties to differ considerably from the fossil conditions studied.

2.4. Short-term change and variability of climate

The analysis of time series is crucial to drawing conclusions on the persistence and significance of spatial patterns observed in the data. The study of Kern et al. (2011) shows that even in the Middle Miocene, known as a time interval with relatively stable climatic conditions, there is evidence for notable shifts in winter temperature and precipitation at a sub-orbital time scale. Based on herpetological data, Böhme et al. (2011) present precipitation records for the Miocene of Central Europe and Spain that point to a high variability of annual precipitation rates, at periods of some 100 ky. It is suggested that major fluctuations in the precipitation gradient over Western Eurasia were responsible for shifts in ecosystem distribution, and particularly for faunal turnover in southwest Europe, or were guiding factors for the migration of faunal communities (Böhme et al., 2011; Furio et al., 2011).

3. Neogene climate and ecosystem evolution in Eurasia — a first synthesis

The results of the publications presented in this volume allow for a first synthesis of Neogene climate and ecosystem evolution in Eurasia. Thereby, we will consider the proxy-data and modelling results separately.

3.1. Results from proxy-data

With the onset of gradual global cooling in the later Middle Miocene, after ca. 13.9 My, and the subsequent re-establishment of a major ice-sheet on Antarctica, fundamental changes of the climate system in the Northern Hemisphere were initiated leading to the onset of the NH glaciation later in the Tortonian (e.g., Zachos et al., 2001; Holbourn et al., 2005; Westerhold et al., 2005). This reorganisation caused a more seasonal distribution of rainfall in the Late Miocene. At the same time continentality of climate increased over Eurasia. For Central Europe, it has already been stated that Neogene cooling primarily affects winter temperature thus leading to an increased seasonality (Mosbrugger et al., 2005). This process is obviously connected to the evolution of grasslands in the continental interior of Eurasia (Bruch et al., 2011). Most likely, a positive feedback mechanism is inherent to this development since open landscapes have a higher albedo than forests.

3.1.1. Western Eurasia

So far, most studies characterise the climate existing in Western Eurasia prior to the onset of cooling in the later Middle Miocene as equable with low seasonality (e.g., Bruch and Zhilin, 2007; Utescher et al., 2009). As shown in the detailed analysis of spatial climate patterns over Western Eurasia, temperature and precipitation gradients are generally less pronounced than today (Bruch et al., 2011). According to most data presented in the present volume, permanently humid conditions predominated during the Mid-Miocene Climatic Optimum (Zachos et al., 2001). Nevertheless, there is evidence for minor precipitation gradients, with somewhat drier conditions prevailing in the southwest and east (e.g., Böhme et al., 2011; Bruch et al., 2011; Jiménez-Moreno and Suc, 2007; Utescher et al., 2007), and for the existence of a Central European Wet Zone (van Dam, 2006; Utescher et al., 2007). The persistence of a latitudinal precipitation gradient in Western Europe throughout the Neogene coincides with the nested structure and diversity patterns of Miocene insectivore faunas over Europe that obviously had their evolutionary centre in the wetter climates of Central Europe (Furio et al., 2011).

The exact time of onset of significantly drier conditions in the southerly part of the study area is still controversial, partly due to the poor fossil record. For the Early Miocene and the Serravallian, palaeobotany-based climate data are lacking. For the Langhian, Bruch et al. (2011) show a decrease in precipitation from Central Europe towards the Mediterranean coast of east Spain. In the Tortonian reconstruction, Spain appears drier compared to Central Europe, but is still considerably wetter than today, with annual precipitation rates over 800 mm. There is, however, evidence for a distinct dry season (Bruch et al., 2011). This is supported by vegetation reconstruction for an early Tortonian time slice showing the presence of taxa indicative of seasonal rainfall in almost all the Spanish sites studied (Utescher et al., 2007). Reconstructions based on small mammal faunas reflect the same pattern. A substantial drying of south Spain is reported to have set in at ca. 8 My (MN11) (van Dam, 2006), data based on large mammal hypsodonty show the same but express only a moderate gradient (Fortelius et al., 2006). Partly differing results are obtained by Böhme et al. (2011) reconstructing annual precipitation based on herpetological assemblages. According to this study, rainfall rates in SW Europe were higher than at present throughout the Tortonian while Langhian to Serravallian precipitation data indicate a very dry Middle Miocene in the southwest, partly characterised by climatic conditions typical for a desert steppe (MAP < 250 mm). These inconsistencies between studies, proxies and methods call for further investigations.

For the Miocene of Central Europe, all plant based precipitation data and vegetational reconstructions point to generally humid conditions with annual precipitation rates well over 1000 mm (e.g., Mosbrugger et al., 2005; Utescher et al., 2007; Kovar-Eder et al., 2008; Utescher et al., 2009; Bruch et al., 2011). A slightly decreasing trend in annual rainfall is reported from the later Zanclean (Utescher et al., 2000). These findings are supported by data obtained from large and small mammal faunas (cf. “Central European Wet Zone”; van Dam, 2006; Eronen et al., 2009) while herpetological data indicate that in the time span from the later Langhian and throughout the Serravallian, precipitation rates were highly variable and frequently fell below the present day level (Böhme et al., 2011). This contradiction can be partly explained by the fact that the precipitation curve presented by Böhme et al. (2011) for Central Europe is a composite record also including sites from relatively dry areas such as the north coastal realm of the Black Sea. Another explanation might be that short-term dry pulses are represented neither in the palaeofloristic record nor plant bearing sediments because the preservation potential of plant remains in arid environments is very low.

As documented by the detailed study of Bertini and Martinetto (2011), the Northern Mediterranean remained under a humid, warm temperate climate until the Late Pliocene (Piacenzian). This holds even for the times of the desiccation of the Mediterranean and the areas of close proximity to the sedimentation area of evaporites. Data indicate that, even in times of ongoing intensification of NH glaciation and the closure of the Panama Strait (Bartoli et al., 2005), no Mediterranean type of climate existed in the study area. Bertini and Martinetto (2011) employ a novel, standardised technique to reconstruct vegetation transects by means of comparative analysis of pollen, leaf and carpological records. The transects illustrate that a warm temperate, humid forest existed in north and central Italy during the Messinian, and throughout the Pliocene, with closest similarities detected with the modern vegetation in south China. Drying pulses, such as the so-called *Lygeum* phase at 5.5 My, are exceptional (Bertini and Martinetto, 2011). Even plants often considered as indicators of drought (*Cupressus*, *Medicago*, *Vitex*) coexisted with plants clearly pointing to humid conditions (Bertini and Martinetto, 2011). Thus, the study by Bertini and Martinetto also suggests the re-interpretation of previous palynomorph records with respect to drying pulses.

For continental areas around the Eastern Paratethys, predominantly warm and wet climate conditions are reported for the Middle Miocene (Ivanov et al., 2011) while slight cooling in combination with significant drying sets in with the Late Miocene. A dry continental area evolved from a dry belt north of the Carpathians. In the later Maeotian and Pontian, wetter conditions prevailed again. A study of orbitally controlled climate cycles reveals the sensitivity of the biosphere of the Eastern Paratethys with respect to precipitation variations (Ivanov et al., 2011).

The reorganisation of the climate system at the end of the Middle Miocene was accompanied by transformations of flora and vegetation structure. In particular, macrothermic floristic elements lost their importance, and evergreen laurel forests disappeared from the Mid-latitudes of this area. At the same time deciduous, arboreal taxa became dominant in the mesophytic forests (Ivanov et al., 2011). However, it can be assumed that global cooling is just one factor triggering these vegetation changes. Palaeogeographical shifts causing isolation and shrinking of the Paratethys certainly reinforced this evolution. Furthermore, orographic uplift intensified at the same time, e.g., in the Carpathians from the Sarmatian onwards (Sanders et al., 2002), leading to an altitudinal differentiation of the vegetation (Ivanov et al., 2011).

For the Black Sea area, there is evidence for seasonal drought throughout the Early and Middle Miocene, as well as the existence of a forest steppe in south Ukraine (Bruch et al., 2011; Ivanov et al., 2011; Syabryaj et al., 2007). The Khersonian is considered to be the driest interval in south Ukraine with the spread of mesophytic grass-steppe communities while Maeotian and Pontian were wetter again (Syabryaj et al., 2007).

According to Akkiraz et al. (2011), Asia Minor was generally wet from Burdigalian to Langhian, with more seasonal rainfall reported from the Serravallian onwards. Early to Middle Miocene vegetation of Anatolia as reconstructed from palynofloras has a humid aspect. Mesophytic forest communities with Juglandaceae, Fagaceae, Myricaceae and Pinaceae were most important (Akkiraz et al., 2011). In the Late Miocene, percentages of herbs and grasses considerably increased (Akgün et al., 2000; Kayseri and Akgün, 2008). Studies of phytoliths partly contradict these interpretations and already indicate wide-spread herbaceous vegetation, from Early Miocene onwards (Strömberg et al., 2007). In fact, the precipitation maps provided by Akkiraz et al. (2011) show a longitudinal precipitation gradient from the west coast of Turkey to drier conditions in inland areas of Western Anatolia persisting from the Aquitanian onwards. Thus, it is shown that the modern gradient already existed in the Early Miocene but was considerably less pronounced than today, possibly because of a reduced elevation of the longitudinally arranged mountain chains at that time.

Summarising the evolution of precipitation patterns in the Eastern Paratethys and Western Asia, it can be stated that a spread of steppe vegetation and a more arid interior of Southeastern Europe and Western Asia occurred at about 10 My. Initial open landscapes were of the so-called parkland type and can be linked to *Hipparion* faunas, related to open spaces and steppe or savannah communities (Ivanov et al., 2011). Precipitation reconstructions based on small and large mammal faunas corroborate the palaeobotany-based patterns suggesting a distinct gradient of decreasing humidity towards the southeast at ca. 11 My (MN9) (e.g., Fortelius et al., 2006).

3.1.2. Eastern Eurasia

The studies of Liu et al. and Yao et al. (both 2011) allow for quantitative reconstructions of climate patterns in Eastern Asia and their changes in time. It is shown that the temperature evolution over north China during the Miocene in general reflects the global trend (Liu et al., 2011). The precipitation reconstruction points to conditions considerably wetter than at present, thus supporting estimates obtained from large mammal faunas pointing to planetary rather than monsoonal patterns in the Early Miocene and during the Mid-Miocene Climate Optimum of north China (Fortelius et al., 2006; Liu et al., 2009). The results presented by the authors favour a Late Miocene onset of the East Asian Summer Monsoon. These results, however, are not quite clear-cut and there is need to improve data coverage (Liu et al., 2011). For south China, detailed palaeoclimate studies based on various quantitative techniques such as the Coexistence Approach and Leaf Margin Analysis indicate that both the South Asian Monsoon and East Asian Monsoon were already established in the Late Miocene (Jaques et al., 2011). In comparison, the Lincang site, located in southwest Yunnan, is mainly under the influence of the South Asian Monsoon, whereas Xiaolongtan, situated in east Yunnan, is more affected by the East Asian Monsoon. Estimating monsoon activity from seasonality of precipitation, the authors come to the conclusion that in the Late Miocene, both monsoon systems had intensities comparable to present. According to the authors, the presumably weak East Asian Winter Monsoon can be explained by the altitude of the Tibetan Plateau being lower at that time. Data presented by Sun et al. (2011) support this hypothesis. There is evidence from vegetation and climate analysis that, throughout the Miocene, the altitudes in west Yunnan were not higher than today and that the uplift of the Hengduan Mountains, part of the eastern Tibetan Plateau, did not occur before the Late Pliocene (Sun et al., 2011). Thus, the South Asian (Indian) Monsoon may have reached farther inland during the Miocene. According to the present results (Yao et al., 2011; Jaques et al., 2011; Utescher et al., 2011), Miocene temperatures and vegetation cover reconstructed for most of the sites in southeast China were close to present. Major differences observed for some of the localities studied are possibly not due to global cooling but are rather caused by post-Miocene changes in altitude.

3.1.3. Results from modelling

Palaeoclimate modelling studies are crucial, not only to test the observed proxy-based spatial palaeoclimate patterns, but also to understand the processes causing these patterns. Moreover, they may help to better understand future climate change since they allow empirical access to climate situations that do not or do not yet exist today and thus can be used as tests for the reliability of climate models (Micheels et al., 2011; Utescher et al., 2011).

According to proxy data-based reconstructions, Cenozoic climates are characterised by relatively warm high latitudes, shallower latitudinal and longitudinal gradients and – in most time intervals – wetter continental interiors than today (e.g., Greenwood and Wing, 1995; Bruch et al., 2007; Ballantyne et al., 2010; Popova et al., in press). Independently from the significant decrease in atmospheric CO_2 from the Eocene onwards (e.g., Pearson and Palmer. 2000), considerable cold month mean temperature anomalies remain surprisingly persistent in the high latitudes and the continental interior of Eurasia over the time-span studied (Utescher et al., 2011). The high-latitude temperature anomalies remain large in the Tortonian, the time of the onset of NH glaciation. Considerable changes in climatic anomalies from the Eocene to Late Miocene are observed for Western Europe that reacted most sensitively to global climate cooling. Here, local effects such as the closure of the Tethys, a pathway for warm water currents, and regressions in the Paratethys certainly played a role. At the same time, the North Atlantic, considerably widening from the Eocene onwards, became increasingly important for the climate system in Central and Western Europe. In the low latitudes of Eurasia, Cenozoic cooling and decreasing CO_2 had only minor effects on continental temperature.

In the models, the representation of shallow latitudinal gradients combined with relatively warm high latitudes, as evident from proxy data, is still unsatisfactory, even in complex models (e.g., Micheels et al., 2007; Steppuhn et al., 2007; Micheels et al., 2011). In a coupled ocean-atmosphere modelling study performed for a Tortonian time slice, the open Central American Isthmus leads to an even weaker THC in the North Atlantic and hence to a reduced oceanic heat transport to the North (Micheels et al., 2011; see also Mikolajewicz and Crowley, 1997; Bice et al., 2000). However, it is shown that the atmosphere can compensate for this effect by increased sensible and latent heat fluxes (Micheels et al., 2011).

The fact that the relatively warm high latitudes observed for the Miocene are not well represented in modelling studies may partly be explained by still incomplete model physics and representation of process interactions. However, inadequately defined boundary conditions may also play a major role. It is shown that assuming forest cover in high latitudes causes considerable warming of the polar regions (e.g., Schneck et al., 2009). Another important factor in this context are palaeogeographical changes such as uplift processes, mostly concerning the Alpidic orogen belt, that possibly experienced their highest rates after the Late Miocene (e.g., Kuhlemann, 2007). It is known, for example, that the palaeo-altitude of the Tibetan Plateau substantially impacts climate in other areas on the Northern Hemisphere. Thus, it can be shown that the uplift of the Tibetan Plateau is a major factor in triggering the evolution of the East Asian Monsoon Systems (Micheels et al., 2011; see also Ramstein et al., 1997; Fluteau et al., 1999; Liu and Yin, 2002). There is evidence that a low Tibetan Plateau caused a weak East Asian Monsoon while the strength of the South Asian (Indian) Monsoon is positively correlated to the SST of the Indian Ocean (Micheels et al., 2011). In general, it can be stated that Tibetan uplift and intensified monsoon led to an aridification of the continental interior of Eurasia (An et al., 2001; Guo et al., 2004). This trend is very evident in the Tortonian model experiment presented herein (Micheels et al., 2011). Micheels et al. (2011) assume that the intensification of the East Asian Monsoon Systems is directly linked to the closure of the Central American Isthmus. On the other hand, Bothe et al. (2009) showed that a wet E Asian continental interior has a significant impact on NH atmospheric circulation patterns with storm tracks over Eurasia arranged more zonally causing low pressure over Europe.

In order to explain global warmth and warm high latitudes, sustained El Nino conditions have been proposed (e.g., Wara et al., 2005). At present, El Nino teleconnections include warmer temperatures over Canada and Alaska (mainly in winter), a cooler, slightly wetter climate around the Gulf of Mexico, and a drier northeast South America (e.g., Trenberth et al., 2002). Precipitation increases in turn over the North Atlantic, Northern Eurasia and Greenland (Bonham et al., 2009). Several papers have suggested that an El Nino condition was a permanent feature of Cenozoic climate (e.g. Molnar and Cane, 2002, 2007; Barreiro et al., 2005; Wara et al., 2005; Fedorov et al., 2006). According to Molnar and Cane (2007) the shallow east-west gradient known from Pliocene equatorial SSTs has a large impact on global climate. Model studies performed for the Pliocene suggest that a positive feedback between the frequency of tropical cyclones and a considerable poleward extension of the Tropical Warm Pools (especially Pacific) may cause significant warming in the high latitudes (Brierley et al., 2009).

François et al. (2011) present a modelling study using the CARAIB (CARbon Assimilation In the Biosphere) biome model aiming to reconstruct the Late Miocene vegetation cover of Western Eurasia. CARAIB uses surface temperatures obtained from a coupled ocean-atmosphere model (COSMOS) for a Tortonian model run (Micheels et al., 2011). The procedure allows a comparison between the modelled vegetation and fossil flora recorded at various localities. The comparison is accomplished at the plant functional type level, in a way that is fully consistent with biome model and palaeobotanical data, and thus provides an independent validation of the palaeoclimate reconstruction obtained from the climate model. François et al. (2011) show that particularly in the mid- and higher latitudes of Western Eurasia, modelled Late Miocene climate is too cool to produce assemblages of plant functional types consistent with the palaeo-record.

4. Conclusions

The integrative approach presented in this volume, linking palaeobotanical and palaeozoological proxy-data, climate and biome modelling, brings about a much better and much more detailed understanding of Neogene climate dynamics in Eurasia. It becomes very clear that the various regions of Eurasia show regionally specific Neogene climate changes which may differ considerably from each other and from the overall global cooling trend. All in all, the results from the various proxy and modelling studies are consistent: latitudinal and longitudinal gradients generally become more pronounced during the Neogene and boundary conditions, such as vegetation type, altitude of mountain chains and distance to coast lines, play a significant role in the regional climate evolution. On the other hand, there are still a number of problems, inconsistencies and open questions. First of all, the data density (in time and space) is far from satisfactory. Moreover, on a more regional level, palaeozoological and palaeobotanical palaeoclimate proxies and modelling results are sometimes equivocal, in particular concerning precipitation. The models can not yet explain the relatively warm high latitudes during the Neogene and we still do not sufficiently understand the role of the various "boundary conditions" (CO_2, palaeogeography, palaeovegetation) in the observed Neogene climate change with its regional differentiation. As usual: this calls for more data and studies!

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References

Akgün, F., Kaya, T., Forsten, A., Atalay, Z., 2000. Biostratigraphic data (Mammalia and Palynology) from the Upper Miocene İncesu Formation at Düzyayla (Hafik Sivas, Central Anataloia). Turkish Journal of Earth Sciences 9, 57–67.

Akkiraz, M.S., Akgün, F., Utescher, T., Bruch, A.A., Mosbrugger, V., 2011. Precipitation gradients during the Miocene in Western and Central Turkey as quantified from pollen data. Palaeogeography, Palaeoclimatology, Palaeoecology 304, 276–290 (this issue).

An, Z., Kutzbach, J.E., Prell, W.L., Porter, S.C., 2001. Evolution of Asian monsoons and phased uplift of the Himalaya — Tibetan plateau since Late Miocene times. Nature 411, 62–66.

Ballantyne, A.P., Greenwood, D.R., Sinninghe Damsté, J.S., Csank, A.Z., Eberle, J.J., Rybczynski, N., 2010. Significantly higher Arctic surface temperatures during the Pliocene indicated by multiple independent proxies. Geology 38, 603–606.

Barreiro, M., Philander, G., Pacanowski, R., Fedorov, A., 2005. Simulations of warm tropical conditions with application to middle Pliocene atmospheres. Climate Dynamics. doi:10.1007/s00382-005-0086-4.

Bartoli, G., Sarnthein, M., Weinelt, M., Erlenkeuser, H., Garbe-Schönberg, D., Lea, D.W., 2005. Final closure of Panama and the onset of northern hemisphere glaciation. Earth and Planetary Science Letters 237, 33–44.

Bertini, A., Martinetto, E., 2011. Reconstruction of vegetation transects for the Messinian–Piacenzian of Italy by means of comparative analysis of pollen, leaf and carpological records. Palaeogeography, Palaeoclimatology, Palaeoecology 304, 230–246 (this issue).

Bice, K.L., Scotese, C.R., Seidov, D., Barron, E.J., 2000. Quantifying the role of geographic change in Cenozoic ocean heat transport using uncoupled atmosphere and ocean models. Palaeogeography, Palaeoclimatology, Palaeoecology 161, 295–310.

Böhme, M., Winklhofer, M., Ilg, A., 2011. Miocene precipitation in Europe: temporal trends and spatial gradients. Palaeogeography, Palaeoclimatology, Palaeoecology 304, 212–218 (this issue).

Bonham, S.G., Haywood, A.M., Lunt, D.J., Collins, M., Salzmann, U., 2009. El Niño-Southern Oscillation, Pliocene climate and equifinality. Philosophical Transactions of the Royal Society A 367, 127–156.

Bothe, O., Fraedrich, K., Zhu, X., 2009. The large-scale circulations and summer drought and wetness on the Tibetan plateau. International Journal of Climatology. doi:10.1002/joc.1946.

Brierley, C.M., Fedorov, A.V., Liu, Z., Herbert, T.D., Lawrence, K.T., LaRiviere, J.P., 2009. Greatly expanded tropical warm pool and weakened Hadley circulation in the Early Pliocene. Science 323, 1714–1718.

Bruch, A.A., Zhilin, S.G., 2007. Early Miocene climate of Central Eurasia — evidence from Aquitanian floras of Kazakhstan. Palaeogeography, Palaeoclimatology, Palaeoecology 248, 32–48.

Bruch, A.A., Uhl, D., Mosbrugger, V., 2007. Miocene climate in Europe — patterns and evolution. Palaeogeography, Palaeoclimatology, Palaeoecology 253, 1–7.

Bruch, A.A., Utescher, T., Mosbrugger, V., NECLIME, members, 2011. Precipitation patterns in the Miocene of Central Europe and the development of continentality. Palaeogeography, Palaeoclimatology, Palaeoecology 304, 202–211 (this issue).

Eronen, J.T., Mirzaie, M., Karme, A., Micheels, A., Bernor, R.L., Fortelius, M., 2009. Distribution history and climatic controls of the Late Miocene Pikermian chronofauna. Proceedings of the National Academy of Sciences USA (PNAS) 106 (29), 11867–11871.

Fedorov, A.V., Dekens, P.S., McCarthy, M., Ravelo, A.C., deMenocal, P.B., Barreiro, M., Pacanowski, R.C., Philander, S.G., 2006. The Pliocene paradox (mechanisms for a permanent El Niño). Science 312, 1485–1489.

Fluteau, F., Ramstein, G., Besse, J., 1999. Simulating the evolution of the Asian and African monsoons during the past 30 Myr using an atmospheric general circulation model. Journal of Geophysical Research 104, 11995–12018.

Fortelius, M., Eronen, J., Liu, L., Pushkina, D., Tesakov, A., Vislobokova, I., Zhang, Z., 2006. Late Miocene and Pliocene large land mammals and climatic changes in Eurasia. Palaeogeography, Palaeoclimatology, Palaeoecology 238, 219–227.

François, L., Utescher, T., Favre, E., Henrot, A.-J., Warnant, P., Micheels, A., Erdei, B., Suc, J.-P., Cheddadi, R., Mosbrugger, V., 2011. Modelling Late Miocene vegetation in Europe: results of the CARAIB model and comparison with palaeovegetation data. Palaeogeography, Palaeoclimatology, Palaeoecology 304, 359–378 (this issue).

Furió, M., Casanovas-Vilar, I., van den Hoek Ostende, L.W., 2011. Predictable structure of Miocene insectivore (Lipotyphla) faunas in Western Europe along a latitudinal gradient. Palaeogeography, Palaeoclimatology, Palaeoecology 304, 219–229 (this issue).

Greenwood, D.R., Wing, S.L., 1995. Eocene continental climates and latitudinal gradients. Geology 23, 1040–1048.

Guo, Z., Peng, S., Hao, Q., Biscaye, P.E., An, Z., Liu, T., 2004. Late Miocene–Pliocene development of Asian aridification as recorded in the Red-Earth Formation in northern China. Global and Planetary Change 41, 135–145.

Holbourn, A., Kuhnt, W., Schulz, M., Erlenkeuser, M., 2005. Impacts of orbital forcing and atmospheric carbon dioxide on Miocene ice-sheet expansion. Letters to Nature 438, 483–487.

Ivanov, D., Utescher, T., Mosbrugger, V., Syabryaj, S., Djordjević-Milutinović, D., Molchanoff, S., 2011. Miocene vegetation and climate dynamics in Eastern and Central Paratethys (Southeastern Europe). Palaeogeography, Palaeoclimatology, Palaeoecology 304, 262–275 (this issue).

Jacques, F.M.B., Guo, S.X., Su, T., Xing, Y.W., Huang, Y.J., Liu, Y.S., Ferguson, D.K., Zhou, Z.K., 2011. Quantitative reconstruction of the Late Miocene monsoon climates of southwest China: a case study of the Lincang flora from Yunnan Province. Palaeogeography, Palaeoclimatology, Palaeoecology 304, 318–327 (this issue).

Jiménez-Moreno, G., Suc, J.-P., 2007. Middle Miocene latitudinal climatic gradient in Western Europe: evidence from pollen records. Palaeogeography, Palaeoclimatology, Palaeoecology 253, 224–241.

Kayseri, M.S., Akgün, F., 2008. Palynostratigraphic, palaeovegetational and palaeoclimatic investigations on the Miocene deposits in Central Anatolia (Çorum Region and Sivas Basin). Turkish Journal of Earth Sciences 17, 361–403.

Kern, A., Harzhauser, F., Mandic, T., Roetzel, R., Ćorić, V., Bruch, A.A., Zuschin, M., 2011. Millennial-scale vegetation dynamics in an estuary at the onset of the Miocene Climate Optimum. Palaeogeography, Palaeoclimatology, Palaeoecology 304, 247–261 (this issue).

Kovar-Eder, J., Jechorek, H., Kvaček, Z., Parashiv, V., 2008. The integrated plant record: an essential tool for reconstructing Neogene zonal vegetation in Europe. Palaios 23, 97–111.

Kuhlemann, J., 2007. Paleogeographic and paleotopographic evolution of the Swiss and Eastern Alps since the Oligocene. Global and Planetary Change 58, 224–236.

Liu, X., Yin, Z.Y., 2002. Sensitivity of East Asian monsoon climate to the uplift of the Tibetan Plateau. Palaeogeography, Palaeoclimatology, Palaeoecology 183, 223–245.

Liu, L., Eronen, J.T., Fortelius, M., 2009. Significant mid-latitude aridity in the middle Miocene of East Asia. Palaeogeography, Palaeoclimatology, Palaeoecology 279, 201–206.

Liu, Y.S., Utescher, T., Zhou, Z.Z., Sun, B.N., 2011. The evolution of Miocene climates in North China: preliminary results of quantitative reconstructions from plant fossil records. Palaeogeography, Palaeoclimatology, Palaeoecology 304, 308–317 (this issue).

Micheels, A., Bruch, A.A., Uhl, D., Utescher, T., Mosbrugger, V., 2007. A Late Miocene climate model simulation with ECHAM4/ML and its quantitative validation with terrestrial proxy data. Palaeogeography, Palaeoclimatology, Palaeoecology 253, 251–270.

Micheels, A., Bruch, A.A., Eronen, J., Fortelius, M., Harzhauser, M., Utescher, T., Mosbrugger, V., 2011. Analysis of heat transport mechanisms from a Late Miocene model experiment with a fully-coupled atmosphere–ocean general circulation model. Palaeogeography, Palaeoclimatology, Palaeoecology 304, 337–350 (this issue).

Mikolajewicz, U., Crowley, T.J., 1997. Response of a coupled ocean/energy 851 balance model to restricted flow through the central American isthmus. Palaeoceanography 12, 429–441.

Molnar, P., 2005. Mio-Pliocene growth of the Tibetan Plateau and Evolution of the East Asian climate. Palaeontologia Electronica 8 (1), 1–23.
Molnar, P., Cane, M.A., 2002. El Niño's tropical climate and teleconnections as a blueprint for pre-Ice Age climates. Paleoceanography 17, 1021.
Molnar, P., Cane, M.A., 2007. Early Pliocene (Pre-Ice Age) El Niño-like global climate: which El Niño? Geosphere 3, 337–365.
Mosbrugger, V., Utescher, T., Dilcher, D.L., 2005. Cenozoic continental climatic evolution of Central Europe. Proceedings of the National Academy of Sciences 102 (42), 14964–14969.
Pearson, P.N., Palmer, M.R., 2000. Atmospheric carbon dioxide concentrations over the past 60 million years. Nature 406, 695–699.
Popova, S., Utescher, T., Gromyko, D., Bruch, A.A., Mosbrugger, V., in press. Palaeoclimate evolution in Siberia and the Russian Far East from the Oligocene to Pliocene — evidence from fruit and seed floras. Turkish Journal of Earth Sciences. doi:10.3906/yer-1005-6.
Ramstein, G., Fluteau, F., Besse, J., Joussaume, S., 1997. Effect of orogeny, plate motion and land-sea distribution on Eurasian climate change over the past 30 million years. Nature 386, 788–795.
Sanders, C., Huismans, R., vanWees, J.D., Andriessen, P., 2002. The Neogene history of the Transylvanian basin in relation to its surrounding mountains. EGU Stephan Mueller Special Publication Series 3, 121–133.
Schneck, R., Micheels, A., Mosbrugger, V., 2009. Modelling the climate impact of high-latitude vegetation in the Late Miocene. Geophysical Research Abstracts 11 EGU2009-10606-1.
Steppuhn, A., Micheels, A., Bruch, A.A., Uhl, D., Mosbrugger, V., 2007. The sensitivity of ECHAM4/ML to a double CO2 scenario for the Late Miocene and the comparison to terrestrial proxy data. Global and Planetary Change 57, 189–212.
Strömberg, C.A.E., Werdelin, L., Friis, E.M., Saraç, G., 2007. The spread of grassdominated habitats in Turkey and surrounding areas during the Cenozoic: phytolith evidence. Palaeogeography, Palaeoclimatology, Palaeoecology 250, 18–49.
Sun, B.N., Wu, J.Y., Liu, Y.S., Ding, S.T., Li, X.C., Xie, S.P., Yan, D.F., Lin, Z.C., 2011. Reconstructing Neogene vegetation and climates to infer tectonic uplift in western Yunnan, China. Palaeogeography, Palaeoclimatology, Palaeoecology 304, 328–336 (this issue).
Syabryaj, S., Molchanoff, S., Utescher, T., Bruch, A.A., 2007. Changes of climate and vegetation during the Miocene on the territory of Ukraine. Palaeogeography, Palaeoclimatology, Palaeoecology 253, 153–168.
Trenberth, K.E., Caron, J.M., Stepaniak, D.P., Worley, S., 2002. Evolution of El Niño-Southern Oscillation and global atmospheric surface temperatures. Journal of Geophysical Research 107, D8-4065. doi:10.1029/2000JD000298.
Utescher, T., Mosbrugger, V., Ashraf, A.R., 2000. Terrestrial climate evolution in Northwest Germany over the last 25 million years. Palaios 15, 430–449.
Utescher, T., Erdei, B., François, L., Mosbrugger, V., 2007. Tree diversity in the Miocene forests of Western Eurasia. Palaeogeography, Palaeoclimatology, Palaeoecology 253, 242–266.
Utescher, T., Mosbrugger, V., Ivanov, D., Dilcher, D.L., 2009. Present-day climatic equivalents of European Cenozoic climates. Earth and Planetary Science Letters 284 (3–4), 544–552.
Utescher, T., Brunch, A.A., Micheels, A., Mosbrugger, V., Popova, S., 2011. Cenozoic climate gradients in Eurasia — a palaeo-perspective on future climate change? Palaeogeography Palaeoclimatology, Palaeoecology 304, 351–358 (this issue).
van Dam, J.A., 2006. Geographic and temporal patterns in the late Neogene (12–3 Ma) aridification of Europe. The use of small mammals as paleoprecipitation proxies. Palaeogeography, Palaeoclimatology, Palaeoecology 238, 190–218.
van Dam, J.A., Reichert, G.J., 2009. Oxygen and carbon isotope signatures in late Neogene horse teeth from Spain and application as temperature and seasonality proxies. Palaeogeography, Palaeoclimatology, Palaeoecology 274, 64–81.
Wara, M.W., Ravelo, A.C., Delaney, M.L., 2005. Permanent El Niño-Like Conditions During the Pliocene Warm Period. Science 309, 758–761.
Westerhold, T., Bickert, T., Röhl, U., 2005. Middle to late Miocene oxygen isotope stratigraphy of ODP site 1085 (SE Atlantic): new constrains on Miocene climate variability and sea-level fluctuations. C, Palaeoclimatology, Palaeoecology 217, 205–222.
Yao, Y.F., Brunch, A.A., Mosbrugger, V., Li, C.S., 2011. Quantitative reconstruction of Miocene climate patterns and evolution in Southern China based on plant fossils. Quantitative reconstruction of Miocene climate patterns and evolution in Southern China based on plant fossils Palaeoclimatology, Palaeoecology 304, 291–307 (this issue).
Zachos, J., Pagani, M., Sloan, L., Thomas, E., Billups, K., 2001. Trends, rhythms, and aberrations in global climate 65 Ma to present. Science 292, 686–693.