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Palaeogeography, Palaeoclimatology, Palaeoecology 238 (2006) 270–280

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Late Miocene climate in the circum-Alpine realm—a quantitative analysis of terrestrial palaeofloras

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Received 14 February 2003; accepted 7 March 2006

Abstract

Selected mega- and microfloras from Central and Southern Europe have been analysed for the time interval Tortonian/Pannonian (MN 9–12) with the Coexistence Approach to obtain quantitative palaeoclimate data. The results give a geographically differentiated picture of the Late Miocene climate in the circum-Alpine area. Spatial patterns are presented in maps for mean annual temperature, temperature of the coldest month, temperature of the warmest month, mean annual precipitation, and mean annual range of temperature. The obtained data show an overall warm, humid, and homogenous climate with very low latitudinal and longitudinal gradients; there is no indication of a Mediterranean type of climate. Palaeogeographic influences on climate patterns are evident; the Pannonian Lake caused mild winters and a lower seasonality of temperature in the Pannonian basin.

Keywords: Palaeoclimate maps; Quantitative analysis; Terrestrial environment; Central Europe; Upper Miocene

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1. Introduction

The Neogene represents a transitional stage between the greenhouse world of the Cretaceous/Paleogene and the Quaternary icehouse situation. It is characterised by major palaeogeographic changes (e.g. closure of the Mediterranean Sea, establishment of the Panama land bridge), by considerable orographic movements in the Himalayas and the Alps, and by an overall cooling trend. Numerous studies have analysed this Neogene climate change, both in the marine and in the terrestrial environment, in order to understand the causal relationships between palaeogeography, palaeo-orography, and climate (e.g. Barron, 1985; Molnar and England, 1990; Wolfe, 1995; Ruddiman et al., 1997; Utescher et al., 2000; Zachos et al., 2001). Thus, the temporal pattern of the Neogene climate change is relatively well known, at least in qualitative terms; little information, however, is available so far regarding the spatial climate patterns and gradients in the Neogene.

Here we analyse quantitatively the geographic climate pattern as reflected by palaeofloras for the Tortonian of Central and Southern Europe. In Europe,

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doi:10.1016/j.palaeo.2006.03.028

the Tortonian (Upper Miocene, partly equivalent to the Paratethyan Pannonian stage) is relatively well represented by sediments and predates not only the major palaeogeographic changes of the Messinian but also the more intense climate fluctuations of the Pliocene (e.g. Zachos et al., 2001). During this time period, the climate in Europe was considerably warmer than today. It is mostly considered to be of the Cfa-type in the Koeppen classification (e.g. Mai, 1995 and references therein); Utescher et al. (2000) estimate the Tortonian mean annual temperature in NW-Germany to be between 14 and 16 °C. The geographic differentiation of the Tortonian climate, however, has hardly been studied systematically. In a semi-quantitative overview, Mai (1995) illustrates the European climate patterns during the Late Miocene by plotting 5 idealised climate diagrams on a map of Europe. Based on a qualitative discussion of the Messinian climate in Italy, Bertini (1994a,b) concludes a latitudinal gradient in temperature. Suc et al. (1995) and Fauquette et al. (1999) were the first to quantify geographic climate patterns for the Pliocene western Mediterranean. They document a climatic differentiation in this area and support the idea of an already well-developed modern Mediterranean type of climate in the Pliocene.

Our quantitative reconstruction of the spatial climate patterns in the Tortonian of Central and Southern Europe is based on 28 floras dating between ~11 and ~7 Ma. These floras were analysed with the Coexistence Approach (Mosbrugger and Utescher, 1997) to obtain quantitative estimates for five climate parameters (mean annual temperature, mean temperature of the warmest month, mean temperature of the coldest month, mean annual range of temperature, mean annual precipitation). With a single rigorous method applied consistently to all floras, it is possible to obtain quantitative climate maps that can be analysed with respect to geographic climate patterns and gradients. Focussing on the circum-alpine realm, these maps also allow the study of climatic effects of palaeogeography (in particular land–sea distribution) and palaeo-orography.

2. Material

Our climate reconstruction is entirely based on palaeofloras (see below). In total, 28 Late Miocene floras have been selected, which are dated within the time interval Tortonian, Pannonian D-F, or mammal zones MN 9–12, respectively. This selection comprises

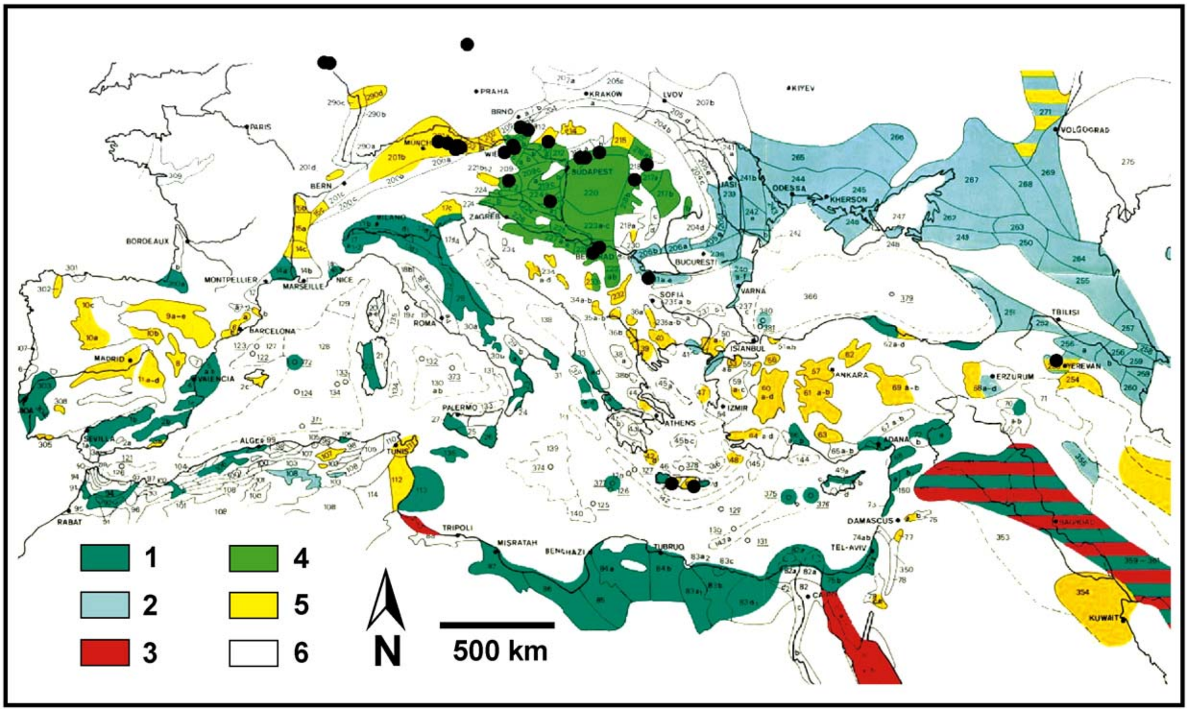

Fig. 1. Sediment distribution map after Steininger et al. (1985: map 8, time slice 11–12 Ma), with positions of the investigated floras. 1: marine; 2: reduced marine; 3: evaporitic; 4: endemic Paratethys; 5: continental; 6: underlying rocks.

Table 1

(A) List of geographic positions of the investigated floras

Locality	Region	Type of flora	Longitude	Latitude	No. of taxa with climate data
AMPFLWANG	Austria (Styria)	fruits and seeds	13.55	48.10	11
AUBENHAM	S Germany	leaves	12.40	48.30	20
BUKKÁBRÁNY	Hungary	leaves	20.75	47.92	16
BULGARIA C1/DR-18	Bulgaria	pollen	23.51	43.87	19
DELURENI	Romania (Borod Basin)	leaves	22.58	46.97	16
DUBONA	Serbia	leaves	20.45	44.31	19
DURINCI	Serbia	leaves	20.75	44.52	20
FRECHEN OPEN PIT MINE	NW Germany	leaves	6.75	50.89	29
GROSSENREITH	Upper Austria	leaves	13.36	48.16	13
HAMBACH OPEN PIT MINE	NW Germany	fruits and seeds	6.47	50.92	37
HIDAS	Hungary	pollen	18.30	46.16	14
HOKTEMBERYAN 5	Armenia	pollen	44.15	40.18	26
KLETTWITZ 12	E Germany	fruits and seeds	13.90	51.55	28
LAAERBERG	Austria (Vienna Basin)	leaves	16.27	48.17	27
LEONBERG	S Germany	fruits and seeds	12.90	48.25	14
LOHNSBURG	Upper Austria	leaves	13.42	48.15	18
MAKRILIA	Greece (Crete)	fruits and seeds, leaves	25.70	35.00	28
MORAVIAN BASIN	Czech Republic (Vienna Basin)	fruits and seeds	17.05	48.70	25
NEUHAUS	Austria (Styria)	leaves	16.08	46.93	20
NEUSIEDL	E Austria	leaves	15.83	47.92	14
NITRA	Slovakia	pollen	18.05	48.19	22
OAS BASIN (Satu Mare)	Romania	leaves	23.25	47.50	17
ROZSASZENTMARTON	Hungary	leaves	19.75	47.75	20
SCHNEEGATTERN	Upper Austria	leaves	13.32	48.04	8
TRIOPETRA	Greece (Crete)	pollen	24.54	35.11	14
VISONTA	Hungary	leaves	20.02	47.75	17
VOESENDORF	Austria (Vienna Basin)	leaves	16.33	48.07	36
WIEN E-F	Austria (Vienna Basin)	fruits and seeds	16.65	48.80	16

(B) List of stratigraphic positions and palaeobotanical references of the investigated floras

Locality name	Stratigraphy	Reference
AMPFLWANG	Pannonian E, ~MN 10 (Mai, 1995)	Gregor (1989)
AUBENHAM	Early Pannonian (Eder-Kovar, 1988), Late Pannonian (E, MN 10) (Mai, 1995)	Eder-Kovar (1988, after Unger 1983)
BUKKÁBRÁNY	Pannonian E/F	Lászlo (1992)
BULGARIA C1/DR-18	Maeotian (eastern Paratethys stage)	Ivanov et al. (2002)
DELURENI	Pannonian E (Eder-Kovar, 1988)	Givulescu (1975)
DUBONA	Late Pannonian	Mihajlovic (1977), Pantic and Mihajlovic (1980)
DURINCI	Pannonian D/E	Mihajlovic (1977), Pantic and Mihajlovic (1980)
FRECHEN OPEN PIT MINE	Late Tortonian	Belz and Mosbrugger (1994), Utescher et al. (2000)
GROSSENREITH	Pannonian, MN 9–10	Eder-Kovar (1988)
HAMBACH OPEN PIT MINE	Late Tortonian	van der Burgh (1988)
HIDAS	Pannonian	Nagy and Planderova (1985)
HOKTEMBERYAN 5	Late Miocene/Late Sarmatian (eastern Paratethys stage)	Eramyan (1975), Manukian (1977, 1978, 1980)
KLETTWITZ 12	Late Miocene	Mai (2001)
LAAERBERG	Early Pannonian E	Eder-Kovar (1988, after Berger 1955)
LEONBERG	Pannonian, MN 9 (cf. Mai, 1995)	Gregor (1989, after Gregor 1982)
LOHNSBURG	Pannonian, MN 9–10	Eder-Kovar (1988)
MAKRILIA	Tortonian	Sachse and Mohr (1996), Sachse (1997)
MORAVIAN BASIN	Pannonian F	Knobloch (1973)
NEUHAUS	Late Pannonian	Eder-Kovar et al. (1995)

Table 1 (*continued*)

(B) List of stratigraphic positions and palaeobotanical references of the investigated floras

Locality name	Stratigraphy	Reference
NEUSIEDL	Pannonian E	Knobloch (1978)
NITRA	Pannonian	Nagy and Planderova (1985)
OAS BASIN (Satu Mare)	Late Pannonian	Givulescu (1994)
ROZSASZENTMARTON	Pannonian E/F	Palfalvy (1952), Vörös (1955)
SCHNEEGATTERN	Pannonian, MN 9–10	Eder-Kovar (1988)
TRIOPETRA	Early Tortonian	van de Weerd (1983)
VISONTA	Pannonian E/F	Palfalvy and Rakosi (1979)
VOESENDORF	Pannonian D/E	Berger (1952), Eder-Kovar (1988)
WIEN E–F	Pannonian E/F	Gregor (1989, after Knobloch 1985)

7 fruit and seed floras, 16 leaf floras, and 5 microfloras. It attempts to provide a sufficient data cover over the area of interest on the one hand, and to obtain a stratigraphic range as narrow as possible, on the other. Moreover, low-diversity floras were avoided due to the method applied to reconstruct palaeoclimate parameters (see below).

All investigated floras are shown on Fig. 1 and their geographic and stratigraphic position is detailed on Table 1 together with the authors of the original palaeobotanical investigations. An overview of the sediment distribution in Europe during the Tortonian and the sedimentary settings at the different localities after Steininger et al. (1985) are also indicated in Fig. 1. All floras are from either continental or Paratethyan sediments; this restriction should lead to a relatively low variation in taphonomic influences (e.g. exclusion of long-distance transport). Focussing on the Eastern Alpine area, floras from the Pannonian Basin (Hungary, Serbia, Poland, Czech Republic, Slovakia) and the Molasse Basin (Austria, S Germany) have been considered. For a better overview on the larger scale climatic situation, some additional localities from the surrounding area have been taken into account (e.g. Armenia, Greece, Germany). Here, few data are available which is mainly due to a lack of modern palaeobotanical investigations, the lack of plant bearing localities, or even a lack of sediments of Tortonian age.

3. Methods

All floras have been analysed with the Coexistence Approach (CA) following Mosbrugger and Utescher (1997). This method allows for a calculation of up to 15 climate parameters based on terrestrial plant remains. Based on the assumption that the climatic requirements of Tertiary plant taxa are similar to those of their nearest living relatives (NLRs), the aim of the CA is to find the climatic ranges in which a maximum number of NLRs of a given fossil flora can coexist. These coexistence intervals–one for each climate parameter–are considered the best description of the palaeoclimatic situation under which the given fossil flora lived. For a detailed discussion and introduction to the method, see Mosbrugger and Utescher (1997), Mosbrugger (1999), and Utescher et al. (2000).

The application of the CA is facilitated by the computer program ClimStat and the database Palaeoflora which contains NLRs of more than 3000 Cenozoic plant taxa, together with their climatic requirements which are derived from meteorological stations located within the distribution areas of the taxa (see also information given on the web site www.palaeoflora.de). The resolution of the calculated climate data varies with respect to the parameter examined; it is highest for temperature-related parameters where it is usually in the range of 1–2 °C; results for mean annual precipitation reach an accuracy of 100–200 mm (see Mosbrugger and Utescher, 1997). Several authors have applied the CA on Oligocene to Pliocene European floras and showed its reliability and good climatic resolution (e.g. Bruch, 1998; Pross et al., 1998; Utescher et al., 2000; Pross et al., 2001; Ivanov et al., 2002).

Typically, the resolution and the reliability of the resulting coexistence intervals increase with the number of taxa included in the analysis, and are relatively high in floras with ten or more taxa for which climate parameters are known. This is the case for all investigated floras except for one, which is Schneegattern with only eight taxa. However, this flora is included because the results proved to be consistent and comparable to nearby localities.

In this study, four climate parameters, i.e. mean annual temperature (MAT), mean temperature of the coldest month (CMT), mean temperature of the warmest month (WMT), and mean annual precipitation (MAP) have been calculated by the CA. In addition, the mean annual range of temperature (MART) as the difference

Table 2
Results of CA analyses

Locality name	MAT [°C]			CMT [°C]			WMT [°C]			MAP [mm]		
	Left border		Right border	Left border		Right border	Left border		Right border	Left border		Right border
AMPFLWANG	14.70	17.75	20.80	4.50	8.90	13.30	26.00	27.05	28.10	1096	1146.5	1197
AUBENHAM	14.10	14.30	14.50	0.10	2.10	4.10	23.80	24.05	24.30	1231	1234.0	1237
BUKABRANY	14.40	15.50	16.60	2.90	4.35	5.80	25.60	26.90	28.20	897	1126.0	1355
BULGARIA C1	15.60	16.40	17.20	5.00	5.80	6.60	24.70	26.00	27.30	823	1065.5	1308
DELURENI	15.60	16.85	18.10	5.00	5.40	5.80	26.50	27.20	27.90	1122	1239.0	1356
DUBONA	14.40	14.90	15.40	3.70	4.25	4.80	26.50	26.60	26.70	1122	1179.5	1237
DURINCI	15.60	16.05	16.50	1.80	3.30	4.80	25.70	26.05	26.40	1003	1120.0	1237
FRECHEN O.P.M.	14.00	14.75	15.50	0.60	2.55	4.50	25.70	26.25	26.80	1231	1279.0	1327
GROSSENREITH	13.60	14.70	15.80	0.60	2.35	4.10	25.70	26.35	27.00	867	919.0	971
HAMBACH O.P.M.	14.40	15.10	15.80	4.70	6.30	7.90	25.60	25.75	25.90	1231	1240.5	1250
HIDAS	11.60	15.00	18.40	6.20	6.60	7.00	25.60	26.20	26.80	1187	1242.5	1298
HOKTEMBERYAN 5	15.60	17.00	18.40	5.00	6.35	7.70	25.70	26.75	27.80	996	1104.5	1213
KLETTWITZ 12	15.70	16.00	16.30	4.70	5.45	6.20	25.70	25.70	25.70	979	1167.0	1355
LAAERBERG	13.30	14.50	15.70	−0.50	2.30	5.10	25.60	26.00	26.40	897	1042.0	1187
LEONBERG	14.40	16.00	17.60	2.90	5.25	7.60	23.00	23.95	24.90	735	1105.0	1475
LOHNSBURG	13.30	14.55	15.80	0.60	2.35	4.10	25.70	26.05	26.40	897	934.0	971
MAKRILIA	15.60	16.80	18.00	7.10	8.65	10.20	25.60	26.55	27.50	979	988.5	998
MORAVIAN BASIN	15.60	16.05	16.50	5.60	5.70	5.80	25.70	26.05	26.40	897	1097.0	1297
NEUHAUS	15.60	15.70	15.80	0.60	3.20	5.80	25.30	25.85	26.40	1231	1293.0	1355
NEUSIEDL	14.00	14.90	15.80	0.10	2.65	5.20	24.70	25.55	26.40	897	1126.0	1355
NITRA	15.20	15.45	15.70	6.60	7.05	7.50	22.80	24.80	26.80	1035	1055.5	1076
OAS BASIN	14.10	14.80	15.50	0.10	3.55	7.00	25.70	26.05	26.40	867	1111.5	1356
ROZSASZENTMARTON	15.60	15.60	15.60	5.00	6.00	7.00	24.70	24.80	24.90	897	1024.0	1151
SCHNEEGATTERN	14.00	14.75	15.50	0.10	2.30	4.50	25.70	26.75	27.80	979	1167.0	1355
TRIOPETRA	15.60	17.00	18.40	5.00	7.20	9.40	24.70	26.25	27.80	735	747.0	759
VISONTA	13.4	14.55	15.70	0.00	2.55	5.10	25.60	25.60	25.60	897	1051.5	1206
VOESENDORF	13.9	14.85	15.80	2.70	3.95	5.20	25.80	26.10	26.40	1036	1066.0	1096
WIEN E–F	15.7	16.10	16.50	2.90	7.55	6.40	23.80	25.60	27.40	1231	1293.0	1355

between WMT and CMT has been taken into consideration. The analysis of these standard parameters provides spatial palaeoclimate patterns, which can easily be compared with the recent situation.

As stated above, the CA calculates for all climate parameters coexistence intervals, which are assumed to encompass the “real climate value”. For the purpose of data visualisation, the middle values of the calculated coexistence intervals are used. An analysis of the Recent European climate by Klotz (1999; see also Pross et al. 2000) shows for subtropical to temperate conditions that the middle values of the coexistence intervals correlate better to the real data than the borders of the intervals. The use of middle values turns out to be appropriate in visualising climatic trends between regions, especially when interpolating over greater distances.

To show the reconstructed climate data in map form, results were processed with the GIS program ArcView. Interpolations between data points were calculated with the *inverse distance weighted* method, which provides a relatively smooth gradient between the single data points, giving detailed patterns between closely situated points and less detail between points separated by greater distances. Nevertheless, it is obvious that the computer-derived interpolation gives purely artificial climate patterns in areas without data. To avoid an over interpretation of the resulting maps, we clearly indicate within these maps the underlying data points, i.e. localities. All maps simply provide a visualisation of the data given in Table 2.

4. Results

All quantitative climate data obtained from the 28 Tortonian localities are given in Table 2 and Figs. 2–6. On the whole, the data are fairly consistent and show only minor noise. All data for mean annual temperature (MAT) are within the span between 14.3 and 17.75 °C and show a consistent increase from NW to SE (Fig. 2). The low range of MATs of only 4.5 °C indicates a relatively homogenous climate within the studied region.

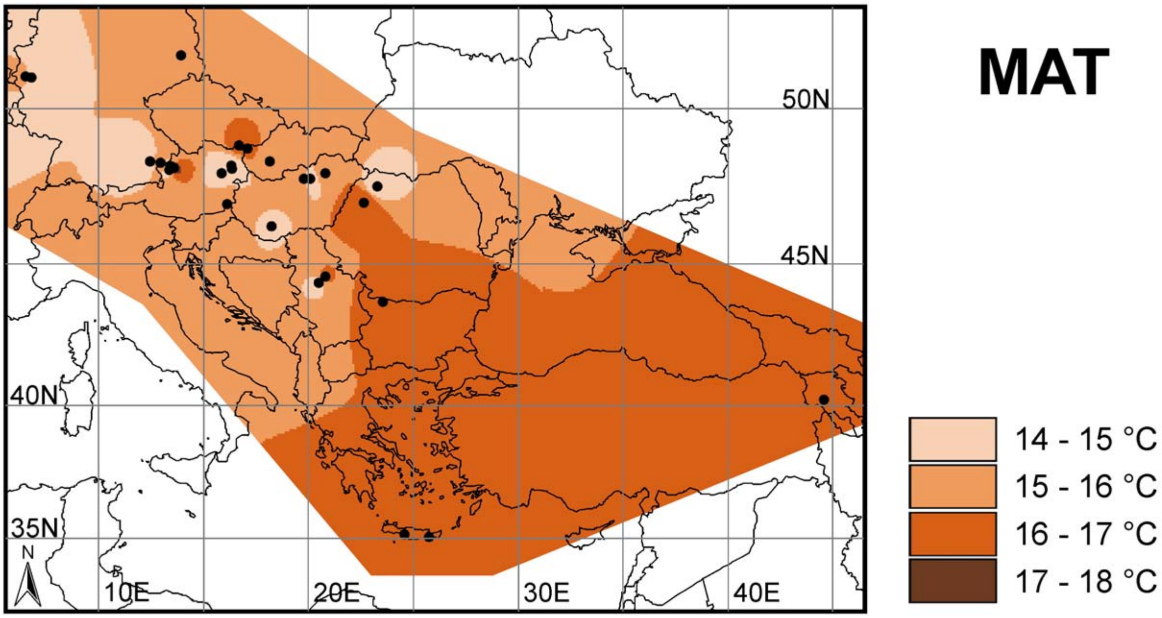

Fig. 2. Map of mean annual temperature reconstruction (middle values of coexistence intervals, IWS interpolated).

Results for summer temperatures (WMT; Fig. 3) show even lower geographic variation. With values between 23.95 and 27.2 °C, they are almost within the range of the resolution of the method. Thus, no significant differentiation of the summer temperature is documented by our data although a slight gradient from NW to SE is indicated as most of the higher values (>26 °C) are situated in the southern part of the region.

Winter temperatures (CMT) are between 2.1 and 8.9 °C (Fig. 4) and show the highest variability of all temperature-related parameters. A basic geographic trend is visible with higher values in the South (Crete) and in the Pannonian Basin. The overall pattern may be

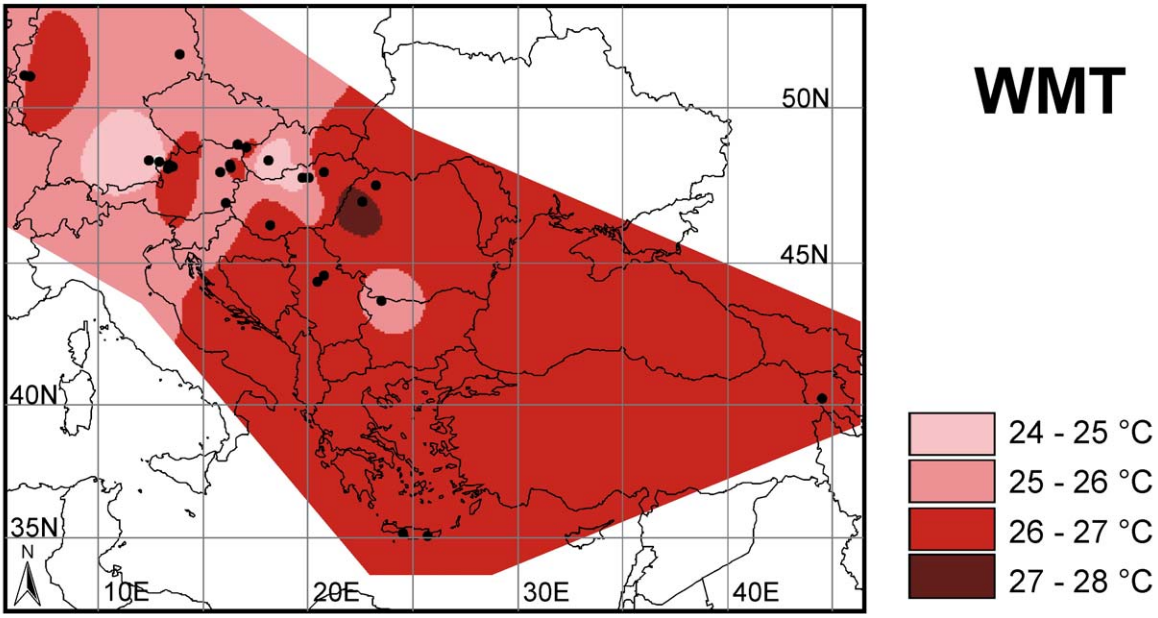

Fig. 3. Map of summer temperature reconstruction (middle values of coexistence intervals, IWS interpolated).

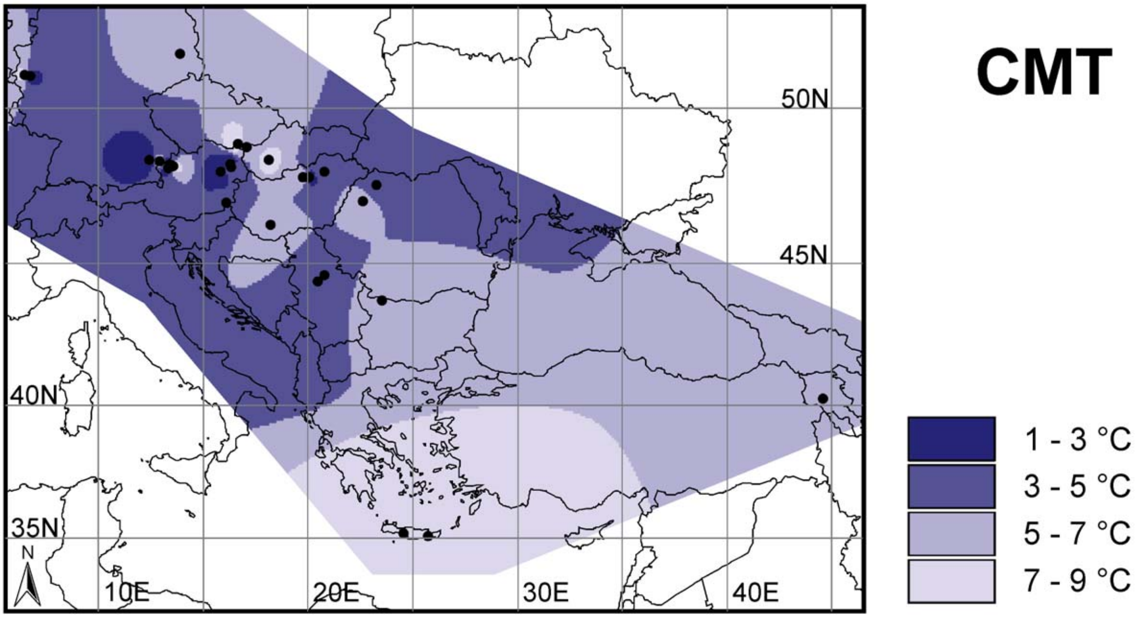

Fig. 4. Map of winter temperature reconstruction (middle values of coexistence intervals, IWS interpolated); note that the legend is in steps of 2 °C.

interpreted as the result of an overlap between N–S and E–W gradients.

The mean annual range of temperature (MART, Fig. 5), calculated as the difference between WMT and CMT, displays similar patterns to CMT, which is obviously due to the geographic homogeneity in WMT. Thus, a comparable picture appears with values varying between 17.75 and 24.45 °C. Lowest seasonalities of temperature occur in the Pannonian Basin and in the south, which clearly corresponds to the pattern observed in CMT.

Mean annual precipitation (MAP) data range between 747 and 1293 mm (Fig. 6). Except for one data

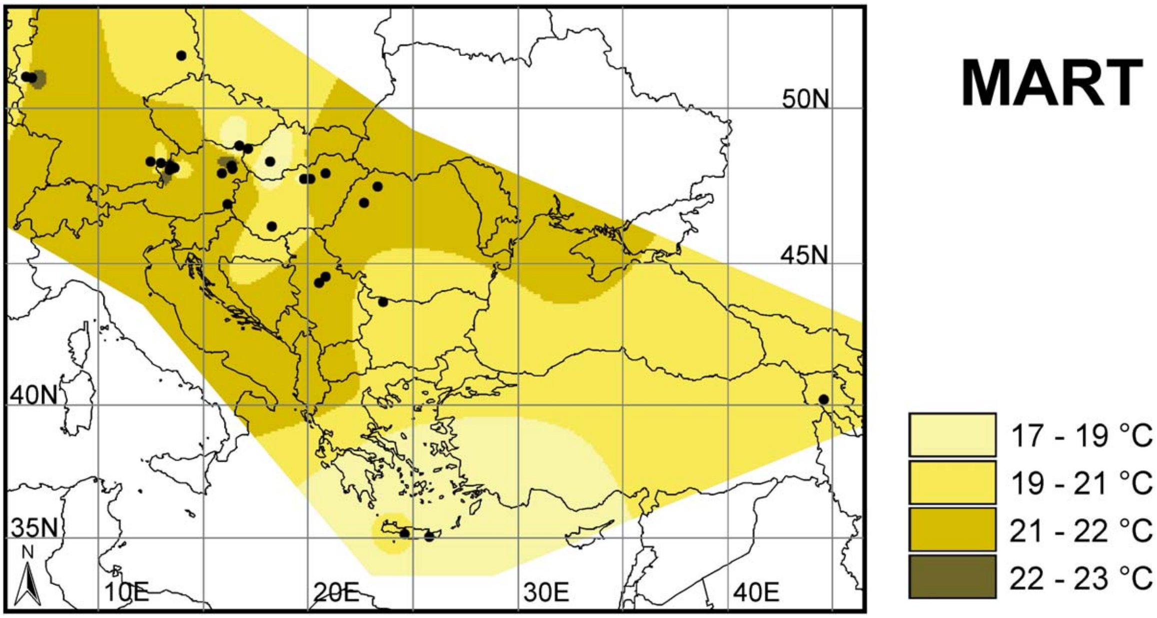

Fig. 5. Map of mean annual range of temperature reconstruction (difference between WMT and CMT middle values, IWS interpolated); note that the legend is in steps of 2 °C.

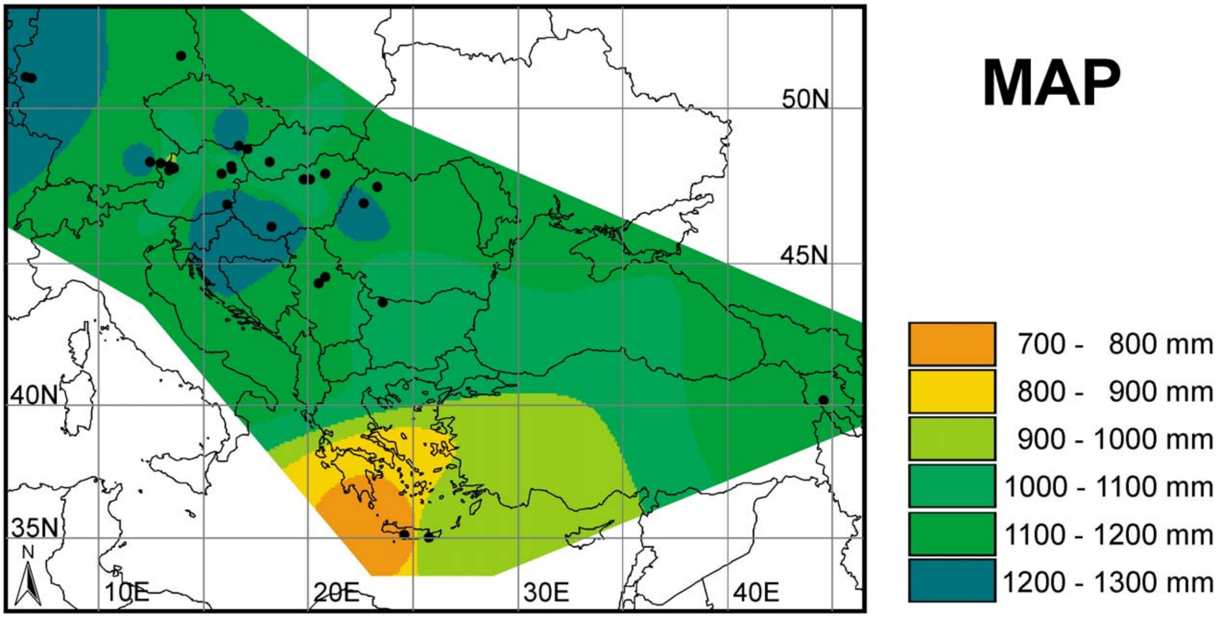

Fig. 6. Map of mean annual precipitation reconstruction (middle values of coexistence intervals, IWS interpolated).

point from Crete, all values are above 900 mm, representing humid conditions with a very low differentiation all over Europe; nevertheless, there is a tendency towards lower precipitation in the south.

Overall, the obtained data are in a relatively narrow range and document a warm and humid climate over all of Central and Southern Europe. Nevertheless, regional differentiations are visible in the climate maps allowing for an interpretation of patterns and gradients.

5. Discussion

The data presented in this study cover a distance from north to south of about 2200 km and from east to west of about 3500 km, with a total area of about 3 million km^2. Due to the fact that the analysis is based on only 28 data points, interpretation has to be carried out with caution and must be restricted to large scale patterns. As stated above, areas outside of the data cover (e.g. Turkey) have to be excluded from interpretations.

Our climate data show a high degree of regional consistency with only minor noise, which indicates that the quality of the data base (i.e. stratigraphy, floral lists) and of the method used for palaeoclimate reconstructions (i.e. the Coexistence Approach) is relatively good. Nevertheless, some climatic discrepancies occur between nearby localities. They can reflect errors in the database (stratigraphy, floral list) or in the method of climate reconstructions, but they may also be caused by real local climatic differentiations or by microclimate effects. In this context it is important to note that even within the recent data set, similar small-scale climatic variations occur. In any case, small-scale climatic variations in our data set should not be overestimated in the analysis of regional climate patterns.

All in all, our quantitative climate data document a largely homogenous, warm and humid climate over the whole study area with only poorly developed longitudinal and latitudinal gradients; in particular for precipitation. This is consistent with previous qualitative investigations (cf. Mai, 1995 and references therein) since all our climate data fit within the Cfa climate of Koeppen's classification. Of particular interest is the high Tortonian precipitation throughout the study area; thus, the climate maps give no indication of a Mediterranean-type climate or of climatic conditions suitable for the establishment of grasslands during the Tortonian. This is in agreement with Suc (1984) and Suc et al. (1995), who stated a Mediterranean climate, only became established during the Pliocene. On the other hand, Suc and Bessais (1990) and Bertini et al. (1998) determine dry, xeric conditions already in the late Tortonian and Messinian in Sicily. However, this cannot be testified with our data.

In addition to these general observations, the climate maps provide a more detailed picture of spatial climate patterns. Low, but visible, differentiations occur which may represent N to S latitudinal and E to W longitudinal climate gradients. For instance, all temperature related climate parameters show warmer values in the south than in the north, as expected. Thereby, the N to S gradient of MAT in the Tortonian is much weaker, about 50% of that of today, thus indicating that the Neogene cooling must have been more pronounced in higher than in lower latitudes. Moreover, the cooling from Tortonian to today was obviously more pronounced in winter than in summer leading to the increased seasonality of temperature which we observe today; the same phenomenon has been observed by Utescher et al. (2000) in their analysis of the Neogene cooling in NW Germany.

A somewhat different pattern appears for the precipitation. Although Tortonian mean annual precipitation data are higher than today and quite homogenous throughout the study area, the north seems to be slightly more humid than the south; again this overall trend is much lower than today. Obviously, the post-Tortonian Neogene cooling trend was linked with a decrease in precipitation (also observed by Utescher et al., 2000), which, however, was more intense in lower latitudes finally leading to today's Mediterranean climate. In this context, it has to be mentioned that the annual oscillation of precipitation may be an even more important parameter for the characterisation of climate and crucial for vegetation. The reconstruction of this parameter has to be a central component of future reconstructions.

Moreover, it is important to note that our precipitation data do not show significant orographic effects. Today, the geometry of mountain ranges causes higher (convective) precipitation around the Alps, Carpathians and the Caucasus. No such effect is seen in our precipitation map, although the Alpine mountain chain had a high mountainous relief (Spiegel et al., 2001) with altitudes possibly up to 3000 m in the Swiss and Western Alps since the Early Miocene and a mountainous relief in the eastern part of the Eastern Alps since the Late Miocene (Frisch et al., 1999). Obviously, the Tortonian mountain chains in Europe did not act as a significant climatic barrier (as they do today) and possibly orographic rainfall was less intense in the warm and humid Tortonian climate. On the other hand, minor orographic effects may be hidden within the resolution of our precipitation data and data cover is indeed still scarce in sensitive areas.

As compared to the latitudinal gradients, E–W oriented longitudinal trends are less clear in our Tortonian climate maps. Whereas MAT and WMT show slightly warmer values in the east, gradients within the other parameters are below resolution. However, longitudinal trends might not be well established in our data because of the distribution of investigated localities. Every comparison from west to east contains a latitudinal component that can be avoided in the future only by a larger database.

Nevertheless, our Tortonian data show a clear difference from the recent situation which is characterised by very hot summers and cold winters in the eastern part of the investigated area. Obviously, the present-day continental climate of Eastern Europe with high seasonality of temperature was not yet developed in the Tortonian. Presumably, this homogeneity in Tortonian climate from E to W was caused by the climatic buffering effect of the Paratethys water body that still occupied large areas of the Pannonian basin during the Late Miocene (cf. Fig. 1; Steininger et al., 1985; Rögl, 1999). The CMTs in particular show this Paratethys effect with slightly higher winter temperatures in the Pannonian Basin as compared to surrounding localities. Because of the very homogenous summer temperatures in the entire region, the map of MART illustrates a similar pattern with moderate seasonality of temperature and reduced continental climatic conditions in the Pannonian Basin.

Our paper is a first attempt to reconstruct spatial climate patterns for the Tortonian using a quantitative approach. The database is far from ideal and needs improvement although the eastern Alpine area is already relatively well covered by localities. Consistently, our results indicate a relatively homogenous, warm and humid climate with very low latitudinal and longitudinal gradients that are locally influenced by the Pannonian Lake; in contrast, an orographic rainfall effect in the alpine mountain chains is not observed. The climatic cooling from the Tortonian to today was highest in higher latitudes, whereas the decrease in humidity mainly took place in lower latitudes, namely in the Mediterranean region.

Acknowledgements

The authors like to thank all colleagues and NECLIME members for providing publications and published flora lists for this work. J. Nebelsick helped to improve the English. We also are grateful to M. Fortelius and Z. Kvacek for their supportive reviews and comments. This work is a contribution to the projects "*Neogene Climate Evolution in Eurasia—*NECLIME" and ESF program "Environments and Ecosystem Dynamics of the Eurasian Neogene (EEDEN)".

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