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Present-day climatic equivalents of European Cenozoic climates

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A B S T R A C T

Recently, continental climate evolution in Central Europe over the last 45 Ma has been reconstructed from the palaeobotanical record using a Nearest Living Relative methodology (Coexistence Approach; CA). The reconstructed climate curves document in detail the transition from almost tropical conditions in the Mid-Eocene to a temperate climate at the Pliocene/Pleistocene transition. The observed climatic shifts are primarily expressed as non-proportional changes of the different variables taken into account. In the present study a published palaeoclimate data set for a total of 42 macrofloras complemented by new calculations is used as base to analyse the climatic space in which a fossil flora existed. To define these spaces CA intervals calculated for 3 temperature (mean annual temperature, cold and warm month mean) and 3 precipitation variables (mean annual precipitation, mean monthly precipitation of the driest and of the wettest month) are combined. Using a global gridded climatology (10' resolution), this climate space is then utilized to identify Recent climate analogues with respect to the variables regarded. For 18 macrofloras climatic analogue regions with respect to 6 variables are identified on the globe. For 16 macrofloras, analogues exist when three temperature parameters and mean annual precipitation are regarded. No Recent equivalents are found in 8 cases. This corroborates the assumption of the temporary existence of non-analogue climates in the Cenozoic. As shown by multivariate statistics the observed anomalies with respect to present-day conditions basically refer to high winter temperatures.

Deploying a GIS, the Recent climate analogues can be presented as sets of grid cells for each flora that can be mapped on a globe. Once identified, these regions can be merged with adequate thematic layers to assess additional proxy data for the palaeofloras. To exemplify the procedure Koeppen climate type, numbers of days with ground frost, as well as Matthews biome classes are reconstructed. The resulting Koeppen types, ranging from A to C, are largely consistent with data previously published. The ground frost record shows almost frost-free conditions for the Mid-Eocene greenhouse and for the Mid-Miocene Climatic Optimum. For the Chattian, up to 7 days with ground frost result. During the Late Miocene Cooling the number of days with ground frost significantly increased. The inferred Matthews biomes reveal changing patterns of evergreen and deciduous forest cover.

When Recent climate analogues are found for a fossil flora, present climate can be used to calibrate the original CA data. It is shown that calibration considerably improves the resolution of the continental climate records.

1. Introduction

Recently, continental climate records over the last 45 Ma have been reconstructed from the macrofloral record of Central and Northwest Europe (Mosbrugger et al., 2005). The technique applied is the Coexistence Approach (CA; Mosbrugger and Utescher, 1997), a quantitative method for calculation of various climate variables. This approach has proven a useful tool for quantitative palaeoclimate analysis in the Cenozoic (e.g., Uhl et al., 2003; Roth-Nebelsick et al., 2004; Bruch et al., 2007; Bozukov et al., 2009). The temperature records obtained reveal continental cooling from almost tropical conditions in the middle Eocene to temperate climate at the Pliocene/Pleistocene transition. Major global climatic events known from marine data archives (e.g., Zachos et al., 2001; Zachos et al., 2005) such as the Late Eocene Cooling and the Mid-Miocene Climatic Optimum are mirrored in the terrestrial curves. It was also shown that climate variability reflects non-proportional changes of different variables. The most prominent changes are observed in winter temperatures, while summer temperatures and mean annual

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precipitation stayed more or less stable until the Pliocene. In Central and Northwest Europe, cooling during the Late Miocene is connected to an increase in seasonality of climate.

Although these records document detailed time series, there is evidence from palaeoclimate studies of various Cenozoic time slices that spatial climate patterns could considerably differ from today (e.g., Bruch et al., 2004; 2006). Also, model studies carried out for various Cenozoic scenarios do not fully explain the observed proxy-data based patterns (e.g., Steppuhn et al., 2009; Micheels et al., 2007). Thus, many aspects of the functioning of the climate system in the Cenozoic are not well understood.

The CA provides quantitative data for basic climate parameters, such as mean annual temperature, mean temperatures of the coldest and the warmest months as well as annual and monthly precipitation. Each variable is calculated independently using climatic requirements of all Nearest Living Relatives (NLRs) known for a fossil flora (Mosbrugger and Utescher, 1997). Here we use published palaeoclimate data and records for the North German Cenozoic (Utescher et al., 2000; Mosbrugger et al., 2005) complemented by new calculation. We combine 6 basic climate variables to define a climatic space in which the fossil flora existed to address the following questions:

- Are there present-day climate equivalents for the inferred palaeoconditions?
- Can these be used for interpreting Cenozoic climates?
- How usual/unusual are the inferred palaeoclimate conditions in the context of present-day climates and what anomalies are found?
- Can present-day climate equivalents, once identified, be used to calibrate the results obtained from the CA? Are they useful to gain access to additional proxies for a fossil flora?

2. Materials and methods

2.1. Floral record

In the present study, climate data obtained for a total of 42 macrofloras floras are studied. The macrofloras (fruits and seed, leaf floras) originate from the North German Cenozoic (Fig. 1; Table 1) and are the same that have been used to reconstruct the climate records published in Utescher et al. (2000) and Mosbrugger et al. (2005). For further details on the floras and the complete set of palaeoclimate data the reader is referred to the above publications. For 23 of the floras additional precipitation data had to be calculated. The complete palaeoclimate data sets for the floras are given in the supplementary online materials (1), together with the new results obtained in this study.

2.2. Definition of the climatic space — identification of present-day equivalents

As stated above all the palaeoclimate data used in the following originate from the application of the Coexistence Approach (CA; Mosbrugger and Utescher, 1997) on the palaeobotanical record. The CA employs climatic requirements of the Nearest Living Relatives (NLRs) of fossil taxa to calculate for a specified climate variable, the intervals in which a maximum number of the NLRs known for the fossil flora may coexist. In the CA procedure, these ranges are identified separately for each climate parameter.

To define the climatic space in which the fossil flora existed, we select six climate parameters frequently employed when describing palaeoclimate conditions, i.e., mean annual temperature (MAT), cold

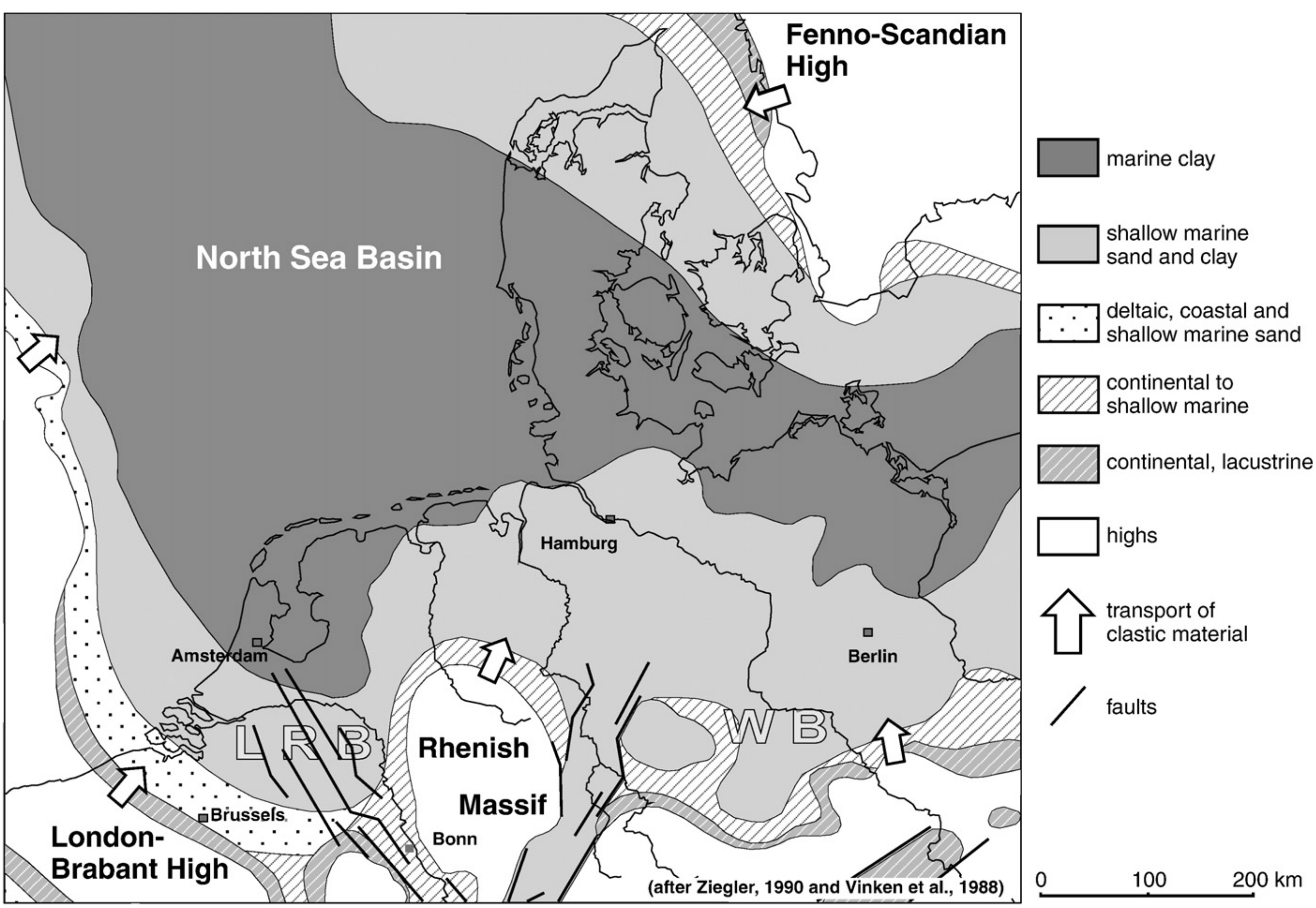

Fig. 1. Palaeogeographical map of North Germany and neighbouring areas showing the Oligocene configuration. Study area: LRB: Lower Rhine Basin; WB: Weisselster Basin.