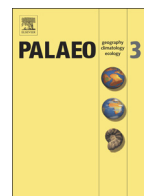




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## Middle Miocene climate and vegetation models and their validation with proxy data

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## ABSTRACT

The Miocene is a relatively recent epoch of the Earth's history with warmer climate than today, particularly during the middle Miocene Climatic Optimum (MMCO, approximately 17–15 Ma). Although the cause of the warming is probably not only attributable to CO<sub>2</sub>, but also to changes in orography and configuration of ocean gateways, this time interval represents an ideal case study to test the ability of climate models to simulate warm climates comparable to those that the Earth may experience in the near future. However, even with higher than present-day CO<sub>2</sub> concentrations, the MMCO warming inferred from terrestrial proxy data has been difficult to reproduce in climate models.

Since fossil flora do not provide direct information on climate, but on flora and vegetation, climate model results are generally compared to climate reconstructions obtained from the fossil flora. In this study, we apply an alternative method by simulating palaeovegetation from the outputs of the climate model, using a dynamic vegetation model. Model vegetation reconstruction can then be compared to the vegetation cover indicated by the fossil flora record at the various localities, provided that a common classification of plant functional types (PFTs) is used for the data and the model. Here, we reconstruct the vegetation of the middle Miocene with the global dynamic vegetation model CARAIB, using the climatologies derived from five atmospheric general circulation models. The reliability of the simulations is examined on a presence/absence basis of PFTs by comparison of vegetation reconstructions to palaeoflora data recorded in the Northern Hemisphere and the Tropics.

This comparison provides an overall agreement around 60% between model and data, when all sites and tree types are considered. Three model simulations out of five show to be better at predicting the absence than the presence. The presence of warm-temperate mixed forests in the middle latitudes, dominated by broadleaved deciduous warm temperate and subtropical trees is generally well reproduced in CARAIB simulations. However, poor agreement is obtained for the presence of tropical PFTs out of the Tropics and for warm PFTs at latitudes northward of 50°N, where climate models remain too cold to produce assemblages of trees consistent with the data. Nevertheless, the model–data comparison performed here highlights several mismatches that could result not only from missing feedbacks in the climate simulations, but also from the data. The results of the likelihood analysis on presence/absence of PFTs illustrate the uncertainties in the PFT classification of the Neogene floral records. The coexistence of some PFTs in the palaeovegetation data is impossible to reproduce in the vegetation model simulations because of the climatic definition of the modern PFTs. This result indicates either a bias in the identification of modern analogues for fossil plant taxa, or a possible evolution of environmental requirements of certain plants.

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## 1. Introduction

In a long-term climatic cooling trend, the middle Miocene represents one of the last warm periods of the Neogene. Terrestrial and marine

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proxy data provide clear indications of globally warm conditions during the middle Miocene Climatic Optimum, MMCO, approximately 17–14.5 Ma BP (Mosbrugger et al., 2005; Bruch et al., 2007; Utescher et al., 2011b; Bruch et al., 2011; Zachos et al., 2008; Shevenell et al., 2008). Deep-sea benthic foraminiferal oxygen-isotopes indicate that temperatures were significantly warmer in the deep ocean and at mid- to high latitudes (Zachos et al., 2008; Shevenell et al., 2008). Later revaluations of tropical sea surface temperature (SST) reconstructions in the Miocene show that SSTs were also well above modern (You et al., 2009; LaRiviere et al., 2012). Palaeobotanical records suggest a strong warming on the continents at mid- and high latitudes, with temperature anomalies ranging between +10 °C and +20 °C in Central and East Asia (Utescher et al., 2011b), a weak equator-to-pole latitudinal temperature gradient (Bruch et al., 2007), and very humid conditions without significant seasonality patterns (Bruch et al., 2011).

Global and regional palaeovegetation studies demonstrate that warm and dense forests were widely distributed in the middle Miocene (Wolfe, 1985; Utescher et al., 2011b; Pound et al., 2012). Palaeovegetation data support the presence of cool-temperate mixed forests in the high-northern latitudes (White et al., 1997), (Pound et al., 2012), warm-temperate mixed forests in mid-latitudes (Utescher et al., 2007b; Utescher et al., 2011b; Retallack, 2007), and even tundra and shrubs in Antarctica (Lewis et al., 2008).

Up to now, several climate simulations and sensitivity studies using general circulation models have been conducted for the middle Miocene, in order to investigate climate mechanisms responsible for the warmer climate at the MMCO (e.g., (Tong et al., 2009; Herold et al., 2010; Henrot et al., 2010; Krapp and Jungclaus, 2011; Hamon et al., 2012; Goldner et al., 2014). Most of them focused on the effect of varying the atmospheric carbon dioxide (CO<sub>2</sub>) concentration (You et al., 2009; Tong et al., 2009; Henrot et al., 2010; Krapp and Jungclaus, 2011; Hamon et al., 2012), as a consequence of the large uncertainties on the actual marine and terrestrial proxy based reconstructions of atmospheric pCO<sub>2</sub> (Pagani et al., 2010; Pearson and Palmer, 2000; Kürschner et al., 2008; Retallack, 2009). However, the latest estimates based on boron isotopes and alkenones agree upon elevated values reaching 500 ppmv during the MMCO (Foster et al., 2012; Zhang et al., 2013; Greenop et al., 2014), matching the values of 300 to 600 ppmv inferred from the reconstructions based on stomatal indices and pedogenic carbonates (Kürschner et al., 2008; Retallack, 2009).

Other mechanisms, such as the reconfiguration of inter-oceanic passages (Bice et al., 2000; Von der Heydt and Dijkstra, 2008, Krapp and Jungclaus, 2011, Zhang et al., 2011; Herold et al., 2012; Hamon et al., 2012; Sepulchre et al., 2014), and the lowering of the topography on land (Herold et al., 2009; Henrot et al., 2010), (Krapp and Jungclaus, 2015) have also been studied. Furthermore, continental cover changes, such as vegetation changes (Henrot et al., 2010; Krapp and Jungclaus, 2011) and a reduction (Hamon et al., 2012; Goldner et al., 2014) or growth (Knorr and Lohmann, 2014) of the Antarctic Ice Sheet (AIS) have been investigated. However, even with higher CO<sub>2</sub> concentrations, the MMCO warming inferred from proxy data has been difficult to reproduce in models (Goldner et al., 2014). It appears that GCMs are either not sensitive enough to CO<sub>2</sub> and palaeogeographic changes, or that there are additional missing forcings and feedbacks to simulate the MMCO warmth (e.g., vegetation and soil feedbacks, climate-ice sheet interactions...). Model-data comparisons based on SSTs and terrestrial temperature reconstructions from palaeovegetation data pointed out that the models tend to underestimate mean annual temperatures in temperate and boreal regions and to overestimate the equator-to-pole temperature gradient compared to proxy-derived estimates (Herold et al., 2010; Pound et al., 2012; Goldner et al., 2014).

The aim of this study is to reconstruct vegetation from middle Miocene climate model simulations and to evaluate the reconstructions of MMCO climate by comparison to palaeoflora records at various locations, using the method of François et al. (2011). The NECLIME (Neogene Climate Evolution in Eurasia) database compiles data of the

fossil flora retrieved from many locations worldwide, at different times of the Miocene (Utescher et al., 2011a). These fossil flora do not provide direct information on climate, but on vegetation. Hence, it is necessary to reconstruct palaeoclimate from the fossil flora before being able to compare these data with climate model results. This has classically been based upon the so-called Coexistence Approach (Mosbrugger and Utescher, 1997) or the Climate Leaf Analysis Multivariate Program (CLAMP) (Wolfe, 1979; Spicer et al., 2009). François et al. (2011) presented an alternative method, where palaeovegetation is derived from the outputs of the climate model, by the means of a dynamic vegetation model. The model derived vegetation distribution is then compared to the vegetation cover documented by the fossil flora, provided that a common classification of plant functional types (PFTs) is used for the data and the model. Forrest et al. (2015) adopted a similar approach based on the relative dominance of different PFTs in the palaeobotanical data to provide quantitative estimates of model-data agreement for the late Miocene. The advantage of PFT-based methods (François et al., 2011; Forrest et al., 2015) is that, at least in theory, they allow to take into account non-climatic factors that can potentially influence plant species distributions, such as atmospheric CO<sub>2</sub>, soil types or seed dispersal capacities. Moreover, the method applied here is applicable both to macro-flora and pollen data, and allows for a location-wise adjustment of proxy data-based vegetation reconstruction and quality control of modelled data. Contrary to previous model-data comparisons (Salzmann et al., 2008; Pound et al., 2012), PFT-based approaches are not based on the biome concept, which is not a directly observable characteristic of vegetation and whose classification requires subjective choices and involves the use of many ecosystem parameters that are not available in the palaeoflora (Forrest et al., 2015; François et al., 2011). This is especially important for Miocene floras for which the information is sparser and less precise than for Pleistocene and Holocene plant assemblages.

In this study, we compare the vegetation reconstructions of the CARAIB dynamic vegetation model, forced with the climatology of five GCMs of different resolution and complexity, to palaeovegetation data from a series of 139 sites, mainly located in the Northern Hemisphere and in the Tropics.

## 2. The CARAIB model

### 2.1. General description

The CARAIB model (CARbon Assimilation In the Biosphere) is a global dynamic vegetation model (Warnant et al., 1994; Otto et al., 2002), Laurent et al., 2008; Dury et al., 2011). It has been widely used to study the role of vegetation in the global carbon cycle and to simulate vegetation distributions at present and future (Warnant et al., 1994; Nemry et al., 1996; Gérard et al., 1999; Dury et al., 2011), and in the past (François et al., 1998; François et al., 1999; François et al., 2006; François et al., 2011; Otto et al., 2002; Henrot et al., 2010). It is made up of five modules respectively describing (1) the hydrological budget, (2) canopy photosynthesis and stomatal regulation, (3) carbon allocation and plant growth, (4) heterotrophic respiration and litter/soil carbon dynamics, and (5) plant competition and biogeography.

The model takes into account a set of herbaceous and arboreal plant functional types (PFTs), which can coexist on the same grid cell. For each of these PFTs, the model calculates the temporal evolution of two carbon reservoirs in the plant (metabolic and structural carbon) and three in the soil (metabolic and structural litter, soil organic carbon). The model time step is one day for updating all water and carbon reservoirs. For photosynthesis and plant respiration a shorter time step of two hours is used, allowing us to take into account non-linear effects associated with the variation of photosynthetic/respiration fluxes over the day. Vegetation cover is updated once a month for herbs and once a year for shrubs and trees. Spatially, the CARAIB model is a grid-point model, and it can be used with different spatial resolutions, ranging for example

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