The past is a guide to the future? Comparing Middle Pliocene vegetation with predicted biome distributions for the twenty-first century

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During the Middle Pliocene, the Earth experienced greater global warmth compared with today, coupled with higher atmospheric CO₂ concentrations. To determine the extent to which the Middle Pliocene can be used as a ‘test bed’ for future warming, we compare data and model-based Middle Pliocene vegetation with simulated global biome distributions for the mid- and late twenty-first century. The best agreement is found when a Middle Pliocene biome reconstruction is compared with a future scenario using 560 ppmv atmospheric CO₂. In accordance with palaeobotanical data, all model simulations indicate a generally warmer and wetter climate, resulting in a northward shift of the taiga–tundra boundary and a spread of tropical savannahs and woodland in Africa and Australia at the expense of deserts. Our data–model comparison reveals differences in the distribution of polar vegetation, which indicate that the high latitudes during the Middle Pliocene were still warmer than its predicted modern analogue by several degrees. However, our future scenarios do not consider multipliers associated with ‘long-term’ climate sensitivity. Changes in global temperature, and thus biome distributions, at higher atmospheric CO₂ levels will not have reached an equilibrium state (as is the case for the Middle Pliocene) by the end of this century.

Keywords: climate change; vegetation; Pliocene; palaeobotany; general circulation model

1. Introduction

Since the industrial revolution, the continuous burning of fossil fuel has rapidly changed the carbon dioxide concentration of the atmosphere increasing from 280 ppmv in pre-industrial time to a modern level of approximately 380 ppmv. According to multi-model simulations published in the latest report of the Intergovernmental Panel on Climate Change (IPCC 2007), the average annual...
global mean surface temperature response to a doubling of atmospheric CO₂ from pre-industrial values will be an increase of approximately 3°C. With continued anthropogenic CO₂ emissions at or above current rates, a doubled atmospheric CO₂ concentration will be reached in less than 90 years. Higher temperatures and carbon dioxide concentrations change the structure and functioning of terrestrial ecosystems, which themselves have a considerable influence on fluxes of energy, water vapour, greenhouse gases and the global carbon cycle. One of the most prominent changes in vegetation distribution identified by modelling exercises under higher atmospheric CO₂ concentrations is a northward shift of taiga forests with much reduced tundra shrub vegetation and a rapid dieback of the Amazon rainforest (e.g. Cox et al. 2000; Cramer et al. 2001, 2004; Kaplan et al. 2003; Haywood & Valdes 2006; Salzmann et al. 2008).

An inherent drawback of future environmental scenarios and model predictions is that they cannot be tested by observational data. However, by looking at geological analogues, we can use past environments as a guide for the understanding of future climate change and a test of the validity of climate models. The Middle Pliocene geological stage, ca 3.6–2.6 Myr ago, is a potential geological analogue as it represents the last interval of time in which the Earth experienced greater global warmth with climate conditions similar to those predicted for the end of the twenty-first century (e.g. Thompson & Fleming 1996; Zachos et al. 2001). During that period, CO₂ values are estimated to have reached 360–440 ppmv (e.g. Raymo et al. 1996) and global mean annual temperatures (MATs) were approximately 3°C higher than today (Chandler et al. 1994; Sloan et al. 1996; Haywood et al. 2000). Many climatic boundary conditions such as the position of continents, fauna and flora or ocean bathymetry were the same as or very similar to the present day, which makes the Middle Pliocene an unparalleled palaeo-laboratory for testing the sensitivity of models that we rely upon for simulating future climate change (Crowley 1996; Dowsett 2006).

Here, we compare global Middle Pliocene biome distributions reconstructed from palaeobotanical data and palaeoclimate model simulations with three new model predictions of equilibrium vegetation conditions for the pre-industrial, early and end of the twenty-first century, with atmospheric CO₂ concentrations of 280, 400 and 560 ppmv, respectively. The use of the BIOME4 model enables us to directly compare vegetation predictions using climatologies from our Middle Pliocene coupled ocean–atmosphere general circulation model (AOGCM) with a Middle Pliocene vegetation reconstruction synthesized from 202 palaeobotanical sites (Salzmann et al. 2008). The data–model comparison also allows us to identify regions for which uncertainties in model physics may cause discrepancies in the reconstruction of past vegetation, which will potentially also affect future model predictions. By applying a qualitative and quantitative data–model comparison approach, this paper contributes to a better understanding of the past and future impact of increased CO₂ on vegetation and climate.

2. Methods

(a) Palaeobotanical data

For data acquisition and data–model comparison, we have used a relational GIS database called Tertiary Environments and Vegetation Information System (TEVIS) on a Microsoft Access and ArcGIS9 platform (Salzmann et al. 2008).
TEVIS integrates previously published marine and terrestrial vegetation data derived from fossil pollen, leaves, wood and palaeosol carbonate into an internally consistent 28-type land-cover classification scheme, equivalent to the vegetation model BIOME4 (Kaplan 2001; figure 1). For our data–model comparison, we have chosen a set of 202 palaeobotanical records, which cover the time period from ca 3.6 to 2.6 Ma, corresponding to the Piacenzian geological stage (Castradori et al. 1998). The Pliocene dataset used in this study and the full reference for each palaeobotanical site including biome codes are available online as electronic supplementary material (appendices S1 and S2).

(b) The coupled ocean–atmosphere general circulation model HadCM3

For our climate model experiments, we employed the coupled climate model HadCM3, which was developed at the Hadley Centre for Climate Prediction and Research and comprises a coupled atmospheric model, ocean model and sea-ice model (Gordon et al. 2000). The atmospheric model consists of 19 layers and has a horizontal resolution of 2.5° in latitude by 3.75° in longitude. The spatial resolution of the ocean model is 1.25°×1.25° with 20 layers in the vertical. The atmospheric model has a time step of 30 min and includes a radiation scheme that can represent the effects of minor trace gases (Edwards & Slingo 1996). A parametrization of simple background aerosol climatology is also included (Cusack et al. 1998). The convection scheme used is that of Gregory et al. (1997). A land surface scheme includes the representation of the freezing and melting of soil moisture. The representation of evaporation includes the dependence of stomatal resistance on temperature, vapour pressure and CO2 concentration (Cox et al. 1999). The ocean model uses the Gent–McWilliams mixing scheme (Gent & McWilliams 1990). There is no explicit horizontal tracer diffusion in the model. The horizontal resolution allows the use of a smaller coefficient of horizontal momentum viscosity leading to an improved simulation of ocean velocities. The sea-ice model uses a simple thermodynamic scheme and contains parametrizations of ice concentration, ice drift and leads (Cattle & Crossley 1995). The model requires no surface energy or moisture flux corrections to be made, even for simulations of a thousand years or more (Gregory & Mitchell 1997).

(c) BIOME4 vegetation model

To predict global patterns in vegetation physiognomy under the different climates simulated by our GCM experiments, the mechanistically based vegetation model BIOME4 was employed (Prentice et al. 1992; Kaplan 2001). BIOME4 was developed from physiological constraints influencing the distribution of different plant functional types (e.g. cool conifer forest, tropical grassland). Primary constraints include the mean temperatures of the coldest months, the number of growing degree days (GDDs) above 5°C and a coefficient (Priestley–Taylor coefficient) for the extent to which soil moisture supply satisfies atmospheric moisture demand. GDDs are calculated by linear interpolation between mid-months and by a one-layer soil moisture balance model (Prentice et al. 1992, 1993). To force the vegetation model, we used a standard anomaly method as employed in several Quaternary and modern simulations (e.g. Haxeltine & Prentice 1996; Texier et al. 1997), whereby a correction factor derived from the GCM systematic error relative to present-day
observations is applied. Owing to the lack of sufficient observational data, the anomaly method could not be employed for Antarctica, and here we used the absolute GCM climate to force BIOME4.

(d) Experimental design and quantitative data–model comparisons

Four model experiments have been carried out with atmospheric CO$_2$ concentrations representing climates at different geological periods (figure 2). The simulations are as follows.

Figure 1. Middle Pliocene palaeobotanical sites and biomes used for the data–model comparisons (for full reference to palaeo-sites see appendices S1 and S2 in the electronic supplementary material or www.antarctica.ac.uk/bas_research/data/access/tevis/). Biomes were grouped into mega-biome categories (see headings in bold), modified from Harrison & Prentice (2003).
Figure 2. Four BIOME4 model experiments including (a) pre-industrial with CO$_2$ concentrations of 280 ppmv, (b) Middle Pliocene with 400 ppmv CO$_2$, (c) future scenario A with 400 ppmv CO$_2$ and (d) future scenario B with 560 ppmv CO$_2$. Refer to figure 1 for biome colour codes.
(i) Pre-industrial experiment with a mid-nineteenth century level of 280 ppmv CO₂.

(ii) Middle Pliocene simulation with an atmospheric CO₂ concentration of 400 ppmv, which is an estimate supported by proxy evidence (e.g. Raymo et al. 1996).

(iii) Future scenario A with 400 ppmv atmospheric CO₂, representing early to mid-twenty-first century conditions.

(iv) Future scenario B with 560 ppmv atmospheric CO₂ concentration and thus double the pre-industrial level, representing mid- to late twenty-first century conditions.

Both the pre-industrial and future scenario model experiments use pre-industrial boundary conditions with ice sheets over Antarctica and Greenland fixed to their modern extent. This is justifiable given the slow response time of the ice sheets to future global warming (IPCC 2007). The Middle Pliocene run was initialized with the PRISM2 dataset for sea surface temperatures (SSTs) and sea-ice distributions supplied by the US Geological Survey’s (USGS) Pliocene Research, Interpretation and Synoptic Mapping (PRISM) Project (Dowsett et al. 1999; Dowsett 2006). The PRISM boundary conditions included in our GCM are (i) modified present-day orography, (ii) reduced Greenland and Antarctic ice-sheet size and height, and (iii) Middle Pliocene vegetation distribution. A full model description of the Mid-Pliocene HadCM3 model can be found in Haywood & Valdes (2004).

A simple linear regression was used to compare published numerical estimates for temperature derived from palaeobotanical data and model simulations (figure 3). A full list of the 59 temperature estimates taken from the literature is provided in Salzmann et al. (2008). The global biome maps were compared numerically by employing the ArcView 3.x extension for the kappa statistic (Jenness & Wynne 2005). The kappa statistic measures the degree of agreement between predicted and observed categorizations of a dataset or map, while correcting for agreement that occurs by chance (Cohen 1960). This method has already been successfully applied for comparing biome maps (Prentice et al. 1992; Harrison et al. 1998). The kappa values (κ) are ranked using a subjective assessment scale between 0 and 1, whereby ‘0’ means that the agreement is no better than would be expected by chance and ‘1’ stands for a perfect match. Monserud & Leemans (1992) suggested that values below 0.4 be considered poor or very poor, 0.4–0.55 fair, 0.55–0.77 good and above 0.7 very good or excellent. However, the kappa results strongly depend on the number of different classes selected and are rarely comparable across studies. Therefore, here, we interpret our kappa values in isolation from previous studies (e.g. Harrison et al. 1998).

For comparing biome reconstructions from fossil data with model simulations, we grouped the 28 biomes into broader units (mega-biomes) to avoid the minimum number of sample points per category becoming too low for a meaningful kappa statistic. The mega-biome categories follow the grouping described in Harrison & Prentice (2003), with the exception of warm-temperate forest and steppe-tundra biomes, which we assigned to temperate forest and tundra mega-biomes, respectively. The seven mega-biome groups to which we assigned the 28 biomes are tropical forest, savannah and dry woodland, grassland and dry shrubland, desert, temperate forest, boreal forest and tundra (figure 1).
3. Results

(a) Major patterns of global Middle Pliocene biome distribution

In this section, we describe major changes of global vegetation distribution during the Middle Pliocene (figure 2b) compared with pre-industrial (figure 2a). The differences in the HadCM3 climatologies that force the BIOME4 model simulations are shown in figure 4. A comparison between palaeobotanical data and model reconstructions is used to validate the Pliocene model outcome and to identify uncertainties in model physics. Both vegetation reconstructions provided by 202 data points (figure 1) and the HadCM3/BIOME4 model (figures 2b and 4a) indicate a Middle Pliocene climate much warmer and wetter than today. The comparison between the model-simulated and data-reconstructed Middle Pliocene biomes indicates a fair agreement with the highest kappa value of all comparisons ($\kappa=0.42$; table 1). A good degree of accordance is also indicated by the linear regression plot showing an $R^2$-value of 0.855 for the relationship among model-simulated and data-reconstructed Middle Pliocene temperatures (figure 3a).

One of the most prominent changes of vegetation distribution during the Middle Pliocene, in comparison with pre-industrial (figure 2a), occurred in the polar and subpolar regions. Both model simulation and data reconstruction indicate that, in many areas, polar tundra vegetation was replaced by taiga forest. The boundary between these biomes was situated approximately 250 km (Siberia) to 2500 km (Canadian Arctic) to the north, indicating a regional increase in MAT of more than 10°C (e.g. De Vernal & Mudie 1989; White et al. 1997; Bennike et al. 2002; sites 50, 13 and 7 in figure 1). In line with a warmer and moister than modern Middle Pliocene climate is a parallel northward expansion of temperate forests in Eurasia and North America. In Europe, highly diverse subtropical and warm-temperate forests with East Asian and North American affinities became dominant containing thermophilous taxa such as Engelhardia, Liquidambar, Gingko and Magnolia (Mai 1995). The data–model comparison reveals that the expansions of these forests, which are well documented by numerous palaeobotanical records, are partly missed by the Middle Pliocene BIOME4 model. Instead, the simulation indicates that Pliocene deciduous temperate forests predominated in most parts of central Europe (figure 2).

The second most prominent difference between the Middle Pliocene and present biome distributions is seen in the tropical and subtropical regions. The HadCM3/BIOME4 model simulates a massive reduction in the Amazon rainforest, which is partly replaced by vegetation, indicating much drier climate condition for northeast and central South America (figures 2b and 4a). By contrast, wetter biome types such as savannah and woodland expanded in Africa and Australia, resulting in shrinking deserts on both continents (figure 2). However, for the tropical regions, the kappa statistic (table 1) identifies no agreement between biome reconstructions from data and modelling outcomes ($\kappa<0.2$). Similar discrepancies occur with all other tested models simulating past and future biomes under different atmospheric CO$_2$ concentrations, which points to general uncertainties in model physics or boundary conditions. The delineation of adjacent tropical woodland–grassland biomes such as savannah, woodland and shrubland is often difficult and might additionally hamper, on

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both the data and model sides, the reconstruction of the correct biome (Salzmann et al. 2008). The data–model comparison further reveals that the model overestimates the desiccation of northeast South America and tends to underestimate the expansion of more humid savannah and woodland at the expense of desert in Africa and Australia. For example, palaeobotanical data indicate that in northwest Africa, prior to 2.6 Ma, tropical forests and mangroves regularly reached the modern southern limit of the Sahara at 21° N (sites 114–115 in figure 1; Leroy & Dupont 1994). More humid conditions also prevailed in the dry interior of central Australia, where, during the Middle Pliocene, savannahs largely replaced modern shrubland and semi-desert vegetation (e.g. Macphail 1997). Both examples from palaeobotanical data point to a higher precipitation/evaporation (P/E) ratio in tropical and subtropical Africa and Australia during the Middle Pliocene than suggested by BIOME4.

Table 1. Kappa degree of agreement between global Middle Pliocene mega-biomes reconstructed from published data and model simulations based on different atmospheric CO₂ forcing.

<table>
<thead>
<tr>
<th>region</th>
<th>pre-industrial (280 ppmv)</th>
<th>Pliocene (400 ppmv)</th>
<th>future scenario A (400 ppmv)</th>
<th>future scenario B (560 ppmv)</th>
</tr>
</thead>
<tbody>
<tr>
<td>global</td>
<td>0.32</td>
<td>0.42</td>
<td>0.36</td>
<td>0.35</td>
</tr>
<tr>
<td>polar and boreal (&gt;60° N/S)</td>
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<td>0.41</td>
<td>0.03</td>
<td>0.35</td>
</tr>
<tr>
<td>temperate (23.5°–60° N/S)</td>
<td>0.15</td>
<td>0.36</td>
<td>0.35</td>
<td>0.34</td>
</tr>
<tr>
<td>tropical (&lt;23.5° N/S)</td>
<td>0.06</td>
<td>0.00</td>
<td>-0.02</td>
<td>0.02</td>
</tr>
</tbody>
</table>

Figure 3. Regression plots for Middle Pliocene temperature reconstructions from palaeobotanical data (n=59) versus model-simulated temperature based on different atmospheric CO₂ forcing for the (a) Middle Pliocene with 400 ppmv (Y = -6.617 + 1.308X, R² = 0.855), (b) future scenario A with 400 ppmv (Y = -10.875 + 1.403X, R² = 0.841) and (c) future scenario B with 560 ppmv (Y = -9.01 + 1.386X, R² = 0.844).

In this section, we test the degree to which the Middle Pliocene vegetation and climate resemble those of a future world under elevated CO₂ levels. We use the kappa statistic to measure the agreement between Middle Pliocene vegetation reconstruction from data and model simulations (table 1), as well as between the Middle Pliocene model reconstruction and future model scenarios (table 2). Our
comparisons also include pre-industrial model outputs, which provide a ‘control’ in representing vegetation distribution under low CO$_2$ levels. A simple linear regression is applied to evaluate similarities between Middle Pliocene numerical climate estimates derived from palaeobotanical data and future model simulations (figure 3$b,c$).

The Middle Pliocene biomes reconstructed from model and data compare favourably with predicted vegetation for the twenty-first century based on different atmospheric CO$_2$ forcing (figure 2). The kappa statistic indicates a fair agreement with model-simulated and data-reconstructed Middle Pliocene biomes (tables 1 and 2). As is the case with the Middle Pliocene, a future world with higher atmospheric CO$_2$ concentrations appears to be generally wetter and warmer than today. However, the kappa statistic indicates a better agreement for the ‘future scenario B’, with a higher atmospheric CO$_2$ concentration of 560 ppmv, than for the ‘future scenario A’, with only 400 ppmv (table 2). The

Figure 4. Differences in mean annual (i) surface air temperature (°C) and (ii) precipitation (mm d$^{-1}$) predicted by the HadCM3 model for (a) Middle Pliocene (400 ppmv CO$_2$) minus pre-industrial (280 ppmv CO$_2$), (b) future scenario A (400 ppmv CO$_2$) minus Middle Pliocene (400 ppmv CO$_2$) and (c) future scenario B (560 ppmv CO$_2$) minus Middle Pliocene (400 ppmv CO$_2$).

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regression coefficient and slope of both linear regressions corroborate the kappa statistic (figure 3b,c). The better agreement with the higher CO$_2$ scenario is mostly due to the differences in the magnitude of vegetation changes in the polar and subpolar regions (tables 1 and 2).

The higher CO$_2$ concentration causes a more pronounced northward shift of boreal forests with much reduced tundra vegetation, which closely resembles the Middle Pliocene biome distribution. In line with this climate and vegetation change is a parallel shift of temperate forest vegetation zones to the north. However, both data–model and model–model comparisons demonstrate that even an increase in atmospheric CO$_2$ to 560 ppmv alone is not enough to produce a temperature rise in the polar regions sufficient to reduce the polar tundra vegetation to the same extent as in the Middle Pliocene (figure 4b,c). According to the future scenario B, large areas of northern Siberia and the northernmost Canadian Arctic will be still cold enough to support the growth of shrub tundra (figure 2d).

In tropical regions, simulated future vegetation changes under higher atmospheric CO$_2$ concentrations also closely resemble those during the Middle Pliocene. Whereas aridity causes a significant reduction of rainforest in the Amazonian basin, a shrinking Sahara and reduced semi-desert vegetation points to much higher P/E ratios in Africa and Australia. BIOME4 also simulates a change towards more moisture-demanding vegetation for the Indian subcontinent and in central North America.

### 4. Discussion

Our data–model comparison supports the hypothesis that the Middle Pliocene geological stage can be used as a ‘test bed’ for future global warming. The vegetation distribution ca 3 Ma ago shows many similarities with a modern ‘world’ simulated under elevated CO$_2$ concentrations. The prediction of a generally warmer late twenty-first century with a far northward-displaced tundra–taiga boundary is consistent across previously published modelling exercises (e.g. Cramer et al. 2001; Kaplan et al. 2003; ACIA 2005; IPCC 2007). However, the differences in the amplitude of the northward shift of boreal forests in our comparison suggest that the Middle Pliocene world at high latitudes was still by several degrees warmer than its predicted future analogue. Additional inconsistencies occur when comparing the Middle Pliocene vegetation reconstruction with model simulations on a more regional scale. This is in particular

<table>
<thead>
<tr>
<th>region</th>
<th>pre-industrial (280 ppmv CO$_2$)</th>
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</tr>
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<tbody>
<tr>
<td>global</td>
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</tr>
<tr>
<td>tropical</td>
<td>0.43</td>
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<td>0.49</td>
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true for subtropical and tropical South America, Africa and Australia, for which the prediction of precipitation changes seems to be a source of uncertainty. The most important factors that complicate the use of Middle Pliocene biome distributions as a simple blueprint for future environmental changes are as follows.

(a) Differences between Middle Pliocene and modern boundary conditions

Our data–model comparison emphasizes the role of CO₂ as an important greenhouse gas, controlling future climate changes. This is in line with previous sensitivity studies, which identified atmospheric CO₂ concentrations as the major force in Northern Hemisphere glaciation (Berger et al. 1999). However, the differences in high-latitude warming between the Pliocene reconstruction and future simulations reveal that even an increase in atmospheric CO₂ concentrations of nearly 50 per cent above the Middle Pliocene level alone is not sufficient to produce a comparable northward shift of boreal forests. Previous modelling exercises by Haywood & Valdes (2004) have shown that a major contributing mechanism to global Pliocene warmth was the reduced extent of high-latitude terrestrial ice sheets (50% reduction on Greenland and 33% reduction on Antarctica), resulting in a strong ice-albedo feedback. Coupled CO₂, ice sheets and vegetation distributions are ‘slow’ feedback mechanisms, which change on a longer time scale and are in our future scenarios fixed to either modern or Middle Pliocene conditions. Therefore, our future scenarios only consider the ‘fast’ feedback mechanisms or the so-called ‘Charney climate sensitivity’ (Charney 1979), such as water vapour, clouds and sea ice, which were allowed to change in response to climate change. Hansen et al. (2006) have shown that climate models, which only incorporate the Charney sensitivity and not the full sensitivity, clearly underestimate the temperature increase in response to higher CO₂ concentrations. A major part of this sensitivity is from the ice-sheet albedo feedback (Hansen et al. 2007), which might also be the most important forcing mechanism causing the lower polar and subpolar temperatures in our future scenario. The uplift of the western cordillera of North America since the Middle Pliocene may be of additional importance for the Northern Hemisphere cooling as indicated by model sensitivity tests (Bonham et al. 2009). The differences in the extent of Antarctic land and sea ice may also explain the discrepancies between predicted and reconstructed vegetation in South Africa and southeast/southwest Australia. For both regions, our model simulates, in accordance with IPCC (2007), a future decrease in precipitation, whereas the Middle Pliocene vegetation reconstruction from palaeobotanical data clearly indicates a higher P/E ratio (figure 1; Salzmann et al. 2008).

(b) Uncertainties in model physics and inconsistencies between model simulations

Our model results suggest that, beside the shift of boreal forests, the simulated dieback of the Amazon rainforest is one of the biggest vegetation responses to elevated atmospheric CO₂ concentrations. However, the few palaeobotanical data available for South America indicate that, during the Middle Pliocene, the decrease of rainforest cover in the Amazon basin was probably less severe than simulated by BIOME4 (Carvalho 2003; Salzmann et al. 2008). This is also
supported by climate model intercomparison exercises, which show that HadCM3, which we used for our vegetation runs, tends to underestimate the present and future precipitation in Amazonia (e.g. Cox et al. 2004; Cramer et al. 2004; Schaphoff et al. 2006). Uncertainties in simulating precipitation and discrepancies between climate model predictions are also described in the latest IPCC (2007) report for the African Sahel and Sahara. For these regions, both our Pliocene reconstruction and future prediction indicate a clear vegetation change towards wetter climate conditions. The future increase in humidity in tropical Africa may be even higher. Inconsistencies between palaeodata- and BIOME4-derived Middle Pliocene tropical vegetation suggest that HadCM3 again tends to underestimate the increase in the P/E ratio under elevated CO2 scenarios.

(c) Difficulties in comparing past and future ‘non-modern analogue biomes’

As each plant species responds individually, changes in temperatures, precipitation or atmospheric CO2 concentrations may result in extinction, shifts in species distribution, disruption of extant communities and eventually in the formation of novel species associations (e.g. Hobbs et al. 2006). Those novel plant communities or biomes do not have a present analogue. An example from the geological past of vegetation without modern equivalent is the highly diverse Middle Pleistocene warm-temperate forests of central and western Europe, which were replaced over the course of repeating glacial and interglacial periods by ‘impoverished’ modern deciduous forests (e.g. Mai 1995). These non-analogue warm-temperate forests may be responsible for the uncertainties of the BIOME4 model reconstructing the correct distribution of Middle Pliocene forests for Eurasia, as inferred from palaeobotanical data. The emergence of novel ecosystems as an ecological response to environmental change can also be expected to take place in the future. In this context, it is important to consider that our BIOME4 scenario predicts the potential natural vegetation under elevated atmospheric CO2 concentrations only while neglecting the omnipresent human impact. However, anthropogenic land-cover change is regarded as the second major driving force that will create new ecosystems without modern analogues in the future (Overpeck et al. 2003; Hobbs et al. 2006; Williams et al. 2007).

5. Conclusions

The data–model comparison presented here demonstrates that the Middle Pliocene warm period can be used as a guide for predicting future environmental change under elevated atmospheric CO2 concentrations. A global increase in temperature, shrinking deserts and a northward shift of boreal forests are the most prominent regional changes identified by all model simulations. The best agreement between future and past model runs was achieved with a future CO2 scenario of 560 ppmv. However, as our future vegetation predictions are based on short-time ‘Charney’ sensitivity only, the ‘true’ or equilibrium temperature increase and vegetation response to elevated CO2 will be underestimated. It is thus likely that a biome distribution similar to the Middle Pliocene may already occur at an atmospheric CO2 concentration below double the pre-industrial level. However, owing to the slow response of polar ice sheets to global warming, it is
very unlikely that such a rapid vegetation change will take place within the next few hundred years.

The viability of the Middle Pliocene as a test bed allows, to a certain degree, an advanced analysis and validation of climate models predicting future climate change.

Our validation emphasizes the importance of ice-sheet albedo feedbacks on global warming and highlights the need for further studies on the past extent of land and sea-ice coverage as a vital boundary condition for Pliocene model simulations. Our data–model comparison also revealed uncertainties in model physics, which cause discrepancies in the prediction of Middle Pliocene tropical vegetation cover, which may also have significance for our predictions of tropical vegetation cover for the future. In order to further understand the differences in model response to imposed palaeoclimatic boundary conditions, future work will focus on a systematic intercomparison study of Pliocene simulations derived from multiple general circulation models (Chandler et al. 2008).

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References


