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High resolution climate and vegetation simulations of the Mid-Pliocene, a model-data comparison over western Europe and the Mediterranean region

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Abstract

The Middle Pliocene (around 3 Ma) is a period characterized by a climate significantly warmer than today, at the global scale, as attested by abundant paleoclimate archives as well as several climate modelling studies. There we perform a detailed comparison between climate model results and climate reconstructions in western Europe and the Mediterranean area. This region is particularly well suited for such a comparison as several climate reconstructions from local pollen records covering the Mid-Pliocene provide quantitative terrestrial climate estimates. They show evidence for temperatures significantly warmer than today over the whole area, mean annual precipitation higher in northwestern Europe and equivalent to modern values in its southwestern part. To improve our comparison, we have performed high resolution simulations of the Mid-Pliocene climate using the LMDz atmospheric general circulation model (AGCM) with a stretched grid which allows a finer resolution over Europe. In a first step, we applied the PRISM2 (Pliocene Research, Interpretation, and Synoptic Mapping) boundary conditions except that we used modern terrestrial vegetation. Second, we simulated the vegetation for this period by forcing the Dynamic Global Vegetation Model ORCHIDEE with the climatic outputs from the AGCM. We then supplied this simulated terrestrial vegetation cover as an additional boundary condition in a second AGCM run. This gives us the opportunity not only to compare the generated vegetation cover to pollen records but also to investigate the model's sensitivity to the simulated vegetation changes in a global warming context.

Model results and data show a great consistency for mean annual temperatures, indicating increases by up to 4°C in the study area. Comparison of the simulated winter and summer temperatures to pollen-based estimates show some disparities, in particular in the northern Mediterranean sector. The latitudinal distribution of precipitation depicted by pollen data over land is not reproduced by the model. Most excess Mid-Pliocene precipitation occurs over the North Atlantic but a slight weakening of the atmospheric transport does not allow for wetter conditions to establish in northwestern Europe, as

suggested by the data. Continental moisture patterns predicted by the model are similar to those of the mean annual precipitation. Model results broadly underestimate the levels of available moisture indicated by the data. The biogeophysical effects due to the changes in vegetation simulated by ORCHIDEE, are weak, both in terms of the hydrological cycle and of the temperatures, at the regional scale of the European and Mediterranean mid-latitudes. In particular, they do not contribute to improve the model-data comparison. Their main influence concerns seasonal temperatures, with a decrease of the temperatures of the warmest month, and an overall reduction of the intensity of the continental hydrological cycle. Predicted climatic changes do not only arise from local processes but also result from an altered large-scale circulation initiated by regional-scale land cover changes.

1 Introduction

Past well-documented episodes of significant climate warming provide climate change scenarios that can help us to test the sensitivity of physical models of the climate system and to evaluate the significance of their results in the context of future climate change prediction. It is necessary to look back to the Middle Pliocene to find the last notable and stable phase of global warmth, considered as the closest potential analogue of the expected near future climate state (Jansen et al., 2007). Indeed, the warming that occurred between around 3.3 and 3 million years before present is the most recent interval in geological history during which a significantly warmer-than-present global climate was maintained over a period longer than any interglacial stage of the Quaternary (Dowsett et al., 1996) in an almost similar to present geographic configuration (Crowley, 1996). Estimates of sea surface temperatures (SSTs) (Dowsett et al., 1996, 2005; Dowsett, 2007a) as well as pollen records and plant megafossils suggest that global average temperatures were approximately 2 to 3°C greater than today, i.e., a level of warming within the range of projected global temperature increase for the mid to late 21st century (Meehl et al., 2007). Atmospheric concentrations of carbon dioxide (absolute value as high as 425 ppmv, Raymo et al., 1996) are also comparable to what could occur during the 21st century. The Middle Pliocene, which itself contains episodic climate fluctuations, takes place at the transition from relatively warm stable global climate conditions to the significant global cooling of the Pleistocene, just before the initiation of the late Plio-Pleistocene Northern Hemisphere major glaciations, approximately 2.7 million years ago (Leroy et al., 1998; Zachos et al., 2001; St. John and Krissek, 2002). The causes of the Mid-Pliocene optimum remain uncertain. A combination of increased levels of greenhouse gases in the atmosphere and an enhanced meridional ocean heat transport has been proposed as a leading explanation (e.g., Crowley, 1996; Dowsett et al., 1996; Raymo et al., 1996). Potential causes such as orographic effects related to an altered elevation of major mountain chains (Rind and Chandler, 1991), ice-albedo feedbacks relationships resulting from a reduced extent of high-latitude terrestrial ice sheets and sea-ice cover (Haywood and Valdes, 2004) or permanent El Niño-like conditions (e.g., Molnar and Cane, 2002) have also been invoked.

The Mid-Pliocene therefore appears a very interesting period to study given the predictions of future global warming. Climate modelling can help determining the causes of the warming. This period has been selected for detailed study and is reasonably well-documented through both marine and terrestrial proxy climate records (e.g., Cronin, 1991; Thompson and Fleming, 1996; Poore and Sloan, 1996) that have allowed the reconstruction of comprehensive global datasets, all of which suitable for integration into GCMs (PRISM2, Dowsett et al., 1999). Indeed, many simulations have been performed to investigate the nature and variability of climate during the Middle Pliocene, from the examination of the global response of atmosphere(-ocean) general circulation models (A(O)GCMs) (GISS, NCAR GENESIS, UKMO, IAP AGCMs and HadCM3 AOGCM) to such boundary conditions (Chandler et al., 1994; Sloan et al., 1996; Haywood et al., 2000a; Haywood and Valdes, 2004) to the evaluation on regional scale climate changes (Haywood et al., 2000b, 2001; Jiang et al., 2005). Various sensitivity analyses have been performed to explore the potential causes for the Pliocene warmth

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(Haywood et al., 2007; Lunt et al., 2008). Following current extensive research efforts to understand climate-vegetation interactions (Cosgrove et al., 2002, and references therein), several of the latest studies have considered the climatic impact of the Mid-Pliocene vegetation cover. If its influence on global climate appears to be rather minor, the authors nonetheless show that it must be considered on a regional scale at mid to high latitudes (Jiang et al., 2005), especially in the regions encountering the most prominent changes of vegetation, e.g., in the polar and subpolar regions (Salzmann et al., 2009; Lunt et al., 2009). It can affect the seasonality of temperatures over wide regions (Haywood and Valdes, 2006).

Within this framework, our objective is to perform such an analysis of model sensitivity to vegetation changes, through the use of a combined data and modelling approach, centred on western Europe and the Mediterranean region as a well-documented study case. Indeed, the existence of reconstructions of the Mid-Pliocene climate based on palynological analyses provides a detailed quantification of the main climatic variables of the period and a reliable description of the vegetation of this region at time of global warming (Fauquette et al., 1998b, 2007). We rely on these terrestrial paleoclimate archives to examine the performance of the atmospheric general circulation model LMDZ in simulating the Mid-Pliocene climate, mainly in terms of temperatures and precipitation. This AGCM uses a stretched grid which allows for a finer resolution over Europe. This gives us the opportunity to refine our comparison between model results and climate reconstructions from local pollen data and allows us to investigate specific regional aspects of the Pliocene paleoclimate response of western Europe and Mediterranean regions. Moreover, high resolution is essential for the description of the Mediterranean climate which is strongly driven by local processes induced by the complex orography of this region (Li et al., 2006).

Our experimental design also accounts for the influence of the Middle Pliocene vegetation on the climate. Indeed, we simulate the vegetation for this period by forcing the Dynamic Global Vegetation Model ORCHIDEE (DGVM) (Krinner et al., 2005) with the climatic outputs from our first AGCM run, which uses a modern vegetation cover.

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We then supply this simulated vegetation coverage as an additional boundary condition in a second AGCM run, as a first step of including the vegetation feedback into an atmospheric-vegetation fully coupled simulation design. The numerical experiments are therefore designed to investigate vegetation distributions during the Mid-Pliocene and to explore in detail the sensitivity of the climate model results to different representations of the land cover. We examine the consistency between the vegetation cover produced by the vegetation model and palynological paleodata. We discuss the accuracy of the resulting simulated climate for the Mid-Pliocene by comparing the second experiment to the first one and their fit to the paleoclimatic reconstructions.

2 Experimental design

We employ the high resolution version ofthe LMDZ.3.3 atmosphere GCM (Li and Conil, 2003), which is one component of the Institut Pierre Simon Laplace coupled ocean-atmosphere GCM (Marti et al., 2005). We use a stretched grid with a resolution down to 60 km over Europe. In previous works, this configuration has been evaluated for the present-day climate state (Jost et al., 2005) and has already been used to explore the Last Glacial Maximum, the Heinrich Events 1 and 4 paleoclimates (Jost et al., 2005; Kageyama et al., 2005; Sepulchre et al., 2007, respectively). First, two numerical experiments have been carried out, the first for the modern period, referred to as CTRL, and which is the same as in Jost et al. (2005) in which AMIP monthly mean SSTs and sea ice extent boundary conditions were prescribed (Taylor et al., 2001), the second corresponding to Middle Pliocene conditions. The climatological averages were computed from the last ten years of each 11-year run.

All numerical simulations are forced by the present-day orbital configuration. Atmospheric CO_2 and CH_4 concentrations are set to values of 315 ppmv and 790 ppbv, respectively. Therefore, the impacts arising from the increase in atmospheric CO_2 (up to an absolute level of 425 ppmv) occurring during the Middle Pliocene, as indicated by several proxy estimates (Kürschner et al., 1996; Raymo et al., 1996), are not taken into account in this study. This may imply an underestimation of temperatures that will be discussed when comparing to climatic reconstructions.

The prescribed boundary conditions for the Middle Pliocene are applied according to the PRISM2 reconstruction (Dowsett et al., 1999; Dowsett, 2007a) compiled by the United States Geological Survey's Pliocene Research, Interpretation and Synoptic Mapping group (PRISM), covering the time-slab between 3.29 and 2.97 Ma BP (geomagnetic polarity time scale of Berggren et al., 1995). This global synthesis of the paleoenvironmental and paleoclimatic conditions of the Middle Pliocene epoch consists of a $2^\circ \times 2^\circ$ digital data set that derives from a series of studies conducted at a large number of marine and terrestrial sites and areas (e.g., Cronin, 1991; Dowsett et al., 1992, 1994, 1996; Poore and Sloan, 1996; Williams et al., 2005). It is the most complete and detailed global reconstruction of climate and environmental conditions for any warm period prior to the recent past. A detailed description of the PRISM2 data set and how it was created can be found in Dowsett et al. (1999). Mid-Pliocene surface conditions involve, with respect to the present configuration (Fig. 1):

1. a +25 m sea-level rise leading to slightly modified coastlines;
2. a substantial reduction of ice-sheets size and height (by 50% for Greenland and by 33% for Antarctica) and of sea-ice, the Arctic being seasonally ice free;
3. an altered orography, e.g., a reduced elevation of major mountain chains, such as the Rocky Mountains, related to late Cenozoic uplift;
4. increased SSTs at middle to high latitudes, especially in the northeastern North Atlantic sector, but unchanged SSTs in low latitudes;
5. and the presence of warmth- or moisture-loving vegetation at middle to high latitudes.

As stated in the introduction, previous modelling studies have emphasized the role of warmer sea surface temperatures and reduced land and sea ice extent, as specified by

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the PRISM2 data set, in determining the Mid-Pliocene climate (Haywood and Valdes, 2004; Jiang et al., 2005). Paleogeographic change has also been invoked as a major contributing mechanism to global Pliocene warmth (Rind and Chandler, 1991). In our simulations, we have therefore adjusted the $2^\circ \times 2^\circ$ PRISM2 set of elevations to fit the high resolution grid, by using the present spatial variability as a reference (see Fig. 1).

As far as the vegetation is concerned, rather than translating the PRISM2 vegetation categories into the plant functional types (PFTs) used by our model, given the differences between both vegetation classification schemes, we use the modern (including anthropogenic) vegetation cover in a first experiment, hereafter referred to as PLIO-*modernveg*. We then simulate the vegetation for this period by forcing the DGVM ORCHIDEE (Krinner et al., 2005) off-line, with the climate outputs derived from PLIO-*modernveg*. ORCHIDEE is capable of predicting the geographical vegetation distribution using ten PFTs (and bare soil) that can co-exist within one model grid-cell, in response to a set of GCM-derived climatic variables. The forcing data for ORCHIDEE are produced by a weather generator, driven by the monthly anomalies fields between the simulated Mid-Pliocene climate and the results of the CTRL simulation, added to a present-day observed climatology (New et al., 1999). The newly predicted Mid-Pliocene vegetation map is then supplied as an additional boundary condition in a second AGCM run, referred to as PLIO-*paleoveg*. We have not extended the iterative process further as the simulated climate-vegetation equilibrium is usually reached very soon after the first integration (Claussen, 1994). We therefore assume that the continuation of the iterative process would not alter significantly the predicted vegetation types and distribution. The use of ORCHIDEE provides a detailed view of Mid-Pliocene vegetation cover that then can be compared with the palynologic record, despite there not being full compatibility between PFTs used by the model and the biome typology of pollen data. Comparing the two Mid-Pliocene climate simulations also allows a quantification of the influence of the vegetation on calculated warming and moisture levels. However, a potential weakness of our vegetation simulation is that we have not allowed for changes in stomatal conductance and leaf area index (LAI) that result from a higher atmospheric CO_2, consistent with the fact that we have not modified this level in the AGCM simulation either. As shown recently, the hydrological consequences of changes in stomatal conductance and CO_2 fertilization are not negligible (Gedney and Valdes, 2000; Piao et al., 2007; Alkama, 2007), given their influence on transpiration.

3 Climate reconstruction from pollen data

Terrestrial data, i.e., mainly fossil pollen data but also plant megafossil records, vertebrate paleontological or paleohydrological data, have provided the basis for reconstructing the Mid-Pliocene vegetation. Abundant data exists for Europe and the Mediterranean area and many of them were used within the PRISM2 vegetation reconstruction (Dowsett et al., 1999) or the new global biome reconstruction for the Mid-Pliocene based on a combined proxy and modelling approach (Salzmann et al., 2008). The paleobotanical data also support several paleoclimatic inferences. Here we compare our climate simulation results with climatic estimates based on pollen data covering the Mid-Pliocene in western Europe and the Mediterranean region, on a quantitative basis.

The climate was reconstructed from pollen data using the “Climatic Amplitude Method” developed by Fauquette et al. (1998a,b) to quantify the climate of periods for which no modern analogue of the pollen spectra exists. In this method, past climate variables are estimated by transposing the climatic requirements of the maximum number of modern taxa to the fossil data. This approach does not rely on the analysis of entire pollen assemblages, but on the relationship between the relative pollen abundance of each individual taxa and climate. Presence/absence limits, as well as abundance thresholds, have been defined for 60 taxa from modern pollen spectra and the literature. This method takes into account not only presence/absence criteria but also pollen percentages to provide more reliable reconstructions. For example, low abundances of some subtropical taxa (e.g., *Microtropis fallax*) are meaningful and should be taken into account as pollen grains of these plants are generally under-represented because suffering some disadvantages in the transport. Conversely, low abundances of wind-

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pollinated taxa (e.g., *Quercus, Alnus*) may reflect long-distance transport of these high pollen producers by air and water. In this case, very low pollen percentages are not significant. The most probable climate for a fossil pollen assemblage is estimated as the climatic interval in which the highest number of taxa can exist. The climatic estimate is presented as an interval and as a "most likely value", which corresponds to a weighted mean according to the size of the climatic intervals of all taxa exceeding their presence/absence and/or abundance thresholds. As the precision of the information obtained from a taxon's climatic interval is inversely related to the breadth of this interval, the weights are greater for taxa with smaller intervals.

High latitude/altitude taxa were excluded from the reconstruction process. The identification and exclusion of high latitude/altitude plants are based on numerous palynological studies (e.g., Suc et al., 1995a,b, 1999) showing that the Pliocene vegetation zonation follows a similar latitudinal and altitudinal zonation to the one observed in present-day southeastern China (Wang, 1961), where most of the taxa that had disappeared from Europe by the late Neogene may be found. Therefore, the obtained estimates correspond to the climate at low to middle-low altitude (Fauquette et al., 1998a). Also, *Pinus* and non-identified Pinaceae (due to the poor preservation of these desiccate pollen grains) have been excluded from the pollen sum of the fossil spectra (Fauquette et al., 1998a, 1999). The pollen grains of these taxa are often over-represented in the sediments due to their high production and overabundance in air and water (fluvial and marine) transports (Heusser, 1988; Cambon et al., 1997; Beaudouin et al., 2007).

In this paper, we present reconstructions of five bioclimatic variables estimated from the pollen data: the mean annual temperature (T_{ann}), the temperatures of the coldest and of the warmest months (T_{cold} and T_{warm}), the mean annual precipitation (P_{ann}) and the moisture index α (i.e., the ratio of the mean annual actual to potential evapotranspiration, E/PE). The climate in western Europe and in the western Mediterranean area is estimated using pollen spectra from the sites of Susteren 752/72 (Zagwijn, 1960), La Londe K (Clet and Huault, 1987), Saint-Isidore (Zheng, 1990), Garraf 1 (Suc and

Cravatte, 1982), Tarragona E2 (Bessais and Cravatte, 1988), Rio Maior F16 (Diniz, 1984a,b), Andalucia G1 (Suc et al., 1995a), Habibas 1 (Suc et al., 1999) and Oued Galaa (Suc, 1989) (Fig. 2f). Some of these climatic estimates have already been published: mean annual temperatures and precipitation values are given in Fauquette et al. (1998a,b, 1999, 2007).

In Western Europe, the sites of Susteren, La Londe and Rio Maior show forest vegetation dominated by Taxodiaceae, with Ericaceae and trees of warm mixed forest (*Quercus*, *Carya*, *Pterocarya*, *Acer*, *Carpinus*, *Fagus*). The vegetation rich in Ericaceae is characteristic of the moor landscapes of the Atlantic coast.

In the northern Mediterranean region, sites of Garraf and Saint-Isidore show forest environments dominated by Taxodiaceae (*Taxodium/Glyptostrobus* or *Sequoia* depending on local environment conditions, respectively swamps and slopes), accompanied by subtropical evergreen broadleaved plants such as *Engelhardia*, *Symplocos* and *Distylium*. The presence of *Cathaya*, *Tsuga*, *Cedrus*, *Abies* and *Picea* in the pollen data indicates the development of mid- to high-altitude forests near the sites.

The site of Tarragona makes the transition from northern to southern Mediterranean region. In the southern Mediterranean region (sites of Tarragona, Andalucia, Habibas and Oued Galaa), herbs are prevalent, trees are scarce and certainly developed on reliefs. This region is characterized by Mediterranean xerophytic ecosystems (matorral composed by *Olea*, *Phillyrea*, *Pistacia*, *Ceratonia*, evergreen *Quercus*, *Nerium*, *Cistus*) and southward, by open steppe-like vegetation dominated by subdesertic plants such as *Lygeum*, *Neurada*, *Nitraria*, *Calligonum*, *Geraniaceae* and *Agavaceae*.

The climate reconstructed from these pollen data shows higher temperatures than today for most of the sites (squares, diamonds, triangles on Fig. 2). Most likely values are about 2 to 6°C higher for mean annual temperatures, 0 to 7°C for mean temperatures of the coldest month and 0.5 to 5.5°C for mean temperatures of the warmest month (except at Oued Galaa: almost 1°C lower than today). Mean annual precipitation are higher than today in northwestern Europe (most likely values from 250 to 550 mm/yr higher than today), but drier than or equivalent to modern values in the southwestern Mediterranean area (maximum 150 mm/yr higher). The distribution of the available moisture anomalies is characterized by minor changes (5–15%) both in northwestern Europe and North Africa but by a marked increase in southern Europe (from 30 up to more than 50%), corresponding to high Mid-Pliocene α values, close to their maximum (see Fig. 2).

4 Simulation results over western Europe and the Mediterranean area and model-data comparison

4.1 Two-meter air temperatures

The examination of the two-meter annual mean air temperature anomaly field (PLIO-*modernveg* minus CTRL) in the study area, i.e., over a sector extending from 15° W to 25° E and between 30 and 60° N (Fig. 2a), reveals warmer conditions compared with the present climate, in response to the imposed PRISM2 Mid-Pliocene boundary conditions. The model results indicate an annual mean terrestrial temperature rise of 1 to 4°C on average in western Europe and over the Mediterranean region, as compared with the control simulation. The differences in temperatures appear to be statistically significant over the study area, as confirmed by the use of a Student's T-test at a 99 % confidence level, thus illustrating the consequences of the forcing delivered by warmer SSTs, a reduced sea-ice cover and the altered orography specified in the boundary conditions. Given the proximity of our study area to the North Atlantic, it reveals the strong influence on the European climate of the dramatically warmer SSTs over the North Atlantic (see Fig. 1a), a main factor determining the Mid-Pliocene climate (Jiang et al., 2005). The model-data comparison shows a broad agreement in the general trend of continental warming, even though simulated anomalies are 1–2°C weaker than the most likely values from the paleoclimatic reconstructions (Fig. 3a).

Seasonal temperatures are reproduced with a lower accuracy. The model simulation predicts an homogeneous warming during winter months, as indicated by the T_{cold}

anomalies between Mid-Pliocene and CTRL, thus generally overestimating the temperature increase around the Mediterranean basin (Fig. 2b). The latitudinal gradient depicted by pollen data, with decreasing temperatures anomalies from North to South, is therefore not reproduced (Fig. 3b). Concerning the warmest month (Fig. 2c), the model simulates a more moderate warming for the Mid-Pliocene compared to the coldest month but also with more contrast between western Europe and the Mediterranean area. Some regions such as Sicily or Tunisia, even experience some slight cooling, also shown by the data (Oued Galaa). However, the model does not capture the whole pattern of T_{warm} reconstructed from pollen data, with greater discrepancies in the northern Mediterranean sector (Fig. 3c).

4.2 Hydrological cycle

As compared with the present climate in the study area, wetter conditions dominated during the Mid-Pliocene: the precipitation anomaly computed by the model for the Middle Pliocene conditions (PLIO-*modernveg* run) is a ~20% increase over the study area compared with the CTRL experiment. However, this general pattern hides regional heterogeneities in the distribution of mean annual precipitation (Fig. 2d). A general increase in precipitation by up to more than 900 mm/yr is simulated over the North Atlantic Ocean. A clear region of enhanced precipitation is also observed over the Mediterranean Sea: simulated annual mean precipitation anomalies during the Mid-Pliocene is as high as ~380 mm/yr, which represents a 67% increase relative to modern values. Conversely, precipitation slightly decreases, by a few percents, over continental western Europe. A further examination reveals that the precipitation decrease over western Europe is mainly derived from a large reduction of large-scale precipitation. However, increased convective activity occurs over the continent, especially during summer (Fig. 4).

Estimates of mean annual precipitation show far less consistency between model results and data than for temperatures, although biases remain moderate, i.e., lower than 300 mm/yr for the whole domain (Fig. 3d). The main discrepancy concerns the latitudinal distribution of the precipitation. Indeed, in western Europe and the northern Mediterranean area, model results underestimate the wetter conditions depicted by pollen data (except at Saint-Isidore). Conversely, throughout the southern Mediterranean sector, positive PLIO−CTRL anomalies are indicated by model results, which only correspond to the reconstructions at one out of the four southern Mediterranean sites. The precipitation at the other 3 sites is actually decreasing by up to 200 mm/yr, which is not at all reproduced by the model.

Model estimates of hydrological variables such as the available moisture show a similar PLIO−CTRL anomalies distribution to that of the mean annual precipitation (Fig. 2e vs. 2d). Terrestrial areas of northern Europe display a Mid-Pliocene E/PE ratio similar to the modern one in northern Europe, in agreement with the data. The Mid-Pliocene experiment predicts an increase in available moisture all around the Mediterranean basin that however does not reach the high levels indicated by pollen data along the Spanish coast (Figs. 2e and 3e).

4.3 Mid-Pliocene vegetation distribution and vegetation-induced effects on climate

4.3.1 Mid-Pliocene vegetation as simulated by ORCHIDEE

The DGVM ORCHIDEE provides insights into the distribution and character of the Mid-Pliocene vegetation cover as a consequence of warmer climate (Fig. 5c and 5d). A temperate forest cover, dominated by broadleaved evergreen trees in western Europe and in the Mediterranean sector, is accompanied by grassland, which extends over northeastern European regions. To the east, the arboreal coverage is composed by boreal and temperate deciduous species, as well as temperate needle leaf trees in the Alps. The vegetation model predicts the presence of tropical plant functional types confined along the southern Mediterranean coasts, which are absent from this region today and in the CTRL run.

The ORCHIDEE results for the Middle Pliocene are significantly different from the

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modern vegetation distribution used in the PLIO-*modernveg* simulation over Europe and the Mediterranean region (Fig. 5). The main vegetation differences identified in the simulated Mid-Pliocene vegetation cover compared with the modern one include:

1. a general expansion of temperate forest cover in Europe and the Mediterranean region for the Mid-Pliocene (predicted fractional coverage of more than 90% over 20% of the land, up to 45% for all tree types), whereas the major part of the present vegetal cover consists of crops,

2. associated with boreal trees in eastern Europe (~20–30% of broad-leaved summergreen trees),

3. the presence of tropical trees along the southern Mediterranean coasts,

4. and a significant decrease of bare soil in North Africa (by 20%).

The model results suggest that temperate forest is the dominant vegetation type in the European and Mediterranean region during the Mid-Pliocene, associated with a reduced coverage of arid desert in North Africa. These major changes of vegetation distribution are consistent both with the PRISM2 coarse vegetation reconstruction and the latest biome map provided by the vegetation model BIOME4 (Salzmann et al., 2008), forced by climatology derived from the HadAM3 GCM (Haywood and Valdes, 2006).

Pollen data and vegetation simulations are generally in good agreement, especially concerning the expansion of the warm-temperate forest in Europe, despite few discrepancies. For instance, pollen data show for southern Spain and North Africa an open subdesertic landscape dominated by grasses, indicating arid conditions. However, arboreal pollen grains are also present, indicating that trees were certainly developing on reliefs. The second noticeable difference concerns the presence of tropical trees simulated by ORCHIDEE, whereas no tropical plants are recorded in pollen data: at most subtropical plants are recorded.

4.3.2 Vegetation-induced effects on climate

As far as the vegetation impact on climate is concerned, the main differences in experiment PLIO-*paleoveg* compared with the PLIO-*modernveg* run are shown on Fig. 6. The spatial average of the mean annual temperature difference over the region of interest is on the order of a tenth of a degree between the two simulations over continental Europe. The PLIO-*paleoveg*–CTRL T_{ann} anomalies are thus very similar to the previous PLIO-*modernveg*– CTRL one. The addition of the paleovegetation produces few statistically significant changes in the modelled climate, except over some areas such as North Africa where an annual mean cooling that reaches more than 1°C is simulated and in a few other cases, such as over northwestern Europe (British Isles) and the Alps that are slightly, up to around 0.5°C, warmer (not shown). The model's sensitivity to Pliocene land cover characterization is therefore limited in terms of 2-m mean annual temperature changes over the studied area.

The vegetation impact on the simulated climate mainly occurs during the summer season (Fig. 6). Simulated temperatures of the warmest month (Fig. 6a) are reduced by 0.9°C on average on the studied area, cooler by 1 to 2°C over western Europe and North Africa, and as much as 3°C over eastern Europe, as compared with PLIO-*modernveg*. The most significant variations are observed over the latter regions. They correspond to a reduced summer warming over Europe and cooler T_{warm} over North Africa at Mid-Pliocene times, relative to the present. In winter, the vegetation-induced cooling is not significative.

As regards the model-data comparison, the effect of the more realistic vegetation treatment is quite negligible and does not induce any improvement of the simulated mean annual cycle of 2-m air temperature (Fig. 7). The lack of observations located further inland in areas displaying statistically significant differences prevents from evaluating the accuracy of the summer temperature anomalies trend provided by the PLIO-*paleoveg* experiment.

Examining model diagnostics for the annual precipitation (not shown) indicates average conditions that are rather drier than the PLIO-*modernveg* pattern, with negative local disparities, from 50 to −250 mm/yr, between the two runs. Variations in the intensity of precipitation are centred around the Alps but are rarely statistically significant, except over parts of northwestern Europe. PLIO-*paleoveg*-CTRL negative anomalies are more pronounced over northwestern Europe than PLIO-*modernveg*-CTRL whereas the Mediterranean basin records smaller positive anomalies. As a result, the model-data comparison for this variable is even less satisfactory over western Europe and the northern Mediterranean when a more realistic vegetation is introduced in our Pliocene experiment but slightly improves over the southern Mediterranean region (Figs. 3 and 7). The decrease in precipitation rate can be explained by a further decrease of large-scale precipitation, all over the year, except in summer, during which the increase in convective precipitation contributes to a wetter season in the PLIO-*paleoveg* experiment, as compared to PLIO-*modernveg* (Fig. 6b).

E/PE values computed for PLIO-*paleoveg* results are similar to those of PLIO-*modernveg* over northwestern Europe. Significant changes in the ratio between the two experiments are recorded over the same areas as those regarding annual precipitation, i.e., north and west of the Mediterranean Sea. They result in a marked decrease, by down to −25%, of the available moisture in the PLIO-*paleoveg* experiment, compared to PLIO-*modernveg*. PLIO-*paleoveg*-CTRL anomalies are still positive in most of the Mediterranean area but lower than their PLIO-*modernveg*-CTRL counterparts and exhibit negative values over southeastern Europe. The model-data comparison therefore slightly deteriorates (Fig. 7).

5 Discussion

In this study, we have first investigated the ability of the high resolution zoomed version of the LMDz AGCM to reproduce the warmer and slightly wetter conditions of the Mid-Pliocene by means of a quantitative model – pollen data comparison over Europe and the Mediterranean area. Then we have considered the relative impact of the reconstructed vegetation on the simulated climatic response at the regional scale.

5.1 High resolution climate modelling in a warmer context

5.1.1 A good agreement for near surface temperatures

For the mean annual near surface temperature field, the simulated Mid-Pliocene warming relative to the present is broadly consistent with previous modelling studies, particularly that of Haywood et al. (2000b) for the study area, and with the quantitative paleoclimatic reconstructions (Fauquette et al., 2007). For most sites, the discrepancy is small given both the interannual variability of the model and the large and less precise entire climatic intervals surrounding the most likely values reconstructed by the pollen indicators (Fig. 3a).

Some biases remain, i.e., underestimated T_{ann}, which is not unexpected since our experimental design does not encompass all of the forcings that are possible for this epoch, particularly the changing CO_2 levels. In terms of radiative forcing, the deficit in CO_2 in our PLIO experiment (315 ppmv), as compared with the estimated Mid-Pliocene level (about 400 ppmv), is similar to the rise from 280 to 335 ppmv during the period from preindustrial to modern times. Simulations with such rising CO_2 levels have produced a general global warming of $\sim$1°C, in agreement with observations (Notaro et al., 2005). The direct physiological impact of higher than today CO_2 concentrations on vegetation is not accounted for either in the paleoclimate reconstructions themselves, which may lead to significant bias (Wu et al., 2007). For the colder period of the Last Glacial Maximum, a better agreement between simulated and reconstructed winter cooling over western Europe and the Mediterranean area has been mainly achieved by explicitly accounting for the CO_2 decrease in the new climate reconstructions (Ramstein et al., 2007).

On the other hand, accounting for higher Mid-Pliocene CO_2 levels may not contribute to reduce the discrepancies between model results and pollen-based reconstructions that have been identified for the distribution of seasonal temperature changes, in particular the overestimation of the simulated T_{cold} around the Mediterranean basin. Indeed, Notaro et al. (2005) found that the physiological forcing due to rising CO_2 result in a significant simulated wintertime warming, even exceeding the response of annual temperature. Inconsistencies between simulated and reconstructed seasonal temperatures could reflect the inadequation between SSTs over the Mediterranean Sea and pollen data that are located along the coast. The increase in summer SSTs between Mid-Pliocene and CTRL is too low as compared to the T_{warm} anomalies depicted by pollen data over the northern Mediterranean but too high in winter as compared to the T_{cold} anomalies according to pollen data over the southern Mediterranean. As model results are influenced to a large extent by the SST forcing (see Kageyama et al. (2005) for a similar result in a glacial context), it would be worth testing the range of this forcing within the PRISM time-slab. Over the Mediterranean Sea, maximum and minimum warming SST reconstructions indicate a possible ~1°C change (Dowsett et al., 2005). A representation of the SSTs pattern consistent with ocean-atmospheric fluxes, could also be simulated by a high resolution model of the Mediterranean Sea locally coupled with a global atmosphere model, such as the Sea Atmosphere Mediterranean Model (SAMM) (Somot et al., 2008). Moreover, the introduction of an active Mediterranean Sea significantly amplifies the 21st climate change response over large parts of Europe, with respect to its corresponding Atmosphere Regional Climate Model. Indeed, climate change projections based on many global and regional models agree about a pronounced warming of several degrees for the end of the 21st century over the Mediterranean region, with a maximum in the summer season (Giorgi and Lionello, 2008). This region might be especially vulnerable to future global climate change. The greater warmth experienced during the Mid-Pliocene period is comparable to what is projected over the Mediterranean area, although seasonal temperature patterns may differ. It would therefore be worth examining the influence of an interactive Mediterranean Sea or a fully coupled ocean in the Mid-Pliocene context.

5.1.2 A clear discrepancy for hydrological values

As regards estimates of precipitation values, the main discrepancy seems to be the underestimation of continental precipitation in much of northern Europe, whereas the precipitation rate is overestimated over the southern Mediterranean, despite a robust pollen data signal. The presence of an extensive wet zone in northwestern and central Europe is moreover suggested by other proxies (small mammals for instance, van Dam, 2006). In this respect, the latitudinal gradient of precipitation indicated by pollen data resembles the general trend that emerges from a review of climate change projections for the 21st century (Meehl et al., 2007). Global warming is expected to cause a large decline of precipitation over the Mediterranean region, except for the northern areas in winter (Giorgi and Lionello, 2008), following what has already been observed during the 20th century (Lionello et al., 2006). These data-model inconsistencies show a general difficulty to simulate regional hydrologic processes, even when using a refined-grid numerical model. Salzmann et al. (2008) also identified many discrepancies when comparing precipitation estimates from the HadAM3 GCM and literature for selected regions including the Mediterranean area.

One of the factors which could explain the continental precipitation underestimation over western Europe is the simulated decrease of large-scale precipitation. In the model, large-scale precipitation is defined as the part of the precipitation related to moisture convergence due to large-scale atmospheric circulation, as opposed to convective precipitation, which is related to instable atmospheric vertical profiles. Large-scale mid-latitude precipitation is therefore largely related to the development of synoptic scale perturbations over the oceans, especially in winter. Total precipitation notably increases over the warm ocean regions of the North Atlantic, rising by more than 30% as compared with the present-day control case as an annual mean. This increase is attributable to preponderant moist convective precipitation events, which outweigh a diminished large-scale precipitation pattern. Indeed, the former represents 60% of the total precipitation signal in the PLIO experiment for only 20% in the CTRL one. High levels of evaporation are also simulated for the North Atlantic and are responsible for a large increase in latent heat fluxes.

These major changes in evaporation and convective precipitation are positively correlated with the prescribed SSTs, one of the main factors determining the Mid-Pliocene climate together with a reduced sea ice extent (Jiang et al., 2005). The pattern of greatest warming with increasing latitude was recently confirmed by the re-evaluation of Mid-Pliocene North Atlantic SST estimates by means of a multiproxy analysis (Robinson et al., 2008). The North Atlantic is nonetheless the region that encompasses the greastest temporal variability within the Mid-Pliocene warm period (Dowsett et al., 2005), of the order of ±2–3°C. Additional experiments including these new SST reconstructions are necessary to investigate in detail the impact of the SST distribution over the North Atlantic on the European continental climate. The sensitivity of the European climate to North Atlantic SST has already been pointed out for a glacial context by Pinot et al. (1999) from AGCM experiments and by Kageyama et al. (2006) for coupled ocean-atmosphere experiments. In a Mid-Pliocene ocean-atmosphere coupled experiment (Haywood and Valdes, 2004; Haywood et al., 2007), total precipitation rates are reduced over the North Atlantic compared to the fixed SST experiment, particularly in winter, because of lower SSTs predicted by the model over this region. Indeed, the inclusion of an interactive ocean would allow a further examination of the potential feedback from the oceans, as it is supposed to have a significant influence on atmospheric dynamics, on ocean-atmosphere fluxes and hence on total precipitation rates. In particular, it would allow a better representation of the possible enhanced meridional ocean heat transport, which could compensate the simulated decrease in intensity of the large-scale atmospheric circulation due to the smaller meridional temperature gradient of the Mid-Pliocene.

The resultant reduced ability of the atmosphere to carry moisture evaporated from the ocean over the continent (Fig. 8a), especially during summer, can therefore account for the fact that the aforesaid additional oceanic humidity supply is not converted into precipitation over the northwestern European continent. A slight weakening of zonal wind speeds, by 1–2 m/s over North Atlantic and up to a maximum of 3 m/s, is also simulated over the northwestern European continent (Fig. 8b). This westerly wind pattern is nevertheless not supported by the data either, as suggested by the development of Ericaceae moors along the European Atlantic coast (Suc et al., 1995a,b) which would rather point to an intensification of the wind strength.

According to basic baroclinic theory (Eady, 1949), the weaker meridional temperature gradient in the North Atlantic should have the effect of decreasing the storminess. However, this is not the case in our PLIO simulations (Fig. 9). Other factors are therefore playing an important role in mid-latitude transient eddies. These could develop thanks to more available latent heat flux over the warmer oceans (Hoskins and Valdes, 1990; Laîné et al., 2009). Also the lower Rockies could modify the connection between the Pacific and Atlantic storm-tracks, favouring more feeding of Atlantic storms by Pacific perturbation remnants (Lunt et al., 2008). The role of these different factors could only be evaluated through dedicated sensitivity experiments (e.g., changing the topography only or the SSTs only compared to the pre-industrial conditions). The simulated PLIO large-scale precipitation decrease is all the more surprising since stronger storm-track activity should favour this type of precipitation. It could be, however, that in a case of a warmer ocean such as in PLIO, the increase in storm-track activity favours convective precipitation, to the detriment of large-scale precipitation. This calls for a more detailed study and additional sensitivity experiments which are out of the scope of the present paper.

These results are in contrast with those of other GCMs, which predict weaker storm tracks (Chandler et al., 1994; Sloan et al., 1996). As for the simulated precipitation field, the UKMO AGCM has been able to capture the general pattern depicted by the data over the study area. Indeed, Haywood et al. (2000b)'s simulations show an annual zonal average precipitation similar to modern values between around 30 and 42° N and higher than today between 42 and 51° N, in particular in western Europe and western Mediterranean, as a result of an enhancement of the westerly atmospheric transport of heat and moisture. Predicted Mid-Pliocene precipitation rates even decrease over the Mediterranean basin as compared with today in their coupled ocean-atmosphere experiment (Haywood and Valdes, 2004; Haywood et al., 2007), in response to a northward shift of the Atlantic storm track and the presence of an enhanced Azores high-pressure system, which helps to divert the Atlantic precipitation from the Mediterranean onto northwestern Europe. Similar features of increased anticyclonic circulation associated with a shift in the location of mid-latitude storm tracks could also lead to the substantial drying of the Mediterranean region that is projected for the near future (Giorgi and Lionello, 2008). On the contrary, a slight increase in precipitation over the Meditarreanean region is simulated by our model in the PLIO experiment (Fig. 4b), which can be partly related to a weakening of the Azores high-pressure system as well as to warmer Mediterranean SSTs.

It is nonetheless difficult to directly compare the climatic response of all of the different models that have already been used to simulate the Mid-Pliocene, since no uniform experimental design was set at the time of performing our experiments. Even the reference climate simulations use a set of boundary conditions from different data bases. The intercomparison between climate models simulations of the Mid-Pliocene that will be carried out in the near future according to the same set of boundary conditions (Chandler et al., 2008; Haywood et al., 2009) will help to distinguish the effects of the imposed PRISM data sets on the apparent disagreement in the climatic response of the models from the impacts of any internal model physics or missing mechanisms.

As for convective precipitation, a coherent signal is observed between simulated precipitation and temperature over the continent, with increased convective precipitation as compared to present, in particular during the summer season. However the use of a finer grid numerical model in our experiment, by accentuating the land-ocean contrast, can lead to a higher atmospheric water-holding capacity over land than over the ocean, and thus, a reduced relative humidity for continental air masses advected from the ocean. It can have the effect of tempering the increase in convective precipitation.

In addition, the moisture levels indicated by the data are generally underestimated by the model, meaning that predicted recycling of continental water may not be intense enough. It is of importance since annual variation of land precipitation also partly results from local moisture recycling, despite a greater atmospheric control in the study area. On this point, several issues can be raised.

The relatively low atmospheric CO_2 concentration we used in our simulations, as compared with the level commonly used in more recent simulations, hampers the model-data comparison. On the one hand, the radiative effect of an increase in atmospheric CO_2 could produce an intensified hydrological cycle, with increasing soil moisture in the mid-latitudes (Levis et al., 2000). On the other hand, atmospheric CO_2 also affects the global hydrological cycle through its direct physiological effect on stomatal conductance and CO_2 fertilization, which can either have an amplifying or a dampening impact (Piao et al., 2007; Alkama, 2007). Higher CO_2 levels imply an increase in transpiration due to an increased foliage area but would also probably lead to a concurrent decline in transpiration by reducing stomatal conductance. Of the two the latter response is believed to be the preponderant factor at least for our model (Alkama, 2007). The net physiological effect of elevated CO_2 concentration on transpiration could therefore be negative and result in a weakened hydrological cycle and an increasing aridity. Such an additional simulated decrease in soil moisture would not help to reduce model-data discrepancies but match climate change projections over the Mediterranean region for the 21st century (Giorgi and Lionello, 2008).

In this respect, the representation of physical processes such as ground hydrology may play a non negligible role. Local soil moisture changes can lead to variations in the regional intensity of the water cycle during the warm season when the convection precipitation regime intensifies. In our experiment, soils are drying out during the summer in response to the warmer ground temperatures. The representation of subsurface hydrological processes in the current land surface scheme used in the AGCM is indeed rather simple. The introduction of a groundwater component with an explicit representation of the water table in the land surface model would help to produce much wetter soil moisture profiles and more dry-period evapotranspiration (Miguez-Macho et al., 2007), in a better agreement with the α data. In addition, it could reinforce the potential for regional recycling of water (Anyah et al., 2008). As the orography of the Mid-Pliocene was relatively flat, shallow water table conditions must have actually occured, leading to significantly wetter soil through the exchanges of water between the unsaturated soil and the underlying aquifer.

Lastly, water recycling also varies according to the vegetation characteristics. It is therefore worth taking into account a distribution of vegetation boundary conditions consistent with the precipitation rates and more generally, with the Mid-Pliocene climatology. This is the subject of our second experiment.

5.2 Evaluating the consequences of vegetation changes on the Mid-Pliocene climate

In response to the climate forcing of the first PLIO-*modernveg* run, ORCHIDEE simulates a potential vegetation distribution for the Mid-Pliocene which differs all the more from the one used in PLIO-*modernveg* since this latter corresponded to a modern (including anthropogenic) vegetation cover. Here we thus carry out a comparison of the impact of a forest-dominated vegetation against a human-dominated one, in which forests replace crop and pasture areas as well as expanses of bare soil, in the global warming context of the Mid-Pliocene. In this respect, it concurs with a number of recent studies on the relevance of taking into account the impact of land use change on surface climate (e.g., Kleidon, 2006; Bala et al., 2007; Davin et al., 2007).

5.2.1 Near surface temperatures

The effect of introducing a potential paleovegetation for the Mid-Pliocene on the simulated surface temperatures is found to be quite limited, as Jiang et al. (2005) demonstrated in their sensitivity study. In our study area, the vegetation feedback does not even have a strong impact on the regional scale, except during summer, when it contributes to a reduction of the seasonality of temperature, as in Haywood and Valdes (2006).

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Despite the mean land surface temperature not being very sensitive to land cover change, our simulation results point out that the Mid-Pliocene forest spread results in a surface cooling in most of western Europe, compared to the PLIO-*modernveg* experiment. When considering alterations in the land cover, various competitive terms contribute to affect surface temperature: the radiative forcing due to change in albedo and water vapour and non-radiative processes, e.g., the alteration of turbulent exchanges of sensible and latent heat (Kleidon, 2006; Davin et al., 2007). In our model simulations, modifying the vegetated cover by roughly converting grasslands to forests has two main opposite effects on temperature. On the one hand, the general reduction in surface albedo results in an increased net surface solar absorption, which means warming. Anomalies of the annual mean surface albedo of a few percents are produced by the AGCM over the study area (Fig. 6c). On the other hand, converting grasslands to tree-type vegetation tends to increase the land surface evapotranspiration rates. This effect is especially relevant during the summer months in northwestern Europe, with evapotranspiration anomalies between the two Mid-Pliocene simulations reaching 250 mm/yr (Fig. 6d). The subsequent increase in latent heat fluxes, of the order of a few tens of W/m^2 during summer, proportional to evaporation, explains the cooling of the near-surface atmosphere over land. The increase in latent heat cooling seems to outweigh the increase in surface solar radiation heating, meaning that the non-radiative processes dominate the summer climate response.

The evapotranspiration changes could also result in an increase in low-level cloudiness that would further cool the surface climate since cloud formation tends to limit the solar radiation income. Indeed, it has been shown that cloud feedbacks initiated by evapotranspiration changes may play a major role in determining the overall climatic impact of land cover change, in the context of deforestation over tropical regions (Bala et al., 2007). However, our simulation results do not suggest any increase in low-level cloudiness over the concerned areas nor any significant relationship between evapotranspiration and clouds changes. Thus, the impact of the cloud response on the energy balance of the climate system seems rather limited at such latitudes despite the globally warmer climate of the Mid-Pliocene as compared with today.

5.2.2 Hydrological cycle

Vegetation changes also modify the surface water balance. Our simulation results suggest a weakening of the hydrological cycle over land in the PLIO-*paleoveg* run compared with the PLIO-*modernveg* one, except during summer.

As already observed in the PLIO-*modernveg*–CTRL comparison, the model is still particularly sensitive to large-scale atmospheric effects in the PLIO-*paleoveg* run. The reduction in winter large-scale precipitation is more pronounced in the latter run, which accounts for the deterioration of the model-data comparison over land. The further weakening of the winds, which may be due to increased roughness length because of vegetation change, affects the large-scale transport of heat and moisture. Indeed, the two Mid-Pliocene simulations show noticeable differences in regional precipitation minus evaporation rates with a marked decrease of the net atmospheric moisture convergence over land. It means that biophysical effects of land-cover change are not only felt at regional scales but may also impact the general atmospheric circulation and give rise to remote climate changes through nonlinear feedbacks (Gedney and Valdes, 2000; Chase et al., 2000; Baidya Roy et al., 2003). These changes being more diffuse, their evaluation is all the more complicated at the local scale, where changes in precipitation result from a combined effect of local vegetation changes, as well as in remote locations, through the atmospheric pathway. This also applies to temperatures.

Besides, a strengthening of moist convective precipitation events, in frequency or intensity, is simulated in the PLIO-*paleoveg* run during summer over land and during winter over the ocean, as compared to the PLIO-*modernveg* experiment. This convective rainfall response is linked to an intensification of the evapotranspiration, and the associated increasing water vapour content in the atmosphere. Mean annual precipitation rates therefore increase over the North Atlantic. The enhancement of summer convective rainfall over land is nonetheless not sufficient to counterbalance the decrease of large-scale precipitation, which occurs over the rest of the year (Fig. 6b).

5.2.3 Why do vegetation changes not really contribute to a more accurate simulation of the Mid-Pliocene climate, as compared to paleodata?

To conclude, our simulations demonstrate a moderate vegetation impact on temperature extremes and hydrological cycle over Europe and the Mediterranean area but which does not improve the model-data comparison of our first run (Fig. 7).

Regarding our experimental design, the fact that the vegetation distribution we use for the PLIO-*paleoveg* run was produced by a model-driven climate means that biases inherent in the GCM simulation (e.g., physics, boundary conditions, CO_2 levels) may lead to biases in the predicted vegetation (Cosgrove et al., 2002; Crucifix and Hewitt, 2005). It is therefore not unexpected that the vegetation distribution produced by ORCHIDEE does not completely match the vegetation reconstructions depicted by the pollen data. For instance, tropical trees may be simulated as a consequence of the too warm T_{cold} or simply because the vegetation classification used by the model is not as specific as the biome typology of pollen data.

Consequently unrealistic vegetation changes may drive inadequate perturbations in the atmosphere dynamics, which can therefore not contribute to improve the Mid-Pliocene climate simulation. It is nonetheless expected that such a deterioration of the climate signal is quite negligible as the vegetation impact on climate has been shown to be moderate in the European and Mediterranean mid-latitudes.

Furthermore the climate-vegetation system could be sensitive to the initial distribution of vegetation (Claussen, 1994), as several stable states may exist by starting the iterative process from different initial conditions (Crowley and Baum, 1997). In our case, we have not tested whether we would obtain the same Mid-Pliocene vegetation starting from a vegetation different from the modern.

We have also assumed that the largest vegetation change is obtained after the first iteration. As the resulting climate change is quite limited in the study area, significant vegetation alteration would probably not occur by extending further the iterative process.

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Our field of analysis of past climate-vegetation characteristics is also partly limited by the geographic location of our study area, because vegetation change appears to have quite little influence on climate in the mid-latitude regions, resulting in not very significant results (Bala et al., 2007). Examination of high resolution simulations centred over regions located in the low or high latitudes could help to better capture past climate-vegetation feedbacks associated to the warmer climate of the Mid-Pliocene.

The incomplete simulation design can be also invoked, as it prevents all of the vegetation effects on climate from being effective. Indeed, conversion of vegetation does not only affect the climate system through the surface-energy budget but also through the carbon cycle. Plant-climate interactions are sensitive to atmospheric CO_2 concentration. For instance, water balance depends on vegetation growth conditions that are highly CO_2-dependent. A poor representation of LAI and stomatal conductance have been shown to disturb the hydrologic cycle (Alkama, 2007). Therefore, it appears possible to improve model-data comparison in future simulations. This is actually also true for pollen-based climate reconstructions, which do not include either the vegetation dependence on high Mid-Pliocene atmospheric CO_2 concentration and are calibrated for pollen originating from plants growing under modern CO_2 levels. Also, as landscape dynamics does not only affect the climate system at local or regional scale but can also have significant global impacts by altering large-scale circulations, ocean feedbacks will need to be considered.

6 Conclusions

This paper presents the results of a high resolution modelling experiment of the Mid-Pliocene climate, focusing on western Europe and the areas surrounding the Mediterranean Sea. Our motivation was twofold: (1) to evaluate the simulated climatologies by comparing them to paleoclimatic reconstructions from pollen records from individual locations and (2) to assess in detail the effects of altered vegetation boundary conditions, in the context of a climate warmer than today.

We find that the AGCM results are consistent with the evidence of increased temperatures provided by the data. Simulation results further indicate that continental moisture levels were quite different from today. However, the poor comparison of model versus data as regards the annual precipitation field or the E/PE pattern raises the issue of the accuracy of the imposed boundary conditions data sets for the Mid-Pliocene, the representation of the internal physics of the model and the pollen interpretation.

In order to more rigorously address this problem, it is now necessary to carry out an intercomparison between climate models simulations of the Mid-Pliocene according to an uniform experimental design. Such a project is already underway as part of Plio-MIP (Pliocene Model Intercomparison Project) (Chandler et al., 2008; Haywood et al., 2009). This will allow to explore the range of variability of the models' responses to the Mid-Pliocene warming, and to explain the dispersion of the results in terms of differences in the physics or in the parametrization of physical processes. Our next step in modelling the Mid-Pliocene climate will involve the use of fully-coupled atmosphere-ocean-vegetation models under prescribed boundary conditions from the PRISM3D data set (Cronin et al., 2005; Dowsett, 2007b; Robinson et al., 2008; Salzmann et al., 2008). This is essential in the exploration of the roles of the ocean circulation, the atmosphere and the land surface changes and their contribution to Mid-Pliocene global warmth.

Many sensitivity studies about each PRISM boundary condition, such as the test on the vegetation cover carried out in this paper, have already been achieved. On the basis of our modelling results, we show evidence of an influence of the vegetation cover on the regional climate; however, the inclusion of a more appropriate vegetation distribution produces few significant changes at the mid-latitudes investigated in this study. Further work regarding the description of the hydrological cycle and relative to its parametrization will help to better take into account the vegetation impact on climate.

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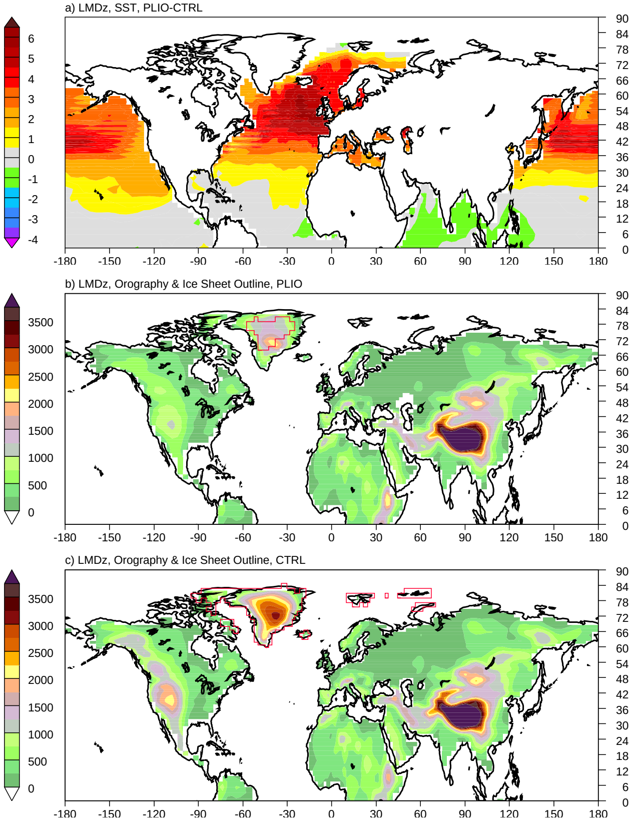

Fig. 1. Mid-Pliocene paleoenvironmental conditions in the Northern Hemisphere, originating from PRISM2 (Dowsett et al., 1999): **(a)** mean annual SST anomaly (°C) from the present climate (Taylor et al., 2001); **(b)** Mid-Pliocene absolute values of orography (m) and ice sheet outline in red, as compared to **(c)** present.

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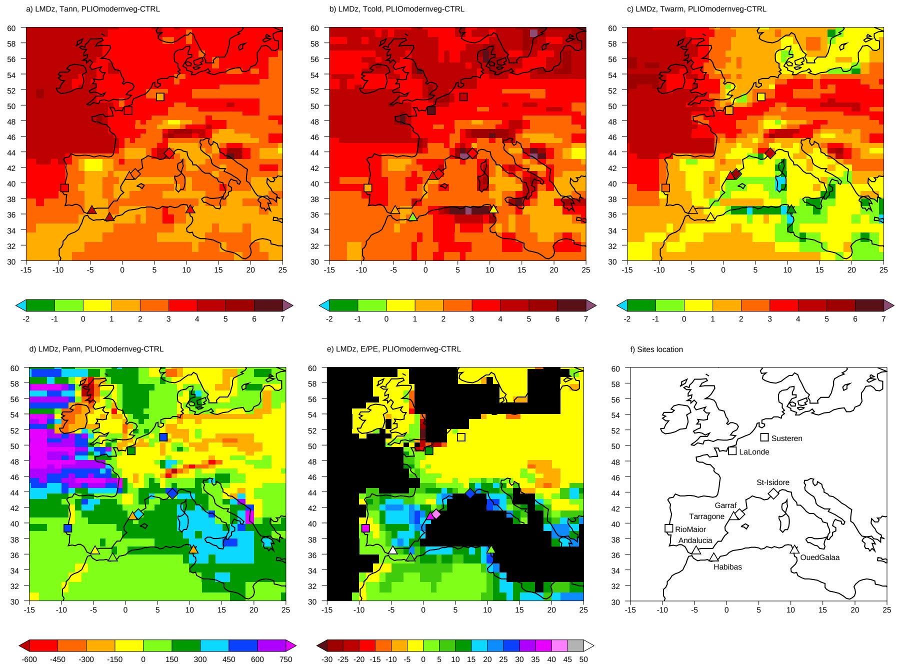

Fig. 2. Mid-Pliocene anomalies from the present climate, PLIO-*modernveg* results: **(a)** annual mean surface temperature (°C), **(b)** mean temperature of the coldest month (°C), **(c)** mean temperature of the warmest month (°C), **(d)** annual mean total precipitation rate (mm/yr), **(e)** moisture index (actual/potential evapotranspiration ratio) (%), as compared with pollen-based climatic reconstructions (T_{ann}, P_{ann} from Fauquette et al., 2007). **(f)** Sites location. Western Europe (squares), Northern Mediterranean (diamonds) and Southern Mediterranean (triangles) regions are distinguished (see Sect. 3).

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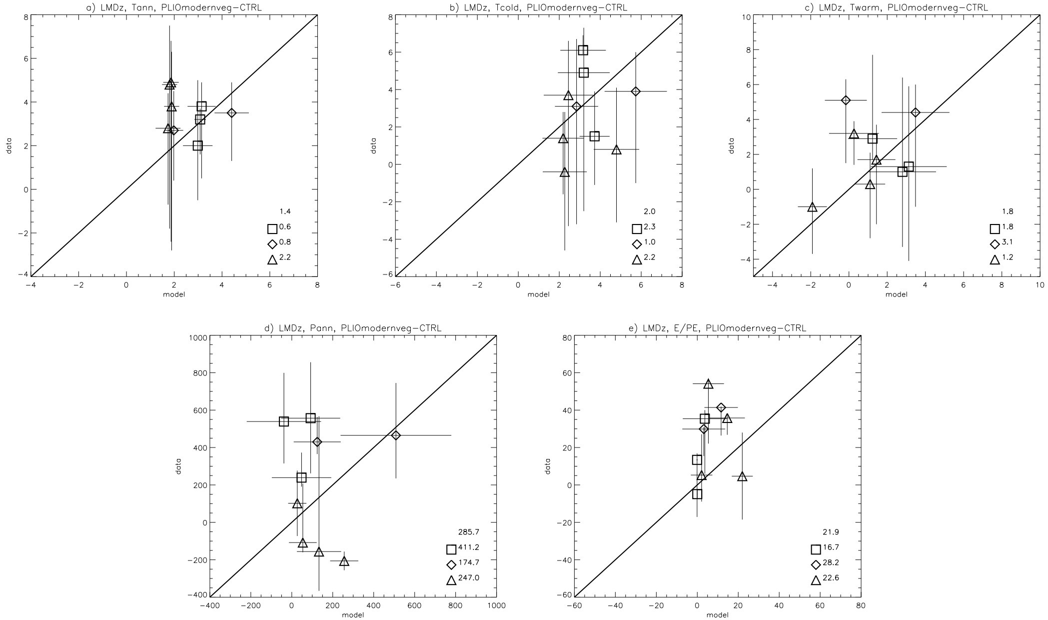

Fig. 3. Mid-Pliocene anomalies from the present climate, PLIO-*modernveg* results: **(a)** annual mean surface temperature (°C), **(b)** mean temperature of the coldest month (°C), **(c)** mean temperature of the warmest month (°C), **(d)** annual mean total precipitation rate (mm/yr), **(e)** moisture index (actual/potential evapotranspiration ratio) (%). Models results (x-axis) are compared with pollen-based indicators (y-axis). At the bottom right of each plot, numbers indicate mean absolute errors from the best estimates, for the whole domain and for each cited region (Western Europe (squares), Northern Mediterranean (diamonds) and Southern Mediterranean (triangles)). Horizontal bars represent model standard deviations of interannual variability and vertical bars climatic intervals estimated from fossil pollen assemblages.

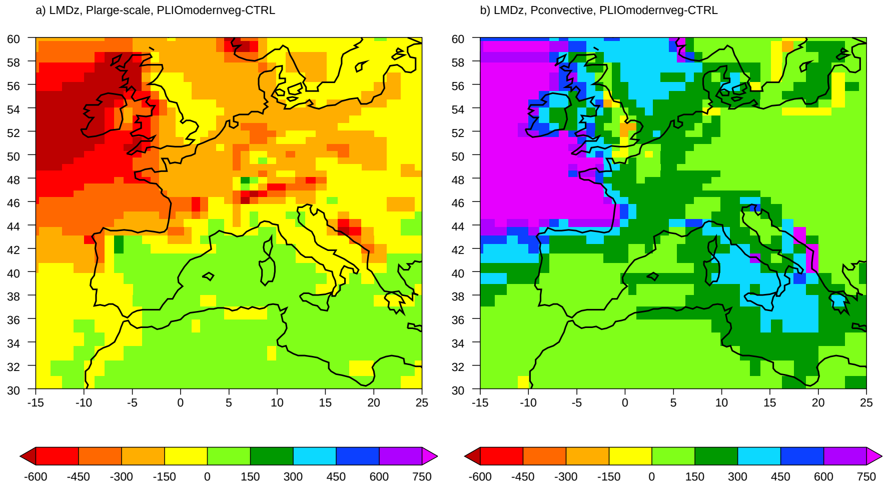

Fig. 4. (a) Large-scale precipitation and **(b)** convective precipitation, in mm/yr. Mid-Pliocene anomalies from the present climate, PLIO-*modernveg* results.

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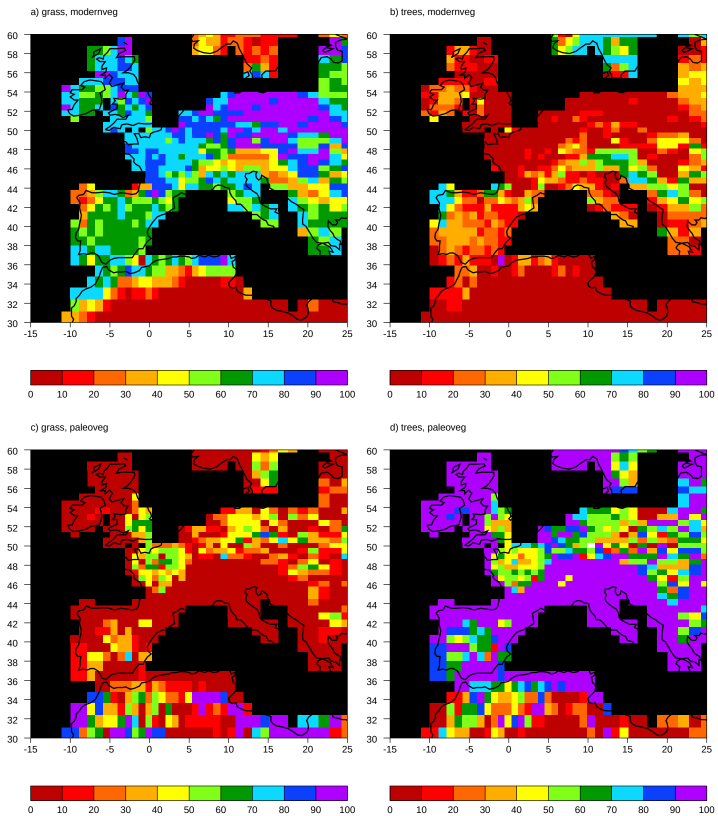

Fig. 5. Maximum percentage of herbaceous and arboreal coverage, i.e., the fraction calculated as the combination of grasses and crops and the sum of the arboreal PFTs, respectively, in the modern vegetation and simulated by ORCHIDEE for the Mid-Pliocene epoch: **(a)** modern herbaceous fraction, **(b)** modern arboreal fraction, **(c)** Mid-Pliocene herbaceous fraction, **(d)** Mid-Pliocene arboreal fraction.

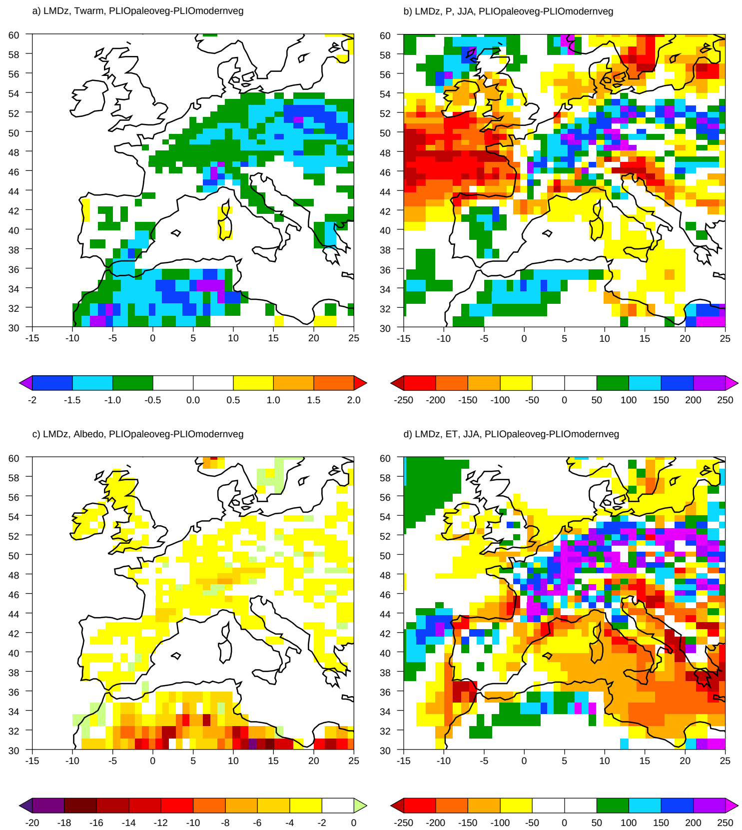

Fig. 6. Anomalies between PLIO-*paleoveg* and PLIO-*modernveg* runs: **(a)** mean temperature of the warmest month (°C), **(b)** summer (JJA: June, July and August) total precipitation rate (mm/yr), **(c)** albedo (%), **(d)** summer (JJA: June, July and August) evapotranspiration (mm/yr).

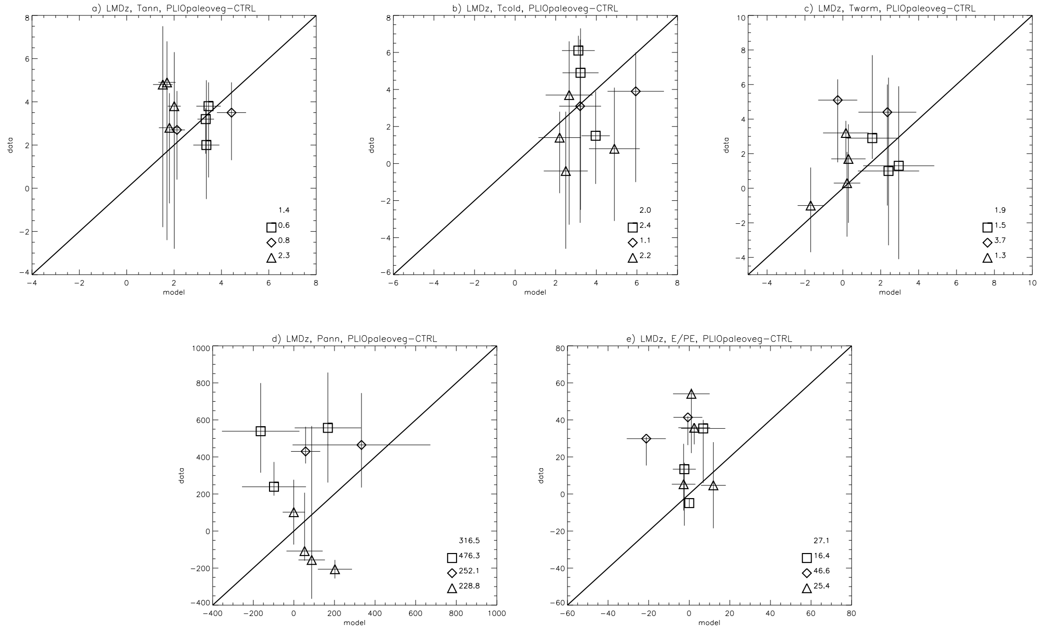

Fig. 7. Same as for Fig. 3 but PLIO-*paleoveg* results.

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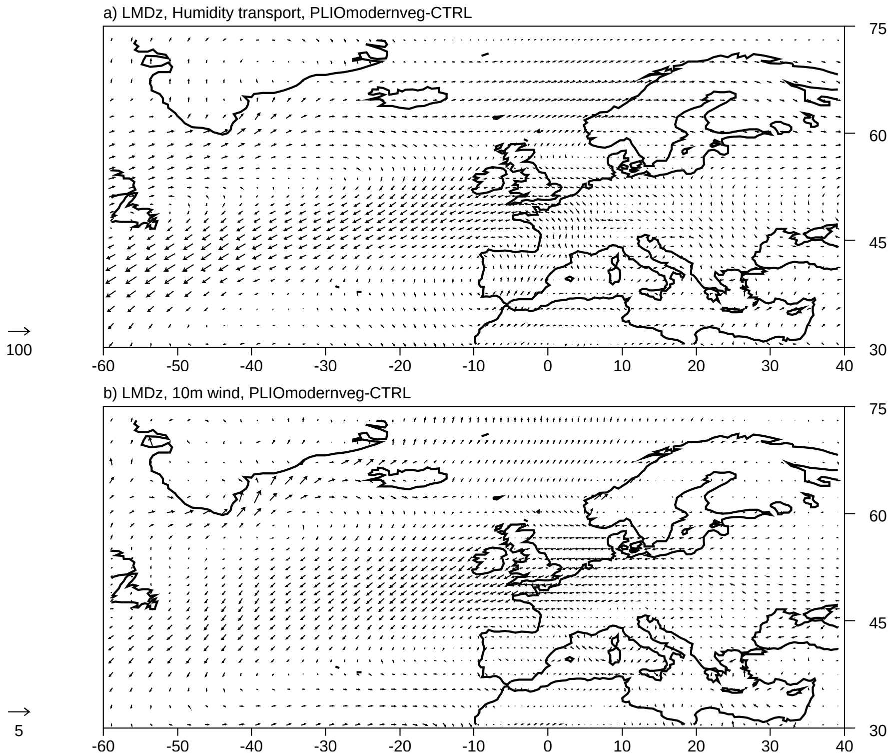

Fig. 8. **(a)** Humidity transport and **(b)** surface wind vectors (m/s) over North Atlantic. Mean annual mid-Pliocene anomalies from the present climate, PLIO-*modernveg* results.

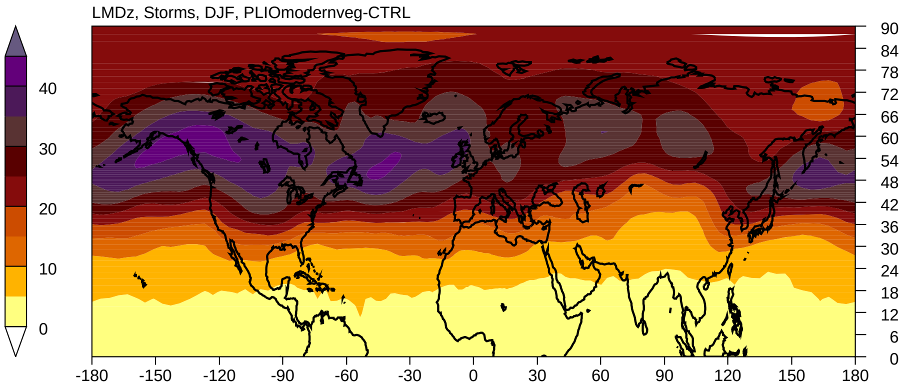

Fig. 9. Storminess (m) in the Northern Hemisphere, defined as the high pressure filtered standard deviation of the 500 hPa geopotential height (the filter keeps the variability for timescales between 2–7 days). Winter (DJF: December, January and February) Mid-Pliocene (PLIO-*modernveg* results) anomalies from the present climate.

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