Evaluation of Simulated Climate in Lower Latitude Regions during the Mid-Pliocene Warm Period Using Paleovegetation Data

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Abstract

Paleovegetational dataset during the mid-Pliocene warm period (MPWP) in lower latitudes are applied to evaluation for annual-mean MPWP climate simulated by a general circulation model (GCM). GCM-derived warmer climate in mid-latitude and wetter condition in subtropics during MPWP are generally confirmed by the terrestrial proxy data. The comparisons of their general patterns reveal an ability of GCM to predict the sustained-warmer climate under the different forcings from present day. In comparison to the proxy data, the enhanced rainfall over semi-arid regions in accordance with the alteration of Hadley/Walker circulation in MPWP is supported but the extent may be partially underestimated. The paleobotanical data in the lower latitudes indicate an importance of interactive response of vegetation to climate under the equilibrium warmer state of the earth system.

1. Introduction

Geographical distributions of surface ecosystem, including vegetation, are primarily influenced by climate changes. Global patterns of vegetation also change regional climate as a boundary forcing (e.g., Harrison et al. 1995) or through biogeophysical and/or biogeochemical feedbacks (e.g., Claussen 2009) on atmosphere-ocean-land interactions in the past and the future (e.g., Haywood and Valdes 2006; O'ishi et al. 2009). Evaluations of simulated paleoclimate with reconstructed paleovegetation data could test for the abilities of numerical climate models to simulate climate change under different boundary conditions and different forcing mechanisms (Bradley 1999).

The mid-Pliocene warm period (MPWP), between 3.29 and 2.97 million years ago, is one of the accessible scenarios in which global climate was substantially warmer than present day (PD) with modern geographical continent/ocean distributions and relatively higher CO_2 concentration in the atmosphere (e.g., Haywood et al. 2010). Paleoenvironmental data in MPWP reveal significant warmer climate in mid- and high-latitude, especially in the northern North Atlantic (~16 K), with the absence of increase in sea surface temperature (SST) in low latitude (e.g., Dowsett et al. 2009). Zonal gradient of SST in low latitude during MPWP is also largely different to that in PD. Kamae et al. (2011, hereafter KUK11) shows changes in wet/dry climate in low latitude in accordance with the alterations of Hadley/Walker circulation corresponding with the changes in meridional/zonal SST pattern. Figure 1a shows map of reconstructed vegetation during MPWP by paleobotanical data. In comparison to vegetation pattern in PD, the terrestrial proxy records in MPWP indicate; (1) poleward expansion of temperate/boreal forest at the expense of boreal forest and tundra grassland in mid- and high-latitude in accordance with the warmer climate, and (2) expansion of tropical savannas and woodland in Africa, Central Asia, and Australia at the expense of deserts corresponding with moister climate in the semi-arid regions (Salzmann et al. 2008, hereafter S08).

Previous studies discussing about responses of geographical patterns of vegetation under MPWP climate (e.g., Haywood et al. 2009; Lunt et al. 2009) used reconstructed paleovegetation dataset for Pliocene Research, Interpretation and Synoptic Mapping phase 2 (PRISM2), based on terrestrial proxy records in 74 sites (Thompson and Fleming 1996). S08 archived the new MPWP vegetation reconstruction (Fig. 1a) based on proxy data from 202 sites. Though some limitations (see Section 4), the state-of-the-art terrestrial proxy data

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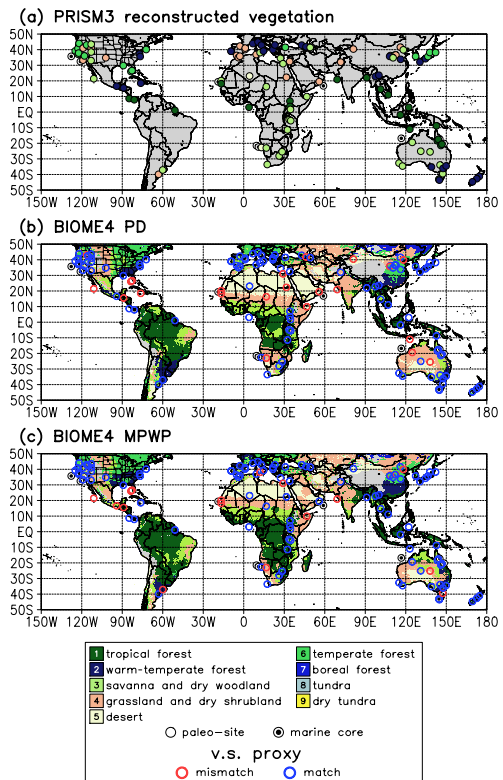
Fig. 1. (a) PRISM3 paleovegetation sites (118 sites in this study) and biomes during MPWP (modified from Haywood et al. 2009). Full references to paleo-sites are summarized in Salzmann et al. (2008, hereafter S08). (b) Biomes in PD and (c) MPWP simulated by BIOME4 model. Red (blue) circles denote that the simulated biome mismatches (matches) with the reconstructed type of MPWP biomes on individual sites. All biome types are classified into the MEGABIOME scheme.

allows us to evaluate the reproducibility of climate modeling for the sustained warmer interval by comparing the dataset with the climate simulated by the numerical climate model predicting the changes in tropical atmospheric circulations and monsoon/desert climate patterns in the lower latitudes. For that purpose, we evaluate the consistency of biomes deduced by BIOME4 model driven by climate parameters derived from KUK11 with the PRISM3 paleovegetation dataset (S08).

2. Data and method

2.1 BIOME4 model and experimental design

The equilibrium biogeography model, BIOME4 (Kaplan et al. 2003), is used to translate the climate data from the general circulation model (GCM) experiments into vegetation distributions. The model predicts the most-prevailed vegetation types (biomes) as a function of the seasonal cycle of climate parameters by physiological considerations. The BIOME4 and earlier members of the BIOME model family reproduced modern natural vegetation well and are suitable tools for the paleovegetation simulations (e.g., Harrison et al. 1998; Kaplan et al. 2003; see Supplement 1). For diagnostic purposes, we adopted an anomaly procedure (e.g., Harrison et al. 1998; Kaplan et al. 2003; Haywood et al. 2009) for biome simulations. To apply this procedure, differences in the climatological values of monthly mean precipitation, temperature, and percent of potential sunshine
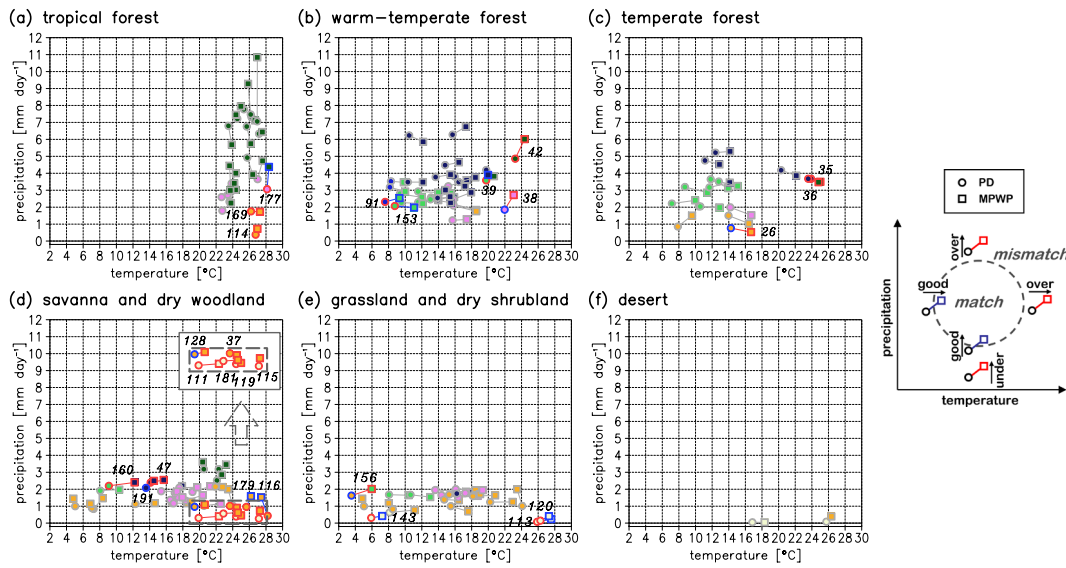
Fig. 2. Differences in the climate parameters for BIOME simulations between MPWP and PD. (a) Annual-mean surface air temperature (°C), and (b) precipitation rate (mm day^{-1}). Plotted symbols are evaluations of the climate parameters in individual sites. Details of the evaluations are described in Section 4.

Fig. 3. Locations of paleovegetation sites in which the simulated biomes classified into MEGABIOME types are (a) match in MPWP with the proxy data but mismatch in PD and (b) mismatch in MPWP. Colors in the circles represent the reconstructed vegetation on the individual sites classified into the MEGABIOME classification scheme. The code noted by each site reveals the site number used in S08.

hours between MPWP and PD are derived from climate simulations conducted in KUK11 and then added to a modern climatology. The atmospheric GCM used in KUK11, developed by Meteorological Research Institute (Yukimoto et al. 2006), has horizontal T42 resolution. The boundary conditions for the MPWP climate simulation (Haywood et al. 2010) include (1) modified continental elevation, (2) reduced ice-sheet size and height, (3) the SST and sea ice distribution (Dowsett et al. 2009), and the higher CO_2 concentration (405 ppmv). Details of the models and experimental setups for the biome and climate simulations are described in Supplement 1.

The climate parameters simulated in KUK11, annual-mean surface temperature and precipitation, which forced the biome simulation are shown in Fig. 2. The temperature anomaly in MPWP (Fig. 2a) is characterized by moderate changes in low latitude and increases (~1 to 5°C) in mid-latitude. The precipitation decreases over tropical Indian Ocean, tropical western Pacific, equatorial central Pacific, central South Pacific and equatorial western Atlantic, and increases over tropical and subtropical North Africa, central and subtropical South Asia and subtropical Oceania according to the changes in the Hadley and Walker circulations (Fig. 2b).

2.2 Data-model comparison on each site

The PRISM3 vegetation reconstruction (S08) was compiled from fossil pollen and plant macrofossil data from 202 terrestrial sites covering all continents and classified into 28 types of BIOME4 classification scheme. Figure 1a shows the location and biome type of paleobotanical data on each site. The dataset shows an exceptionally better spatial coverage relative to the previous version of the dataset (Thompson and Fleming 1996), allowing more detailed reconstruction of MPWP climate, especially in subpolar and subtropical regions. The use of the BIOME4 classification scheme allows a numerical comparison between climate parameters deduced from vegetation simulations with observational PD and GCM-derived anomaly (MPWP minus PD) climate data.

For the purposes of detecting relatively large changes in climate resulting in major alterations of vegetation, we adopted a simplified biome classification scheme, MEGABIOME, grouping individual biomes into major vegetation types (Harrison and Prentice 2003). We distinguish match or mismatch of MEGA-BIOME types between proxy and simulation by a criterion, whether the fraction of the area in which the simulated MEGABIOME is the same to the reconstructed type in the 1 grid of the GCM (~2.8°) square region is above 5% (match) or below (mismatch). The estimate of mismatches between the data and the model in this study using MEGABIOME scheme is relatively conservative.

This study only focuses on the relatively warmer regions and major pattern in differences of MEGABIOME because of some limitations (see Section 4). The paleobotanical data in the region between 45°S and 45°N are used in this study. We also eliminate the data in which the locations of the sites are higher than 2,000 m altitude. 118 sites of the paleovegetational proxy records used in this study are mapped in Fig. 1.

3. Results of biome simulations

Figures 1b and 1c show simulated vegetation patterns in the lower latitudes predicted by BIOME4 during PD and MPWP, respectively. The biomes are classified into the 9 types of MEGABIOME scheme. The MPWP vegetation in the lower latitudes (Fig. 1c) generally shows larger area of moister biomes than those in PD (Fig. 1b) in accordance with the precipitation increase (Fig. 2b). Tropical forest in equatorial and eastern South America, equatorial and South Africa, and southeastern Asia expand for wider regions in MPWP relative to PD. In subtropical North and South Africa, Central Asia, and Australia, savanna and grassland shift poleward, thus reducing the fractional coverage of desert. For example, the fractions of the areas for tropical forest and desert in MPWP relative to those in PD on African continent change for +65% and −30%, respectively. The MPWP biomes also reveal poleward displacements of warm-temperate, temperate, and boreal forest in mid-latitudes, particularly in North America, Europe, and Asia, relative to PD. The increase in the coverage of warmer-temperate forest in the mid-latitudes regions are mainly corresponding with the warmer surface condition (2~5°C) in MPWP (KUK11). The relative contributions of differences of the potential sunshine hours and atmospheric CO_2 concentration between MPWP and PD for the alterations in the biome patterns are minor (figures not shown) than those of the temperature and precipitation.

Blue/red circles in Fig. 1b (1c) represent whether the simulated biomes on individual sites in PD (MPWP) are match or mismatch with the reconstructed types of MPWP vegetation (Fig. 1a). The simulated MPWP vegetation (Fig. 1c) shows relatively better consistency with the reconstructed MPWP biomes (Fig. 1a) rather than that in PD (Fig. 1b), particularly in the semi-arid regions. Figure 3a shows locations of the 10 sites in which the simulated biome types are inconsistent with the proxy data (Fig. 1a) in PD (Fig. 1b) but consistent in MPWP (Fig. 1c). Site numbers used in S08 are labeled. The improving consistencies in the subtropical North Africa (site No. 113, 116), Arabian Peninsula (No. 120), and subtropical Australia (No. 179) correspond with the expansions of tropical forest, savanna, dry woodland, and grassland replaced by the drier biomes in the regions. The simulated transitions of biome types in the mid-latitudes are partly supported by the proxy records (No. 20, 91, 143, and 153). It is also noting that the simulated MEGABIOMEs on several sites in the MPWP experiment mismatch with the data (Fig. 3b). Generally, the discrepancies between the data and the model are located in subtropics, failing to reproduce the moister biomes by the model (savanna and forest are revealed by the data but grassland and savanna are simulated in the

Fig. 4. Scatter diagram with annual-mean surface temperature (°C) and precipication rate (mm day⁻¹) on each site. A set of circle and square denote climate parameters in PD and MPWP on each site determined by the anomaly procedure, respectively. (a) The sites in which paleovegetation record is classified into tropical forest, (b) warm-temperate forest, (c) temperate forest, (d) savanna and dry woodland, (e) grassland and dry shrubland, and (f) desert. Colors in the symbols represent the simulated vegetation classified into the MEGABIOME types. Red (blue) symbols denote that the simulated biome mismatches (matches) with the reconstructed type on individual sites. Grey symbols denote that both the PD and MPWP biomes match with the proxies. Labeled codes reveal site numbers used in S08. Schematic of the evaluations of climate parameters determined by the anomaly procedure is appended on the right side.

model). Relationships between anomalies in the climate parameters and the improvement of consistency (Fig. 3a) or the mismatch in MPWP biome simulation (Fig. 3b) are discussed in Section 4.

4. Evaluation of simulated MPWP climate

In this study, reproducibility of the anomaly (MPWP minus PD) climate derived from GCM is evaluated using paleovegetation records. However, the comparisons of the data and the model contain nonnegligible uncertainties. Discrepancies in the biome types between the data and the model using the anomaly procedure could be related to uncertainties in: (1) proxy data (spatial and/or temporal representativeness of sampling and non-uniformity); (2) present-day baseline climate (ground-based observation and human influences); (3) anomaly climate (GCM schemes and boundary conditions); and (4) biome simulation (BIOME4 scheme and experimental designs). Point-by-point comparisons in regional scale (scale with representativeness of a proxy data) contain considerable uncertainties as listed above. In larger scale (synoptic or continental scale), however, changes in climate state simulated by GCM might be major factor for inconsistencies of general patterns between data and model. BIOME4 simulations are mainly determined by climate parameters if contributions of other factors (soil property and atmospheric CO_2 concentration) are minor. The determinations of biome types by annual-mean climate parameters are limited, especially in the higher latitudes or high altitude regions, because the BIOME4 simulations under cold climate are strongly affected by seasonality in the parameters (e.g., accumulated growing-season warmth). In the lower latitude and low altitude regions, however, the general patterns of the alterations of

MEGABIOME types are corresponding with the large-scale changes of the climate parameters, which is apparent in the annual-mean value.

With the climate parameters and the match/mismatch of the PD and MPWP biome simulations with the proxy data, we evaluate the anomaly climate as: (1) under (over) estimate when the climate parameter is deficient (excess) for the "match" range; or (2) good estimate when the climate parameter in MPWP is inside but that in PD is outside of the "match" range. The evaluations are not applied in case both the simulated biomes in PD and MPWP are consistent with the proxy data. Figure 4 shows the climate parameters in PD and MPWP with the simulated biome types and the matching/mismatching in the individual sites. The major factors for the alterations in simulated MEGABIOME types in MPWP from PD are the intensification of subtropical rainfall and the mid-latitude warming (Fig. 2). The simulated biomes plotted with surface temperature and rainfall in Fig. 4 are the most prominent types in the range of 2.8° square (1 GCM grid size) around the individual sites. Comparing to the matching range (gray and blue symbols), the mismatching cases (red symbols) are often outlier, implying the factor for the mismatching might be the under/over estimate in the climate parameters. In contrast, simulated biomes in some sites in MPWP match with the proxy data although those in PD mismatch, indicating the anomaly climate in the sites are good estimates (blue symbols in Fig. 4). The schematic of the determinations for the evaluations of climate parameters is also shown in Fig. 4.

The climate parameters in the sites predicting tropical forest as the most prominent type are only found in the condition under relatively sufficient rainfall (above ~2 mm day⁻¹) and warmer environment (above ~20°C). In the cases of sites No. 114 and 169, the simulated types during MPWP are savanna or grassland although the reconstructed MPWP biomes are classified into tropical forest (Fig. 3a). These inconsistencies between the paleodata and the models are attributed to the insufficient rainfall in these sites during MPWP. In contrast, simulated biome transits from savanna in PD to tropical forest in MPWP on the island of Timor (No. 177), according with the increase in precipitation (+1.3 mm day⁻¹). We determine the evaluations of the precipitation anomalies superimposing on the PD climate as "under estimate" in the sites No. 114 and 169, and "good estimate" in No. 177. The evaluation method described above is also applied to the other types of MEGABIOMEs. Warm-temperate and temperate forests are dominant under conditions with sufficient amount of rainfall (Figs. 3b and 3c). Savanna and dry woodland are limited in relatively dry condition (Fig. 3b). Grassland sites (Fig. 3e) are appeared in the drier climate than savanna but wetter than desert (Fig.

Table 1. Evaluation for simulated anomaly climate in each site represented in Fig. 2. Upper panel listed evaluation for the surface air temperature and bottom panel shows that for the precipitation rate.

Evaluations	Site numbers
Surface temperature	
under estimate	−
good estimate	91, 153
over estimate	35, 36, 38, 42
Precipitation	
under estimate	26, 37, 111, 114, 115, 116, 119, 156, 169, 181
good estimate	113, 116, 120, 143, 177, 179
over estimate	47, 160, 191

3f). We exclude the sites No. 39 (Haiti) and No. 128 (Namibia) from the evaluation because the factors for the improving consistencies in MPWP relative to PD in these sites are not evident in the annual-mean changes of temperature and precipitation. The evaluations of the climate parameters in the individual sites are summarized in Table 1.

Figure 2 shows the changes in annual-mean temperature and precipitation simulated in KUK11 and their evaluations determined by the above method (Fig. 4 and Table 1). The simulated changes in biome types (Figs. 1b and 1c) corresponding with the temperature change (Fig. 2a) are consistent with the terrestrial proxies in several sites in mid-latitude (Caspian Sea and Central China). In contrast, the simulated MPWP temperatures on 4 sites in the Central America (No. 35, 36, 38, and 42) are evaluated as overestimates. In this region, particularly around the continental Mexico, the geographical density of the paleosites for SST reconstruction (Dowsett et al. 2009) is relatively scarce, resulting lower confidence in the GCM simulation in KUK11. In case for the precipitation change (Fig. 2b), the precipitation increases (~0.2 to 2.0 mm day^{-1}) in the semi-arid regions (subtropical North Africa, Arabian Peninsula, and subtropical Australia) are evaluated as sufficient (No. 113, 116, 120, 177, and 179) or underestimate (No. 114, 115, 111, 119, 169, and 181) for the reconstructed changes in the MEGABIOME types. The proxy-based biomes also reveal overestimate of simulated rainfall in some sites on western coast of the Pacific (Northeastern China and Southeastern Australia) in MPWP. The paleosites which are evaluated as the overestimates of the precipitation are only found in the relatively higher latitudes (southward from 35°S and northward from 35°N) although the major changes in precipitation are concentrated in the lower latitudes. These results reveal that the modeled-increases of precipitation in the subtropical regions are qualitatively consistent in all sites but the extents are partly deficient for the reconstructed-changes of the biomes.

The proxy data on some sites in semi-arid regions indicate the underestimates of precipitation increases in this study, which did not include the effects of the alterations in the geographical pattern of vegetation on the surface boundary in the GCM simulation (see details for the experimental design noted in Supplement 1). Differences of surface albedo and hydrological properties by altering the vegetation cover could change climate pattern through biogeophysical processes (surface/atmospheric heat budget and hydrological cycle). Simulated biomes with climate parameters derived from climate simulation prescribing the MPWP vegetation on surface boundary condition reveal larger expansions of moister vegetations in semi-arid regions than those in this study (see Supplement 2). The previous studies (Haywood and Valdes 2006; Lunt et al. 2009) also reveal that the interactive responses of vegetation to climate under the sustained warmer earth system contribute for the warmer conditions in mid- and high-latitude and the wetter climate in subtropics, which has an essential role for the evolutions of flora and fauna, including Hominids (e.g., Haywood and Valdes 2006; KUK11). These results indicate that the alteration of the terrestrial ecosystem has an important role for regional climate patterns under the warmer and moister condition for the sustained time.

5. Conclusion

The simulated climate during MPWP in the lower latitudes is evaluated by the paleovegetation data. The predicted MPWP biomes based on the climate parameters show (1) meridional shift of temperate forest corresponding with the warming in the mid- latitudes and (2) expansions of forests, savanna and grassland, and shrinking of desert in the subtropical regions according to the wetter conditions. The paleobotanical data supports the above tendencies including the changes in the geographical patterns of monsoon/desert climate in low latitude regions in accordance with the alterations of Hadley/Walker circulation under the sustained greenhouse world. In addition, the biome simulation including interactive response of vegetation to climate through the biogeophysical processes in the lower latitudes contributes to the more humid environment in the subtropics which is suggested by the paleodata.

This study also shows the regional inconsistencies between the data and the model, i.e., the overestimates of surface temperature around the Caribbean Sea and the overestimates of precipitation on the western coast of the Pacific. Further studies assessing about consistencies between different GCMs for the vegetation simulations are required for more confident evaluation of MPWP climate modeling in the future. Applications of the data-model comparison conducted in this study for the higher-latitude regions and other Pliocene simula-

tions using air-sea coupled GCMs or earth system models are also facilitated. They could help to provide insight into the earth climate system in the warmer world.

Supplements

Supplement 1 gives the document about the models and the experimental designs. Supplement 2 represents the simulated biome driven by the climate parameters with the forcing of the MPWP vegetation on surface boundary in climate simulation.

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