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Comparison of simulated changes of climate in Asia for two scenarios: Early Miocene to present, and present to future enhanced greenhouse

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Abstract

We use a climate model (GENESIS) to simulate the changes in climate associated with two scenarios, one from the past and one from the future, with a focus on the Asian continent. The two scenarios are: (1) Early Miocene to Present—a period of uplift of the Himalayan–Tibetan plateau and of decreasing concentration of atmospheric carbon dioxide; and (2) Present to Future Enhanced Greenhouse—a period of increasing concentration of atmospheric carbon dioxide. In the past climate scenario, the combination of uplift and decreased concentration of greenhouse gas causes the model to simulate widespread cooling and, primarily due to the effect of uplift, greatly increased precipitation in southern Asia and decreased precipitation in northern Asia. In the future climate scenario, the increased concentration of atmospheric carbon dioxide causes the model to simulate widespread warming and, by comparison with the past climate scenario, relatively small changes in precipitation; the changes are generally towards increased precipitation, except in parts of northern China. The output of the climate model, along with the changed concentration of atmospheric carbon dioxide, is also used to calculate changes in biome distributions. Owing to the high concentrations of atmospheric carbon dioxide in both the past and future scenarios, relative to present, the simulations of Early Miocene biomes and Future biomes are somewhat similar—and both are very unlike the Present.

Keywords: Asia; Early Miocene; Climate

1. Introduction

There have been large changes in the climate of Asia since the Early Miocene (An et al., 2001; Guo et al., 2002). Many of these climatic changes, which include widespread cooling, increased aridity in the Asian interior, and intensification of the winter and summer Asian monsoon circulations, have been simulated by climate models with prescribed uplift of the Himalayas and Tibetan Plateau and a lowering of the concentration of atmospheric carbon dioxide (Ruddiman et al., 1997a,b; Kutzbach et al., 1997; Prell and Kutzbach, 1997; An et al., 2001; see also earlier references included in these papers). The potential future climate changes associated with increased concentration of atmospheric carbon dioxide have also been simulated by many different climate modeling groups, and most of these models indicate warming and small increases of precipitation in much of Asia (IPCC, 2001). However, it is difficult to compare these past and future climate scenarios, and the differences relative to the present, unless the simulations are made

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with the same model. The purpose of this paper is to examine specific simulations of Early Miocene, Present, and Future climates over the Asian continent using the GENESIS climate model for all three experiments.

2. Model

The GENESIS climate model (Pollard and Thompson, 1997) that was used in the past, present and future climate experiments consists of an atmospheric model with T31 horizontal spectral resolution (approximately 3.7° latitude by 3.7° longitude) and 18 vertical levels, a 50-m mixed-layer ocean with a sea-ice parameterization, and a land surface hydrology module with soil moisture and snow cover parameterizations. The three climate simulations are each run for 20 years, and the results shown here are based upon the average climate of the last 5 years of integration.

3. Boundary conditions

Mountain/Plateau elevations: We use the distribution of mountains/plateaus as specified in Ruddiman et al. (1997a) to represent Early Miocene conditions. The land elevations in the region of the Himalayas and the Tibetan plateau are set to 0.25 of modern elevations, the Rocky Mountains and African highlands are set to 0.75 of modern, and the Alps, Andes, and Antarctic Ice Sheet are set to 1.0 of modern (i.e., no change in elevation). The Greenland Ice Sheet is removed and the underlying land elevation is set to 250 m; the land surface albedo of that region is prescribed to have a value typical of tundra-covered ground. Ruddiman et al. (1997a) provide a more complete discussion of these choices of surface topography boundary conditions.

Atmospheric carbon dioxide concentration: The concentration of atmospheric carbon dioxide for the period since the Early Miocene is only partially constrained by observations (Ruddiman et al., 1997a,b). Future scenarios also include a range of carbon dioxide concentration levels, depending upon assumptions of population and energy usage (IPCC, 2001). For both the Early Miocene simulation and the Future simulation, we use an atmospheric carbon dioxide concentration of three times present ($3 \times CO_2$), or, more specifically, three times the value of 330 ppm that was used in the control simulation of the climate model: $330\ \text{ppm} \times 3 = 990\ \text{ppm}$. For the Future climate simulation, this value is at the high end of a range of carbon dioxide concentration estimates for the year 2100. For the Early Miocene climate simulation, estimates of carbon dioxide concentration range from values near present to values three times present or higher (Crowley and Berner, 2001). A rationale for using enhanced greenhouse gas forcing for the Early Miocene was presented in Ruddiman et al., 1997a, based upon isotopic analyses of marine organic carbon and upon changes of vegetation as evidence of a changed photosynthetic pathway. A more recent study (Retallack, 2001), based upon counts of leaf stomatal abundance, places CO_2 concentration at or above 1000 ppm until about 8 million years ago. However, another recent study (Pagani et al., 1999), based upon carbon isotope analyses of marine sediments, indicates that CO_2 concentrations may have been at or below preindustrial levels (i.e., 280 ppm) in the Miocene. Clearly, the carbon dioxide concentration level for the period from the Miocene to the present, and for the Future, remains uncertain. For illustrative purposes, however, we use the same level of carbon dioxide concentration in both past and future scenarios, such that changes between the Early Miocene simulation and Future simulation can be attributed solely to the changed topography.

4. Results

4.1. Simulated climate changes—Early Miocene to Present

Simulations of climate changes since the Early Miocene have been discussed in considerable detail elsewhere (Ruddiman et al., 1997a,b; Kutzbach et al., 1997). In particular, these previous studies have emphasized the seasonal changes of climate, including the intensification of both the Asian summer and winter monsoons associated with uplift, and the general lowering of temperature associated with decreased concentration of atmospheric carbon dioxide. Moreover, Ruddiman et al. (1997a,b) isolated the effects of uplift and the effects of carbon dioxide lowering by analyzing simulations that separate these two boundary condition changes. For example, they showed that Northern Hemisphere land surface temperatures were lowered about 5 °C in both summer and winter by replacing “no mountains” with “modern mountains” and that a similar lowering of about 5 °C in both summer and winter could be achieved by lowering carbon dioxide concentrations from “two times present” to “present” levels. Although these earlier results of Ruddiman et al. (1997a,b) and Kutzbach et al. (1997) were obtained using a climate model (CCM1) of lower horizontal and vertical resolution than the GENESIS model used here, the results are similar and the reader is referred to these earlier studies for more details of the seasonal changes. This paper summarizes not only annual average changes (Figs. 1 and 2), but also includes area average changes of temperature, precipitation, and precipitation-minus-evaporation for various latitude zones in Eastern Asia

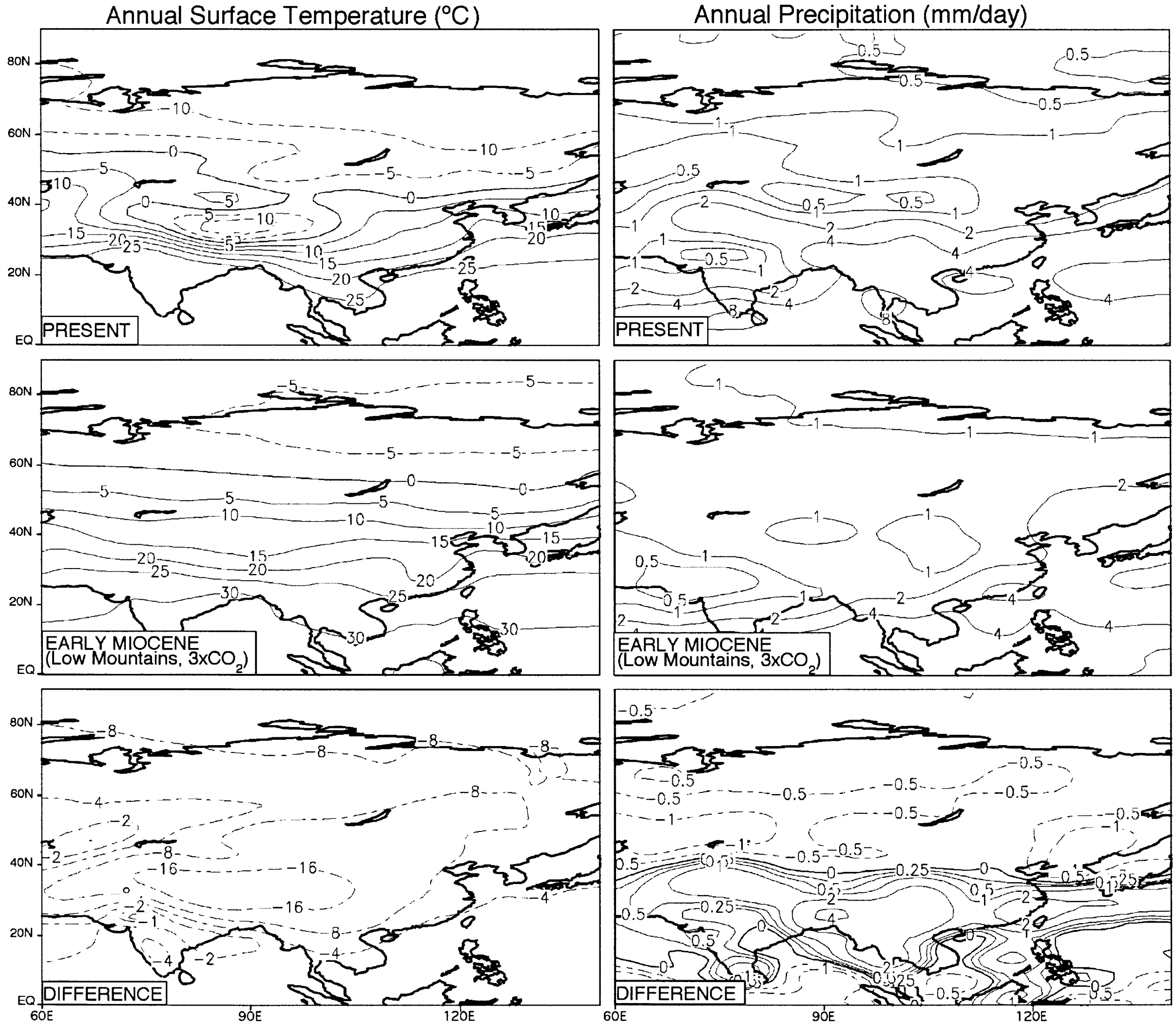

Fig. 1. Simulation of Annual Surface Temperature (°C), left, and Annual Precipitation (mm/day), right. The simulations are from a global climate model, and are shown here for the region from 60° E to 150° E and from Equator to Pole. The simulations are for the Present (top) and for the Early Miocene (middle). The bottom panels show differences in climate, Present minus Early Miocene; thus, the simulated effect of uplift and lowering of atmospheric carbon dioxide concentration is to cause widespread cooling, wetter conditions in southern Asia, and drier conditions in northern Asia.

(Table 1). Because of the somewhat higher horizontal resolution of the GENESIS model (3.7° latitude by 3.7° longitude) relative to the previous-used model (4.4° latitude by 7.5° longitude), these area average calculations are based upon a larger number of grid cells than would be the case at lower resolution.

The imposed carbon dioxide decrease and mountain/plateau uplift that occurs between the Early Miocene and Present scenarios causes a simulated cooling on the order of 5–10 °C over much of the Asian continent, with even larger cooling (15 °C) in the region of the uplifted terrain (Fig. 1, Table 1). In regions outside the area of uplifted terrain, about half the cooling is due to effects of uplift, while half is due to CO_2 lowering (not shown, but similar to Ruddiman et al., 1997a,b). As already mentioned, uplift causes strengthened monsoons and increased seasonality of precipitation (Kutzbach et al., 1997; Ruddiman et al., 1997a,b). Summer monsoon precipitation is increased in India, Southeast Asia, and China; summer and winter precipitation is decreased north of about 40° N. These seasonal changes result in increases of annual average precipitation exceeding 50% in some parts of southern Asia, and decreases of annual average precipitation exceeding 25% in some parts of northern Asia (Fig. 1, Table 1). In China, summarized for the latitude zone 25–40° N and longitudes east of 100° E (Table 1), the annual average temperature declines from 18 to 9 °C, and the annual average precipitation increases from 1.7 to 2.7 mm/day.

4.2. Simulated climate changes—Present to Future

The simulated changes of climate due to the imposed increased concentration of CO_2 include widespread warming of 3–6 °C in the annual average (Fig. 2). In the northern polar region, were sea-ice cover and snow cover are reduced, this warming exceeds 8 °C (see Ruddiman et al., 1997a,b; Kutzbach et al., 1997). Precipitation increases in most of Asia (Fig. 2), but the changes are relatively small compared to those associated with uplift (Fig. 1). In China (Table 1), the annual average temperature increases from 9 to 13 °C, and the area average change of precipitation, 25–40° N, is near zero; precipitation increases slightly in the south of China, and decreases slightly in the north (Fig. 2). Precipitation-minus-evaporation decreases slightly in China, owing to the warmer conditions (Table 1). In the region south of 25° N and in the regions north of 40° N there are small increases of precipitation (Table 1).

Table 1
Temperature, precipitation, precipitation minus evaporation: Early Miocene (EM), Present (P) and Future (F)

Latitude (N)	Temperature (°C)			Precipitation (mm/day)			P–E (mm/day)		
	EM	P	F	EM	P	F	EM	P	F
60–70°	−4	−11	−6	1.3	0.9	1.1	0.7	0.4	0.55
40–60°	4	−3	1	2.0	1.4	1.5	0.7	0.4	0.37
25–40°	18	9	13	1.7	2.7	2.7	−0.1	0.8	0.7
15–25°	25	19	22	3.5	5.3	5.5	0	2.0	2.0

Results for four areas in Asia east of 100° E (15–25°, 25–40°, 40–60°, and 60–70° N).

The changes in precipitation due to increased greenhouse gas concentrations simulated by the GENESIS model are in general agreement with the intermodel comparisons summarized for nine climate models by the IPCC (2001); for Eastern Asia, these models tend to show little or no change (plus to minus 5%) south of about 20° N, and small increases (5–20%) between about 20° N and 50° N.

4.3. Simulated climate changes—Early Miocene to Present to Future

The simulated changes in annual average temperature, precipitation, and precipitation-minus-evaporation for Asia east of 100° E, and for four latitude bands (15–25°; 25–40°; 40–60°; and 60–70° N) are summarized for all three experiments in Table 1. This summary permits direct comparison of the Early Miocene and Future scenarios for these four areas. Overall, for the four areas, temperature decreases by 6–9 °C from the Early Miocene to Present, but then increases by 3–5 °C between the Present and Future. Thus, the warming, relative to present, in the Future climate scenario "recovers" about half of the cooling simulated between the Early Miocene and Present.

Precipitation changes show different trends north and south of about 40° N (Table 1). South of 40° N, precipitation increases significantly (50% or more) from the Early Miocene to the Present, due primarily to uplift and enhanced summer monsoon rainfall. The precipitation in this region also increases slightly

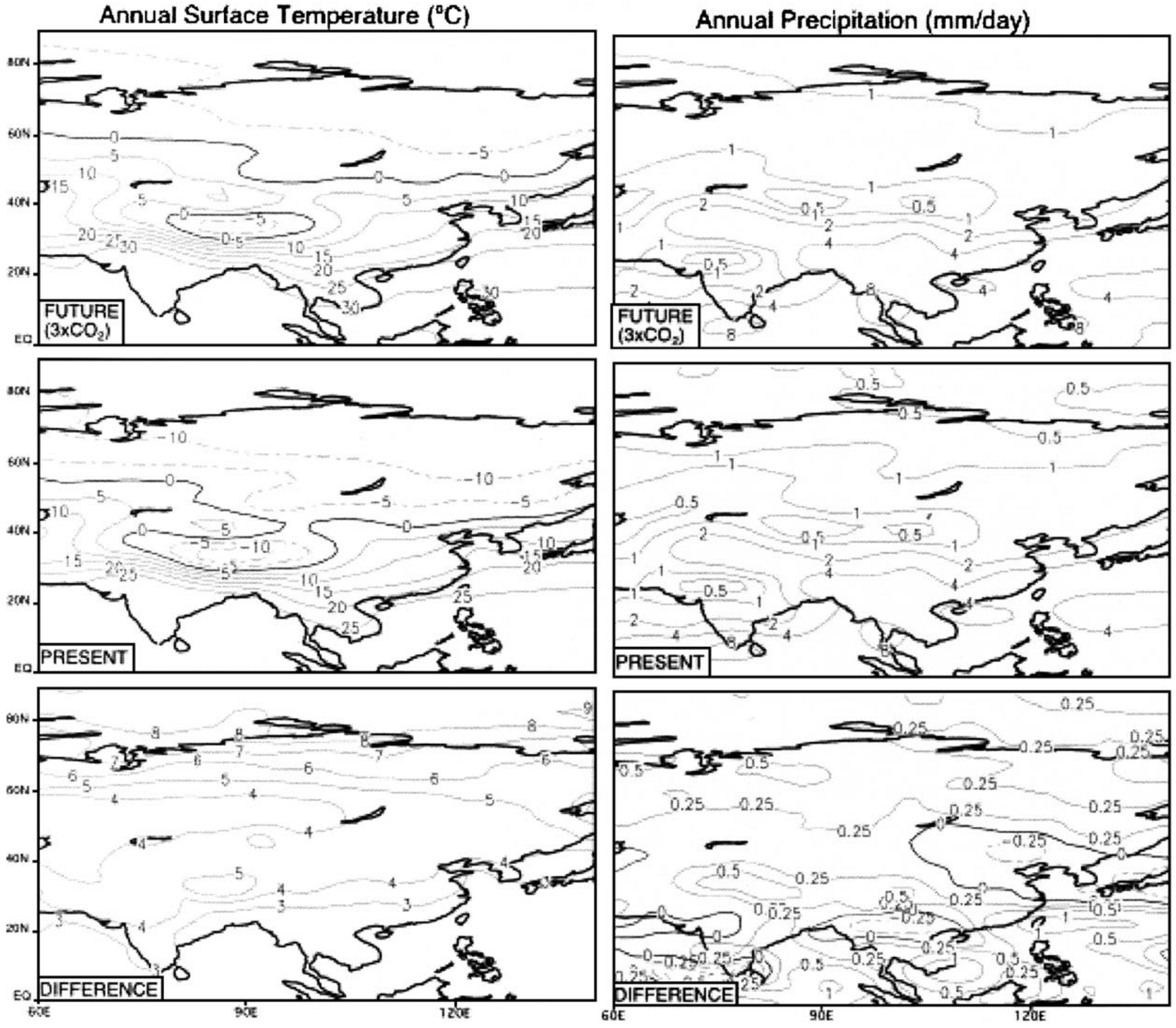

Fig. 2. Simulation of Annual Surface Temperature (°C), left, and Annual Precipitation (mm/day), right. The simulations are from a global climate model, and are shown here for the region from 60° E to 150° E and from Equator to Pole. The simulations are for the Future (top) and for the Present (middle). The bottom panels show differences in climate, Future minus Present; thus, the simulated effect of increasing atmospheric carbon dioxide concentration is to cause widespread warming and relatively small regional changes in precipitation (see text for details).

between the Present and Future. North of 40° N, precipitation decreases significantly (25% or more) from the Early Miocene to the Present, due to increased continentality associated with the uplift to the south. Precipitation increases (5% or more) between the Present and Future; thus, in the north, the trend of increased aridity from Early Miocene to Present is slightly reversed in the Present to Future scenario.

Changes in precipitation-minus-evaporation, Early Miocene to Present to Future, follow closely the changes in precipitation in the far north and south. However, in midlatitudes (25–60° N) the increased temperature in the Future scenario leads to sufficient increases of evaporation such that Present to Future (P–E) decreases in spite of steady or increased precipitation.

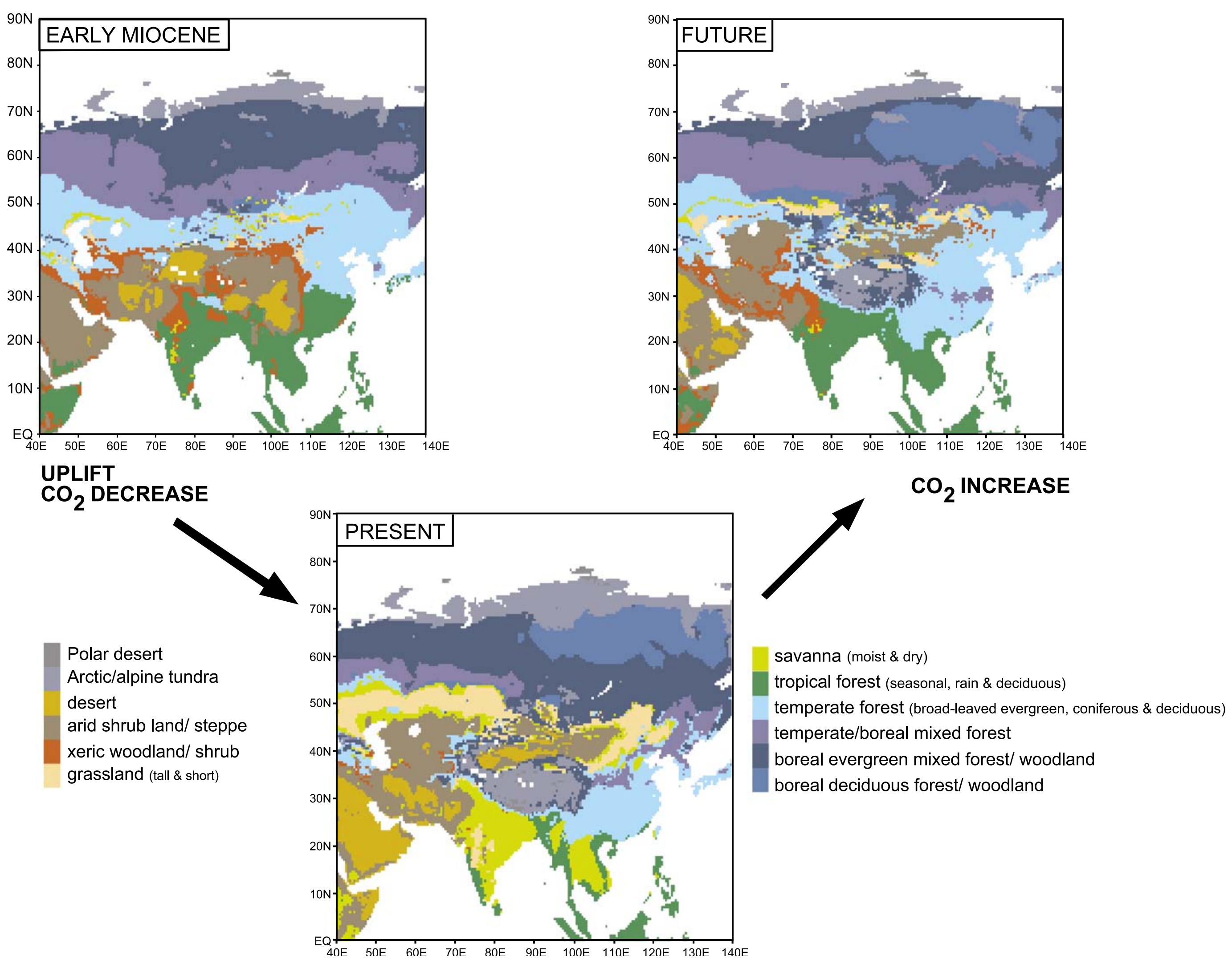

Fig. 3. Vegetation biomes for the Early Miocene, Present, and Future Scenarios. The biomes were obtained by using output from the climate model simulations as input to Biome 3, and include the physiological effects of higher CO_2 levels in the past and future scenarios (see text for details; for clarity, the results are shown for 12 broad-scale biomes that represent combinations of the 18 biomes simulated in the biome model).

4.4. Simulated changes in biome distributions

We used BIOME 3 (Haxeltine and Prentice, 1996), an equilibrium vegetation model, to translate the simulated changes in monthly average temperature, precipitation, and insolation, and the changed atmospheric carbon dioxide concentration, into biome categories (tundra, forest, savanna). The BIOME model includes parameterizations for the response of vegetation to changes in atmospheric carbon dioxide concentration: increased (decreased) CO_2 causes increased (decreased) photosynthesis and increased (decreased) water use efficiency. The resulting biomes, grouped into broad categories, are shown in Fig. 3. We used modern climatological data to derive the present biomes, and used the modern data plus the differences of the temperature, precipitation and insolation (Early Miocene and Future) from the Control (Present) simulation to derive the Early Miocene and Future biomes. This method of calculating biomes with BIOME 3 from the results of climate model simulations was used in a previous study by Ruddiman et al. (1997a), except that study used the lower-resolution CCM1 climate model instead of GENESIS, used $2 \times CO_2$ for the Early Miocene simulation instead of $3 \times CO_2$, and showed results for 18 biomes rather than 12 biomes. Here, we use only 12 biomes to simplify the coloring scheme of the figure; this lumping of categories results in some differences between the biome distributions, as simulated for the Present, and observations that may use other biome categories.

The dominant trends in biomes, Early Miocene to Present, and Present to Future, are seen in Fig. 3, and summarized here. The trends in biomes from the Early Miocene to the Present are similar to those reported previously based upon simulations with the lower-resolution climate model (Ruddiman et al., 1997a). The vegetation shifts from tropical forest toward savanna in South Asia, from tropical or temperate forest toward temperate forest in much of South and East China, from temperate forest toward desert/steppe/grassland north and east of the Tibetan plateau, from mixed temperate/boreal forest toward boreal forests in North Asia, and from boreal forest toward tundra along the northern coast of Asia. When the Future scenario of climate changes and the carbon dioxide increase are used as input to the biome model, these trends are largely reversed (Fig. 3). Thus, the simulated biomes for the Early Miocene and Future scenarios (both with three times present levels of carbon dioxide) resemble each other far more closely than either resemble the Present scenario (Fig. 3). The difference in biomes between the Early Miocene and Future scenarios is due only to the changed topography in the region of the Tibetan Plateau—because we set the elevated CO_2 levels to the same high value in both cases.

These biome changes represent only the response of vegetation to the imposed change of climate, rather than the coupled system response that would include the two-way interactions between vegetation and climate. Previous work has shown that shifts from desert to grassland, and from tundra to forest, caused by changes in orbitally forced insolation, result in positive feedbacks that further increase rainfall and temperature, respectively (Doherty et al., 2000; Ganopolski et al., 1998; Claussen and Gayler, 1997). Therefore, one can anticipate that the use of coupled climate–vegetation models might result in climate changes that exceed the changes reported here. The regions south of 40° N might have become even wetter, and the regions north of 40° N might have become even drier, in response to uplift.

Levis et al., 2000, using a coupled climate–vegetation model, found that increasing levels of atmospheric CO_2 concentration could lead to either an increase or a decrease in available soil moisture, depending upon the vegetation changes and the regional climate's ability to recirculate water vapor. In midlatitudes, they found that increasing levels of CO_2 generally led to reduced precipitation because the reduction in transpiration due to increased plant water use efficiency resulted in less recycling of water vapor for precipitation. This particular feedback didn't operate as effectively in the tropics.

5. Conclusions

These simulations of Asian climates for Early Miocene and Future scenarios illustrate that both the Early Miocene and Future are significantly warmer than present. In the simulations, this increased warmth is due primarily to the prescribed increased concentration of atmospheric carbon dioxide (three times present levels). Although both simulations are warmer than present, the Early Miocene scenario is warmer than the Future scenario because of its lower land elevation. The changes in precipitation between the Early Miocene and both the Present and Future scenarios are also large, due primarily to the role of mountain/plateau uplift in enhancing monsoon circulations since the Miocene. There is increased summer monsoon precipitation in the south and decreased precipitation in the north. By comparison with the response of precipitation to uplift, the response of precipitation to carbon dioxide changes is relatively small. Therefore, both Present and the Future scenarios have significantly wetter climates than the Early Miocene in south and East Asia. In northern Asia, where the reduction of precipitation due to uplift was relatively smaller, the Future scenario is wetter than Present, but still drier than in the Early Miocene scenario. While the simulated climates of the Early Miocene and Future scenarios are significantly different due to uplift, the simulated biomes are more similar. This greater similarity in biomes, relative to climate, is due to the large physiological response of vegetation to changes in carbon dioxide concentration, which were set to be the same for both the Early Miocene and the Future scenarios. Thus, the combination of the warmer climate and elevated CO_2 level causes the biome distributions of the Early Miocene and Future scenarios to be similar, except in the regions of the large differences in summer precipitation caused by uplift, and both the Early Miocene and Future biome distributions differ markedly from the Present.

The simulated climate of the Miocene has been compared with indicators of Miocene climate from the aeolian sediments of the Loess Plateau of China (An et al., 2001; Guo et al., 2002) and from marine sediments of the Indian and Pacific Oceans (An et al., 2001).

A future project would be to compare the simulated Miocene vegetation with estimates of paleovegetation from the Miocene. Such a comparison would assist in validating the accuracy of the model. In addition, it will be important to include the effects of the atmosphere's interaction with a dynamic ocean rather than a mixed layer ocean (Rind et al., 1997; Vavrus and Kutzbach, 2002; Kutzbach et al., in preparation). The exact level chosen for atmospheric carbon dioxide concentration if of major importance for the climate and biome simulations of both the Early Miocene and the Future, and further work is required to more firmly establish the level of carbon dioxide concentration in the Early Miocene.

Comparison of these climate scenarios and biome distributions for the Early Miocene and for the Future serves to indicate the potentially very large changes in climate and biomes that may occur in Asia if carbon dioxide concentrations rise to levels approaching three times present.

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References

An, Z., Kutzbach, J.E., Prell, W.L., Porter, S.C., 2001. Evolution of Asian monsoons and phased uplift of the Himalaya–Tibetan plateau since Late Miocene times. Nature 411, 62–66.

Claussen, M., Gayler, V., 1997. The greening of the Sahara during the mid-Holocene: results of an interactive atmosphere–biosphere model. Global Ecology and Biogeography Letters 6, 369–377.

Crowley, T.J., Berner, R.A., 2001. CO2 and climate change. Science 292, 870–872.

Doherty, R., Kutzbach, J.E., Foley, J., Pollard, D., 2000. Fully-coupled climate/dynamical vegetation model simulations over Northern Africa during the mid-Holocene. Climate Dynamics 16, 561–573.

Ganopolski, A., Kubatzki, C., Claussen, M., Brovkin, V., Pethourkov, V., 1998. The influence of vegetation–atmosphere–ocean interaction on climate during the mid-Holocene. Science 280, 916–1919.

Guo, Z.T., Ruddiman, W.F., et al., 2002. Onset of Asian desertification by 22 Myr ago inferred from loess deposits in China. Nature 416, 159–163.

Haxeltine, A., Prentice, I.C., 1996. BIOME3: an equilibrium biosphere model based on ecophysiological constraints, resource availability and competition among plant functional types. Global Biogeochemical Cycles 10, 693–709.

IPCC, 2001. Climate change 2001: the scientific basis—summary for policymakers and technical summary of the working group 1 report; part of the contribution to the IPCC Third Assessment. Cambridge University Press, 98 pages.

Kutzbach, J.E., Ruddiman, W.F., Prell, W.L., 1997. Possible effects of Cenozoic uplift and CO2 lowering on global and regional hydrology. In: Ruddiman, W.F. (Ed.), Tectonic Uplift and Climate Change. Plenum, New York, pp. 149–170.

Levis, S., Foley, J.A., Pollard, D., 2000. Large-scale vegetation feedbacks on a doubled CO2 climate. Journal of Climate 13, 1313–1325.

Pagani, M., Arthur, M.A., Freman, K.H., 1999. Miocene evolution of atmospheric carbon dioxide. Paleoceanography 14 (3), 273–292.

Pollard, D., Thompson, S.L., 1997. Climate and ice-sheet mass balance at the last glacial maximum from the GENESIS version 2 global climate model. Quaternary Science Reviews 16, 841–864.

Prell, W.L., Kutzbach, J.E., 1997. The impact of Tibet–Himalayan elevation on the sensitivity of the monsoon climate system to changes in solar radiation. In: Ruddiman, W.F. (Ed.), Tectonic Uplift and Climate Change. Plenum, New York, pp. 171–201.

Retallack, G.A., 2001. A 300-million-year record of atmospheric carbon dioxide from fossil plant cuticles. Nature 411, 287.

Rind, D.G., Russell, W.F., 1997. The effects of uplift on ocean–atmosphere circulation. In: Ruddiman, F. (Ed.), Tectonic Uplift and Climate Change. Plenum, New York, pp. 123–147.

Ruddiman, W.F., Kutzbach, J.E., Prentice, I.C., 1997a. Testing the climatic effects of orography and CO2 with general circulation and biome models. In: Ruddiman, W.F. (Ed.), Tectonic Uplift and Climate Change. Plenum, New York, pp. 203–235.

Ruddiman, W.F., Raymo, M.E., Prell, W.L., Kutzbach, J.E., 1997b. The uplift-climate connection: a synthesis. In: Ruddiman, W.F. (Ed.), Tectonic Uplift and Climate Change. Plenum, New York, pp. 471–515.

Vavrus, S., Kutzbach, J., 2002. Sensitivity of the thermohaline circulation to increased CO2 and lowered orography. Geophysical Research Letters 29 (11) (10.1029/2002 GL014814), 41-1 to 41-4.