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Mid-Holocene greening of the Sahara: first results of the GAIM 6000 year BP Experiment with two asynchronously coupled atmosphere/biome models

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Abstract The mid-Holocene ‘green’ Sahara represents the largest anomaly of the atmosphere-biosphere system during the last 12 000 years. Although this anomaly is attributed to precessional forcing leading to a strong enhancement of the African monsoon, no climate model so far has been able to simulate the full extent of vegetation in the Sahara region 6000 years ago. Here two atmospheric general circulation models (LMD 5.3 and ECHAM 3) are asynchronously coupled to an equilibrium biogeochemistry model to give steady-state simulations of climate and vegetation 6000 years ago, including biogeophysical feedback. The two model results are surprisingly different, and neither is fully realistic. ECHAM shows a large northward extension of vegetation in the western part of the Sahara only. LMD shows a much smaller and more zonal vegetation shift. These results are unaffected by the choice of ‘green’ or modern initial conditions. The inability of LMD to sustain a ‘green’ Sahara 6000 years ago is linked to the simulated strength of the tropical summer circulation. During the northern summer monsoon season, the meridional gradient of sea-level pressure and subsidence over the western part of northern Africa are both much weaker in ECHAM than in LMD in the present as well as the mid-Holocene. These features allow the surface moist air flux to penetrate further into northern Africa in ECHAM than in LMD. This comparison illustrates the importance of correct simulation of atmospheric circulation features for the sensitivity of climate models to changes in radiative forcing, particularly for regional climates where atmospheric changes are amplified by biosphere-atmosphere feedbacks.

1 Introduction

The mid-Holocene climate, around 6 ka (6000 years before present), was different from the present-day in several important respects. Paleocological data, synthesized most recently by the BIOME 6000 project (Prentice and Webb 1998), indicate warmer growing seasons in the Northern Hemisphere mid- to high latitudes, and in some regions warmer winters as well, e.g. winter temperatures in north and northeast Europe were 1–3 K warmer than present (Cheddadi et al. 1997). The largest difference between the mid-Holocene and present climates however is in northern Africa where conditions very much wetter than today are indicated by paleoclimatological reconstructions using ancient lake sediments (Street and Grove 1976; Street-Perrott and Harrison 1985; Yu and Harrison 1996), offshore marine pollen data (Dupont 1993), paleodune evidence (Sarnthein 1978), archaeological evidence (Petit-Maire 1989) and terrestrial pollen and plant macrofossil records (Street-Perrott and Perrott 1993; Jolly et al. 1998a, b). According to the BIOME 6000 reconstructions by Jolly et al. (1998b) grassland and shrubland vegetation were found at least as far north as 23°N, whereas today the desert extends southwards to 12°N.

It has been hypothesized (Kutzbach and Street-Perrott 1985; COHMAP members 1988) that differences between modern and mid-Holocene climates were caused by changes in the Earth’s orbit. Six thousand years ago perihelion was close to the autumnal equinox, the tilt of the Earth’s axis was about 0.7° greater than today, and the eccentricity of the Earth’s orbit around the Sun was slightly larger (0.187 instead of 0.167
today). These changes led to increased solar radiation in the Northern Hemisphere summer, which increased land-sea contrast and amplified the African and Indian summer monsoons, thereby increasing moisture transport into northern Africa. This hypothesis is now generally accepted, partly because experiments with atmospheric general circulation models (AGCMs) repeatedly confirmed its plausibility (e.g. Kutzbach and Guetter 1986; Mitchell et al. 1988; Phillips and Held 1994; Dong et al. 1996; Kutzbach et al. 1998). However, it has recently become clear that orbital forcing at 6 ka cannot produce a realistically large expansion of vegetation in northern Africa when changes in land and ocean surface conditions are not taken into account. This conclusion has been demonstrated with 18 AGCMs within the Paleoclimate Modelling Intercomparison Project (PMIP) (Joussaume and Taylor 1995; Harrison et al. 1998; Joussaume et al. 1999). AGCM sensitivity studies for 6 ka, with prescribed but appropriately modified land-surface conditions (e.g. Street-Perrott et al. 1990; Foley et al. 1994; TEMPO 1996; Kutzbach et al. 1998) have shown that positive feedbacks between climate and vegetation may have been involved, amplifying treeline shifts in boreal latitudes as well as vegetation changes in the tropics. Such sensitivity studies formed the background of the GAIM 6000 year BP experiment (Anon 1994) which recommended the use of coupled atmosphere-biosphere models to quantify these feedbacks. The GAIM 6000 year BP experiment in turns stimulated the development of the BIOME 6000 project (Prentice and Webb 1998), whose first objective has been to provide a view of the biosphere that can be used as a benchmark for paleoclimate modelling.

Feedbacks between vegetation and atmospheric circulation in the tropics can partly be explained in terms of Charney’s (1975) theory of a self-induction of deserts through albedo enhancement in the Sahel (Lofgren 1995a, b; Claussen 1997; Claussen and Gayler 1997; Texier et al. 1997; Zheng and Eltahir 1998). Interactively coupled atmosphere-vegetation models have been used to test the plausibility of this theory (Claussen 1997). However, recent applications of such models to the mid-Holocene have yielded somewhat divergent results. Claussen and Gayler (1997) found a rather strong increase of vegetation cover in the Sahara, more or less agreeing with paleoecological reconstructions for the western part of northern Africa. Texier et al. (1997) also found that biosphere feedbacks were important in this region, but were not able to produce such an extensive greening. A recent sensitivity experiment (Broström et al. 1998), using a geographically realistic land-surface pattern for 6 ka based on Hoelzmann et al. (1998), was likewise not able to sustain the vegetation initially prescribed.

These differences in results are certainly caused by differences among the atmospheric models used (ECHAM by Claussen and Gayler 1997; LMD by Texier et al. 1997; CCM by Broström et al. 1998). The two groups running coupled atmosphere-biosphere models used the same vegetation model. The only difference concerns the method of coupling (direct in ECHAM; anomaly based in LMD).

We first eliminate the different coupling methods as the cause of the different model results, and then investigate the role of differences in simulated features of the large-scale circulation as possible causes of differential sensitivity of the coupled models.

### 2 Models and coupling strategies

#### 2.1 Biome model

Biomes, i.e. macro-ecosystems in equilibrium with climate, are computed using the BIOME model (version 1.0) developed by Prentice et al. (1992). In the BIOME model, 14 plant functional types are assigned climate tolerances in terms of bioclimatic variables of which the most important are coldest monthly mean temperature, yearly temperature sum, and the ratio of actual to equilibrium evapotranspiration. The model predicts which plant functional type can occur in a given environment, i.e. for a given set of bioclimatic variables. Competition between different plant types is treated indirectly by the application of a dominance hierarchy which excludes certain types of plants as dominants based on the presence of other types rather than because directly of climate. Finally, the biomes are defined as combinations of dominant plant types.

The BIOME model is based on physiological considerations (as regards the choice of bioclimatic control variables and of their numerical prescribed thresholds for each plant type) rather than relying on correlations between climate and biomes as they exist today. Therefore the BIOME model is suitable as a tool to assess changes in natural vegetation in response to changes in climate. BIOME does not simulate the transient behaviour of vegetation, so it is not suitable for full integration into an AGCM (see Foley et al. 1998), but it can be interfaced with an AGCM through equilibrium asynchronous coupling as used here.

#### 2.2 LMD atmospheric general circulation model

The LMD AGCM (Sadourny and Laval 1984; Harzallah and Sadourny 1995) is a grid-point model that has 64 points regularly spaced in longitude (5.625°) and 50 points regularly spaced in the sine of latitude (~2.3° in equatorial regions and ~4° to 6° poleward of 40°). Eleven vertical sigma levels are unevenly spaced, four being in the planetary boundary layer where the resolution is the finest, four in the free troposphere and 3 in the stratosphere. The model is used with full seasonal cycle but no diurnal cycle for insolation. Calculations of radiative transfers are done using the scheme described in Fouquart and Bonnel (1980) for solar radiation and the scheme developed by Morcrette (1991) for infrared radiation. Condensation is produced using three schemes in a sequential mode: (1) a moist adiabatic adjustment scheme (Manabe and Strickler 1964), (2) a Kuo-type scheme (Kuo 1965) which allows for the formation of tropical convective clouds associated with large-scale moisture convergence, and (3) supersaturation for non-convective precipitation.

The land-surface scheme is based on SECHIBA (Ducoudrè et al. 1993), with modifications to allow a more physiologically and ecologically realistic treatment of canopy conductance, seasonal variations of leaf area index (LAI) and their effects on land-atmosphere energy and water exchanges (de Noblet et al. 1996). Each AGCM grid cell is assigned fractional covers of 17 different land-surface types (biomes). The area of uncovered soil, surface albedo and roughness length are computed every day, within the AGCM, depending on the foliage density (i.e. LAI). Values of albedo with and without fresh snow cover, of surface roughness and vegetation height are prescribed for each biome at full development. Other prescribed parameters include (1) the maximum water storage of