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Synergistic feedbacks from ocean and vegetation on the African monsoon response to mid-Holocene insolation

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Abstract. We used a coupled ocean-atmosphere General Circulation Model without flux corrections, iteratively coupled to a biome model, to explore the impact of vegetation and ocean feedbacks on mid-Holocene monsoon change in northern Africa. We show that both feedbacks significantly increase the northward penetration and the intensity of the monsoon rainfall. The major contribution of the ocean is to enhance the inland moisture advection, whereas that of vegetation is to increase local recycling. Synergistic interactions between ocean and vegetation feedbacks play a critical role in the African monsoon changes, yielding to model results in much better agreement with observations.

Introduction

Sub-Saharan West Africa is very sensitive to monsoon rain variability [Druyan, 1989]. Several studies relate the variability in the intensity of the rainy seasons in this region to sea surface temperature anomalies [e.g. Folland *et al.*, 1986; Semazzi *et al.*, 1996]. Others invoke continental factors such as surface albedo and vegetation cover [e.g. Charney, 1975; Xue and Shukla, 1993]. Much wetter conditions prevailed in this region 6 000 years ago [e.g. Jolly *et al.*, 1998; Street-Perrott and Perrott, 1993]. They are attributed to an enhancement of the monsoon activity caused by changes in Earth's orbital parameters. However with the orbital forcing alone, atmospheric general circulation models (GCM) underestimate the moisture increase north of 18°N [Joussaume *et al.*, 1999], suggesting that ocean and land surface feedback need also to be considered.

Recent simulations in which vegetation changes were prescribed to the atmospheric model [Street Perrott *et al.*, 1990; Kutzbach *et al.*, 1996], or computed using coupled atmosphere-biome models [Claussen and Gayler, 1997; Texier *et al.*, 1997] showed that vegetation contributes to enhance the orbitally-induced monsoon change. More recently, coupled ocean-atmosphere simulations also highlighted the positive feedback of the ocean [Hewitt and Mitchell, 1998; Kutzbach and Liu, 1997]. However, even if some results are consistent with paleodata in many places, the full reconstruction of past vegetation [Jolly *et al.*, 1998] and lake level status [Street-Perrott and Perrott, 1993] across northern Africa has not been simulated yet. Only one simulation with a model of intermediate complexity included interactions between ocean, atmosphere and terrestrial vegetation [Ganopolski *et al.*, 1998]. Vegetation extended at the expense of desert areas, but the ocean only accounts for a small part to these changes. The

ocean model though does not resolve the full ocean equatorial dynamics, and the rather coarse resolution prevents the simulation of detailed regional monsoon changes. We propose to use a more comprehensive model to address the possibility of synergistic interaction between vegetation and ocean feedbacks in the tropics with a focus on the climate of northern Africa.

Experimental design

We used the IPSL (Institut Pierre Simon Laplace, Paris) global coupled ocean-atmosphere GCM [Braconnot *et al.*, 1997; Braconnot *et al.*, in press], iteratively coupled to the BIOME1 vegetation model [Prentice *et al.*, 1992]. The atmospheric model has 64 points in longitude, 50 points regularly spaced in sine of the latitude and 11 sigma levels, and includes the land-surface scheme SECHIBA [Ducoudré *et al.*, 1993]. The oceanic model has 92 points in longitude, 76 points in latitudes and 31 vertical levels. The two models exchange once a day surface temperature, sea-ice cover, momentum, heat and fresh water fluxes, including river runoff. None of these fluxes are corrected and the simulations are stable. The modern-day mean seasonal cycle is reasonably well represented, despite a 2°C cold bias in tropical sea surface temperatures (SST) and a 2° too far north location of the summer monsoon rainfall peak in Africa [Braconnot *et al.*, smi]. To compute vegetation changes, the biome model is forced with the mean climate change simulated by the coupled ocean-atmosphere model (Figure. 1).

We did four simulations with this model: a 150-year simulation for the present day climate (OA0k), a 150-year simulation for the mid-Holocene climate (OA6k) with Earth's orbital parameters prescribed as in the Paleoclimate Modeling Intercomparison Project [Berger, 1978; Joussaume and Taylor, 1995], and two 50-year simulations for the mid-Holocene climate (OAV6k and OAV₁6k) for which we also prescribed as boundary conditions the biome distributions reconstructed respectively from OA6k and OAV6k (Figure 1). In all simulations the CO₂ level was kept to its present value (345 ppm). The length of our simulations is sufficient to study changes in the seasonal cycle, which mainly affect the upper ocean, but not to bring the deep ocean to equilibrium. However, the oceanic drift of 0.2°C/century at the ocean surface and of 0.04°C/century at depth is similar in all simulations and negligible compared to the imposed perturbation. Our analysis and biome reconstructions are based on 20-year mean annual cycles, using years 80 to 100 for OA0k and OA6k and the last twenty years for OAV6k and OAV₁6k.

Ocean and vegetation feedbacks on monsoon changes

The 6000 years BP Earth's orbital parameters increase the amplitude of the seasonal cycle of solar radiation in the north-

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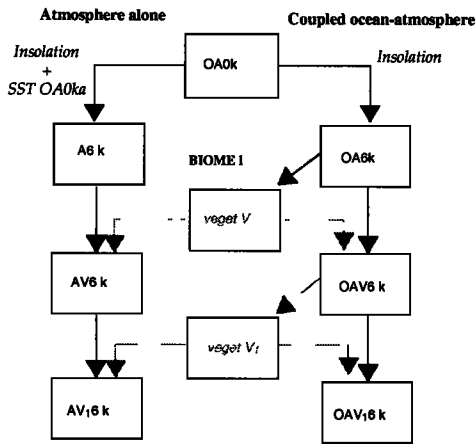


Figure 1. Schematic diagram of the experimental design. For the two iterations with the biome model, the vegetation was reconstructed respectively from OA6k and OAV6k departures to OA0k and then prescribed as boundary condition over land both in the coupled model and the atmosphere alone model.

ern hemisphere. As a result, insolation in June-July-August-September was about 5% larger than it is today. The continental thermal low deepened over the warmer land, which favoured the inland penetration of moisture from the ocean, thereby increasing the monsoon rain intensity. In OA6k, the Sahara is 1.5 to 2°C warmer than today and rainfall is increased up to 5 mm/d in a few places (Figure 2). In the Atlantic, the simulated sea surface temperatures (SST) are warmer to the north of 15°N and colder to the south. This dipole resembles the oceanic anomalies involved in modern Sahel droughts [Folland et al., 1986]. It favours late summer precipitation to the north of the present day position of the rainbelt [Braconnot et al., in

press; Hewitt and Mitchell, 1998]. Over land, the simulated surface cooling results from a larger cloud cover, which reflects back to space solar radiation, and from larger evapotranspiration. When vegetation is made interactive, all these patterns are reinforced. The warming is larger than 3°C in north-west Africa and the precipitation increase exceeds 5 mm/day across a broad region (Figure 2).

The largest change in precipitation is found over land between 20°W-30°E and 12°N-23°N. Compared to OA0k, it represents an increase of 37% in OA6k and of 69% in OAV16k. Rainfall (P) in this region receives most of its moisture from the low-level south-west monsoon flow off the tropical Atlantic. Local evaporation (E) also helps maintain monsoon activity by providing a local source of moisture. Since we consider only monthly averages, P-E can be used to represent the amount of precipitation (P) resulting from moisture advection. Total rainfall is the sum of these two contributions (Figure 3). At present (OA0k), P-E is larger than E only during July and August (Figure 3). In OA6k, the change in P-E accounts for most of the change in precipitation. Moisture advection dominates local recycling from June to September, period during which precipitation is larger than 2mm/day. When vegetation interacts (OAV16k), the local recycling provides most of the additional precipitation change, because plants are more efficient than a bare soil at extracting soil water for evapotranspiration (Texier et al., in press). Note also that advection is larger in May. The dominant biomes in the region are no more Desert and Steppe but Savanna. The surface albedo is then reduced by 6%, which favours the surface warming in spring and triggers the monsoon onset by increasing the land-sea contrast (Figure 3). These results confirm that the land surface conditions have a large impact on monsoon changes. They also show that when both ocean and vegetation feedbacks are included the rainy season lengthens leading

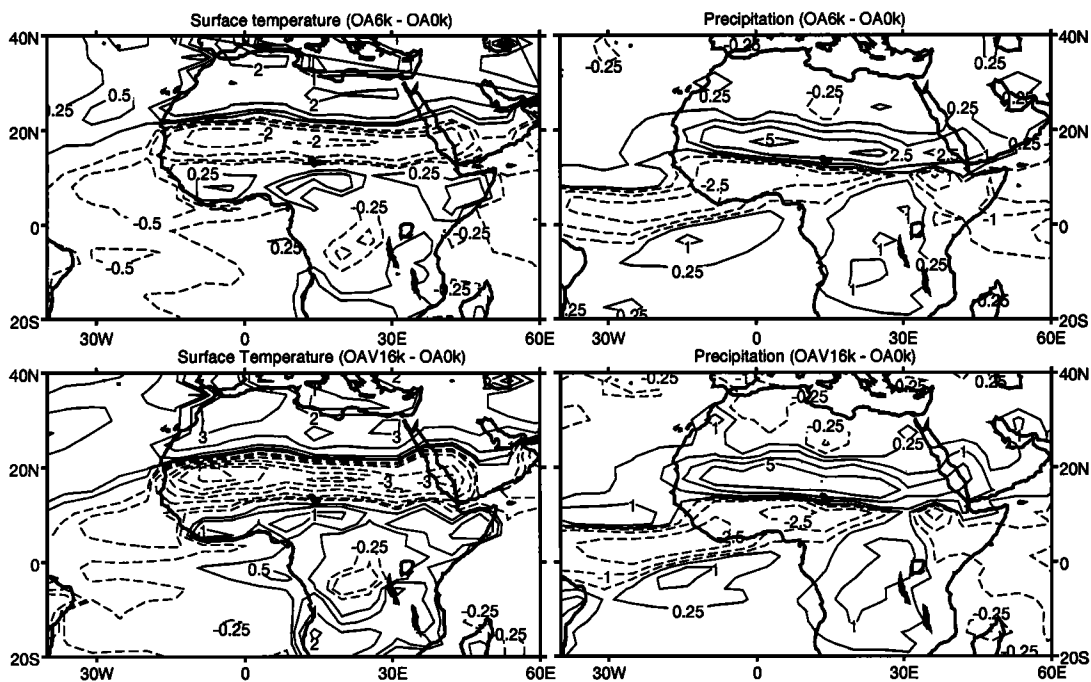


Figure 2. 6 000 BP change in June-July-August-September surface temperature (left) and precipitation (right) over Africa as simulated with the coupled ocean-atmosphere model (top) and with the coupled ocean-atmosphere-vegetation model (bottom). Isolines are +/- 0.25, 0.5, 1, 2, 3, and 4 Celsius for temperature and +/- 0.25, 1, 2.5 and 5 mm/day for precipitation.

Africa (20°W-30°E 12°N-23°N) land for the coupled model

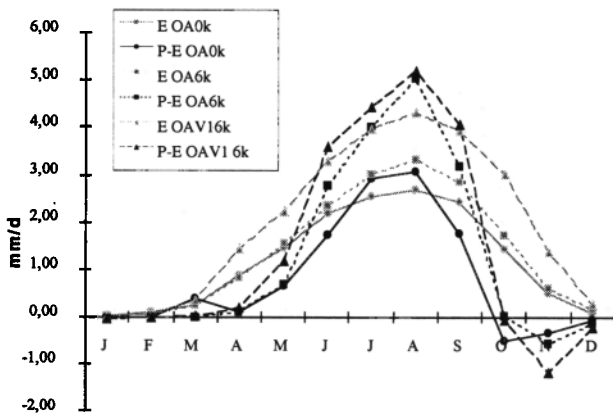


Figure 3. Evaporation (E) and precipitation minus evaporation (P-E) averaged over Africa from 20°W to 30°E and 12°N to 23°N and plotted as a function of months for the coupled simulations of modern climate (OA0k), of 6000 BP climate with no change in vegetation (AO6k), and for the last iteration at 6 000 BP with the biome model (OAV1 6k). Total precipitation is the sum of E and P-E. Values are in mm/day.

to larger than 2 mm/day precipitation rates from May to October.

Synergism between ocean and vegetation feedbacks

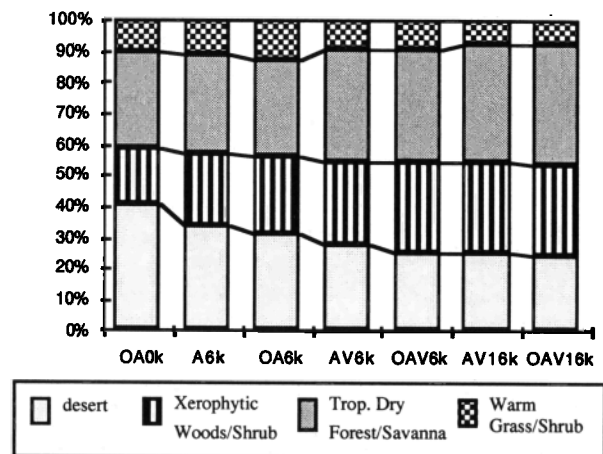
To better infer the role of the interactive ocean in the monsoon response we ran three additional 20-year simulations with the atmospheric model alone (Figure 1). In A6k we only changed insolation as in OA6k. In AV6k and AV₁6k, we respectively prescribed the same vegetation as in OAV6k and OAV₁6k (Figure 1). To avoid any bias that could arise from differences between modern climatology and SST simulated by the coupled model, we prescribed as surface boundary condition in all these simulations the daily SSTs simulated by OA0k from years 80 to 100. With this methodology, OA0k is the reference for all 6000 years BP simulations. Contrarily to standard atmosphere-biome coupled experiments we intentionally did not prescribe to AV and AV₁ the vegetation respectively reconstructed from A and AV, because we wanted to see how important is the role of the ocean in further shifting the monsoon rainfall to the north for a given biome distribution. However, even if we did not use them to force the atmospheric model, we reconstructed these biome distributions in order to compare the two sets of experiments (Figure 4).

Four biome types are found in western north Africa (20°W to 30°W; 5°N to 30°N) with varying proportions across the simulations. Figure 4 shows that at each iteration with the biome model, the reduction of desert area is larger for the simulation which includes ocean feedback (OA6k versus A6k, OAV6k versus AV6k and OAV₁6k versus AV₁6k). The largest reduction of desert (15% compared to present) is produced by OAV₁6k, resulting in a 5° northward shift of the desert/steppe boundary (Figure 4b). Warm grass shrub is also reduced. The two biome types are replaced by more moisture-demanding plants: xerophytic wood/scrub and tropical dry forest/savanna. Since vegetation is the same in coupled and atmosphere-alone simulations, the recycling efficiency is also

quite similar. Indeed, between 12°N and 23°N, the evaporation increases by 17 % in OA6k versus 11% in A6k, and by 57 % in OAV₁6k versus 50 % in AV₁6k compared to OA0k. On the other hand, the moisture advection increases by 57 % for OA 6k versus 39% for A6k, and by 81% in OAV₁6k versus 60% in AV₁6k, which stresses that the ocean response has a large impact on the advection.

The vegetation change we prescribed to both OAV₁6k and AV₁6k resulted from the change in precipitation produced in OAV6k. The interesting point is that the atmosphere-vegetation alone system in AV₁6k is not able to sustain the amount of precipitation simulated in OAV6k (Figure 4). This implies that the equilibrium atmosphere-vegetation system would have stabilized to a vegetation extent which is between the one simulated by AV6k and AV₁6k. The biome distribution we prescribed to the atmospheric model is thus overestimated

biome distribution (20°W-30°E 5°N-30°N)



Annual mean precipitation zonally averaged from 20°W to 30°E over land

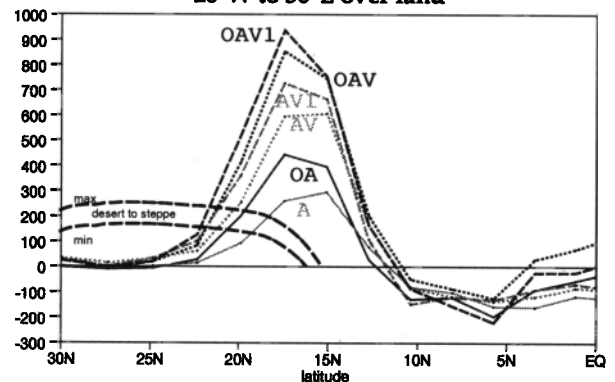


Figure 4. Biome distribution over West Africa in a region extending from 20°W to 30°E and 5°N to 30°N (top). Annual mean precipitation change at 6 000 BP (in mm/year) zonally averaged over North Africa from 20°W to 30°E over land (bottom) for the coupled and atmosphere-alone simulations in response to 6 000 BP changes in insolation (respectively OA and A) and in response to the 6 000 BP change in insolation and vegetation for the two iterations with the biome model (respectively OAV and OAV1 for the coupled simulations and A1 and AV1 for the atmosphere-alone simulations). The hatched lines represent the additional precipitation required to support grassland compared to modern biome distribution [Joussaume *et al.*, 1999].

compared to the one we would have prescribed in an equilibrium atmosphere-biome model. On the other hand, precipitation still increases with a slight northward shift in OAV_{16k}, which clearly demonstrates that synergistic interactions occur between vegetation and ocean feedbacks.

Additional iterations with the biome model are required to reach full equilibrium of coupled ocean-atmosphere system. We stopped after 2 iterations to save computer time because the changes between OAV_{6k} and OAV_{16k} were small compared to those we obtained between OA_{6k} and OAV_{6k}. We also know from other coupled atmosphere-biome experiments [Texier *et al.*, 1997], Claussen and Gayler, 1997] that additional iterations are not likely to change our results.

Conclusion

Our study clearly demonstrates that interactive ocean and vegetation are both needed to reproduce the wetter climatic conditions prevailing in northern Africa during the mid-Holocene, as indicated by proxy data [Jolly *et al.*, 1998]. However, we still do not simulate enough additional precipitation in the vicinity of 23°N. Part of this may be model dependent, because our atmospheric model is known to produce a too large subsidence in Sahara (De Noblet *et al.*, *smi*). Moreover, the vegetation model was asynchronously coupled because it is a static model. We hope that in near future these results will be improved with synchronously coupled ocean-atmosphere-dynamical vegetation models. In any case, these results point to the importance of introducing vegetation feedbacks in future climate change scenarios, which have up to now only been based on coupled ocean-atmosphere models.

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