Comment on "Climate-Driven Ecosystem Succession in the Sahara: The Past 6000 Years"

Victor Brovkin[1]* and Martin Claussen[1,2]

Kröpelin *et al.* (Research Articles, 9 May 2008, p. 765) interpreted a sediment record from Lake Yoa in the east-central part of North Africa as support for a weak biogeophysical climate-vegetation feedback in the Sahara during the mid-Holocene. We argue that the new data do not invalidate earlier modeling results on strong land-atmosphere coupling in the Western Sahara for which the Lake Yoa record is far less representative.

Abrupt climate changes in the past provide invaluable insights on rapid climate dynamics in the future. The climate system is full of numerous feedbacks between different system components, such as vegetation and atmosphere, and North Africa might be one of the important tipping points in the system (*1*). That is why a question about the abruptness of past changes in this region requires detailed investigation.

Kröpelin *et al.* (*2*) presented fascinating details of desiccation of the east-central part of North Africa over the past 6000 years. Although we acknowledge the progress in paleoclimatic reconstruction, we disagree with some of the authors' conclusions. Kröpelin *et al.* state that their data imply a "disagreement with modeling results indicating abrupt mid-Holocene vegetation collapse," suggesting "that the implicated biogeophysical climate-vegetation feedback may have been relatively weak." We argue that the new data do not invalidate earlier hypotheses and modeling results (*3*–*6*).

The proposed biogeophysical feedback between vegetation cover and precipitation in the Sahara (e.g., *5*–*7*) operates through modification of surface albedo (a fraction of solar irradiation reflected back to space) and moisture recycling in the presence of plants. In North Africa, the difference in albedo values between vegetated surfaces and desert can be particularly large, with bare ground albedo values exceeding 0.5 in some areas (*8*, *9*). Vegetated surface traps more solar irradiation and warms the air column over land. Elevated temperature contrast between the land and adjusted ocean leads to an intensification of the regional atmospheric circulation, which results in more rainfall. As shown in modeling studies by Claussen and Gayler (*4*) and Renssen *et al.* (*3*), the biogeophysical feedback is most relevant for the Western Sahara (Fig. 1). The eastward increase in aridity in mid-Holocene Sahara is supported by geological data. Although sparsely distributed pollen records reveal that a large part of the Sahara in the mid-Holocene was covered with steppe or xerophytic shrubs (*10*), some reconstructions suggest that the western part of the Sahara was more humid than its eastern part (*11*).

The first computer simulation of transient Holocene dynamics of the Sahara was undertaken by using the CLIMBER-2 model (*12*) which does not resolve any difference between the western and the eastern part of the Sahara. In this simulation, the transition from a "green" to a barren Sahara took place within several hundred years about 5000 years before the present (yr B.P.) at a much faster pace than the driving force of changes in summer insolation. The geological records of dust transport into the North Atlantic (*13*) exhibit an even faster transition from weak to strong dust flux around 5500 yr B.P. Certainly, the dust records should be interpreted with care because the abrupt change in the dust depositions may reflect not only a decrease in vegetation cover but also an increase in the source area of the dust caused by lake desiccations.

Later model results about abruptness of North African vegetation changes in mid-Holocene give a more mixed picture. In the transient simulation with the ECBILT-CLIO-VECODE model (*3*), high climate variability masked out the abrupt climate changes in the Western Sahara. However, increased climate instability about 6000 yr B.P. was interpreted as a system shift from moist to dry regime. Liu *et al.* (*14*) used another fast climate-vegetation model, FOAM-LPJ, and found the abrupt changes not in the western but in the eastern part of the Sahara (Fig. 1), although the later results do not seem to be supported by the Lake Yoa record (*2*). Abrupt vegetation changes in the Eastern Sahara simulated by FOAM-LPJ (*14*) are associated not with the strong biogeophysical feedback but with a nonlinear response of

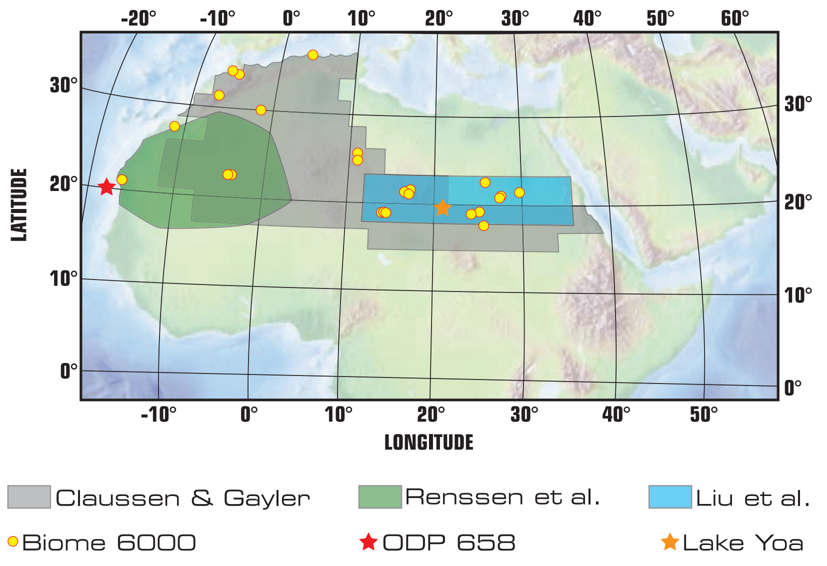

Fig. 1. Simulated difference between mid-Holocene and present-day vegetation cover, revealing changes mainly in the Western part of the Sahara, the focus of earlier hypotheses of abrupt ecosystem change in the Sahara. Gray shading indicates changes from mid-Holocene vegetated state to present-day desert (*4*); the green shaded area has more than 30% reduction in vegetation cover during the Holocene (*3*). A strong positive biogeophysical feedback between vegetation cover and precipitation in the Western Sahara found in (*3*, *4*) may result in an abrupt shift from wet to dry regime. The blue shaded area indicates the area of abrupt vegetation changes attributed to a nonlinear response of vegetation to precipitation from simulation by Liu *et al.* (*14*). The stars indicate the position of Lake Yoa (19.03°N, 20.31°E) and Ocean Drilling Program site 658C (20.45°N, 18.35°W). The record from Lake Yoa does not seem to show evidence of abrupt ecosystem transitions (*2*), whereas the marine sediment core reveals an abrupt change in dust transport from the continent (*13*). Yellow circles indicate sites with mid-Holocene steppes or xerophytic shrubs from the BIOME-6000 database (*10*).

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vegetation cover to precipitation. In contrast, model studies (*3*, *4*) that simulate mid-Holocene expansion of vegetation cover into the Western Sahara (Fig. 1) attribute a substantial part of this expansion to the strong coupling between land and atmosphere. Detailed understanding of model differences regarding the strength of biogeophysical feedback requires further investigation.

In conclusion, the jury is still out on the invalidation of the earlier assertion of abrupt ecosystem changes in the Sahara. To prove or falsify the hypothesis on abrupt changes in the Western Sahara, a convincing summary of terrestrial paleoclimatic records from this region has to be presented. Until then, the conclusion of Kröpelin *et al*. (*2*) on weak biogeophysical feedback is not justified in general.

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Response to Comment on "Climate-Driven Ecosystem Succession in the Sahara: The Past 6000 Years"

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The Lake Yoa record and archaeological data provide adequate evidence that mid-Holocene aridification did not occur abruptly across all of North Africa. Modeling results on the issue of abrupt versus gradual desiccation of the Sahara are sufficiently diverse that paleoecological data from a continuous natural archive can usefully guide the evaluation of model parameters responsible for this diversity.

We thank Brovkin and Claussen (*1*) for their insightful comment and the opportunity to clarify our findings (*2*). We agree with the authors to the point that our reconstruction of gradual desiccation of the terrestrial ecosystem in the east-central Sahara does not necessarily imply weak biogeophysical feedback in the western Sahara and that land-atmosphere and/or atmosphere-vegetation interactions there may have been sufficiently different to have resulted in a distinct regional trajectory of mid-Holocene desiccation. The principal objective of our study (*2*) was to correct the popular notion (e.g., *3–6*) that the iconic record of Saharan dust deposition in marine sediments off the Mauritanian coast (*7*) represents Holocene landscape evolution across North Africa, including the central and eastern Sahara, and that climate-modeling results (*8*) supposedly support this exaggerated viewpoint.

We consider our paleoecological record from northern Chad to be representative for a sizable portion of the central and eastern Sahara (*2*). The conclusions of our study are consistent with the regional chronologies of multi-indicator archaeological evidence from shifting prehistoric occupation sites in the Egyptian and Sudanese Sahara, which similarly suggest a continuous southward retreat of monsoonal rainfall causing gradual environmental deterioration during the middle Holocene (*9*), notwithstanding transitory climatic perturbations that are a common feature of all desert margins.

We are aware of the moisture gradient between the western and eastern parts of the Sahara that is treated as such in recent climate-vegetation simulations (e.g., *10–12*). However, some state-of-the-art general circulation climate models (*13*) have suggested that landscape desiccation was gradual in both the eastern and western Sahara, consistent with our reconstruction, whereas other experiments with similar models (*11*, *14*) simulated mid-Holocene vegetation collapse exactly for the region where Lake Yoa is located [blue shaded area in figure 1 in (*1*)]. Also, the mechanisms considered responsible for abrupt vegetation changes observed in various model output are diverse: a positive vegetation-climate feedback due to modification of surface albedo (*15*, *16*), a threshold response of vegetation to particular modes of climate variability (*14*), microscale vegetation-soil feedback (*12*, *17*), or a transition from negative to positive vegetation-climate feedback at increasing time scales (*18*). Clearly, modeling results on the issue of abrupt versus gradual desiccation of the Sahara are sufficiently diverse that paleoecological data from a continuous natural archive (*2*) can usefully guide the evaluation of model parameters responsible for this diversity.

We subscribe to the caution formulated by Brovkin and Claussen (*1*) about the inferred rapidity of the mid-Holocene transition from a "green" to a barren Sahara recorded in the Ocean Drilling Program site 658 sediment sequence (*7*). Here we agree with Holmes (*19*) that the abrupt increase in dust flux at that location may be partly due to the relatively sudden desiccation of one or more large and shallow lake basins in the source area of dust delivered to the Atlantic Ocean offshore Mauritania; today this is mostly northern Mauritania and central Algeria. However, we are less optimistic than Brovkin and Claussen that a new summary of terrestrial climate-proxy records from the western Sahara will conclusively resolve the issue of whether ecosystem changes there were gradual or abrupt. All known depositional sequences from the region are incomplete over the critical time interval, and a continuous and high-quality paleoenvironmental archive comparable to the Lake Yoa sequence is unlikely to be found.

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