

Holocene climate instability during the termination of the African Humid Period

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Received 20 November 2002; revised 8 January 2003; accepted 17 January 2003; published 25 February 2003.

[1] The termination of the Holocene African Humid Period (~9 to ~6 kyr BP) is simulated with a three-dimensional global coupled climate model that resolves synoptic variability associated with weather patterns. In the simulation, the potential for “green” and “desert” Sahara states becomes equal between 7.5 and 5.5 thousand years ago, causing the climate system to fluctuate between these states at decadal-to-centennial time-scales. This model result is supported by paleoevidence from the Western Sahara region, showing similar paleohydrological fluctuations around that time. For the present-day, only the desert Sahara state is stable in the model. **INDEX TERMS:** 3344 Meteorology and Atmospheric Dynamics: Paleoclimatology; 3322 Meteorology and Atmospheric Dynamics: Land/atmosphere interactions; 1620 Global Change: Climate dynamics (3309); 4255 Oceanography: General: Numerical modeling; 9305 Information Related to Geographic Region: Africa. **Citation:** Renssen, H., V. Brovkin, T. Fichefet, and H. Goosse, Holocene climate instability during the termination of the African Humid Period, *Geophys. Res. Lett.*, 30(4), 1184, doi:10.1029/2002GL016636, 2003.

1. Introduction

[2] The early-to-middle Holocene was a humid period in Northern Africa, with vegetation cover extending greatly into the Sahara [Gasse, 2000; Prentice *et al.*, 2000]. A current paradigm is that this African Humid Period (AHP) was associated with a strengthening of the summer monsoon due to an increase in the summer insolation [Kutzbach and Street-Perrott, 1985]. Marine core-based studies indicate that the AHP termination around 5–6 kyr before present (BP) was much more abrupt than might be expected from the slowly decreasing summer insolation [deMenocal *et al.*, 2000]. Climate model experiments have linked the abruptness of the AHP termination to an atmosphere-vegetation feedback that amplified the desertification [Claussen *et al.*, 1999]. This positive biogeophysical feedback [Charney *et al.*, 1975] assumes that a decrease in vegetation cover and the associated increase in surface albedo reduce precipitation in the Sahara/Sahel, thus implying self-induction of deserts.

Model studies elaborated radiative and hydrological mechanisms of atmosphere-vegetation interaction [Xue and Shukla, 1993] and suggested that at least two states could be stable in the region: 1) a “desert” equilibrium, with low precipitation and absent vegetation, and 2) a “green” equilibrium, with moderate precipitation and permanent vegetation cover [Claussen, 1998; Brovkin *et al.*, 1998; Wang and Eltahir, 2000].

[3] So far, the effect of this biogeophysical feedback on climate-vegetation dynamics through the Holocene has only been analyzed in model experiments lacking the influence of explicitly simulated high-frequency (daily-to-decadal) climate variability. This may explain why these experiments do not show the centennial-scale paleohydrological fluctuations found in many paleorecords. For example, sedimentological and paleobotanical data obtained from former lakes in the Western Sahara give clear evidence for alternating high and low lake levels between ~9 and 5 kyr BP [Fabre and Petit-Maire, 1988; Lézine *et al.*, 1990; Dammati, 2000]. Here, we use transient simulations performed with a three-dimensional coupled climate model to show that, between 7.5 and 5.5 kyr BP, the interannual variability in precipitation caused similar fluctuations at decadal-to-centennial time-scales.

2. Model and Experimental Design

[4] To investigate the effect of high-frequency (daily-to-decadal) climate variability on the Holocene climate evolution in the Sahara/Sahel, we have conducted a numerical experiment covering the last 9 thousand years with the 3-dimensional global ECBilt-CLIO-VECODE climate model. This model consists of three components representing dynamics of the atmosphere, ocean-sea ice and vegetation. The atmospheric component is version 2 of ECBilt, a spectral quasi-geostrophic model with three vertical levels and a T21 horizontal resolution. Simple parameterizations for the diabatic heating due to radiative fluxes, the release of latent heat, and the exchange of sensible heat with the surface are incorporated [Opsteegh *et al.*, 1998]. ECBilt includes a full hydrological cycle that is closed over land by a bucket model for soil moisture and river runoff. Cloud cover is prescribed according to present-day climatology. In the model, precipitation is independent of cloud cover. The ocean-sea-ice component CLIO consists of a free-surface,

primitive-equation oceanic general circulation model with 20 vertical levels and $3^\circ \times 3^\circ$ latitude-longitude resolution, coupled to a dynamic-thermodynamic sea-ice model [Goosse and Fichefet, 1999]. The ECBilt-CLIO model gives a reasonable representation of the modern climate [Goosse *et al.*, 2001; Renssen *et al.*, 2002]. It has been recently coupled with VECODE, a model that simulates the dynamics of two main terrestrial plant functional types, trees and grasses, and desert as a dummy type [Brovkin *et al.*, 2002]. Simulated vegetation changes only influence the land-surface albedo in ECBilt-CLIO, and have no effect on other processes, e.g. soil hydrology. It is important to realize that, compared to comprehensive general circulation models, our model represents a simplified description of the coupled system (e.g., low spatial resolution, prescribed cloud cover). This simplification is inevitable given the long time-scales involved in this study.

[5] In the performed experiment, the model was forced by annually varying insolation [Berger, 1978] and long-term trends (i.e. without high-frequency variations) of the atmospheric concentrations [Raynaud *et al.*, 2000] of CO_2 and CH_4 for the 9–0 kyr BP period. All other forcings were kept constant at their preindustrial values (i.e. 1750 AD). Similar transient simulations have been performed with 2.5-dimensional models [Claussen *et al.*, 1999; Crucifix *et al.*, 2002; Brovkin *et al.*, 2002]. However, compared to these studies, our model has a much higher spatial resolution and includes an atmospheric component that resolves the synoptic variability associated with weather patterns.

3. Results

[6] During the first 5 kyr, the Northern Hemisphere's summer temperature gradually declines by 0.9°C under the influence of the decreasing insolation and CH_4 concentration (Figure 1a). In the last 3 kyr, a warming of 0.3°C is simulated, which follows the 130-ppbv increase in CH_4 level. The prescribed natural CO_2 concentration change is too weak (20 ppmv/9 kyr) to cause significant climate variations and is only included for completeness.

[7] In the Western Sahara/Sahel the model simulates from 9 to 7.5 kyr BP a green equilibrium characterized by a mean annual precipitation of 290 mm yr^{-1} and a vegetation fraction of 70% (Figures 1b–1c). This green state is associated with a relatively strong land-sea thermal gradient (Figure 1d), which strengthens the summer monsoons, leading to an increased transport of humid air towards the continent and enhanced convective precipitation over land. After 7.5 kyr BP, precipitation and vegetation concentration decrease to values of 210 mm yr^{-1} and 50%, respectively. In addition, the variability in vegetation fraction increases significantly (standard deviation is 9.2% for 9–7.5 kyr BP and 12.2% for 7.5–5.5 kyr BP). This phase with high variability lasts until ~ 5.5 kyr BP. The time period separating the “green” spikes ranges from 110 to 370 years, which is similar to the lake-level fluctuations observed in paleodata from the Western Sahara (200–500 years [Fabre and Petit-Maire, 1988; Lézine *et al.*, 1990], e.g., Figure 2). Subsequently, the variability decreases substantially and the system moves towards a desert state reached around 1 kyr BP, with an annual precipitation of 60 mm yr^{-1} and a vegetation fraction of only 10%.

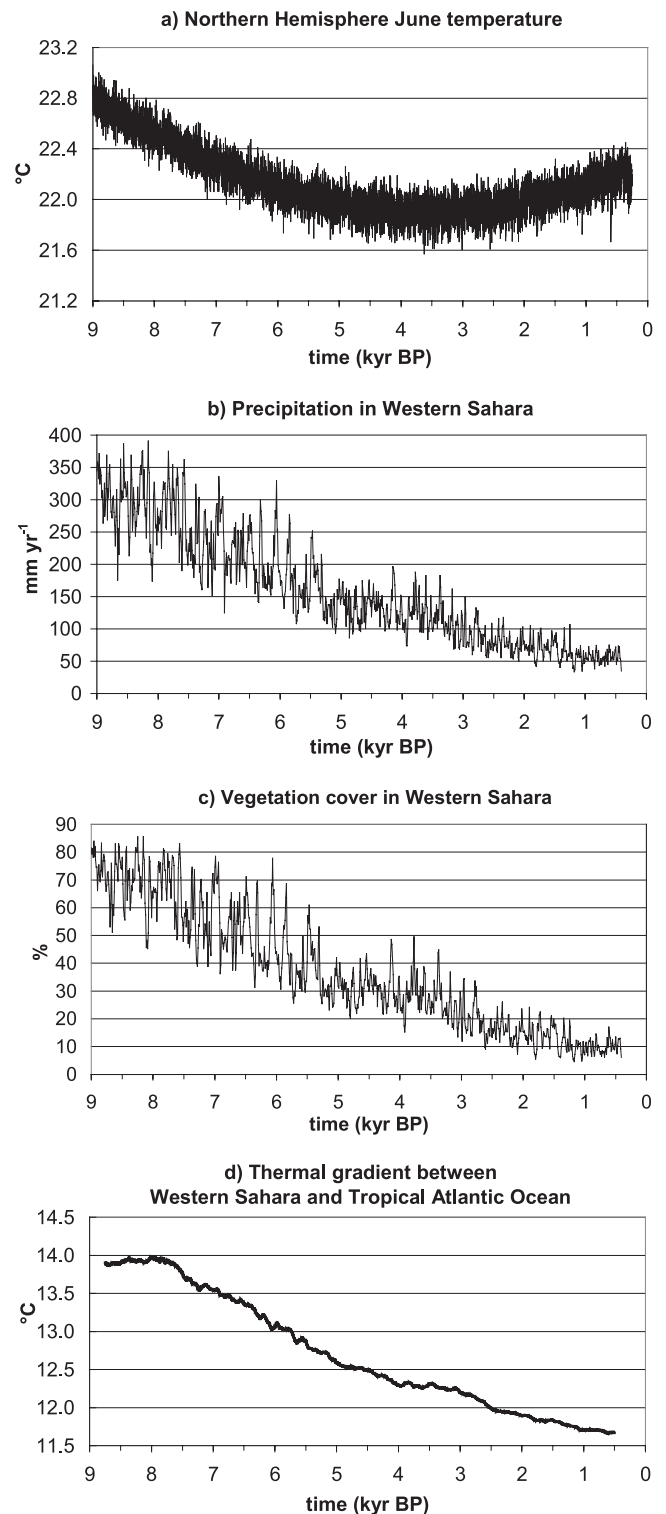


Figure 1. Simulated climate evolution during the last 9 thousand years: a) annual mean surface temperature ($^\circ\text{C}$) in the Northern Hemisphere, b) decadal mean precipitation (mm yr^{-1}) and c) vegetation cover (%), both in the Sahara/Sahel region (mean over 6 grid cells covering 14°W to 3°E , 17°N to 28°N), d) land-sea thermal gradient ($^\circ\text{C}$), shown here as the 500-yr running mean July surface temperature difference between two grid points (22°W , 3°N and 11°W , 19°N).

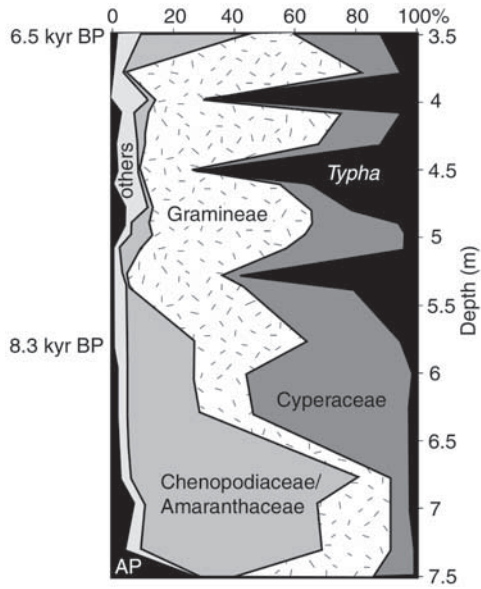


Figure 2. Summary pollen percentage diagram derived from a former lake bed in the Western Sahara (Chemchane, Mauretania, 20°56'N, 12°13'W, redrawn from *Lézine et al.* [1990]), showing the Early-to-Mid Holocene evolution of four major nonarboreal taxa (*Typha*, Cyperaceae, Gramineae, Amaranthaceae-Chenopodiaceae), arboreal pollen (AP), and sum of all others. Note the strong fluctuations of *Typha* (associated with freshwater lake environments) between 8 and 6.5 ¹⁴C kyr BP (~8.8 and ~7.4 cal kyr BP). Similar fluctuations have been found at other sites in the region [Fabre and Petit-Maire, 1988; Damnati, 2000].

[8] To analyze the stability of the green and desert states through time, we carried out additional 200-yr long sensitivity experiments for 9 kyr BP, 6 kyr BP, and 0 kyr BP in which we kept the main forcings constant (i.e. insolation and atmospheric CO₂ and CH₄ concentrations). In these simulations, we prescribed the vegetation cover (either 100% desert or 100% grass) in the Sahara region (11°N–33°N, 20°W–35°E) during the first 100 years, after which the vegetation model was allowed to adjust to the different atmospheric conditions during the remaining 100 years. The four experiments can be characterized as follows: 1) desert 9 kyr BP, 2) desert 6 kyr BP, 3) green 6 kyr BP, and 4) green 0 kyr BP. Based on these sensitivity experiments (Table 1), a stability diagram was constructed following the conceptual model analysis proposed by *Brovkin et al.* [1998] (Figure 3). This diagram shows that, at 0 kyr BP, only the desert equilibrium is stable, while at 9 kyr BP and 6 kyr BP, both green and desert equilibria are stable in addition to a third intermediate unstable state. Compared to 9 kyr BP, the green equilibrium is closer to the intermediate unstable state at 6 kyr BP. In combination with the relatively strong variability in precipitation in the green state (Table 1), this might explain why around 6 kyr BP (and not at 9 kyr BP) stochastic variations in precipitation are able to induce several pronounced transitions between the green and intermediate states (Figures 1b–1c). Indeed, in the “desert 9 kyr BP” experiment, the model quickly recovers to the green state (74% vegetation cover) when the vegetation is allowed to adjust to the forcing. In both the “desert” and

Table 1. Precipitation and Vegetation Fraction in Western Sahel/Sahara (17–28°N, 14°W–3°E) Simulated With Interactive Vegetation and Prescribed Vegetation Cover (Desert or Grass)

Simulation	Precipitation (mm yr ⁻¹)	Vegetation fraction (%)
9k, interactive	334 ± 50	77 ± 6.8
9k, desert	42 ± 4	0
6k, interactive	180 ± 23	40 ± 4.5
6k, desert	31 ± 6	0
6k, grass	393 ± 25	100
0k, interactive	46 ± 11	5 ± 1.2
0k, grass	303 ± 21	100

Shown are mean values and standard deviations based on 5 and 10 decadal means for simulations with interactive and prescribed vegetation, respectively.

“green” 6 kyr BP experiments, however, the model returns to an intermediate state (62% and 45% vegetation cover, respectively).

[9] Our results demonstrate that the interannual variability in precipitation and vegetation cover plays an important role in the system dynamics. Under influence of this variability, “pure” desert and green states are not stable, as the solutions evolve towards some intermediate values in the sensitivity experiments. Furthermore, the sensitivity experiments show that the variability in precipitation is less in the desert state, making this state more probable than the green one. It should be noted that in the real world the variability in precipitation would interact with the cloud cover. This is not accounted for due to prescribed cloud cover in the present model. Likewise, the effect of vegetation changes on the hydrological cycle is not considered here. Regrettably, the impact of these approximations cannot be estimated in this study.

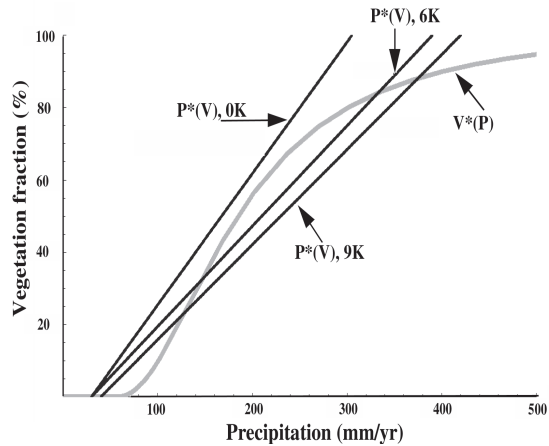


Figure 3. Stability diagram for the precipitation-vegetation system in the Sahara/Sahel region constructed following *Brovkin et al.* [1998]. The gray curve represents $V^*(P)$, the dependence of equilibrium vegetation (V) on annual mean precipitation (P), simulated by VECODE under prescribed changes in precipitation. The straight black lines represent $P^*(V, t)$, the linear model of precipitation as a function of vegetation cover and time (t), simulated by ECBilt-CLIO in sensitivity experiments with prescribed vegetation cover for the 9 kyr BP, 6 kyr BP, and 0 kyr BP cases. Intersections of black and gray curves correspond to the equilibria in the climate-vegetation system.

[10] To explore the oceanic contribution to the variability in precipitation, we have performed two additional sensitivity experiments with an identical design as “desert 6 kyr BP” and “green 6 kyr BP”, but without an interactive ocean (i.e. with 6 kyr BP sea-surface conditions prescribed). These experiments revealed that the high frequency variations in oceanic surface temperature are responsible for only 20% of the variability in precipitation.

4. Concluding Remarks

[11] The 6 kyr BP climate has been frequently used to evaluate the sensitivity of climate models to changes in radiative forcing, whereby attention has been focussed at the equilibrium response in the monsoon region of Africa (e.g., PMIP, Paleoclimate Modelling Intercomparison Project [Joussaume *et al.*, 1999; Intergovernmental Panel on Climate Change (IPCC), 2001]). The multiple equilibria found in our model imply that this approach needs to be modified, as equilibrium simulations for 6 kyr BP starting from modern (desert) conditions probably yield results that differ substantially from paleodata. Thus, besides the PMIP snapshot simulations, experiments with “green” initial conditions are necessary, and ideally the evaluation should include the transient response of the coupled system.

[12] Our results have important implications for our insight in the future climate in the Sahara/Sahel region. Recent estimates suggest that precipitation is to increase here significantly under influence of anthropogenic warming of climate [IPCC, 2001]. Such an increase in precipitation might enhance the climate variability in the Sahara/Sahel region substantially, as it could move the system in the direction of the situation that occurred in the mid-Holocene, with the green state becoming potentially stable in addition to the desert state [Brovkin *et al.*, 1998]. One recent study suggests that, indeed, some expansion of grassland into the Sahara is theoretically possible, if the atmospheric CO₂ concentration increases well above pre-industrial values and if vegetation growth is not disturbed [Claussen *et al.*, 2003]. Another model study confirms that higher atmospheric CO₂ levels could lead to longer or more frequent wet spells in the Sahel region [Wang and Eltahir, 2002]. However, the expected future amplitude of vegetation cover changes in northern Africa is less than is estimated for the mid-Holocene climate. In any case, it is clear that simulations of future climate in the region require interactive vegetation model components, because high precipitation variability is, to a substantial part, caused by the atmosphere-vegetation feedback [see, e.g., Zeng *et al.*, 1999].

[13] **Acknowledgments.** The constructive comments of two anonymous referees are gratefully acknowledged. T. Fichet is Research Associate at the Belgian National Fund for Scientific Research. This study is part of the Second Multiannual Scientific Support Plan for a Sustainable Development Policy (Belgian State, Prime Minister’s Services, Federal Office for Scientific, Technical, and Cultural Affairs). The authors thank J.M. Campin for programming the coupling of VECODE to ECBilt-CLIO.

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