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The Climate of 6000 Years BP in Near-Equilibrium Simulations with a Coupled AOGCM

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Abstract. The response of a coupled atmosphere-ocean general circulation model and an uncoupled atmosphere general circulation model to boundary conditions for 6000 years ago has been studied. The set of quasi-equilibrium simulations enables a separation of the contributions from changes in the ocean circulation, the CO_2 concentration, and the insolation to the total response. The results indicate that all three factors have considerable impact on the climate change signal and here especially on the northern African and Indian monsoon. Multi-century adjustment processes associated with the inertia of the deep ocean play only a minor role for the climate change signal of the upper ocean and the atmosphere.

1. Introduction

The climate 6000 years before present is one focus of the Paleoclimate Model Intercomparison Project (PMIP, *Joussaume and Taylor* [1995]). One reason for this is that for this period proxy data are relatively plentiful. The differences to the present-day climate are mainly attributed to insolation and atmospheric CO_2 concentration changes. In PMIP, stand-alone atmospheric general circulation models (AGCMs) have been forced with changed insolation and CO_2 concentration, but with present-day sea surface temperature (SST) and sea-ice distribution. The enhancement of the Indian and African summer monsoon turns out to be the prominent signal relative to the present-day climate [*Joussaume et al.*, 1999]. Recently, atmosphere-ocean general circulation model (AOGCM) simulations have been performed with the same boundary conditions. In these simulations SST and sea ice are able to adjust to the external forcing. As a result of the interactive ocean the consistency between the model simulations and proxy data is improved: The precipitation over northern Africa increases further. These coupled experiments have been integrated at most 200 years [*Braconnot et al.*, 2000; *Hewitt and Mitchell*, 1998] or only a few iterations of an asynchronous coupling scheme have been performed [*Kutzbach and Liu*, 1997]. On the other hand, multi-century AOGCM integrations with increasing atmospheric CO_2 concentration show that the long-term adjustment due to the inertia of the deep ocean leads to a considerable signal several centuries after the change of the forcing [*Manabe and Stouffer*, 1994; *Voss and Mikolajewicz*, 2001].

Here we analyse a set of AOGCM integrations addressing the question of the near-equilibrium climate response of the atmosphere-ocean system due to a modified external forcing, which resembles the conditions at 6000 years ago. To separate the impacts of insolation, reduced CO_2 concentration, and the oceanic feedback, four 1000-year AOGCM integrations and two 20-year AGCM simulations have been performed.

2. The Model and Experimental Setup

The ECHAM3/LSG AOGCM consists of the AGCM ECHAM3 with a T21 horizontal resolution (ca. 5.6° in the grid space) and 19 layers in the vertical. The ocean general circulation model LSG uses a grid spacing similar to the Gaussian grid of the atmosphere model and 11 layers. The periodically synchronous coupling scheme applied consists of alternating synchronous (15 months) and ocean-only integrations (48 months). The temporary switching off of the atmospheric component results in a considerable reduction of the computer time. For the atmosphere-ocean fluxes of mass, heat, and momentum, monthly mean flux corrections have been applied. More details of the AOGCM and the coupling are given in *Voss et al.* [1998].

Four 1000-year AOGCM simulations have been performed. In run *6K* the mid-Holocene insolation (eccentricity=0.0187, obliquity=24.11°, date of perihelion= Sep.20) and CO_2 concentration (280 ppm) have been prescribed according to PMIP [*Joussaume and Taylor*, 1995]. The results are compared to a control run *CTL1* with present-day insolation and CO_2 concentration (345 ppm) as well as to a simulation (*CO2*) where only the CO_2 concentration has been reduced to the mid-Holocene value. Since in this run a different insolation algorithm was used, we compared the results to a second control run (*CTL2*) with the same formulation for the insolation. The long-term averages of both control runs do not differ significantly (Figure 1) except for the seasonal cycle in northern high latitudes.

To estimate the impact of the oceanic feedback two 20-year simulations with uncoupled ECHAM3 AGCM have been performed in the standard PMIP setup, prescribing monthly mean climatologies for SST and sea ice derived from the control simulation *CTL1*. The simulations have been performed under mid-Holocene (*6Ku*) and present-day conditions (*CTLu*).

Here we consider averages over the years 701-1000 for the coupled runs and over the last 20 years of the atmosphere-only simulations, respectively.

3. Atmospheric Response

The change in insolation and the reduction in CO_2 concentration partially counteract one another, but their net effect is a global mean cooling of approx. 0.3 K (Figure 1a). The signal in the near surface temperature is overlaid

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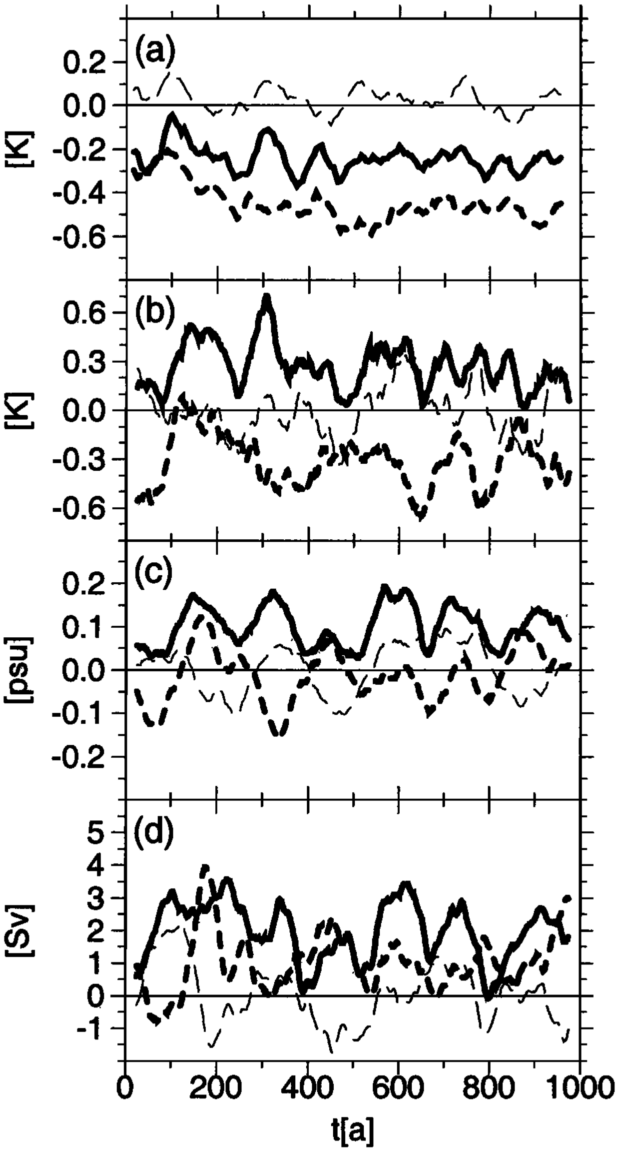

Figure 1. Time series of (a) the global mean near surface temperature, (b) the sea surface temperature for the North Atlantic, (c) the sea surface salinity for the North Atlantic, and (d) the meridional streamfunction at 30°N and 1500 m depth in the Atlantic. Shown are 50-year running mean differences of *6K-CTL1* (solid), *CO2-CTL2* (dashed), and *CTL2-CTL1* (thin long dashed).

by multi-decadal variations of the order of 0.1 K (peak-to-trough value). Over the Arctic, the North Atlantic, the North Pacific, and Eastern Europe the temperature rises (Figure 2a). The warming in the Arctic is associated with a reduction of the ice-covered area between 2 (May) and 8 · 10^{11} m^2 (December). Cooling dominates in the tropics and subtropics. The reduced CO_2 concentration alone leads to a global cooling of 0.5 K (Figure 1a). The insolation effect is responsible for a global mean warming tendency of 0.2 K. If the insolation effect were isolated, the near-surface temperature would be found to increase almost everywhere, except in the tropics. Over Africa and India the cooling exceeds 1 K (Figure 2b). The warming due to insolation changes exceeds the CO_2-induced cooling in the Northern Hemisphere. The interactive ocean enhances the temperature response (Figure 2c). The warming in the high latitudes as well as the cooling in the tropics, subtropics and Southern Hemisphere are more pronounced than in the uncoupled AGCM simulations.

For the monsoon regions of India and northern Africa all three investigated mechanisms (insolation changes, reduced CO_2 concentration, and oceanic feedback) contribute to the cooling. Over central North America the cooling is caused by the CO_2 reduction and the impact of the ocean. In eastern Europe the strong warming due to the insolation changes (>1 K, Figure 2b) is damped by the CO_2-induced cooling. For this anomaly the coupling to an interactive ocean is essential: the estimated warming due to the oceanic feedback (Figure 2c) is of similar magnitude as the insolation response (Figure 2b). The effect of the oceanic feedback is strongest in winter, when the coupled model shows the largest response in surface temperatures and sea ice in the northern North Atlantic and in the Arctic. Due to the oceanic feed-

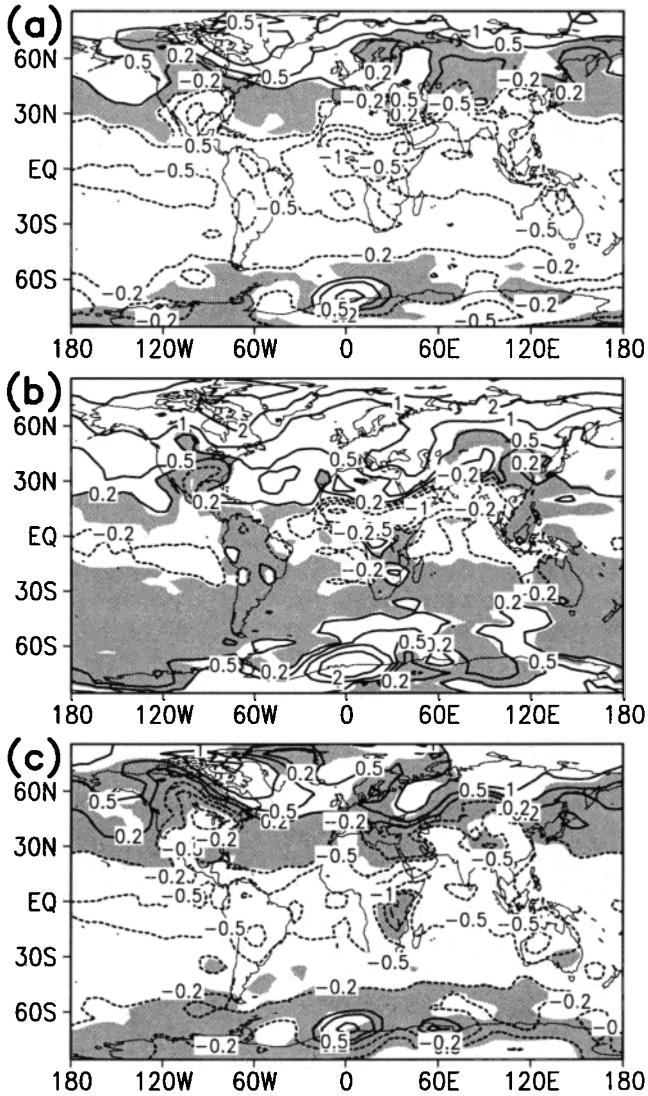

Figure 2. Climate change pattern of the near surface temperature [K] (a) for the total response (*6K-CTL1*), (b) for the effect of insolation ((*6K-CTL1*)-(*CO2-CTL2*)), and (c) for the effect of interactive ocean ((*6K-CTL1*)-(*6Ku-CTLu*)). Shading indicates a nonsignificant response on a 95% level of a t-test. Contours: ±0.2, ±0.5, ±1, ±2, ±5 K.

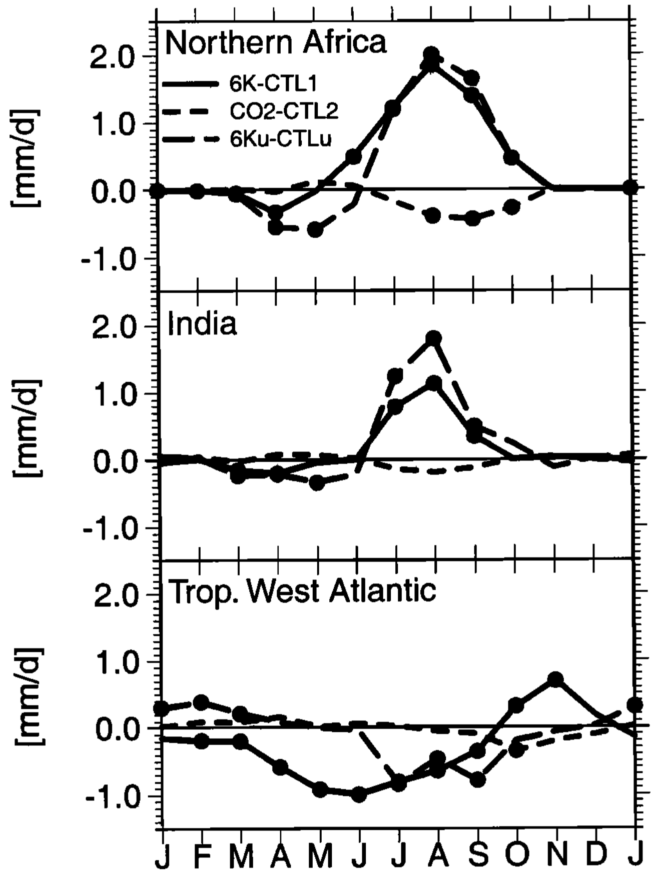

Figure 3. Area averaged monthly mean precipitation changes over land for northern Africa (17°W-28°E; 8°N-19°N) and for India (73°E-96°E; 25°N-36°N) as well as over the tropical west Atlantic (62°W-17°W; 3°S-14°N). The dots indicate a significant response on a 95% level of a t-test. The annual cycle of the mid-Holocene runs is adjusted such that the global mean root mean square of the differences of the incoming solar radiation between 6000 years ago and present-day is minimized.

back the winter pressure fields indicate a more zonal flow over northeastern Europe (not shown).

The most pronounced changes in precipitation occur in low latitudes. Over India and northern Africa the mid-Holocene boundary conditions lead to enhanced monsoon precipitation (Figure 3). Over India the intensification in the uncoupled experiment *6Ku* is stronger than in the coupled run *6K*, while both experiments show a similar enhancement over northern Africa. Here the *6K* simulation shows an earlier onset of the rainy season. The CO_2 reduction leads to a weakening of the signal in this region. However, the northward shift of the northern African monsoon, which has been found in proxy data [*Jolly et al.*, 1998], is underestimated in both mid-Holocene experiments (not shown). Over the western tropical Atlantic negative precipitation anomalies dominate in the *6K* run (Figure 3) which affect the ocean climate significantly (see below). In contrast the uncoupled run *6Ku* shows a much weaker annual mean signal in precipitation with a different seasonal distribution. The CO_2-induced response is only weak: except for October the signal is nonsignificant.

In the three described regions the precipitation anomalies are closely related to cloud cover and vertical velocity. Increasing (decreasing) precipitation is accompanied by increasing (decreasing) cloud cover and anomalous rising (sinking) at 500 hPa. In the rainy season enhanced upward motion over northern Africa and anomalous subsidence over the tropical west Atlantic region has been simulated. Both regions are connected through an eastward flow anomaly in the lower troposphere. As a result the westward moisture transport from tropical Africa to the Atlantic weakens. This feature is more pronouced in the coupled integration *6K* than in the uncoupled run *6Ku*.

4. Oceanic Response

The freshwater flux into the ocean is directly affected by the mid-Holocene forcing. Over the tropical west Atlantic the precipitation is substantially reduced (by about 9% for the annual mean, resulting in 0.03 Sv less freshwater input into the ocean; Figure 3). The analysis of the atmospheric moisture transports reveals the strongest changes for the American watershed: over North America the import into the Atlantic and Arctic drainage basin is reduced by 6% and over South America the export is enhanced by 3%. Overall the atmospheric freshwater export from the Atlantic and Arctic drainage basin increases by 0.03 Sv. In the western tropical Atlantic and north of 30°N the salinity increases (Figure 1c). This leads to an intensification of the North Atlantic overturning circulation by 1.8 Sv (Figure 1d). The effect of the higher surface salinities on North Atlantic overturning is partly compensated by the higher surface temperatures in the sinking region (especially in winter) caused by enhanced incoming shortwave radiation (Figure 1b). Due to deep convection the North Atlantic deep water is saltier (between 0.05 psu and 0.1 psu) and warmer (by typically 0.1 K). Together with the surface cooling the warming in the deeper layers reduces the vertical temperature contrast at 30°N. Thus, the oceanic northward heat transport at this latitude shows - in spite of the intensified overturning - only a slight enhancement (2%) which is only statistically significant for long timescales.

The CO_2 reduction alone leads to an intensification of the North Atlantic overturning by 1.2 Sv as well (Figure 1d). Here no significant salinity anomaly has been found in the North Atlantic, but the SST decreases (Figure 1b+c). As a result the density of the surface water becomes higher and the overturning intensifies. This result compares well with the weakening of the overturning in simulations with increased CO_2 concentration [*Voss and Mikolajewicz*, 2001].

5. Conclusions

In the coupled AOGCM experiment the mid-Holocene conditions lead to a warming in northern high and mid latitudes and to a cooling in the tropics. The coupling leads a further intensification of the simulated northern African summer monsoon intensifies compared to an uncoupled AGCM experiment and becomes more consistent with estimayes from proxy. This effect has also been found in other studies [*Kutzbach and Liu*, 1997; *Hewitt and Mitchell*, 1998; *Braconnot et al.*, 2000].

The 1000-year integrations enable a better identification of the climate change signals. In most regions the anomalies are of the same order of magnitude as the long-term internal variability of the system. The long-term (multi-century and longer) adjustment processes associated with the long memory of the deep ocean are of little importance for the climate signal in the atmosphere and the upper ocean. That is, the signal which penetrates into the deeper layers of the ocean is weak.

The lower CO_2 concentration and the ocean feedback have substantial impact on the climate signal. The CO_2 reduction leads to a global cooling and a weakening of the African and Indian monsoon signal. The oceanic feedback amplifies the temperature signal induced by the insolation changes (stronger warming in the northern high and mid latitudes and cooling elsewhere).

Both, the CO_2 reduction and the combined effect of CO_2 reduction and changes in insolation, intensify the overturning circulation in the Atlantic. However, the responsible mechanisms differ: in the *CO2* experiment the temperature effect (decrease of the North Atlantic SST) dominates whereas in the *6K* run the salinity effect dominates (advection of saltier water from the tropics to the North Atlantic). Thus, the insolation changes alone do not have a substantial impact on the Atlantic's meridional overturning, but tend to shift the system slightly towards a salinity dominated regime.

The inclusion of an interactive vegetation can lead to further enhancement of the rainfall over northwest Africa and improve the consistency with proxy data [*Doherty et al.*, 2000; *de Noblet-Ducoudre et al.*, 2000]. This topic will be subject of a future model study.

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