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# On the importance of initial conditions for simulations of the Mid-Holocene climate

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CPD

2, 315–326, 2006

Initial conditions in  
simulations of  
mid-Holocene climate

H. Renssen et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

EGU

## Abstract

Three simulations of the Mid-Holocene (6 ka) climate were performed with the ECBilt-CLIO-VECODE coupled atmosphere-ocean-vegetation model to study the impact of initial conditions. These experiments were forced with identical 6 ka forcings (orbital parameters and atmospheric greenhouse gas concentrations) and differed only in initial conditions. Two simulations were designed as equilibrium experiments, with one being initialized with preindustrial conditions as required by the protocol of the Paleoclimate Modelling Intercomparison Project (PMIP), while in a second experiment early Holocene (9 ka) initial conditions were used. These equilibrium simulations were run for 2100 years with 6 ka forcings. The third experiment was set up as a transient simulation, also starting from early Holocene conditions, but forced with annually changing orbital parameters and greenhouse gas levels. The results of the last 100 years are compared and reveal no statistically significant differences, showing that in this model the initial conditions have no discernible impact on the 6 ka climate. This suggests that the PMIP set-up for 6 ka simulations is valid, with the condition that spin-up phase should be long enough (at least 600 years) to allow the deep ocean to adjust to the change in forcings.

## 1 Introduction

The Mid-Holocene (6 ka) is frequently used as a reference period to evaluate the sensitivity of climate models to changes in radiative forcing, e.g., in the first and second phases of the Paleoclimate Modelling Intercomparison Project (PMIP, Joussaume and Taylor, 2000; Crucifix et al., 2005). Within PMIP, all models use an identical experimental setup to make intermodel comparisons possible (e.g., Joussaume et al., 1999; Braconnot et al., 2000). The PMIP experimental setup for Mid-Holocene simulations includes the forcing conditions and model spin-up. Compared to preindustrial forcings, the orbital parameters and atmospheric greenhouse gas concentrations are changed

CPD

2, 315–326, 2006

### Initial conditions in simulations of mid-Holocene climate

H. Renssen et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

EGU

to represent conditions at 6 ka. The spin-up procedure requires models to start with initial conditions obtained from a model state in quasi-equilibrium with pre-industrial forcings. After completion of the experiments in PMIP, the model results are evaluated by comparison with proxy data (e.g., Prentice et al., 1998; Joussaume et al., 1999). A key region for model-data comparisons is Northern Africa, which experienced a much wetter climate at 6 ka than today under influence of the orbitally forced enhancement of the summer monsoons (i.e. “green” Sahara).

The choice of the preindustrial initial conditions for 6 ka experiments is disputable, as potentially a different 6-ka climate state can be obtained when different initial conditions are used. Possibly, the use of early Holocene (e.g., 9 ka) initial conditions is more appropriate because the climate of that time could have been closer to the mid-Holocene climate. This could for instance be the case in the Sahara/Sahel region that was in a ‘green’ state in the early-to-mid Holocene (from ~11 to 5 ka) during the so-called African Humid Period (e.g., deMenocal et al., 2000), which includes the 6 ka time-slice (e.g., Hoelzmann et al., 1998; Prentice et al., 2000). Previous model studies have suggested that both the green and desert states could have been stable under 6 ka forcings (Renssen et al. 2003), implying that potentially simulations initialized with preindustrial conditions could produce a desert state in Northern Africa instead of the required green state.

To study the influence of the initial conditions on the simulated 6-ka climate, we compare here the results of three simulation experiments performed with the ECBilt-CLIO-VECODE model, which describes the global coupled atmosphere-ocean-vegetation system. In addition to an experiment with the “standard” PMIP setup (i.e. preindustrial initial conditions), we have performed an experiment with 6 ka forcings that is initialized with conditions derived from a simulation in quasi equilibrium with forcings for 9 ka. These two experiments are compared with 6 ka results from a transient experiment that is integrated forward in time, forced with annually varying orbital and greenhouse gas forcing and starting from the same 9 ka initial conditions.

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## Initial conditions in simulations of mid-Holocene climate

H. Renssen et al.

---

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[⏪](#)[⏩](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

## 2 Model and experimental setup

We applied version 3 of the ECBilt-CLIO-VECODE coupled climate model of intermediate complexity. The atmospheric model is ECBilt, a quasi-geostrophic model with T21-L3 resolution (Opsteegh et al., 1998). CLIO is the oceanic component and consists of a free-surface, primitive-equation ocean general circulation model (OGCM), coupled to a dynamic-thermodynamic sea-ice model (Goosse and Fichefet, 1999). The OGCM includes 20 levels in the vertical and has a  $3^\circ \times 3^\circ$  latitude-longitude horizontal resolution. VECODE is 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). Details about the model are available at <http://www.knmi.nl/onderzk/CKO/ecbilt.html>. With an earlier version of the model (i.e. version 2), we studied the Holocene climate evolution in Northern Africa (Renssen et al. 2003). The differences between versions 2 and 3 are discussed at <http://www.knmi.nl/onderzk/CKO/differences.html>.

With ECBilt-CLIO-VECODE-version-3 we performed two equilibrium 6 ka experiments in which identical changes in forcings are applied relative to a standard set of preindustrial conditions. The most important change is the modification of the orbital parameters to their 6-ka values according to Berger (1978). In addition, to account for different values in atmospheric trace gas concentrations at 6 ka, the levels of CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O were set at 267.6 ppm, 589.1 ppb and 262.3 ppb, respectively (Raynaud et al., 2000). The two experiments were run with these forcings for 2100 years, starting from different initial conditions. The first experiment (hereafter “6kPI”) was started from a state obtained from a 2500-year control run with preindustrial conditions in accordance with the PMIP protocol, while a second simulation (hereafter “6k9k”) was initialized with a state derived from a 1500-year long experiment with orbital and greenhouse gas forcings for 9 ka. Note that these 9 ka conditions do not account for the remnant Laurentide Icesheet in North America, implying that the early Holocene initial state is slightly too warm compared to proxy data (Renssen et al., 2005a).

In addition to these equilibrium experiments, we performed a third simulation that

### Initial conditions in simulations of mid-Holocene climate

H. Renssen et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

was set-up as a transient experiment (6kTR). It was started from the same 9 ka initial conditions as 6k9k, but was integrated forward in time towards preindustrial times, forced by annually changing values in orbital parameters and atmospheric concentrations of CO<sub>2</sub> and CH<sub>4</sub>. At 6 ka, these values were identical to the ones prescribed in 6kPI and 6k9k. The level of N<sub>2</sub>O was kept constant at 262.3 ppb throughout the 6kTR experiment. The results of 6kTR have been analyzed in detail for high-latitude climates (Renssen et al., 2005a, b, c).

### 3 Results and discussion

In our coupled atmosphere-ocean-vegetation system, the oceans are the component with the longest memory due to their large heat capacity. Consequently, any potential differences between our experiments that are caused by initial conditions and that are related to the memory of the system could be expected to be primarily present in the oceans. Therefore, we focus our global scale analysis on the oceans. For Northern Africa, we also consider vegetation because it has been suggested that in this region the vegetation-climate system could have two stable equilibria (i.e., “green” and desert) under 6 ka forcings.

The globally averaged ocean temperature (Fig. 1a) provides a clear picture of the influence of the initial conditions and the time that is required to reach a new quasi equilibrium. On a global scale, the 9 ka initial temperature is close (3.12°C, see Table 1) to the final 6 ka state (3.11°C), while the preindustrial climate is considerably colder (3.07°C). After about 600 years, the global ocean temperature is similar in 6kPI and 6k9k, implying that the influence of the cold initial preindustrial conditions is no longer discernible at the global scale. The temperature fluctuations in the remaining 1500 years of the experiments can be attributed to natural variability. The final level (3.11°C) of the global ocean temperature in 6kPI and 6k9k is the same as in 6kTR at 6 ka (Table 1). The same is true for the sea-ice volumes in both hemispheres (Fig. 1b, Table 1) and the strength of the overturning circulation (Table 1), showing that the differ-

## Initial conditions in simulations of mid-Holocene climate

H. Renssen et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[⏪](#)[⏩](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

ences in experimental setup between the considered simulations have no discernible impact on the final 6 ka ocean state in our model. The evolution of the Northern Hemispheric sea-ice volume (Fig. 1b) clearly shows the slow adjustment to the annually changing forcings in 6kTR.

5 In addition to the discussed oceanic variables, we have also analyzed the spatial patterns of surface temperature and precipitation anomalies, thereby considering the averages over the last 100 years of 6kPI and 6k9k, and the relevant 100 years of 6kTR (i.e. 6050–5950 yr BP). To see if the differences between these average 6 ka climates were statistically significant, we performed a student-t test at the 95% level (not shown).  
10 In short, there were no consistent anomalies in surface temperature or precipitation that were statistically significant.

In Northern Africa, the initial conditions for vegetation differ considerably for 6kPI and 6k9k. This is illustrated by the vegetation cover, which has a mean value of 27.5% in the preindustrial “desert” state and 67.1% in the 9 ka “green” state (Table 1). In  
15 200 years of simulation with 6 ka forcing, 6kPI and 6k9k converge at the 6 ka level of 6kTR (i.e. vegetation cover of about 54%, not shown). This is no surprise, as it was already noted that precipitation and temperature in 6k9k and 6kTR show no consistent statistical anomalies over Northern Africa compared to 6kPI. Consequently, it may be concluded that in our model only the “green” state is stable over Northern Africa at 6 ka  
20 and that initial conditions have no distinct impact on the 6 ka vegetation in this region.

It should be noted that this conclusion for Northern Africa is model-dependant. For instance, in an earlier model version (ECBilt-CLIO-VECODE version 2), both desert and green states were potentially stable in Northern Africa under 6 ka forcings (Renssen et al. 2003). In a transient experiment identical to 6kTR that was performed  
25 with this previous version, this bistability was revealed by abrupt centennial-scale shifts between the desert and green states in the western part of Northern Africa (between 15° W and 5° E) during an unstable phase that lasted from 7.5 to 5.5 ka (Renssen et al., 2003, 2006). This instability is related to Charney’s biogeophysical feedback (Charney, 1975; Charney et al., 1975) between surface albedo, influenced by vege-

---

## Initial conditions in simulations of mid-Holocene climate

H. Renssen et al.

---

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

tation cover, and precipitation. Compared to the experiment with version 2, in 6kTR the Holocene desertification in Northern Africa differs on two points. First, the largest change from “green” to desert takes place more to the east (i.e. in the central-eastern Sahara between 10° E and 35° E), and second, the unstable phase with accelerated desertification due to Charney’s biogeophysical feedback occurs later (i.e. between 5.2 to 3.2 ka). Consequently, at 6 ka the climate in 6kTR is still in the “green” state. In the ECHAM-BIOME model, the “green” state is also the only equilibrium that exists under 6 ka forcings (Brovkin et al., 1998)

The similarity between the 6 ka climates in 6kTR and the other experiments (6kPI and 6k9k) implies that the climate in 6kTR is in equilibrium with the 6 ka forcings, suggesting that the annual changes in forcing are small enough for the system to adjust continuously during the mid-Holocene. In other words, assuming an adjustment time (or memory) of ~600 years, the climate at 6.0 ka is still influenced by the forcings at 6.6 ka in 6kTR, but the changes in forcings between 6.6 ka and 6 ka are apparently not large enough to yield a statistically different climate compared to 6kPI and 6k9k. This is good news for model-data comparisons as carried out for the 6 ka climate within PMIP (e.g., Joussaume et al., 1999), as one can expect that the climatic changes experienced in the “real world” (as registered in proxy data) are closer to the results of 6kTR than to those of the other experiments.

If we assume that our inferences about the indiscernible influence of initial conditions are reasonable, it would imply that the PMIP protocol for 6 ka experiments is valid. An important requirement is that the integration time during spin-up allows for adjustment of deep oceans to the 6 ka forcings. Our simulations suggest that the spin-up phase should at least have a duration of 600 years (see Fig. 1a).

## 4 Concluding remarks

In our model, the initial conditions (either preindustrial or early Holocene) have no discernible impact on the final 6 ka climate that is obtained after running our model for

### Initial conditions in simulations of mid-Holocene climate

H. Renssen et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

2100 years with constant forcings for 6 ka. After about 600 years, both 6kPI and 6k9k have reached the final level of deep ocean temperature that is matching the 6 ka level in our transient experiment 6kTR. The vegetation in Northern Africa reaches the same 6 ka level after about 200 years in both the equilibrium experiments with different initial conditions, giving no indication for bistability of the vegetation-atmosphere system under 6 ka forcings. Assuming that these conclusions are applicable to other models, our results suggest that the PMIP setup for 6 ka experiments is reasonable as long as the experiments have a long enough spin-up time (i.e. at least 600 years) to account for the relatively slow response of the deep ocean.

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## Initial conditions in simulations of mid-Holocene climate

H. Renssen et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

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CPD

2, 315–326, 2006

---

## Initial conditions in simulations of mid-Holocene climate

H. Renssen et al.

---

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

EGU

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CPD

2, 315–326, 2006

---

**Initial conditions in  
simulations of  
mid-Holocene climate**

H. Renssen et al.

---

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

EGU

## Initial conditions in simulations of mid-Holocene climate

H. Renssen et al.

**Table 1.** Annual mean values for some key variables for the 6 ka climates simulated in the three experiments. For 6kPI and 6k9k, the averages over the last 100 years of the 2100-year long simulations are shown, while for 6kTR the 100-year means for the 6050–5950 yr BP period are presented. The standard deviations for 6kPI are given between brackets for the 6 ka climate (i.e., the last 100 years of the simulation). For comparison, also the initial values for 6kPI and 6k9k are shown.

	Experiments				
	init	6kPI 6 ka	6k9k Init	6k9k 6 ka	6kTR 6 ka
<b>Global ocean variables</b>					
Global ocean temperature (°C)	3.07	3.11 (0.001)	3.12	3.11	3.11
Sea-ice volume NH ( $10^3 \text{ km}^3$ )	43.2	27.8 (1.7)	19.2	28.0	27.8
Sea-ice volume SH ( $10^3 \text{ km}^3$ )	11.8	10.4 (0.7)	10.4	10.5	10.7
NADW exported at 20° S (Sv)	13.7	13.6 (0.8)	13.5	13.7	13.6
Max. Meridional overturning in Southern Ocean (Sv)	19.2	18.9 (1.3)	19.7	19.0	19.1
<b>North Africa (10° W–35° E, 15° N–30° N)</b>					
Vegetation cover (%)	27.5	53.4 (1.9)	67.1	55.0	53.9
Surface albedo (%)	34.3	28.8 (0.4)	25.7	28.5	28.7
Temperature (°C)	24.2	24.4 (0.1)	24.5	24.4	24.4
Precipitation (mm/yr)	269.9	452.9 (12.4)	567.9	463.2	456.7

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

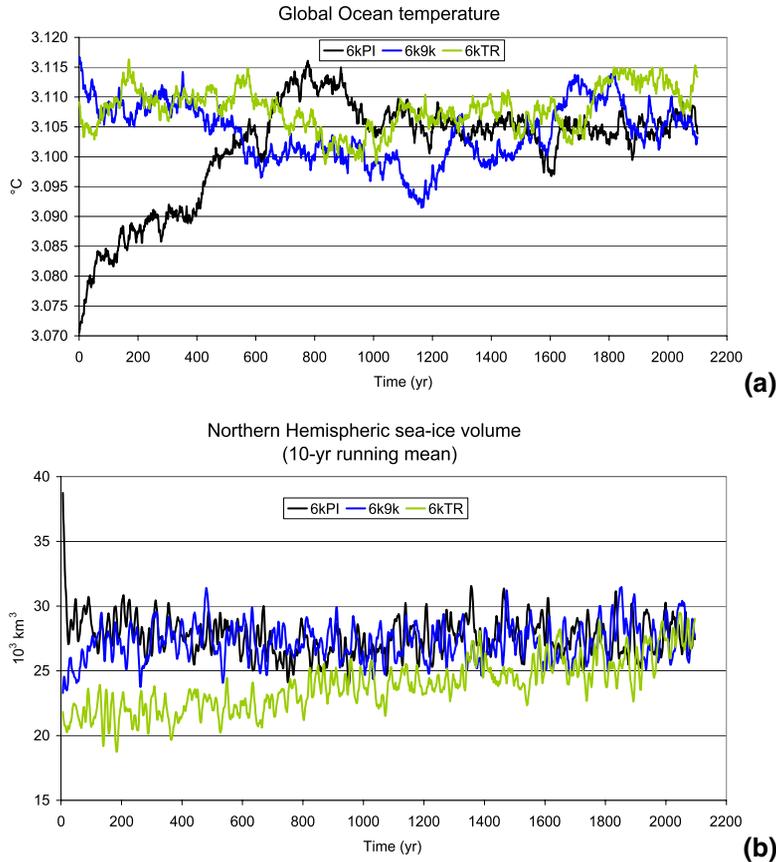
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**Initial conditions in  
simulations of  
mid-Holocene climate**

---

H. Renssen et al.

---



**Fig. 1.** Simulated annual means of the globally averaged ocean temperature (a, top) and sea-ice volume in the Northern Hemisphere (b, bottom). Note that the forcings for experiments 6kPI and 6k9k are kept constant at 6 ka values, while the forcings for 6kTR are changing every year. The shown values for 6kTR represent the period 8050 yr BP ( $t=0$ ) to 5950 yr BP ( $t=2100$ ). The averages over the last 100 years are presented in Table 1.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)