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Global characterization of the Holocene Thermal Maximum

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ABSTRACT

We analyze the global variations in the timing and magnitude of the Holocene Thermal Maximum (HTM) and their dependence on various forcings in transient simulations covering the last 9000 years (9 ka), performed with a global atmosphere-ocean-vegetation model. In these experiments, we consider the influence of variations in orbital parameters and atmospheric greenhouse gases and the early-Holocene deglaciation of the Laurentide Ice sheet (LIS). Considering the LIS deglaciation, we quantify separately the impacts of the background melt-water fluxes and the changes in topography and surface albedo.

In the analysis we focus on the intensity of the maximum temperature deviation relative to the preindustrial level, its timing in the Holocene, and the seasonal expression. In the model, the warmest HTM conditions are found at high latitudes in both hemispheres, reaching 5 °C above the preindustrial level, while the smallest HTM signal is seen over tropical oceans (less than 0.5 °C). This latitudinal contrast is mostly related to the nature of the orbitally-forced insolation forcing, which is also largest at high latitudes, and further enhanced by the polar amplification. The Holocene timing of the HTM is earliest (before 8 ka BP) in regions not affected by the remnant LIS, particularly NW North America, E Asia, N Africa, N South America, the Middle East, NE Siberia and Australia. Compared to the early Holocene insolation maximum, the HTM was delayed by 2–3 ka over NE North America, and regions directly downwind from the LIS. A similar delay is simulated over the Southern Ocean, while an intermediate lag of about 1 ka is found over most other continents and oceans. The seasonal timing of the HTM over continents generally occurs in the same month as the maximum insolation anomaly, whereas over oceans the HTM is delayed by 2–3 months. Exceptions are the oceans covered by sea ice and North Africa, were additional feedbacks results in a different seasonal timing. The simulated timing and magnitude of the HTM are generally consistent with global proxy evidence, with some notable exceptions in the Mediterranean region, SW North America and eastern Eurasia.

1. Introduction

The Holocene Thermal Maximum (HTM) was a relatively warm climatic phase between 11 and 5 ka BP, as indicated by numerous proxy records (Kaufman et al., 2004; Jansen et al., 2007, 2008; Wanner et al., 2008; Miller et al., 2010a; Bartlein et al., 2011). The relatively warm conditions during the HTM are commonly associated with the orbitally-forced summer insolation maximum (Wanner et al., 2008; Bartlein et al., 2011). However, proxy records suggest that both the timing and magnitude of maximum warming varied substantially between different regions across the globe, suggesting involvement of additional forcings and feedbacks (Jansen et al., 2007; Bartlein et al., 2011). One important additional factor affecting the early Holocene climate is the remnant Laurentide Ice sheet (LIS). At mid-to-high latitudes of the Northern Hemisphere, the spatio-temporal complexity of the HTM can be explained by the cooling effect of the LIS, delaying the HTM by 1–2 thousand years compared to the orbitally-forced insolation maximum, particularly in NE North America, the North Atlantic, Western Europe and a zonal band across Eurasia (Kaufman et al., 2004; Kaplan and Wolfe, 2006; Renssen et al., 2009). It is however not clear how the HTM expression at other latitudes relates to orbital forcing and the response to the early Holocene LIS. Although reconstructions of annual-mean temperatures appear to suggest a rather uniform timing of the HTM across the globe (Ljungqvist, 2011), larger differences may exist for different seasons, given the seasonal nature of the orbital forcing.

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Model experiments have shed light on the response of the climate system to orbital forcing during the Holocene. For instance, snapshot simulations performed for 6 ka BP within the framework of the Paleoclimate Modelling Intercomparison Project (PMIP) I and II, suggest that in summer most northern hemisphere continents were about 1–2 °C warmer relative to the preindustrial era due to enhanced summer insolation (Braconnot et al., 2007; Otto et al., 2009; Zhang et al., 2010). Over the oceans, models indicate a less expressed 6–0 ka BP temperature response, varying from +0.5 °C in the North Atlantic Ocean to even a small negative anomaly in the tropical oceans (Braconnot et al., 2007). However, it is likely that simulations for 6 ka BP do not always reflect the conditions during the HTM, as proxy-based reconstructions suggest that the timing of the HTM was much earlier than 6 ka BP at many locations (e.g., Kaufman et al., 2004; Jansen et al., 2007; Bartlein et al., 2011). Moreover, northern hemisphere summer may not have been the season with the largest response in all places (e.g., Davis, 1984).

To improve our understanding of the global expression of the HTM, it is necessary to study the characteristics of the maximum temperature anomaly in transient climate model simulations. In an earlier study (Renssen et al., 2009), we analyzed the HTM at the Northern Hemisphere mid-to-high latitudes, based on a comparison of simulated July temperatures and selected proxy-based reconstructions. In the present paper, we extend this analysis by specifically considering the *global scale*, thereby focusing on the *relative timing of the HTM in different regions*, the variation in *seasonal expression* and the explanation of these differences. This focus is expressed in the following questions:

- What is the maximum warming compared to the preindustrial climate?
- What is the timing of the HTM in ka BP?
- What was the seasonal expression of the HTM? In what month of the year is the maximum warm anomaly occurring?
- How consistent are the model-based simulations of the HTM with the proxy-based records?

Our main experiment includes the following forcings: orbital parameters, atmospheric greenhouse gas concentrations, and the impact of the early Holocene Laurentide ice sheet deglaciation (albedo, ice topography and meltwater discharge). By comparing the results of this experiment with those of a simulation with just orbital and greenhouse gas forcing, we are able to analyze the separate impacts of the main forcings. For our analysis, we use the same experiments as discussed in Renssen et al. (2009, 2010).

2. Methods: model and experimental setup

2.1. The model

The model and experimental design have been described in detail in two recent papers (Renssen et al., 2009, 2010), so here only a summary is provided. We performed our simulations with the global ECBilt-CLIO-VECODE3 model. This is an earlier version of the model recently renamed to LOVECLIM, which has been discussed by Goosse et al. (2010). The atmospheric module ECBilt, is a quasi-geostrophic model with T21L3 resolution (Opsteegh et al., 1998), corresponding to ~5.6° latitude by ~5.6° longitude at the surface. The oceanic component CLIO consists of a free-surface, primitive-equation oceanic general circulation model coupled to a dynamic-thermodynamic sea-ice model (Goosse and Fichefet, 1999). CLIO has 20 levels in the vertical and a 3° × 3° latitude-longitude horizontal resolution. Coupled to ECBilt is VECODE; a vegetation 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). ECBilt-CLIO simulates a reasonable present-day climate (Goosse et al., 2001; Renssen et al., 2002). In addition, the response of ECBilt-CLIO-VECODE to mid-Holocene orbital forcing was comparable to that of comprehensive general circulation models (Braconnot et al., 2007). Due to the simplifications in the general circulation equations for the atmosphere, our model has a better performance at mid- and high latitudes than in the tropics (Goosse et al., 2010). This should be kept in mind when interpreting the simulation results. The sensitivity of ECBilt-CLIO to a doubling of the atmospheric CO_2 concentration is within the range of comprehensive GCMs at high latitudes in winter, but slightly weaker at low to mid-latitudes in summer (Petoukhov et al., 2005).

2.2. Experiments

We discuss here two experiments that cover the last 9000 years: ORBGHG and OGMELTICE. These experiments have been discussed before by Renssen et al. (2009, 2010). We started our simulations at 9 ka BP because before that time the influence of the Younger Dryas cold phase, representing major reoganizations of the climate system, may still have had an important impact on climate through the long memory of the deep ocean. Experiment ORBGHG is forced by annually varying values of orbital parameters following Berger (1978), and atmospheric concentrations of the main greenhouse gases CO_2 and CH_4 based on ice core measurements (Raynaud et al., 2000). In ORBGHG, the ice sheets are kept fixed at their present-day configuration. In addition to identical orbital and greenhouse gas forcing as in ORBGHG, in OGMELTICE we also prescribed the impact of the early Holocene LIS deglaciation that lasted until ~6 ka BP. To account for the LIS background melt flux, freshwater was added to the North Atlantic Ocean near the St. Lawrence River Outlet and the Hudson Strait. This additional freshwater flux was adapted from Licciardi et al. (1999) and was set to 0.09 Sv (1 Sv = 10^6 m^3s^{-1}) between 9.0 and 8.4 ka BP, decreasing slightly to 0.08 Sv between 8.4 and 7.8 ka BP, finally dropping to 0.01 Sv between 7.8 and 6.8 ka BP. In OGMELTICE, we also included the impact of the disintegrating LIS during the period 9 to 7 ka BP, by updating surface albedo and topography at 50-year timesteps. The modified surface albedo and topography related to the LIS were based on Peltier (2004), who reconstructed maps of ice sheet extent and thickness since the last glacial maximum (21 ka BP) at 500 year intervals. To obtain the surface albedo and topography at 50-year timesteps, we linearly interpolated in time between the maps provided by Peltier (2004). In both ORBGHG and OGMELTICE, we kept all other forcings (i.e. solar constant, aerosol content) constant at preindustrial values. To obtain initial conditions for OGMELTICE, we spun up the model for 1000 years with 9 ka BP meltwater flux and LIS albedo and topography, starting from a state derived from ORBGHG.

2.3. Insolation

As orbitally-forced changes in insolation are considered the most important driver of long-term Holocene climate change, we discuss here briefly the details of the prescribed insolation. We employed in our model a calendar with 360 days per year, with each month containing 30 days and with the vernal equinox fixed at day 81 (i.e. March 21). This is common practice in Holocene climate modelling studies (e.g., Crucifix et al., 2002; Weber et al., 2004; Braconnot et al., 2007). A calendar with the duration of the months depending on their angular length (Joussaume and Braconnot, 1997) would have been more accurate. However, this would have required major adjustments to the model code that were considered unfeasible within this project.

Within the time-frame considered here, the maximum difference in insolation relative to the preindustrial period is at the very