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Climate evolution during the Holocene: a study with an Earth system model of intermediate complexity

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Abstract An Earth system model of intermediate complexity, MoBiDiC, has been used to simulate the transient variations in continental temperature, sea-surface temperature (SST), thermohaline circulation (THC) and sea-ice cover over the last 9000 years (9 kyr). Experiments were designed to determine (a) the deviation of the climatic system with respect to equilibrium over the last 9 kyr, (b) the individual contributions of oceans and vegetation to climatic changes, as well as the potential synergies between these components, and (c) the relative importance of precession, obliquity and CO₂ concentration changes during this period. Results show a monotonous cooling trend in the northern high latitudes between 9 kyr BP and the present day, both over the oceans and the continents. North of 60°N, this cooling is noticed throughout the year, but the largest variations appear in spring and summer (up to 6 °C over continents). Along with this cooling, the model exhibits a southward shift of the northern treeline by about 600 km. Most of this shift takes place between 4 and 1 kyr BP. During this period, reorganisations of the boreal forest introduce a lag of about 200 years in the system with respect to a state in equilibrium with the external forcing. Sensitivity experiments illustrate the strong impact of this vegetation shift both on the oceans and the continents, especially in spring and early summer. However, the model exhibits a weak synergy between vegetation and ocean throughout the Holocene. Finally, a sensitivity study to the forcing components shows the dominant role of the astronomical forcing with respect to CO₂, as well as the non-linear behaviour of climate in response to obliquity and precession.

1 Introduction

The Holocene (taken here as the last 9000 years) appears in the polar records as a period of relative stability when compared to glacial ages. However, important changes occurred in paleoenvironmental conditions in the northern mid- and high latitudes as well as in the tropics.

In Europe, for example, paleobotanic reconstructions suggest that the surface temperature went through a maximum about 6000 years ago with, in particular, milder winters than today in Scandinavia (Huntley and Prentice 1988). Similarly, foraminifera- and diatom-based reconstructions (Ruddiman and Mix 1993; Koç et al. 1993; Kerwin et al. 1999) reveal that the SST in the northern North Atlantic was higher than today during the early Holocene, with a deviation in summer that could have been as high as 4 °C. In the tropical areas, changes are essentially seen in precipitation, the Asian and African monsoons being more intense and shifted northwards between 9 and 5 kyr BP as compared to today (Street-Perrott et al. 1990; Gasse 2000).

Since the pioneering modelling study of the Holocene climate by Kutzbach and Otto-Bliesner (1982), there has been a general consensus to consider the astronomical forcing as the fundamental cause of these variations. Indeed, at 9 kyr BP, the Earth reached the perihelion during the northern summer, while today it occurs in winter. This effect can be quantified by the change in the precession parameter (eccentricity times the sine of the longitude of the perihelion) that increased from –0.0145 (Northern Hemisphere summer solstice at perihelion) to 0.0164 (Northern Hemisphere summer solstice at aphelion) over this period (Fig. 1a) (Berger 1978). The consequence for the Northern Hemisphere is a gradual weakening of the amplitude of the seasonal cycle of insolation at the top of the atmosphere, resulting in a decrease in the hemispheric average of June insolation by 33 W/m² (6%) to the benefit of the January insolation. In addition to precession, obliquity (i.e. the tilt of
the Earth’s rotational axis) decreased by about 1° over the last 9 kyr BP (Fig. 1b). Such a decrease in obliquity causes a decrease of insolation in the summer hemisphere. Hence, in the Northern Hemisphere, the effects of precession and obliquity on June insolation summed up during the Holocene. For example, at 65°N, the summer solstice insolation decreased by about 46 W/m$^2$ (10%) between 9 kyr BP and today (Fig. 1c). In addition to its effect on summer insolation, the decrease in obliquity caused an increase in annual mean insolation between 43°S and 43°N at the expense of the high latitudes. Namely, annual mean insolation at 65°N decreased by 2.5 W/m$^2$ (slightly more than 1%) between 9 kyr BP and today (Fig. 1d).

In order to test to which extent the astronomical forcing could explain the observed climatic changes, a large number of model studies have been performed. The first ones were based on atmospheric general circulation models (AGCMs) (Kutzbach and Otto-Bliesner 1982; Kutzbach et al. 1993; Hall and Valdes 1997; Joussaume and Braconnot 1997; Joussaume et al. 1999). These model studies pinpointed the main consequences of the changes in the seasonal and spatial distributions of insolation between the mid-Holocene and today, i.e. for 6 kyr BP, warmer summers in the Northern Hemisphere and intensified northern tropical monsoon due to enhanced sea-land temperature contrast. However, they did not succeed in reproducing correctly the amplitude of the climatic changes as recorded in data. For example, in the Sahara, the precipitation increase between the mid-Holocene and today simulated by these AGCMs was too small to allow vegetation to develop in this area as suggested by paleoenvironmental records. This is most likely because important potential sources of feedbacks, such as vegetation and ocean, were not taken into account. In this context, a growing effort has been devoted to assess the impact of vegetation changes in AGCMs. Foley et al. (1994) showed, for example, that in AGCM simulations of the 6 kyr BP climate, prescribing a more northward extension of taiga (cold boreal forest) caused, at northern high latitudes, an additional warming of 4 °C in spring and 1 °C in the other seasons. Likewise, Kutzbach et al. (1996) noticed that replacing desert with grassland in North Africa further enhances summer precipitation by 12% in this area. TEMPO (1996) and Harrison et al. (1998) adopted the inverse approach by showing that, when using the climate simulated at 6 kyr BP by various AGCMs, the BIOME vegetation model predicts an expansion of boreal forest to 1.20 times of its modern area as well as an expansion of ‘moisture-demanding’ vegetation in the African and Asian subtropics. As a step beyond, several coupled vegetation-atmosphere models have been developed and utilised to study the mid-Holocene climate. Claussen and Gayler (1997) simulated, with the ECHAM-BIOME model, an increase by 300% in summer precipitation in North Africa, along with a 6° northward advance of savanna in the western Sahara, which suggest that the climate changes in response to the astronomical forcing are even larger when the positive feedbacks between climate and vegetation are taken into account. This result was subsequently corroborated by Texier et al. (1997) and Doherty et al. (2000) (with, however, a less dramatic increase in North African precipitation). Texier et al. (1997) also reported a reduction of boreal tundra area by 25%.

In parallel, simulations of the mid-Holocene climate with coupled atmosphere–ocean models (AOGCMs) highlighted the positive feedback of the ocean for the penetration of northern summer monsoon (Kutzbach and Liu 1997; Hewitt and Mitchell 1998; Bush 1999; Braconnot et al. 2000). Otto-Bliesner (1999) also stressed the possible role played by changes in ENSO regimes for Sahel precipitation. Very recently, AOGCM simulations with an interactive vegetation component started to be conducted: Braconnot et al. (1999) found that the positive feedbacks of vegetation and ocean for summer monsoon do not merely sum up but exhibit a positive

![Fig. 1a–d Astronomical forcing over the last 9 kyr BP. a Precession parameter, defined as eccentricity times the sine of the perihelion; b obliquity; c summer solstice insolation at 65°N; d Annual mean insolation at 65°N](image-url)