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The climate and vegetation of Marine Isotope Stage 11 – Model results and proxy-based reconstructions at global and regional scale

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A R T I C L E I N F O

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A B S T R A C T

The climate of Marine Isotope Stage (MIS) 11, the interglacial roughly 400,000 years ago, is investigated for four time slices, 416, 410, 400, and 396 ka. We compare results from two climate models, the earth system model of intermediate complexity CLIMBER2-LPJ and the general circulation model CCSM3, to reconstructions of MIS 11 temperature, precipitation and vegetation, mainly from terrestrial records. The overall picture is that MIS 11 was a relatively warm interglacial in comparison to preindustrial, with Northern Hemisphere (NH) summer temperatures early in MIS 11 (416–410 ka) warmer than preindustrial, though winters were cooler. Later in MIS 11, especially around 400 ka, conditions were cooler in the NH summer, mainly in the high latitudes. Climate changes simulated by the models were mainly driven by insolation changes, with the exception of two local feedbacks that amplify climate changes. Here, the NH high latitudes, where reductions in sea ice cover lead to a winter warming early in MIS 11, as well as the tropics, where monsoon changes lead to stronger climate variations than one would expect on the basis of latitudinal mean insolation change alone, are especially prominent. Both models used in this study support a northward expansion of trees at the expense of grasses in the high northern latitudes early during MIS 11, especially in northern Asia and North America, in line with the available pollen-based reconstructions. With regard to temperature and precipitation changes, there is general agreement between models and reconstructions, but reconstructed precipitation changes are often larger than those simulated by the models. The very limited number of records of sufficiently high resolution and dating quality hinders detailed comparisons between models and reconstructions.

1. Introduction

Quantitative reconstructions of interglacial climates are of particular interests in light of the current anthropogenic warming, natural climate system dynamics (e.g. Solomon et al., 2007; Melles et al., 2012) and human–environment interactions (e.g. Yasuda and Shinde, 2004; Ruddiman, 2003; Weber et al., 2010). The temperature and moisture evolution for the most recent interglacial, the Holocene, has been established for different regions and selected time-slices using multi-decadal- to annual-resolution proxy records (e.g. Solomon et al., 2007; Wanner et al., 2008; Litt et al., 2009; Tarasov et al., 2009; Bartlein et al., 2011). For earlier interglacials, the availability of quantitative reconstructions remains relatively poor, and if reconstructions are available, the temporal and spatial resolution, as well as the dating quality of the climate archives, leave room for improvement.

The scientific interest in Marine Isotope Stage (MIS) 11 climate development has grown increasingly during the last decade (e.g. Burckle, 1993; Droxler et al., 2003; Rousseau, 2003; McManus et al., 2003; Desprat et al., 2005; Kandiano and Bauch, 2007; Ashton et al., 2008; Kariya et al., 2010). This interest is driven by the length of the MIS 11 interglacial, which at ~30 ka was longer than all subsequent interglacials, and the observed similarities to the current (MIS 1) interglacial in terms of orbital configuration, greenhouse gas concentrations, and sea level (e.g. Berger and Loutre, 1996; Hodell et al., 2000; Loutre and Berger, 2003; Lüthi et al., 2008; Tzedakis, 2010; Yin and Berger, 2010, 2012; McManus et al., 2011; Raymo and Mitrovica, 2012). Orbitally forced insolation variations and

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increased greenhouse gas concentrations have been proposed as the predominant forcings of higher temperatures, but during phases of muted precession and eccentricity the obliquity has also been proposed as the causal variable of interglacial length (Jouzel et al., 2007; Tzedakis et al., 2009). Model results by Yin and Berger (2012) indicate that the warmth of MIS 11 was due to its greenhouse gas concentration, while insolation alone would actually have led to a cooling.

While a substantial number of publications exist for proxy data representing MIS 11 climate and environments, surprisingly few studies using climate models and even fewer data-model comparisons have been published to date. Results obtained using a 2-dimensional climate model were presented by Loutre (2003) and Loutre and Berger (2003). Yin and Berger (2010, 2012) used the intermediate complexity model LOVECLIM to compare the climatic effects of changes in astronomical forcing and CO_2 on the climate of MIS 11 with other interglacials during the last 800,000 years. Herold et al. (2012) compared the climate of MIS 11 and several other interglacials (MIS 1, 5, 9, 11 and 19), using the full complexity climate model CCSM3. Melles et al. (2012) presented general circulation model (GCM) experiments with an interactive vegetation component (using GENESIS 3.0 coupled to BIOME4), focused on the Arctic region around Lake El'gygytgyn, NE Asia, for 410 ka, corresponding to the timing of peak northern hemisphere (NH) summer warmth. Finally, Milker et al. (2013) compared sea surface temperature (SST) reconstructions of MIS 11 with results from time slice simulations using CCSM3. In the current study we used one model of intermediate complexity (CLIMBER2-LPJ) and one comprehensive general circulation model (CCSM3) to simulate climate and vegetation dynamics during the earlier warmest part of MIS 11. We use CLIMBER2-LPJ for a transient simulation of MIS 11 climate, while using CCSM3 allows gaining a higher resolution insight into MIS 11 climate for selected time slices. Finally, climate changes determined by the two climate models are used to reconstruct the biome distribution, which is more often reconstructed than specific plants, by using the BIOME4 model.

A comparison of model simulations to climate and vegetation reconstructions based on proxy records helps in the evaluation of results and in better understanding the role of different climate drivers on past environments, from which both the data and modeling communities may profit. In this paper we present results of the model-simulated climate and vegetation cover during the MIS 11 full interglacial phase (~420–390 ka, roughly corresponding to substage 11.3 or 11c) – the earliest, longest and warmest phase of MIS 11 and one of the warmest interglacial intervals of the last 800 ka (Jouzel et al., 2007; Melles et al., 2012). These results are then compared and discussed together with published vegetation and climate reconstructions.

2. Data and methods

2.1. CLIMBER2-LPJ

CLIMBER2-LPJ (Kleinen et al., 2010) is a coupled climate carbon cycle model consisting of the earth model of intermediate complexity (EMIC) CLIMBER2 (Petoukhov et al., 2000; Ganopolski et al., 2001) coupled to the dynamic global vegetation model (DGVM) LPJ (Sitch et al., 2003; Gerten et al., 2004). This combination allows model experiments on time scales of an entire interglacial with land surface processes much more highly resolved (Kleinen et al., 2011).

CLIMBER2 consists of a 2.5-dimensional statistical-dynamical atmosphere with a latitudinal resolution of 10°. In the longitudinal direction the model resolves seven unevenly spaced sectors of subcontinental scale, which is equivalent to a mean longitudinal resolution of roughly 51°. It also contains an ocean model resolving three zonally averaged ocean basins with a latitudinal resolution of 2.5°, a sea ice model, and the dynamic terrestrial vegetation model VECODE (Brovkin et al., 2002). In addition, CLIMBER2 contains an oceanic biogeochemistry model, a model for marine biota (Ganopolski et al., 1998; Brovkin et al., 2002, 2007), and a weathering model.

To CLIMBER2 we have coupled the DGVM LPJ in order to investigate land surface processes at a significantly higher resolution. LPJ is run on a $0.5 \times 0.5°$ grid and is called at the end of every model year simulated by CLIMBER2. Monthly anomalies from the climatology of the temperature, precipitation, and cloudiness fields are passed to LPJ, where they are added to background climate patterns based on the Climatic Research Unit CRU-TS climate data set (New et al., 2000). In order to retain realistic interannual variability in these climate fields, the anomalies are not added to the climatology, but rather to the climate data for one year randomly drawn from the range 1901–1930. The change in the LPJ carbon pools is then passed back to CLIMBER2 as the carbon flux between atmosphere and land surface and is employed to determine the atmospheric CO_2 concentration for the next model year.

2.2. Community Climate System Model Version 3 (CCSM3)

The National Center for Atmospheric Research (NCAR) CCSM3 is a state-of-the-art coupled GCM that runs without any flux corrections. The global model is composed of four separate components representing atmosphere, ocean, land, and sea ice (Collins et al., 2006). Here, we use the low-resolution version of CCSM3 which is described in detail by Yeager et al. (2006). In this version, the resolution of the atmosphere is given by T31 (3.75° transform grid) spectral truncation with 26 layers, while the ocean model has a nominal horizontal resolution of 3° (like the sea-ice component) with 25 levels in the vertical. The latitudinal resolution of the ocean grid is variable, with finer resolution around the equator (0.9°). The land model is defined on the same horizontal grid as the atmosphere and includes components for biogeophysics, biogeochemistry, the hydrological cycle, as well as a dynamic global vegetation model. In order to improve the simulation of land hydrology, the Oleson et al. (2008) parameterizations for canopy interception and soil evaporation have been implemented for the land component.

2.3. BIOME4

Both CLIMBER2-LPJ and CCSM3 contain internal dynamic vegetation components. For the purpose of comparison to palaeovegetation reconstructions, the output of these models is less than ideal, though. DGVMs determine the grid cell coverage of certain plant functional types, but palaeovegetation reconstructions are usually reported in terms of biomes. We therefore also used the model BIOME4 to determine the biome distribution for the four selected time slices.

BIOME4 is a coupled carbon and water flux model that predicts the steady-state vegetation distribution, structure, and biogeochemistry, taking into account interactions between these effects (Kaplan, 2001). The model is the latest generation of the BIOME series of global vegetation models, which have been applied to a wide range of problems in biogeography, biogeochemistry and climate dynamics (Prentice et al., 1992; VEMAP Members, 1995; Haxeltine and Prentice, 1996; Jolly and Haxeltine, 1997; Kaplan et al., 2006; Tarasov et al., 2012). BIOME4 has been specifically developed with the intention of improving the simulation of cold-climate, high-latitude vegetation (Kaplan, 2001; Kaplan and New, 2006).

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