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Investigating the sensitivity of the Atmospheric General Circulation Model ECHAM 3 to paleoclimatic boundary conditions

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Abstract We present atmospheric simulations of three different time slices of the late Quaternary using the ECHAM 3 general circulation model in T42 resolution. In this work we describe the results of model runs for the time slices 6000 years BP (last climate optimum), 21 000 BP (last glacial maximum) and 115 000 years BP (glacial inception). Although the solar insolation is known for all time slices, a complete data set of the other boundary conditions which are necessary for running the atmospheric model exists only for the last glacial maximum in the form of the CLIMAP reconstruction. For the other two time slices, which are interglacial states like the modern climate, sea surface temperatures, land albedo and ice sheet topography are kept at modern values and only the solar insolation is changed appropriately. The response of the model to solar insolation changes is quite reasonable. The modelled anomalies are small and roughly opposite in sign for 6000 BP and 115 000 BP, respectively. In the case of last glacial maximum, the glacial ice sheet topography and ice albedo produce a much larger climate anomaly in the model. However, to enable a real test of model performance under glacial boundary conditions, the CLIMAP sea surface temperatures, which are now known to be partly inaccurate, should be replaced by an updated "state-of-the-art" reconstruction.

Key words Atmospheric response · General circulation models · Glacial maximum · Milankovitch Theory · Paleoclimate · Climate optimum · Glacial inception

Introduction

The use of general circulation models of the atmosphere (AGCMs) for climate studies has a long tradition. With the creation of the Atmospheric Modelling Intercomparison Project (AMIP) these studies have received a more formal international basis. The expertise of AMIP helped in defining the Paleoclimate Modelling Intercomparison Project (PMIP) where a number of AGCMs are used for paleoclimatic simulations. As a participant of PMIP we performed several simulations of the paleo-atmosphere with prescribed boundary conditions as defined in PMIP. In the following we report on first results of simulations at distinct times in the past: at 6000, 21 000 and 115 000 years before present (BP). In addition, we compare these results with a control run simulating the present atmospheric state.

We are especially interested in the simulation of the surface climatology which could be used to derive upper boundary conditions for ocean models. Ocean models may in turn be used to simulate the state of the paleo-ocean. At present, this two-step approach is the only way to model the atmosphere/ocean system in the past. Coupled atmosphere/ocean models already applied to the present climate are not yet in a state to be used for simulations of the paleoclimate.

Many atmospheric simulations were performed for the time of the last glacial maximum (LGM) at approximately 21 000 years BP. The data set to define the boundary conditions and the data used for verification are most complete for the LGM as compared with other times in the past. From a more theoretical point of view it is also interesting to compare simulations at 6000 and 115 000 years BP because these times correspond to roughly opposite insolation anomalies. At 6000 years BP (the last climate optimum) the summer insolation was higher than at present, whereas summer insolation was smaller at 115 000 years BP (the time of possible glacial inception at the beginning of the last glacial cycle).

For the time 6000 BP one can be sure that there were no remains of glacial ice sheets over Europe and North America. This was the reason to choose 6000 BP as the time slice for the simulation of the climate optimum (CO) within PMIP, and not the time of the inso-

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lation maximum in the northern hemispheric summer around 8000 BP.

The general circulation model ECHAM 3

Model description

The ECHAM model is a general circulation model of the atmosphere which was initially developed at the European Centre for Medium Range Weather Forecast in Reading, England. It was later modified at the Max-Planck-Institut für Meteorologie in Hamburg (Germany) to adjust the model for climate simulations (DKRZ Modellbetreuungsgruppe 1994; Roeckner et al. 1992). The model is based on the primitive equations including radiation, a hydrological cycle (with clouds) and a soil model.

Given the initial state and prescribed boundary conditions, the model calculates the temporal evolution of all model variables. The model equations are solved in the spectral domain with triangular truncation at some distinct wave number. In this work the T42 version was used, which corresponds to a Gaussian grid of 128×64 points with a spatial resolution of approximately 2.8 degrees in latitude and longitude.

The vertical representation is realised by 19 layers, where the two lowest layers are sigma layers (parallel to the orography) and the top two layers are at pressure isosurfaces with the last one being at 10 hPa. In between, there is a smooth transition. The time integration of the model is performed with a time step of 24 min in the T42 resolution.

The ECHAM 3 (T42) model is able to simulate most aspects of the presently observed time-mean circulation and its variabilities with remarkable skill (Roeckner et al. 1992). There are still a few problem areas, but the errors are much less pronounced than in simulations with previous model versions.

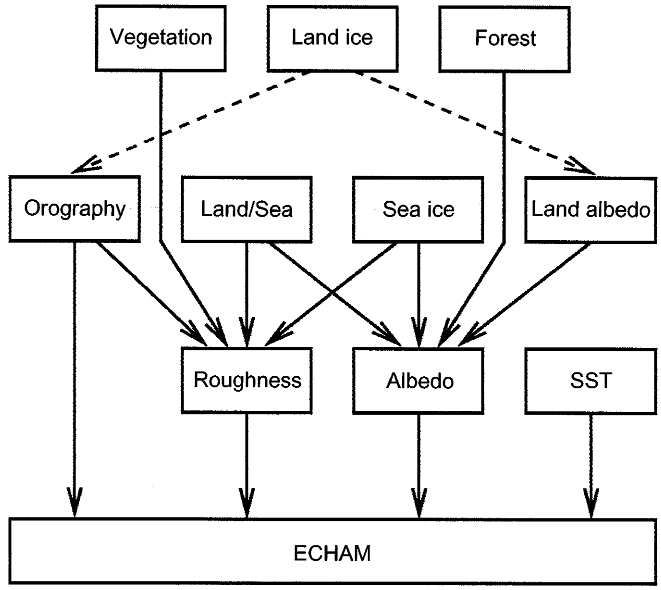

Fig. 1 The boundary conditions at the surface of the Earth which are needed to run the ECHAM model. The quantities orography, surface roughness, albedo and sea surface temperature (SST) enter into the ECHAM model and have to be prescribed. They are either taken directly from observation or calculated from observed quantities. The land ice distribution is implicitly determined by the observed orography and land albedo, but it has to be considered for other time slices

Present boundary conditions

Since ECHAM is a global atmospheric model, it has no lateral boundaries, but open boundaries at the top and bottom of the atmosphere. At the top of the atmosphere the insolation pattern has to be prescribed, which can be calculated with good accuracy for times up to several million years ago (Berger 1977; Laskar 1988; Laskar 1989). The boundary conditions at the bottom of the atmosphere are given by the properties of the Earth's surface. The quantities which have to be prescribed are illustrated in Fig. 1.

The orography is taken from a United States Navy data set. The terrain heights include the modern continental ice sheets. The surface roughness is calculated in different ways over land and over sea, where the land/sea distribution is also taken from a United States Navy data set. Over sea, the Charnock formula is used, altered according to Miller et al. (1992); over sea ice the roughness length is assumed to be constant. Over land it is a function of the vegetation and the variance of the orography, where the vegetation is taken from Wilson and Henderson-Sellers (1985).

The albedo over land is taken from satellite data (Geleyn and Preuss 1983). If snow is present, the albedo is a function of temperature and fractional forest area (Robock 1980; Matthews 1983). Over sea ice and land ice the albedo is a function of temperature (Robock 1980; Kukla and Robinson 1980); over sea it is a function of the solar zenith angle.

The sea surface temperatures (SSTs) and the sea ice distribution are taken from the COLA/CAC AMIP data set, which was prepared by the Center for Ocean-Land-Atmosphere Interactions (COLA) at the University of Maryland and the Climate Analysis Center (CAC) at the National Meteorological Center (NMC) within the Atmospheric Modelling Intercomparison Project (AMIP).

Past boundary conditions

The boundary conditions used for the different model runs are listed in Table 1. The time slice to be modelled is defined by the insolation used, which depends on the Earth's orbit. The elliptical orbit of the Earth around the Sun is characterised by three parameters: eccentricity, obliquity (the angle between the Earth's axis and