ELSEVIER

Quaternary Science Reviews 25 (2006) 832–845

QSR

The relative role of oceanic heat transport and orography on glacial climate

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Received 20 July 2004; accepted 12 July 2005

Abstract

During the Last Glacial Maximum, the Earth's orography and oceanic heat transport contribute to a cooling in the North Atlantic. By using an atmospheric general circulation model of intermediate complexity, we investigate the sensitivity of the atmospheric temperature and circulation during glacial climate, focussing on the impact of the orography and different oceanic heat transports. The results show a strong dependence of the glacial Northern Hemisphere circulation pattern to the changed orography. The blocking effect of the elevated orography due to the Laurentide Ice Sheet over the North American continent forced a deflection of westerlies, their enhancement and a southward displacement over the Atlantic. Independently, the glacial climate is influenced by the oceanic heat transport. The reduced oceanic heat transport on the glacial climate shows a 20–40% contribution for the total cooling relative to the present-day climate in the North Atlantic and polar regions. Finally, we find that the altered orography in the Northern Hemisphere and different oceanic heat transports result in a changed hydrological cycle, a reduction of the Hadley circulation and a southward shift of the Intertropical Convergence Zone in the boreal winter during glacial times.

1. Introduction

The Last Glacial Maximum (LGM) at about 21,000 years B.P. is the period when the most recent glaciation cycle was at its peak. This period is well captured by marine sediment cores, terrestrial climate records and ice-core data (e.g. Jouzel et al., 1987; Farrera et al., 1999; Mix et al., 1999; Alley and Clark, 1999; Bard, 1999; Clark et al., 2002). The abundance of LGM data allows us to reconstruct global sea surface temperature (SST) fields and the sea-ice margins in the Atlantic Ocean. However, various SST reconstructions (e.g. CLIMAP 1981; GLAMAP 2000—German Glacial Atlantic Ocean Mapping Project; Pflaumann et al., 2003; Mix et al., 2001; Sarnthein et al., 2003; Paul and Schäfer-Neth, 2003; Weinelt et al., 1996) differ in the constructing methodology and in the LGM definitions for time intervals, but all suppose climatic stability with maximum glacial sea level low stand.

The CLIMAP (1981) SST and sea-ice reconstruction is characterized by sea-ice margins in Northern Hemisphere reaching far south and a general cooling of the surface waters, except for some areas in the tropical Pacific Ocean, where sea temperatures were higher than present-day values. An additional reduction of CLIMAP SSTs in the tropics (Lohmann and Lorenz, 2000) can provide for consistency with more actual paleo-data (Farrera et al., 1999) and snow lines (Lorenz and Lohmann, 2004). The CLIMAP (1981) reconstruction with applied additional tropical cooling at the surface boundary of an ocean model provokes weakening of the overturning circulation (Prange et al., 2002; Knorr and

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0277-3791/$ - see front matter
doi:10.1016/j.quascirev.2005.07.007

Lohmann, 2003). However, some new reconstructions give evidence for substantially reduced sea ice coverage with vast ice-free areas in the Nordic Seas (Weinelt et al., 1996; de Vernal and Hillaire-Marcel, 2000; Sarnthein et al., 2003; Paul and Schäfer-Neth, 2003). The GLAMAP 2000 (Pflaumann et al., 2003; Sarnthein et al., 2003; Paul and Schäfer-Neth, 2003) and Weinelt et al. (1996) SST reconstructions, taken as boundary conditions to an ocean general circulation model (OGCM), provoke even more intense overturning strength compared to the present-day simulation (Romanova et al., 2004; Prange et al., 2004), which maintains the warm temperatures in the Nordic Seas. To examine the atmospheric response to different oceanic background conditions, we use the corresponding heat transports, as obtained from an OGCM integrated under LGM conditions, to force an atmospheric general circulation model (AGCM).

During the LGM the orography over North American and European continents was altered due to the highly elevated Laurentide, Fennoscandian and Barents Sea Ice Sheets. Along with the modified thermal forcing, the changed orography over North America can strongly influence the atmospheric circulation causing splitting of the zonal flow and its deviation from the present-day circulation (Kutzbach and Wright, 1985; Manabe and Broccoli, 1985; Broccoli, 2000). As well, the blocked entrance of the Barents Sea and the build-up of continental ice on the Barents Sea shelf during LGM can influence the hydrological cycle over northwest Europe and have a significant impact over North Atlantic Ocean (Pflaumann et al., 2003).

The relative importance of thermal and orographic forcing upon dependence of the strength of zonal mean flow upon the extratropical stationary wave field has been investigated by several authors. Using an AGCM, Nigam et al. (1987) found that the orographical factor has two times greater influence than the heating factor in the upper troposphere, and that their contributions are equal for the lower troposphere. Other authors (Valdes and Hoskins, 1989; Chen, 2000) found predominance of the thermal factor for maintaining the extratropical stationary wave structure in the lower troposphere. Held and Ting (1990) pointed out that the dominance of each factor depends mainly on the strength of the low-level mid-latitude westerlies. Using a coupled atmosphere-ocean climate model, Kim (2004) investigated the effect of the ice sheet topography and the change of CO_2 concentration on the LGM climate. He found that climate cooling of the LGM is more than half that due to the reduction of the atmospheric CO_2.

This study, therefore, provides LGM simulations forced with oceanic heat transports, based on different glacial reconstructions, and concentrates on the sensitivity of the atmospheric circulation system to: (i) different thermal forcing conditions; (ii) large-scale orographic obstacles such as the Laurentide Ice Sheet over North American continent; and (iii) the glacial atmospheric CO_2 reduction. Its objective aim is to deconstruct the effects of orographically and thermally induced responses and to assess the significance of each factor for the modified flow regime compared to the present-day conditions. The paper is organized as follows: the second section gives a description of the methodology and the experimental set-up, and the third section shows the results. The results are discussed in Section 4, and the conclusions are given in Section 5.

2. Methodology

2.1. Boundary conditions

The present-day simulation is forced with SST and ice compactness taken from the Atmospheric Model Intercomparison Project (AMIP) (Phillips et al., 1995). The temperature fields represent climatological averages for the time period from 1979 to 1994. The CLIMAP (1981) SST and sea-ice extent reconstruction for the LGM, based on foraminiferal assemblages, is taken as a boundary condition for simulating glacial conditions. The validity of CLIMAP reconstruction is strongly discussed, especially in the tropical areas (e.g. Farrera et al., 1999; Mix et al., 1999; Bard, 1999) indicating too warm SSTs. Hence, one experiment is carried out forced with CLIMAP (1981) SSTs but additional cooling of 3 °C in the tropics. This experiment aims to reduce the temperature discrepancies between marine and terrestrial proxy data for the LGM. The new reconstruction, GLAMAP 2000, provides SSTs and sea-ice margins for another boundary condition. In this reconstruction, the winter sea ice extent is similar to the CLIMAP summer sea ice margin and the Nordic Seas are ice-free during summer months. The average surface temperature in the Atlantic Ocean is by 0.7 °C higher than in the CLIMAP reconstruction.

The glacial runs use glacial orography, land-sea and glacier masks (Peltier, 1994). The CO_2 concentration is fixed to 360 ppm for the present-day experiment and is reduced to 200 ppm for the glacial run according to observational values (e.g. Barnola et al., 1987; Keeling et al., 1996). The Earth's obliquity, orbital eccentricity and vernal equinox mean longitude of perihelion for the present day and glacial runs are taken for the years 2,000 year A.D. and 21,000 year B.P., respectively, and are calculated according to Berger (1978).

2.2. Ocean circulation model

The above mentioned SSTs and sea-ice cover are applied to the AGCM ECHAM3/T42 (Roeckner et al., 1992; Lohmann and Lorenz, 2000). The resulting monthly averaged surface air temperatures, surface