GEOPHYSICAL RESEARCH LETTERS, VOL. 26, NO. 13, PAGES 1893-1896, JULY 1, 1999

Sensitivity of the European LGM climate to North Atlantic sea-surface temperature

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Abstract. Recent reconstructions of Sea-Surface Temperatures (SSTs) for the Last Glacial Maximum (LGM, 21kyr BP) based on foraminifera and dinoflagellate proxies suggest that the north Atlantic may have been warmer than estimated by CLIMAP [1981]. To better understand the impact of such a warm north Atlantic on the global LGM climate, we used two different AGCMs to perform sensitivity studies. With the new, warmer SSTs, both models simulate a hydrological cycle and temperatures very different from those obtained with the CLIMAP boundary conditions. The most noticeable differences occur in winter over North America and Siberia whereas southern Europe is only weakly affected at all seasons. Whichever the conditions prescribed over the north Atlantic, both models underestimate the large cooling recorded by continental proxy data over the Mediterranean Basin.

Introduction

Many AGCM simulations (e.g. [*Broccoli and Manabe,* 1987]) have shown the impact on the general atmospheric circulation of the major changes in boundary conditions associated with the LGM. The very cold conditions and sea-ice cover prescribed over the north Atlantic and the presence of Fennoscandian and Laurentide large ice-sheets, perturbed the extratropical atmospheric circulation (e.g. [*COHMAP members,* 1988]). In particular, these changes in boundary conditions strongly constrain the glacial climate over Europe.
However, an intense debate exists about the values of the north Atlantic SSTs at LGM and recent papers based on foraminifera [*Weinelt et al.,* 1996; *Veum et al.,* 1992], coccoliths [*Hebbeln et al.,* 1994], dinoflagellates [*de Vernal et al.,* 1997] and biomarkers [*Rosell-Melé and Koc,* 1997] show a very different picture from CLIMAP [1981, hereafter CLIMAP]. These new reconstructions suggest that the Nordic seas might have been warmer than the CLIMAP reconstructions, with less sea-ice extent.
We have performed several experiments to test the sensitivity of two different AGCMs to changes in LGM north Atlantic SSTs, to infer the impact of a warmer north Atlantic on the European terrestrial environment.

Simulation results for PD and LGM using CLIMAP SSTs

PD experiments

The AGCMs used are the LMD5 and the UGAMP models. The differences between both models are discussed in detail in the PMIP documentation (www-pcmdi.llnl.gov/pmip). Both models are able to simulate the extratropical Present-Day (PD) climate which is strongly influenced by the thermal contrast between ocean and land, and by orography. Over Europe, the main features of the precipitation and temperature fields are in reasonable agreement with available climatologies [*Masson et al.,* 1999].

LGM experiments using CLIMAP SST

The two simulations described in this study use the same set of boundary conditions for the LGM simulation, as recommended by PMIP (Paleoclimate Modeling Intercomparison Project) [*Pinot et al.*, in press]: the insolation of 21 kyr BP (calendar years), CO_2 set at 200ppm partial pressure, paleo-topographies deduced from Peltier [1994] and SSTs from CLIMAP [1981] (Fig 1a, 1b). The vegetation cover is the same for the PD and the LGM runs except over the ice-sheets.

Both the LMD5 [e.g. *Fabre et al.,* 1998] and the UGAMP [*Dong and Valdes,* 1998] models reproduce the major characteristics of the LGM climate found in previous simulations (an important cooling over the ice-sheets and over the north Atlantic due to the ice cover, a smaller temperature decrease in the equatorial area [*Pinot et al.,* in press] and a reduced globally hydrological cycle).

On Europe, the common response of both models to full glacial boundary conditions, is mainly explained by the presence of extensive sea-ice over the Atlantic ocean. This forcing factor induces a diabatic cooling over the northern Atlantic and determines a zonal circulation

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Paper number 1999GL900361.
0094-8276/99/1999GL900361$05.00

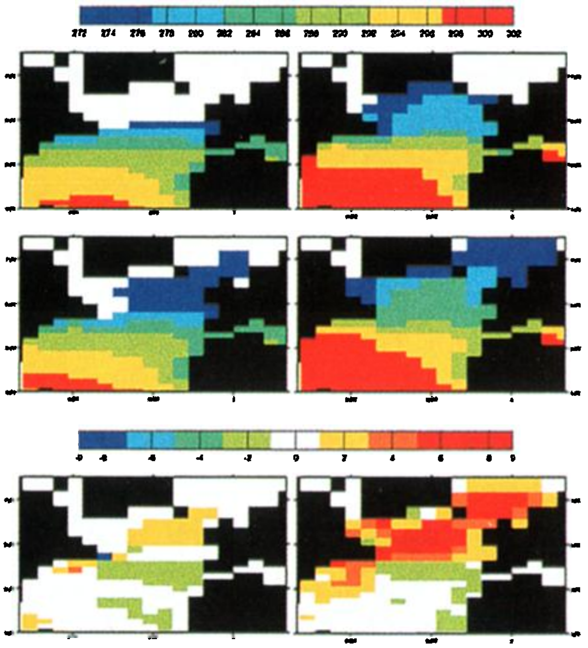

Figure 1. top: LGM CLIMAP [1981] SST (Fig 2a and 2b); middle: new warm SST LGM reconstruction (Fig 2c and 2d); bottom: differences between the two reconstructions (Fig 2e and 2f). The results are given on the LMD5 grid, on the right for the summer season and on the left for the winter season (K).

over north Atlantic and western Europe [*Kageyama et al.*, 1999].

A sensitivity experiment for the LGM

The composite SST data set

We have first built a new sea-ice data set, merging the reconstructions based on dinoflagellates cysts [*de Vernal et al.*, 1997] for the western north Atlantic and based on foraminifera faunal changes [*Weinelt et al.*, 1996] for the northeastern Atlantic ocean. We then derived an SST data set consistent with the first one and using the SST reconstructions from both indicators. Along the 20°W meridian, differences between the warmer SSTs based on dinoflagellate and the colder ones based on foraminifera have been smoothed. Everywhere else, the CLIMAP SSTs have been used, with a gradual transition to the other data sets at 10°N (the differences at this latitude were inferior to 1°C).
The differences between CLIMAP and the new LGM SST reconstructions are larger in summer (Fig 1f) than in winter (Fig 1e). In the new reconstruction, sea-ice is reduced over the northeastern Atlantic ocean in summer and over the central and northeastern Atlantic ocean in winter. The SSTs are warmer than CLIMAP by up to 2°C in winter and 8°C in summer. Despite the SST changes being more important in summer, the stronger impact of this new SST data set on the atmospheric circulation and on the continental temperatures occurs in winter, because the sea-ice cover reduction in winter increases the interaction between atmosphere and ocean.

It should be pointed out that the composite SST reconstruction is based on different micropaleontological indicators (the dinoflagellate cysts and the planktonic foraminifers). They still need an intercalibration before a consistent picture of the sea-surface conditions over the north Atlantic during the LGM can be obtained. This evaluation is the object of the on-going EPILOG project, and is beyond the scope of this paper. The major aim of this new SST reconstruction is to investigate the impact of a warm LGM north Atlantic on the European climate in contrast with the cold north Atlantic situation depicted by CLIMAP.

Results of sensitivity experiments

The same LGM sensitivity experiment has been performed with the LMD5 and the UGAMP models, modifying only the north Atlantic SSTs. In this section, the simulation using the CLIMAP SSTs serve as our reference LGM simulation.

Hydrological cycle. Over the north Atlantic, the warmer SSTs (less sea-ice) induce a strong change in the rate of evaporation at the surface. However, most of the increase in the transfer processes constituting the hydrological cycle remains local and only contributes to reinforce local recycling. For the CLIMAP LGM simulations, local recycling is equal to 88% for LMD5 and 77% for UGAMP. In contrast, it reaches values of 98% for LMD5 and 86% for UGAMP for the warmer SST experiments. The evaporation increase when using warm

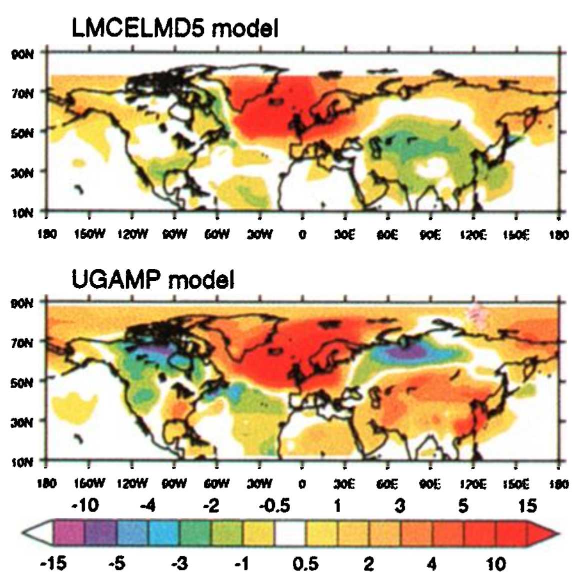

Figure 2. Temperature of the coldest month (K) in the northern hemisphere, differences between the experiment with CLIMAP SST and the experiment with the new warm SST reconstruction.

Table 1. Energy budget over northern Atlantic ocean (60°W 5°E - 50°N 90°N) and over Europe (10°W 50°E - 30°N 60°N) for the PD, LGM with CLIMAP SST (LC) and LGM with the new warm SST reconstructions (LW). Fluxes are counted positively for the atmosphere, LHF = Latent heat flux, SHF = sensible heat flux, HBA = heat budget for the atmosphere, GT = ground temperature.

	LMD5			UGAMP		
ATL. OC.	PD	LC	LW	PD	LC	LW
LHF	34	8	31	41	12	35
SHF	16	2	22	26	9	30
HBA	-40	-75	-37	-44	-72	-33
GT	5.8	-13.2	-3.2	3.7	-15.4	-5.3
EUROPE	PD	LC	LW	PD	LC	LW
LHF	41	27	29	24	13	15
SHF	37	35	34	57	49	49
HBA	-20	-24	-24	-23	-36	-36
GT	13.9	6.5	7.2	13.2	4.2	6.2

SSTs at LGM is associated with more latent heat release, which reaches values close to those obtained in the PD simulation (22W/m^2 for LMD5, 30W/m^2 for UGAMP). Conversely, the latent heat release is strongly damped when using CLIMAP SSTs (8W/m^2 for LMD5, 12W/m^2 for UGAMP) (Table 1). Using warm composite SSTs also leads to a severe increase in the sensible heat flux reaching 22W/m^2 for LMD5 and 30W/m^2 for UGAMP. These values are even higher in LGM simulation using the new SST data set than for PD (Table 1). Over Europe, the energy budget of the atmosphere (Table 1) is similar to the reference LGM CLIMAP SST run. As shown before, all the changes in the hydrological cycle over the Atlantic ocean essentially lead to more local recycling. Indeed, the latent heat transport from the Atlantic ocean toward Europe is reduced for both LGM simulations when compared to the PD simulation.

Temperature changes. We observe that the temperatures, when warm Nordic SSTs are prescribed, are colder in winter in Siberia and North America whereas the temperature over Europe are warmer (these changes are associated to changes in circulation). Nevertheless, over the Mediterranean basin both models are weakly affected (Fig 2) by the changes in boundary conditions.

Comparison of LGM simulations with pollen data over Southern Europe. New estimates of climatic conditions prevailing over the north of the Pyrenees-Alps line (NPA, ≥40°N) and south of that line (SPA, including sites in Italy, Greece and Turkey) have been obtained recently at 15 pollen data sites [*Peyron et al.,* 1998]. The LGM temperatures of the coldest month (MTCO) deduced from the pollen data are drastically colder than today by 30°C (+/-10°C) over NPA and around 15°C (+/-5°C) over SPA.
Using CLIMAP SSTs as boundary conditions, the LMD5 and UGAMP models depict a strong cooling over NPA (10°C for LMD5 and 12°C for UGAMP) whereas SPA only experiences a cooling of around 8°C and 10°C respectively. These models are therefore far from reproducing the large temperature decrease estimated from pollen reconstructions.
On the other hand, using warmer north Atlantic SSTs, LMD5 and UGAMP models simulate winter temperatures 5°C warmer than those estimated using the CLIMAP boundary conditions over NPA and 1 or 2°C higher MTCO over SPA (Fig 2) .
The important result is that the terrestrial temperature over SPA and NPA simulated by both models, under both cold (CLIMAP) or warm (composite new data set) north Atlantic SST conditions, are largely underestimated. As far as we do not expect a north Atlantic SST reconstruction drastically outside these limits, we strongly believe that the discrepancy between model results and terrestrial data for southern Europe at LGM is not due to the uncertainty that still remains on the north Atlantic SSTs reconstruction.

Discussion and conclusion

We have tested the sensitivity of both the LMD5 and UGAMP AGCMs to warmer than CLIMAP [1981] LGM north Atlantic SSTs using new reconstructions based on foraminifera and dinoflagellates. We used two different AGCMs in order not to obtain model-dependent results. We found that these new SSTs have a major impact on the hydrological cycle and energy budget over the north Atlantic ocean, but a rather small impact over southern Europe: these results show the weak sensitivity of the Mediterranean basin terrestrial temperatures simulated by both models to the prescribed LGM north Atlantic SST changes. Whichever north Atlantic SST reconstruction is used (cold: CLIMAP or warm: new SST data set), model results underestimate the cooling inferred from pollen data.
Among the causes for such a discrepancy, a plausible explanation is the vegetation impact. This forcing factor is not accounted for in these experiments mainly because no realistic global reconstruction is currently available. Previous sensitivity studies (using an asynchronously coupled global atmosphere-biome model [*Kubatzki and Claussen,* 1998] or using an AGCM with an ice-age vegetation reconstruction as boundary conditions [*Crowley and Baum,* 1997]) showed that the climatic impact of vegetation changes may explain a cooling over the Mediterranean basin. Additional experiments also suggest that colder than CLIMAP SST in the north Pacific and the tropics, as well as ice-sheets higher than those estimated by Peltier [1994] may also contribute to explain differences between models and data.

Acknowledgments. This work have been supported by CEA, CNRS and EC under contracts number ENV4-

CT95-0075. We thank the EPD (European Pollen Database) for providing the pollen reconstructions. The sea-surface temperature data set from the German group of Kiel was kindly provided by Dan Seidov. The authors thank Gerhard Krinner and Masa Kageyama for fruitful comments on the manuscript.

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(Received December 7, 1998; revised April 2, 1999; accepted April 30, 1999.)