Impact of the North American ice-sheet orography on the Last Glacial Maximum eddies and snowfall

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GEOPHYSICAL RESEARCH LETTERS, VOL. 27, NO. 10, PAGES 1515-1518, MAY 15, 2000

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Abstract. The present work evaluates the influence of the North American ice-sheet orography on the Last Glacial Maximum (LGM, 21,000 years ago) atmospheric circulation and snowfall in the northern mid-latitudes, focusing on the North Atlantic sector. Three Atmospheric General Circulation Model experiments are analysed: a control and an LGM climate simulation, and an LGM run with "flat" ice-sheets over northern North America. This ice-sheet orography affects lee-cyclogenesis over North America and forces differences in stationary waves and therefore in the baroclinicity of the mean flow. As a result, the Atlantic storm-track is reinforced in the "flat ice-sheet" experiment compared to the LGM one. This, in turn, has a profound impact on snowfall over northern Europe, implying a coupling between the two ice-sheets.

Introduction

The northern hemisphere atmospheric circulation at the Last Glacial Maximum (LGM, 21,000 years ago) is strongly influenced by the presence of the Laurentide and Fennoscandian ice-sheets over northern North America and northwestern Eurasia because of their high surface albedo and their altitude. Many of the modelling studies of the LGM climate have shown that a surface anticyclonic circulation develops over both ice-sheets, and that at mid-tropospheric levels, the north American ice-sheets (mainly the Laurentide, which is much larger) could be associated with a split of the mid-latitude jet-stream or an amplified upstream ridge/downstream trough pattern over the American continent [*Broccoli and Manabe*, 1987; *COHMAP members*, 1988; *Joussaume*, 1993]. A large part of this response has been demonstrated to be an orographic effect of the American ice-sheets [*Rind*, 1987; *Felzer et al.*, 1996; *Cook and Held*, 1988], consistent with the theoretical effects of orography on the atmospheric circulation [*Manabe and Terpstra*, 1974; *Hoskins and Karoly*, 1981; *Yu and Hartmann*, 1995].

The LGM boundary conditions also have a strong impact on the transient eddies. In particular, in all the European PMIP (Palaeoclimate Modelling Intercomparison Project) models, the Atlantic storm-track undergoes a strong eastward shift that appears to be constrained by the sea-ice edge rather than by the American East coast land-sea contrast [*Kageyama et al.*, 1999]. The North American ice-sheet could also play an important role in this change of the Atlantic storm-track: first, modified stationary waves result in a modified baroclinicity of the flow, and therefore in different conditions of synoptic wave development; second, such an orographic feature could modify lee-cyclogenesis processes that occur today in the lee of the Rockies [*Whittaker and Horn*, 1984; *Lefevre and Nielsen-Gammon*, 1995]. These two aspects are studied in the present paper for the winter season (December-January-February), when the Atlantic transient eddies are strongest.

Transient eddies are sensitive to ice-sheets, but they also have an impact on them, since they are the main source of precipitation in the extratropics. Indeed, large ice-sheets have been suggested to make storms take a northward route [*Shinn and Barron*, 1989] and help maintain the ice-sheet mass balance. In the present study, we examine whether the North American ice-sheets have an influence on the snowfall over northern Europe via a modification of the Atlantic storm-track.

Paper number 1999GL011274.
0094-8276/00/1999GL011274$05.00

AGCM and numerical experiments

This study uses the UK Universities' Global Atmospheric Modelling Programme (UGAMP) AGCM with resolution T42 in the horizontal. The resolution of this model is therefore significantly higher than the $8^o \times 10^o$ or R15 resolutions used in the previous "flat ice-sheet" studies [*Rind*, 1987; *Felzer et al.*, 1996], and allows for a reasonable representation of the northern hemisphere storm-tracks, although the Atlantic storm-track is still too weak compared to reanalyses [*Kageyama et al.*, 1999]. Present and LGM climate simulations performed with this model have been described elsewhere [*Hall et al.*, 1996a; 1996b; *Dong and Valdes*, 1998].

The present-day (CTRL) and LGM experiments are the UGAMP PMIP simulations [*Joussaume and Taylor*, 1995]: in the LGM simulation, the sea-surface temperature (SST) difference is prescribed [*CLIMAP*, 1981]; ice-sheets are imposed [*Peltier*, 1994]; the insolation parameters are set for 21,000 years ago, the CO_2 level is decreased from 345 ppm to 200 ppm. The third experiment (NL for No Laurentide) is an LGM sensitivity experiment to the North American ice-sheet orography, in which all boundary conditions are the same as in the LGM run except for "flat", 10 m-high, ice-sheets over northern North America. Therefore, comparing NL to CTRL for the winter season essentially shows the impact of the SSTs and sea-ice, since in CTRL, northern North America is generally covered at the location of the LGM ice-sheets. Comparing NL to LGM shows the in-

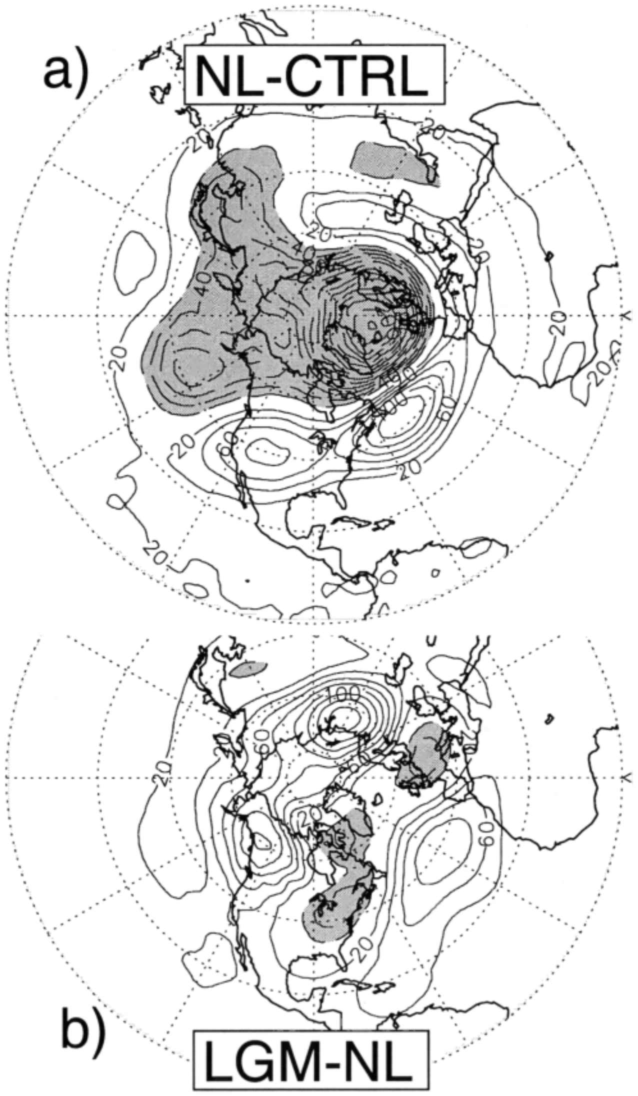

Figure 1. DJF 500 hPa geopotential height anomalies: (a) NL − CTRL (b) LGM − NL, contours every 20 m, shading for values smaller than −20 m. The North American (Laurentide and Cordilleran) ice-sheets that have been lowered to 10m in NL cover Canada and southern Alaska. In NL and LGM, CLIMAP(1981) sea-surface temperatures are prescribed, with sea-ice extending at latitudes lower than 50°N in the North Atlantic.

fluence of the North American ice-sheet proper, in a glacial environment.

Stationary Waves

The CTRL winter circulation, in reasonable agreement with observations (not shown), is marked by the Aleutian and Icelandic lows, with a clear ridge over western America. In the NL run (Figure 1a), the structure of the 500 hPa geopotential height anomalies over America, the Atlantic ocean, and even downstream over Europe are quite zonal, with a sharpening of the meridional gradient in geopotential height due to much colder conditions (land-ice and sea-ice) in the polar regions, but weaker changes at the equator. LGM SSTs and sea-ice are thus confirmed to be important in determining the changes in atmospheric circulation.

The orographic forcing of the Laurentide ice-sheet (Figure 1b) introduces zonal asymmetries in the mid-tropospheric circulation structure. Not only the North American ridge/trough system clearly amplifies, but the response of the atmospheric circulation extends over the extra-tropical Atlantic and Eurasia, with a mid-latitude high over the Atlantic, a trough over Europe and a ridge over northwestern Asia. The anomaly pattern closely resembles the response to the orographic forcing of an idealised circular mountain in the extratropics [*Hoskins and Karoly*, 1981; *Yu and Hartmann*, 1995]. This confirms that the amplified American

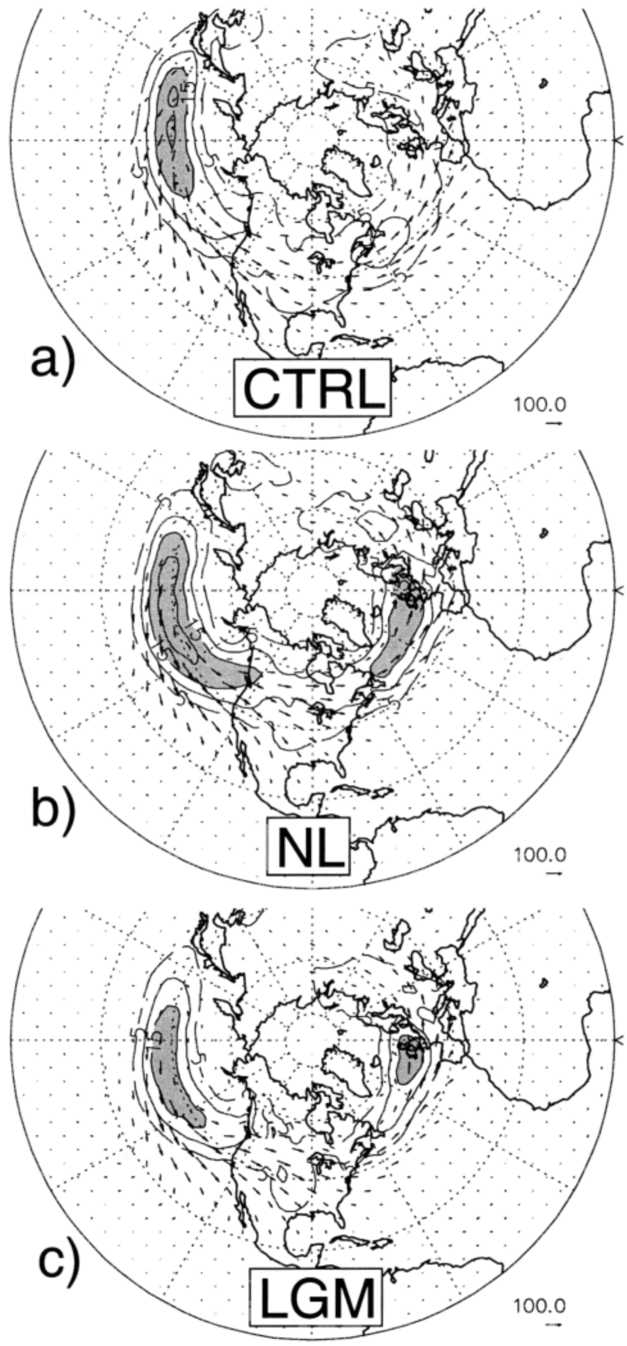

Figure 2. DJF High-pass filtered 3D E-vectors *Hoskins et al* [1983]: 700 hPa $\overline{v'T'}$ (contours every 5 K.m.s^{-1}, values over 15 K.m.s^{-1}shaded), and 250 hPa $(\overline{u'^2 - v'^2}; -\overline{u'v'})$.

Table 1. Results from the tracking algorithm for North America and the West Atlantic

	CTRL	NL	LGM
maximum genesis density ($(10^6 km^2 season)^{-1}$)			
North America	2.0	2.4	1.0
West Atlantic	0.8	1.0	2.4
maximum track density ($(10^6 km^2 season)^{-1}$)			
North America	5	6	3.5
West Atlantic	5.5	8	9
growth/decay rate (day^{-1})			
North America	0.5	0.5	0.3
West Atlantic	0.4	0.3	0.3
mean speed ($km.hr^{-1}$)			
North America	45	50	40
West Atlantic	40	55	65

ridge/trough pattern seen in many AGCM experiments is mainly an orographic effect of the Laurentide ice-sheet. The pattern also suggests that this ice-sheet is near the "small mountain" regime [*Valdes and Hoskins*, 1991] and the flow is mainly deflected up and over the orography.

Transient Eddies

The NL and LGM storm-tracks are of the same magnitude in terms of both lower-level (meridional heat flux) and upper-level (momentum flux) transient activities (Figure 2). However, their spatial extension is modulated by the North American ice-sheet orography: while large values in $\overline{v'T'}$ are reached from the American Atlantic coast to northwestern Europe in NL, these only appear over the East Atlantic and northwestern Europe in LGM; the upper-level activity is high over America and downstream over the Atlantic and Europe in NL, while it shows a clear local minimum over the West Atlantic in LGM and is weaker over eastern Europe. This suggests that both upper-level perturbations and low-level genesis are affected by the Laurentide orography, particularly over the west Atlantic. In this region, the transient heat and momentum fluxes are both weaker in LGM than in NL, despite a stronger baroclinicity (stronger jet-stream aloft). This apparent contradiction can be understood in terms of the competition between the growth of the depressions and their advection eastward by the background wind, a process that explains the present-day local winter minimum in the Pacific storm-track (compared to its maxima in autumn and spring) [*Nakamura*, 1992].

To investigate the characteristics of the weather systems in the AGCM further, we have used a tracking algorithm [*Hodges*, 1996], which identifies and follows closed lows deeper that 4 hPa in the 0.75-daily mean-sea-level pressure fields (planetary waves are filtered out). Only the tracks which last longer than 3 days have been kept in the statistical analysis. The results from this analysis are summarised in Table 1 for North America and the northwestern Atlantic. Over the latter area, the mean speed of the perturbations is faster in LGM than in NL, and in NL than in CTRL, following the differences in background wind. On the other hand, the growth/decay rate of the perturbations is lower in NL and LGM than in CTRL, confirming that the advection of perturbations can prevent their growth at the background speeds typical of the NL and LGM experiments. The differences in the background mean wind, resulting in an increased baroclinicity, also explain the increased cyclogenesis density from CTRL to NL and from NL to LGM. However, the track density is similar in NL and LGM, larger than in CTRL. This can be explained by the characteristics of the depressions over North America, upstream from the West Atlantic: cyclogenesis density, as well and the growth/decay rate and track density, are significantly lower in LGM than in NL and CTRL.

The North American ice-sheets therefore have a local effect on the weather systems, lowering cyclogenesis over North America and decreasing the growth/decay rate. It is also directly responsible for the difference in jet-streams over the West Atlantic. Indeed, this difference in jet-streams between NL and LGM is not forced by the transient eddies since their forcing, as determined through the E-vector divergence (not shown), is weaker in LGM than in NL. On the other hand, this transient eddy feedback on the mean flow is important at the end of the Atlantic storm-track over the Northeastern Atlantic and Western Europe. Over this region, both the transient eddy forcing and the jet-stream are stronger in LGM than in NL, and in NL compared to CTRL. Therefore, the orographic forcing of the mean flow appears to be more important at the western end of the Atlantic storm-track, while the transient forcing is more important at its eastern end, showing a mechanism for an indirect and remote forcing of the orography onto the mean flow.

Consequences on snowfall

In NL as well as in LGM, the Atlantic storm-track is stronger than in CTRL, showing the importance of sea-ice and SSTs in determining the overall amplitude of the storm-track. However, it is obvious that the North American ice-

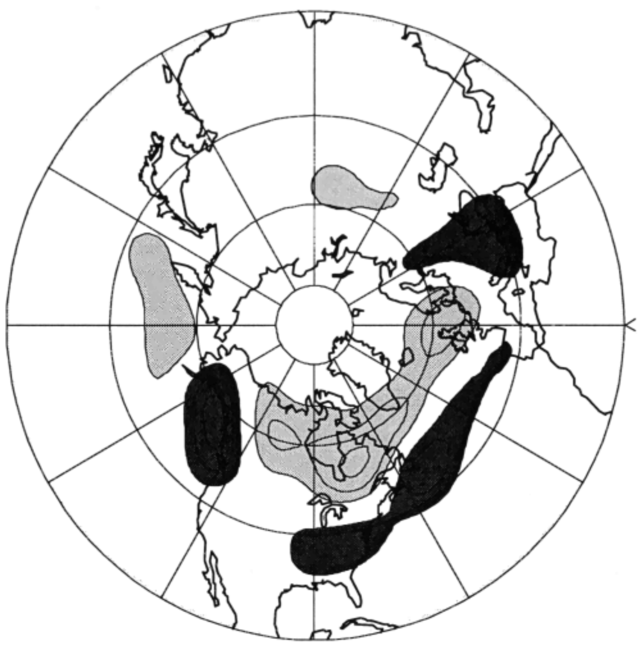

Figure 3. DJF LGM−NL difference in snowfall. Contours every 0.25 $mm.day^{-1}$, 0 contour omitted, light (dark) shading for values smaller than −0.25 (greater than +0.25) $mm.day^{-1}$.

sheet orography has an important influence both on the stationary and the transient northern hemisphere eddies. It is responsible for an amplification of the ridge-trough pattern over America and a shortening of the Atlantic storm-track, which only develops over the eastern Atlantic in the LGM run.

Figure 3 shows that these changes in eddy activity have a strong influence on the winter snowfall: the North American ice-sheet orography induces weaker snowfall over the northern North Atlantic and stronger snowfall at around 40°N. This can be related to weaker transient activity on the northwestern Atlantic, but also to weaker lower-troposphere temperatures (Figure 1) and to the mean wind which is more southwesterly in LGM, rather than westerly in NL (Figure 1b). This implies that larger snowfall, at least on the western and highest part of the Fennoscandian ice-sheet, is achieved with a low North American ice-sheet, which provides a mechanism coupling the two ice-sheets and suggests an asynchronous building of the LGM large mid-latitude ice-sheets.

Acknowledgments. We wish to thank Kevin Hodges for his efficient help in the use of his tracking algorithm. This is LSCE contribution number 384.

References

Broccoli, A. J. and S. Manabe, The influence of continental ice, atmospheric CO_2, and land albedo on the climate of the last glacial maximum., *Clim. Dyn.*, *1*, 87–99, 1987

CLIMAP, Seasonal reconstructions of the Earth's surface at the Last Glacial Maximum, *Map Chart Series MC-36, Geological Society of America, Boulder, Colorado*, 1981.

COHMAP members, Climatic changes of the last 18,000 years: observations and model simulations, *Science*, *241*, 1043–1052, 1988

Cook, K. and I. M. Held, Stationary waves of the ice age climate, *J. Climate*, *1*, 807-819, 1988

Dong, B. and P. J. Valdes, Simulations of the Last Glacial Maximum Climates using a general circulation model: prescribed versus computed Sea Surface Temperatures, *Clim. Dyn.*, *14*, 571-591, 1998

Felzer, B.,R. J. Oglesby, T. Webb III and D. E. Hyman, Sensitivity of a general circulation model to changes in northern hemisphere ice sheets, *J. Geophys. Res.*, *101*, 19077-19092, 1996

Hall, N. M. J., B. Dong and P. J. Valdes, Atmospheric equilibrium, instability and energy transport at the last glacial maximum, *Clim. Dyn.*, *12*, 497–511, 1996

Hall, N. M. J., P. J. Valdes and B. Dong, The maintenance of the last great ice sheets: a UGAMP GCM study., *J. Climate*, *9*, 1004-1019, 1996

Hodges, K. I., Spherical nonparametric estimators applied to the UGAMP model integration for AMIP, *Mon. Weather Rev.*, *124*, 2914–2932, 1996

Hoskins, B. J. and D. J. Karoly, The steady linear response of a spherical atmosphere to thermal and orographic forcing, *J. Atmos. Sci.*, *38*, 1179-1196, 1981

Hoskins, B. J., H. H. Hsu, I. N. James, M. Masutani, P. D. Sardeshmukh and G. H. White, Diagnostics of the global atmospheric circulation based on ECMWF analyses 1979–1989, *Tech. Rep. WRCP-27*, 1989

Hoskins, B. J., I. N. James and G. H. White, The shape, propagation and mean-flow interaction of large-scale weather systems, *J. Atmos. Sci.*, *40*, 1595-1612, 1983

Joussaume, S., Paleoclimatic tracers: an investigation using an Atmospheric General Circulation Model under ice age conditions. 1. Desert Dust., *J. Geophys. Res.*, *98*, 2767-2805, 1993

Joussaume, S. and K. Taylor, Status of the Paleoclimate Modeling Intercomparison Project (PMIP), *Proceedings of the first international AMIP scientific conference (Monterrey, California, USA, 15–19 May 1995), WRCP-92* 425–430, 1995.

Kageyama, M., P. J. Valdes, G. Ramstein, C. D. Hewitt, and U. Wyputta, Northern Hemisphere storm-tracks in present day and last glacial maximum climate simulations: a comparison of the European PMIP models, *J. Climate*, *12*, 742-760, 1999

Lefevre, R. J. and J. M. Nielsen-Gammon, An objective climatology of mobile troughs in the northern hemisphere, *Tellus*, *47A*, 638–655, 1995

Manabe, S. and T. B. Terpstra, The effects of mountains on the general circulation of the atmosphere as identified by numerical experiments, *J. Atmos. Sci.*, *31*, 3-42, 1974

Nakamura, H., Midwinter Suppression of Baroclinic Wave Activity in the Pacific, *J. Atmos. Sci.*, *49*, 1629–1642, 1992

Peltier, W. R., Ice age paleotopography, *Science*, *265*, 195–201, 1994

Rind, D., Components of the Ice Age Circulation, *J. Geophys. Res.*, *92*, 4241-4281, 1987

Shinn, R. A. and E. J. Barron, Climate sensitivity to continental ice-sheet size and configuration, *J. Climate*, *2*, 1517-1537, 1989

Valdes, P. J. and B. J. Hoskins, Nonlinear orographically forced planetary waves, *J. Atmos. Sci.*, *48*, 2089–2106, 1991

Whittaker, L. M. and L. H. Horn, Northern hemisphere extratropical cyclone activity for four mid-season months, *J. Climatol.*, *4*, 297-310, 1984

Yu, J.-Y. and Hartmann, D. L., Orographic influences on the distribution and generation of atmospheric variability in a GCM, *J. Atmos. Sci.*, *52*, 2428-2443, 1995

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(Received December 1, 1999; revised March 8, 2000; accepted March 15, 2000.)