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Freshwater discharges in a simulation of the Last Glacial Maximum climate using improved river routing

R. Alkama,^{1,2} M. Kageyama,¹ and G. Ramstein¹

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[1] The large ice-sheets over North America and Europe at the Last Glacial Maximum (LGM) strongly disturbed river pathways. This has never been taken into account in simulations of the LGM climate, even if it could have an impact on the freshwater input to the ocean. Here, we have introduced a more realistic river routing in LGM atmospheric general circulation model simulations. A comparison with classical LGM simulations shows that the discharge into the Arctic Ocean is not drastically different. Even if the Ob and Yenisei rivers could not reach the Arctic Ocean because of the Fennoscandian ice sheet (which results in a lake South of this ice sheet), the discharge of other rivers nearby is increased due to the influence of this lake. The maximum monthly discharge into the North Atlantic Ocean decreases by 34000 m³/s between 54 and 66°N, while it is stronger by 35000 m³/s between 28 and 54°N. **Citation:** Alkama, R., M. Kageyama, and G. Ramstein (2006), Freshwater discharges in a simulation of the Last Glacial Maximum climate using improved river routing, *Geophys. Res. Lett.*, 33, L21709, doi:10.1029/2006GL027746.

1. Introduction

[2] During the last glacial period an ice sheet over the Barents and Kara seas blocked the large northbound Russian rivers and ice dammed lakes formed in front of the ice sheets. Based on marine geological and geophysical data, the Last Glacial Maximum (21 kyr Bp) ice sheet limit has been identified on the Barents and Kara sea-floor off the mainland [Svendsen *et al.*, 2004]. Nevertheless, the extent of the Fennoscandian Ice sheet is more uncertain in the eastern part of the Kara Sea. Mangerud *et al.* [2004] suggest that the ice sheet in this region was too small to block the Ob and the Yenisei rivers. On the contrary, the newest reconstruction of the LGM topography ICE-5G [Peltier, 2004] implies the existence of a proglacial lake because the height of the ice sheet in this region is about 800 m. The presence of a proglacial lake can induce considerable changes in the regional climate, particularly on the temperature. Krinner *et al.* [2004], using a high resolution AGCM coupled with a thermal lake model, showed that the presence of a proglacial lake at 90 kyr BP implies a damped thermal seasonal cycle (warmer winters and cooler summers) that leads to an increase in the ice-sheet thickness

close to the lake, due to a drastic reduction of snow melting in summer. In addition, many studies [e.g., Manabe and Stouffer, 2000; Ganopolski and Rahmstorf, 2001] have shown the great sensitivity of the thermohaline circulation (THC), and potentially of the global climate, to fresh water forcing in key areas such as the North Atlantic, especially at LGM. Despite all its potential impacts, to date no LGM simulation has considered the influence of a change in river routing and ice dammed lakes. Here, we study two LGM atmospheric general circulation model (AGCM) simulations. Both have been run using the CLIMAP [1981] sea surface conditions and the ICE-5G [Peltier, 2004] ice-sheet reconstruction. Following previous studies, the first model maintains modern river basins and routing. The second one uses river basins and routing consistent with ICE-5G ice-sheets.

2. Experiments and Model Description

[3] We use the LMDZ.3.3 AGCM developed at Laboratoire de Météorologie Dynamique [Hourdin *et al.*, 2006], at a resolution of 72 × 46 points on a regular longitude-latitude horizontal grid, with 19 sigma-coordinate levels in the vertical. The soil hydrology scheme consists of two layers, the upper one having a varying depth, and the total soil depth being constant (2 m) [Ducoudré *et al.*, 1993]. When the soil maximum water content is reached, runoff occurs and is routed to the ocean or to lakes. Fifty major rivers are explicitly routed, while the others are grouped together and define the model's 'coastal flow'. Precipitation and snow melt occurring on the ice sheets are directly routed to the ocean.

[4] Previous simulations of the LGM climate used either the CLIMAP ice sheet reconstruction or, within PMIP1 framework [Joussaume and Taylor, 2000], the ICE-4G [Peltier, 1994] reconstruction. In the present work, we use the most recent ICE-5G reconstruction [Peltier, 2004], which takes into account a better definition of ice limit for the Fennoscandian ice sheet and is used in the PMIP2 intercomparison project [Harrison *et al.*, 2002]. In this work we study the result of three experiments. The control simulation (CTRL) has specified CO₂, CH₄ and N₂O concentrations of 345 ppm, 760 ppb and 260 ppb respectively, and a modern land-sea mask and topography. The sea surface characteristics are prescribed from the AMIP 1979–1989 climatology [Gates *et al.*, 1998]. The other two experiments account for the LGM climate. The orbital parameters are changed to the 21 kyr BP values [Berger, 1978], the CO₂, CH₄ and N₂O concentrations are reduced to 185 ppm, 350 ppb, 200 ppb respectively (<http://www-lsce.cea.fr/pmip2/>). The sea surface temperature and sea ice are prescribed following CLIMAP Project Members

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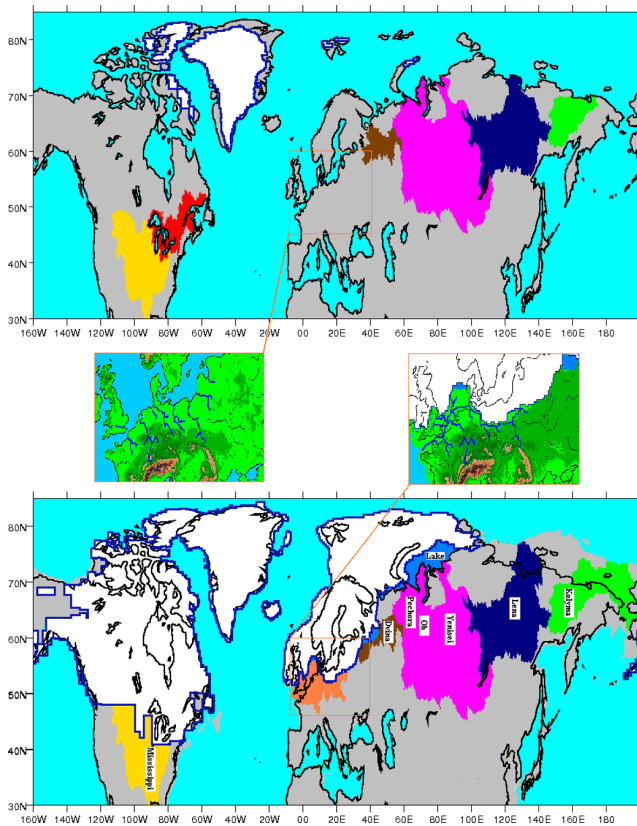


Figure 1. (top) Modern and (bottom) LGM main river basins of the North Hemisphere. The purple colour represents the Ob, Yenisei and Pechora river basins. The orange colour represents the LGM paleo-Rhine river basin which drains modern Rhine, Elbe, Oder, Thames and Seine Rivers. LGM river basins have been derived from the ICE-5G topography.

[1981]. The ice-sheets are prescribed to the ICE-5G reconstruction and a modified land-sea mask consistent with the ICE-5G topography is used. Even though the effect of the vegetation on the climate of LGM may not be negligible on a regional basis [Crowley and Baum, 1997; Wyputta and McAvaney, 2001], we have used the same vegetation as today (as recommended by PMIP1). The first simulation, labeled the ‘LGMM’ (M referring to Modern rivers), uses modern rivers. The second simulation uses more realistic LGM rivers and is termed ‘LGMR’ simulation (R standing for Realistic LGM rivers). The differences between CTRL and LGMM are:

- (1) The lengthening of the rivers due to sea level fall.
- (2) Partial or total coverage of river basins by the ice sheets, for example for the Canadian and the Scandinavian rivers.

[5] The main differences between LGMM and LGMR are: (1) The Ob, Yenisei and Pechora rivers are blocked by the East Fennoscandian ice sheet and flow into a large lake at the southern flank of the ice sheet. The Dvina River discharges into a small lake situated to the West of the Pechora basin instead of into the Arctic Ocean. We have therefore considered an extreme scenario of changes in river routing on this region, a scenario which is compatible with the Peltier ICE-4G and ICE-5G reconstructions.

(2) The European rivers which today discharge into the North Atlantic between 54°N and 66°N are directed southward due to the presence of the ice sheet and the 120 m sea level drop. For example the paleo-Rhine, Elbe and Oder Rivers do not flow toward the Nordic or Baltic seas but to the Atlantic Ocean via the paleo-English channel. Their connection with the Thames and Seine Rivers formed one of the largest rivers at LGM (Figure 1).

(3) There is no difference in American river drainage between the LGM simulations, except in the southwest part of the Saint-Lawrence basin which is rerouted into the Mississippi basin in the LGMR simulation (Figure 1). In comparison to the Mississippi River basin (3 225 000 km²), this draining area is too small (100 km²) to impact the total Mississippi river runoff.

[6] Initially, we have chosen to perform our experiments using an atmosphere-only general circulation model. This guarantees that the ocean surface characteristics are exactly the same in both Last Glacial Maximum experiments and that the computed changes are linked to changes in river routing only. A second step will be to prescribe these river routing changes in an atmosphere-ocean coupled model to assess their impact on the ocean circulation.

3. Results

3.1. Main LGM-CTRL Climate Differences

[7] The mean and standard deviation of annual stream flows for the model output in the CTRL simulation generally range from about one-half to double the observed values (Table 1). The significant differences usually occur for small-scale basins which are more sensitive to small biases (e.g., the Kolyma River). The overall picture is well reproduced, especially considering the low resolution of the model.

[8] At the LGM, large portions of the Arctic rivers basins were covered by ice-sheets. The temperature was significantly lower than today (Figure 2a) and evaporation over

Table 1. Mean and Standard Deviation of Annual Stream Flow^a

River Name	Annual River Discharge, m ³ /s				Station
	Data	CTRL	LGMM	LGMR	
Ob	12673 ± 1840	10336 ± 3663	1993 ± 995	-	Salehard
Yenisei	18408 ± 1320	11542 ± 3374	3650 ± 868	-	Igarka
Lena	16718 ± 2000	11202 ± 2905	7010 ± 1213	8090 ± 846	Kusur
Kolyma	3197 ± 838	7514 ± 2120	7582 ± 1262	7662 ± 741	Kolymskoye
Mississippi	14437 ± 3100	14581 ± 6139	19065 ± 2891	19279 ± 3235	Tarbert Landing

^aObservations from <http://rims.unh.edu>, except for Mississippi River data, from <http://www.rivdis.sr.unh.edu>.

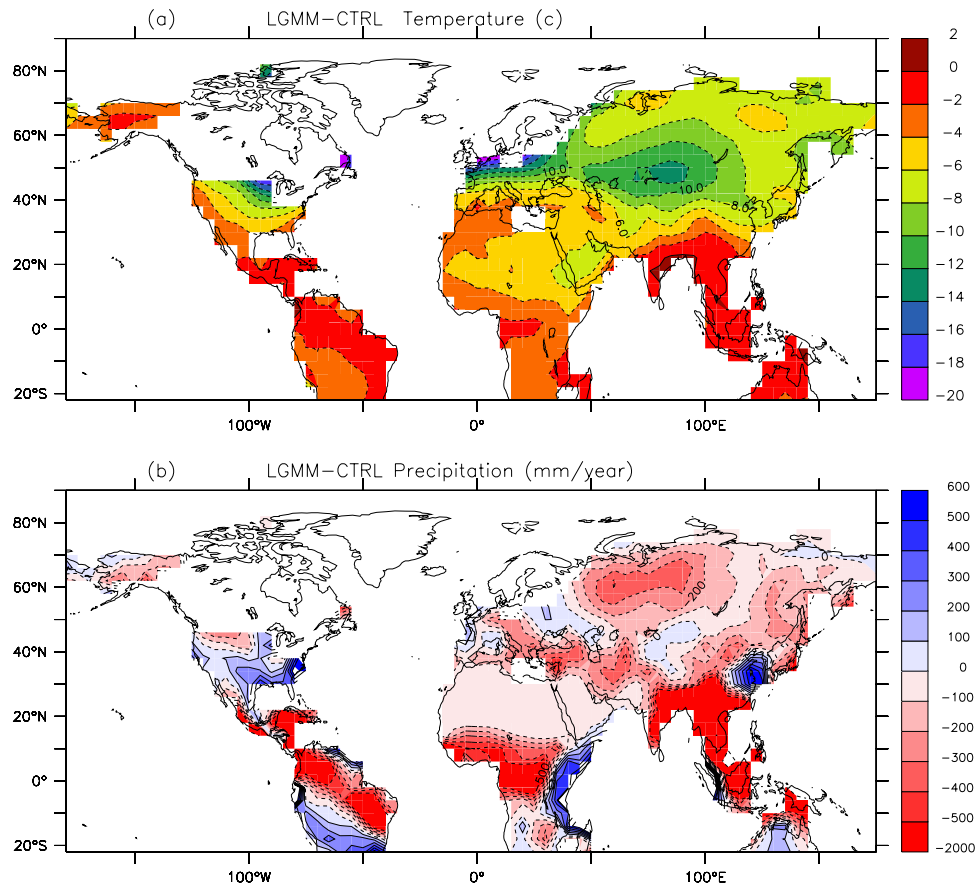


Figure 2. The geographical distributions of (a) annual surface air temperature anomalies and (b) annual precipitation anomalies. The anomalies represent the difference between the LGMM and CTRL experiments.

the oceans and consequently precipitation overland were significantly reduced (Figure 2b). This explains the reduction of the total rivers discharge into the Arctic Ocean in the LGMM and LGMR simulations compared to the CTRL simulation (Figure 3a). For example, the reduction of the Ob and Yenisei annual flows amount to 80% and 68% respectively (Table 1). The seasonal cycle of river discharges is also modified. At the LGM, snow begins to melt in May whereas it has already largely disappeared in the modern simulation at the same time. This difference corresponds to an extra runoff difference of $90\,000\text{ m}^3/\text{s}$ for the month of May.

[9] Figures 3b and 3c show the simulated flows of the Lena and Kolyma rivers. Over this area, the LGM temperatures are colder than the for CTRL by about 10°C and only get positive from mid May to September. The precipitation is also weaker in LGM than in CTRL. All these factors explain the shape of the climatological flows in these Figures 3b and 3c: stronger in summer, weaker in winter. The climatological flows are larger in CTRL than in LGM, except for the Kolyma River in July and August where the LGM runoff is higher than the CTRL one. For this latter river basin, precipitation exceeds evaporation in June for the LGM, contrary to the CTRL. In addition, significant precipitations in July and accumulation of snow in June explain the stronger flow for the LGM summer.

3.2. Main Rivers Which Flow Into the Arctic Ocean

[10] The difference between LGMM and LGMR is very small (Figure 3a), with slightly greater values for LGMM in June and July and slightly weaker ones in August and September. The Ob and Yenisei, with a maximum discharge of $20\,000\text{ m}^3/\text{s}$ in June and July, flow into the proglacial lake in the LGMR simulation instead of the Arctic Ocean in the LGMM simulation. Nevertheless, the difference in the total runoff to the Arctic Ocean between the simulations does not exceed $5000\text{ m}^3/\text{s}$. This compensation is mainly due to an increase of the model's coastal flow in the nearby area. Indeed, from August to the end of September, the total runoff from these rivers is stronger than the difference between the Ob and the Yenisei flow due to an increase of the precipitation over Siberia (Figure 4). This increase is induced by stronger evaporation from the proglacial lake in summer (more than 50 mm/month) and also leads to an increase of Lena river discharge of about $3500\text{ m}^3/\text{s}$ from June until October (Figure 3c). In addition, the presence of proglacial lakes reduces summer temperatures by $\sim 4^\circ\text{C}$, and increase winter temperatures by $\sim 1^\circ\text{C}$. The difference between LGMM and LGMR is weak in both the Kolyma (Figure 3b) and Lena (Figure 3c) basins, compared to the difference between LGM and the CTRL. The flow of the Kolyma River, further east than the Lena basin, is not significantly affected by the lake, although a weak difference in flow exists. The ground temperatures in LGMR are

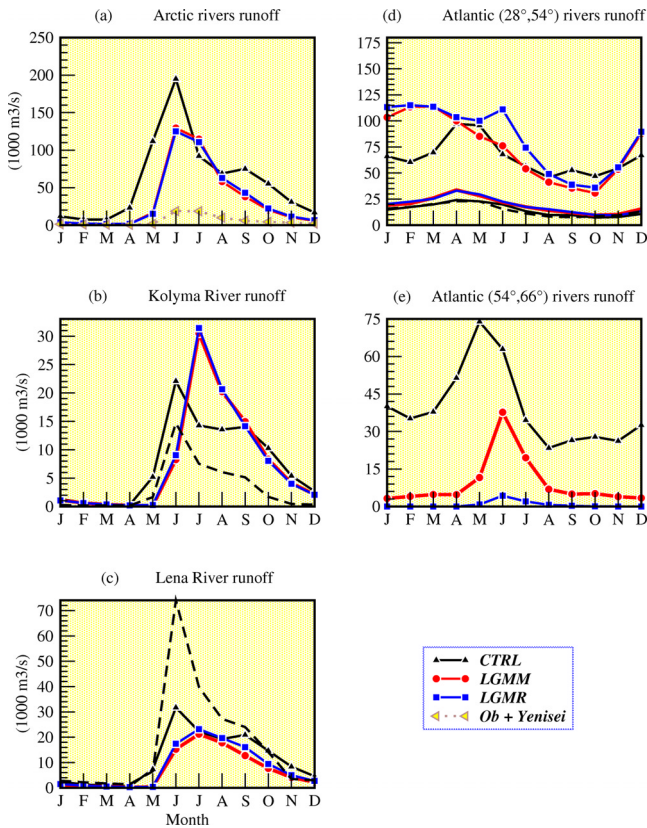


Figure 3. Seasonal discharge from (a) the rivers which pour into the Arctic (m^3/s) and the Ob and Yenisei flows at the LGM; (b and c) CTRL and LGM discharge from the Kolyma and Lena Rivers, respectively, the rivers which pour into (d) the Atlantic between 28° and 54°N and the Mississippi runoff (solid line without symbols) and (e) the Atlantic between 54° and 66°N . Dashed lines represent river flow measurements.

slightly higher than in LGMM and seasonal rains begin earlier. This helps explain the stronger flow observed in May and June and a lower one in August and September.

3.3. Rivers Which Flow Into North Atlantic Ocean

[11] To better illustrate the changes for this region, we separate the North Atlantic into two sectors. First, North of 54°N , the river input to the ocean is generally weaker in the LGM compared to CTRL due to smaller drainage basins (most of the basins are covered by the ice sheets). Second, the presence of the ice-sheet blocks the European rivers which flow into the North Atlantic or the North Sea between 54 and 66°N . These are generally diverted to the South i.e. between 28 and 54°N , which defines our second sector.

3.3.1. North Atlantic Between 28° and 54°N

[12] Total discharge from rivers which flow into the North Atlantic between 28 and 54°N is higher for the LGM than for the CTRL (Figure 3d) throughout the year. This is partly explained by the behaviour of rivers such as the Mississippi, whose flow is increased due to increased precipitation (Figure 2b) over this basin at the LGM. The higher total discharge for this band of latitude in LGMR compared to the LGMM comes from the difference in European river discharge. These rivers are principally fed by snow melt. Their flow is minimum in winter and maximum in summer, resulting in a maximum difference of $35000 \text{ m}^3/\text{s}$ in June. This significant change represents around 30% of the total LGMM freshwater discharge in this band of latitude for this month.

3.3.2. North Atlantic Between 54° and 66°N

[13] The difference between the LGMM and CTRL simulations is large, even if the seasonal cycle is similar (Figure 3e). The difference is mainly due to the presence of ice sheets which cover most parts of the basins at the LGM. The surface which contributes to the river drainage is consequently reduced. Also, the precipitation minus evaporation budget is larger in CTRL at those latitudes. The change in river drainage drastically reduces the total runoff towards the North Atlantic Ocean between 54° and 66°N ,

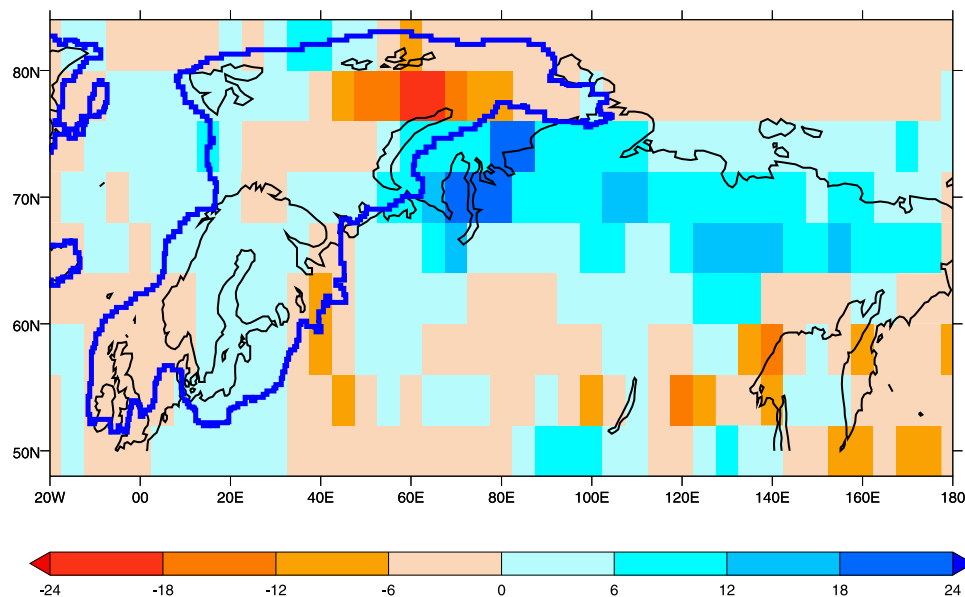


Figure 4. Summer LGM minus LGM precipitation (mm/month).

with a maximum difference of 34000 m³/s in June between LGMR and LGMM (around 90% of the total LGMM discharge). In this region, most rivers are fed by snow melt with a maximum flow occurring in June (which corresponds to the maximum annual temperature).

[14] The responses between 54° and 66°N and 28–54°N are therefore significantly different.

4. Discussion and Conclusion

[15] This study provides a brief discussion of the atmospheric response to realistic river routing and ice-dammed lakes for the Last Glacial Maximum. Like Krinner *et al.* [2004], we find that proglacial lakes play an important role in regional climate dynamics. The comparison between the LGM simulations performed with modern and LGM river routing shows that a realistic LGM river routing generates an additional flow with a maximum of 34000 m³/s in June in the North Atlantic between 28 and 54°N, compared to the model predictions based on the modern rivers drainage, whereas during the same month a reduction of 35000 m³/s is simulated between 54 and 66°N. The strong difference in flow to the Atlantic between 28 and 54°N is primarily a result of the southward shift of some European rivers which are blocked by the presence of the ice sheet.

[16] The total discharge into the Arctic Ocean is not drastically different between both simulations. Even if the Ob and Yenisei rivers were blocked by the ice sheet and flowed into a large lake during the LGM instead of the Arctic Ocean, the discharge of other rivers nearby is increased due to the enhanced precipitation induced by strong summer evaporation over the lake. This compensates for the lack of water flow due to the change of Ob and Yenisei routing.

[17] To conclude, this work raises the question of the impact of these changes on the ocean circulation and on the global climate itself through potential changes of the THC. Although Manabe and Stouffer [2000] showed that an additional fresh water flux of 30000 m³/s during 500 years flowed into the North Atlantic considerably weakens the THC in present day situation, this value is only comparable to the excess runoff in June in our simulation, and for a more southern discharge location (between 28° and 54°N). The runoff anomalies for the other periods of the year are significantly weaker, especially in February and March, which today are the months of maximum convection. We can therefore expect only a small impact of the discharge changes on the THC. Only coupled simulations, still running, would allow for a proper conclusion about the

sensitivity of the ice age climate to an improved representation of LGM rivers. [Ganopolski and Rahmstorf, 2001].

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