Impact of floods versus routing events on the thermohaline circulation

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[1] The last deglaciation was interrupted by three major cooling events, the Younger Dryas, the Preboreal Oscillation and the 8.2-ka cold event. As the Laurentide Ice Sheet retreated, different outlets from Lake Agassiz became available causing the proglacial lake to drain to a new level in a rather short timescale (flood) and divert continental runoff over hundreds of years (routing). Here we use an Earth System Model to investigate the impact of floods (short term, high amplitude) versus routing events (long term, low amplitude) on the thermohaline circulation and the resulting climate change. We show that the initial outbursts of freshwater are not strong enough to influence large-scale climate and can therefore not be the cause of millennial-scale climate variability. However, routing events have the potential of weakening the thermohaline circulation and therefore causing a cool event in the Northern Hemisphere. **Citation:** Meissner, K. J., and P. U. Clark (2006), Impact of floods versus routing events on the thermohaline circulation, *Geophys. Res. Lett.*, *33*, L15704, doi:10.1029/2006GL026705.

1. Introduction

[2] Warming of the Northern Hemisphere during the last deglaciation was interrupted by several abrupt cooling events, with the three largest being the Younger Dryas (12.9–11.5 cal ka), the Preboreal Oscillation (PBO) (11.5 cal ka) and the 8.2–ka cold event (Figure 1). *Johnson and McClure* [1976] first postulated that an increased freshwater flux to the St. Lawrence River associated with the diversion of continental runoff from the Mississippi River triggered the Younger Dryas cold event by causing an increase in North Atlantic sea ice. *Rooth* [1982] subsequently proposed that this Mississippi-to-St. Lawrence routing caused the Younger Dryas through its effect on the thermohaline circulation and attendant poleward ocean heat transport. This routing hypothesis gained support through the combined evidence for a drop in the level of Lake Agassiz, such as would be associated with the opening of a lower lake outlet that drained east to the St. Lawrence River, and an increase in the salinity of the Gulf of Mexico at the start of the Younger Dryas [*Broecker et al.*, 1989]. The association of routing events with the Preboreal Oscillation [*Fisher et al.*, 2002], the 8.2-ka event [*Barber et al.*, 1999] (Figure 1), and other cold events during the last deglaciation suggests a more generalized role for routing in explaining millennial-scale climate variability [*Clark et al.*, 2001].

[3] In addition to diverting continental runoff, the opening of a new outlet causes a proglacial lake to drain to a new level. The time it takes for the lake to lower to its new outlet is unknown, but is typically estimated to last for months to a year, and the associated lake-drainage event is referred to as a flood [*Teller et al.*, 2002; *Donnelly et al.*, 2005]. Accordingly, increases in the freshwater flux associated with the opening of new outlets for proglacial lakes such as Lake Agassiz are comprised of two components; a short-lived flood (<1 yr) and a routing event that is sustained as long as the lower outlet remains open (10^2–10^3 yr). Using the opening of an eastern outlet for Lake Agassiz drainage associated with the Younger Dryas as an example, Lake Agassiz lake level lowered by 110 m, with a corresponding volume loss of 9500 km^3 [*Leverington et al.*, 2000], while at the same time, runoff from the Lake Agassiz drainage basin, with an area of $\sim$1.4 $\times$ 10^6 km^2 [*Licciardi et al.*, 1999], was diverted from the Mississippi basin to the St. Lawrence basin by way of the newly opened eastern outlet. The increase in freshwater flux to the St. Lawrence River associated with a loss of 9500 km^3 from the lake will depend on the duration of the lake-level lowering, for example, 0.3 Sv if a duration of one year, 0.06 Sv if a duration of five years, etc. Based on climate and ice sheet models, *Licciardi et al.* [1999] estimated the increase in freshwater flux to the St. Lawrence River associated with the drainage-basin diversion to be 0.05 Sv for the duration of the use of the eastern outlet ($\sim$1400 yr) (Figure 1).

[4] Earlier work emphasized the routing of continental runoff over floods as a cause of abrupt climate change [*Rooth*, 1982; *Broecker et al.*, 1989; *Teller*, 1990]. More recent work, however, has emphasized the role of floods in triggering abrupt climate change [*Teller et al.*, 2002; *Clarke et al.*, 2003; *Teller and Leverington*, 2004; *Teller et al.*, 2005; *Donnelly et al.*, 2005; *Lowell et al.*, 2005; *LeGrande et al.*, 2006]. In doing so, it is necessary to assume that the lake-level lowering occurred in months to a year. Otherwise, if the volume of most known lake-level lowerings [*Leverington et al.*, 2000, 2002] is distributed over any longer interval, the attendant freshwater fluxes become similar to or less than the freshwater fluxes associated with the diversion of the drainage basin, as shown by the Younger Dryas example above.

[5] At this time, it is not possible to resolve, from the geologic record, the duration of a lake-level lowering event. Assuming that proglacial lakes did drain rapidly enough (<1 yr) to generate floods, however, the question remains as to how its effect on the Atlantic meridional overturning circulation (AMOC) compares to that of a smaller freshwater flux of much longer duration associated with routing (Figure 1). Here we examine this question by using an Earth System Model to investigate the impact of floods (short

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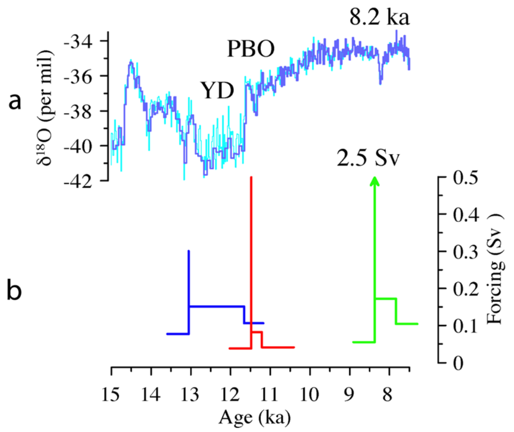

Figure 1. (a) The Greenland ice core (GISP2) δ^{18}O record [*Grootes et al.*, 1993; *Stuiver and Grootes*, 2000]. (b) Freshwater fluxes used in our experiments, with initial 1-yr flood followed by increased flux associated with routing. Blue: fluxes used for Younger Dryas (YD) simulation [*Licciardi et al.*, 1999; *Leverington et al.*, 2000]. Red: fluxes used for Preboreal Oscillation (PBO) simulation [*Licciardi et al.*, 1999; *Fisher et al.*, 2002]. Green: fluxes used for the 8.2-ka event simulation [*Licciardi et al.*, 1999; *Clarke et al.*, 2004].

term, high amplitude) versus routing events (long term, low amplitude) on the AMOC and attendant climate change for three major cooling events during the last deglaciation (Figure 1).

2. Model and Experimental Design

[6] We use the UVic Earth System Climate Model (ESCM, Version 2.6) to evaluate the effects of a flood versus a routing event on the AMOC and attendant climate change. The UVic ESCM consists of a global ocean general circulation model (Modular Ocean Model, Version 2 [*Pacanowski*, 1995]) coupled to a vertically integrated two dimensional energy-moisture balance model of the atmosphere, a dynamic-thermodynamic sea ice model [*Bitz et al.*, 2001] and a land surface scheme [*Matthews et al.*, 2003]. The model version including the atmospheric, ocean and sea ice model is described in *Weaver et al.* [2001]. It is driven by seasonal variations in solar insolation at the top of the atmosphere and seasonally-varying wind stress at the ocean surface [*Kalnay et al.*, 1996].

[7] Three different meltwater events are simulated using reconstructed estimates of freshwater fluxes (floods and routing events) for the Younger Dryas (YD), the Preboreal Oscillation (PBO) and the 8.2-ka event [*Licciardi et al.*, 1999; *Leverington et al.*, 2000, 2002; *Fisher et al.*, 2002; *Clarke et al.*, 2004]. In each case, we integrate the model for over 5000 years into equilibrium under corresponding boundary conditions (orbital parameters [*Berger*, 1978] and atmospheric CO_2 of 240 ppm, 260 ppm and 260 ppm for the YD, PBO and 8.2-ka event, respectively). We use elevated topography based on a reconstruction of the Laurentide ice sheet for each considered time slice [*Licciardi et al.*, 1998]. Each run is then integrated for another 2000 years with prescribed fluxes in the respective river basin (St. Lawrence River for YD, Mackenzie River for PBO and Hudson Strait for 8.2-ka event) before the meltwater event (see Tables 1 to 3). The meltwater events consist of a one-year flood followed by a routing event over several hundred years. Each routing event was terminated when runoff was diverted elsewhere, with an attendant decrease in the freshwater flux to each of the river basins examined here [*Licciardi et al.*, 1999]. Accordingly, we prescribe a decrease in the freshwater flux for rerouting after each meltwater event based on the estimates of *Licciardi et al.* [1999]. Four simulations are carried out for each event (model runs A–D, see Tables 1 to 3). Model runs A simulate all the different stages of each freshwater event (flood, routing and rerouting). Model runs B, C and D skip one or two stages for each event (B runs: flood and rerouting only; C runs: routing and rerouting only and D runs: rerouting only).

3. Results

[8] Figure 2 shows the time series of maximum overturning stream function in the North Atlantic. The strength of the thermohaline circulation before each meltwater perturbation amounts to 15.1, 15.5 and 16.6 Sv for the YD, PBO and 8.2-ka event respectively. The circulation is in all three cases stronger than estimates of the circulation during the Last Glacial Maximum and less vigourous than the present-day circulation. In all three cases, adding freshwater to the ocean results in a decrease of the maximum overturning stream function, but in none of the simulations is the freshwater flux strong enough to cause a shutdown of the thermohaline circulation. The circulation is weakened during each flood and routing event and recovers after the event. The strength of the meridional overturning after each event depends on the freshwater flux during the rerouting phase.

[9] It is striking that for all three simulated events, model runs A and C (as well as B and D) yield a very similar response, indicating that the impact of the one-year floods is negligible compared to the routing and rerouting events. This result is not very surprising if one considers the total

Table 1. Model Simulations for the Younger Dryas Event: Discharge Through St. Lawrence Valley Into the North Atlantic

	Integration Time, years	Freshwater Flux, Sv	YD_A	YD_B	YD_C	YD_D
Control	7000	diagnostic	x	x	x	x
Before event	2000	0.077	x	x	x	x
Flood	1	0.3	x	x		
Routing	1300	0.151	x		x	
Rerouting	2000	0.106	x	x	x	x

Table 2. Model Simulations for the Preboreal Oscillation: Discharge Through the Clearwater-Athabasca-Mackenzie River Valleys Into the Arctic Ocean

	Integration Time, years	Freshwater Flux, Sv	PB_A	PB_B	PB_C	PB_D
Control	7000	diagnostic	x	x	x	x
Before event	2000	0.038	x	x	x	x
Flood	1	0.5	x	x		
Routing	250	0.082	x		x	
Rerouting	2000	0.041	x	x	x	x

Table 3. Model Simulations for the 8.2-ka Event: Discharge Through Hudson Bay and Hudson Strait Into the North Atlantic Ocean

	Integration Time, years	Freshwater Flux, Sv	8.2_A	8.2_B	8.2_C	8.2_D
Control	8500	diagnostic	x	x	x	x
Before event	2000	0.055	x	x	x	x
Flood	1	2.5	x	x		
Routing	500	0.172	x		x	
Rerouting	2000	0.104	x	x	x	x

amount of freshwater added to the ocean in each scenario. For the Younger Dryas a total amount of 9.5 10^{12} m^3 freshwater has been released through St. Lawrence Valley into the North Atlantic during the flood whereas the following routing event ($6.2 \cdot 10^{15}$ m^3) is 10^3 times larger. In all three scenarios the total amount of meltwater runoff is at least one order of magnitude larger for the routing events than for the floods (1.6 10^{13} m^3 versus 6.5 10^{14} m^3 for the PBO; 7.9 10^{13} m^3 versus 2.7 10^{15} m^3 for the 8.2-ka event).

[10] The response of the climate system to freshwater perturbations at high latitudes depends on the region where the perturbation is applied as well as the duration and the amplitude of the perturbation. The same perturbation can also cause a different response depending on the climate state itself [*Ganopolski and Rahmstorf*, 2001; *Meissner et al.*, 2002]. Finally, different climate models show different sensitivities to freshwater perturbations. Although the present study faces several uncertainties - the climate state itself is not very well known at the onset of cooling events and the duration and amount of meltwater released is based on reconstructions - we believe that the main conclusion is robust. The freshwater perturbation during short-term floods is negligible compared to routing events. Routing events have the potential to influence climate in the Northern Hemisphere for centuries. On the other hand, the initial outburst of freshwater may have had catastrophic impacts on the local environment, but are unlikely to trigger long-term climate change.

[11] The only flood to have had any significant impact on the thermohaline circulation was that associated with the 8.2-ka event (Figure 2c). This is not surprising, as it was the largest flood of all those reconstructed during the last deglaciation [*Teller and Leverington*, 2004], but its effect on the overturning circulation was still considerably smaller than the effect of the routing in the present study. *Renssen et al.* [2002] and *Wiersma and Renssen* [2006] carried out several simulation of the 8.2-ka event by introducing a fixed freshwater pulse of $4.67 \times 10^{14} m^3$ within 10, 20, 50 and 500 yr. They found that the 20-yr pulse reproduced best the cooling registered in Greenland ice cores. However, because the 8.2-ka flood was associated with the very last stages of deglaciation of the Laurentide Ice Sheet, it was a unique event and is not representative of potential meltwater floods during glaciations.

4. Conclusions

[12] The UVic Earth System Model was used to investigate the impact of floods versus routing events on climate. We show that the initial outbursts of freshwater are not strong enough to influence large-scale climate and can therefore not be the cause of millennial-scale climate variability. However, routing events have the potential of weakening the thermohaline circulation and therefore causing a cool event in the Northern Hemisphere. Whereas the largest catastrophic short-term floods are a very special case during deglaciations (need for a retracted ice sheet in order to allow a large proglacial lake to grow), routing events can

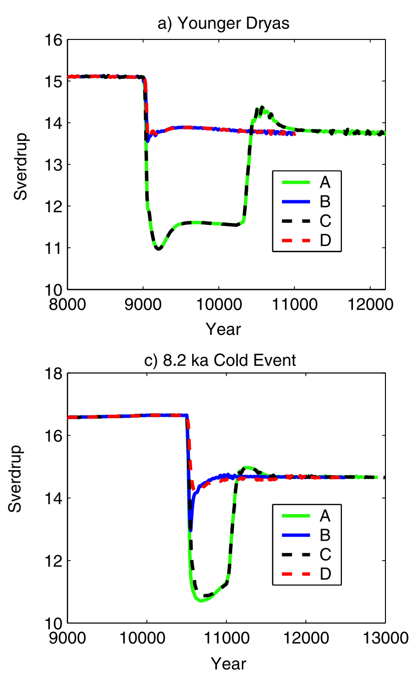

Figure 2. Time series of maximum meridional overturning (in Sverdrup) for model simulations of (a) the Younger Dryas, (b) the Preboreal Oscillation and (c) the 8.2-ka event. Please refer to Tables 1 to 3 for a description of model simulations A to D for each meltwater event.

occur any time the southern ice margin pulls back far enough to allow drainage to one of the two possible eastern outlets (Hudson River or St. Lawrence River). This was likely common during times of intermediate ice volume, such as marine isotope stage 3, and may have been the cause for Dansgaard-Oeschger events [*Clark et al.*, 2001]. Recently, the absence of geomorphic evidence for a flood during the YD has been used as the basis to question the role of freshwater forcing of this event [*Lowell et al.*, 2005; *Teller et al.*, 2005; *Broecker*, 2006], and by extension, of other cold events. Because our results suggest that floods would not cause millennial-scale cold events such as the YD, then the absence of evidence for a YD flood may indeed suggest that such a flood did not occur, perhaps because the lake drained more slowly than assumed, but it cannot be used to question a freshwater-forcing mechanism for the YD. Instead, our results suggest that we should refocus attention on routing events as an important mechanism of abrupt climate change.

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References

Barber, D. C., et al. (1999), Forcing of the cold event of 8,200 years ago by catastrophic drainage of Laurentide lakes, *Nature*, *400*, 344–348.

Berger, A. L. (1978), Long-term variations of daily insolation and quaternary climatic changes, *J. Atmos. Sci.*, *35*, 2362–2367.

Bitz, C. M., M. M. Holland, A. J. Weaver, and M. Eby (2001), Simulating the ice-thickness distribution in a coupled climate model, *J. Geophys. Res.*, *106*, 2441–2464.

Broecker, W. S. (2006), Was the Younger Dryas triggered by a flood?, *Science*, *312*, 1146–1148.

Broecker, W. S., J. P. Kennett, B. P. Flower, J. T. Teller, S. Trumbore, G. Bonani, and W. Wolfli (1989), Routing of meltwater from the Laurentide ice-sheet during the Younger Dryas cold episode, *Nature*, *341*, 318–321.

Clark, P. U., S. J. Marshall, G. K. C. Clarke, S. W. Hostetler, J. M. Licciardi, and J. T. Teller (2001), Freshwater forcing of abrupt climate change during the last glaciation, *Science*, *293*, 283–287.

Clarke, G. K. C., D. W. Leverington, J. T. Teller, and A. S. Dyke (2003), Superlakes, megafloods, and abrupt climate change, *Science*, *301*, 922–923.

Clarke, G. K. C., D. W. Leverington, J. T. Teller, and A. S. Dyke (2004), Paleohydraulics of the last outburst flood from glacial Lake Agassiz and the 8,200 BP cold event, *Quat. Sci. Rev.*, *23*, 389–407.

Donnelly, J. P., N. W. Driscoll, E. Uchupi, L. D. Keigwin, W. C. Schwab, E. R. Thieler, and S. A. Swift (2005), Catastrophic meltwater discharge down the Hudson Valley: A potential trigger for the Intra-Allerod cold period, *Geology*, *33*, 89–92.

Fisher, T. G., D. G. Smith, and J. T. Andrews (2002), Preboreal oscillation: North Atlantic cooling caused indirectly by a glacial Lake Agassiz flood, 11,300 years ago, *Quat. Sci. Rev.*, *21*, 873–878.

Ganopolski, A., and S. Rahmstorf (2001), Rapid changes of glacial climate simulated in a coupled climate model, *Nature*, *409*, 153–158.

Grootes, P. M., M. Stuiver, J. W. C. White, S. J. Johnsen, and J. Jouzel (1993), Comparison of oxygen isotope records from the GISP2 and GRIP Greenland ice cores, *Nature*, *366*, 552–554.

Johnson, R. G., and B. T. McClure (1976), A model for Northern Hemisphere continental ice sheet variation, *Quat. Res.*, *6*, 325–353.

Kalnay, E., et al. (1996), The NCEP/NCAR 40-year reanalysis project, *Bull. Am. Meteorol. Soc.*, *77*, 437–471.

LeGrande, A. N., G. A. Schmidt, D. T. Shindell, C. V. Field, R. L. Miller, D. M. Koch, G. Faluvegi, and G. Hoffmann (2006), Consistent simulations of multiple proxy responses to an abrupt climate change event, *Proc. Natl. Acad. Sci. U. S. A.*, *103*, 837–842.

Leverington, D. W., J. D. Mann, and J. T. Teller (2000), Changes in the bathymetry and volume of glacial Lake Agassiz between 11000 and 9300 14C yr B.P., *Quat. Res.*, *54*, 174–181.

Leverington, D. W., J. D. Mann, and J. T. Teller (2002), Changes in the bathymetry and volume of glacial Lake Agassiz between 9200 and 7600 14C yr B.P., *Quat. Res.*, *57*, 244–252.

Licciardi, J. M., P. U. Clark, J. W. Jenson, and D. R. Macayeal (1998), Deglaciation of a soft-bedded Laurentide ice sheet, *Quat. Sci. Rev.*, *17*, 427–448.

Licciardi, J. M., J. T. Teller, and P. U. Clark (1999), Freshwater routing by the Laurentide Ice Sheet during the last deglaciation, in *Mechanisms of Global Climate Change at Millennial Time Scales*, *Geophys. Monogr. Ser.*, vol. 112, edited by P. U. Clark, R. S. Webb, and L. D. Keigwin, pp. 177–201, AGU, Washington, D. C.

Lowell, T. V., et al. (2005), Testing the Lake Agassiz Meltwater Trigger for the Younger Dryas, *Eos Trans. AGU*, *86*, 365, 373.

Matthews, H. D., A. J. Weaver, M. Eby, and K. J. Meissner (2003), Radiative forcing of climate by historical land cover change, *Geophys. Res. Lett.*, *30*(2), 1055, doi:10.1029/2002GL016098.

Meissner, K. J., A. Schmittner, E. C. Wiebe, and A. J. Weaver (2002), Simulations of Heinrich Events in a coupled oean-atmosphere-sea ice model, *Geophys. Res. Lett.*, *29*(14), 1671, doi:10.1029/2001GL013514.

Pacanowski, R. C. (1995), MOM 2 documentation: User's guide and reference manual, *Tech. Rep. 3*, GFDL Ocean Group, Geophys. Fluid Dyn. Lab., Princeton, N. J.

Renssen, H., H. Goosse, and T. Fichefet (2002), Modeling the effect of freshwater pulses on the early Holocene climate: The influence of high-frequency climate variability, *Paleoceanography*, *17*(2), 1020, doi:10.1029/2001PA000649.

Rooth, C. (1982), Hydrology and ocean circulation, *Prog. Oceanogr.*, *11*, 131–149.

Stuiver, M., and P. M. Grootes (2000), GISP2 oxygen isotope ratios, *Quat. Res.*, *53*, 277–284.

Teller, J. T. (1990), Volume and routing of late-glacial runoff from the southern Laurentide Ice Sheet, *Quat. Res.*, *34*, 12–23.

Teller, J. T., and D. W. Leverington (2004), Glacial Lake Agassiz: A 5000 yr history and its relationship to the $\delta^{18}O$ record of Greenland, *Geol. Soc. Am. Bull.*, *116*, 729–742.

Teller, J. T., D. W. Leverington, and J. D. Mann (2002), Freshwater outbursts to the oceans from glacial Lake Agassiz and their role in climate change during the last deglaciation, *Quat. Sci. Rev.*, *21*, 879–887.

Teller, J. T., M. Boyd, Z. Yang, P. Kor, and A. Fard (2005), Alternative routing of Lake Agassiz overflow during the Younger Dryas: New dates, paleotopography, and a re-evaluation, *Quat. Sci. Rev.*, *24*, 1890–1905.

Weaver, A. J., et al. (2001), The UVic Earth System Climate Model: Model description, climatology, and applications to past, present and future climates, *Atmos. Ocean*, *4*, 361–428.

Wiersma, A. P., and H. Renssen (2006), Model-data comparison for the 8.2 ka BP event: Confirmation of a forcing mechanism by catastrophic drainage of Laurentide Lakes, *Quat. Sci. Rev.*, *25*, 63–88.

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