7.4 **ASSESSING MODEL SENSITIVITY TO NORTH ATLANTIC FRESHWATER PERTURBATIONS USING PAST ABRUPT EVENTS**

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1. Introduction

The Atlantic Meridional Overturning Circulation (AMOC) is thought to have played an important role in past abrupt climate changes (National Research Council, 2002). During these abrupt events, large volumes of glacial meltwater spilled into the North Atlantic, particularly from the North American, or Laurentide, ice sheet. The excess meltwater freshened surface waters, lowering their density. This reduced deep water formation, slowed the AMOC and rapidly cooled large parts of the Northern Hemisphere. These freshwater perturbations happened repeatedly during the last glacial period and at times during our current interglacial period, the Holocene.

Likewise, the AMOC may be sensitive to anthropogenic climate change. Future climate change will likely affect the buoyancy of North Atlantic waters in two ways. First, a warmer atmosphere is expected to minimize the cooling of Atlantic waters as they flow northward. This will lower the density of surface waters in the North Atlantic and could slow the AMOC. However, atmosphere-ocean general circulation models (AOGCMs) disagree about the degree to which this circulation will slow. For example, in simulations with increased greenhouse gas concentrations completed for the IPCC Fourth Assessment Report, the response of AOGCMs varied widely, from a 14 Sverdrup (Sv) to a 3 Sv decrease in the strength of the AMOC by 2100 (Schmittner et al., 2005). In turn, these models' predictions of climate change in the circum-North Atlantic region have large uncertainties. Second, warming is expected to cause melting of high-latitude ice sheets, freshening surface waters in the North Atlantic and lowering their density. Simulations indicate that melting of Greenland further weakens the AMOC (e.g., Jungclaus et al., 2006), however, there is large spread in model sensitivity to freshwater additions (Stouffer et al., 2006).

One way to evaluate the sensitivity and credibility of these climate models is to consider the forcing and response during past freshwater perturbations.

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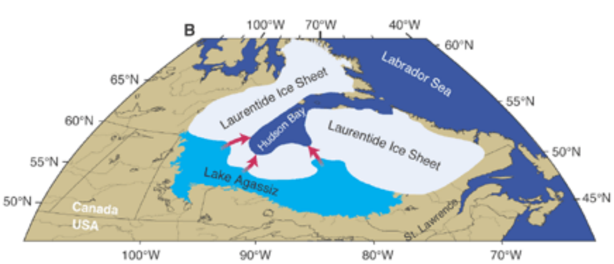
Two caveats exist to this approach. First, past events are useful primarily for examining haline, rather than both thermal and haline, forcing. Second, past freshwater forcing was larger than that expected in the coming centuries. These are only minor limitations, however. Haline forcing is still a key uncertainty, as is the climate response to a change in the AMOC, regardless of its cause. The larger forcings of the past also offer a better signal-to-noise ratio. One such past event that has garnered attention as a model test case is the 8.2 ka event, which occurred during the early Holocene roughly 8200 years ago.

2. The 8.2 ka Event

The 8.2 ka event was one of the largest abrupt climate changes during the Holocene. Glacial meltwater entered the North Atlantic at several locations during this time. The Laurentide ice sheet, which had built up on North America during the last glacial period, was the source of this freshwater. By the early Holocene, much of the ice sheet had melted since the last glacial maximum at 21 ka, but remnants remained around the Hudson Bay (Figure 1). As the ice sheet continued to shrink, some meltwater flowed down the St. Lawrence River (Licciardi et al., 1999). Other meltwater collected in a large proglacial lake, called Lake Agassiz, which was separated from the Hudson Bay by the remnant ice sheet.

Figure 1. *Geography of Hudson Bay region around 8.2 ka. From Clarke et al. (2003).*



Eventually, the remaining ice sheet melted enough to allow Lake Agassiz to drain, probably subglacially, into the Hudson Bay. The volume of Lake Agassiz, estimated by mapping of lake deposits, was approximately 1.6 x 10^{14} m^3, or about twice the volume of the present-day Caspian Sea (Clarke et al., 2003, 2004). Ice sheet modeling by Clarke et al. (2004) predicted that it took six months for the lake to drain. Simultaneous with lake drainage, at least one-third of the existing Laurentide ice sheet was also released into the Hudson Bay (Dyke and Prest, 1989). Following the drainage of Lake Agassiz, meltwater runoff was re-routed from the St. Lawrence River to the Hudson Strait (Licciardi et al., 1999).

There are many paleoclimate records spanning this time period and they suggest that widespread climate changes occurred in Greenland, Europe and North America (Morrill and Jacobsen, 2005). Evidence from the tropics is not as clear, although there are clear indications of a reduction in methane production and of a shift in the Intertropical Convergence Zone in the vicinity of Cariaco Basin (Alley et al., 1997). The event is particularly clear in central Greenland ice cores, where a negative $\delta^{18}O$ excursion is estimated to reflect a cooling with maximum amplitude of 3.3 ± 1.1 °C and lasting, in total, about 160 years (Kobashi et al., 2007; Thomas et al., 2007).

3. Model Experiments

We have used NCAR's Community Climate System Model, version 3 (CCSM3; Collins et al. 2006) to simulate the 8.2 ka event. The CCSM3 consists of four component models that are coupled without flux corrections: the Community Atmosphere Model version 3, the Community Land Surface Model version 3, the Community Sea Ice Model version 5, and a modified version of the Parallel Ocean Program Model 1.4.3. The horizontal resolution of the atmosphere and land models is T42, approximately 2.8º, and the atmosphere model has 26 vertical levels. The horizontal resolution of the ocean and sea ice models is nominally 1º with significantly greater resolution in the tropics and North Atlantic. The ocean model has 40 vertical levels.

Before adding the freshwater perturbation associated with the drainage of Lake Agassiz, we spun up the model to equilibrium with relevant background climate forcings: orbital parameters (Berger, 1978), trace gas concentrations (CO_2: 260 ppm, CH_4: 660 ppb, N_2O: 260 ppb; Monnin et al., 2001, Flückiger et al., 2002), remnant Laurentide ice sheet (Peltier et al., 2004), and an ice melt runoff flux down the St. Lawrence River (0.05 Sv; Licciardi et al., 1999). To the control simulation, we added a flux of 2.5 Sv over one year to the Labrador Sea to represent the drainage of Lake Agassiz, based on the best estimates of Clarke et al. (2004). Given the short duration of the lake drainage, it is possible that the climate response could depend on climate variability. In particular, LeGrande et al. (2006) showed that the response can depend on the background strength of the AMOC. To account for this, we added the lake drainage flux to several different years of the control simulation, corresponding to years with relatively weak and strong AMOC.

4. Results

The maximum AMOC response in our simulations tends to be in the second decade after lake drainage, with a decrease of about 10% compared to control values (Table 1). AMOC values comparable to the control were restored by the third decade. Our anomalies are much smaller than those previously reported for the GISS ModelE (LeGrande et al., 2006), which shows decreases in AMOC strength of nearly 40% in some cases (Table 1). The GISS simulations were completed using modern, rather

Table 1. Response of AMOC to Agassiz lake drainage of 2.5 Sv for one year

Simulation	Control AMOC (Sv)	First decade Δ AMOC	Second decade Δ AMOC	Third decade Δ AMOC	Forcings
NCAR CCSM3 (weak AMOC)	19.4	***-9%***	***-8%***	-1%	Orbital, trace gas
NCAR CCSM3 (strong AMOC)	22.4	-9%	***-14%***	-3%	Orbital, trace gas
NCAR CCSM3 (all forcings)	16.4	-2%	***-9%***	N/A	Orbital, trace gas, ice sheet, St. Lawrence runoff
GISS ModelE (weak AMOC)*	~20	-6%	-24%	-9%	Modern
GISS ModelE (strong AMOC)*	~33	-27%	-38%	-6%	Modern

* from LeGrande et al. (2006)
Bold type for CCSM3 simulations indicates a significant difference from the control at 95% level.

than 8.2 ka boundary conditions, but the modern background state is not too different from our simulations that incorporate only 8.2 ka orbital and trace gas forcing (Table 1). Additional Agassiz lake drainage experiments have been completed with other models but the freshwater flux prescribed in those simulations are at least twice as large as the flux used in this study, limiting any direct comparisons.

Anomalies in climate variables such as annual 2-meter air temperature were even shorter-lived, recovering in less than a decade (Table 2). The largest air temperature anomalies in Greenland were still smaller than that reconstructed from ice core evidence (3.3±1.1°C, Kobashi et al., 2007).

Table 2. Response of Greenland annual 2-meter air temperature to Agassiz lake drainage

Simulation	First decade ΔT (°C)	Second decade ΔT (°C)	Third decade ΔT (°C)
NCAR CCSM3 (weak AMOC)	***-1.4***	-0.7	-0.1
NCAR CCSM3 (strong AMOC)	***-1.5***	-0.4	-0.3
NCAR CCSM3 (all forcings)	***-1.0***	-0.3	N/A
GISS Model E (weak AMOC) *	-0.5	-0.9	-1.4
GISS Model E (strong AMOC) *	-0.7	-1.3	-0.7

* from LeGrande et al. (2006)
Bold type for CCSM3 simulations indicates a significant difference from control at 95% level

5. Discussion

Overall, the response of the model to the Agassiz lake drainage appears to be smaller and shorter-lived than the 8.2 ka event as recorded in proxy records. That said, a quantitative proxy record of AMOC strength during the event is still lacking, even though several qualitative records show an obvious slowdown that lasted on the order of a century (Ellison et al., 2006, Kleiven et al., 2008).

We have yet to consider several additional forcings associated with the drainage of Lake Agassiz. The same collapse of the Laurentide ice sheet that caused the lake drainage sent about one-third of the remaining ice sheet into the Hudson Bay (Dyke and Prest, 1989). The exact duration of this collapse is not known, but is likely to have been on the order of decades. Based on mapping of glacial deposits (Dyke and Prest, 1989) and the estimated total sea level rise during the 8.2 ka event (Tornqvist et al., 2004), this volume is estimated to have been 3.6×10^{14} m^3. If drained over a 50 year period, this corresponds to a flux of 0.2 Sv. After the Laurentide ice sheet collapsed, the Hudson Bay and Hudson Strait presented a lower outlet to the sea than the St. Lawrence and the baseline flow of glacial runoff was then re-routed from the St. Lawrence to the Hudson Strait. Both of these forcings would prolong the freshwater perturbation in the Labrador Sea, potentially lengthening and enhancing the climate response. In fact, results from a model of intermediate complexity suggest that lake drainage had the smallest effect on ocean circulation of any of these fluxes (Meissner and Clark, 2006).

6. References

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