The sea-level fingerprint of the 8.2 ka climate event

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ABSTRACT

The 8.2 ka cooling event was an abrupt, widespread climate instability. There is general consensus that the episode was likely initiated by a catastrophic outflow of proglacial Lakes Agassiz and Ojibway through the Hudson Strait, with subsequent disruption of the Atlantic meridional overturning circulation. However, the total discharge and flux during the 8.2 ka event remain uncertain. We compute the sea-level signature, or "fingerprint," associated with the drainage of Lakes Agassiz and Ojibway, as well as the expected sea-level signal over the same time period due to glacial isostatic adjustment (GIA) in response to the Late Pleistocene deglaciation. Our analysis demonstrates that sites relatively close to the lakes, including the West and Gulf Coasts of the United States, have small signals due to the lake release and potentially large GIA signals, and thus they may not be optimal field sites for constraining the outflow volume. Other sites, such as the east coast of South America and western Africa, have significantly larger signals associated with the lake release and are thus better choices in this regard.

Keywords: Holocene, sea level, climate, lake drainage, glacial isostatic adjustment.

INTRODUCTION

The relationship between perturbations in freshwater flux arising from the melting of global ice reservoirs and potential variability in the Atlantic meridional overturning circulation (MOC) is a central question in current climate research (Broecker, 1997). In particular, what level of ongoing freshwater release from polar ice sheets (Greenland, Antarctica) and mountain glaciers would be sufficient to disrupt the MOC and thus induce abrupt, large-scale fluctuations in future climate? One route to resolving this issue may lie in Holocene climate records, which reveal a "prominent, widespread" instability 8.0–8.4 k.y. ago (Alley et al., 1997), a period in which some climatic conditions, such as the vigor of the MOC, were otherwise largely similar to those of the present day.

Greenland ice-core proxies indicate that the so-called "8.2 ka climate event" was characterized by dry, dusty conditions, a dramatic increase in forest-fire frequency, and a rapid cooling of as much as ~6 °C (Alley et al., 1997; Thomas et al., 2007). This event has also been correlated with a diverse suite of climate proxies, particularly in the circum–North Atlantic region (see Alley and Ágústsdóttir, 2005; Rohling and Pälike, 2005; Wiersma and Renssen, 2006, for relevant reviews).

There is increasing consensus that the 8.2 ka event was triggered by a catastrophic outflow of the proglacial Lakes Agassiz and Ojibway (henceforth Lake Agassiz-Ojibway) through the Hudson Strait and into the Labrador Sea (Barber et al., 1999). (However, Rohling and Pälike [2005] noted a deterioration of climate that precedes the outflow by several centuries.) This lake discharge scenario is consistent with the analysis of sediment deposition patterns through the strait and an improved age estimate for the freshwater release (Barber et al., 1999). Moreover, numerical models indicate that a freshening of the North Atlantic of sufficient magnitude would lead to a transient weakening of the MOC and yield climate anomalies that are consistent with the observational record (Renssen et al., 2001; LeGrande et al., 2006; Wiersma and Renssen, 2006).

The total freshwater discharge through the Hudson Strait, and its duration, remain uncertain. Estimates of the volume extend from a lower bound of $1–2 \times 10^{14}$ m^3 (De Vernal et al., 1997; Barber et al., 1999; Leverington et al., 2002; Clarke et al., 2004) to significantly higher values of 5×10^{14} m^3 (von Grafenstein et al., 1998), though the latter may include a significant ice component. These volumes are often expressed in terms of the equivalent eustatic (i.e., globally uniform) sea-level rise, and, in this parameterization, the bounds are ~0.4 m and 1.4 m, respectively. Clarke et al. (2004) argued that the massive drainage of the proglacial lakes occurred in one or more discrete flooding events lasting as little as six months. They estimated a discharge rate of 5×10^6 m^3 s^{-1} (or 5 Sv).

The above inferences of discharge volume were based on estimates of the size of Lake Agassiz-Ojibway (e.g., Leverington et al., 2002) and/or climate model studies (e.g., Renssen et al., 2001). Törnqvist et al. (2004a) recently obtained a sea-level record associated with the 8.2 ka event from two cores within the Mississippi Delta. Both cores contained basal salt marsh peat that accumulated immediately on the consolidated Pleistocene basement. The deepest of the two peat samples (8.25–8.42 ka) was abruptly overlain by a lagoonal deposit indicating rapid flooding, whereas the stratigraphically higher sample (8.01–8.17 ka) occurred in a thicker peat bed that gradually gave way to overlying mud. The combination of the stratigraphy and the dating indicates that these two sea-level index points straddle the 8.2 ka event and suggest a maximum sea-level rise of 1.2 m in this area from which they inferred a meltwater volume of 4.3×10^{14} m^3 (Törnqvist et al., 2004a).

The question arises as to whether such records of sea-level change can provide direct constraints on the discharge volume around the

8.2 ka event. The rapid release of meltwater, whether from ablation of ice or from the discharge of proglacial lakes following the breach of an ice dam, may produce a sea-level change that departs significantly from the eustatic value. In particular, the sea-level change associated with each source of meltwater will have a highly nonuniform geometry, or "fingerprint" (e.g., Mitrovica et al., 2001).

In the present study we compute the sea-level fingerprint associated with the rapid drainage of Lake Agassiz-Ojibway. We also estimate the contemporaneous signal associated with the melting of global, Late Pleistocene ice reservoirs, or glacial isostatic adjustment (GIA). Our maps will be an important guide for choosing field sites that provide optimal constraints on the freshwater discharge responsible for the 8.2 ka climate event, and we will identify target regions suitable for this purpose. We will also use the maps to reassess constraints on the 8.2 ka meltwater release presented by Törnqvist et al. (2004a).

MODELS AND NUMERICAL APPROACH

Our GIA calculations adopt a spherically symmetric, Maxwell viscoelastic Earth model, with elastic and density structure given by PREM (Dziewonski and Anderson, 1981), and a slightly modified version (see below) of the ICE-5G glaciation history (Peltier, 2004). The geographic extent of the Laurentide ice sheet at 8.5 ka is indicated in Figure 1. The ICE-5G model is composed of both an ice history and a radial profile of mantle viscosity, with the latter denoted as the VM2 profile (Peltier, 2004). We adopt a three-layer approximation to VM2, with two layers in the lower mantle (3.3×10^{21} Pa s from the core-mantle boundary to 1800 km depth, and 2.2×10^{21} Pa s above this) and an isoviscous (4×10^{20} Pa s) upper mantle. A 96-km-thick elastic lithosphere is used. Both the ice history and radial viscosity profile are issues of ongoing debate within the GIA literature, and our choice of ICE-5G is simply intended as an illustrative example. We considered other radial viscosity profiles, and none of the main conclusions in this study were significantly altered. The GIA-induced sea-level change was computed by applying the generalized sea-level equation and pseudospectral algorithm (up to spherical harmonic degree and order 256) described in detail by Kendall et al. (2005). These predictions include both a eustatic meltwater term and gravitational and deformational signals driven by the surface mass loading.

Next, we turn to the rapid drainage of Lake Agassiz-Ojibway. A model of these lakes was constructed as follows. First, the geographical extent of the lake was obtained from the final Kinojévis stage of the lake history illustrated in Figure 2E of Leverington et al. (2002). This boundary was superimposed on the 8.4 ka topography output in the GIA calculation, and the perimeter was adjusted so that the southern boundary of the lake coincided with a common topographical contour. Second, the boundary defined by the model ice margin was adjusted so that it coincided with the northern edge of the lake perimeter. The extent and depth of the proglacial lake model is shown in Figure 1. The volume of our lake model (~1.4×10^{14} m^3) is close to the volume cited by Leverington et al. (2002) (1.63×10^{14} m^3) and it is in the midrange of the lower bound of inferences cited within the Introduction.

The sea-level change, or fingerprint, driven by the outflow of the proglacial lakes was computed using a special, elastic case of the sea-level algorithm described above. (The rapid time scale of the discharge event ensures that the response is an instantaneous reflection of the discharge pattern.) The sea-level fingerprint is a linear function of the outflow amplitude. Thus, if the size of the meltwater release was doubled (while keeping the geometry fixed), the predicted sea-level change would also double. Accordingly, when we present the fingerprint map, we normalize the response by the equivalent eustatic sea-level change associated with the outflow model (a volume of 1.4×10^{14} m^3 coincides with a eustatic change of 0.4 m). In this way, the sea-level response to any arbitrary-size outflow from the Lake Agassiz-Ojibway system can be determined by simply scaling the normalized fingerprint by the eustatic sea-level change for this model outflow.

RESULTS AND DISCUSSION

Figure 2 shows a prediction of the sea-level fingerprint associated with the drainage of our Lake Agassiz-Ojibway model. The physics associated with this prediction is relatively straightforward. The Lake Agassiz-Ojibway

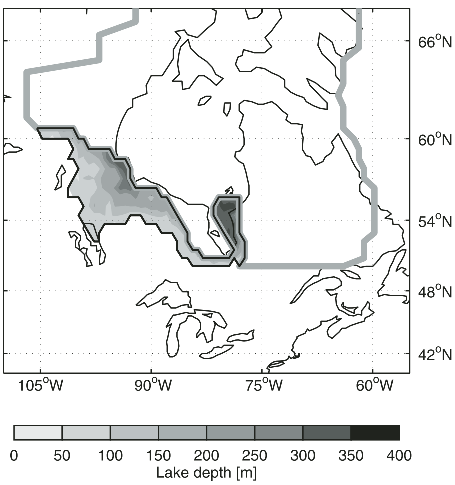

Figure 1. Map showing a model of the geographic extent of the combined proglacial Lake Agassiz-Ojibway immediately prior to its catastrophic drainage at ca. 8.4 ka. The lake boundaries were derived from Leverington et al. (2002) and the Laurentide component of the ICE-5G ice model (Peltier, 2004); the lake-floor topography was calculated using the adopted GIA model (see text). The boundary of the model Laurentide ice sheet at 8.5 ka is indicated by the solid gray line.

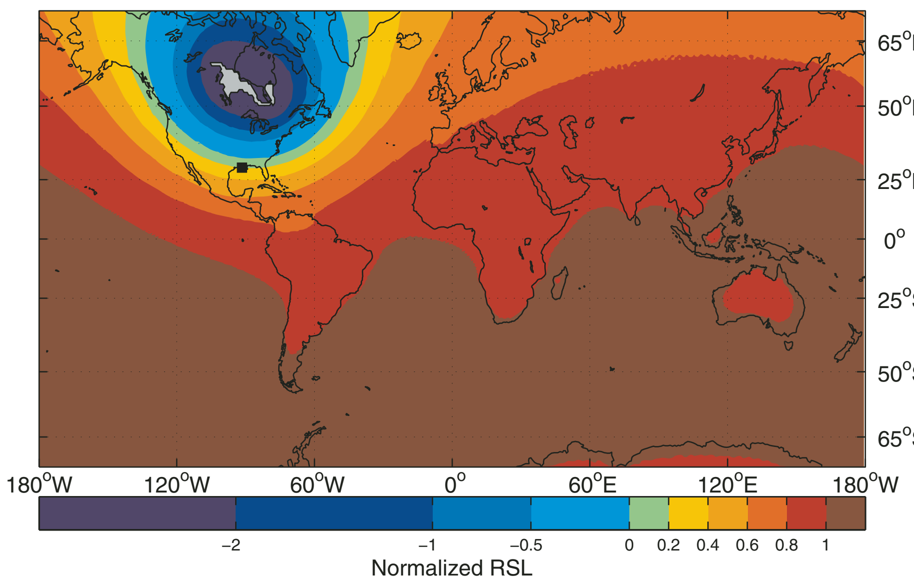

Figure 2. Numerically predicted sea-level fingerprint due to the catastrophic drainage of Lake Agassiz-Ojibway at 8.4 ka (Fig. 1), normalized by the eustatic rise (0.4 m). The blue contours show the zone of predicted sea-level fall; the remaining contours, from green to dark red, are regions of progressively higher sea-level rise. The black square denotes the site of sea-level measurements by Törnqvist et al. (2004a) within the Mississippi Delta.

system acted, through gravitational attraction, to tilt the ocean toward it. When the lakes drained, two things happened: (1) The average sea level rose (by an amount equal to the eustatic sea-level change); (2) the gravitational attraction and tilt disappeared and ocean water moved away from the lakes. In the near field of the lakes, within ~2000 km, the second contribution is greater than the first, and the net effect is a sea-level fall (blue contours). As one moves progressively farther from the location of the lakes, the predicted sea-level rise increases, eventually exceeding the eustatic value (i.e., the dark red region with values greater than unity).

At the field site in the Mississippi Delta used by Törnqvist et al. (2004a), the normalized sea-level fingerprint has a value of 0.2 (Fig. 2). Thus, the sea-level change at this site associated with the drainage of Lake Agassiz-Ojibway is one-fifth the eustatic value. Consequently, for our model lake volume of ~1.4×10^{14} m^3 (Fig. 1), which has a eustatic sea-level rise of 0.4 m, the sea-level rise that would occur at the Mississippi Delta site is 0.4/5 m = 0.08 m. Törnqvist et al. (2004a) inferred a total sea-level rise of 1.2 m across a time interval spanning the 8.2 ka event. We conclude that the meltwater contribution of Lake Agassiz-Ojibway to this sea-level signal is unlikely to have exceeded ~0.1 m at this site.

Disintegrating ice over Hudson Bay during the 8.2 ka event may also have contributed to the observed sea-level rise. We performed a numerical experiment in which we rapidly melted the Hudson Bay and Hudson Strait components of the ice model at the time of the 8.2 ka event and computed the associated (elastic) sea-level fingerprint. The normalized fingerprint we obtained was very similar to the sea-level change associated with the lake discharge (Fig. 2), with the exception that the contours were shifted slightly northward (reflecting the relative location of Hudson Bay and the proglacial lakes; Fig. 1). At the Mississippi Delta sites considered by Törnqvist et al. (2004a), the predicted ice unloading fingerprint was 0.4 times the eustatic value of the meltwater. As an illustrative example, if the melting over Hudson Bay that occurred during the 8.2 ka event had a eustatic equivalent sea-level rise of 0.5 m, then the local sea-level rise at the Mississippi Delta sites would have been ~0.2 m (or a total rise, including lake discharge, of ~0.3 m). The small size of this signal suggests that GIA effects (including meltwater signals from all global ice complexes) may have played an important role in the observed sea-level change of 1.2 m cited by Törnqvist et al. (2004a). We next turn to this GIA contribution.

Figure 3 shows our ICE-5G-based prediction of the rate of change of relative sea level from 9.0 to 8.5 ka associated with GIA (i.e., prior to the onset of the 8.2 ka event). The melting of global (model) ice reservoirs gives rise to a background (eustatic) sea-level rise of ~1 m per century (orange-to-red contour). Superimposed on this trend are the deformational and gravitational effects associated with GIA (Mitrovica and Milne, 2002). Regions previously covered by ice are experiencing a large postglacial rebound of the crust and the net effect is a sea-level fall (blue contours). Encircling these regions is a zone of accentuated sea-level rise associated with the subsidence of the peripheral bulge (dark reds to red). In the far field of the Late Pleistocene ice sheets, perturbations in sea level arise from ocean loading effects and the migration of water toward the peripheral bulges known as "ocean syphoning" (e.g., Mitrovica and Milne, 2002).

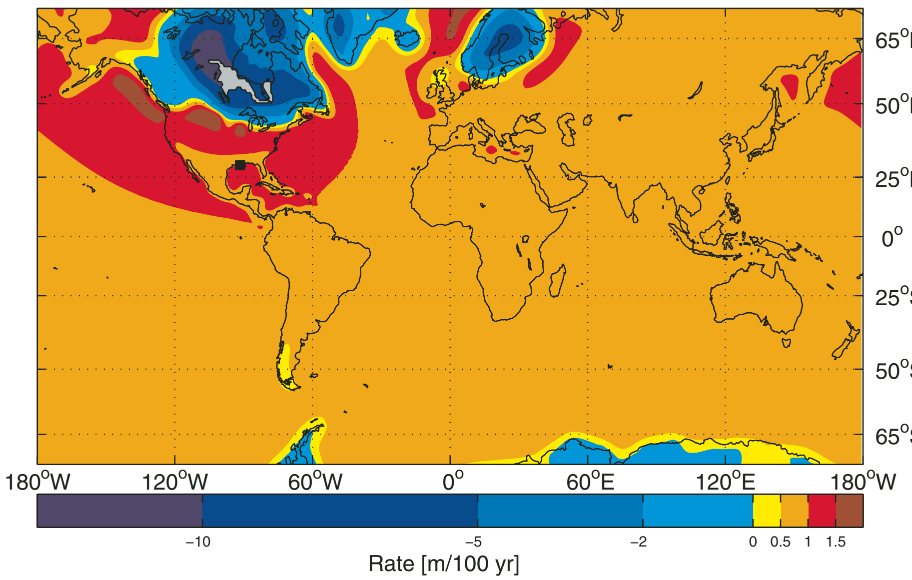

Figure 3. Numerically predicted rate of change of sea level due to GIA (including the eustatic meltwater component) computed over the interval from 9.0 ka to 8.5 ka. The predictions do not include the drainage of Lake Agassiz-Ojibway. The calculations adopt the ICE-5G model (Peltier, 2004) of the Late Pleistocene glaciation history and a modified VM2 radial profile of mantle viscosity (see text for details). The black square denotes the site of sea-level measurements by Törnqvist et al. (2004a) within the Mississippi Delta.

A suite of these GIA-related sea-level signals are active in the Mississippi Delta, including bulge subsidence, ocean loading, syphoning, and the background (eustatic) trend associated with the net melting of ice reservoirs (Fig. 3). Figure 3 indicates a total GIA signal at this location of ~1 m per century for the time interval from 9 to 8.5 ka. The GIA-induced sea-level signal from 8 to 7 ka is about a factor of two smaller, mostly reflecting a reduction in the meltwater signal (Peltier, 2004), and largely compatible with a reconstructed rate of ~0.35 m per century for the same time interval (Törnqvist et al., 2004b).

The 1.2 m sea-level change inferred by Törnqvist et al. (2004a) from cores collected within the delta occurred over a time window that, given dating uncertainties, may range from a few decades to possibly as much as ~400 yr. If the time window is greater than ~50–100 yr, then we would conclude, on the basis of the rates predicted for the delta in Figure 3, that the observed 1.2 m rise is dominated by a GIA signal. If the time window is as small as a couple of decades, then the GIA signal would be ~20 cm. In this case, we would conclude that the total volume of Lake Agassiz-Ojibway plus meltwater from the rapid collapse of Hudson Bay ice was significantly higher than generally assumed. We consider this possibility to be unlikely: The highest published estimates of Hudson Bay ice plus lake discharge across the 8.2 ka event are ~1.4 m of eustatic equivalent (von Grafenstein et al., 1998), and the fingerprint results in Figure 2 indicate that this upper-bound discharge would lead to no more than an ~0.2–0.5 m signal in the Mississippi Delta (depending on the relative contributions of ice melting and lake drainage).

FINAL REMARKS

The proximity of the Mississippi Delta to the proglacial Lake Agassiz-Ojibway leads to a relatively small sea-level fingerprint for the discharge associated with the 8.2 ka event (Fig. 2). We conclude that the outflow generated no more than ~0.1 m of sea-level rise within this region if one accepts most estimates of the volume of the lake. This suggests that the 1.2 m rise in sea level across the 8.2 ka event inferred by Törnqvist et al. (2004a) may, if it is robust, have been dominated by GIA effects. A final word on this issue will require better geochronological controls on the sea-level rise.

If, for example, a similar-amplitude rise in the delta is confined to a time window of less than a few decades, then this would suggest that the total volume of the lake plus meltwater from rapid Hudson Bay ice collapse was significantly larger than is currently accepted.

The amplitude of the sea-level rise in response to freshwater release in the Labrador Sea increases as one considers sites at greater distance from Lake Agassiz-Ojibway. Along the east coast of South America or along western Africa, the sea-level fingerprint is approximately the eustatic value; hence, for the model lake system in Figure 1, this would translate into a total sea-level rise of ~0.4 m. The predicted GIA rate along most of the same coasts is ~0.75 m per century (Fig. 3). Thus, sea-level records at such sites with a time resolution better than a century would have a discharge-induced sea-level signal that is comparable to, or greater than, the GIA contribution. One might also consider sites close to the ancient lakes (e.g., northern Manitoba or Ontario, U.S. East Coast). We note, for example, recently published sea-level data from Chesapeake Bay (Cronin et al., 2007) that suggest a sea-level deceleration or stillstand ca. 8.3 ka, which might be consistent with our model predictions.

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