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Relative sea-level data from southwest Scotland constrain meltwater-driven sea-level jumps prior to the 8.2 kyr BP event

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ABSTRACT

The most significant climate cooling of the Holocene is centred on 8.2 kyr BP (the '8.2 event'). Its cause is widely attributed to an abrupt slowdown of the Atlantic Meridional Overturning Circulation (AMOC) associated with the sudden drainage of Laurentide proglacial Lakes Agassiz and Ojibway, but model simulations have difficulty reproducing the event with a single-pulse scenario of freshwater input. Several lines of evidence point to multiple episodes of freshwater release from the decaying Laurentide Ice Sheet (LIS) between ~8900 and ~8200 cal yr BP, yet the precise number, timing and magnitude of these events — critical constraints for AMOC simulations — are far from resolved. Here we present a high-resolution relative sea level (RSL) record for the period 8800 to 7800 cal yr BP developed from estuarine and salt-marsh deposits in SW Scotland. We find that RSL rose abruptly in three steps by 0.35 m, 0.7 m and 0.4 m (mean) at 8760–8640, 8595–8465, 8323–8218 cal yr BP respectively. The timing of these RSL steps correlate closely with short-lived events expressed in North Atlantic proxy climate and oceanographic records, providing evidence of at least three distinct episodes of enhanced meltwater discharge from the decaying LIS prior to the 8.2 event. Our observations can be used to test the fidelity of both climate and ice-sheet models in simulating abrupt change during the early Holocene.

1. Introduction

A prominent climate anomaly is centred on 8200 yr BP in Greenland ice-core records (Figs. 1 and 2) and is registered as an abrupt cooling of ~3.3 ± 1.1 °C that lasted for 160 yrs (Kobashi et al., 2007; Thomas et al., 2007). The widely cited (e.g. Alley et al., 1997; de Vernal et al., 1997; Barber et al., 1999; Törnqvist and Hijma, 2012) causal mechanism of the event is a weakening or complete shutdown of the Atlantic Meridional Overturning Circulation (AMOC) in response to the sudden drainage of Laurentide proglacial Lakes Agassiz and Ojibway (LAO) dated to 8740–8160 cal yr BP (1σ age range) in the Hudson Bay (Barber et al., 1999). However, it is unclear whether the drainage occurred as a standalone freshwater pulse or as several separate events. Indeed, climate modelling studies based on a single freshwater pulse of 2.5 Sv for one year (Sverdrup, $1.0 = 10^6\ m^3\ s^{-1}$) fail to simulate the observed 8.2 climatic response (Morrill et al., 2014) using a median estimate of forcing inferred from flood hydrograph simulations of the final LAO drainage (Clarke et al., 2004).

A growing body of empirical and modelling evidence is beginning to support a multi-event model of LAO drainage (Leverington et al., 2002) and/or nonlinear Laurentide Ice Sheet (LIS) collapse within a critical time interval (hereby referred to as 8900 to 8200 cal yr BP). Pronounced two-step increases in planktonic $\delta^{18}O$ and polar foraminifera abundance (*Neogloboquadrina pachyderma* s.) occur in two sub-polar North Atlantic cores, MD99-2251 and MD03-2665, situated 1250 km apart, that are interpreted as two episodes of increased surface ocean freshening and cooling within this time interval (Fig. 2; Ellison et al., 2006; Kleiven et al., 2008). Hematite-rich glaciolacustrine sediments in the Hudson region (the "red-bed") widely thought to represent the stratigraphic signature of LAO drainage (e.g. Barber et al., 1999; Hillaire-Marcel et al., 2007), contain two peaks of terrestrially-sourced detrital carbonate (Hillaire-Marcel et al., 2007) and two stacked sequences of reverse to normal graded sediments which could record two separate

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drainage events (Lajeunesse and St-Onge, 2008).

Recent evidence from shelf-sea and estuarine sediments complicate the story as these contain evidence of a third event. A well-resolved near-field record of LIS retreat is provided by Jennings et al. (2015), who observed detrital carbonate peaks (DCPs) at 8694–8609 (DCP6a), 8609–8489 (DCP6b) and 8219–7998 cal yr BP (DCP7) (Fig. 2g) in Cartwright Saddle core MD99-2236, which they attribute to episodes of abrupt freshwater discharge. The second event, DCP6b, is manifest as the downstream equivalent of the Hudson Bay "red-bed", which Jennings et al. (2015) re-interpret as a final phase in the abrupt opening of the Tyrrell Sea following retreat of Laurentide ice – not a drainage of LAO. Recent ice-sheet modelling predicts that the dynamic separation, or "saddle-collapse" of the Keewatin and Labrador domes, which occurred during deglaciation over the Tyrrell Sea, produced a meltwater pulse with peak discharge rates of ~0.21 Sv between ~8800 and ~8600 yrs BP (Gregoire et al., 2012). This provides a possible mechanism for a meltwater pulse concomitant with the Tyrrell Sea 'opening' event. Jennings et al. (2015) interpret the later event, DCP7, as the signature of LAO drainage(s) due to its close coincidence with the 8.2 event. However the significance of DCP7 in forcing the 8.2 event is unclear as it post-dates the onset of the 8.2 event, dated in Greenland ice-cores at ~8247 cal yr BP (Thomas et al., 2007), by a minimum c. 30 yrs, albeit this could reflect chronological uncertainties within the Jennings et al. (2015) record (i.e., the 8.2 to 9.7 ka BP time interval is constrained in this record by two ^{14}C ages). Nevertheless, this three-event model of abrupt freshwater discharge is supported by estuarine records from the Gulf of Mexico where Simkins et al. (2012) observed prominent magnetic susceptibility anomalies at ~8800, ~8600 and ~8100 cal yr BP. It has been suggested that previous near-field sea-bed records that describe evidence of one or two events (Hillaire-Marcel et al., 2007; Hoffman et al., 2012) are limited by core resolution and may record additional events (Jennings et al., 2015).

Notwithstanding the limited chronological control across the critical time interval, the Cartwright Saddle record from core MD99-2236 arguably provides the best-resolved near-field history of final LIS retreat because of its relatively high resolution and stratigraphic continuity. The interpretation of a three-event freshwater discharge model includes the potential abrupt drainage(s) of LAO as well as a possible large ice-sheet contribution associated with the saddle collapse of the Keewatin and Labrador domes (Gregoire et al., 2012). If correct, the causal mechanisms of the 8.2 event are more complex than that suggested by the consensus view of a single- or double-event drainage of LAO. The Jennings et al. (2015) record describes a sequence of freshwater events prior to the 8.2 event but little is known regarding the magnitudes of such events, critical constraints for modelling studies of the AMOC. Understanding the pathways of freshwater routing is also critical as some authors predict transport into the sub-tropical North Atlantic (Condron and Windsor, 2011; Hill and Condron, 2014) rather than the sub-polar gyre (Jennings et al., 2015; Kleiven et al., 2008; Ellison et al., 2006).

Relative sea-level (RSL) records provide a means to test the hypothesis that the DCP events in Cartwright Saddle core MD99-2236 were significant freshwater discharge events from the LIS. Regional land-based water/ice mass variability will alter the geoid thus producing an associated sea-level pattern, also termed "fingerprint", that is non-uniform across the globe (e.g. Mitrovica et al., 2001). In the case of a point source of land water/ice mass loss, RSL will be negative near to the former source location and positive in the intermediate to far-field regions. This is illustrated in Fig. 1, which shows the predicted percentage of the global sea-level equivalent mass loss from the drainage of Lake Agassiz-Ojibway at 8.4 ka (Kendall et al., 2008) using a geophysical model (Mitrovica and Milne, 2003).

Three well-dated RSL records based on radiocarbon-dated basal peats (therefore minimally affected by sediment compaction) exist for the centuries prior 8.2 ka, and both contain an abrupt departure from background rates of RSL rise, or a RSL 'jump'. In the western Netherlands (Rhine-Meuse Delta), Hijma and Cohen (2010) define a eustatic equivalent sea-level jump of 3.0 ± 1.5 m at

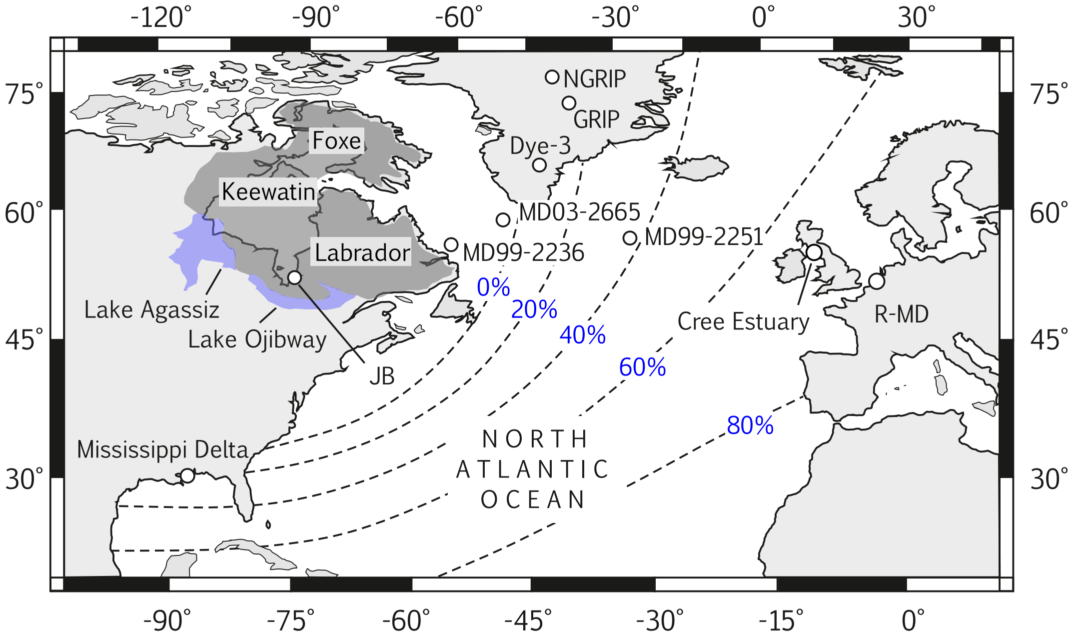

Fig. 1. Map of circum-North Atlantic with key locations mentioned in text. Blue and dark grey shading indicates the approximate extent of Laurentide Ice Sheet and proglacial lakes Agassiz and Ojibway at ~8900 cal yr BP (after Dyke, 2004). Dashed lines denote the spatial variability of RSL rise associated with a LAO source of meltwater release from GIA modelling (after Kendall et al., 2008). JB = James Bay. R-MD = Rhine-Meuse Delta. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)