Timing and magnitude of the sea-level jump preluding the 8200 yr event

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ABSTRACT

Evidence from terrestrial, glacial, and global climate model reconstructions suggests that a sea-level jump caused by meltwater release was associated with the triggering of the 8.2 ka cooling event. However, there has been no direct measurement of this jump using precise sea-level data. In addition, the chronology of the meltwater pulse is based on marine data with limited dating accuracy. The most plausible mechanism for triggering the cooling event is the sudden, possibly multistaged drainage of the Laurentide proglacial Lakes Agassiz and Ojibway through the Hudson Strait into the North Atlantic ca. 8470 ± 300 yr ago. Here we show with detailed sea-level data from Rotterdam, Netherlands, that the sea-level rise commenced 8450 ± 44 yr ago. Our timing considerably narrows the existing age of this drainage event and provides support for the hypothesis of a double-staged lake drainage. The jump in sea level reached a local magnitude of 2.11 ± 0.89 m within 200 yr, in addition to the ongoing background relative sea-level rise (1.95 ± 0.74 m). This magnitude, observed at considerable distance from the release site, points to a global-averaged eustatic sea-level jump that is double the size of previous estimates (3.0 ± 1.2 m versus 0.4–1.4 m). The discrepancy suggests either a coeval Antarctic contribution or, more likely, a previous underestimate of the total American lake drainage.

INTRODUCTION

The period of abrupt cooling that started 8247 yr ago (Thomas et al., 2007) and was centered ca. 8.2 ka (all ages in calendar years) is the most pronounced Holocene climate excursion (Alley and Ágústsdóttir, 2005). There is general consensus that drainage of Laurentide proglacial Lakes Agassiz and Ojibway was the driving mechanism for the 8.2 ka cooling. The event is often seen as an analogue for possible future freshening of the North Atlantic, and serves as a test case for assessing the sensitivity of ocean circulation to freshwater perturbations in climate models. Accurate constraints on the timing and magnitude of the drainage event are essential for such applications.

The timing for the lake drainage was first established at 8470 ± 300 yr by dating bivalves above and below the preserved drainage deposit (Barber et al., 1999; 1σ). In the Labrador Sea, the deposits associated with the lake drainage record two drainage events that postdate 8560 ± 70 yr (Hillaire-Marcel et al., 2007; 1σ). Foraminifers within the deposit are mostly older than this date, indicating settling of reworked material; the youngest date from the unit being 8420 ± 80 yr (Hillaire-Marcel et al., 2007; 1σ). Evidence for two stages of lake drainage is provided by other proximal marine and proglacial lake sites (Teller et al., 2002; Ellison et al., 2006), with the largest drop in lake volume being associated with the first event (Teller et al., 2002). A single age obtained from foraminifers in the North Atlantic dates the second freshwater event to 8343–8184 yr (Ellison et al., 2006; 2σ), while an age of ca. 8490 yr was indirectly derived for the first event (Ellison et al., 2006; no uncertainty given). All these calibrated ages are from radiocarbon dates and include marine reservoir age corrections of uncertain accuracy. For this reason it is probable that the actual age uncertainty associated with these age estimates of the event exceeds the quoted interval limits.

There is considerable debate regarding the total volume of ice-lake freshwater that was released into the North Atlantic and to what extent decay of the Laurentide ice sheet contributed, in addition to lake drainage. Reconstructions of Lakes Agassiz and Ojibway (Leverington et al., 2002) suggest a volume of 163,000 km^3 or 0.46 m equivalent eustatic sea-level rise (SLR) for the most favored ice configurations (Earth radius 6370 km; 70% covered by oceans). However, coeval rapid disintegration of the Laurentide ice sheet could have increased the total rise to a maximum of 1.4 m global SLR (Von Grafenstein et al., 1998). By shifting the ice margins 1° north or south, the lake volumes would be ~200% and 45% of the favored volume (Leverington et al., 2002). Pinpointing the sea-level jump using geological data from coastal settings has the potential to provide independent constraints on the total volume of freshwater released. A first attempt was made using data from the Mississippi Delta, where two vertically separated peat layers, predating and postdating the 8.2 ka event, were radiocarbon dated (Törnqvist et al., 2004; Fig. 1). The 1.19 ± 0.2 m elevation difference constrains total relative SLR at the site, i.e., contributions by local subsidence and eustasy as well as the sea-level jump. Since then, geophysical modeling (Kendall et al., 2008) indicated that the Mississippi Delta likely recorded only 20% of the eustatic value associated with the meltwater pulse due to its proximity to the source area. The documented 1.19 m rise is now considered to mainly reflect background SLR (BSLR) due to local glacio-hydro-isostatic adjustment (GIA) (Kendall et al., 2008) and modest eustatic SLR caused by the steady melting of the remaining ice masses at the time. It is also clear that the duration of the Mississippi RSL jump extends well into and beyond the 8.2 ka cooling period (Fig. 1), thus including post–8.2 ka event SLR.

In summary, thus far the 8200 yr sea-level jump has not been directly measured and the existing 0.4–1.4 m range is based on projection, source reconstruction, and modeling. To properly constrain the magnitude of this event, a distant site is required with series of highly resolved sea-level index points collected from a small area, ideally spanning a sufficiently long period of time to determine pre- and post-event rates of RSL change. The Rhine-Meuse delta in the Netherlands provides such a site, recording the abrupt rise within sediments that are preserved at depths of 13–25 m below present sea level (Hijma et al., 2009). This paper details this evidence and provides the first calculation of magnitude and timing of the sea-level jump based on well-dated, precise paleo–sea-level data.

MATERIAL AND METHODS

We collected and dated (mainly basal) peat samples from within the Rhine-Meuse delta (Figs. 1 and 2). Autochthonous terrestrial plant macrofossils were picked from sampled peats for radiocarbon dating (details

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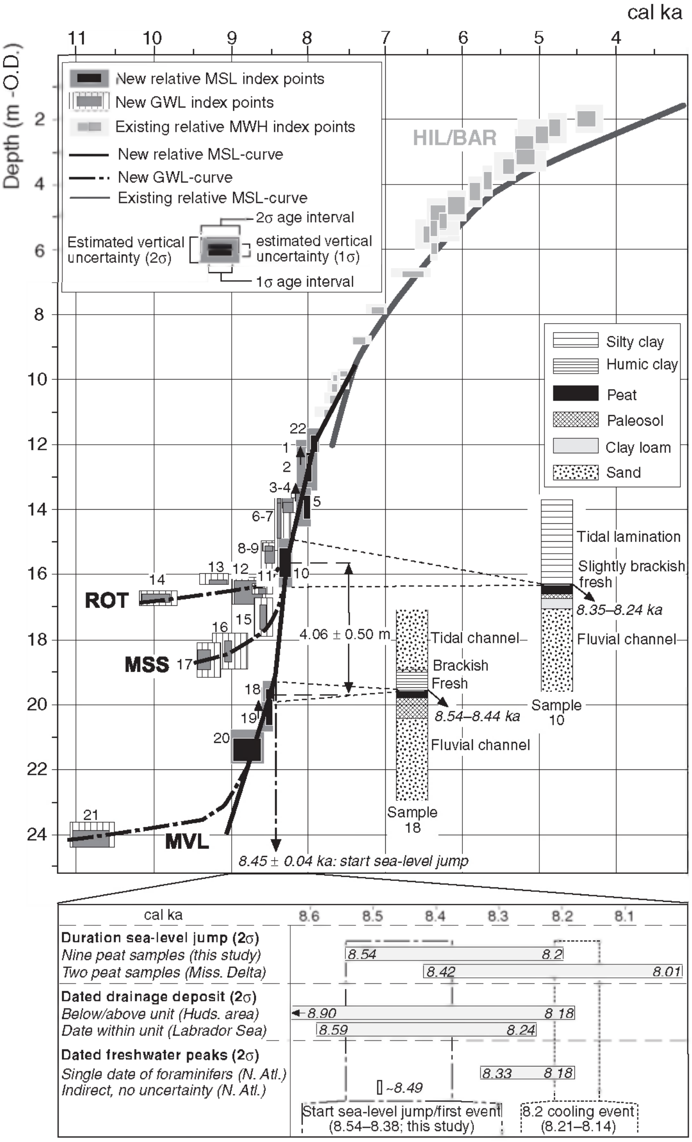

Figure 1. Relative sea-level rise in western Netherlands based on geological data (9–7.5 ka, this study; 7.5–4 ka, Van de Plassche, 1982; Berendsen et al., 2007). Upper panel plots age-depth index points and shows that sea-level jump commenced ca. 8.45 ka (calendar years ago, cal). Sedimentological (lithology, structure) and paleoenvironmental (pollen, diatoms) indicators are plotted as core logs for two sites with transgressed basal peat that most closely bracket jump magnitude. Groundwater-level (GWL) rise (depicted for sites ROT, MSS, and MVL) is plotted as sigmoidal curves that show initial fluvial-controlled groundwater levels graded to paleovalley floodplain level (dipping from 17 to 24 m between ROT and MVL), then gradual establishment of sea-level control in coastal zone and eventual full pick-up of mean sea-level (MSL) rise (20–18, 10, 5, 1–2, 22). Arrows above index points indicate that their depths are possibly overestimated, because of uncertain amounts of compaction. Lower panel compares timing of Rotterdam jump with other published sites. End of jump coincides with start of 8.2 ka event; onset appears to have been two centuries before. Dates from Hudson (Huds.) area (Barber et al., 1999; postdate southeast Hudson Bay and predate East Hudson Strait) were recalibrated using Marine04-curve (Hughen et al., 2004) using reservoir effects defined in original publications. The 2σ interval of Labrador Sea date (Hillaire-Marcel et al., 2007) was obtained by calibrating original radiocarbon date (7950 ± 80 ^{14}C yr B.P.). Miss.—Mississippi; N. Atl.—North Atlantic; O.D.—Dutch Ordnance Datum; MHW—mean high water.

in the GSA Data Repository[1] Table DR1). All radiocarbon ages were calibrated using OxCal 4.0.5 software (Bronk Ramsey, 2001). Following established methodologies developed in the study area (Jelgersma, 1961; Van de Plassche, 1982), and successfully applied globally since (Törnqvist et al., 2004), these coastal peats provide high-quality sea-level index points. The method relies on the notion that under conditions of forced transgression, coastal peat forms extensively around local mean high water level (MHW) in a landward-shifting zone. Where peats are collected in densely sampled series (Fig. 1), paleo–water-level history is pinpointed with a precision of <0.5 m and <100 yr. It is necessary to estimate the former tidal range in order to specify local mean sea levels (MSL) at the time of the event. Before 8 ka, the Rhine-Meuse delta was situated on the margins of a shallow basin (the southern North Sea) (Lambeck, 1995) with microtidal conditions. MSL was probably <0.5 m below MHW at the Rhine River mouth (Van der Molen and De Swart, 2001) (Table DR2). Height uncertainties defined at 1σ and 2σ ranges around local MSL (Fig. 1; Table DR2) include assessments of the water depth in which the peat formed, minor postdepositional compaction, tidal amplitude uncertainty, and errors arising from measuring surface elevation and sample depth.

RESULTS

At sites MVL, MSS, and ROT (see Fig. 2), five dates obtained from peat just below a regionally traceable contact (Fig. 2; Data Repository) yielded 1σ calibrated (cal) ages of 8512 ± 45, 8587 ± 50, 8490 ± 53, 8498 ± 43, and 8505 ± 45 cal yr B.P. (samples 9, 15, 18, 19, and a, yielding a combined age of 8522 ± 37 yr; Figs. DR1–DR3, and Appendix DR1). The stratigraphic contact records a sudden water-level rise that was caused by a sea-level jump ca. 8.5 ka (the maximum date for the start of the event).

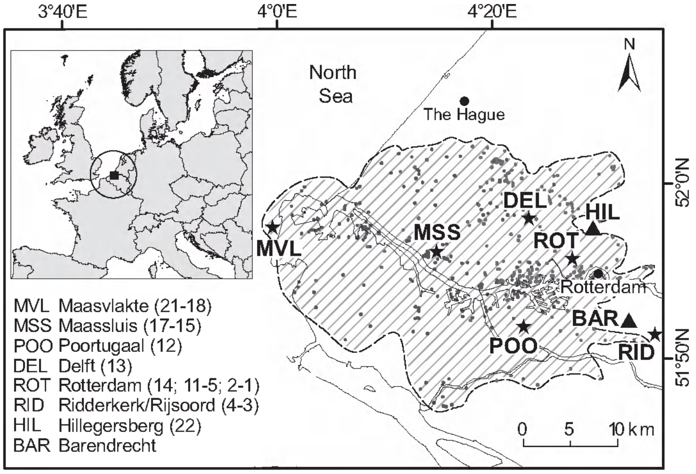

Figure 2. Location map of study area and research sites. Stars indicate sites used for constructing pre–7.5 ka sea-level curve; triangles mark sites with post–7.5 ka data. Numbers between brackets refer to numbers listed in Figure 1. Hachured area (778 km^2) indicates where drainage event (drowned organic layer at relevant depth) is recognized in borehole descriptions (dots).

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[1] GSA Data Repository item 2010070, Table DR1 (details of the samples used to construct Fig. 1, together with three photos of sedimentary successions associated to the sea-level jump);Table DR2 (vertical error calculations); Table DR3 (calculation of the rate of background sea-level rise); Table DR4 (magnitude of the sea-level jump error calculations); and Appendix DR1 1 (OxCal CQL-routines and plots regarding the timing of the start of the sea-level jump), is available online at www.geosociety.org/pubs/ft2010.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

Abrupt drowning transformed the former swamps (peats) into fluvial-tidal open-water environments (gyttja mud) throughout the river-mouth area (Hijma et al., 2009) (Fig. 2). Radiocarbon-dated terrestrial plant macrofossils from the base of the gyttja mud give a minimum age for the start of the event. At site ROT, three dates from this layer (samples 6 and 7, both 8373 ± 34 cal yr B.P., and sample b, 8421 ± 57 cal yr B.P.; Table DR1) have a combined average age of 8385 ± 16 yr B.P. (1σ; Appendix DR1). These minimum and maximum ages narrowly bracket the start of the event to 8544–8375 yr B.P. (2σ) with a mean of 8450 ± 44 yr B.P. (1σ) (Figs. 1 and 3; details in Appendix DR1).

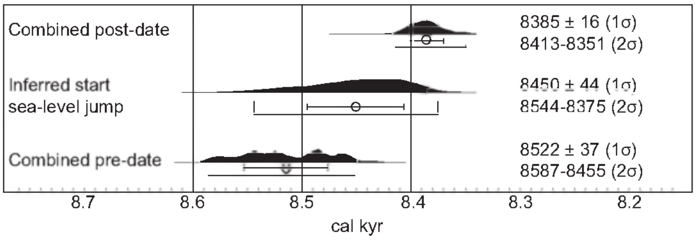

Figure 3. OxCal plot (Bronk Ramsey, 2001) of calculated timing of sea-level jump. Calculation is based on weighted average of five dated samples directly below (9, 15, 18–19, and a) and three dated samples directly above (6, 7, and b) drowning event layer.

Samples 18–19 and 10 (Table 1, Fig. 1) predate and postdate the presumed sea-level jump in the study area. These samples were taken from basal freshwater peats that are nonerosively overlain by clastic subaqueous deposits. Sample 19 was taken from a peat layer at the same site as sample 18 (~5 km apart), from a similar sedimentary succession and a similar sample depth, yielding similar ages (Table 1; Fig. DR3). Diatom analyses revealed a brackish assemblage for the clays overlying sample 19, clearly indicating that at site MVL, the swamp environment was converted to estuarine conditions during the abrupt rise. As sample 19 has an uncertain compaction error (see the Data Repository), this sample has not been used for calculating the magnitude of the event. At site ROT, diatom analyses around samples a and b (~1 km apart from sample 10) indicate a slightly brackish environment both before and after the event, while laminations within the overlying clays indicate increased tidal influence (Fig. DR1). These transgressive paleoenvironmental and sedimentological data make the top-of-peat samples 18 and 10 excellent sea-level indicators. The difference in elevation and age between samples 18–19 and 10 is 4.06 ± 0.50 m and 195 ± 68 yr, respectively (1σ). This height range includes the presumed sea-level jump, as well as background relative sea-level rise in the 195 ± 68 yr that separate the two samples.

BSLR at Rotterdam was relatively large due to its location in an area of long-term tectonic subsidence, combined with additional postglacial GIA-related subsidence (Kiden et al., 2002; Vink et al., 2007). Based on our sea-level index points for the centuries before and after the event, the rate of BSLR was 10 ± 1.5 mm/yr (1σ; Table DR3). This rate is supported by geophysical modeling (Vink et al., 2007) that predicts a BSLR of 9–10 mm/yr relative sea-level rise at the study site between 9 and 8 ka. The observed rise of 4.06 ± 0.50 can therefore be split into 1.95 ± 0.74 m of BSLR and a sea-level jump of 2.11 ± 0.89 m (1σ; Table DR4). Geophysical modeling of gravimetric effects indicates that the western Netherlands likely recorded ~70% of the global mean for a meltwater pulse released from a Laurentide source (Kendall et al., 2008). If this is correct, the global eustatic jump would be ~3 m ± 1.25 m (1σ) with an equivalent water volume of 10.7 ± 4.5 × 10^{14} m^3. The probability that the full 4.06 ± 0.50 m rise is all due to BSLR is ~10% (t-test; Table DR4).

DISCUSSION AND CONCLUSIONS

A sea-level jump of magnitude discussed above must have influenced marine deltas across the world, especially at far-field sites. Numerous delta studies from Southeast Asia (Hori and Saito, 2007; Liu et al., 2007; Tamura et al., 2009) attribute drowning and backstepping events observed in deltaic sedimentary archives to an abrupt sea-level rise. The jump is therefore of global significance, not just for the link to the 8200 ka climatic event, but also for its circumoceanic sedimentary imprint. Despite its importance, no area other than the Rhine-Meuse delta provides a self-consistent series of sea-level index points of sufficient precision to quantify the jump as well as the BSLR. Our chronology suggests that the start of the jump occurred ~100 yr before it was recorded in the Mississippi Delta (Fig. 1). Precise sea-level data from far-field sites is needed to further constrain the magnitude of this event.

Previous studies considered the global sea-level equivalent of the event to have been between 0.4 and 1.4 m (Von Grafenstein et al., 1998; Barber et al., 1999; Renssen et al., 2001; Leverington et al., 2002; Bauer et al., 2004; Clarke et al., 2004; Törnqvist et al., 2004; Wiersma et al., 2006; Kendall et al., 2008), considerably smaller compared with the magnitude recorded near Rotterdam. This discrepancy necessitates consideration of other potential contributions to this event, two of which are discussed here. (1) The Antarctic ice sheet is a possible cocontributor to accelerated SLR in the centuries preceding the 8.2 ka climate event. As the Atlantic Meridional Overturning Circulation slowed down in the North Atlantic due to the meltwater release, this changed the meridional density gradient, which may have led to increased Antarctic Intermediate Water Formation (Stocker, 1998) and warming of circum-Antarctic seas (the so-called bi-polar seesaw). This would have affected the coastal margins of the Antarctic ice sheet and, to a more limited extent, the Antarctic interior. However, there is no strong evidence for massive changes in Southern

TABLE 1. SAMPLES USED FOR CALCULATING SEA-LEVEL JUMP MAGNITUDE

ID*	Laboratory number	Lat., Lon.† (°N, °E)	Depth (m O.D.)§	Vertical error margin# (m O.D.)	^{14}C yr B.P.	Cal yr ago**	Cal age range (2σ) (cal yr ago; %)	Dated material	Reference
10	UtC-14940	51°55′25″ 4°27′59″	16.3	15.18–16.10	7486 ± 41	8298 ± 55	8383–8199; 95.4	Mainly *Alisma plantago-aquatica* and *Scirpus lacustris* (top fen peat)	Hijma et al. (2009)
18	UtC-15344	51°57′22″ 3°59′44″	19.6	19.51–20.04	7700 ± 60	8490 ± 53	8591–8401; 95.4	*Alnus* fruit (top fen-wood peat)	This paper
19	GrN-21460	52°0′2.2″ 3°59′21.5″	20.65	19.82–20.63	7720 ± 40	8498 ± 43	8584–8422; 95.4	Top fen-wood peat	This paper

Note: cal—calendar.
*Identification number corresponds to Figure 1.
†Latitude, longitude in degrees, minutes, seconds (WGS 1984).
§O.D. = Dutch Ordnance Datum; approximate mean sea level.
#Details of error margin calculation in Table DR2 (see footnote 1).
**Mean of calibrated age (±1σ)

Ocean circulation ca. 8.5–8.2 ka. Any significant increased SLR contribution from Antarctica would have been fully recorded in areas where the impact of the North American drainage event on relative SLR was limited, such as in the Mississippi Delta, but no indications exist for this. (2) Underestimated Laurentide and Greenland contributions are a second possible source. The evidence for multistaged lake drainage (Clarke et al., 2004; Ellison et al., 2006; Hillaire-Marcel et al., 2007) and the proposed timing for first and last events (Ellison et al., 2006; Hillaire-Marcel et al., 2007; Fig. 1) imply that at least two events produced the total jump of 2.11 ± 0.89 m at Rotterdam. The duration of the Rotterdam event matches a two-staged lake drainage scenario better than a single-event model. The onset of accelerated transgression at Rotterdam likely coincides with the first event of lake drainage and partial Laurentide ice disintegration (Ellison et al., 2006; Fig. 1). Some 150–200 yr of partial lake recharge later, a second drainage event caused the final collapse of the Hudson Bay ice dam, with a more substantial reduction of ice volume (Ellison et al., 2006). The latter event preceded the peak of the 8.2 ka cold spell by just a few decades (Ellison et al., 2006; Fig. 1).

Considering all the available data, a two-staged lake drainage event together with rapid disintegration of affected parts of the Laurentide ice sheet is the most probable explanation for the sea-level jump associated with the 8.2 ka event. Other high-quality sea-level data sets from around the world are needed to further constrain the magnitude of the jump and its globally distributed eustatic fingerprint. If there was a significant Antarctic contribution, the fingerprint will differ strongly from one caused by the Laurentide lake drainage event alone (Kendall et al., 2008). Further resolving the details of the 8.2 ka event is vital if this event is to be used to test the performance of climate models and to assess their capacity to simulate future climate response to the anticipated freshening of the North Atlantic Ocean.

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