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Links between early Holocene ice-sheet decay, sea-level rise and abrupt climate change

Torbjörn E. Törnqvist[1,2*] and Marc P. Hijma[1]

The beginning of the current interglacial period, the Holocene epoch, was a critical part of the transition from glacial to interglacial climate conditions. This period, between about 12,000 and 7,000 years ago, was marked by the continued retreat of the ice sheets that had expanded through polar and temperate regions during the preceding glacial. This meltdown led to a dramatic rise in sea level, punctuated by short-lived jumps associated with catastrophic ice-sheet collapses. Tracking down which ice sheet produced specific sea-level jumps has been challenging, but two events between 8,500 and 8,200 years ago have been linked to the final drainage of glacial Lake Agassiz in north-central North America. The release of the water from this ice-dammed lake into the ocean is recorded by sea-level jumps in the Mississippi and Rhine-Meuse deltas of approximately 0.4 and 2.1 metres, respectively. These sea-level jumps can be related to an abrupt cooling in the Northern Hemisphere known as the 8.2 kyr event, and it has been suggested that the freshwater release from Lake Agassiz into the North Atlantic was sufficient to perturb the North Atlantic meridional overturning circulation. As sea-level rise on the order of decimetres to metres can now be detected with confidence and linked to climate records, it is becoming apparent that abrupt climate change during the early Holocene associated with perturbations in North Atlantic circulation required sustained freshwater release into the ocean.

The early Holocene is the most recent portion of Earth history with rapid ice-sheet retreat and sea-level rise under interglacial climate conditions, and, as such, relevant in the context of future ice-sheet–sea-level interactions. Despite its temporal proximity, this time period remains poorly studied. This is surprising, especially as rates of eustatic sea-level rise during this time (on the order of 1 cm yr^{-1} or more)[1,2] fall well within the range of recent predictions for the latter part of the twenty-first century[3]. With the caveat that the relatively warm early Holocene conditions in the high-latitude Northern Hemisphere — a critical region for global climate change — were primarily driven by orbital rather than greenhouse-gas forcing, a recent position paper[4] concluded that "the early to mid Holocene may be key to understanding future sea-level change."

The onset of the Holocene has been linked to rapid global sea-level rise due to meltwater pulse-1B, a phenomenon now believed to constitute a millennial-scale period of high (up to ~2.5 cm yr^{-1}) rates of sea-level rise[2,5], rather than a relatively short-lived pulse as originally postulated[6]. We define the early Holocene to end at 7 kyr BP (all ages herein are presented in calendar years before AD 1950), given the marked deceleration in rates of eustatic sea-level rise after this time[1]. This also corresponds to the end of significant Laurentide Ice Sheet (LIS) melting, dated at 6.8 ± 0.3 kyr BP[7].

It has been stated[8] that "detailed empirically based RSL (relative sea level) graphs for the full period of the early Holocene sea-level rise are disappointingly few". The reason for this is twofold. First, the limited vertical resolution (>5 m) of coral-based reconstructions that are frequently used for the last deglaciation render them less effective for resolving the last few tens of metres of sea-level rise (after 9–10 kyr BP). Second, Holocene RSL change has been extensively studied using coastal-peat records that provide much better vertical resolution. However, data density from these records decreases dramatically before 6–8 kyr BP[9,10] due to limited peat formation and preservation, as well as the fact that many of these records occur offshore.

Studies of ice-sheet–sea-level interactions cannot be successful unless the response of the solid Earth to mass redistributions, known as glacial isostatic adjustment (GIA), is fully accounted for. In view of the critical role of GIA corrections for the interpretation of present-day sea-level change from instrumental records (that is, tide gauges, satellite altimetry and GRACE)[11], successfully removing the GIA component from these records is paramount. This ultimately must occur by means of GIA modelling. Studies[9,10] have shown that the early Holocene commonly exhibits offsets between GIA model predictions and RSL reconstructions, thus presenting an obstacle to progress. We attribute this to the rapid transfer of meltwater from the remaining ice sheets to the global ocean during this time, driving rapid and spatially complex GIA responses during the culmination of the last deglaciation.

The present contribution highlights the prospect for significant advances towards unravelling the ocean–cryosphere–atmosphere system during the early Holocene. Among others, we stress the need to better understand abrupt climate change under interglacial conditions, and the key role herein for new high-resolution RSL records along with concerted efforts to synthesize existing sea-level data. A comprehensive review of early Holocene RSL records has been provided elsewhere[8] and is not repeated here. We focus primarily on abrupt sea-level rise events (sea-level jumps) that, in some cases, can be linked to abrupt climate change between ~9.5–6.5 kyr BP, a time window for which a few sufficiently detailed RSL records have recently become available. We also stress the importance of GIA modelling to spur continued progress towards understanding early Holocene RSL change.

Ice sheets and ice-dammed lakes

Coral-based reconstructions[6] suggest that about half (~50–60 m) of the global sea-level rise since the Last Glacial Maximum occurred during the early Holocene. At the onset of the Holocene (Fig. 1a), the LIS was several times the size of the Greenland Ice Sheet (GIS), whereas it was essentially gone by the end of the early

[1]Department of Earth and Environmental Sciences, Tulane University, 6823 St. Charles Avenue, New Orleans, Lousiana 70118-5698, USA, [2]Tulane/Xavier Center for Bioenvironmental Research, Tulane University, 6823 St. Charles Avenue, New Orleans, Louisiana 70118-5698, USA. *e-mail: tor@tulane.edu

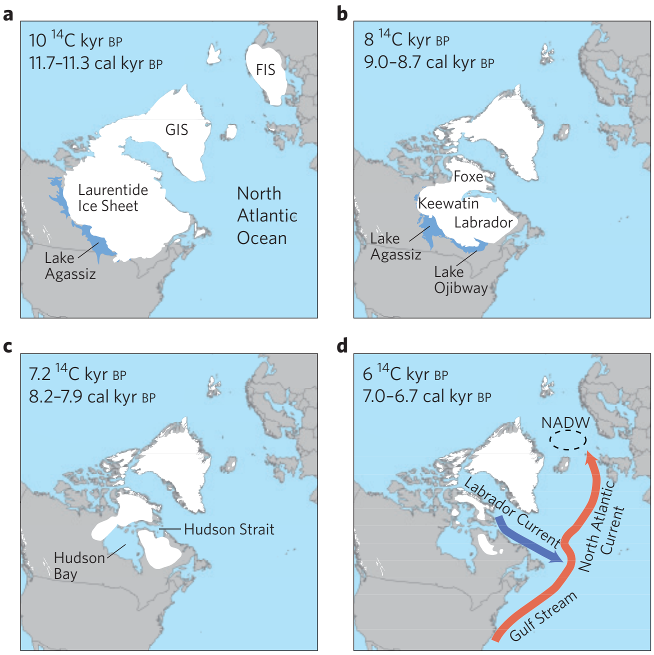


Figure 1 | Deglaciation of the Northern Hemisphere during the first half of the Holocene (largely based on ref. 12). **a**, Onset of the Holocene. FIS, Fennoscandian Ice Sheet; GIS, Greenland Ice Sheet. **b**, Final stage of proglacial Lake Agassiz, including the major domes of the Laurentide Ice Sheet (Foxe, Keewatin and Labrador). **c**, Initial stage following final Lake Agassiz drainage through Hudson Bay and Hudson Strait. **d**, Final stage of the Laurentide Ice Sheet, as well as a simplified configuration of surface ocean currents and principal region of North Atlantic deep-water formation (NADW). Note that it is not implied that these features were not operational during earlier stages of the Holocene.

Holocene[7,12] (Fig. 1d). The Fennoscandian Ice Sheet disappeared before 9 kyr BP, so during the remainder of the early Holocene eustatic sea-level rise was largely controlled by ice loss from the LIS and the Antarctic Ice Sheet (AIS). However, their relative contribution is still the subject of vigorous debate.

Compared with the AIS, the LIS retreat (Fig. 1) is reasonably well-constrained spatially[12], but the lack of ice-thickness data is problematic. This has resulted in markedly different estimates of the LIS sea-level contribution. Recent estimates[7] have suggested that the LIS added ~30 m of meltwater between 11–7 kyr BP. However, the associated ice-sheet reconstruction[13] differs substantially from the widely used ICE-5G model[14] (the new ICE-6G model is not yet publicly available) that assumes a much thinner ice sheet for this time interval (notably, east of the Hudson Bay), and hence an LIS contribution of only ~20 m. For the AIS, ice loss during the early Holocene was substantial[15,16]. Model studies that are partly constrained by ice-thickness evidence from nunataks suggest a ~6 m (ref. 15) to ~14 m (ref. 14) contribution; that is, about half the contribution by the LIS.

Even proglacial Lake Agassiz-Ojibway (henceforth called Lake Agassiz; Fig. 1a,b), the largest and perhaps most intensively studied meltwater reservoir of the last deglaciation, cannot be readily converted into accurate freshwater volumes. Although the southern Lake Agassiz shorelines have been well mapped, constraining ice margins on its northern side is considerably more difficult. As the portions of proglacial lakes that border ice margins tend to be the deepest, this is not a trivial issue. The most detailed available reconstructions[17] typically allow for 1° shifts from the favoured ice-margin position, which have been translated into values that deviate from favoured lake volumes by about 45–200%.

Sea-level jumps and abrupt climate change

Although meltwater pulses are prominent features throughout the last deglaciation, attention has focused overwhelmingly on the 10^0–10^1-metre-scale phenomena associated with major ice-sheet collapses up to the Pleistocene–Holocene transition. However, their early Holocene 10^{-1}–10^0-metre-scale cousins are of particular interest because they can often be tied to relatively well-constrained freshwater sources; specifically, Lake Agassiz.

It is widely believed[18] that North Atlantic deep-water formation (Fig. 1d) due to the high density of relatively salty and cold surface waters plays a pivotal role in global ocean circulation. The resulting Atlantic meridional overturning circulation (AMOC) enables enhanced heat transport to high latitudes. There is compelling evidence that large freshwater fluxes into the North Atlantic Ocean can strongly reduce the AMOC and thus act as potential triggers of abrupt cooling events[18]. Model studies at varying levels of complexity[19,20] have shown that freshwater volumes are a critical variable in this context, and this is where sophisticated sea-level studies can play a prominent role. High-resolution RSL reconstructions — defined here as those that attain decimetre-scale vertical resolution and sub-centennial-scale time resolution — are increasingly capable of quantifying the magnitude of freshwater volumes. Furthermore, unlike the earlier stages of the last deglaciation, the early Holocene enables the study of abrupt climate changes under interglacial conditions which may render them more suitable as analogues for the future than their glacial counterparts.

The 8.2 kyr BP cooling event (Fig. 2a) is currently the only major abrupt climate change where the full chain of events — from a well-mapped meltwater source to an exceptionally well-dated climate response — can be tied together. It is characterized by Northern Hemisphere cooling with a mean annual temperature drop of 3.3 ± 1.1 °C in Greenland[21]. A triggering mechanism associated with the final Lake Agassiz drainage (Fig. 1b,c) became conceivable by virtue of revised geochronological data due to an anomalous marine ^{14}C reservoir effect in the Hudson Bay area[22] and a coeval sea-level jump (defined here as an abrupt, annual to decadal-scale sea-level rise) in the Mississippi Delta[23]. However, these inferences were tentative in view of limited temporal resolution. Indeed, the apparent time gap between the Lake Agassiz drainage (centred on 8.47 kyr BP)[22] and the abrupt cooling observed in Greenland ice cores[24] was used to argue for a two-stage process[25], where the final drawdown during the second phase of drainage provided the critical mass to trigger the widespread 8.2 kyr BP climate response. An increasing body of evidence lends support to this idea (Fig. 2b,c). This includes North Atlantic deep-sea records[26] that have identified two spikes of surface ocean freshening and cooling, as well as terrestrial speleothem records exhibiting changes in monsoonal activity in Asia and South America[27], although it must be stressed that the 'precursor' to the 8.2 kyr BP event proper is absent from numerous palaeoclimate records[28], including the Greenland ice cores (Fig. 2a). However, sea-level jumps identified in the Rhine-Meuse Delta[29] (Fig. 2d) and the Mississippi Delta[30] (Fig. 2e) suggest that the former may include both drainage events of Lake Agassiz (the first stage was initiated 8.54–8.38 kyr BP, 2σ error), whereas the latter captures the second stage only (8.31–8.18 kyr BP, 2σ error).

After correction (primarily for gravitational and elastic effects) based on previously published GIA model calculations[31], the Rhine-Meuse Delta RSL record indicates a sea-level jump of 3.0 ± 1.2 m (ref. 29; 1σ error; with a corresponding drainage volume of ~6–15×10^{14} m^3), whereas the Mississippi Delta record implies a magnitude of 1.5 ± 0.7 m (ref. 30; conservatively interpreted here as 1σ error; with a drainage volume of ~3–8×10^{14} m^3) for the final stage. As even the latter range exceeds the estimate[17] of the volume of Lake Agassiz during its final episode (1.63×10^{14} m^3), Lake Agassiz may have been larger than believed and/or a significant LIS contribution must be added; for example, due to rapid ice-sheet saddle collapse[32]. We note, however, that reconstructions of the LIS sea-level contribution[7] (Fig. 2g) have inferred relatively low rates around this time window. Also, we cannot rule out an AIS contribution around this time.

As well as freshwater volumes, fluxes are considered particularly relevant within the context of AMOC sensitivity. Hydraulic modelling[33] concluded that the final stages of Lake Agassiz drainage produced one or more peak freshwater fluxes of ~4–9 Sv (1 Sverdrup = 1×10^6 m^3 s^{-1}) over six months. This is far higher than predicted high-end estimates for GIS melt in the twenty-first century (0.07 Sv, as inferred from the GIS component of the 2 m sea-level rise scenario in ref. 3). The fluxes discussed here within the 9.5–6.5 kyr BP time window are shown in Fig. 2h; earlier Holocene catastrophic freshwater fluxes have been reviewed elsewhere[8,25] and are probably too small to have a detectable sea-level signature.

Another cooling event with a lower amplitude and duration (Fig. 2a), but with a comparable spatial extent, has been identified around 9.2 kyr BP[34]. A recent study has suggested that vastly smaller amounts of freshwater (4×10^{12} m^3, ~0.15 Sv if it occurred in one year), beyond the resolution of sea-level reconstructions, might have triggered this abrupt cooling[35]. It has been hypothesized that the triggering outburst was merely the culmination of a period of enhanced freshwater discharge that had preconditioned the North Atlantic Ocean in a similar fashion as discussed above for the 8.2 kyr BP event[34].

The problem of freshwater forcing volumes and their possible climate responses is further complicated by a more enigmatic, yet potentially much larger, meltwater pulse that has been inferred around 7.6 kyr BP. This phenomenon has received considerable interest in recent years by means of high-resolution RSL data from Fennoscandia[36] along with reconstructions of LIS retreat[7] (Fig. 2f,g). However, the proposed ~4.5 m abrupt rise in eustatic sea level[36] cannot be detected in relatively nearby, detailed RSL records from northwest Europe[37] (Fig. 2d). Moreover, no North Atlantic climate response for this time interval has been reported (Fig. 2a,b). Clearly, this conundrum needs to be resolved.

Sea-level fingerprinting

Future progress in understanding ice-sheet–sea-level interactions will hinge strongly on our ability to attribute past episodes of sea-level rise to spatially constrained meltwater sources. Gravitationally driven distortions of the geoid, due to the growth and decay of ice masses[38,39], are a key element of current GIA models. This theory has been used increasingly over the past decade, commonly with the purpose of 'fingerprinting' the origin of meltwater fluxes[31,40] (Box 1). Sea-level fingerprinting will probably play a prominent role in predictions of spatially variable rates of RSL change in the future[11]. Although this approach holds great promise, its application in (palaeo)sea-level studies is still in its infancy.

Within this context, the final stages of Lake Agassiz drainage offer a unique opportunity to compare reconstructed sea-level jumps with model predictions; a straightforward comparison requires conditions with only one sizeable and well-mapped source of abrupt mass loss, as other sources can be neglected. Here we carry out such a comparison to assess whether state-of-the-art RSL records can capture spatial patterns as derived from theory. Although only a few sufficiently detailed RSL records exist, they seem to be consistent with model predictions (Fig. 3). However, important caveats should be recognized. As discussed above, it is likely that the final Lake Agassiz drainage occurred in two stages

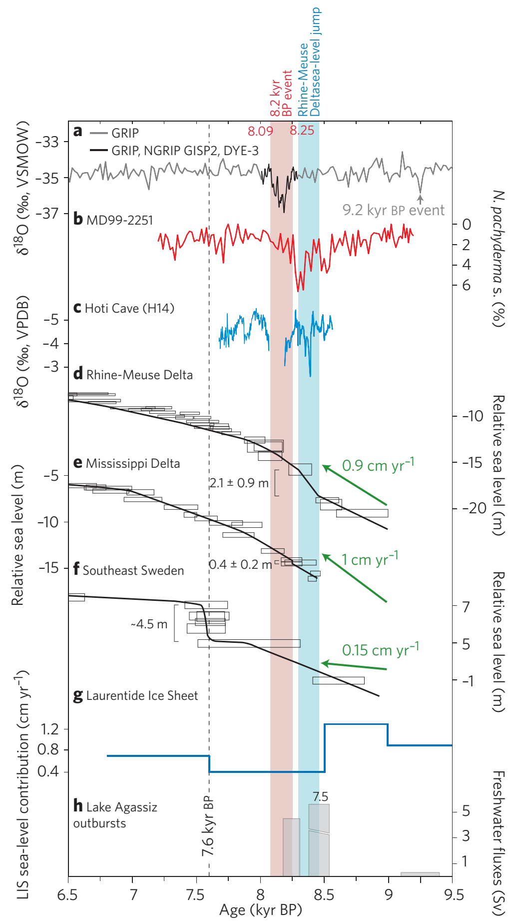
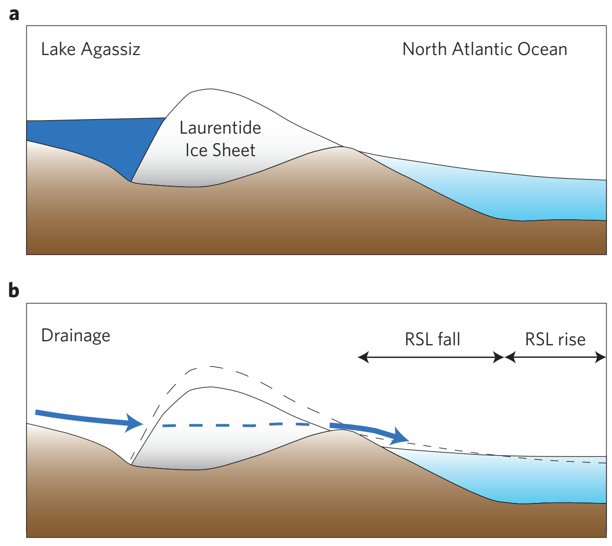


Figure 2 | Early Holocene high-resolution palaeoclimate and relative sea-level records. Ages are expressed with respect to AD 1950. **a**, Greenland ice-core $\delta^{18}O$ record, including a 10-year weighted mean time series around the 8.2 kyr BP event[24] and a 20-year weighted mean from the GRIP (Greenland Ice Core Project) core for the remainder of the record[47]. **b**, *Neogloboquadrina pachyderma* s. abundance in North Atlantic deep-marine sediments[26]. The ~100 year offset with respect to the other time series is likely to be caused by age uncertainties due to the marine ^{14}C reservoir effect. **c**, Speleothem $\delta^{18}O$ record reflecting Asian monsoon activity in Hoti Cave, Oman (stalagmite H14)[27]. Note the precursor to the 8.2 kyr BP event proper that can be recognized in several of the palaeoclimate records (**b**,**c**). **d**–**f**, Relative sea-level records from basal peat in the Rhine-Meuse Delta, the Netherlands[29,37] (**d**), the Mississippi Delta, Louisiana, USA[23,30,48] (**e**) and isolation basins in southeast Sweden[36] (**f**). The boxes are defined by the 2σ calibrated age range and the 2σ vertical uncertainty associated with a variety of errors. The relative sea-level curve from the Netherlands plots below the post-8 kyr BP data[37] as they indicate mean high water, whereas the pre-8 kyr BP data[29] indicate mean sea level. The onset of the sea-level jump was obtained by combining several ^{14}C ages that bracket its stratigraphic signature (midpoint of 8.45 kyr BP). The end of the sea-level jump (midpoint of 8.30 kyr BP) is defined by the next sea-level index point in the succession. The magnitude of sea-level jumps is indicated; note that the small sea-level jump in the Mississippi Delta relies primarily on stratigraphic evidence[30]. Green arrows indicate glacial-isostatic-adjustment-modelled rates of relative sea-level rise for 9.0–8.5 kyr BP[31]. **g**, Laurentide Ice Sheet (LIS) sea-level contribution[7]. **h**, Freshwater fluxes associated with catastrophic Lake Agassiz outbursts. The timing of the two final stages of Lake Agassiz drainage is derived from the 2σ age range of the onset of sea-level jumps in the Rhine-Meuse Delta[29] and Mississippi Delta[30], respectively. Their magnitudes are mean values for the most likely six-month drainage scenarios[33]; for consistency, the magnitude of the freshwater flux around 9.2 kyr BP[35] has been recalculated by assuming a similar duration.

Box 1 | Losing gravitational attraction



When a large ice sheet melts or a proglacial lake drains into the ocean, sea level will change non-uniformly around the globe[38–40]. Before a meltwater event, the mass of the ice sheet or lake gravitationally attracts the surrounding ocean water, and sea level in its proximity is raised. When this attraction disappears or decreases, ocean water will move away from the region and, counter-intuitively, sea level close to the meltwater source will fall, despite the net addition of water to the ocean. A schematic cross-section from Lake Agassiz across the LIS (Labrador dome; Fig. 1b) to the North Atlantic Ocean shows changes in sea level before (**a**) and after (**b**) the final outburst. Before the drainage, the combined mass of Lake Agassiz and the LIS pulled ocean water towards the region and raised sea levels. The drainage of the lake, combined with disintegration of portions of the LIS, resulted in decreased gravitational attraction and, within a ~2,000 km radius, the net change was an RSL fall[31] (Fig. 3). Beyond this region, the net effect was an RSL rise, but only at an 8,000–10,000 km distance was the net effect equal to the globally averaged eustatic rise due to the drainage event (that is, normalized RSL = 1). This non-uniform pattern of RSL change is known as the sea-level fingerprint. Thus, by comparing high-resolution RSL records from different parts of the world, the fingerprint concept can be used to pinpoint meltwater sources. It must be stressed that elastic and rotational effects also play a role over the short timescales of concern here. In particular, elastic effects approach gravitational effects in magnitude, and amplify the fingerprint[50].

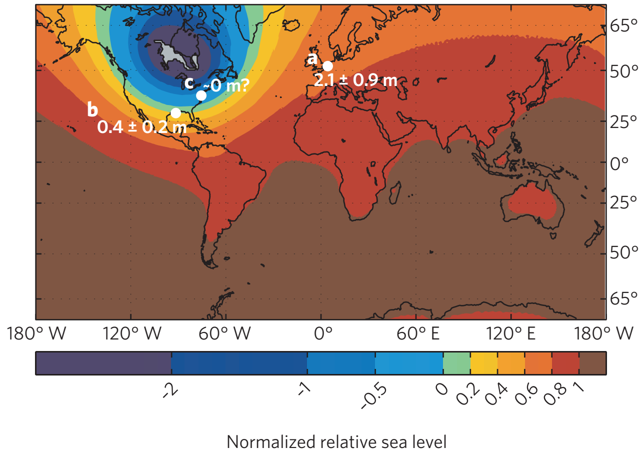


Figure 3 | Modelled sea-level fingerprint[31] of the final Lake Agassiz drainage compared with relative sea-level records. Sea-level jumps of different magnitudes around 8.2 kyr BP (with 1σ errors) have been reported from the Rhine-Meuse Delta[29] (**a**) and the Mississippi Delta[30] (**b**). In contrast, a record from Chesapeake Bay[49] (**c**) identified a period of marsh accretion centred on ~8.3 kyr BP (preceded and followed by phases of marsh drowning), interpreted here as an RSL slowdown (or possibly an RSL stillstand) that corresponds to the model prediction of zero RSL change at this time in this area. Note that this interpretation is tentative, given possible tidal-range changes around this time.

that may have been several centuries apart. Separation of these two stages in RSL records is therefore crucial, which places high demands on temporal resolution; but, with the currently available precision in ^{14}C dating (<20 ^{14}C yr at the 1σ level for Holocene samples), this can be overcome[30].

It should also be noted that the next generation of sea-level studies may face a new set of challenges. Sea-level indicators are rarely directly related to mean sea level; rather, they are related to an associated tide level[41]. Thus, variations in past tidal range are a potentially compounding factor. Indeed, recent palaeotidal modelling[42,43] has shown that the tidal range along the Atlantic coast of northwest Europe and North America has been up to three times higher during the early Holocene compared with the present. Ironically, these studies also showed that the opening of the Hudson Bay and Strait system (a major dissipation site for global tidal energy) contributed to a considerable reduction in tidal range throughout the Atlantic Ocean, coincident with the Lake Agassiz drainage and the 8.2 kyr BP event. Clearly, these are complications that cannot be ignored by sea-level studies that aim for decimetre-scale vertical resolution. In a similar vein, steric and dynamic ocean effects — for example, due to weakening of the AMOC — can cause sea-level variations of comparable magnitude[44], and therefore must also be addressed.

Synthesis and outlook

Recent sea-level reconstructions for the early Holocene have led to various new insights and demonstrate considerable promise for the future. Particular progress has been made with respect to the recognition of decimetre to metre-scale sea-level jumps that, in several cases, can be linked to abrupt climate changes such as the 8.2 kyr BP event. These new records, along with other palaeoclimate time series, increasingly suggest that abrupt climate change during interglacial conditions, such as those of the early Holocene, requires sustained freshwater forcing or multiple freshwater releases that allow for the preconditioning (that is, freshening) of surface ocean waters. Given the absence of a likely source for a similar magnitude of freshwater release in the North Atlantic within the next century (even under a worst-case scenario), concerns about abrupt climate change based on the 8.2 kyr BP event seem to have waned[18,30,45]. However, as the 9.2 kyr BP cooling event might have been triggered by a freshwater flux several orders of magnitude smaller[35], this issue is far from resolved.

On the other hand, the relative contribution of the LIS and AIS to the ~50–60 m early Holocene eustatic sea-level rise remains poorly constrained. Sea-level fingerprinting is likely to play a central role in resolving this important problem. Our comparison of RSL data with model predictions, using the final stages of Lake Agassiz drainage as a known meltwater source, shows that detailed RSL reconstructions are becoming increasingly capable of resolving sea-level fingerprints and testify to the potential of this approach.

Our analysis reveals several research avenues that are poised for rapid progress, including: (1) partitioning of ice volumes and melt rates between the LIS and the AIS during the early Holocene to help reduce key uncertainties about the last deglaciation; (2) constraining freshwater volumes as potential triggers of abrupt cooling to better assess the probability of future abrupt climate change; (3) refining GIA models by means of increasingly rigorous model-data comparisons.

To attain these goals, high-resolution sea-level studies from strategically selected localities are needed in tandem with considerably more detailed reconstructions of ice-sheet retreat, including ice-sheet modelling to constrain ice thicknesses. The close ties between the field-based sea-level community and GIA modellers have a long and prolific history; we expect this synergy to intensify in the future. Given the rapid adjustments of the solid Earth during the early Holocene, successful model-data comparisons for this time interval — which has often proven challenging — would further increase the confidence in GIA models, including their role in predicting future RSL change. Furthermore, given the high rates of early Holocene sea-level rise, GIA models will be pivotal in estimating background rates of RSL rise (as exemplified by Fig. 2d–f), and thus allowing the magnitude of sea-level jumps to be determined[29]. To enable the type of progress envisioned here, we anticipate that future generations of GIA models will increasingly incorporate three-dimensional Earth models[46].

Finally, we advocate a community-wide effort to establish a global, open-access repository of geological sea-level data that have been subjected to rigorous error assessment. Although work along these lines has been undertaken before for restricted geographic areas[9,10], no comprehensive and publicly available sea-level databases currently exist. Efforts like these will ultimately be critical to better predict future RSL change at the regional scale.

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Additional Information

The authors declare no competing financial interests.